Fall 2022

MICROBIOMES OF THE BUILT ENVIRONMENT

The BRIDGE

LINKING ENGINEERING AND SOCIETY

NATIONAL ACADEMY OF ENGINEERING

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The
BRIDGE

NATIONAL ACADEMY OF ENGINEERING

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The Bridge publishes articles on engineering research, education, and practice; science and technology policy; and the interface between engineering and technology and society. The intent is to stimulate debate and dialogue both among members of the National Academy of Engineering (NAE) and in the broader community of policymakers, educators, business leaders, and other interested individuals. *The Bridge* relies on its editor in chief, NAE members, and staff to identify potential issue topics and guest editors. Invited guest editors, who have expertise in a given issue's theme, are asked to select authors and topics, and independent experts are enlisted to assess articles for publication. The quarterly has a distribution of about 7000, including NAE members, members of Congress, agency officials, engineering deans, department heads, and faculty, and interested individuals all over the country and the world. Issues are freely accessible at *www.nae.edu/TheBridge*.

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The BRIDGE

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LINKING ENGINEERING AND SOCIETY

A Word from the NAE Chair

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NATIONAL ACADEMIES *Sciences Engineering Medicine*

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.

The **National Academy of Engineering** was established in 1964 under the charter of the National Academy of Sciences to bring the practices of engineering to advising the nation. Members are elected by their peers for extraordinary contributions to engineering. Dr. John L. Anderson is president.

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A Word from the NAE Chair

Engineering Leadership

Donald C. Winter, Chair, NAE

I expect that few individuals today would question the notion that we live in challenging times. Today's challenges are very diverse—from climate change and covid-19 to economic disruption and national security threats in Europe and the Pacific.

Society calls out for leadership: leaders who can not only provide a vision for the future but define an achievable roadmap to get there. Unfortunately, there is a tendency to look at leadership as a skill applicable primarily in the business, military, or political domains. Even those who accept the concept of engineering leadership tend to think of it in terms of projects or entrepreneurship.

But national and international public policies are often dependent on engineering concepts, and consequently also dependent on effective engineering leadership. They need and deserve expert assessment of the potential opportunities and the implications of alternative policies, best addressed through a systems engineering approach. This is an area where, I believe, the National Academy of Engineering can and should play a critical role.

The policies behind the transition from hydrocarbon-based energy sources to renewable sources, to address CO_2 emissions and the resulting impacts on the planet, are a good example of the need for engineering leadership. While there is general agreement on the objectives of such policies, there is little agreement on the path to achieve those objectives. In particular, there is great uncertainty about a suitable investment strategy to achieve the desired results. Various policy measures have greatly differing returns on investments and can have significant collateral impacts.

Providing uninterrupted power 24 hours a day, 365 days a year, is massively challenging! The difficulties are evident in Europe, where the transition to solar and wind power has been complicated by varying weather conditions, early deactivation of nuclear power sources, and limits on natural gas availability from Russia.

Without a systems perspective on the full impact of various policies and an executable roadmap to achieve the desired resilient and dependable electric grid, the resulting problems should not be a surprise. The transition of electric power must be engineered to be successful.

To provide uninterruptible power, solar and wind power need either a storage mechanism, such as batteries, or a resilient supplemental source. Unfortunately, scaling existing battery technology to the levels required is proving to be problematic. The future use of "green hydrogen" as a storage medium holds promise but the challenges of generating, storing, and distributing hydrogen at the scale required are formidable.

An alternative supplemental source of power that does not contribute to global CO_2 emissions is nuclear. While events at Chernobyl (1986) and Fukushima Daiichi (2011) remind us of the dangers posed by poorly designed and operated reactors, it is also important to remember that those were designs from many years ago.[1] France, which has 56 operable reactors (built between 1980 and 2002, with more under construction), safely produces 70 percent of its electric power from nuclear.[2]

What may come from a new generation of nuclear technologies?

The topic is the subject of a study, initiated and coorganized by the NAE, that will "identify opportunities and barriers to the commercialization of new and advanced nuclear reactor technologies in the United States over the next 30 years as part of a decarbonization strategy."[3] Looking at a range of perspectives, including

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[1] The earliest of the four Fukushima Daiichi reactors was built in 1967; the next two were built in the early 1970s. Their designs date from the 1960s.

[2] https://www.world-nuclear.org/information-library/country-profiles/countries-a-f/france.aspx

[3] https://www.nationalacademies.org/our-work/laying-the-foundation-for-new-and-advanced-nuclear-reactors-in-the-united-states

safety, nuclear waste, and workforce requirements, the committee is expected to issue its report early in 2023. The scope of the committee's effort is daunting but so is the opportunity. Along with a parallel Academies effort on nuclear fuel cycles,[4] funded by the DOE, the NAE has a unique opportunity to provide meaningful input to national policy debates on the future direction of electric power generation in the United States.

The study on the commercialization of new nuclear energy technologies is somewhat unique among the many studies underway in the National Academies. Its scope is quite broad and it addresses a very general but critically important topic. All too often, the Academies are asked to examine fairly specific programs that are already underway. With the freedom to explore a wide range of technology options and mechanisms of implementation, the committee—chaired by NAE member **Richard A. Meserve**—can provide the engineering leadership that this topic needs. The imprimatur of the NAE should greatly enhance the acceptance of its observations and assessments.

It must be noted that this stage for leadership has been set by the mechanism of funding for this committee effort. The majority of funding came through a gift from NAE member **James J. Truchard**. This independent funding enables flexibility in the study and avoids limitations associated with efforts that occur later in the policy development cycle.

While the majority of the Academies' study efforts are in response to government requests, the opportunity to provide true engineering leadership through independently financed studies is noted and valued. Many other areas would benefit from such examinations. Just think of the public policy implications of establishing a viable pathway to green hydrogen production and distribution, or a nationwide infrastructure to support electric vehicles. Such investigations will require other contributors with the vision and generosity of James Truchard. We extend to him our sincerest thanks—and need to look for others so inclined.

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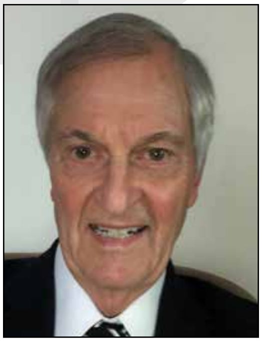
[4] https://www.nationalacademies.org/our-work/merits-and-viability-of-different-nuclear-fuel-cycles-and-technology-options-and-the-waste-aspects-of-advanced-nuclear-reactors

Editor's Note

Thoughts on the Future of the Building Microbiome



Ronald M. Latanision (NAE) is a senior fellow at Exponent.

The global covid-19 pandemic has not only imposed immediate changes on daily life, work, education, and commerce but also ushered in new thinking about the ways—and places—we work, study, and live. While some buildings are upgrading their HVAC systems to reduce risks of airborne transmission in the wake of the pandemic, buildings of all kinds (offices, apartments, schools, hotels, hospitals, etc.) face a public that is concerned about its health and the capacity of buildings to reduce risks and assess health conditions.

I sense that the public's concern will change buildings for the long term. That sense is the product of having served a few years ago on a NASEM study committee tasked with assessing (i) the state of knowledge regarding microbial communities (bacteria, viruses, fungi, etc.)—the "microbiomes" of the built environment—and, importantly, (ii) the implications for human health, sustainability, security, and the design and construction of physical infrastructure systems and other elements of the built environment. The committee's consensus report, *Microbiomes of the Built Environment: From Research to Application*, was published in 2017.

In many ways this committee anticipated the current state of affairs on our small planet in terms of the covid-19 pandemic that followed. Among the committee members—who included civil engineers, architects, microbiologists, pathologists, bioinformatics experts, and a materials engineer (yours truly[1])—were this issue's guest editors **Chuck Haas** and Vivian Loftness as well as contributing authors Jack Gilbert, Diane Gold, and Andrew Persily.

In this issue of *The Bridge* a postpandemic sense of the future, near and long term, is presented by an outstanding collection of authors. Going forward, both new and existing buildings must and will respond to the events of the past 2-plus years. A number of questions need to be addressed:

What developments in engineering and technology are needed to ensure public health in enclosed public or high-occupancy private spaces, whether for work, residence, education, transportation, sports, entertainment…?

What changes are being implemented?

How will approaches differ for existing vs. new structures?

What are the technical and/or policy challenges?

I also expect that buildings will require new materials—for detectors and sensors of all kinds, for example—and that discussions will evolve between building designers who identify a materials need and materials researchers who can design and engineer the materials to meet that need.

The Materials Genome Initiative (MGI) provides the basis for such conversation. MGI was launched in 2011 during the Obama presidency by the White House Office of Science and Technology Policy (OSTP) to help (i) accelerate the design, discovery, development, and deployment of advanced materials and (ii) reduce costs through the integration of advanced computation

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[1] For me, this experience was a proverbial drink from a firehose. I have a PhD microbiologist daughter, but almost no personal research or engineering experience with biology.

and data management with experimental synthesis and characterization. The vision is to design materials with required properties from first principles in a fraction of the time and at a fraction of the cost of traditional empirical materials development. MGI is reshaping materials education and practice, in service to societal and national needs.

The built environment is fundamental to life all over the world, and my hope and expectation is that, with public will and political will as the drivers, safe and healthy buildings will become the norm in architecture and construction.

Ron M. Latanision

Issue Editors' Note

Microbial Challenges in the Built Environment

Charles Haas

Vivian Loftness

Charles Haas (NAE) is the LD Betz Professor of Environmental Engineering, Drexel University. Vivian Loftness is Paul Mellon University Professor of Architecture, Carnegie Mellon University.

On average, individuals spend 87 percent of their time indoors (Klepeis et al. 2001). Therefore, human exposures in this environment need to be characterized to determine where, how, and how much intervention is needed to reduce risks. While the focus here is on microbial exposure, indoor exposure to chemicals (Li et al. 2019), including secondary organics produced by indoor reaction (Yang and Waring 2016) and radioactive isotopes (e.g., radon) (Field et al. 2006), is also important.

There is a long history of reported adverse health effects associated with microorganisms or their metabolites in the indoor environment (Nag 2019). Yet over the past decade—starting well before the SARS-CoV-2 outbreak in late 2019—there has been an explosion of scholarship with respect to the indoor microbiome (figure 1).

There is clear evidence for adverse effects of diverse microbial pathogens in the indoor environment (table 1). Human exposure can result from either inhalation or fomites (i.e., individuals touching contaminated surfaces and then transferring pathogens to the nose, mouth, or eyes). These pathogens include human coronaviruses such as SARS (severe acute respiratory syndrome) and MERS (Middle East respiratory syndrome).

National Academies Consensus Report

In 2017 a committee of the National Academies of Sciences, Engineering, and Medicine produced a consensus report summarizing the state of knowledge of the microbiome of the indoor environment and identifying research needs (NASEM 2017).[1] It was recognized that the indoor environment represents a highly coupled ecosystem of human and other inhabitants (including animals, pets, and insects), engineered building systems, and microbial communities (figure 2).

In addition to pathogens, noninfectious diseases or syndromes, some of which may be mediated by microbial metabolites or fragments from organisms whose growth is promoted by permissive conditions (e.g., humidity or temperature) in buildings, are of concern. The committee found strong evidence of association among the following[2] (although mechanisms are mostly not certain):

- upper respiratory tract symptoms
- wheezing
- coughing
- shortness of breath
- development of asthma
- exacerbation of asthma
- hypersensitivity pneumonitis.

The dynamics of the indoor microbiome are influenced by complex processes, both intrinsic to a building and

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[1] We were members of the committee, as were the following contributors to this issue: Jack Gilbert, Diane Gold, and Andrew Persily.

[2] There were other outcomes for which insufficient or inconsistent evidence was available.

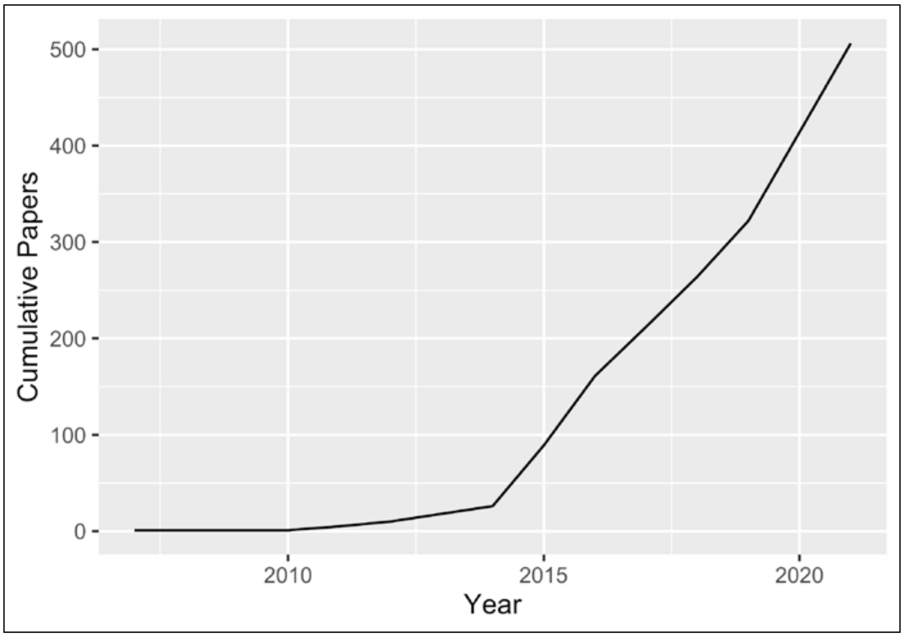

FIGURE 1 Papers published with the term "indoor microbiome" (Google Scholar, 4/23/2022).

TABLE 1 Mode of transmission—inhalation or fomite interaction—for selected pathogens implicated in human infections.

Super kingdom	Via inhalation	Via fomites
Bacteria	*Bacillus anthracis* *Coxiella burnetii* *Chlamydia psittaci* *Legionella* *Mycobacterium tuberculosis* Atypical mycobacteria	*Clostridium difficile* *Staphylococcus aureus* *Enterococcus*
Fungi	*Cryptococcus neoformans* *Histoplasma capsulatum* *Aspergillus fumigatus*	*Trichophyton mentagrophytes* *Trichophyton rubrum*
Protozoa	*Acanthamoeba* spp.	
Viruses	Variola (smallpox) Rubella Norovirus Rotavirus Adenovirus Coxsackie virus Influenza Rhinovirus Coronaviruses (Middle East respiratory syndrome [MERS], severe acute respiratory syndrome [SARS])	

Source: NASEM (2017).

due to exchanges with external environments, as illustrated in figure 3. Not shown in this figure are important sources of pathogens resulting from aerosolization of any water from indoor sources such as humidifiers (Tyndall et al. 1995) and showers (Hamilton et al. 2019).

The 2017 committee identified 12 priority research areas under the following five themes:

- Characterize interrelationships among microbial communities and built environment systems of air, water, surfaces, and occupants.
- Assess the influences of the built environment and indoor microbial exposures on the composition and function of the human microbiome, on human functional responses, and on human health outcomes.
- Explore nonhealth impacts of interventions to manipulate microbial communities.
- Advance the tools and research infrastructure for addressing microbiome–built environment questions.
- Translate research into practice.

Significance in Light of Covid-19

The covid-19 pandemic and consideration of means of transmission have increased attention to the role of the indoor environment in disease transmission. The provision of clean water and adequate sanitation is recognized as one of the greatest 20th century engineering advances (Constable and Somerville 2003). In light of the pandemic, it has been argued that improvement in indoor air quality is now an urgent engineering need for the control of respiratory infectious diseases (Morawska et al. 2021).

For SARS-CoV-2, the aerosol route of transmission may be the dominant (Tellier 2022)—though not exclusive (Kraay et al. 2021)—one. Recognition of the importance of this route for covid-19 transmission was initially handicapped by a misunderstanding of how suspended particles behave in the indoor environment (Randall et al. 2021). However, for other organisms, fomite or droplet routes may be more significant (Kraay et al. 2018), so the control of fomite risks from touched surfaces cannot be neglected.

In This Issue

The aim of this issue is to outline problems associated with the microbiome in the built environment and to review approaches to address them, toward enhanced design, engineering, and operation of more healthful indoor air in the future.

Stating the Problems

The first several articles state the problems. Brent Stephens, Kyle Bibby, and Karen Dannemiller begin by discussing the impacts of covid-19 on understanding microbial and viral exposures in the built environment. They intro-

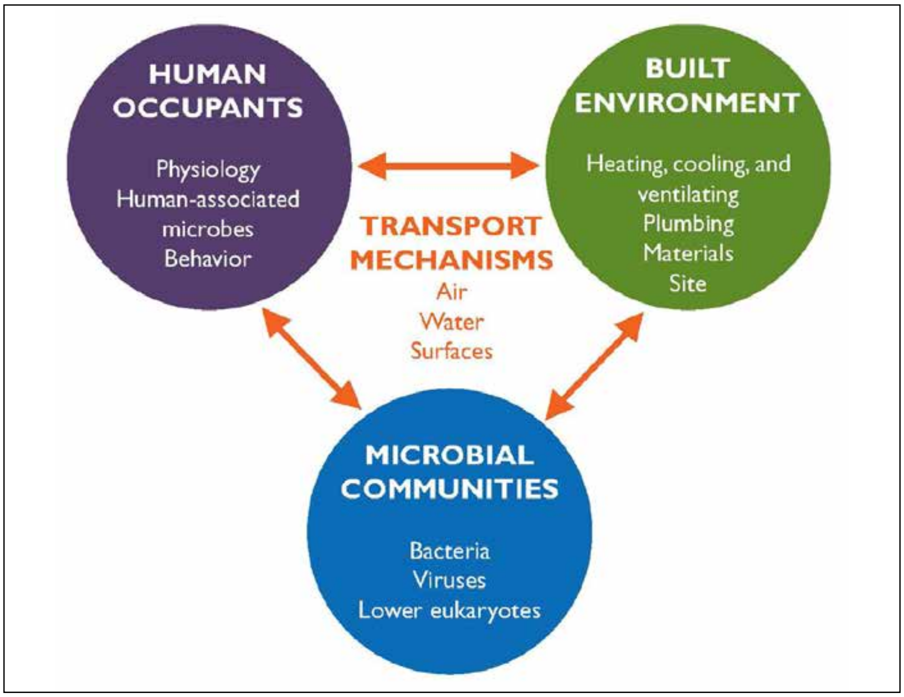

FIGURE 2 The complex interactions among human occupants, built environments, and associated microbial communities. Source: NASEM (2017).

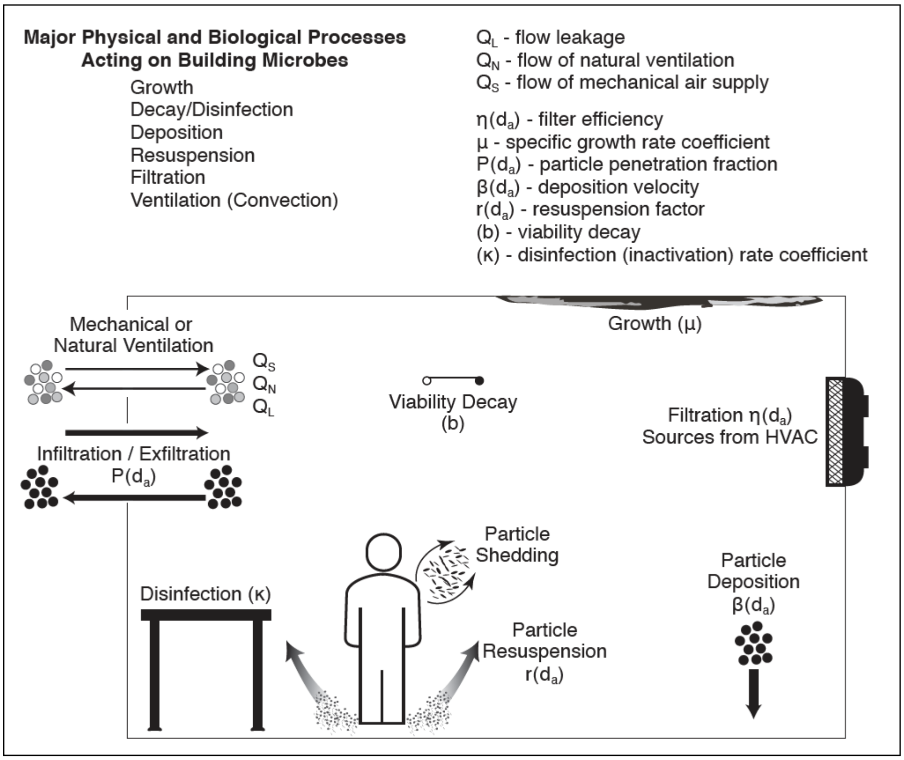

FIGURE 3 Physical processes govern the assembly of indoor microbial communities, with values and coefficients representing ventilation sources and losses. The term d_a is the aerodynamic diameter of a particle (or cell), and parameters that include (d_a), such as $P(d_a)$ or $\beta(d_a)$, indicate that the value of this parameter is influenced by the aerodynamic diameter of a particle. Source: NASEM (2017).

duce strategies for measuring viral disease prevalence in wastewater, building dust, air, and on surfaces, and call for the expansion of both random population and individual testing, while recognizing associated costs, inconvenience, and differing data resolution requirements, among other factors.

Erica Hartmann then looks at engineering and design factors as well as the role of urban development in healthful built environments. There are important considerations in the possible benefits of outdoor versus indoor air; effective filtration and correct use of cleaning products are relevant, as are impacts on energy use and cost. The creation of healthful built environments requires mindful attention to design, maintenance, energy demands, and equity.

The third article, "Estimating Indoor Microbial Risks as Applied to Covid-19," presents the application of quantitative microbial risk assessment (QMRA) as an invaluable approach to hazard identification, dose response, exposure assessment, and risk characterization of respiratory pathogens. Advances are needed to better account for population heterogeneity and incorporate dose-response models in disease transmission models.

Exploring Solutions

The next series of articles consider solutions to microbial challenges in the built environment. Active air interventions are discussed by Jelena Srebric and Don Milton as "an important mechanism for reducing risks of [airborne] infection transmission." The authors explain the utility and challenges of ventilation, filtration (including portable devices), and germicidal ultraviolet light. They also call for "significant investment" to develop and test technologies, standards and certification for them, research to better understand the link between interventions and health outcomes, and policies that support improved residential ventilation.

Andrew Persily and Jeffrey Siegel highlight standards and actions to improve ventilation performance, which is as critical as handwashing, face masks, vaccination, and distancing. They point out the need to "recognize the large amount of variation between buildings and their ventilation systems, which directly relate to what can and should be done in a given building." The authors also cite the utility of CO_2 monitoring, operations and maintenance, and the need for research to inform updated standards.

Hooman Parhizkar, Alen Mahić, and Kevin Van Den Wymelenberg affirm the importance of ventilation standards and HVAC operating scenarios to control disease transmission risk. They used a reference building for their risk-energy decision support platform to calculate risk of disease transmission taking into account current ventilation standards, air exchange rates, relative humidity values, and associated energy consumption. Looking ahead, they write that "Future energy codes, ventilation standards, and HVAC system operational and maintenance guidelines would all benefit from a concurrent understanding of how key indoor air variables implicate annual energy use and airborne disease transmission risks."

The built environment includes water-related structures, whose water-generated microbiomes can affect public health. Kerry Hamilton and Timothy Bartrand present an extensive and detailed table, ordered by level of public health risk, of microenvironment-associated water microbiomes—from medical devices to cooling towers, showerheads, fountains, pools and hot tubs, and ice machines, among others. For each they summarize primary exposure routes, public health significance, data and knowledge gaps, and best practices in management, with relevant citations throughout.

In an article titled "Microbial Surface Transmission in the Built Environment and Management Methods," Amanda Wilson, Diane Gold, and Paloma Beamer discuss fomite transmission of respiratory and other pathogens (including *C. difficile* and *Staphylococcus*). They acknowledge the role of human behavior not only in pathogen transmission but also in an overzealous approach to surface cleaning that "leads to fewer interactions…with…nonharmful microorganisms that aid in immune system development." Infection control methods should protect nonharmful microorganisms, encourage proper use of cleaning chemicals, and prioritize layered engineering strategies (e.g., proper ventilation and air filtration, use of UV light).

Building on the topic of beneficial microorganisms, Megan Thoemmes, Sarah Allard, and Jack Gilbert distinguish between "pets and pests," and caution that "People now come into contact with a smaller subset of diverse organisms that are important not only for immune development but also for the reduction of pathogen abundance indoors." They envision "a future where microbial biocontrol can be engineered into building materials…to provide surfaces that both actively reduce the emergence and persistence of dangerous pathogens and create immune-activating exposure to decrease the incidence of chronic immune disease."

Looking Ahead

The pandemic highlighted significant inequities in microbial exposure and health, and to prepare for future public health challenges, responsible engineering practice requires consideration of these as much as standards, ventilation performance, filtration, and other engineering approaches. Diane Gold, Tyra Bryant-Stephens, Elizabeth Matsui, and Lee Ann Kahlor review the specific problems due to covid-19—such as amplified poverty, housing instability, more crowding (as individuals lost jobs or their own homes and moved in with extended family)—and their role in increased respiratory infection incidence, morbidity, and mortality. Given the historical practices that created the present-day state of US housing and neighborhoods, the authors call for systemic changes as well as community engagement, respectful research methods, more effective risk communication, and improved housing quality.

In the final article, Robert Dunn and Megan Thoemmes explain humans' unconscious and conscious awareness of microbes. The former is represented in "the extraordinary sophistication" of the immune system; the latter is comparatively recent and lacks the capacity to distinguish between harmful and beneficial microbes. Loss of exposure to the latter is associated with problems of gut health, skin health, and even mental health. Their point is that "in the long term people need to understand how to manage the microbiomes of daily life in more sophisticated ways to favor beneficial species, ignore benign species, and strategically target problem species."

Conclusion

This timely issue of *The Bridge* conveys some of the breadth of the challenges and potential solutions to microbiomes in the built environment. It is also clear that much is still to be learned.

Advances in the application of tools of molecular biology to the indoor microbiome (Gilbert and Stephens 2018) will enhance understanding of the fate, transport, proliferation, and impacts of microorganisms indoors and the role of exchanges with outdoor environments. Based on such knowledge and the incorporation of risk assessment, engineering interventions for risk reduction can be better designed.

The covid-19 pandemic has been a wake-up call to the engineering community and society. The articles in these pages illustrate some paths forward to better prepare for future such challenges. To design, construct, operate, and maintain more healthful buildings, a multidisciplinary program of fundamental, applied, and translational research is necessary, and it should involve federal, local, and nongovernmental funding sources to address the challenges posed in this issue.

Acknowledgments

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Covid-19 spurred advances in research, monitoring, and knowledge of microbes and viruses in the built environment.

Covid-19 Impacts on Understanding Microbial and Viral Exposures in the Built Environment

Brent Stephens, Kyle J. Bibby, and Karen C. Dannemiller


Brent Stephens


Kyle Bibby


Karen Dannemiller

Covid-19 has dramatically shifted the world's attention to the microbiology of the built environment, albeit focused on a single virus: the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). This focus has altered the trajectory of research and development for understanding and tracking microbes and viruses.

We believe that the covid-19 pandemic has produced major shifts in public awareness of the microbiology of the built environment, in public and institutional knowledge of transmission pathways of pathogens, and

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Brent Stephens is professor, chair, and Arthur W. Hill Endowed Chair in Sustainability, Department of Civil, Architectural, and Environmental Engineering, Illinois Institute of Technology. Kyle Bibby is professor and Wanzek Collegiate Chair, Department of Civil and Environmental Engineering and Earth Sciences, University of Notre Dame. Karen Dannemiller is associate professor, Civil Environmental and Geodetic Engineering and Environmental Health Sciences, The Ohio State University.

in technologies and approaches to monitor microbes and viruses. Granted, these shifts are narrowly focused on respiratory viruses, but they can translate to other microbes and viruses.

> *Progress and preparation for the future depend on many factors (e.g., social, political, and economic), and engineers should be actively engaged.*

Engineers, informed by knowledge in exposure science, pathogen transmission dynamics, and engineering controls, have played a critical role and demonstrated their unique value to public health, especially in the monitoring and modeling of microbial and viral transmission and exposures. Progress and preparation for the future depend on many factors (e.g., social, political, and economic), and engineers should continue to be actively engaged.

Understanding Microbes in the Built Environment

In the decade prior to 2020 and the onset of covid-19, there was tremendous growth in understanding of the microbiology and microbial ecology of indoor environments. Advances in rapid, affordable DNA sequencing technologies, spurred by research investments by private foundations, significantly expanded knowledge beyond what conventional techniques (e.g., culturing and microscopy) could reveal.

Precovid Research

Insights emerged about the unique nature of the microbiology of indoor environments (as distinct from natural Earth systems) and the factors that structure the vast diversity of indoor microbial communities, such as moisture, building operation (e.g., ventilation and window opening), and occupant density and activities (Gilbert and Stephens 2018). Specific microorganisms were even associated with positive health outcomes. One notable study found that *Lactobacillus johnsonii* isolated from house dust—and ultimately attributed to dog occupancy—was protective against allergy inflammation and viral infection (Fujimura et al. 2014).

Research characterized microbial communities across a variety of environments, from homes (e.g., Lax et al. 2014) to hospitals (e.g., Lax et al. 2017), retail stores (e.g., Hoisington et al. 2016), public transportation (e.g., MetaSUB International Consortium 2016), and even the International Space Station (e.g., Haines et al. 2019). This work was largely done in academic and medical spheres before covid-19, with the exception of some nascent industrial applications such as probiotic cleaners (Caselli et al. 2018; Stone et al. 2020).

Covid-Associated Awareness

We posit that the emergence of covid-19 rapidly transformed public and institutional awareness of the microbiology of the built environment, at least as it relates to viral infection (not necessarily as it relates to broader microbial ecology). Much of the informed public now has at least a basic familiarity with polymerase chain reaction (PCR) tests and rapid antigen tests; before the pandemic, knowledge of these tools was mostly limited to physicians and researchers.

In addition, major shifts in human behaviors in buildings include enhanced surface cleaning, occupancy limitations, behavior modification, and increased awareness of air handling equipment, ventilation, and air cleaning. Indoor carbon dioxide (CO_2) measurements gained traction as an indicator of occupancy and ventilation rates (and inferred infectious risk), and debates about the efficacy of differing air filtration or cleaning approaches entered the public sphere.

We expect that this awareness will expand beyond the specific case of covid-19 to other applications, including other infectious agents and microbes that affect health outcomes such as allergies and asthma.

Microbial Transmission in the Built Environment

Covid-19 highlighted the importance of understanding transmission and exposure routes for viruses in the built environment—as well as tremendous gaps in scientific and public knowledge about these areas.

A Needed Surge in Research

Despite the impacts of respiratory viruses on public health and the economy, and considerable knowledge of microbial exposures and pathogen transmission in other contexts, only a handful of studies have explored the critical mechanistic characteristics of viruses such as influenza in the built environment. Researchers have investigated the quantity and size resolution of human-emitted particles containing influenza virus (Lindsley et al. 2015; Milton et al. 2013; Yan et al. 2018), the virus's survival rates in air and on environmental surfaces (Greatorex et al. 2011; Marr et al. 2019), and the role of different pathways for influenza transmission according to physics- and engineering-based principles (Jones and Adida 2011). Gaps in knowledge of these parameters for other respiratory viruses are even wider.

Since covid-19 emerged, in a span of less than 2 years a rich body of literature on measuring and modeling SARS-CoV-2 in indoor and built environments, informed by robust knowledge of factors that affect indoor exposures to a range of contaminants, rapidly advanced understanding of the transmission of covid-19. Studies detecting SARS-CoV-2 genetic material in air and on surfaces (e.g., Liu et al. 2020) and viable SARS-CoV-2 in indoor air (e.g., Lednicky et al. 2020a) provided evidence for possible environmental transmission pathways.

Computational models further quantified distributions of SARS-CoV-2 in indoor environments (e.g., Vuorinen et al. 2020), and mechanistic models demonstrated the likely dominant pathways of covid-19 transmission (e.g., Azimi et al. 2021).

A Paradigm Shift in Understanding

This work has helped usher in a "paradigm shift to combat respiratory infections" in the built environment (Morawska et al. 2021). This shift calls for reimagining the prevailing understanding of pathogen transmission and microbial exchange.

Before and during the early months of covid-19, and to an extent still today, medical and public health communities held closely to infection control guidelines that did not align terminology and control measures with the physics and engineering principles that govern the underlying mechanics of disease transmission. Rapidly advancing scholarship on covid-19 illuminated these discrepancies, highlighting the shortcomings of commonly used terminology that makes artificial distinctions between terms such as "close contact," "droplet," "airborne," and "droplet nuclei" transmission based on a confusing conflation of particle sizes, transmission distances, and exposure routes.

Thanks to the pioneering work of engineers and scientists, it is now recognized that these terms are largely disconnected from the physical behavior of particles transmitted between people in the built environment (Li 2021; Tang et al. 2021). The cited research shows that evidence of "close contact" transmission is not the same as evidence of large particle (i.e., "droplet") transmission. The latter was previously defined by a relatively arbitrary cutoff of approximately 5 μm in droplet diameter, capable of transmitting no more than 1–2 m.

It is now more widely understood that "close contact" transmission includes a continuum of small to large particle exposures that can be emitted, transmitted, and inhaled over short distances. In fact, the smallest aerosol particles are concentrated in close proximity of an infected individual such that precautions to mitigate "close contact" transmission artificially conflate distance and particle size, with dire consequences for the use of less effective nonpharmaceutical interventions such as cloth masks. And "droplet" transmission is now better characterized by very large droplets (>50 or 100 μm) that do not remain suspended in air but rather "spray" directly onto individuals and surfaces.

> *Infection control guidelines should be informed by the physics and engineering principles that govern the underlying mechanics of disease transmission.*

Increased understanding of this disconnection moved public health guidance from initially advising against masks[1] and calling only for social distancing, to advising "face coverings" (with low efficiency for capturing small aerosol particles) and social distancing to combat droplet/close contact transmission, to now advising wearing the best mask (e.g., N95 or similar) one can comfortably wear to protect against small aerosol particle transmission over any range of distances.

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[1] It is also relevant that masks were limited in supply early on and were therefore reserved for healthcare and other "frontline" workers.

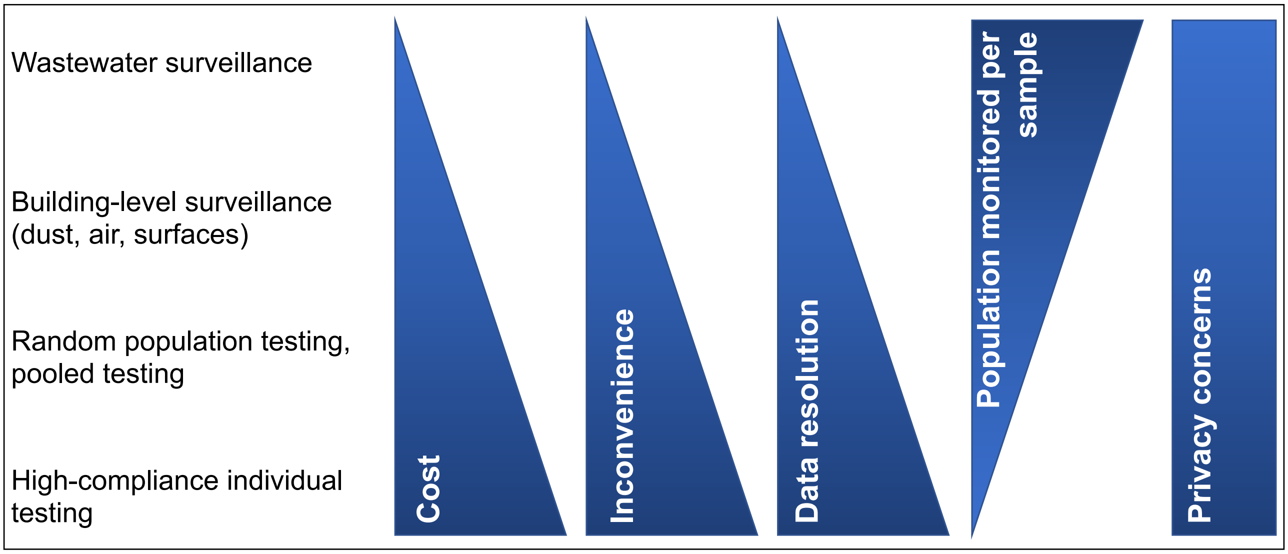

FIGURE 1 Strategies for measuring viral disease prevalence and their relative associated cost, inconvenience, data resolution, population monitored, and privacy concerns. Values are relative and not to scale.

The disentangling of conflating factors, driven in large part by scientists and engineers, has the potential to save lives if widely adopted by the medical and public health communities.

Revolutionized Approaches to Monitoring Microbes in the Built Environment

Historically, microbial and disease monitoring approaches in the built environment were limited to highly specific use-cases (e.g., pathogen control in hospitals and biosecurity applications). This has been transformed by the covid-19 pandemic.

Disease prevalence information has been critical in monitoring the course of the pandemic and selecting appropriate mitigation strategies. Novel environmental sensing approaches include monitoring for viral fragments in air, on building surfaces and in dust, and in wastewater to interpret the disease trends in a subpopulation. These technologies are built on understanding established by fundamental studies of the microbiology of the built environment (NASEM 2017).

The spectrum of methods to measure the prevalence of viral disease includes wastewater surveillance, building-level surveillance (e.g., dust, air, surfaces), random population and pooled testing, and high-compliance individual testing (figure 1). They are associated with per-sample differences in cost, inconvenience, data resolution, population monitored, and privacy concerns, and can be used individually or in combination depending on data resolution needs and resource availability.

Individual Testing

The most straightforward method to measure disease prevalence is repeated individual testing, such as through saliva testing or nasal swabs combined with PCR or rapid antigen tests. These measures offer high-resolution data and rapid identification of infected individuals who can then be isolated to mitigate transmission. However, only one person is monitored per sample at high per-sample cost and some individual inconvenience, at least as compared with community-level testing approaches.[2]

Another technique involves pooling samples, which still results in testing inconvenience but saves testing resources and allows for population monitoring (Deckert et al. 2020).

Community-Level Testing

Monitoring of wastewater from sewer systems has proven extremely effective for determining disease prevalence in communities. Many infected individuals shed the virus in feces, and it can then be detected in wastewater samples. This method has been substantially advanced and widely implemented during the covid-19 pandemic.

One sample can provide aggregate information for up to 2 million individuals depending on the catchment area (Hart and Halden 2020). The technique does not identify infected individuals directly, but, for

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[2] While in-home test kits have been made available for free to the public, there are still costs associated with administering such programs.

example, was used for mitigation to notify individuals on the University of California San Diego campus to get tested—the notices increased testing rates as much as 13-fold (Karthikeyan et al. 2021). These samples also do not require the inconvenience of routine individual testing as most individuals do not need to take any action except when notified.

Other environmental monitoring strategies have been deployed during the pandemic. They include air sampling and surface swabs (e.g., Angel et al. 2022; Harvey et al. 2021; Lednicky et al. 2020b; Santarpia et al. 2020) and generally monitor a small population (i.e., that of a building or part of a building) to provide higher-resolution data, although at a higher per-person cost than wastewater because of the greater number of sites and samples needed. Wastewater monitoring at the building scale is often challenging because of difficult access points, outdated sewer maps, and the fact that not everyone sheds the respiratory virus in feces (Wang et al. 2020).

The technique of monitoring of viral RNA in building dust has precedent in monitoring for other pathogens, allergens, and antibiotic resistance genes and was implemented successfully on the main campus of the Ohio State University.[3] Dust collected from isolation rooms of covid-positive students was shown to have an overall higher concentration and higher percent of positive detects compared to surface swabs and air samples from the same environments (Renninger et al. 2021). Notably, SARS-CoV-2 RNA may persist for at least 4 weeks in building dust, so improvements are needed to discriminate between recently shed and relic RNA to confirm recent infection (Renninger et al. 2021).

In summary, existing tools and novel techniques have together improved monitoring capability for viral disease prevalence. Appropriate techniques can be expanded to other viral diseases and broader constituents of the microbiome of the built environment, both for monitoring and to inform mitigation strategies. Any approach to population monitoring must address ethical and privacy concerns.

What's Next for Research on Microbial and Viral Exposures in the Built Environment?

The global focus on a singular virus has had an unprecedented impact on the understanding, monitoring, measurement, and modeling of pathogens in the built environment, and also likely altered awareness of the broader microbial ecology of the built environment.

Increased knowledge of the importance of indoor air in infectious disease transmission has led to federal resources for improving ventilation and filtration in buildings and the US Environmental Protection Agency's Clean Air in Buildings Challenge.[4] These resources and initiatives also emphasize the need for robust industry and federal standards to assess technologies for cleaning indoor air backed by solid science and engineering to avoid negative unintended consequences (Collins and Farmer 2021).

Industry and federal standards backed by science and engineering can help avoid negative unintended consequences.

The following questions may guide thinking about further steps:

- Can advances in rapid antigen at-home covid tests be leveraged to monitor for other relevant microbes in the built environment and in people?
- How can measurements and models be better integrated to facilitate understanding and validation of the effectiveness of covid-19 interventions—and preparation for the next pandemic or other microbial-related public health threat?
- Not least, what unintended ethical and privacy concerns might arise from approaches to population-scale monitoring of microbes and viruses?

Declaration of Competing Interest

KJB and KCD are coinventors on a patent application applying dust surveillance for indoor disease monitoring applications.

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[3] Dust collected from campus buildings will help track COVID-19. Ohio State News, Aug 26, 2021.

[4] https://www.epa.gov/indoor-air-quality-iaq/clean-air-buildings-challenge

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Healthful built environments require attention to design, energy consumption, air exchange, maintenance, and equity.

Engineering and Design Factors for Healthful Built Environments

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In Maslow's hierarchy, shelter is a physiological need, humans' most fundamental requirement, and the basis of safety. People expect built environments to protect them not only from harsh elements like extreme weather but also from less visible threats, such as pathogens and toxic chemicals.

The engineering challenge of meeting these expectations increases in complexity following the complexity of the demands: It is relatively easy to build a structure that provides shade from the sun, somewhat more complicated to also keep out the rain, and much more sophisticated engineering approaches are needed to protect occupants from air- or waterborne pathogens. Moreover, it is extremely challenging to achieve all of these without exposing the occupants to potentially harmful chemicals.

Role of Urban Development and Engineering in Pathogen Spread

Host-pathogen interactions are a function of evolution and ecology, an intricate dance involving pathogen virulence, host resistance, and third-party species that can act as reservoirs or be the victim of "spillover"[1] (Harvell 2004). As with many natural phenomena, human activities have accelerated the rate of new disease outbreaks (Harvell 2004).

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[1] Spillover occurs when there is close contact between humans and nonhuman hosts.

Urban Development

The historical transition from a nomadic lifestyle to agrarian civilizations with domesticated livestock increased the transfer of microorganisms—including viral, bacterial, and fungal pathogens—between humans and other animals (Piret and Boivin 2020; van Schaik 2022). More recently, increased population density, changes in land use, and rapid global travel have exacerbated the spread of infectious disease, increasing the frequency and magnitude of pandemics (Mankiewicz et al. 2021; Piret and Boivin 2020).

Once introduced to humans, pathogens can spread via several routes—including water, air, surfaces (fomites), or close physical contact with other building occupants—all of which are facilitated by various aspects of modern civilization. Thus, the structure and interconnectedness of urban areas and buildings can affect the number and frequency of transmission events.

Engineering and Building Design

Although high-density urban areas favor the transmission of communicable disease, smart engineering can help protect residents from exposure.

Among the earliest examples of engineering approaches to impede the spread of pathogens are water distribution and sanitation systems (Montgomery and Elimelech 2007). Indeed, access to water and sanitation through engineered systems can effectively eradicate waterborne diseases. However, even today access to clean water is not universal, and creative engineering and design solutions are needed to overcome obstacles to the development, adoption, and maintenance of urban and other water treatment systems (Montgomery and Elimelech 2007; Piret and Boivin 2020; Tulchinsky 2018, chapter 5).

Even where clean water is available, design can facilitate adoption of best practices. For example, in hospitals proper placement of sinks makes healthcare workers more likely to adhere to hand hygiene guidelines and not use sinks for disposal of food or beverages, reducing the spread of hospital-acquired infection and the development of biofilms that can harbor pathogens (Grabowski et al. 2018; Zellmer et al. 2015). Thus, building design plays an important role in encouraging good behavior and preventing the spread of pathogens.

The ongoing covid pandemic has emphasized the importance of airborne pathogen transmission. Sanitation, hand hygiene, and disinfection all remain essential practices, but engineering controls and building design are also critical in limiting exposure (Mankiewicz et al. 2021; Piscitelli et al. 2022).

Physical and Chemical Controls and Side Effects

Indoor versus Outdoor Air Quality

Ventilation is emerging as one of the most valuable tools for maintaining healthy built environments (in this issue, see Persily and Siegel). Increased ventilation is associated with decreased covid transmission as well as higher productivity in workers and lower absenteeism in students (Leung 2015; Persily 2015; Piscitelli et al. 2022). Regardless of the exact mechanism underlying these effects, increasing air exchange rates is almost universally considered to positively impact occupant health.

The use of outdoor air as a diluent for contaminant-laden, CO_2-rich indoor air is predicated on good outdoor air quality. In some areas, outdoor air should not be directly introduced because of the presence of contaminants, especially particulate matter (PM) and oxidants (Leung 2015). Yet even with the potential for high PM, outdoor air quality is often vastly better than indoor air quality by other metrics, including concentrations of volatile organic chemicals (VOCs) (Liu et al. 2018).

> *The structure and interconnectedness of urban areas and buildings can affect the number and frequency of pathogen transmission events.*

Local conditions play an important role in determining outdoor air quality. Concerns include levels of PM, nitrogen and sulfur oxides (NOx, SOx), ozone, biological contaminants (viruses, bacteria, fungi, pollen), and VOCs (e.g., benzene) (Jones 1999; Leung 2015; Mankiewicz et al. 2021). Notably, many of these pollutants can be far worse indoors than out, as they have important indoor sources. For example, PM and combustion byproducts are released during activities such as cooking, in which case the focus should be on exhausting cooking fumes rather than increasing overall ventilation (Jones 1999; Leung 2015).

The nature and chemistry of contaminants may differ depending on whether they originated indoors or out. For example, bacteria carried in from outdoor air are much less likely to be human-associated than bacteria originating from indoor sources (i.e., occupants) (Leung 2015; Prussin and Marr 2015).

Filtration

Regardless of whether the source is indoors or out, the same strategies for improving indoor air quality apply. PM, biological matter, and ozone can be removed via filtration (Persily 2015). However, care needs to be exercised in selecting the most appropriate filter and in maintaining and changing filters. Under suboptimal conditions, filters may become a source of pollutants if organic matter is allowed to accumulate and react with ozone, thereby releasing volatile byproducts (Zhang et al. 2011). The same is true of adsorbents, which can be used to remove VOCs but can also become a source of VOCs if not properly maintained (Zhang et al. 2011).

> *Filtration technologies should be evaluated on their ability not only to remove a pollutant of interest but also to generate clean air.*

As ozone is highly reactive, one alternative to filtration is increased ventilation. While a high ventilation rate might increase introduction of ozone from outdoor air, it concomitantly removes rapidly generated reactants and products (NASEM 2022). Thus, the introduction of ozone as a contaminant from outdoor air is most problematic at low ventilation rates.

Many of the products generated by ozone result from uncontrolled reaction with skin lipids (Liu et al. 2021). Smart use of catalysts could efficiently decompose ozone without generating unwanted byproducts.

Highly reactive chemical systems, like ozone, plasma, or photocatalytic oxidation, have intentionally been introduced to air purifiers with the goal of degrading organic contaminants. While these technologies may be effective at reducing a specific contaminant of concern, anything involving highly reactive chemistries may release byproducts like secondary or gaseous oxidation products, NOx, and ultrafine particles (Afshari et al. 2020; Zhang et al. 2011). Some air cleaners (e.g., electrostatic precipitators) also unintentionally generate ozone. These technologies can similarly release unintended harmful byproducts (Afshari et al. 2020). In light of these phenomena, technologies should be evaluated not only on their ability to remove a pollutant of interest but also to generate clean air.

Research Needed

A major challenge to evaluating technologies on this basis is that the definition of "clean" air is nebulous. One possible criterion might be that technologies not create harmful byproducts, although this does not guarantee that the resultant air poses a lower risk to occupant health.

Overall, the health impacts of air cleaning technologies are unclear. Well-designed, rigorous real-world studies are needed to elucidate both the effects of air cleaning on air composition and subsequent impacts on human health and the mechanisms underlying these effects (Cheek et al. 2021; Liu et al. 2022). Such studies are especially necessary as there are no indoor air standards—in contrast to, for example, drinking water or outdoor air—to provide an objective metric.

Surface Cleaning

Surface cleaning is also an important element of building maintenance and an essential practice for the elimination of fomite transmission. However, many cleaning products incorporate VOCs and semi-VOCs that can act as irritants and have long-term negative health effects (Velazquez et al. 2019). Additionally, many surface cleaning products and technologies rely on oxidation, which can result in the formation of unintended harmful byproducts and oxidants, as discussed for air purifiers (Velazquez et al. 2019; Wang et al. 2020).

Although problematic in terms of air quality, oxidative cleaning strategies (e.g., peroxide or peracetic acid) are often preferred over other antimicrobials (e.g., triclosan and quaternary ammonium compounds) because of their broad spectrum of efficacy and lower tendency to promote the development of resistance (Velazquez et al. 2019). While antimicrobials play a pivotal role in treating and preventing human diseases, their efficacy and utility are jeopardized by overuse, including in agriculture (van Schaik 2022; Velazquez et al. 2019). Unnecessary use of antimicrobials can also promote resistance to clinically relevant drugs (van Schaik 2022; Velazquez et al. 2019), exacerbating the already dire global challenge of treating infections (Murray et al. 2022).

More targeted cleaning strategies, such as cleaning products specifically aimed at viruses or moisture control for mold problems, rather than broad-spectrum antimicrobials, may alleviate some of these issues.

Energy, Equity, and Other Considerations

Human-induced climate change can increase conditions that lead to poor outdoor air quality and by extension indoor air quality. It behooves everyone to be mindful of energy consumption and carbon footprint in designing healthy built environments (Leung 2015).

While increasing ventilation and filtration undoubtedly benefit building occupants, they increase the already massive energy demand required to heat and cool buildings (Mankiewicz et al. 2021). For comfort, outdoor air must be conditioned: heated or cooled, humidified or dehumidified. Thus, increasing outdoor air intake may not be economical. Similarly, high-efficiency filters require more energy to circulate air than their lower-efficiency counterparts.

Increased energy demands are accompanied by increased costs, which may be prohibitive in some cases. Additionally, interventions like retrofits or portable air purifiers are expensive and thus not equitably accessible (Cheek et al. 2021; Lamplugh et al. 2020). Conversely, a singular focus on energy efficiency, as in the case of passive houses, neglects the health of building occupants.

Providing equal, affordable access to clean air—whether “clean” is defined based on concentrations of contaminants or health endpoints—is essential from a social justice perspective, acknowledging that marginalized communities disproportionately experience poor air quality (Demetillo et al. 2020; Van Horne et al. 2022). Moreover, in terms of disease prevention, experiences with clean water yield important lessons: without equal access, diseases persist (Montgomery and Elimelech 2007).

Finally, even when all economic and access concerns are addressed, personal preference or aesthetic considerations may prevent uptake. Wherever possible, the best way to improve air quality is to remove the source of contaminants, by, for example, using alternative, less toxic solvents or removing unnecessary or potentially harmful ingredients from personal care products. However, in occupational settings, if the replacement is more difficult to use, workers may opt to continue using the more toxic substance (Lamplugh et al. 2019). Similarly, noise levels may influence the use of air handlers or purifiers (Afshari et al. 2020).

Creating Healthful Built Environments

Building design should address health (Persily 2015). To build adequately protective environments, all of the above considerations need to be taken into account, and conflicting demands (e.g., controlling exposure to pathogens without increasing exposure to harmful chemicals or expanding carbon footprint) need to be resolved. At the very least, all these demands have clear and measurable outcomes: specific pathogens or chemicals to be avoided and energy targets to be met.

> *Conflicting demands—e.g., controlling exposure to pathogens without increasing exposure to harmful chemicals or expanding carbon footprint—need to be resolved.*

Increasingly, expectations are shifting from illness prevention to a more proactive approach to health and well-being. Buildings of the future will be expected to

- provide shade from the sun and allow for appropriate daylighting to promote mental health;
- filter out UV radiation to prevent cancer and allow sufficient UV exposure for vitamin D production;
- prevent the spread of infectious disease and allow for early-life microbial exposures that mitigate the later development of allergies, asthma, and other autoimmune disorders (Mankiewicz et al. 2021); and
- do all this while being carbon and energy negative, potentially by harvesting solar energy.

The *design* of healthful built environments entails teasing apart the nuances of these exposures and integrating them in building design and operation as well as neighborhood planning and urban development (Green 2014; Mankiewicz et al. 2021; van Schaik

2022). *Maintenance* will avoid the use of chemicals with negative impacts on human and environmental health. *Energy demands* associated with these design and operation practices will be met through more sustainable practices in architecture and energy generation. Healthful built environments will also aim to counter health disparities and promote *equity*.

Conclusion

While the ability to design structures that offer protection from harm is improving, more information is needed about how to build environments that promote health. The development of "green" and "well" building standards is a good start (Mankiewicz et al. 2021; Persily 2015).

In addition, for building maintenance and cleaning, manufacturers are moving away from traditional harsh chemicals, particularly antimicrobials, and exploring the use of alternative products and cleaning strategies, including temperature and humidity control, which may have a larger impact on pathogen survival than cleaning (Hu et al. 2022; Velazquez et al. 2019).

Also encouraging, market pressures are increasing for organic or "natural" ingredients in personal care products as consumers shy away from synthetic additives like antimicrobials and preservatives (Mordor Intelligence 2022). This shift in manufacturing could help with source control, effectively eliminating some organic contaminants.

By taking a holistic approach, balancing all aspects of indoor environmental quality and critically reevaluating building operations and product use, healthful built environments are possible.

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There is no average dose at which the estimated risk to a population is zero, so decision making must incorporate a concept of acceptable residual risk.

Estimating Indoor Microbial Risks as Applied to Covid-19

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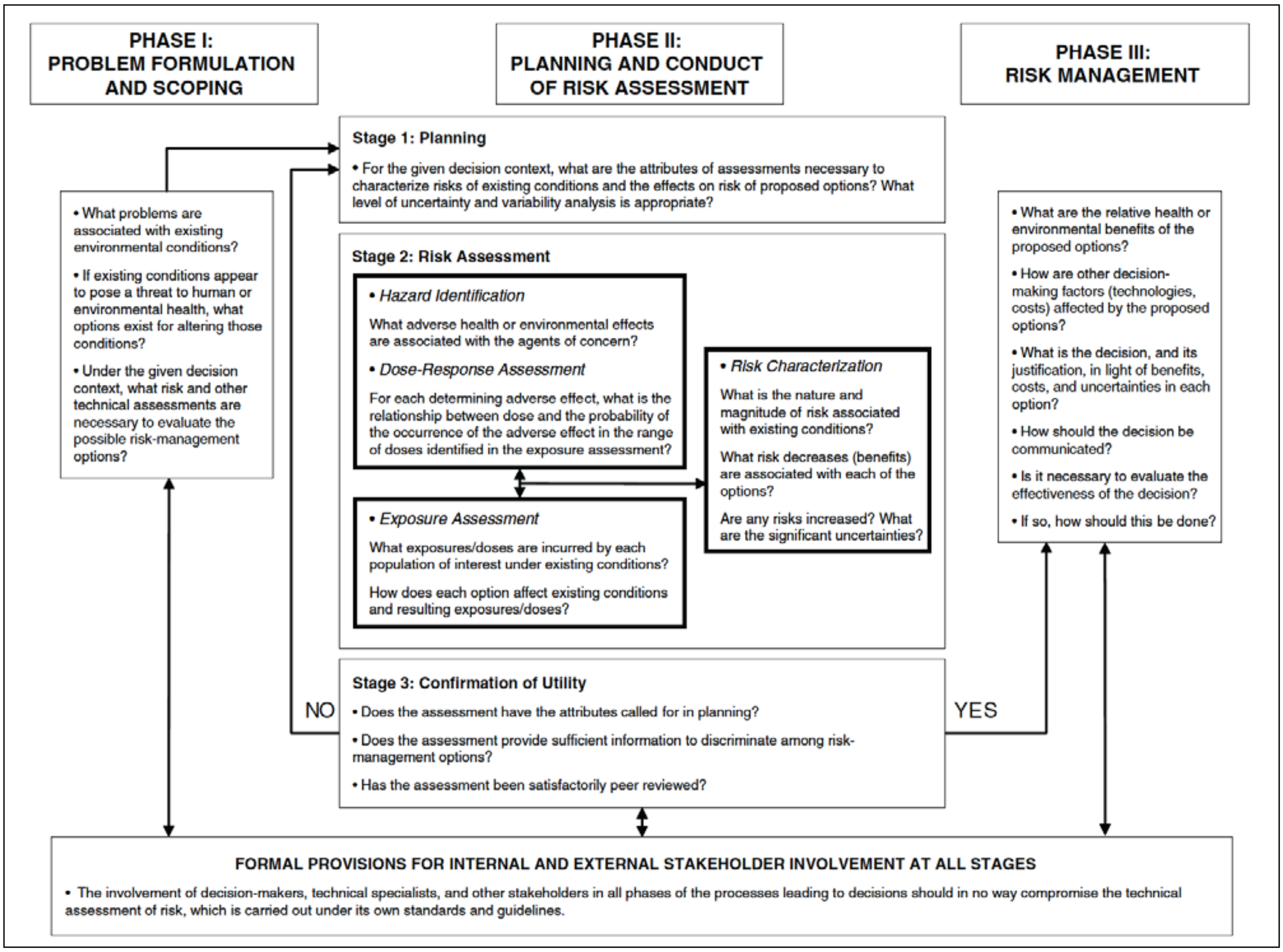
Charles N. Haas

The estimation of risk from exposure to microorganisms in the indoor environment is useful to assess the degree to which controls, such as engineering interventions, are needed. Risk assessment is a "[s]ystematic process to comprehend the nature of risk, express and evaluate risk, with the available knowledge" (SRA 2018, p. 8). The objective of this article is to explain how quantitative microbial risk assessment could be applied to understanding and controlling risks from SARS-CoV-2.

Introduction

The use of risk assessment in enabling decision making for environmental health protection is over 40 years old, since its role was elucidated in 1976 (EPA 1976). By the time of the 1983 National Research Council report, *Risk Assessment in the Federal Government* (NRC 1983)—often called "the Red Book"—over 150 health risk assessments had been completed (Anderson 1983).

The centrality of risk assessment to management of risks from environmental contaminants is illustrated in figure 1 (NRC 2009). The key technical activities of risk assessment (Stage 2 of Phase II) are hazard identification, dose-response assessment, exposure assessment, and risk characterization. These drive subsequent steps of the process and are discussed below.



PHASE I: PROBLEM FORMULATION AND SCOPING

- What problems are associated with existing environmental conditions?
- If existing conditions appear to pose a threat to human or environmental health, what options exist for altering those conditions?
- Under the given decision context, what risk and other technical assessments are necessary to evaluate the possible risk-management options?

PHASE II: PLANNING AND CONDUCT OF RISK ASSESSMENT

Stage 1: Planning

- For the given decision context, what are the attributes of assessments necessary to characterize risks of existing conditions and the effects on risk of proposed options? What level of uncertainty and variability analysis is appropriate?

Stage 2: Risk Assessment

- *Hazard Identification*

What adverse health or environmental effects are associated with the agents of concern?

- *Dose-Response Assessment*

For each determining adverse effect, what is the relationship between dose and the probability of the occurrence of the adverse effect in the range of doses identified in the exposure assessment?

- *Exposure Assessment*

What exposures/doses are incurred by each population of interest under existing conditions?

How does each option affect existing conditions and resulting exposures/doses?

- *Risk Characterization*

What is the nature and magnitude of risk associated with existing conditions?

What risk decreases (benefits) are associated with each of the options?

Are any risks increased? What are the significant uncertainties?

Stage 3: Confirmation of Utility

- Does the assessment have the attributes called for in planning?
- Does the assessment provide sufficient information to discriminate among risk-management options?
- Has the assessment been satisfactorily peer reviewed?

PHASE III: RISK MANAGEMENT

- What are the relative health or environmental benefits of the proposed options?
- How are other decision-making factors (technologies, costs) affected by the proposed options?
- What is the decision, and its justification, in light of benefits, costs, and uncertainties in each option?
- How should the decision be communicated?
- Is it necessary to evaluate the effectiveness of the decision?
- If so, how should this be done?

FORMAL PROVISIONS FOR INTERNAL AND EXTERNAL STAKEHOLDER INVOLVEMENT AT ALL STAGES

- The involvement of decision-makers, technical specialists, and other stakeholders in all phases of the processes leading to decisions should in no way compromise the technical assessment of risk, which is carried out under its own standards and guidelines.

FIGURE 1 The role of risk assessment in decision making. Source: NRC (2009).

Contemporaneously with the Red Book, dose-response relationships for key waterborne pathogens were published (Haas 1983). This was then broadened into the area called quantitative microbial risk assessment (QMRA), and systematically presented in a monograph (Haas et al. 2014).

What Is Quantitative Microbial Risk Assessment?

There are at least two key differences between QMRA and the general principles of risk assessment (particularly as applied to most chemical contaminants). The first is that, since exposure to even a small number of organisms in a single event can result in an adverse effect, the component of variability due to the stochastics of small numbers becomes important. This difference is accounted for with the use of mechanistically based dose-response models. The second difference calls for estimating in vivo body burden to understand the kinetics of adverse effects, because pathogens multiply in vivo and can be emitted back into the environment, serving as an additional source of illness. This requires coupling with population-scale disease transmission models, which QMRA takes into account.

QMRA has now been applied to a broad range of venues, routes of exposure to pathogens, and types of microorganisms. The approach is now being applied to assess risks from SARS-CoV-2.

Hazard Identification

Specific pathogen(s) and adverse effects can often be identified from clinical case reports. This was certainly the case with SARS-CoV-2.

However, in some cases, the specific pathogen may not be known, at least initially. The 1976 outbreak of what became known as Legionnaires' disease was via a previously unidentified bacterium, now called *Legionella pneumophila* (Fraser et al. 1977). And the phenomenon of Sick Building Syndrome (Nag 2019) may in part be mediated by microorganisms or microbial fragments or metabolites as yet not definitively confirmed.

When a pathogen is not known, it is possible to use indicators for risk assessment such as the presence of coliform or enterococci bacteria, as widely used in the management of swimming exposures in "natural recreational waters" (Federigi et al. 2019).

Emission rates can be directly measured from infected individuals or indirectly estimated based on microbial concentrations in emitted aerosols.

Dose Response

For infectious microorganisms (rather than the metabolites or toxins they may produce), for a response to occur, the pathogen must evade the host responses to proliferate, colonize at a susceptible site, and produce adverse effects in vivo. All infectious pathogens for which dose-response relationships have been developed[1] can be described by two simple models, exponential or beta Poisson, that incorporate probabilistic host-pathogen survival probabilities (Haas et al. 2014). These models, in which dose is regarded as the average exposure to a population, have two significant properties:

- There is no average dose at which the estimated risk to a population is zero. Decision making must therefore either directly or indirectly incorporate a concept of acceptable residual risk.
- At low dose, there is a linear relationship between dose and risk.

The exponential dose-response relationship is functionally equivalent to the more empirical Wells-Riley approach long used in indoor air infectious disease analysis (Sze To and Chao 2010). Prior to covid-19, these models were demonstrated as suitable for many other pathogens potentially transmissible by the respiratory route, including:

- Bacteria: *Legionella pneumophila*, the causative agent of Legionnaires' disease (Armstrong and Haas 2008); nontuberculosis *Mycobacterium* (Hamilton et al. 2017)
- Viruses: Influenza (Watanabe et al. 2012), rhinovirus and respiratory syncytial virus (Jones and Su 2015)
- Protozoa: *Naegleria* (Rasheduzzaman et al. 2019).

Following the SARS-1 outbreaks in 2003, dose-response models were developed for analogs to that coronavirus (Watanabe et al. 2010). The best models were in exponential form. For SARS-CoV-2, the routes of exposure are inhalation and (to a lesser degree) fomite exposure.[2]

By adjusting one parameter in the exponential model to "anchor" it to the early SARS-CoV-2 cluster at a restaurant in Guangzhou (Xie et al. 2020), a revised model was found to be sufficient to explain attack rates in a variety of other clusters (Parhizkar et al. 2021). It remains to be seen whether this updated model for SARS-CoV-2 produces results that remain true for more recent and future variants of the virus. However, this does indicate that the virus responsible for covid-19 is amenable to dose-response modeling.

Exposure Assessment

Exposure assessment relies on direct measurements of pathogens at the point of exposure; modeling of the dose based on source emissions, transport, and decay; or a combination of these approaches. In this issue the article by Stephens and colleagues (2022) outlines modeling and measurements of pathogens relevant to the indoor environment.

Emission rates are a function of the pathogens themselves. They can be directly measured from infected individuals (Coleman et al. 2022) or indirectly estimated based on microbial concentrations in emitted aerosols (Riediker and Tsai 2020).

One issue with exposure assessment of pathogens is that often data are obtained (or modeled) based on gene copies (RNA or DNA) of the pathogen. These are not synonymous with the occurrence of the viable infectious agent, and the ratio between gene copies and viable infectious organisms may depend on analytical

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[1] Notably absent are dose-response models for fungi. These organisms are known to be important, and this represents a considerable data gap (Weiskerger and Brandão 2020).

[2] For other pathogens, dose-response models are available for ingestion, dermal, and other routes.

methods and on intrinsic differences in persistence of the nucleic acid and the viable organism. This is an area where further research, for both SARS-CoV-2 and other pathogens, is needed. A QMRA may still be done, however, by incorporating probability distributions for this ratio (Pitol and Julian 2021).

Risk Characterization

Risk characterization is the integration of information from dose-response and exposure assessments to provide overall estimates of risk with attendant uncertainties. As shown in figure 1, it represents an interface to risk management and so should be presented in a way that is useful and actionable for decision makers.

There are many inputs to an exposure assessment, each with elements of uncertainty and variability. In dose response, there is typically uncertainty in the parameters of the exponential or beta-Poisson model. There may be additional uncertainties, such as in the ratio of viable infectious organisms to gene copies of organisms. These various elements of uncertainty and variability can be described by probability distributions.

To obtain the risk characterization with corresponding uncertainties a Monte Carlo approach can be used to sample repeatedly from each of the input distributions and "build up" the resultant distribution for estimated risk. Good practices for use of this method have been developed and are broadly accepted (Burmaster and Anderson 1994).

With current hardware and software, it is straightforward and rapid to run 10,000 or 100,000 trials to achieve a good prediction. As examples of risk characterization, two recent studies on covid-19 have been published, described below.

Early in the covid-19 outbreak, one of the routes of transmission was thought to be fomites (see Haas and Loftness in this issue). A comprehensive risk assessment of fomite exposure (primarily based on data collected during the early months of the outbreak with the original virus strain) indicated that exposure via the fomite route posed only a minor risk and did not justify special cleaning procedures for surface decontamination of SARS-CoV-2 (Pitol and Julian 2021).

More recently, a comprehensive air and surface sampling program for SARS-CoV-2 nucleic acid was conducted on a university campus to compare risks from inhalation and fomite exposure (Zhang et al. 2022). The authors coupled the experimental measurements with other data in a Monte Carlo assessment and concluded that inhalation risk was orders of magnitude more significant than fomites.

Advances Needed

QMRA is clearly useful in efforts to understand and characterize microbial risks in the indoor environment, including from SARS-CoV-2. However, there remain areas where this approach could advance. These include the following:

- The exponential and beta-Poisson models describe the proportion adversely affected. The applicability of dynamic models incorporating time to effect and internal host immune response needs further exploration (Haas 2015). It may be that, by incorporating factors of the dynamics of host response (Pujol et al. 2009), impacts of multiple exposure events could be more accurately assessed.

> *Risk characterization is the integration of information from dose-response and exposure assessments to estimate risk with attendant uncertainties.*

- Populations exposed are heterogeneous, both intrinsically and via factors influencing exposure (e.g., differential activity patterns). These patterns can be coupled with dose response to develop overall risk models. For example, differential mobility patterns might be assessed using mobile phone geolocation data, with suitable privacy protections (Grantz et al. 2020). Variations in the angiotensin-converting enzyme 2 (ACE2) receptor may modulate susceptibility to covid-19 (SeyedAlinaghi et al. 2021), and other genetic determinants of susceptibility may be elucidated. Such information can be used in elaborations of dose response to incorporate intrinsic differential infectivity in subpopulations (such as by genetic factors or concurrent environmental exposures) in quantitative models.
- Covid-19 is clearly a contagious disease whose transmission is mediated by the environment. There is

a large literature on disease transmission models, including the incorporation of intermediate environmental stages, such as survival in air or on surfaces (Li et al. 2009). But work is needed to incorporate dose-response models (most likely in their dynamic forms) in these transmission models. For example, relationships for the infection rate and incubation parameters in disease transmission models (Godio et al. 2020) could be developed from static and dynamic dose-response data, as suggested for other pathogens (Prasad et al. 2017).

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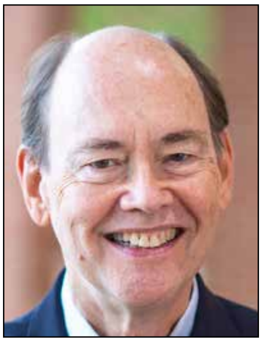
Ventilation, filtration, and germicidal UV air disinfection can be even more effective with investment, standards, research, development, and policies to support their use.

Active Air Interventions

Jelena Srebric



Donald Milton

Jelena Srebric and Donald K. Milton

Active air interventions are an important mechanism for reducing risks of infection transmission due to inhalation of airborne microorganisms in public congregant settings. While use of masks and respirators as source control and personal protection are by now well-established means of communicable respiratory infection control, active air interventions have the advantages of not requiring individual behavior change and protecting building occupants before detection of a local epidemic.

Recent Lessons Learned

Experiences during the SARS-CoV-2 pandemic, as well as earlier studies of influenza, indicate that increased ventilation, filtration, and air disinfection with germicidal ultraviolet (GUV) light are effective active interventions (Fischer et al. 2022; Gettings et al. 2021; Parhizkar et al. 2022). But ventilation measurements during the pandemic showed that many heating, ventilation, and air conditioning (HVAC) systems, especially in public spaces, such as schools or buses, did not have sufficient capacity to safely accommodate their population (CDPH 2020; Zhu et al. 2022).

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Administrative measures that allow risk management by reducing exposure to rebreathed air (Rudnick and Milton 2003) without ventilation system augmentation include decreases in both (i) population density (limiting occupancy rates and effectively increasing the ventilation rate per person) and (ii) time continuously spent in a space. Because of the constraints imposed by such measures on the core activities of building occupants, facilities need scalable active interventions that complement existing ventilation to relax administrative measures.

Active Interventions to Prevent Airborne Infection Transmission

Active interventions to prevent airborne infection transmission fall into the following categories:

- central HVAC systems with improved filtration or in-duct GUV;
- portable, in-room filtration or enclosed GUV systems; and
- upper-room and direct in-room GUV.

In this article we focus on these three control strategies. They have been well studied and have well-known benefits and risks.

Control of relative humidity (RH) with increased RH during winter has been proposed as an additional means of controlling airborne infection transmission. However, high indoor RH in cold climates presents risks of mold and allergen exposure and structural damage to buildings (Fisk et al. 2007, 2019; IOM 2004). Furthermore, control of RH is less well studied and its effectiveness is unknown.

Ventilation is frequently discussed in terms of air changes per hour (ACH); we discuss the three approaches noted above in terms of the equivalent air changes per hour (eACH) that each can provide.

Central HVAC Systems with Additional Filtration or In-Duct GUV

Central HVAC Systems

Central HVAC systems are tasked with the supply of clean air to occupied spaces by running outdoor air and recirculated building air through a filtration system. The air conditioning, filtration, and circulation subsystems of central HVAC account for roughly half of total building energy use (Heidarinejad et al. 2014). Active interventions with additional filtration can be an expensive operational upgrade because they require continuous or extended operation of the central HVAC fans rather than allowing cycling based on reduced demand for ventilation, cooling, or heating. If cycling takes place both the media filtration and/or in-duct GUV interventions would be ineffective during downtime periods, which could be a majority of the time.

For public buildings, such as typical educational facilities, MERV-13 filtration[1] was a recommended upgrade of central HVAC to reduce the risk of airborne covid-19 transmission (NYSERDA 2021). This recommendation considers operational trade-offs between filtration efficacy in removing microorganisms and required fan capacities to handle the greater pressure drop due to the additional filtration.

> *Active air interventions have the advantages of not requiring individual behavior change and protecting building occupants before detection of a local epidemic.*

A typical classroom, for example, could see an increase from 7 to 9 eACH when upgrading from MERV-8 to MERV-13, but research is needed to examine the full effects of these operational recommendations. Public transportation vehicles, such as buses, could upgrade their filtration systems to MERV-10 filtration to achieve a similar air cleaning effect due to high airflow rates. These suggested upgrades provide significant air cleaning, as if the air change rate were roughly tripled (NIOSH 2003).

In-Duct GUV

In-duct GUV is an alternative to media filtration that allows for air disinfection without occupant exposure to GUV. Such systems typically use 254 nm germicidal UV light capable of inhibiting the reproduction of microorganism cells and thus inactivating them.

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[1] A minimum efficiency reporting value (MERV) rating measures a filter's effectiveness in preventing the transmission of dust and other contaminants.

The GUV lamps need to be appropriately sized and operated to provide a sufficient dose of light to microorganisms that move through the ducts at fairly high velocities. They also require continuous energy input. The eACH achieved by in-duct GUV cannot exceed the ACH that would be achieved by operating the system without recirculation, typically from 2 to 4 ACH.

In-duct GUV systems are best used as a supplement to existing or upgraded filtration, rather than a standalone system, because they do not filter particulate matter.

Portable, In-Room Filtration or Enclosed GUV Systems

Localized air filtration can match or even exceed the risk reduction potential of upgraded centralized filtration systems. The CDC's National Institute for Occupational Safety and Health has shown that local filtration supplementing a centralized system can reduce exposure by 65 percent; used in combination with even loose-fitting masking, two local filtration devices reduced exposure by up to 90 percent (Coyle et al. 2021). Another study demonstrated that combining increased ventilation with portable in-room filtration could reduce exposure by 80 to 90 percent (Blocken et al. 2021).

> *Combining increased ventilation with portable in-room filtration could reduce exposure by 80 to 90 percent.*

Localized systems have to be properly sized, distributed, and maintained to be effective; typical installations provide approximately 3 eACH (EPA 2018). Care must also be exercised to avoid creating a tripping hazard (from electric cords), and noise from the devices may discourage their use (Olsiewski et al. 2021).

Unit distribution in a room should be uniform to promote mixing and facilitate the removal of pathogens close to their source. Importantly, a unit should be placed in areas with stagnant airflow—such as, in a classroom, an air recirculation zone near a wall with a blackboard—to limit the possibility of creating high aerosol concentrations where an individual might spend a significant amount of time (Srebric et al. 2008).

If properly used, localized air filtration systems can work really well and have been widely successfully deployed in schools during the pandemic.

Upper-Room and Direct In-Room GUV

Upper-room GUV using fixtures that emit 254 nm UV-C was first demonstrated for control of measles in elementary schools in the late 1930s and early 1940s (Wells et al. 1942).[2] It has been extensively deployed in hospitals dedicated to treatment of *Mycobacterium tuberculosis* infections over the last 60 to 70 years (Nardell 2021). Far-UVC air disinfection using KrCl (krypton chloride) excimer lamps, which emit primarily 222 nm UV-C, was introduced more recently; significant production capacity and commercial availability began in 2020.

Germicidal UV employs UV-C wavelengths in the range of 200 to 275 nm. Because high-dose 254 nm UV-C can cause severe eye irritation (although it is not a significant skin cancer risk compared with UV-B in sunlight), fixtures are designed and installed (up to 6½ feet above the floor) so that very little of the GUV enters the occupied part of the room.

The eACH achievable with in-room GUV depends on the wavelength, intensity, and distribution of GUV in the room in addition to the target organism's sensitivity to inactivation at the wavelength used. Studies of conventional 254 nm GUV systems show a five- to tenfold risk reduction with use of both properly sized and distributed light sources and a ceiling fan that brings air upwards to the inactivation zone (First et al. 1999; Mphaphlele et al. 2015; Zhu et al. 2014). The equivalent ventilation rates achieved with these systems can range from 20 to hundreds of eACH in test chambers (McDevitt et al. 2008), and approximately 100 eACH have been reported for an installation in school classrooms (Wells et al. 1942).

Recent research on the 222 nm GUV systems, which do not need to be restricted to the upper room, suggests that they may substantially improve effectiveness compared with the older systems. Because higher doses of 222 nm GUV, when filtered to remove longer-wavelength near UV-C (Buonanno et al. 2021; Eadie et al. 2021; Narita et al. 2022), are safe for skin and eye exposure (Kaidzu et al. 2021; Welch et al. 2022a)

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[2] The ultraviolet light spectrum is divided into UV-A, UV-B, and UV-C with progressively shorter wavelengths. UV-A (315–99 nm) and UV-B (280–314 nm) from sunlight penetrate the atmosphere, whereas UV-C (100–279 nm) is absorbed by the ozone layer and does not. UV-C is further categorized as near (231–79 nm), far (200–30 nm), and vacuum (<200 nm).

when used within the recently revised exposure guidelines (ACGIH 2022), and because the GUV is not restricted to the upper room, it has great potential to protect against short-range (conversational distance) as well as longer-range exposures (across a room or hallway). A laboratory test recently demonstrated that a high-density installation of 222 nm GUV fixtures could achieve more than 180 eACH (Eadie et al. 2022).

Challenges to GUV Implementation

The primary challenges associated with implementing conventional GUV (254 nm UV-C) have been (i) widespread misunderstanding of its skin safety and (ii) the potential for severe eye irritation, which is due to improper installation. Because 254 nm UV-C does not penetrate to the basilar layer of the skin and because exposures in the occupied, lower room are limited by concerns about acute eye irritation, the risk of skin cancer from 24/7 exposure to conventional GUV indoors at the maximum recommended dose is equivalent to the skin cancer risk of being outside at noon on a sunny June day in North America for 10 minutes (CIE 2010; Forbes et al. 2021). But acute eye irritation is possible with exposures to 254 nm GUV well below those that result in acute or chronic effects on the skin. The fixtures must therefore be installed more than 7 feet from the floor and ceilings must be more than 8 feet high. When the devices are installed properly, actual GUV doses to room occupants are well below recommended limits and eye irritation from the lamps does not occur (First et al. 2005; Nardell et al. 2008).

The effectiveness of conventional GUV is dependent on air movement to ensure that contaminated air moves up and through the irradiated zone frequently, yet slowly enough to give aerosols sufficient GUV exposure to inactivate pathogens (Pichurov et al. 2015). Safe and effective installation of conventional GUV systems requires special skills and training, but formal training and certification programs are currently lacking. Newer 222 nm GUV systems are less dependent on air movement and easier to install safely because higher exposure levels are eye and skin safe (Blatchley et al. 2022; Kaidzu et al. 2019; Welch et al. 2022a). However, special skill and training are still needed and training and certification programs are lacking for this technology as well.

Discussion

Media filtration, whether central or in-room, is well-understood technology. Distributed air cleaning solutions are an effective option for active air intervention especially in the short term. However, if not properly sized and operated, the increased energy demand could be significant and of concern for its climate impact (Heidarinejad et al. 2018). In comparison, active air interventions in the central HVAC system, whether by filtration or GUV, are more energy intensive. They may also be less effective at controlling airborne microorganisms emitted by building occupants, compared to properly operated in-room active air interventions.

> *Safe and effective installation of GUV systems requires special skills and training, but training and certification programs are lacking.*

Conventional upper-room GUV is also well understood, with over 80 years of research and field application experience. Its energy efficiency can be far greater than that of central HVAC-based technologies, with an order of magnitude lower cost per infection prevented (ASHRAE 2019, ch. 62; Ko et al. 2001). Far-UVC technologies hold great promise to improve on both the energy efficiency and safety profiles of conventional GUV.

What's Needed to Move Forward with GUV

There remain important questions about how to optimize this newer technology in terms of fixture design and placement, performance against short-range transmission, and optimal amounts of GUV to provide. As a new technology, the cost of equipment is expected to decline as more producers enter the market. Future developments in LED and other technologies will likely eventually supplant the current KrCl excimer lamp technology, with further increases in energy efficiency.

Current conventional upper-room GUV and far-UVC technologies are ready for widespread use in preventing superspreading events in large congregant settings, such as dining facilities, nursing homes, hospital waiting rooms, convention centers, entertainment venues, and religious meeting houses.

The newer 222 nm GUV has a large potential payoff due to both its ability to disinfect air in the vicinity of occupants and virus sensitivity to germicidal UV light (McDevitt et al. 2010; Welch et al. 2022b). But significant investment in developing this technology, including testing efficacy in laboratory and community studies, as well as standards and certification will be needed.

Importantly, the home is both an important site of respiratory infection transmission and residential buildings are generally poorly ventilated. Current residential building stock relies primarily on outdoor air infiltration, and the median home in the United States has an ACH of approximately 0.5 (Nazaroff 2021). Therefore, a focus of policy should be to improve ventilation in homes; the role of other active interventions in homes is beyond the scope of this paper.

Finally, research is needed on different interventions and occupant health outcomes, and to provide a systemic foundation to not only link risk reduction to specific active air interventions but also reduce uncertainties in quantifying these relationships in buildings and transportation vehicles.

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Improvements to ventilation system performance vary by building, use, existing system capacity, local climate, and other factors.

Improving Ventilation Performance in Response to the Pandemic

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Photo: Daria Perevezentsev / U of T Engineering

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In response to the covid-19 pandemic and in recognition of the importance of airborne disease transmission, there have been multiple calls to ensure adequate building ventilation, in some cases recommending increased ventilation rates (ASHRAE 2021; CDC 2021; REHVA 2021; WHO 2021). The cited organizations stress that ventilation is one element of a layered approach to managing the risk of airborne disease transmission; other measures include handwashing, face masks, vaccination, and distancing.

Introduction

The importance of ventilation has been recognized for as long as people have occupied buildings (e.g., Beecher and Stowe 1869; Janssen 1999; Klauss et al. 1970; Wargocki 2021), with increased interest driven recently by the pandemic, climate change, and other issues. This increased attention to ventilation is a positive step given the well-established connection of ventilation to indoor air quality (IAQ) and to the health, comfort, and performance of building occupants (ASHRAE 2020). However, in pursuing efforts to address ventilation it is important to understand that potential changes in

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ventilation depend on the specific building being considered, its existing ventilation and space conditioning systems, the local climate, and outdoor pollutant levels, among other factors.

In this article we use the term "ventilation" broadly to include outdoor air and exhaust ventilation, heating and cooling, humidification and dehumidification, and contaminant removal using filtration and other technologies.[1] This usage is consistent with ASHRAE Standard 62.1, which defines ventilation as "the process of supplying air to or removing air from a space for the purpose of controlling air contaminant levels, humidity, or temperature within the space" (ASHRAE 2019a). Note that this definition does not mention outdoor air delivery. Some people think of ventilation exclusively as outdoor air delivery, while others think of it as air supply to an occupied space without reference to the amount of outdoor air it might contain. It is therefore essential to identify the specific airflow of interest when discussing ventilation.

Approaches to Improving Ventilation

Given the impact of ventilation rates on airborne infectious disease transmission, improving ventilation is clearly important (Morawska et al. 2021; WHO 2021). However, it is essential that such efforts recognize the large amount of variation between buildings and their ventilation systems, which directly relate to what can and should be done in a given building.

One of the first things to consider before modifying ventilation in a particular building is how it is ventilated: Is there a mechanical system that brings outdoor air into the building and distributes it to the occupied spaces? What kind of system is it (e.g., central or local)? How much outdoor air does the system provide? How is the outdoor air intake rate controlled and can it be modulated?

Is the building naturally ventilated? If so, does it have a natural ventilation system with openings and other components sized and located based on engineering principles? Or does it simply have operable windows? Is the building ventilated primarily by uncontrolled infiltration and exfiltration through unintentional leaks in the building envelope? All buildings, even very tight ones, generally have significant rates of outdoor air entry via envelope infiltration driven by weather conditions and the operation of building equipment (e.g., local exhausts). While infiltration will dilute internally generated air contaminants, including infectious aerosols, it is uncontrolled, unfiltered, and unconditioned and can degrade IAQ and increase energy requirements.

Other key system attributes include the level of particle and gas-phase pollutant removal, the ability to improve filtration (which is sometimes space- or fan-capacity constrained), and the capacity to condition (heat and cool) additional outdoor air.

The impacts of these attributes on ventilation performance and the ability to reduce the risk of airborne disease transmission are system specific. For example, calls to increase outdoor air intake must recognize that many systems, including the forced-air space conditioning systems used in most US homes, do not bring any outdoor air into a building. In fact, some systems (e.g., baseboard and radiator heating) have no air distribution at all. Newer homes are more likely to have outdoor air intake than older ones, but the fraction of US dwellings with mechanical outdoor air intake is very small.

Even in systems that bring outdoor air into the building, increasing the outdoor air ventilation rate may not be possible given existing duct sizes and configurations, fan and space conditioning capacities, and control limitations. The outdoor air ventilation rate in a naturally ventilated building is determined by wind and indoor-outdoor temperature differences as well as the size and position of ventilation openings.

> *Substantial variations between buildings and their ventilation systems directly impact what can and should be done in a given building.*

Many pandemic-motivated recommendations suggest opening windows to increase natural ventilation (e.g., REHVA 2021), but this can affect comfort, energy, security, safety, moisture, and IAQ (if outdoor air quality is poor). In addition, the ventilation associated with open windows is hard to predict in terms of its magnitude and direction (inward or outward). The intent

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[1] Filtration, air cleaning, and other "interventions" are covered in this issue by Srebric and Milton (2022).

here is not to suggest that opening windows is not an option but rather that these factors can impact the benefits of doing so.

In considering various approaches to ventilation, it is critical to also consider how the air is distributed within the space, bearing in mind that ventilation is most effective when air is supplied to the occupant's breathing zone and indoor-generated pollutants are removed near their source. Some ventilation approaches may lead to uncontrolled and potentially undesirable airflow and contaminant transport in the building.

Pandemic-Aware Ventilation

Implementing recommendations to increase outdoor air rates and/or improve filtration may not be possible with existing systems in some buildings. But ventilation system performance can be improved in almost all buildings by inspecting the system and ensuring that its components are in place and functional. These efforts should also verify that the system is operating as intended per its design and that the design is still relevant to the current building usage and occupancy.

> *Ventilation system performance can be improved in almost all buildings by inspecting the system and ensuring that its components are in place and functional.*

Buildings, especially nonresidential buildings, are generally commissioned before occupancy to ensure that the various systems are properly installed and functioning. In the case of ventilation systems, this process (commonly referred to as testing and balancing) is required by ASHRAE Standard 62.1 and is a cornerstone of ventilation system maintenance. However, over time, systems can degrade as sensors go out of calibration, dampers break or get stuck, filters become clogged, and other inevitable events occur. Such changes will result in the system not operating as intended in terms of outdoor air intake rates and other aspects of system performance, contributing to both poor IAQ and increased energy consumption.

An additional consideration is that building and space use often changes over time, leading to different ventilation requirements. Too often these changes in space use and occupancy are not accompanied by modifications to the ventilation system in response to the new conditions. For these reasons, a common recommendation in response to the pandemic is to verify that the system is operating as intended and that it is consistent with current space use (ASHRAE 2021).

Along the same lines, systems require operations and maintenance (O&M), which includes periodic inspections of system components, filter changes, sensor calibration, and other actions. ASHRAE Standard 62.1 includes O&M schedules for nonresidential buildings.[2]

Carbon Dioxide Monitoring

There have been many proposals to monitor indoor CO_2 concentrations to better manage ventilation, and many such measurement programs have been put in place. CO_2 monitoring can be a useful tool for obtaining information about ventilation rates but requires knowledge of how indoor CO_2 concentrations relate to ventilation, sensor calibration and maintenance, careful measurement procedures, and recognition that infectious aerosols behave very differently from CO_2 molecules. Nevertheless, measuring CO_2 concentrations over time can indicate whether the system is providing the expected outdoor air ventilation rates.

This topic merits more discussion than space allows; ASHRAE (2022) recently published a *Position Document on Indoor Carbon Dioxide* that addresses this topic and includes cautions on the application of indoor CO_2 monitoring.

Standards

In addition to recommendations to enhance ventilation, there have been calls to revise ventilation standards to address airborne disease transmission (Morawska et al. 2021). Standards such as ASHRAE 62.1 and 62.2 (ASHRAE 2019a,b) and CEN 16798-1 (2019) focus primarily on the control of odor and irritation, but health impacts are a factor in their requirements (Persily 2015). While these standards do not address airborne infection control directly, the topic was discussed in developing Standard 62.1.

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[2] In this issue, the article by Parhizkar et al. (2022) addresses ventilation standards.

Discussions and actions to revise these standards are certainly merited, but the organizations and committees responsible for those standards need to define and justify new ventilation rates and other requirements. Some have proposed specific ventilation requirements for infection control (e.g., Li et al. 2021), recognizing the need to consider not just outdoor air ventilation but also "effective" ventilation rates provided by filtered recirculated air and other removal mechanisms. To support these changes, there is a compelling need for research that quantitatively establishes the benefits of ventilation in the context of specific infectious diseases.

Conclusion

Ventilation has a fundamental role in managing airborne infectious disease transmission in the context of a broader layered approach. But before making changes to the way a building is ventilated, one must understand how the ventilation system design and operation and other building features may impact infectious disease transmission. Understanding the system and ensuring that reliable ventilation is provided are great first steps for infection control, improved IAQ, and energy efficiency.

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Innovative technologies, practices, and control systems are needed to balance risk of disease transmission and operational energy use.

Toward Integrating Numeric Disease Transmission Risk in Energy Codes and Ventilation Standards

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The covid-19 pandemic has dramatically increased public awareness of airborne disease transmission and the importance of mitigation strategies to remove virus-laden particles from indoor air. Improved ventilation, filtration, and humidification have been confirmed as effective methods to mitigate inhalation dose of the SARS-CoV-2 virus (Morris et al. 2021; Parhizkar et al. 2022), and indoor air strategies are prioritized by the White House (2022) and recommended as one of the layered approaches in CDC guidance.[1]

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[1] Centers for Disease Control and Prevention, Ventilation in buildings (https://www.cdc.gov/coronavirus/2019-ncov/community/ventilation.html)

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Existing Ventilation Standards and Energy Codes

Current ventilation standards for common buildings such as offices and schools were established to primarily address occupancy comfort, odors, and irritation and to manage many indoor- and outdoor-sourced contaminants—not to manage airborne disease transmission risk (ASHRAE 2019; Parhizkar et al. 2021). There is no direct construct for quantitatively limiting airborne disease transmission risk or monitoring indoor microbial communities in ventilation standards for common buildings.

Current energy codes were intended to reduce energy consumption while maintaining minimum requirements for function, human comfort, and fresh air. Some prescriptive energy codes require demand control ventilation strategies to reduce fresh air intake during periods of low occupant density, but less attention has been given to allowances for above-minimum ventilation during health risk events such as disease transmission and wildfire. In fact, there is no construct in prescriptive energy codes for managing variability of health risks, whether the exposures are indoor- or outdoor-sourced, but performance-based energy codes do provide a pathway for intermittent "safe mode" operations.

There is a need for both ventilation standards and energy codes that allow buildings to dynamically address the variability in acute human health risks during "high-risk" (or "risk-on") periods while managing energy use differently than during "low-risk" (or "risk-off") periods. There is also a need for greater coordination between energy and air quality standards.

It is not possible to prescribe health risk mitigation measures that work equally well for every building all the time, nor is it appropriate to constantly apply all risk mitigation strategies. At a minimum, it is important to manage acute health risks associated with periodic events (such as wildfire smoke or airborne disease surges) while limiting chronic health exposures and factors exacerbated by fossil fuel–associated climate change.

A Risk-Energy Decision Support Platform

The risk of airborne disease transmission depends on several building- and occupant-related factors that are subject to rapid change. Properly managing both human health priorities (in this case, airborne disease transmission) and operational energy use concurrently requires an integrated framework that considers key variables of human activity, heating, ventilation, and air conditioning (HVAC) operations, and the associated energy and health risk outcomes.

In this paper we introduce a decision-support platform that articulates the relationships between human activity, key indoor air (HVAC system) parameters, the resultant annual operating energy use, and associated probabilistic risk of airborne disease transmission. With the goal of increasing dialogue among people developing energy and air quality operations and standards, we demonstrate the application of this platform by evaluating both the infection risk to occupants and annual operational energy use of a reference small office building (~500 m^3).

The analysis presented does not contemplate system implications associated with a real-world building retrofit or simple control modifications; rather, it describes the implications of design decisions and operating parameters using a simulated example.

Platform Parameters

SafeAirSpaces (https://safeairspaces.com/) is a single-zone aerosol risk estimation platform (described in Parhizkar et al. 2021) for evaluating the risk of covid-19 transmission with several input parameters related to indoor air and occupant behavior.

> *There is a need for greater coordination between energy and air quality standards.*

The model calculates the concentration of inhaled and deposited dose in susceptible individuals' respiratory system according to the sick persons' (i.e., index-emitters) expiratory/respiratory activity, use of face masks, and indoor air parameters, and it references a relevant dose-response relationship to estimate likelihood of disease transmission (Parhizkar et al. 2021). A dose-response relationship "can be regarded as the probability that a single individual exposed to the average dose of *d* will have the effect" (i.e., acquire infection) (Haas 2021, p. 706).

The dose response estimated by SafeAirSpaces corresponds well with a recent human challenge study (Killingley et al. 2022) that established the so-called

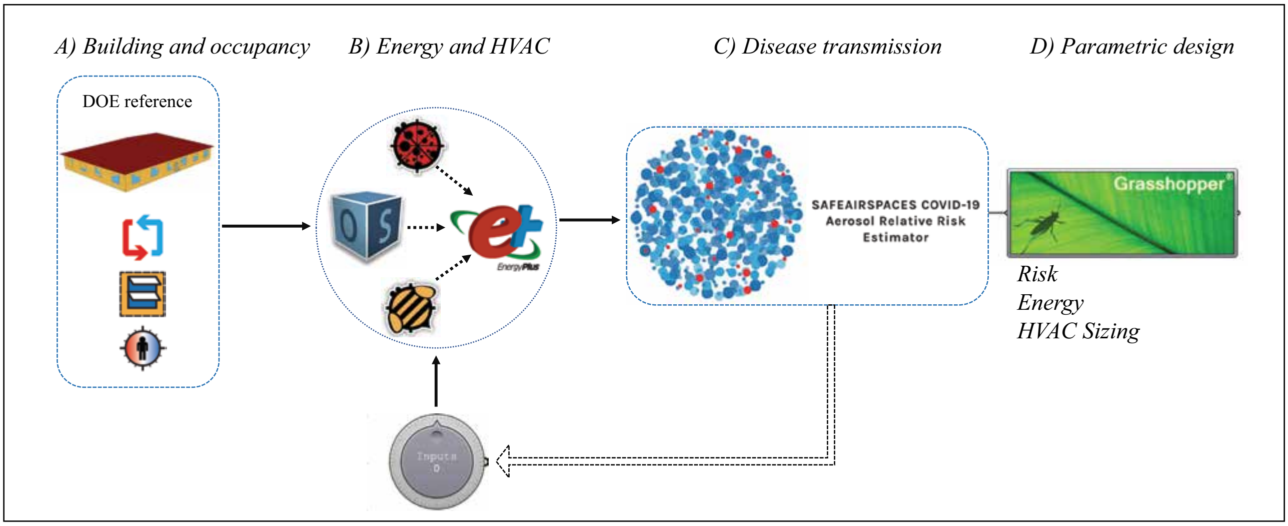

FIGURE 1 Parametric platform workflow illustrating the modeling steps: **(A)** Import (into Rhinoceros) the building geometry, occupancy parameters, HVAC equipment and setpoint definitions, and window operations, all built on the DOE (2011) reference model. **(B)** Develop energy and HVAC parameters in OpenStudio (NREL 2022) using Ladybug and Honeybee plug-ins for EnergyPlus simulation. **(C)** Anchor energy analysis outcome to SafeAirSpaces disease transmission platform in Grasshopper plug-in. **(D)** Conduct risk and energy simulation in Grasshopper plug-in. HVAC = heating, ventilation, and air conditioning. Logos used with permission.

"infectious dose" required to produce infection in about 50 percent of human volunteers.

The parametric approach in our study used the SafeAirSpaces model and developed a more comprehensive platform in which inputs required for calculating the risk of disease transmission are derived from energy and comfort simulation software. We relied on published calculations, including the single-zone well-mixed aerosol dynamics assumption, but updated the risk model with a humidification viral decay parameter (Dabisch et al. 2021). We excluded any consideration of recirculated air for risk estimates. The decision-support framework is visually presented in figure 1.

To demonstrate the utility of this platform, we studied a benchmark commercial reference building developed by Pacific Northwest National Laboratory (PNNL) that supported energy and ventilation calculations (Winiarski et al. 2006, 2007). We imported an IDF (input data format) file (EnergyPlus v. 8.0) into Honeybee v. 1.4 plug-in and Ladybug tools in Grasshopper v. 1.0.0007 coding language in which the SafeAirSpaces aerosol risk estimation platform was developed.

The PNNL reference model is a single-story small office (511 m^2) located in climate zone 4C (Salem, OR), with a 24.4 percent window/wall ratio on the south façade and 19.8 percent for the other three orientations. It has five HVAC zones spanning a central primary zone, perimeter office spaces, and an unoccupied attic zone. Heating and cooling systems comprise air-source heat pumps with a backup gas furnace.

We used ASHRAE 62.1-2013 (ASHRAE 2015) minimum ventilation rates as inputs for Case 1 (baseline) to assign the minimum outdoor air requirement of each zone according to the IDF reference model (Case 1 energy use is also compliant with ASHRAE 90.1-2013). We defined three additional cases to study alternate minimum outdoor airflow rates and levels of filtration, as shown in table 1. Annual operational energy use was simulated. We calculated the average monthly covid-19 transmission risks for a typical office space with the following conditions:

Floor area = 113 m^2, ceiling height = 3 m,
number of occupants = 7, number of index patients = 1
high emitter (as defined in Parhizkar et al. 2021),
event duration = 2 hours

For each case, we conducted an annual energy simulation resulting in 8760 hourly values. We calculated the risk of disease transmission using the average values of combined air exchange rates and relative humidity values during weekdays from 08:00 to 17:00 for each month of the year and applied these values to a 2-hour event duration for disease transmission risk estimation.

TABLE 1 Parameters for four cases studied for a space of 113 m^3. ACH = air changes per hour; HEPA = high-efficiency particulate air [filter]; HVAC = heating, ventilation, and air conditioning.

	Case 1	**Case 2**	**Case 3**	**Case 4**
HVAC system	Air-source heat pump with gas furnace backup (heating), air-source heat pump (cooling), and single zone, constant air volume air distribution, one unit per occupied thermal zone (air handling and distribution)			
Minimum outside air	0.048985 (m^3/s) ~0.5 ACH 100% outside air + infiltration (no filter)	0.404123 (m^3/s) ~3 ACH 100% outside air + infiltration (no filter)	1.21 (m^3/s) ~9 ACH 100% outside air + infiltration (no filter)	0.048985 (m^3/s) ~0.5 ACH 100% outside air + infiltration + 5 equivalent ACH via in-room HEPA filtration
Thermostat setpoint	75°F cooling, 70°F heating with no intentional humidification and/or dehumidification			
In-room HEPA	None	None	None	560 m^3/h per 37 m^2

Calculation Results and Implications

Figure 2A shows the average of the combined air changes per hour (ACH) in one of the south-facing perimeter office spaces for each month. For each case, combined air exchange was calculated as the sum of infiltration and mechanical ventilation.

Figure 2B shows the average relative humidity for each month, with values of 30–45 percent, dependent on weather and HVAC parameters and no humidification during the heating season.

Figure 2C shows results of the SafeAirSpaces simulations of monthly average disease transmission risk for a 2-hour period during a typical workday. Although not historically characterized in these terms, current ventilation standards and alternate HVAC operating scenarios can be associated with disease transmission risk potential. For the cases studied, the indoor air parameters produce estimated disease transmission risks of 7–25 percent. Modifying ventilation or filtration produces meaningful changes in airborne disease transmission risk.

Figure 2D illustrates the associated annual energy consumption for each case, with values spanning 309–806 MJ/m^2 (27–71 kBTU/f^2) annually. We observed that while 9 ACH in Case 3 delivered the lowest risk of disease transmission, Case 4 with in-room HEPA filtration delivered significantly lower risk of disease transmission than Case 1 and with lower energy consumption than Case 3.

These results underscore the important relationships between HVAC system definitions and modes of operation, airborne disease transmission health risks, and annual operating energy consumption. The potential to reduce disease transmission risk is substantial (a 70 percent reduction) based on mitigation strategies, but in some cases these strategies also drive wide variance (250 percent) in operational energy consumption.

In addition to energy implications, increasing outside airflow through existing HVAC systems is not always possible because of comfort implications associated with limited heating/cooling capacity, condensation, and limitations in fan and duct capacity. Therefore, innovative technologies, practices, and control systems that aim to balance risk of disease transmission and operational energy use are needed.

The capital and maintenance costs associated with renovating HVAC systems and alternate operational parameters should be analyzed according to both acute and long-term impacts on human health and energy use. Adding in-room HEPA filtration to existing buildings with inadequate ventilation is shown to be an effective short-term disease transmission risk mitigation strategy, and the benefits of increasing outside air ventilation rates extend beyond disease transmission (Allen et al. 2016; Satish et al. 2012).

Conclusion

This paper demonstrates the potential for an integrated disease transmission risk and energy simulation platform to provide building design decision support and HVAC operations guidance. The aim is to help balance the optimization of human health outcomes with energy investments and to guide safer and more energy-efficient modes of building operations and the development of future codes and standards.

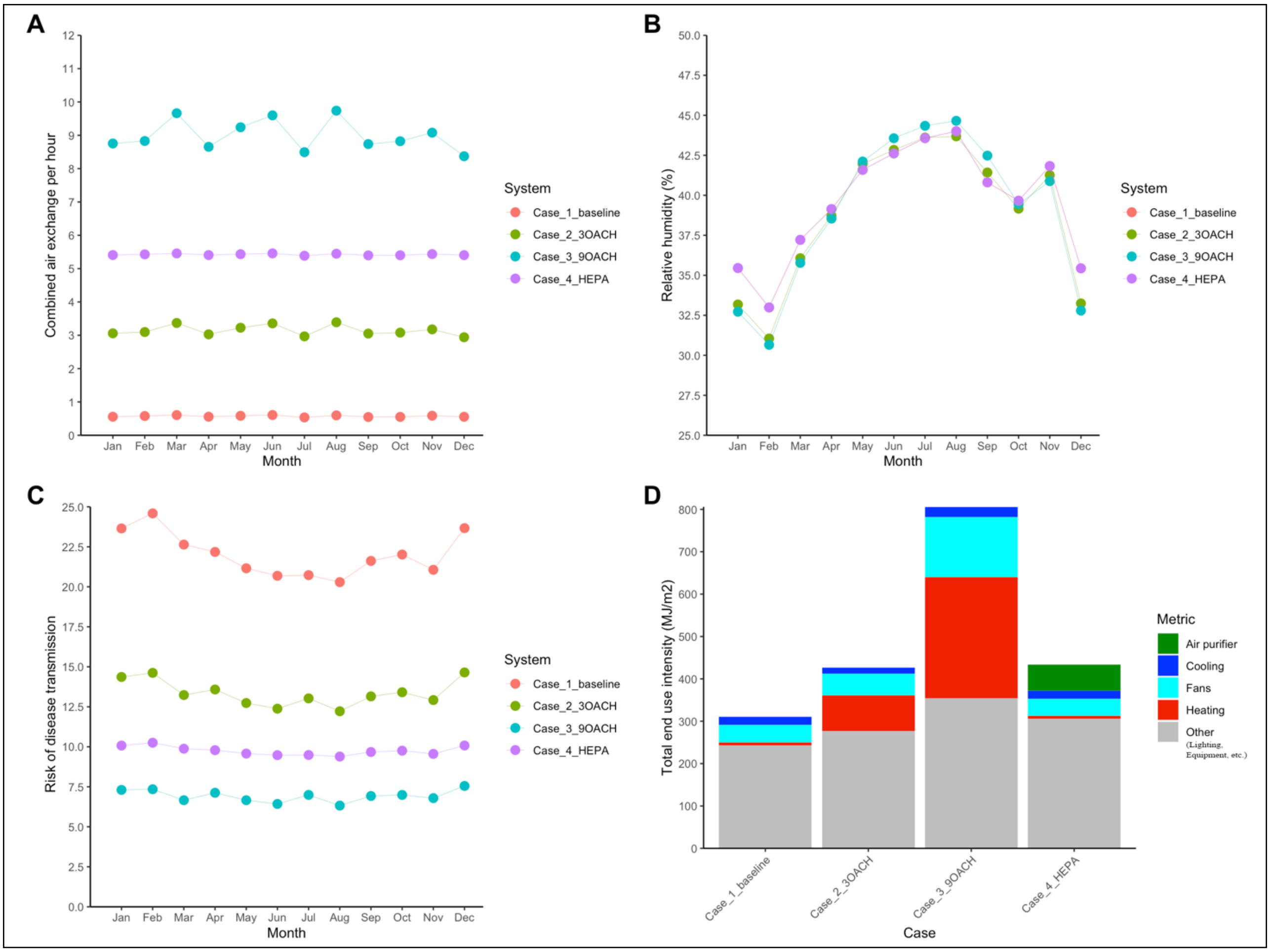

FIGURE 2 Results of four case studies depending on (A) combined air exchange rate per hour, (B) relative humidity, (C) risk of disease transmission, and (D) energy use intensity of air purifier, cooling, fans, heating, and components such as lighting and other equipment. ACH = air changes per hour; HVAC = heating, ventilation, and air conditioning

Future research should explore the impacts of a variety of HVAC systems with options to evaluate risk of disease transmission and energy use in buildings with alternate fractions of recirculated air (through MERV filters[2]) and outside air.

Future energy codes, ventilation standards, and HVAC system operational and maintenance guidelines would all benefit from a concurrent understanding of how key indoor air variables implicate annual energy use and airborne disease transmission health risks. Setting specific disease transmission risk thresholds is not a concept currently considered by building owners or standards development organizations, but the field has progressed to the point that such consideration is now possible—and necessary, given the severity and persistence of the covid-19 pandemic and increasingly dire climate crises. We provide a framework for advancing this dialogue.

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[2] A minimum efficiency reporting value (MERV) rating measures a filter's effectiveness in preventing the transmission of dust and other contaminants.

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Research and data are needed to improve understanding of water-related microbiomes in buildings to reduce disease outbreaks and enhance public health.

Microenvironment-Associated Water Microbiomes and Priorities for Public Health Research

Kerry A. Hamilton and
Timothy Bartrand


Kerry Hamilton


Timothy Bartrand

A "microenvironment" is the immediate small-scale environment of a structure or organism (or part of it), as distinct from the larger environment, and can create niches for microbial growth.[1,2] Differentiating the relative risks between microenvironments in buildings is critical to ranking intervention strategies that will reduce public health risks while promoting a healthy indoor microbiome.

In this article, we highlight water microenvironments that are important from a public health perspective to (i) identify key microenvironments and microbiomes that affect public health risks, (ii) provide a qualitative assessment of the relative risk posed by water microenvironments in buildings, and (iii) identify data gaps that will inform research priorities and risk management efforts.

Water-Related Microbiomes in Buildings

As recognized in the "One Water" construct,[3] water systems are a continuum connecting water sources—surface waters, groundwaters, seawater, and brackish water (for desalination) or greywater/wastewater (for reuse)—to

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treatment, distribution, detention, and use in building water systems, points of use, drains, collection systems, and wastewater treatment systems. The microenvironment-associated water microbiome in buildings—plumbing systems, points of use, and features such as drains—is influenced by, but distinct from, the microbiome in other parts of the system (e.g., heating, air conditioning, ventilation).

The diversity of systems and sources points to (and data support) a wide variety of water-related microbial communities in buildings. Understanding and managing the water-related microbiome therefore require substantial data collection and synthesis.

Table 1 summarizes the water-related microbiome for key microenvironments in buildings. For 15 microenvironments it characterizes primary exposure route(s), public health significance, key microbiome characteristics and microbial community details where available, qualitative risk evaluation/priorities, data and knowledge gaps, and best management practices.

- In terms of public health significance, disease outbreaks vary by microenvironment; they include SARS-CoV-2, norovirus, and Legionnaire's disease, and have been associated with *Clostridium difficile*, *Mycobacterium* species, and *Staphylococcus* bacteria, among others.
- Qualitative risk evaluation/priorities are designated as follows: low = unlikely to pose a nontrivial public health risk; medium = poses a nontrivial risk under some "typical" conditions or during periods of operational deficiency; high = likely to cause a nontrivial public health risk under routine operating conditions; uncertain = considerable unknown factors present challenges to designation.
- Cited studies discuss examples of water-related microbiome characteristics and are only a sampling of the many relevant studies conducted to date.

Analysis, Key Data and Knowledge Gaps, and Research Priorities

Microenvironments are generally recognized as important because of their potential to harbor pathogens and promote their growth and because they are associated with exposures of public health consequence. We assign them a qualitative risk and priority based on their association with adverse health impacts. However, that assessment does not account for impacts on infrastructure or other non-health-related implications of the water-related microbiome. That qualification notwithstanding, the risk and priority assessments presented in table 1 can guide future data collection efforts and, equally importantly, analysis and meta-analysis of microbiome data related to priority microenvironments.

We offer the following conclusions and suggestions for measures to support progress in this important area for public health.

- Research is needed on ways to reduce uncertainties and mitigate risks associated with understudied and/or unregulated water system microenvironments such as the unpressurized portion of showers and other shower components, bathroom drains, decorative water features, and fountains; heating, ventilation, and air conditioning systems including condensate, humidifiers, and misters; cooling towers; point-of-use devices; and certain medical devices.
- Increased study is needed to (i) better understand the aerosol inhalation route of exposure resulting from water fixtures, systems, and/or devices; and (ii) devise more effective controls and barriers that reduce the occurrence of respiratory pathogens in building water supplies and associated accessories.
- Improved methods for investigating microbial ecology in situ in the environment can improve understanding of disease transmission routes, prioritize microorganisms for further focus, and identify novel control strategies.
- Use of genomic tools (e.g., whole genome sequencing) to link infections to sources can aid in identifying and prioritizing water microbiome–associated hazards.[4]
- Making additional (typically non-fecal-oral) waterborne illnesses (e.g., nontuberculous mycobacteria) notifiable can increase awareness of microenvironment roles in disease.
- To reduce public health risk in buildings, it is essential to develop, maintain, and monitor water management plans.

TABLE 1 Microenvironment-associated water microbiomes, listed from highest to lowest/most uncertain risk. HVAC = heating, ventilation, and air conditioning; POU = point of use; spp. = species.

Microenvironment	Primary exposure route(s)	Public health significance	Key microbiome characteristics and microbial community details where available	Qualitative risk evaluation/ priorities*	Data and knowledge gaps	Best practices in management
Medical devices (e.g., heater-coolers, dental equipment)	Aerosol inhalation	Nonsterile tap water used for equipment manufacture testing and/ or use; small-diameter aerosol-generating equipment provides high exposures[1]	High bacterial diversity in dental unit water lines,[2] with most common genera *Afipia* spp. and *Sphingomonas* spp.; total cell concentration and bacterial community changed as water circulated in dental unit water lines and several pathogen-containing genera present, community changed after stagnation and treatment[5]	**High**	Optimized disinfection and cleaning practices for medical equipment; evidence-based water safety plan implementation for healthcare environments; design of equipment to reduce aerosol exposures; advanced molecular techniques for understanding biofilms/reservoirs and transmission of pathogens, especially in situ; additional studies of microbial ecology of medical equipment	Increase ventilation; evaluate equipment placement and containment of aerosols; provide clear guidelines for equipment disinfection and cleaning; use personal protective equipment; use appropriately treated water for medical and dental equipment manufacture and use; for healthcare environments, develop water safety plans that promote temperatures and hydraulics that do not favor pathogen growth; use whole genome sequencing to link infections to sources for improved infection control protocols; educate clinicians about waterborne infection sources[6]

continued

TABLE 1 Continued

Microenvironment	Primary exposure route(s)	Public health significance	Key microbiome characteristics and microbial community details where available	Qualitative risk evaluation/ priorities*	Data and knowledge gaps	Best practices in management
Cooling towers and evaporative condensers	Aerosol inhalation	Outbreaks linked to aerosol exposures	Microbial community more diverse than natural environments[7]; temperature affects biome—biofilm becomes primary reservoir for *Legionella* spp.[8] with high importance of ciliate and amoeba hosts[7]; disinfection strategies that reduce *Legionella* spp. also reduce microbial diversity and promote *Pseudomonas* spp.[9]	**High**	Impact of microbiome on pathogen dynamics not fully understood; optimize treatment strategies (e.g., biocide dosing); effect of environmental variables and cooling tower design and operation practices on aerosol size distribution, fate, and transport; microorganism characterization in condensates	Ensure high level of routine and poststartup maintenance and cleaning; registration and testing for cooling towers; implement risk management plans; inspect and audit cooling towers; implement setback distances or barriers; install/improve aerosol drift eliminators
HVAC systems (condensate), humidifiers and dehumidifiers, and misters	Aerosol inhalation	Outbreaks linked to aerosol exposures[10]; exposure to other water constituents and particulate matter[11]	Humidifier community less rich and diverse than drinking water; bacteria dominated by Proteobacteria and Cyanobacteria, community affected source water and humidifier timing/ operations[12]; humidifiers can be a source of pathogens, allergens, and endotoxins[13]	**Uncertain–high** (high exposure and growth potential)	Sparse information available about pathogen concentrations (e.g., *Legionella* spp., fungi) in condensate, misters, or humidifiers; characterization of aerosols and impacts of design, operation, and maintenance strategies	Implement water management practices according to guidelines, considering appropriate system siting, system startup cleaning, maintenance, and disinfection practices

continued

TABLE 1 Continued

Microenvironment	Primary exposure route(s)	Public health significance	Key microbiome characteristics and microbial community details where available	Qualitative risk evaluation/ priorities*	Data and knowledge gaps	Best practices in management
Showerheads, hoses, unpressurized portions of associated plumbing (e.g., mixing valves)	Aerosol inhalation	Outbreaks from exposure to aerosols generated by showers; potential for exposures of susceptible populations and occupational exposures	Showerheads and connected unpressurized plumbing tend to have higher microbial densities than typical plumbing system components[14]; showerhead conditions can select for pathogenic species such as *Mycobacterium avium*[15]; age of plumbing fixtures is a key determinant of their microbiome[16]	**Medium** (nonhealthcare facilities)–**high** (showers in healthcare facilities and in facilities serving susceptible populations)	Aerosol size and quantity distributions for the full range of showerhead types and flow rates (particularly water-conserving showerheads and showerheads with complex flow paths); impact of water quality in supply (disinfectant type, temperature, pH, and other factors) on showerhead microbial community; impact of use frequency on microbial community	Prevent aerosols; increase ventilation; reduce pathogen growth conditions (e.g., through periodic disinfection/ cleaning or high-temperature treatment); flush/ divert low-quality water
Drainage outlets (sinks, tubs, shower stalls, and drains)	Oral (accidental ingestion); fomites; aerosol inhalation	Outbreaks associated with sink drains or components[17]	Community structure highly variable across individual sinks; Proteobacteria, Burkholderiaceae, Moraxellaceae, and Sphingomonadaceae were common, with human skin as a contributor to P-trap communities[18]	**Medium** (residential)–**high** (healthcare facilities and susceptible populations)	Role of sink components incl. drains as pathogen reservoirs; understanding of transmission pathways from source	Establish clear maintenance protocols for water systems (incl. drainage components), incl. cleaning, biofilm removal and disinfection; limit nutrient disposal in sinks[19]; prevent splashes from drains through sink design[20]

continued

TABLE 1 Continued

Microenvironment	**Primary exposure route(s)**	**Public health significance**	**Key microbiome characteristics and microbial community details where available**	**Qualitative risk evaluation/ priorities***	**Data and knowledge gaps**	**Best practices in management**
Decorative water features	Aerosol inhalation	Outbreaks linked to aerosol exposures	Pathogens present in both planktonic and biofilm communities[21]	**Low–medium** (nonhealthcare settings)–**high** (healthcare facilities, hotels)	Aerosolization information for water features; impact of maintenance practices on reducing pathogens in water features as some outbreaks have occurred despite maintenance practices in place[22]	Evaluate safety of water features in healthcare settings; routinely maintain and clean water features following guidelines
Pools, spas, water parks, and hot tubs	Oral (accidental ingestion); dermal (e.g., *Pseudomonas* spp.); aerosol inhalation	Outbreaks due to fecal pathogens or linked to aerosol exposures to spas or hot tubs[23]; evidence of exposure to disinfection byproducts[24]; dermal exposure to antibiotic resistance genes[25]	Bacteroidetes, Firmicutes, Actinobacteria, and Deinococcus-Thermus phyla common in children's paddling pools; consortia dominated by intestinal and skin microbiota[26]; wildlife a source of fecal pollution in outdoor pools[27]; diverse fungal communities in indoor pools[28]; ozonation/ chlorination reduces bacterial diversity[29]	**Uncertain** (event-driven for fecal episodes)–**medium** (upkeep- and maintenance-driven for opportunistic pathogens)	Characterization of aerosol emission factors; identification of spa pool designs that reduce aerosol emissions	Implement water management practices incl. disinfection and filter maintenance according to guidelines; implement response plan for postcontamination event; advise individuals not to swim with active gastrointestinal illness

continued

TABLE 1 Continued

Microenvironment	Primary exposure route(s)	Public health significance	Key microbiome characteristics and microbial community details where available	Qualitative risk evaluation/ priorities*	Data and knowledge gaps	Best practices in management
Drinking water fixtures; faucets (unpressurized components incl. aerator, mixing valve, hot and cold plumbing behind mixing valve)	Oral; aerosol inhalation	Outbreaks associated with faucet aerator colonization[30]	Diversity increased with water temperature in hot tap water, but hot tap water bacterial community was less diverse overall compared to cold and shower water[31]; *Hartmanella* amoeba are dominant eukaryotic predator in biofilms but no association of pathogens with amoeba in faucet biofilms; residual chlorine was dominant factor predicting *Legionella* and *Mycobacterium* abundance[32]; Proteobacteria, Bacteroidetes, Acidobacteria, Nitrospira, and Actinobacteria were the most abundant phyla and pathogens were detected in 0.5% total reads[33]	**Low** (residential)–**medium** (healthcare facilities); many aspects **uncertain**	Sink components (incl. faucets, aerators, valves) as pathogen reservoirs; impacts of aerator and other component design and placement; electronic faucet impacts, high variability in aerosol generation rates; impact of biofilm microbial community	Reduce aerosols from faucets; reduce sink backflow and water retention
Nonpotable systems (e.g., reclaimed water, dual reticulation for onsite irrigation purposes)	Oral (accidental ingestion); dermal; aerosol inhalation	Evidence of introduction of wastewater into environment or drinking water sources and subsequent exposures; occupational exposures to nonpotable systems; reservoir for antibiotic-resistant pathogens or resistance genes[34]	Large body of literature on wastewater microbiome[35]; microbial diversity and load, resistome and antibiotic resistance genes decrease during recycled water treatment[36]; reclaimed water systems have distinct microbial ecology compared to potable water[37]	**Low–medium** (event-driven in controlled systems, with potential for low-probability, high-impact events)	Historical focus on fecal pathogens, additional consideration of opportunistic, antibiotic resistance, and other pathogens as well as aerosol exposures beneficial for log reduction target guidance; broader consideration of resistome and microbial community and implications for risk	Implement risk-based guidance for nonpotable systems, incl. log reduction targets; develop additional regulations and guidance for nonpotable reuse; monitor systems for contaminants

continued

TABLE 1 Continued

Microenvironment	Primary exposure route(s)	Public health significance	Key microbiome characteristics and microbial community details where available	Qualitative risk evaluation/ priorities*	Data and knowledge gaps	Best practices in management
Building supply (service line and water from the supplying drinking water distribution system)	Oral (particularly for self-supplied water**); aerosol inhalation (after detention in building water system)	Outbreaks due to treatment failures or loss of distribution integrity in public water systems; inoculation of building water systems with low concentrations of opportunistic pathogens	Microbiomes composed of a core community and ephemeral constituents[38]; microbiome may change seasonally or at other time scales[39]; the core microbiome varies with primary water source, upstream treatment, and water quality (particularly disinfectant type and concentration)[40]; microbial community tends to be more diverse at high water age and low-disinfectant locations than high-disinfectant, low water age locations[41]	**Low** (medium to very large water systems)–**medium** (small water systems and self-supplied water)	Broader knowledge of the association between system characteristics and microbiome; characterization of healthy, stable, and protective biofilm communities; interaction and influence of water supply on microenvironments in building water systems and at plumbing fixtures	Support research and investment in small system water supplies; promote approaches such as water safety planning for improved water quality management in public water systems
Hot water plumbing (incl. mixing valves, water heaters, and water heater sediments)	Oral; aerosol inhalation	Potential for degradation of water quality and pathogen growth niches (e.g., biofilms, favorable growth temperatures)	Hot water diversity can be lower than for cold water[31]; hot water provides pathogen growth niches[42]; stagnation/ water demand alters microbiome[43]	**Low** (water management plan in place)–**medium** (no plan in place)	Simultaneous impacts of multiple factors (e.g., pipe material, disinfectant used, stagnation, water heater operation, building design incl. sustainable buildings, plumbing design) on pathogen growth and risk; implications of water quality trade-offs among management practices, incl. premise plumbing in drinking water microbiome initiatives; impact of mixing valve placement and design on contaminants incl. pathogens	Maintain water heater at high enough temperatures (e.g., 60°C) to discourage pathogen growth; conduct regular water heater desludging and maintenance; monitor performance of (recirculating) hot water systems

continued

TABLE 1 Continued

Microenvironment	Primary exposure route(s)	Public health significance	Key microbiome characteristics and microbial community details where available	Qualitative risk evaluation/ priorities*	Data and knowledge gaps	Best practices in management
Cold water plumbing	Oral; aerosol inhalation	Potential for degradation of water quality and development of pathogen growth niches (e.g., biofilms, favorable growth temperatures)	Opportunistic pathogen and eukaryotic communities differ throughout plumbing system[44]	**Low** (water management plan in place)–**medium** (no plan in place)	Simultaneous impacts of multiple factors (e.g., pipe material, disinfectant used, stagnation, water heater operation, building design incl. sustainable buildings, or plumbing design) on pathogen growth and risk; implications of water quality trade-offs among management practices, incl. premise plumbing in drinking water microbiome initiatives; impact of mixing valve placement and design on contaminants incl. pathogens	Ensure temperature maintenance; design and maintain good hydraulic performance (e.g., reduce stagnation times and dead ends); maintain chlorine residual (e.g., with regular flushing)
Ice machines	Inhalation (splash from water accumulated in ice machine drains); aspiration of water from contaminated ice; oral/ fomite transmission of pathogens (e.g., *Clostridium difficile*) in contaminated ice via consumption or handling	Nosocomial infections (incl. *Legionella*)[45] and infections from ingestion of purchased ice or ice at restaurants and facilities serving the public	Although the ice machine microbiome is not well studied, pathogens are known members of ice machine microbial communities[45]	**Low–medium** (ice machine risks are relatively easy to control via awareness and maintenance and through improved ice machine design)	Exposure factors (e.g., aerosol generation from splash in ice machine drains, transfer rates between machine components, chutes, and ice); metagenomic data for biofilms in chutes, ice cubes, and drain water; relationship between drain and chute microbiomes and those of the water supply and air	Improve protocols for ice machine cleaning and maintenance; improve design to reduce splash and aerosol generation and to reduce transfer from chute biofilms to ice

continued

TABLE 1 Continued

Microenvironment	Primary exposure route(s)	Public health significance	Key microbiome characteristics and microbial community details where available	Qualitative risk evaluation/ priorities*	Data and knowledge gaps	Best practices in management
Toilets	Fomites; aerosol inhalation	Source of pathogen aerosols[46] and role in contaminating surfaces via deposition[47]; contaminated lid surfaces and fomite exposure[48]; potential role in aerosol-related outbreak[49]	Microbial communities composed of bacteria from skin and gut/feces; toilet handles and seats enriched with Firmicutes and Bacteroidetes[50]; toilets can serve as reservoirs of resistome and antibiotic-resistant bacteria[51]	**Low**	Extent to which toilet lids or other interventions reduce aerosol spread and risk; impact of toilet design and environmental variables on flush aerosol emission rates; accumulation of contaminants in toilet water and air over multiple flushes; impact of rainwater or greywater on microbial plume; implications in water, sanitation, and hygiene (WASH) settings	Prevent aerosols, increase ventilation, reduce pathogen growth conditions; additional suggestions in Vardoulakis et al. (2022)[52]
POU filters and reservoirs (incl. point-of-entry devices, water softeners, appliances, and associated water lines and filters)	Oral (exposure to chemical or microbial contaminants; filter performance can be reduced by biofilm formation); inhalation (pathogens grown in POU filters and reservoirs)	Potential for degraded performance of devices intended to reduce exposure to lead and arsenic; unknown public health significance of pathogens grown in POU reservoirs; evidence of water softeners and role in water quality degradation[53]; water stagnation in appliance water lines provides growth niche	Amplification of microorganisms incl. human pathogenic species observed in POU filters[54]; water quality (particularly secondary disinfectant type and concentration) and use characteristics influence the microbiome in POU devices[55]	**Uncertain** (POU devices vary widely in design and application and their impacts on water quality are expected to vary widely; few studies on the microbiome in POU devices have been published to date)	Impact of biofilms in POU devices on device performance (contaminant removal and retention); the potential for POU and appliance filters, lines, and reservoirs to amplify pathogens to levels of public health significance in typical use scenarios	Change filters periodically; consider microbiological processes when selecting POU devices

* Qualitative risk evaluation/priorities: Low = unlikely to pose a nontrivial public health risk; Medium = poses a nontrivial risk under some "typical" conditions or during periods of operational deficiency; High = likely to cause a nontrivial public health risk under routine operating conditions; Uncertain = considerable unknown factors present challenges to designation.

** Self-supplied water use = water withdrawn from a ground- or surface-water source by a user rather than being obtained from a public supply.[56]

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An understanding of pathogen transmission is necessary to effectively protect the built—and human—microbiome.

Microbial Surface Transmission in the Built Environment and Management Methods

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The early widespread concern during the covid-19 pandemic about surface transmission of the disease has waned. There was only one confirmed case, to our knowledge, of surface transmission: a susceptible elderly person used a toothpick after touching a contaminated elevator button (Xie et al. 2020).

The dominant transmission route of current variants of covid-19 is airborne (Miller et al. 2021), but the potential risk of surface transmission—sometimes referred to as "fomite" (a surface capable of harboring pathogens) transmission (Boone and Gerba 2007)—is not zero. Anything in the air can end up on a surface and hands, leading to possible hand-to-mucosa transmis-

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sion, given receptors in the mucosa of the nose, upper airways, and mouth (Prü 2022).

Covid-19 transmission risk from a single touch with a contaminated surface is estimated at less than 1/10,000 (Pitol and Julian 2021; Wilson et al. 2021a), but the fomite transmission route is important for other pathogens and was even recognized historically. As early as the 17th century, the British intentionally gave blankets used by smallpox patients to Native Americans to infect them as a form of biological warfare (Patterson and Runge 2002).

Transmission Methods and Factors

Fomites can lead to infection via pathogen contact with an opening in the body (e.g., open wound, facial mucosal membrane). An infected individual can transfer a bodily fluid containing an infectious pathogen to their hand and (i) to others' hands and eventually fomites or (ii) directly to fomites. These are then touched by susceptible individuals, who may then touch a facial mucosal membrane and/or contaminate other surfaces within hours (Reynolds et al. 2016). For respiratory pathogens, transmission may be via sputum, saliva, or nasal mucus (Adenaiye et al. 2021); for fecal-oral pathogens, the concern may be hand contamination from feces or vomit (Donskey 2010; Phan et al. 2018).

> *Risk of contamination spread depends in part on the survivability of organisms and the frequency with which individuals touch their face, surfaces, or others' hands.*

The risk of contamination spread also depends on the survivability of organisms (Casanova et al. 2010); the frequency with which individuals touch their face (Nicas and Best 2008), fomites (Beamer et al. 2012), or others' hands (Jones et al. 2020); and transfer efficiency (the fraction of pathogens transferred to or from hands during a hand-to-fomite contact) (King et al. 2020). Examples of fecal-oral pathogens that pose fomite transmission risks are norovirus (Kraay et al. 2018), vancomycin-resistant *Enterococci* (Tacconelli and Cataldo 2008), and *Clostridioides difficile* (*C. difficile*) (Weber et al. 2013).

For respiratory pathogens, an infected individual may aerosolize pathogens via sneezing, breathing, talking, coughing, singing, or playing a musical instrument (Coleman et al. 2022; Dhand and Li 2020; Fabian et al. 2008; He et al. 2021; Noti et al. 2012). While some infections (e.g., tuberculosis) are contracted strictly via inhalation, many respiratory viruses, such as rhinovirus (e.g., the "common cold") or influenza A, can be transmitted via the upper airways, with receptors for the viruses in the mucosa (Jacobs et al. 2013; Richard et al. 2020), making surface transmission more theoretically relevant if aerosols containing these pathogens deposit on fomites that are then touched.

Computational research has demonstrated that reduced airborne concentrations due to source control (e.g., via infected individuals' mask use) can reduce fomite transmission (Wilson et al. 2021b) and that airflow patterns can influence deposition patterns on fomites and thus pathogen accruement on hands (King et al. 2015; Wilson et al. 2021c). The risks that fomites pose in this case depend, again, on the rates at which aerosols are produced and deposit on surfaces and the survivability of airborne pathogens on surfaces.

Another factor influencing the importance of pathogens transmitted via surfaces is virulence versus pathogenicity. Some organisms (e.g., norovirus, SARS-CoV-2, rotavirus) are pathogenic in nonimmunocompromised hosts; others (e.g., *C. difficile*, *Pseudomonas aeruginosa*, *Staphylococcus aureus*) are opportunistic, meaning they may be more pathogenic in compromised hosts relative to healthy nonelderly hosts. This can change the impact of fomite transmission of organisms like *C. difficile* by environment; for example, such transmission is of significant concern in healthcare settings with immunocompromised hosts.

Survivability and factors that affect spatial spread are crucial to evaluating fomite transmission since environmental persistence influences environmental spread. Survivability factors such as temperature and humidity (Lin and Marr 2020; Marr et al. 2019) can affect transfer efficiency (Lopez et al. 2013). The concentrations of pathogens emitted from infected individuals are also a key consideration; a pathogen with a fast environmental decay rate could nonetheless pose meaningful risk if generated and introduced to the environment in large quantities.

Importance of Human Behaviors

Aside from environment survivability, human behavior is a key factor in characterizing risks posed by fomites, as even the most contaminated surface may pose little risk if it is rarely touched. Frequency of surface touches has a positive linear relationship with microbial bioburden on surfaces (Adams et al. 2017), suggesting surface cleaning and hands-free design as invaluable ways to reduce risk.

Activity pattern studies of fomite exposures to microbial (and chemical) contaminants, to inform risk assessments, demonstrate that human interactions with fomites are frequent. For example, even older children may make over 1000 hand-to-surface contacts in an hour (Beamer et al. 2012). Hand-to-face contact data have been collected for children and adults (Beamer et al. 2012; Nicas and Best 2008) taking account of potential gender differences (or lack thereof) (Beamer et al. 2012; Zhang et al. 2020), and the influence of environment type (indoor vs. outdoor setting; Tsou et al. 2018) and masked vs. unmasked (Lucas et al. 2020).

Most of the data on hand-to-surface frequency for adults have been collected in the context of healthcare surfaces and healthcare worker hand hygiene (King et al. 2021; Phan et al. 2018; Smith et al. 2012). Such studies have been used to identify and define high-touch surfaces for prioritization in cleaning and disinfection protocols (Huslage et al. 2010) with careful selection of cleaning agents to reduce chemically induced health challenges. In office settings, studies have explored the role of hand dominance and social networks in fomite transmission (Zhang et al. 2018, 2020).

More data on hand-to-nasal orifices and hand-to-eye contacts and their duration for children and adults are needed to advance fomite transmission microbial risk assessment capabilities.

Infection Control Methods and Impacts

Controlling transmission is increasingly important for pathogens that are more commonly transmitted via fomites, especially those with antimicrobial resistance, the "overlooked pandemic" (Laxminarayan 2022). A traditional control approach has been cleaning and disinfection. But while the intention is to reduce the presence of pathogens, this approach also affects overall microbial communities on surfaces, with potential human health impacts, raising a recent question, Are we *too* clean?, particularly in home settings when no one is sick.

Protecting Nonharmful Microorganisms

The "hygiene hypothesis" is that decreases in infections and simultaneous increases in autoimmune and allergic diseases are related: reduction of microbes in environments leads to fewer interactions not only with pathogens but also with "old friends," nonharmful microorganisms that aid in immune system development (Frew 2019). Evidence for this was observed in a study of Amish and Hutterite children: the Amish children, who worked more directly with animals, had lower rates of asthma and more diverse microbial communities in dust in their homes (Ober et al. 2017; Stein et al. 2016). Differences in microbial communities in dust between urban and rural environments (Shan et al. 2020) and between indoors and outdoors have also been reported (Barberán et al. 2015).

Studies have been used to identify and define high-touch surfaces for prioritization in cleaning and disinfection protocols.

Other beneficial microbiome health relationships include the skin microbiome vis-à-vis atopic dermatitis (Lynde et al. 2016), and the gut microbiome's role in preventing infection from *Helicobacter pylori* (a risk factor for gastric cancer; Wroblewski et al. 2010) and C. *difficile* as well as its potential effects on irritable bowel syndrome and cardiovascular diseases (Shreiner et al. 2015).

Health Impacts of Chemical Disinfection

Further potential consequences of surface cleaning and disinfection include inhalation and dermal exposures to cleaning and disinfection chemicals, increasing health risks such as asthma, especially in occupational settings where cleaning and disinfection is frequent, such as in health care (Arif and Delclos 2012; Dumas et al. 2021), although some have demonstrated that these risks can be relatively low (Weber et al. 2016).

When using cleaning and disinfection products, wipes instead of sprays can help reduce the aerosolization and inhalation of chemicals. Proper use of chemicals (e.g., observing recommended contact times) is also important to achieve effective microbial reductions. Disinfectants and sanitizers registered with the US Environmental Protection Agency[1] should be considered rather than products without evaluated efficacy data.

The "more is better" rule does not apply to cleaning and disinfection.

The "more is better" rule does not apply to cleaning and disinfection. Targeted surface hygiene approaches have been proposed that can be tailored to the virulence and primary routes of a pathogen, by, for example, focusing on high-touch surfaces (Huslage et al. 2010) or specific moments (e.g., right after cooking with raw meat) to guide cleaning and disinfection (Bloomfield 2019).

Engineering Strategies

Engineering strategies can also be used to control fomite transmission. They may include proper ventilation and air filtration (Morawska et al. 2020), use of ultraviolet light (Kovach et al. 2017), and incorporation of antimicrobial materials such as silver-impregnated fabrics (Gerba et al. 2016) and copper materials (Bryce et al. 2022).

For all types of transmission routes, engineering controls are more effective and reliable than those that are administrative or related to the use of personal protective equipment (Sehgal and Milton 2021). The latter methods may involve cleaning and disinfection, hand hygiene compliance, or glove use, all of which rely on consistent human behaviors in order to be effective. Ideally, multiple controls with rigorous protocols should be layered to enhance infection control.

We note, however, that time, personnel, products, and resources to effect multiple controls may not be equally available. Inequities may place greater infection burdens on low-income and/or marginalized communities with limited financial, communal, or geographical access to necessary infrastructure, resources, and technologies.[2]

Conclusion

While likely not a primary route for covid-19 transmission, fomites are important for a number of other pathogens of concern. Layered strategies are needed to control fomite transmission routes, including engineering controls (e.g., ventilation and air filtration to reduce the settling of pathogens on surfaces), fomite cleaning and disinfection, and hand hygiene. Strategies for targeted hygiene are recommended to reduce potential negative health effects from exposure to cleaning and disinfection chemicals and the unnecessary removal of beneficial and nonharmful microorganisms.

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[1] USEPA Pesticide Registration (https://www.epa.gov/pesticide-registration)

[2] For a discussion of inequities in access to effective infection control, see Gold et al. (2022) in this issue.

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Beneficial microbial and macrobial exposures can increase immune health and reduce the spread of disease.

Embracing Healthy Microbiomes, Including Access to Nature and Pets

Megan S. Thoemmes, Sarah M. Allard, and Jack A. Gilbert

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> *"…to maintain the air within the room as fresh as the air without…."*
> – Florence Nightingale (1859)

Microbial interactions that occur in built spaces are strong determinants of human health. These interactions underlie the need to establish diverse, long-term exposures that regulate immune development and to limit short-term exposures to specific taxa that can lead to infection, death, or detrimental neurological effects.

Yet, despite long-standing recognition of the importance of human-microbe interactions indoors, the microbiology of the built environment (BE) has never been so much at the nexus of attention and study as it has been

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since the start of the covid-19 pandemic. SARS-CoV-2, the virus that causes covid-19, has led to unprecedented shifts in sociocultural behaviors and keen interest in the potential for microbial transmission in homes, offices, hospitals, schools, and other public places.

However, the full biological and physicochemical context of the built environment must also be considered, as it can influence the distribution of a pathogen, including species abundances and functional potential of microbes that can survive in a harsh, highly selective environment.

Here, we discuss how the indoor microbiome is shaped by BE use and design, how this affects pathogen transmission, how the covid-19 pandemic has altered behavior and building management practices, and finally, how built environments can be manipulated to create healthier spaces.

Microbiology of the Built Environment

Many animals construct their own dwellings. Ants, termites, bees, and wasps are obvious examples, and many birds, mammals, reptiles, and amphibians also construct their own spaces to create a protective environment.

In some cases, animals have been shown to manipulate their BE microbiome to promote positive microbial interactions. For example, the beewolf digger wasp actively cultures bacteria from the genus *Streptomyces* to include in the construction of its larval housing, the cocoon (Kaltenpoth et al. 2005; Kroiss et al. 2010). These bacteria provide biocontrol against potentially harmful fungal pathogens by significantly increasing the probability of larval survival through the production of antifungal compounds, including antibiotics like streptochlorin and piericidin derivatives (Kroiss et al. 2010).

Human history similarly offers examples of active engagement in biocontrol in built structures. Attempts to control BE microbiology have largely stemmed from a fear of disease, and efforts to characterize the origin and long-term viability of BE-associated microorganisms were based on the recognition that their eradication would be beneficial (Lidwell and Lowbury 1950; Wright et al. 1944).

For thousands of years, it has been known that indoor dampness affects human health, yet it was not until the 19th century that a link was made to microorganisms (Carnelley et al. 1887), and it is only in the past 20 years that researchers have attempted to understand the microbiome of dwellings with respect to their ecology (Gilbert and Stephens 2018).

Modern molecular approaches have made it possible to rapidly and cost-effectively characterize the microbial communities of homes, workspaces, and hospitals; identify the factors that impact their temporal dynamics; and distinguish the building and lifestyle factors that determine their survivability and activity (Gilbert and Stephens 2018; Kelley and Gilbert 2013; Stephens et al. 2019). With this new knowledge, the scientific community is exploring how best to manage BE microbiology to enhance health-promoting interactions. Efforts include the use of biocontrol with living microorganisms (Caselli et al. 2016; González et al. 2020; Vandini et al. 2014) and exploration of how building use could influence potential health outcomes (Kembel et al. 2012).

Contributors to the Built Environment Microbiome

Humans

The human microbiome is not limited to what is found on and in the human body. Humans shed nearly a billion bacteria a day and are frequently colonized by microorganisms, resulting in continual exchange with surrounding people and places (Stephens et al. 2019). Homes and other buildings host sloughed-off skin and microbes, and they are the places where people are most commonly exposed to other species (Gilbert and Stephens 2018).

> *Buildings are often designed to limit exposure to the outdoor environment, decreasing the rate of colonization by outdoor species.*

Not only do people spend most of their time indoors (Klepeis et al. 2001), but buildings are often intentionally designed to limit exposure to the outdoor environment, thereby decreasing the rate of colonization by outdoor species (Lax et al. 2014). Thus, the built environment can be considered an extension of an individual's microbial self, as it is inoculated so readily

BOX 1 The built environment metabolome

The built environment metabolome—the accumulation of all small molecules found in the environment, including those produced by cellular organisms during metabolic processes—has been investigated in a limited way. A focus on eradicating microbial life has minimized efforts to understand how these microorganisms survive in the harsh indoor environment. However, it has been established that bacterial and fungal metabolism occurs in dust and that this activity requires the presence of water (Kirjavainen et al. 2016). The resulting microbial germination can lead to the synthesis of metabolites (e.g., alcohols, amines, ketones, and aromatic compounds), creating a metabolic cocktail that can vary significantly between surface materials and in the context of building use (Ezeonu et al. 1994; Schleibinger et al. 2008). Many of these compounds can produce detectable odors as volatile organic compounds (VOCs). Further, environments that are continually or frequently wetted, such as those in bathrooms and kitchens, can result in a much greater diversity of VOCs, including dimethylsulfide, benzothiazole, amides, and pyridine (Adams et al. 2017). These VOCs can influence human behavior and have been associated with neuroactivity that can lead to long-term neurological consequences (Evans 2003).

by microbes from the body that the microbial signature of a new occupant in a room can be detected within 24 hours (Lax et al. 2014, 2017).

Pets and Pests

Pets and/or pests can also significantly contribute to the indoor microbiome, with beneficial or negative health outcomes (Richardson et al. 2019). Animals such as dogs and some livestock increase microbial diversity and promote species interactions that provide a protective effect against the development of allergic diseases (Fujimura et al. 2014; Lynch et al. 2014; Stein et al. 2016). Alternatively, cats, rodents, and certain insects (e.g., bed bugs and dust mites) can introduce pathogens and allergens and alter the house microbiome and metabolome (box 1) in ways that could be detrimental for occupant health (Kakumanu et al. 2020; Martinez et al. 2018; Salo et al. 2018).

Pathogens

Further, the composition of microbes found in the BE is modulated not only by occupants' presence but also by their disease state (Cantú et al. 2022; Marotz et al. 2021). Recent studies have demonstrated that, although it is primarily transmitted through the air, SARS-CoV-2 is detectable on surfaces in rooms with covid-positive patients and that this distribution is strongly correlated with the proportion of specific bacterial taxa (Ben-Shmuel et al. 2020; Marotz et al. 2021; Zhou et al. 2021). We hypothesize that this could be due to a physical interaction between the virus and the bacterium, which enhances viral stability and survivability outside the body (Neu and Mainou 2020). Although their association has not been fully established, *Rothia* bacteria have been found to correlate with the presence of SARS-CoV-2, both in the human body and on hospital and residential surfaces (Ben-Shmuel et al. 2020; Marotz et al. 2021).

These studies provide only a glimpse into the complexity of interactions between humans, their microbes, and the microbes of the spaces they occupy, highlighting the importance of considering both the broader ecology of BE-associated communities and fine-scale species interactions.

Association between Building Design and Pathogen Dynamics

Archeological studies have shown how the design and use of built environments have influenced the frequency of humans' exposure to disease-causing organisms (Fink 1985). For example, it was proposed that interior rooms in ancestral pueblo homes (New Mexico; 900–1300 AD) had a higher abundance of *Mycobacterium tuberculosis*, as compared to exterior rooms, because of reduced exposure to direct sunlight and low ventilation rates (Frobisher and Fuerst 1983).

Contemporary BEs have become even more sealed and modified, now strikingly distinct from the natural world (e.g., many surface habitats are often severely limited in the availability of water and nutrients), and these conditions have imposed selective pressures on the microbes that can colonize and persist inside. This environmental stress triggers horizontal gene transfer events that facilitate the acquisition of new genes and hence phenotypes (Lax et al. 2017, 2019). In addition, microbial adaptations needed for survival can lead to an increase in antimicrobial resistance and/or virulence over time, as has been shown both in hospitals and on spacecraft (Lax et al. 2017; Urbaniak et al. 2019).

This genetic selection for pathogenic traits is compounded by the loss of many potentially beneficial organisms through attempts to chemically or mechanically remove microbial life in human-occupied spaces (Gilbert and Stephens 2018). People now come in contact with a smaller subset of diverse organisms that are important not only for immune development (Stein et al. 2016) but also for the reduction of pathogen abundance indoors (Kembel et al. 2012).

The author of the first book on nursing, Florence Nightingale (1859), championed the value of opening windows to increase patients' rate of healing and decrease the rate of death. Opening windows is likely to shape the indoor environment in a variety of ways that can benefit patient health (e.g., by increasing oxygen levels). However, here we focus specifically on the effect on the microbiome.

Since Nightingale's time, it has been shown that hospital rooms ventilated with open windows have greater microbial taxonomic diversity and a reduction in the proportion of potential pathogens (Kembel et al. 2012), highlighting the benefit of increased ventilation indoors in mediating the spread of disease. This small action can not only greatly reduce airborne pathogens (which is particularly important when considering viruses that spread in the same ways as SARS-CoV-2) but also create a more complex, competitive environment for pathogens that are typically spread through the touching of surfaces (Stephens et al. 2019).

Influence of the Covid-19 Pandemic on Ventilation and Cleaning Practices

Since the onset of the covid-19 pandemic in March 2020, there has been a shift in public awareness of and approaches to ventilation and cleaning, in both private and public settings; see, for example, the Department of Education guidelines for improving ventilation in schools, colleges, and universities[1] and the Centers for Disease Control and Prevention (CDC) guidance for improving ventilation in homes.[2]

With respect to cleaning, the CDC reported a 20 percent increase in the number of calls to Poison Control about exposure to cleaners and disinfectants from January to March 2020, compared to the same period in the previous 2 years (Chang et al. 2020), indicating an increase both in the use of such products (e.g., bleach) and in unsafe practices with their use (e.g., soaking fresh produce).

As the pandemic continued, scientific studies and outbreak tracing provided clarity on the most prevalent transmission routes of the SARS-CoV-2 virus, showing that person-to-person contact and air are the primary routes of transmission and that surface-based transmission is less likely to result in infection (Prather et al. 2020). This revelation has led to unprecedented public interest in ventilation efficiency (e.g., optimization of air changes per hour, ACH), air filtration practices, and changes to building infrastructure. For example, the CDC recommends improved ventilation as a core mitigation strategy in a layered approach to covid-19 safety in public buildings, including schools.[3] As one example, the University of California San Diego shifted to outdoor classes and upgraded ventilation and air filtration for indoor spaces (see UCSD Return to Learn).

> *Approaches implemented to decrease SARS-CoV-2 transmission had a preventive impact on the spread of other diseases.*

These changes in building use, management, and cleaning practices could have long-term impacts on BE microbiomes. Air filtration and ventilation improvements will further influence microbial community composition/complexity and rates of disease transmission. During the first 2 years of the pandemic, a concurrent decrease in seasonal flu cases (Hayashi and Konishi 2021; Servick 2021) demonstrated that approaches implemented to decrease SARS-CoV-2 transmission had a preventive impact on the spread of other diseases (Zhang et al. 2021).

On the other hand, there is growing concern over the probable increase in the emergence of antibiotic-resistant microorganisms and healthcare-associated infections (HAIs) since the onset of the pandemic, potentially due in part to altered cleaning regimes (Lobie et al. 2021; Mahoney et al. 2021; Seethalakshmi et al. 2022). HAIs are a leading cause of death worldwide (Haque et al. 2018), so the need to develop optimized disease management strategies indoors is of exceptional importance.

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[1] https://www.ed.gov/improving-ventilation-schools-colleges-and-universities-prevent-covid-19

[2] https://www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/improving-ventilation-home.html

[3] https://www.cdc.gov/coronavirus/2019-ncov/community/ventilation.html

Targeted Approaches to Support Healthy BE Microbiomes

To maximize human health in the 21st century, scientists and architects must consider novel ways to design, construct, and manage buildings and cities in a manner that will promote healthy microbial interactions. Improved indoor air quality is a well-established strategy to benefit human health, and can be augmented by innovating strategies that further increase exposure to beneficial microbes, by, for example, advising increased interaction with certain types of pets (especially for young, nonatopic children) and time spent outdoors.

Because there are many scenarios in which such measures are not possible, we envisage a future where microbial biocontrol can be engineered into building materials (i.e., living buildings) (Beckett 2021; González et al. 2020; Ramirez-Figueroa and Beckett 2020) to provide surfaces that both actively reduce the emergence and persistence of dangerous pathogens and create immune-activating exposure to decrease the incidence of chronic immune disease (Gilbert et al. 2018; Stein et al. 2016). This would also lessen the likelihood of exposure to allergens, such as animal dander, that could exacerbate allergic symptoms.

A future that involves biologically active building materials and breathing urban spaces could have profound positive outcomes for health and quality of life. There is still much work to be done to determine which beneficial species are safe for all individuals, particularly those who are immunocompromised, and so we argue that research supporting this vision should be prioritized.

Conclusion

Despite a clear understanding of the potential risk of detrimental microbial exposures in indoor and urban settings, researchers are only just beginning to fully comprehend the implications of actively altering these interactions. The SARS-CoV-2 pandemic provided an ideal opportunity to accelerate research on ways to further reduce pathogenic exposures in homes, offices, and schools. However, it also reignited the question, How clean is too clean? The built environment has been compared to a biological wasteland (Gibbons 2016), but the future of this field points to a reversal of this paradigm, toward repopulating indoor spaces and urban places with beneficial microbial and macrobial experiences. Living buildings might provide targeted beneficial exposures to improve human health and vitality.

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Community engagement, communication, and collaboration are needed to help address poor housing quality that contributes to disease.

Housing-based Inequities in Microbial Exposure and Respiratory Infection Risk

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Research in recent decades has helped disaggregate the components of the built environment that contribute to the increased risk of respiratory infections in poorer neighborhoods (Engineer et al. 2021). The covid-19 pandemic highlighted the role of these components as well as neighborhood-level housing inequities (Pitzalis and Spano 2021)—such as unstable access to housing (Nobari et al. 2022), crowding, and inadequate or faulty plumbing

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and ventilation—in increasing respiratory infection incidence, morbidity, and mortality (Rossen et al. 2021; Tieskens et al. 2021).

The realities of housing circumstances in many underresourced neighborhoods make it very challenging for individuals in households to implement recommended respiratory infection prevention practices such as distancing, quarantine, and effective ventilation. In this article we describe the contributing factors to housing inequities and then explain the critical role of respectful community engagement and risk communication to support collaborative efforts that can mitigate risks and facilitate control strategies.

Factors Associated with Inequity and Infection Risk

To devise housing and neighborhood infection control strategies that complement vaccination and the use of personal protective equipment (when available), it is necessary to understand how respiratory infections and their variants are spread. Infection risk—and hence potentially effective control strategies—vary by virulence (a quantitative measure of the likelihood of causing disease), transmissibility (ease of spread from one host to another), mode(s) of transmission, and whether transmission can occur in asymptomatic people. However, common risk factors for the spread of many respiratory infections (e.g., influenza and tuberculosis) also include urban density, poverty (Lobato-Cordero et al. 2019; Nardell 1989), and associated built environment conditions.

> *Housing circumstances in many underresourced neighborhoods make it very challenging to implement respiratory infection prevention practices.*

Multiple features of poor-quality housing have been tied to poor health generally and to risk of chronic respiratory illness as well as acute respiratory infection specifically. Crowding (Gonzalez et al. 2021), lack of space for family members to isolate or quarantine, and poor ventilation and air filtration all directly affect transmission risk of infectious microbes, as clearly demonstrated during the covid-19 pandemic (Bazant and Bush 2021). Pest infestation, which is more common in housing that is in disrepair and located in disadvantaged neighborhoods, can be allergenic (increasing susceptibility to and exacerbation of asthma, often in the setting of acute respiratory infection; O'Connor et al. 2018), carry pathogens, and negatively influence indoor microbial ecosystems (Kakumanu et al. 2020).

Crowding and Proximity

Beyond crowding in family homes, congregate housing such as dormitories (Cedeno Laurent et al. 2020), homeless shelters, prisons, and nursing homes are the settings of high rates of spread of respiratory infections (Mphaphlele et al. 2015; Nardell 1989).

In homeless shelters, reports have noted between-resident reinfection with tuberculosis, potential TB transmission through ventilation systems, and, on the other hand, the safety and effectiveness of well-maintained upper-room germicidal ultraviolet (UV) air disinfection (Mphaphlele et al. 2015; Nardell et al. 2008) in reducing infection risk. For covid-19 and influenza, direct air transfer between humans is well documented; their potential viability and transmissibility through ventilation systems is less certain than for tuberculosis.[1]

Poor Ventilation and Air Quality

Congregate and individual/family housing in underresourced neighborhoods may lack adequate air exchange for dilution of airborne respiratory infection to reduce risk of spread. The workplaces of people from underresourced neighborhoods may also have suboptimal building ventilation conditions, compounding the risk of bringing home respiratory infections such as covid-19.

For overall respiratory health, along with introduction of outdoor air, there is also a need to prevent outdoor air pollution and allergens from penetrating indoors and to maintain a comfortable temperature and humidity level, while ensuring control of indoor sources of pollution and bioaerosols, including microbial exposures that are detrimental to health (ASM 2004). Building conditions such as temperature and humidity also influence the mode as well as the likelihood of spread of respiratory infections (Lobato-Cordero et al. 2019; Wang et al. 2022).

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[1] For a more extensive discussion of pathogen transmission in the built environment, see Wilson et al. (2022) in this issue.

Guidance for hospitals and other communal spaces to reduce building-related covid-19 risk has included recommendations regarding air filtration of outdoor particle pollution while bringing in adequate fresh air, indoor room particle filtration, and consideration of upper-room germicidal UV to reduce viral particle burden (Klompas et al. 2021; Morawska et al. 2020). Research has demonstrated the risks of indoor air recirculation, which is more common with current-generation air conditioning, in potentially concentrating some infectious airborne microbial exposures (Nardell et al. 2020).

Increasing ventilation is certainly helpful, but it is not possible to provide precise recommendations on air exchange rates that keep pace with changes in covid-19 viral transmissibility (Ghoroghi et al. 2022)—since 2021, with the appearance of new variants, the transmissibility of covid-19 has not only evolved but also, with the Delta and Omicron variants, increased (Mohsin and Mahmud 2022).

Lack of Basic Resources

Adverse housing conditions make the provision of adequate air exchange, as well as isolation or quarantine to reduce respiratory infection risk, infeasible in many homes. Housing mobility programs (Pollack et al. 2019) can offer families a timely solution, and isolation outside the home has sometimes been available (e.g., in a hotel; Huggett et al. 2021). But leaving a loved one with strangers or on their own in temporary housing for isolation or quarantine can be culturally incompatible and emotionally distressing for family members and caregivers.

These challenges are not confined to families in urban areas. For example, while many Native American families in rural homes have benefited from the support of traditional healers and community health representatives[2] to help tend to family members suffering from covid-19 (Solomon et al. 2022), they have been constrained by contaminated water supply, lack of transportation, and inaccessible health communication (Yellow Horse et al. 2022).

Legacy of Discrimination in Housing

Multilayered discriminatory policies that were codified and implemented through racial covenants, redlining, and other unfavorable lending practices more than a century ago created segregated neighborhoods and stripped residents of opportunities to build wealth needed to purchase, repair, and maintain healthy housing. Zoning allowed the siting of nearby pollution sources (Deshmukh et al. 2020; Lane et al. 2022), shown to increase covid-19 mortality risk (Chakraborty et al. 2022). These and other factors also contribute to the presence of urban heat islands (Jesdale et al. 2013) and vacant lots that promote the growth of ragweed, a common allergen (Katz and Batterman 2019). For all these reasons, ensuring a healthy indoor home environment in these neighborhoods can be particularly challenging.

The problems are illustrated in a composite scenario (box 1) drawn from the experiences of participants in the Community Asthma Prevention Program in Philadelphia.

BOX 1 Illustrative scenario of housing-related challenges to health

A mother and her four asthmatic children live in a small rowhouse in Philadelphia. There are two bedrooms and one bathroom; three children sleep in one room (two share a bed and one sleeps on a mattress on the carpet) and the youngest child sleeps with his mother in the other bedroom. The house was built in the late 1800s and sits in the middle of the block.

A tour of the home reveals the following: A damaged kitchen floor (due to a roof leak), with a bucket in the middle of the floor for the leak. Mouse droppings in the kitchen, living room, and bedroom. In the bathroom, some missing vinyl flooring and leaks around the toilet and tub. A basin under the faucet in the sink, which has a leak. In the bedrooms, outside air coming through the window frames; when the weather is cold, the windows are covered with a blanket. Mold in the children's bedroom closet, where clothes are in boxes on the floor. The children sit with the lights off and use space heaters for warmth; the mother explains that she is behind on paying her utility bills and trying to use as little energy as possible.

Before the pandemic, the mother worked two jobs and at night a maternal aunt stayed with the children. Early in the pandemic, worried the aunt would bring the virus into the home from her day job in a hospital, the mother stopped working her night job so she could be with her children.

This composite scenario shows the myriad challenges that many families were already negotiating before the pandemic and how the pandemic compounded those difficulties.

Community Engagement and Risk Communication

The challenges described above are long-standing, complex, and interconnected. They must be addressed

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[2] DHHS Indian Health Service Community Health Representative Program (https://www.ihs.gov/chr/)

by long-term and systemic approaches involving stakeholders at multiple levels, policymakers, engineers, architects, community members, and others. As part of that process, in this article we consider the role of community-engaged research and effective risk communication in addressing health disparities related to the indoor environment.

Community Engagement around Indoor Environmental Health

Black, Hispanic, and Indigenous communities in the United States have endured a lengthy history of exploitative research and medical practices (Corbie-Smith et al. 2002; Nuriddin et al. 2020); thus, public health engagement in these communities can be fraught with mistrust and skepticism. But respectful research methods and communication can foster the development of relationships and trust between public health researchers, engineers, and clinical workers and the minoritized communities they seek to learn from and support (Holzer et al. 2014; Rhodes et al. 2018).

Exposure to misinformation can influence intentions to avoid or seek additional information.

Community-engaged research is (i) driven by needs defined by the community, (ii) conducted in service to helping the community meet its needs, and (iii) wholly collaborative, with scholars working alongside community members to collect data and put it to use for the benefit of the community (Ahmed and Palermo 2010). For example, as noted above in the composite scenario, the Community Asthma Prevention Program works closely with Philadelphia families in underresourced neighborhoods to jointly identify and implement housing repairs that can improve asthma control and that may also reduce covid-19 risk through better-ventilated living spaces (Bryant-Stephens et al. 2021).

Understanding Risk Communication

Risk communication scholars have identified a number of factors that can enhance community-engaged research as it works to build trust, share research findings, and help communities navigate complex health risks.

Risk communication research has evolved dramatically over the past 40 years. What started as a field dedicated to aligning "'lay' perspectives with those of 'the experts'" has evolved to recognize that risk perceptions are subjective and socially constructed (Balog-Way et al. 2020, p. 2242). A more modern approach to risk communication begins with an acknowledgment of the complex (and often environmentally constrained) ways in which a community has already navigated a risk; from there, researchers and community stakeholders can craft an achievable plan for moving forward with mutual goals (Hampel 2006).

One important finding in the risk communication literature is that people are significantly motivated by *others'* information behaviors and expectations (Ahn and Kahlor 2020; Wang et al. 2021). That is, they consider whether people in their family and community expect them to know something about the risk, or whether the topic is more or less avoided. The influence of extended families and social networks becomes even more important in crisis communication contexts, such as natural disasters and pandemics (Eisenman et al. 2007; Kahn et al. 2022).

Like risk itself, risk information behaviors (including seeking, sharing, and avoiding) are socially constructed, and individuals are more heavily influenced by information-related norms than by their own perceived risk, worry about the risk, or hope for its mitigation (Kahlor et al. 2020). Exposure to misinformation can further influence intentions to avoid or seek additional risk information (Kim et al. 2020), as can lack of trust in the government entities expected to mitigate the risk (Ahn et al. 2021).

In the context of covid-19, while public health communication kept pace with scientists' evolving understanding of viral transmission and risk mitigation, the public's tolerance for the pace of science waned as the pandemic dragged on, and purveyors of misinformation quickly "filled" perceived voids in the information landscape (Ayers et al. 2021; Vanderpool et al. 2020). The misinformation was rapidly amplified across social media channels, and a global crisis ensued in which individuals were just as likely to encounter misinformation as factual information (Singh et al. 2020).

However, research suggests that partnerships with community-based organizations and local and mainstream mass media channels have the potential and capacity to support public health efforts to combat misinformation (Korin et al. 2022; Lwin et al. 2021).

It is therefore vital that researchers work with community members, not just to study health risks in the built environment and how to mitigate them, but also to learn how to talk about these risks, who the trusted voices are, how to present each risk in a way that situates it in the larger risk profile for the family and the community,[3] and what resources are available to pursue reasonable changes.

Conclusion

We have highlighted the associations between poor housing quality and disease, as well as challenges to meaningful communication about the related risks. The lingering damage from long-standing discriminatory practices and policies that contribute to unhealthy living conditions must be addressed through extensive, systemic changes. Initiatives at the national, regional, state, city, and neighborhood levels are needed to engage with community stakeholders and families and build collaborative approaches that undo this enduring legacy over the longer term.

But there is also an urgent need for near-term approaches to improve housing quality in order to better protect individuals, families, and communities from respiratory infection transmission and exacerbation of chronic respiratory diseases like asthma. The success of these approaches depends on community engagement and evidence-based risk communication strategies. The covid-19 pandemic persists—and it will not be the last.

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People need to know how to manage the microbiomes of daily life to favor beneficial species, ignore benign species, and target problem species.

The Future of Microbiomes in the Built Environment


Photo: Amanda Ward

Robert Dunn


Megan Thoemmes

Robert R. Dunn and
Megan S. Thoemmes

The story of microbes in the built environment—including houses and apartments, office buildings, schools, barns, production facilities, and other structures—is a story of people's conscious and unconscious knowledge of the world. Conscious awareness of microbes as entities is recent, dating from the work of Antonie van Leeuwenhoek (1677). Humans' unconscious awareness of the surrounding microbial world is far more ancient: it begins with the origin of the vertebrate immune system, hundreds of millions of years ago (Kasahara et al. 2004).

Background

When immune systems were first discovered and studied, they were viewed as defensive. Consequently, efforts to understand the natural history and evolution of immune systems focused on their responses to pathogens. Over the last few decades, however, it has become clear that immune systems are more nuanced. They recognize microorganisms and respond to them as friend or foe depending not only on the identity of the organisms but also on their behaviors (e.g., which metabolite compounds they happen to produce

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at any given time in response to various internal and/or external stimuli; Levy et al. 2016).

Efforts to fully comprehend the extraordinary sophistication with which immune systems recognize and respond to friends or foes are still in their early stages. However, three things have become clear.

First, immune systems can and do recognize a subset of commensal microbes or their products as beneficial (e.g., Peters et al. 2019). Second, in doing so, they not only avoid attacking those organisms but also often provide them food, whether as glycogen in vaginal communities (Miller et al. 2016), mucin or nitrogen in the gut (Reese et al. 2018), or amino acids and lipids on the skin (from the apocrine glands; Barzantny et al. 2012). Third, the responses of human immune systems to microorganisms have evolved over the last 300,000 years in response to changes in the composition of beneficial and dangerous microorganisms in human environments (Brinkworth and Valizadegan 2021; Varki 2009).

This microhistory of the subconscious responses of human bodies to the microbes around them is relevant to an understanding of the microbiomes of the built environment because it is exceptionally distinct from conscious responses to microbes.

Humans' Conscious Responses to Microbes

Conscious responses to microbes began with the development of germ theory by Louis Pasteur and contemporaries (Gaynes 2011). Germ theory ushered in extraordinarily functional and beneficial social responses such as the control of drinking water systems to reduce the probability of fecal-oral transmission of pathogens, hand washing and other general hygiene practices, and, eventually, vaccinations and the development and use of antibiotics (Dunn 2018). Collectively, these interventions have saved hundreds of millions of lives. However, compared to the responses of the human immune system to the microbial world, they remain unsophisticated. Rather than being tailored to favor some microbes and disfavor others, most of these interventions, with the exception of vaccines, focus on killing microbes in general.

Medicine's very successful but largely unsophisticated efforts to control pathogens eventually became part of a broader cultural response to microbes. Efforts to kill microbes were generalized in ways that affected not just drinking water or human bodies but also the built environments in which humans now spend most of their lives (Dunn 2018). This transition built on efforts to take disease control efforts from sanatoriums and apply them in houses (it has been argued that Modernist architecture emerges from sanatorium architecture; Colomina 2019).

In addition, efforts to control all microbes in houses were heightened by the advertisement campaigns of companies selling "cleaning" products. Then the marketing of cleaning products for houses and those for bodies were entangled and interwoven. In much the same way that antiperspirant, which works by closing the apocrine glands that evolved to feed skin microbes (Kong 2011; McGrath 2009), is now sold to large populations who have apocrine glands that do not produce such food, cleaning products are sold for houses to kill dangerous microbes, whether or not such microbes are likely to be present.

Differentiating between Harmful and Beneficial Microbes

Scientists have finally begun—like the human immune system—to recognize which bodily and environmental microbes are beneficial for human health. For example, it is now known that the microbes associated with some fermented foods enrich beneficial bacteria in the gut and promote healthy digestive functions (Marco et al. 2017). Conversely, studies have reported the negative effects for health and well-being of losing certain microbial taxa (Haahtela et al. 2015; von Mutius and Vercelli 2010).

> *Compared to the responses of the human immune system to the microbial world, conscious interventions are unsophisticated.*

Understanding is also emerging about the extent to which the microbes encountered in modern homes differ from those our ancestors would have encountered. Studies of chimpanzee beds suggest that human ancestors are likely to have been predominantly exposed to leaf and soil-associated species for millions of years (Thoemmes et al. 2018). As humans began to gather in larger densities, those leaf and soil species began to be accompanied by larger numbers of pathogens. Globally, humans are now afflicted by problems stemming from more than 1400 pathogen species,[1] compared to the tens of pathogen species that are currently known to afflict chimpanzees and almost certainly afflicted our common ancestors (Dunn et al. 2017).

Clean drinking water, personal hygiene, antibiotics, and vaccinations have brought the vast majority of these pathogens under control in much of the world. At the same time, houses became tightly sealed and humans began to spend more of their daily lives indoors (95 percent of their lives, in many regions; Klepeis et al. 2001). The result is that the microbes people predominantly encounter in their daily lives are species associated with human bodies and pets (Dunn et al. 2013; Lax et al. 2014, 2017; Richardson et al. 2019), along with extremophiles associated with, for example, water heaters, refrigerators, freezers (Savage et al. 2016), and dishwashers (Raghupathi et al. 2018). The International Space Station is an extreme version of this reality, where the microbial environment is dominated by body microbes (Checinska et al. 2015).

The loss of exposure to key microbes is associated with problems of gut health, skin health, and even mental health.

With increased sanitation and restrictive measures to prevent microbial contamination from terrestrial sources, there is little to no opportunity for leaf or soil microbes to enter and colonize air and surface environments. Yet exposure to these same microbes is increasingly recognized as key to immune health (Haahtela et al. 2015).

Impacts of the Covid-19 Pandemic

By the time the covid-19 pandemic began, microbiologists around the world had already begun to study ways to reintroduce beneficial microbes into people's daily lives. Researchers assessed the value of biodiverse plantings outdoors (Hanski et al. 2012), of probiotics and microbial foods (Marco et al. 2017), of opening windows (Richardson et al. 2019), and even of household probiotics (Caselli et al. 2018). These studies recognize that the loss of exposure to key microbes is associated with problems of gut health, skin health, and even mental health. Yet, a holistic understanding of which species should be reintroduced to create healthy buildings is still nascent. The subconscious human body may have fine-tuned "understandings" of which species to favor and disfavor, but the conscious minds of scientists have no such consensus.

Prior to the onset of the covid-19 pandemic, the scientific community was making progress in understanding the impacts of daily human practices on the microbiomes that surround us, and the mainstream Western world seemed eager to embrace ways in which cultivating a particular microbial community in the home might be beneficial. At the same time an increasing number of studies had begun to detail the problems associated with the absence of key microbes, whether in human bodies or in dwellings.

Then, as covid-19 spread around the world, the long tendency of Western humans to kill microbes in general, rather than just pathogens, accelerated (Chang et al. 2020). During the first 2 years (and continuing today) many individuals, perhaps most, moved toward behaviors in their homes that more closely resemble the ways in which one might clean a hospital room, a sanatorium, or a space station—even as products aimed at favoring microbes have become more popular, whether as skin creams, oral probiotics, or microbial foods.

Concluding Thoughts

We perceive that this is a time of general cognitive dissonance, when many individuals are trying to kill all the microscopic life around them and, at the same time, paying for products that favor some species. It is clear that in the long term people need to understand how to manage the microbiomes of daily life in more sophisticated ways to favor beneficial species, ignore benign species, and strategically target problem species.

We expect that this challenge will remain twofold. First, unlike the human immune system, is it not yet feasible for humans to see microbial life in the environs in real time in ways that make obvious and conscious the difference between beneficial and harmful. Second, understanding of what is beneficial and harmful is nascent.

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[1] Editorial: Microbiology by numbers. Nature Reviews Microbiology 9:628 (2011).

At this point it is almost certainly true that, so long as you washed your hands with soap and water and had a source of drinking water that was free of pathogens, sleeping in a bed built like a chimpanzee nest would be healthier than any modern home thus far designed.

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An Interview with . . .

Helen Wang,
Founder and CEO,
6crickets.com

RON LATANISION (RML): Welcome, Helen. We're delighted to talk with you. I understand you're a trained computer scientist and had a substantial career at Microsoft Research.

HELEN WANG: Yes, I spent 14 years there. When I first arrived, I was one of two women researchers at the Systems and Networking research group. Later, I founded and led the security and privacy research group.

RML: Then you decided to change directions. The first question I must ask is how you came up with the name 6crickets for your enterprise.

DR. WANG: Do you like the name?

RML: Yes. Even my grandchildren like it.

CAMERON FLETCHER (CHF): It's delightful.

DR. WANG: We are really passionate about education, particularly for K-12 children, and we don't want to limit ourselves. For example, Amazon.com was not books.com. There is a grand vision behind it, and essentially they achieved that grand vision of being the everything store. With 6crickets similarly, our grand vision is equitable education for every student in every community.

We want to find a place to contribute in huge ways. Of course there are many ways to contribute, and we're evolving. We're 7 years in business and almost every year we've had a substantial pivot to keep evolving our business, to keep reinventing what we're doing and keep learning about this area and evolving our solutions to better fit the problem.

We wanted to come up with a name that we get to define and that doesn't constrain us in our grand scheme. And of course the domain name had to be available. So we created our own word.

CHF: Is the number 6 just random—it could have been 4Crickets, or 9Crickets?

DR. WANG: It rhymes a little bit with crickets, so it sounds better. And 6 is quite a lucky number in Chinese culture. And later other folks told me that crickets are very auspicious as well. We didn't plan for those things, and we're happy it turned out that way.

RML: Making a transition from Microsoft and very sophisticated high-tech engineering to education, you had no degree in precollege education—that's a pretty big transition. Did you work with educators, or how did you begin?

DR. WANG: At Microsoft I founded and managed the Security and Privacy Research Group. It was not easy to leave. But I'm a parent, and that has really driven my interest.

I started this company when my sons were turning 5 and 7. That's a time when their brains and their bodies become capable of doing a lot more cool stuff. As a passionate parent, the same as many other passionate

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This interview took place June 29. It has been edited for length and clarity.

parents, we're looking for ways to inspire our children to love learning and to experience life in many different ways.

One year I had a difficult time planning for my children's summer camps. We are at a time to Uber a ride, and Airbnb home away from home. But when parents are planning or figuring out how to arrange their children's out-of-school time, it's very complex, very frustrating work. It's from the last century! I realized that this was an area where technology really lagged behind.

> *We're looking for ways to inspire children to love learning and to experience life in many different ways.*

Another thing that struck me is that, during the school year, I would work until 5:00 or 6:00, my kids get out of school at 2:30pm, and there's one day that's early release day, ending at 12:30pm. I needed to figure out how to plan for what my kids would do for those afterschool hours when I am still working. Of course, there is the whole summer as well.

Parents work 2000 hours a year: 40 hours a week, let's say 50 weeks of work—you take 2 weeks off—that's 2000 hours. Students are in school for only 1000 hours. So every student has 1000 hours of no school when parents are working. Out-of-school time is *half* of K-12 education!

I was also volunteering at my sons' school, for afterschool enrichment. Gosh, we had fabulous afterschool enrichment—chess, magic, programming, robots, dance, art—with vendors from our local community coming to the schools to teach these extracurricular enrichment classes. That was a lot of work as well.

RML: Do you make an attempt to align the afterschool offerings with the school's needs?

DR. WANG: It's a free space for innovative teaching and learning. But often they reinforce each other. For example, if you take a cooking class, you learn fractions along the way. And if you love gaming, and an enrichment provider teaches you how to do 3D modeling to create a 3D game, you learn programming.

I have really been enlightened in this process. We've got a tremendous testbed for innovative education to take place. The innovation comes from rapid iterations. When we create new things we iterate: we say 'this is a great curriculum' or 'no, this is not the right way to teach the kids, let's try something else.'

I think in education we lack this kind of platform or testbed, to try out new topics or new ways to teach kids, to engage our kids and make it fun for them.

Going back to those 2000 hours, kids have 1000 hours in school with systematic learning, traditional learning, and the other 1000 hours of out-of-school time is a tremendous platform for innovative teaching, for engaging students, for a new way of teaching kids. That was really an *aha* moment.

What really struck me is that a few blocks from our sons' school is a Title 1 school. That school has only extended care programs, but no enrichment whatsoever. It is because their families cannot afford to pay for enrichment programs and they don't have an active PTA seeking and organizing these programs.

It was apparent to me that there is a "Wild Wild West" in out-of-school time. There is a glaring opportunity gap and lack of infrastructure to support the families, the small businesses helping the program, and the schools or districts organizing the programs.

RML: Does that translate into interaction primarily with larger urban school districts or smaller school districts?

DR. WANG: The mission of 6crickets is to bring the best enrichment to every child in every community, whether it's rural, urban, suburban—everywhere. If you have a school you have a community. If you have a community you could have amazing enrichment learning.

RML: I just wondered whether the offerings you provide are attracting the attention of larger urban school districts. For example, Boston public schools could really use what you're doing.

CHF: What is your geographic ambit at this point? I know you're in Seattle and San Diego. What other areas?

DR. WANG: Anywhere in the US because we are a management solution. We have built the infrastructure for out-of-school time. When we talk about infrastructure, that means we need to provide support for every stakeholder in this ecosystem. Who are the key stakeholders in this ecosystem? They're parents, of course, and districts and schools, and enrichment providers. 6crickets provides infrastructure support for all three.

For districts and schools, we provide a management solution so they can harness community partners to provide the best, vibrant enrichment. For the enrichment providers, we provide the tools, the software, and the solution to manage their classes and registrations and so on.

And for the families it's a one-stop shop (figure 1). For kids at a participating school, the parent selects it on our website and can see what programs might be available this summer—for example, here's a school where there's chess, science, algebra games, public speaking, speech writing, Roblox 3D game design, junior robotics, introduction to debate, animation, exploring atoms, electromagnetism, art, Scratch programming language from MIT being taught to young students, introduction to theater, math puzzles, and so on for different grade levels.

6crickets organizes this content. Here's a chess program offered by Strategic Kids, which is a provider. You can see that families have rated it 4½ out of 5 stars. And here's a program, offered by an organization called STEAM for Teens, teaching 3D game design.

We manage these small businesses and organizations to work together. We do the coordination management work to enable vibrant enrichment programs at schools.

CHF: How do you vet the providers? What's the basis for making your platform available to these providers, to ensure some kind of quality?

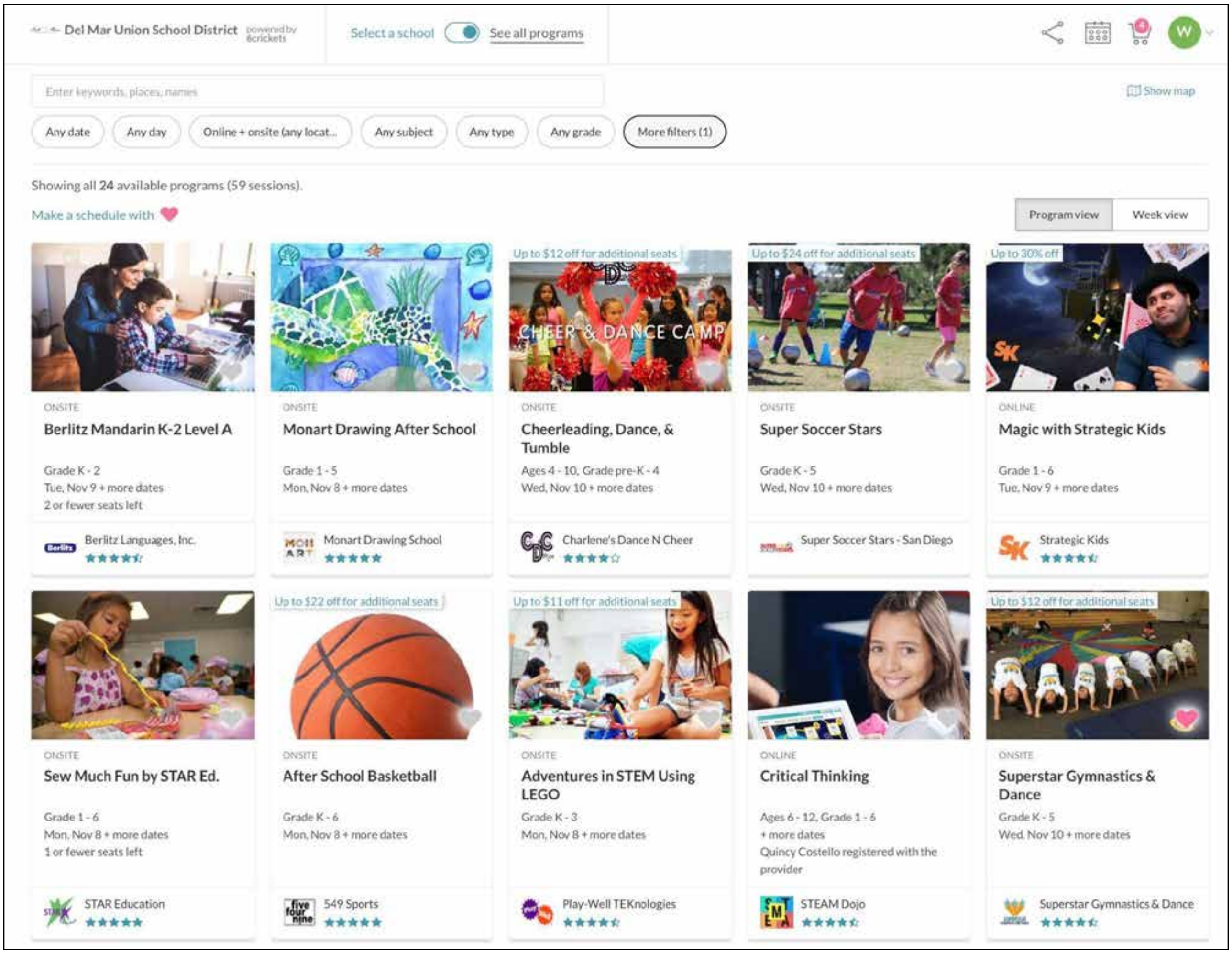

FIGURE 1 6crickets family-facing, one-stop enrichment web portal for an existing district client. Classes or camps (whether in-person or virtual) are vetted by 6crickets from third-party providers and aggregated here. Families can browse programs, read reviews, and register their students for different programs with one login, one form, and one checkout process (if payment is involved). Providers, schools, and districts then receive real-time registration information.

DR. WANG: For some schools we do the sourcing, and some schools have their own existing providers. When we source, we evaluate their quality based on parents' reviews, references, their curriculums, and their methodology in hiring and training instructors. Our service also helps with the vetting process. Whether it's insurance or a background check or covid-19 protocols, there's a whole host of requirements and paperwork that needs to be done. We digitize the entire workflow in out-of-school enrichment.

We recognize that teachers are overworked, so they shouldn't be tasked with extra work in the afterschool hours or over the summer. They can do it if they want, but they should have a choice not to.

> *If you have a school you have a community. If you have a community you could have amazing enrichment learning.*

We have some amazing organizations and small businesses in our communities. We have Broadway stars teaching musical theater, and world champion athletes teaching jump rope and martial arts—and my PhD classmate from UC Berkeley who became a serial entrepreneur in Silicon Valley now has an organization to demystify AI so that not only Googlers' and Microsofties' children can understand it, but every child can. I've met authors, scientists, mathematicians—and chess grandmasters teaching not only the strategy of the game but also strategy in life. We've found magicians who performed at America's Got Talent multiple times; they teach kids how to give a confident and attractive presentation.

RML: I certainly see the potential and the need. I'm trying to understand the mechanics. Suppose I were the superintendent of schools in Boston and I came to you and said, 'We need your services, we need the enrichment opportunities that you provide.' Would you find providers in the Boston area?

DR. WANG: Yes.

RML: And how would you go about doing that?

DR. WANG: The district would put out a call for enrichment providers in the local community.

We invite enrichment providers to apply, then we evaluate them based on their experience, how they hire people, what's their curriculum, which grades they teach, and so on. We vet every one of them; we do background checks, and look at the host of requirements the district has.

So instead of the school district doing a lot of this, we shoulder the work. Core to our solution is a platform that seamlessly interconnects all the parties. It's almost like establishing a network platform.

RML: Given the educational environment in the Boston area, there are a lot of people, universities, and other places pretty actively engaged in precollege education. I'm trying to understand, would they become employees of 6crickets?

DR. WANG: No, they are the providers, with their own businesses. We do the coordination, the management, of all the different businesses, or sometimes it's individual teachers at the school or from another school. We organize all these organizations and people to serve the schools and districts.

RML: I'm just wondering, if, for example, the city of Boston—I'm using Boston because I live here and have grandchildren here—were interested and came to you, would you negotiate with them on the selection of enrichment activities?

DR. WANG: They would say, 'Here's our input, these are the topics we want, and these may be the topics that parents have expressed interest in' through, for example, a survey. Or based on their understanding of their students, maybe they want a math Olympics class. Based on the topics, we recruit providers who teach them—you have so many awesome providers in the Boston area. Also, when you have a demand, the supply will come.

RML: So you're providing the connection between the school and the providers?

DR. WANG: You can view it that way. We not only provide the connection, we shoulder most of the management logistics on behalf of schools and districts.

CHF: Helen, how do you find the providers in Boston? Let's say a school district wants to be able to offer magic, theater, and coding, and they come to you and say that's what they want. How does 6crickets go about identifying and contacting those providers in that school district for those areas?

DR. WANG: We have thousands of providers in our network. When we go to a new area, we launch a recruiting effort. How would anyone find any information today? Google. And also there are some national providers that we already have, and they would be hiring people in Boston or already have a branch there.

RML: I think Cameron and I both see the tremendous need and value of your service. I'm just wondering how you actually translate the need and the market and so on into your business model.

DR. WANG: Our business model is we're selling a management solution to schools and districts. So the districts would pay for such a solution.

CHF: That gets to another question that I had: Are the school districts the ones paying for the afterschool services provided through your platform?

DR. WANG: That's a good question. There are typically two models. It can be either a family-paid program or district-funded program. Someone has to pay for these programs. In a family-paid program, the district can charge a management fee to generate revenue so that it can be a self-sustaining operation. When you're able to generate revenue you can also support students in need. So for family-paid programs, it can be a no-cost, self-propelling, and equitable enrichment operation.

For low socioeconomic school districts and communities with a large percentage of free or reduced-cost-lunch students, it would need to be a district-funded program. But the good news is we have much more funding now, after the pandemic and the ESSER (Elementary and Secondary School Emergency Relief) funding. ESSER III especially highlights afterschool and summer programs and community partnerships—that's what 6crickets has been doing all these years. We could meet what ESSER is asking for exactly.

RML: The pandemic has impacted your business then, has it?

DR. WANG: The pandemic has tremendously impacted all out-of-school time. For a lot of schools, enrichment in out-of-school time is not available. Even when a large percentage of schools reopened, out-of-school activities did not resume.

RML: That's what I was wondering. During the period when schools were closed, that must have impacted your opportunity to work.

DR. WANG: It did. All the classes in spring 2020 were cancelled, with a full refund. But 6crickets has actually grown stronger, I'm happy to report. It's in our DNA, from when I was a computer scientist doing research: you keep pivoting, new scenarios mean new problem formulations.

So immediately, within 2 weeks, our platform supported virtual enrichment. And I taught a class myself to experience what it takes to teach a virtual enrichment class. Then I gave a webinar to all our provider partners on how to teach virtual enrichment classes.

RML: I was about to ask how your training as a computer scientist impacted your business environment.

DR. WANG: I used every bit of my training—problem formulation, constant revision of the problem formulation. Because I understand the problem better, I understand this space better. I would say maybe today 6crickets is the only company that understands out-of-school time this intimately, because it's hard to create a business in this space and it is hard to sell to districts, but we're making huge strides.

> *I used every bit of my training as a computer scientist—especially in problem formulation and constant revision of the problem formulation.*

The pandemic may have given us a pause, but it has also empowered us to innovate tremendously. We understand the entire workflow in out-of-school time. We have automated almost every single piece in out-of-school time. Imagine the kind of efficiency we can have there.

RML: Is there a specific example of a school district that you've worked with?

DR. WANG: Oh, yes, let me show you. We're in many school districts now. If you go to "districts and schools"

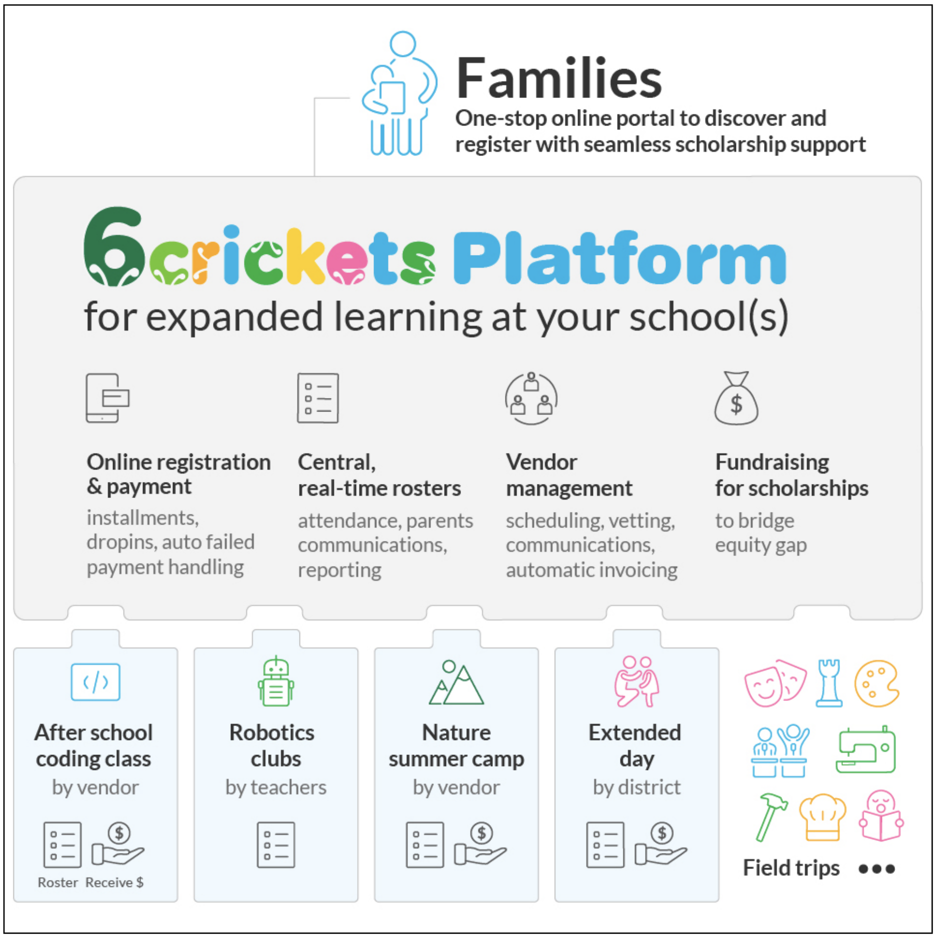

FIGURE 2 6crickets platform overview. A district can use the platform to create a unified expanded learning hub at each school with quality enrichment and any learning activities from community partners including teachers, volunteers, and vendors. The platform is analogous to an "operating system" like iOS or Android.

at 6crickets.com, you can see what we do for them to achieve equitable, vibrant enrichment learning hubs. There is all this information. And at the bottom are representative enrichment programs throughout the country—we're in 29 states.

RML: So your role is to provide the tools for parents to register and administer the program?

DR. WANG: Not just that. That's one level of service. Another level of service is that we take care of the entire workflow management. We have two levels of service.

One level is turnkey enrichment solution. A school may already have providers, or maybe it doesn't have many, or its staff is already overburdened. Our solution will be to help source and train the providers, ensuring that they're high quality and meeting all the district requirements. We also manage the day-to-day workflow, and can help with grant budgeting and provider pricing negotiation. For family-paid programs, we just let the free market govern the pricing, we don't play a role there; but for district-funded programs, we make sure the pricing is fair and win/win.

6crickets created an architecture where every stakeholder has a dashboard—the district, school, providers, and instructors. Why all these dashboards? So you don't do other people's jobs.

RML: This is where your computer science training really comes in.

DR. WANG: It's even more than computer science. One time I showed a computer scientist colleague the 6crickets architecture, he said, "wow, that's the kind of operating system work you did before."

We want to enable enrichment activities to be plugged into this platform (figure 2)—just like your phone today, where you have so many applications. The iOS and Android platform has made developing applications so much easier; we're making delivery of enrichment activities so much easier.

RML: You've been in business for 7 years, 2 of them in the midst of a pandemic. Where do you see 6crickets in 5 years?

DR. WANG: In 5 years we should be in 50 percent of schools in the United States.

RML: What is the fraction today?

DR. WANG: It is still very low.

CHF: Fifty percent, that's exciting. How are you going to achieve that?

DR. WANG: We have built up our work for the past 6 or 7 years now. Today we have achieved this automation—if your school or district does not have enrichment and wants it, we can make it happen. If your school or district already has enrichment, we can make it so much easier and more efficient to manage.

RML: I think the demand is there—every school wants enrichment. You've got tremendous market potential.

CHF: The question is, how do you reach out to all these school districts that could clearly benefit from what you're offering and let them know that you exist and are available for them?

DR. WANG: There's no magic here. It's the hard work of a salesman's job. As a computer scientist at Microsoft, when I created new technology I needed to go to different buildings and let them know and explore adopting our new technology, and that is doing sales to our product counterpart back then at Microsoft Research. Now it's the hard work of going to schools and districts to let them know about the 6crickets work.

RML: I'm curious. How many staff do you have today, and what is your growth plan, given what you've just said? You've got this market, but you've got to reach people, you've got to somehow reach out.

DR. WANG: We are a very lean startup. The world is more connected than ever. You can assemble a wonderful team. When we hire people we're very cautious, but everyone we hire is passionate, smart, and creative. We don't necessarily need a lot of people; largely it's a software solution, but we do a layer of service on top of it. And we're becoming more and more efficient as we develop our software.

CHF: Well, for example, how did you get your contacts at the school districts in Texas, Connecticut, and Massachusetts?

DR. WANG: Two words: hard work. You get a mailing list. What we do here is nothing special. We're a platform as a service, with many parties, for a school and district to adopt—but selling software as a service is not new, it's the same method for anybody who sells software as a service.

We have broad outreach. We have emails for all the PTAs, and we do marketing and outreach and someone responds. It's a typical software-as-a-service sales model. You need marketing, you need sales, you need to go to conferences where your target audience might be.

RML: You have the advantage, in this current environment—with the internet, you can operate with a lean staff, because the internet provides your service description.

DR. WANG: The pandemic has also made virtual meetings the norm rather than the exception.

RML: This conversation reminds me of a meeting I attended at Princeton, probably in the mid-1980s, and I heard **Jeff Bezos** speak, when Amazon was tiny, just beginning. I left that meeting thinking 'wow, there's tremendous potential in what this guy is thinking about.'

The internet, the whole idea of being able to do things online was emerging, but not yet developed, and I get the same sense of potential in terms of what you're dealing with here. People want the service you're offering just like people want to get things delivered to their homes. You've got an opportunity here that's enormous.

When I asked earlier about interaction with academics and educators, I asked because each school district has to provide a curriculum and teach the state requirements. You have an opportunity to supplement their curriculum if you know what they're providing.

DR. WANG: Actually, I love the opportunities for unconstrained free innovation in this space. To change the curriculum for the in-school hours, there's a lot of process, and there's also risk. But in the out-of-school time, wow, the sky is the limit. Your creativity is the limit.

And, with the pandemic, now every child has a device, every child is connected. So that also gives the foundation for a lot of things.

Let me share with you a personal experience, why I'm so passionate about this. When I started grad school at UC Berkeley, I had never taken a probability class. I wondered, how is it that most of my classmates already know this stuff? Now my young teenaged sons have been well exposed to probability.

Our goal is to make sure great enrichment can happen at every school, including Title 1 schools. Then we'll be changing lives, changing generations to come.

RML: Your passion for what you're doing is obvious.

CHF: It's very exciting.

RML: Helen, thank you so much for joining us today. I wish you good luck. I think you're on a track that's really interesting, so I applaud what you're doing.

DR. WANG: Thank you very much.

NAE News and Notes

NAE Newsmakers

Robert O. Ambrose, J. Mike Walker '66 Chair in Mechanical Engineering and director for Space and Robotics Initiatives, Texas A&M University, received the **2022 Thomas A. Edison Patent Award**. The award highlights the creativity of a patented device or process that has the potential of significantly enhancing some aspect of mechanical engineering. Professor Ambrose received the award from the American Society of Mechanical Engineers (ASME) in recognition of his role in creating safer robots for use in outer space.

Dennis N. Assanis, president, University of Delaware, has been appointed by President Biden to serve on the **President's Council of Advisors on Science and Technology** (PCAST). Dr. Assanis is noted for his longstanding career in academic leadership and for his contributions to the field of clean energy and power systems.

Robert D. Braun, head of the Space Exploration Sector at Johns Hopkins University Applied Physics Laboratory, has been selected for the **2022 Yvonne C. Brill Lecture in Aerospace Engineering**. He will present his lecture, "Are We Alone? Grand Challenges in Solar System Exploration," October 4 in conjunction with the NAE Annual Meeting.

Emery N. Brown (NAS/NAM), Edward Hood Taplin Professor of Medical Engineering and Computational Neuroscience, Harvard Medical School, and **Terrence J. Sejnowski** (NAS/NAM), Francis Crick Professor and head, Computational Neurobiology Laboratory, Salk Institute for Biological Studies, share the **2022 Gruber Neuroscience Prize** with neurophysicists Laurence Abbott (NAS) of Columbia University and Haim Sompolinsky of the Hebrew University of Jerusalem.

M. Elizabeth Cannon, president emerita, University of Calgary, has been inducted into the **Alberta Business Hall of Fame**. One of only five women inducted to the Hall of Fame, Dr. Cannon is noted for turning the university into one of the top engineering schools in Canada and for expanding its infrastructure.

Gerbrand Ceder, Chancellor's Professor of Materials Science and Engineering, and **Ramamoorthy Ramesh**, Purnendu Chatterjee Chair in Materials Science and Engineering and Physics, both of the University of California, Berkeley, have been **elected to the American Academy of Arts and Sciences**.

Simon R. Cherry, Distinguished Professor, University of California, Davis, was awarded the **Benedict Cassen Prize** during the Society of Nuclear Medicine and Molecular Imaging 2022 Annual Meeting. It is awarded every 2 years by the Education and Research Foundation (ERF) for Nuclear Medicine and Molecular Imaging in recognition of outstanding achievement and work leading to a major advance in nuclear medicine science. Dr. Cherry is recognized for his pioneering work in the development of PET technology and codevelopment of the EXPLORER total-body PET/CT scanner.

Earl H. Dowell, William Holland Hall Professor and chair, Mechanical Engineering and Materials Science, Duke University, has been honored by ASME with the **2022 Thomas K. Caughey Dynamics Medal** "for significant contributions to the field of nonlinear dynamics in fluid-structure interactions, aeroelasticity, and structural vibrations."

Mark A. Horowitz, Yahoo! Founders Chair, electrical engineering and computer science, Stanford University, is the recipient of the **ACM-IEEE CS Eckert-Mauchly Award** for contributions to microprocessor memory systems. The Eckert-Mauchly Award was initiated in 1979 and recognizes contributions to computer and digital systems architecture. Dr. Horowitz was the first to identify the processor to dynamic random-access memory (DRAM) interface as a key bottleneck that required architecture and circuit optimization, and he pioneered high-bandwidth DRAM interfaces.

James E. Hubbard Jr., Oscar J. Wyatt Jr. '45 Chair I and Hagler Institute Fellow, Texas A&M University–College Station, is the 2022 recipient of the **ASME Adaptive Structures and Materials Systems Award**. The recognition highlights a lifetime of achievement and sustained impact of significant contributions to the sciences and technologies associated with adaptive structures or materials systems.

Robert S. Langer (NAS/NAM), the David H. Koch (1962) Institute Professor, Massachusetts Institute of Technology, is the recipient of the **2022 BBVA Foundation Frontiers of Knowledge Award in Biology and Biomedicine** in recognition of his contributions to messenger (mRNA) therapeutics and delivery technology, which enabled the rapid development of SARS-CoV-2 vaccines. He shares the award with Katalin Karik and Drew Weissman, both of the University of Pennsylvania. Drs. Karik and Weissman discovered how to modify mRNA molecules so that they could be used as a therapeutic agent, while Langer developed the first approaches of nanoparticle encapsulation that allows mRNA to be introduced into the body. The award was presented in a ceremony hosted by the BBVA Foundation on June 16 in Bilbao, Spain.

Cato T. Laurencin (NAS/NAM), university professor; Albert and Wilda Van Dusen Distinguished Professor of Orthopaedic Surgery; professor of chemical and biomolecular engineering, of materials science and engineering, and of biomedical engineering; director, Raymond and Beverly Sackler Center for Biological, Physical, and Engineering Sciences; and chief executive officer, Connecticut Convergence Institute for Translation in Regenerative Engineering, University of Connecticut, has received several honors. He was **elected to the European Academy of Sciences** in recognition of his pioneering work in the field of regenerative engineering. On June 15 he was honored by the American Orthopaedic Association (AOA) at its annual leadership meeting, and he was added to the **AOA Award Hall of Fame** and presented with the **AOA Distinguished Contributions to Orthopaedics Award** in recognition of his personal achievement and broad contribution to the orthopaedic specialty, leadership, impact on patient care, and clinical and basic science research. On July 8 the American Chemical Society announced the award of the **2023 Priestley Medal** to Dr. Laurencin "for pioneering, breakthrough work on polymeric materials and polymer composites for biologic use, and for leadership in inclusion, diversity, equity, antiracism, and learning (IDEAL)." He will accept the medal and deliver an address at ACS Spring 2023 in Indianapolis.

Asad M. Madni, independent consultant and retired president, chief operating officer, and CTO, BEI Technologies Inc., has been **elected a fellow of the Washington Academy of Sciences** in recognition of his outstanding contributions to the field of engineering. The Tufts University School of Engineering has awarded him the **2022 Dean's Medal**, the only medal awarded by deans of the individual schools within Tufts. He was also honored by Tau Beta Pi, the Engineering Honor Society, with its **2022 McDonald Mentor Medal**. According to Tau Beta Pi, the purpose of this award is "to celebrate excellence among Tau Beta Pi educators and engineers who have consistently supported the personal and professional development of their students and colleagues as excellent mentors or advisors."

Tobin J. Marks (NAS), Vladimir N. Ipatieff Professor of Catalytic Chemistry and professor of materials science and engineering, Northwestern University, has been **elected a member of the American Philosophical Society** in the mathematical and physical sciences class in recognition of his accomplishments in the fields of organometallic chemistry, chemical catalysis, materials science, organic electronics, photovoltaics, and nanotechnology.

In February the Department of Electrical Engineering and Computer Science of Kansas University unveiled the **KU EECS Distinguished Service (KEDS) Award** to formally recognize distinguished alumni and associates. **Brian McClendon**, research professor, University of Kansas, is one of the two recipients in the inaugural class of winners. The award was presented at a ceremony on April 28.

Carver A. Mead (NAS), Gordon and Betty Moore Professor of Engineering and Applied Science, Emeritus, California Institute of Technology, has won the **2022 Kyoto Prize in Advanced Technology**, for "leading contributions to the establishment of the guiding principles for VLSI systems design." The Kyoto Prize was founded by **Kazuo Inamori** to "contribute to the progress of the future of humanity while maintaining a balance between the development of science and civilization and the enrichment of the human spirit."

Kishor C. Mehta, P.W. Horn Distinguished Professor of Civil Engineering, Texas Tech University, received the **International Association for Wind Engineering Presidential Award** at the 14th Americas Conference on Wind Engineering held in Lubbock, Texas, in May. He was cited for "career-long contributions to wind engineering with particular reference to wind hazard mitigation, low-rise structures, code development, tornado shelters, EF scale, and leadership to AAWE and IAWE."

Sanjit K. Mitra, Distinguished Professor Emeritus of Electrical and Computer Engineering, University of California, Santa Barbara, has been **elected a member of the Academia Europaea**.

Glaucio H. Paulino, Margareta E. Augustine Professor, Princeton University, is a recipient of the ASME **2022 Melville Medal**, the society's highest honor for best original paper. He was honored, with coauthors Ke Liu and Tomohiro Tachi, for the paper "Bio-Inspired Origami Metamaterials with Metastable Phases Through Mechanical Phase Transitions," published in the September 2021 issue of the *Journal of Applied Mechanics*.

Arati Prabhakar, former administrator, Defense Advanced Research Projects Agency, has been **nominated by President Biden to be his science advisor**. If confirmed, she will be the first woman, first person of color, and first immigrant to hold that cabinet-level position.

Laura J. Pyrak-Nolte, Distinguished Professor of Physics and Astronomy, Purdue University, has been **elected a member of the American Academy of Arts and Sciences**, and **Molly M. Stevens**, professor of biomedical materials and regenerative medicine, Imperial College London, has been **elected an international honorary member**.

Kaushik Rajashekara, Distinguished Professor of Engineering, University of Houston, is a **2022 Global Energy Prize Laureate**, recognized in the New Ways of Energy Applications category for "outstanding contributions to transportation electrification and energy efficiency technologies while reducing power generation emissions." The award ceremony will be held during Russian Energy Week, scheduled to take place in Moscow in October.

Junuthula N. Reddy, Distinguished Professor, Regents' Professor, and the holder of O'Donnell Foundation Chair IV, Texas A&M University–College Station, was awarded the **2022 International Association of Computational Mechanics Congress Medal**, also known as the Gauss-Newton Medal. The award recognizes individuals who have made outstanding and sustained contributions to the computational mechanics field. His many contributions include serving as a prominent member and contributor to the computational and applied mechanics community, authoring the classic and highly popular textbook *Introduction to the Finite Element Method*, and developing a number of novel mathematical models and computational approaches that others have followed, applied, and advanced for more than 40 years. Professor Reddy was honored at the 15th World Congress on Computational Mechanics held in Yokohama, Japan, on August 1.

Elsa Reichmanis, professor and Carl Robert Anderson Chair in Chemical Engineering, Lehigh University, has been chosen by the American Institute of Chemical Engineers (AIChE) to present the **John M. Prausnitz AIChE Institute Lecture for 2022**. Her lecture, "From Silicon to Plastic: It's All about Surfaces, Interfaces, and Processing," will be presented November 16 at the 2022 AIChE annual meeting in Phoenix.

Rachel A. Segalman, chair, Chemical Engineering Department, and Edward Noble Kramer Professor, University of California, Santa Barbara, is the recipient of the **2021 Ernest Orlando Lawrence Award in Condensed Matter and Materials Science**, the DOE's highest scientific honor. Professor Segalman is cited for "significant fundamental materials science and engineering contributions to self-assembly and structure-property relationships in functional polymer systems, with specific applications to photovoltaic, thermoelectric, and membrane technologies." She was honored September 10 during a hybrid award ceremony in Washington, DC.

On May 12 **Peter W. Shor** (NAS), Morss Professor of Applied Mathematics, Massachusetts Institute of Technology, was named the recipient of MIT's **2022–2023 James R. Killian Jr. Faculty Achievement Award**, which recognizes extraordinary professional achievement by MIT faculty. The citation credits Professor Shor with having made "seminal contributions that have forever shaped the foundations of quantum computing. Indeed, quantum computing exists today, in practice, because of Peter Shor. [His] work demonstrates that quantum computers have the potential to open up new avenues of human thought and endeavor."

Chanan Singh, Regents Professor & University Distinguished Professor, Irma Runyon Chair Professor, electrical and computer engineering, Texas A&M University, was honored by the IEEE Power and Energy Society (PES) with the **2022 Lifetime Achievement Award** for his contributions to the education, research, and industrial adoption of reliability theory and practice in large power systems. The award was presented at the IEEE PES general meeting awards gala dinner and ceremony in July.

Jane M. Smith, research professor, Department of Civil & Coastal Engineering, University of Florida, was **inducted into the Waterways Experiment Station (WES) Gallery of Distinguished Employees** in a ceremony July 20 at the US Army Engineer Research and Development Center's headquarters. Dr. Smith is a codeveloper of the numerical steady-state spectral wave model used throughout the world for coastal project planning and design. She was also the wave modeling lead investigator for the Interagency Performance Evaluation Task Force evaluation of Hurricane Katrina and led development of a system to quickly forecast hurricane waves, storm surge, and inundation for the Hawaiian Islands. She was the first woman from the Corps elected to the NAE (2019), and now she is the first woman to receive the **2022 International Coastal Engineering Award** from the American Society of Civil Engineers, "for her outstanding career in coastal engineering research crucial for understanding hurricanes and storm surge and for her leadership in making coastal communities around the world safer."

Michael A. Sutton, Carolina Distinguished Professor Emeritus, University of South Carolina, will receive on November 2 the **2022 Timoshenko Medal**. His research has focused on the creation, application, and worldwide technology transfer of the digital image correlation (DIC) method, which is now used by industry and research titans such as NASA, Proctor and Gamble, Boeing, and the US Army for structures and materials testing. The technology has benefited engineering researchers and, through Dr. Sutton's commitment to technology transfer by helping found South Carolina–based Correlated Solutions Incorporated, has been disseminated globally to a variety of industries, including manufacturing, biomedicine, aerospace, and military systems development.

Vaclav Vitek, professor of materials science and engineering emeritus, University of Pennsylvania, has been **elected to the Royal Society**. His nomination citation describes him as a "founder and global leader of computational materials science." New fellows are formally admitted to the society at its admissions day ceremony in July, where they sign the Charter Book and the Obligation of the Fellows of the Royal Society.

George M. Whitesides (NAS), Woodford L. and Ann A. Flowers University Professor, Harvard University, has won the **Kavli Prize in Nanoscience**. He shares the prize with David Allara, Ralph Nuzzo (NAS), and Jacob Sagiv. In announcing the prize the Norwegian Academy of Science and Letters stated that it "honors four pioneers whose work transformed surface science and has led to applications shaping our daily lives in areas from medical diagnostics to semiconductor devices. These scientists created molecular-scale coatings for surfaces which enable unprecedented control and engineering of surface properties. Theirs was a shared vision, inspired by the concept of organized monolayer films introduced in the 1930s by American physicists and chemists Katherine Blodgett and Irving Langmuir (NAS)."

Yannis C. Yortsos, dean, Viterbi School of Engineering, University of Southern California, won a **2022 Los Angeles Area Emmy Award** from the Television Academy. The award was given for independent programming of a documentary called *Lives, Not Grades*, for which Dr. Yortsos was executive producer. He shares the award with eight other individuals involved in the film's production.

CRA (Computing Research Association) presents an award, usually annually, to a person or organization that has made an outstanding service contribution to the computing research community. The award recognizes service in government affairs, professional societies, publications or conferences, and leadership that has a major impact on computing research. Recently four years of **Distinguished Service Awards** were announced, three of which went to NAE members: for 2019, **Edward W. Felten**, Robert E. Kahn Professor of Computer Science and Public Affairs, Princeton University; for 2020, **James F. Kurose**, Distinguished Professor, College of Information and Computer Science, University of Massachusetts at Amherst; and for 2021, **Katherine A. Yelick**, Robert S. Pepper Distinguished Professor of Electrical Engineering and Computer Science, University of California, Berkeley, and associate laboratory director, Computer Science/Computing Sciences, Lawrence Berkeley National Laboratory.

2022 Charles Stark Draper Prize for Engineering Acceptance Remarks by David A. Patterson

The 2022 Charles Stark Draper Prize for Engineering was presented to Stephen B. Furber, ICL Professor of Computer Engineering, University of Manchester; ***John L. Hennessy,*** *James F. and Mary L. Gibbons Professor of Computer Science and Electrical Engineering, Stanford School of Engineering;* ***David A. Patterson,*** *professor emeritus, University of California, Berkeley; and Sophie M. Wilson, CBE FRS FREng, "For contributions to the invention, development, and implementation of reduced instruction set computer (RISC) chips."*

President Anderson, members of the Draper family, esteemed coawardees, and distinguished guests:

Steve Furber, John Hennessy, Sophie Wilson, and I are very grateful to the National Academy of Engineering for this prestigious award and to the panel of our colleagues who selected us. We were thrilled to receive it.

To understand our contribution, we'll first explain some jargon. When software talks to hardware, it uses a vocabulary called an *instruction set*. Examples of words or *instructions* in the vocabulary are also on the keys of a calculator: add, subtract, multiply, and so on. Programs consist of millions of these simple instructions executed billions of times.

When Hennessy and I were assistant professors in 1980, conventional wisdom was that many information technology problems were due to computer vocabularies being too low level. These instruction sets supposedly placed a large burden on programmers, leading to software bugs and failed software projects. The prevailing philosophy was to raise the level of abstraction to create vocabularies of complex instructions to reduce the gap between people and machines.

In the 1970s microprocessors were found only in home appliances. Hennessy and I believed in Moore's law, the remarkable prediction that the number of transistors per chip would double every year or two. We were convinced that microprocessors would become the foundation of all computing. The question was, what was the best vocabulary or instruction set for these rapidly improving microprocessors? Should it change from the large computers that powered the industry of the 1970s? We each received funding from the Defense Advanced Research Projects Agency to tackle this critical problem.

To understand this vital question about the interface between software and hardware, we need more context. It was so tedious to program in the low-level machine language that computer pioneers soon invented high-level programming languages that were easier to use plus programs that translated from high-level languages to machine language, called *compilers*. The 1993 Draper Prize went to **John Backus** for developing the first programming language (FORTRAN) and its compiler.

While high-level languages were popular for many tasks, conventional wisdom was that compilers were too inefficient to use for some software, such as operating systems. The success of the UNIX operating system from Bell Labs in the late 1970s, written in a high-level language, changed people's minds.

Regarding instruction sets for microprocessors, the programmers' burden of writing in low-level machine language was no longer an issue. Instead, the question was, Can compilers produce efficient programs for a given vocabulary?

We called the large computers with vocabularies that followed conventional wisdom *complex instruction set computers*, abbreviated CISC and pronounced "sisk." We proposed that microprocessors should instead use vocabularies with simple instructions, which we called *reduced instruction set computers*, abbreviated RISC and pronounced "risk." Think of CISC as having many polysyllabic words while RISC has monosyllabic words. Hennessy and I thought it would be easier to build microprocessors that understood RISC vocabularies than CISC vocabularies and easier for compilers to generate RISC programs than CISC programs.

The question then was whether RISC or CISC was faster? While a program might have to read fewer instructions using CISC—since the instructions were more sophisticated—that might mean that the average instruction would take longer to read and execute than a RISC instruction. The analogy is that a page filled with polysyllabic words might take longer to read than a page of mostly monosyllabic words.

This seemingly clear engineering question was emotion packed in the computer design community, which we call *computer architecture*. The CISC advocates believed that RISC was a step in the wrong direction, and would add complexity to software. The RISC advocates thought that was an out-of-date argument and that compilers could hide those details so that programmers couldn't tell the difference. While Berkeley and Stanford are rival institutions in the Bay Area, Hennessy and I both realized that we should join forces to argue for RISC.

An international conference held in Silicon Valley in 1982 organized the first of several debates on RISC versus CISC. Heated conversations continued into the hallways afterward and lasted long into the evening at that event, with several more debates over the next year or two.

To answer whether RISC or CISC is better, we needed to discover the ratios of the average number of instructions a program needs to read—CISC should be fewer than RISC—versus the average time to read one instruction—RISC instructions should be faster than CISC instructions. We ultimately discovered that RISC reads a few more instructions (maybe 30 percent more) but reads them so much faster (maybe 5 times faster) that the net result is that RISC is 3–4 times faster than CISC. Moreover, RISC microprocessors needed less hardware and power than CISC microprocessors. This efficiency advantage would prove to be an unbeatable edge as computers moved off desktops and into people's hands and from devices plugged into the wall to battery powered.

Max Planck said that scientific truth does not triumph by convincing opponents and making them see the light, but that science advances one funeral at a time. Fortunately, in computer architecture, there is a companion industry that tests our ideas in the marketplace, so we don't have to wait for funerals to change the field.

For example, in 1983 across the pond in Cambridge, England, Steve Furber and Sophie Wilson decided to build a new microprocessor for the Acorn personal computer, which was popularized by a BBC television series teaching computer literacy. Furber and Wilson were inspired by the work at Berkeley and Stanford to create an instruction set for that microprocessor that they dubbed the Acorn RISC Machine, abbreviated ARM.

As they tell the story, they had two advantages: (i) no money and (ii) no engineers. The very low resources available to the project made simplicity the highest imperative among the competing design criteria, which matched perfectly with the RISC philosophy of simple instructions. When the ARM1 debuted in 1985 as the first commercial RISC processor, it was faster than any microprocessor on the market.

Apple visited Acorn in 1990, showing interest in using ARM for its new Newton handheld computer, an early forerunner of the iPhone. Only a RISC processor could meet the performance, power, and cost constraints of the Newton. The Acorn company needed to reduce costs, so it agreed when Apple insisted that ARM be spun out as a separate jointly owned company. ARM Ltd. was thus founded as a joint venture with Apple in 1990, rebranding the ARM acronym as the Advanced RISC Machine instead of the Acorn RISC Machine.

Although the Newton wasn't successful, the same characteristics that made ARM attractive to Apple for the Newton also made it popular in chips for cellphones. At that time, Nokia was the leading supplier of cellphones, so the selection of ARM for the Nokia GSM phone was a major boost.

The Nokia experience helped ARM understand the needs of the chips that are at the heart of cellphones—known as *system on a chip* since so much is packed into a single phone microchip—which put ARM in position to ride the explosion in popularity of smartphones, tablets, and other embedded computers for the next 20 years. Today, 99 percent of all processors shipped are based on RISC; more than 200 billion chips have been shipped with ARM processors. That means that so far more than 25 RISC chips have been delivered for every person on the planet. We think the simplicity of RISC meant it was more efficient in use of silicon and power, which made it the winner.

Wrapping up our story, computer architecture is a team sport, so the Draper Prize is recognition for our former students and wonderful colleagues and collaborators at Acorn, ARM, Berkeley, and Stanford. We also thank our families and especially our spouses—my wife Linda, John's wife Andrea, Steve's wife Valerie, and Sophie's partner John—for half a century of support over our long careers. We certainly couldn't have helped make these contributions without them standing by our sides.

Let me close by thanking you once again for this high honor.

2022 China-America Frontiers of Engineering Held as Point-to-Point Hybrid Event

The 2022 China-America Frontiers of Engineering Symposium brought together early-career engineers from China and the United States in a hybrid format July 18–20. NAE member **Eleanor Allen**, lead executive of B Lab Global, and Jing Cheng, Cheung Kong Professor of Biomedical Engineering at Tsinghua University, cochaired the symposium, which the NAE carried out in partnership with the Chinese Academy of Engineering (CAE).

The event was originally scheduled to be held in Chengdu, China, but with travel to and within China restricted because of the pandemic, the NAE and CAE decided to convene the meeting as a point-to-point hybrid. The plan was for US attendees to gather at the National Academies' Beckman Center in Irvine, California, and the Chinese attendees to convene in Chengdu. This is largely what happened, although 2 days before the event, additional travel restrictions were implemented in China, and the attendees there assembled in Beijing or joined the meeting from their home cities. Despite these constraints, technical presentations and breakout sessions provided an opportunity for valuable virtual interactions between the Chinese and US attendees. Moreover, the US attendees had a separate program of poster sessions, discussion groups, and tours prior to each day's virtual meeting with the Chinese. The technical session topics were Wearable Electronics and Human Health, Additive Manufacturing and Beyond, Water Sustainability, and Food Safety in the Context of Big Data and Genomics.

Wearable electronics provide ways to facilitate prevention, early diagnosis, and management of chronic conditions; the next generation of wearable devices are evolving toward more comprehensive functionalities. These innovations are the result of materials, electronic, and computer engineers working with physicians to create wearables that support personalized and preventive medicine. The first talk in this session described electronic tattoos (e-tattoos) that are applied on the human body for medical-grade physiological sensing, and e-skins that are put on robots so they can imitate human sensations such as pressure and temperature. The next presenter discussed machine learning–based methods for obtaining health and performance information from wearable electronics that sense cardiogenic vibration signals and acoustic emissions from joints. The final two speakers provided perspectives on vibration-based energy-harvesting devices for self-powered health monitoring systems and large-area, low-power organic transistor arrays for wearable electronics.

The session on Additive Manufacturing and Beyond presented insights on how the field has transitioned from AM use primarily to rapidly fabricate nonfunctional prototypes to its current role in the production of critical airplane parts and medical implants. Speakers highlighted state-of-the-art AM research in China and the United States as well as AM's challenges, opportunities, and future directions. The presentations covered a range of topics where AM is being researched and applied: architected

US and Chinese speakers in the Water Sustainability session answer questions after their presentations.

nanocomposites for intelligent functional materials, sensors, and devices; biological materials for healthcare and medical applications; energy-efficient and zero-waste 3D printing; and large-scale and infrastructure additive manufacturing.

Local and global water resources are facing a crisis due to population growth and movement, climate change, and ecosystem dynamics. Water sustainability is related to so many aspects of human existence—from food cultivation and processing to electric power generation. Citing case studies in China and the United States, the speakers in this session described innovative water sustainability solutions at various scales. The first presentation provided a perspective on food-energy-water systems generally and with regard to large-scale animal agriculture specifically. This was followed by a talk on the implications of permafrost thawing on water sustainability in the Tibetan Plateau. The next speaker described a field of decision science termed *decision making under deep uncertainty* and its application to the challenge of sustainable water resources planning in the Colorado River Basin. The final presentation was on next-generation electrified membrane technologies for water supply and treatment.

The final session of the symposium focused on how big data has provided the means for technologists to develop innovative solutions to safeguard food supply and safety. This is critically important because it is estimated that 600 million people—almost 1 in 10 of the world's population—fall ill after consuming contaminated food, and 420,000 die every year. However, large datasets alone are not sufficient. It is necessary to extract knowledge for decision making and planning, and this requires tools such as forecasting models and the leveraging of blockchain technology in the food supply chain, among others. The talks in this session covered improved risk management tools facilitated by big data, advances in domain-aware statistical learning methods, and case studies that demonstrated use of genomic sequencing to both enhance the capacity of surveillance for and response to *Salmonella* outbreaks and to track the emergence, spread, and control of resistance to the antibiotic colistin.

The symposium program, list of attendees, and presentation videos or slides are available at the 2022 CAFOE link at www.naefrontiers.org.

Special thanks to NAE member **Diran Apelian**, Distinguished Professor of Materials Science and Engineering at the University of California, Irvine, who arranged for the US attendees to visit several institutes and research facilities on campus: the National Fuel Cell Research Center and Horiba Institute for Mobility and Connectivity, Water-Energy Nexus Center, and Institute for Design and Manufacturing Innovation.

Funding for this activity was provided by The Grainger Foundation and the National Science Foundation. The next CAFOE meeting will be held in the United States in 2024.

The NAE has been hosting an annual US Frontiers of Engineering meeting since 1995 and, in addition to CAFOE, has bilateral FOE programs with Germany, Japan, and the European Union. These meetings bring together highly accomplished early-career engineers from industry, academia, and government and provide an opportunity to learn about developments, techniques, and approaches at the forefront of fields other than their own. The program also facilitates the establishment of contacts and collaboration among the next generation of engineering leaders.

For more information about the activity, or to nominate an outstanding engineer to participate in future Frontiers meetings, go to www.naefrontiers.org or contact Janet Hunziker at JHunziker@nae.edu.

NAE Pacific Northwest Regional Meeting: Human-Robot Interaction

On May 19, Amazon and the University of Washington cohosted the 5th NAE Pacific Northwest Regional Meeting, this one on the topic of Human-Robot Interaction (https://bit.ly/NAESeattle2022).

Originally planned for spring 2020 but postponed twice because of covid, the meeting had nearly 150 attendees: roughly 60 students, 40 faculty members, 40 corporate engineers, and 10 NAE leaders and staff members—including 30 NAE members and 10 Frontiers of Engineering alums.

Sidd Srinivasa, dual-hatted as the Boeing Endowed Professor at the University of Washington's Paul G. Allen School of Computer Science & Engineering and director of robotics AI at Amazon, began the day with an overview of robotics, AI, and the fulfillment process at Amazon: how the pieces fit together to enable hundreds of millions of items to make their way from a fulfillment center to your door in 2 days (as well as any of tens of millions of items in only 1 day, and any of several million items within hours).

Russell Allgor, chief scientist of Amazon WW Operations, described the changes that have been required over time to meet ever-increasing customer expectations for speed, selection, and cost. Optimizing any two of the three is not that hard: Cost and selection, ignoring speed: one massive full-inventory fulfillment center in the middle of the country. Speed and selection, ignoring cost: a large number of large full-inventory fulfillment centers scattered across the land. Speed and cost, ignoring selection: a large number of small limited-inventory fulfillment centers, similarly scattered. Simultaneously optimizing all three, though, is a challenge. Amazon's fulfillment network has evolved to consist of several hundred inbound cross-dock and fulfillment centers, middle-mile sort hubs and trailers, airplanes and air hubs, and last-mile delivery stations and vehicles.

The introduction of robotics has been accompanied by major changes in the design and operation of fulfillment centers. Previously, inventory was stored in library or bin shelving, which pickers accessed on one face from aisles. The introduction of Amazon Robotics autonomous mobile drive units (AR Drives) enabled inventory to be stored in movable pods, with any of the pod's four faces accessible at pick and stow stations on the periphery of the fulfillment center. Importantly, the sides of the pods need not be accessible when the pods are "parked"—aisles are not necessary, which dramatically increases the capacity of the fulfillment center. (Think of a valet carpark.)

Nia Jetter, senior principal technologist in Amazon Robotics AI, focused on the safety aspects of autonomous mobile robots in fulfillment centers. The fleets of AR Drives operate within the confines of enormous "safety cages" where humans venture only rarely, and then only with multiple levels of protective systems. Next-generation mobile robots will share space with humans.

Mike Wolf, principal applied scientist in Amazon Robotics AI, addressed the challenges of integrating robotics at enormous scale, designing processes where humans and robots each do what they do best. He discussed multirobot task assignment and motion planning (fleets of AR Drives moving inventory pods to pick and stow stations), and manipulation challenges in robotic picking (hundreds of millions of unique items, no 3D models, nonrigid items).

In a bit of a deviation from the day's theme—no humans involved—Byron Boots, dual-hatted as a professor in UW's Allen School and principal research scientist at the NVIDIA Seattle Robotics Research Lab, described recent progress in high-speed off-road autonomous vehicles under the DARPA RACER (Robotic Autonomy in Complex Environments with Resiliency) program. The off-road environment—unprepared terrain, no maps, no GPS, sensor perturbations—is dramatically more challenging than urban or highway environments and requires rethinking perception, planning, and control.

And in an orthogonal deviation—no physical robots involved—Gérard Medioni, vice president and distinguished scientist at Amazon, described Amazon's "Just Walk Out" technology and the "Amazon One" approach to customer identification, both of which rely on remarkable recent progress in computer vision, which he also described. A key message was the need to invent on behalf of the customer: customers identify the pain point (e.g., "Waiting in line to check out is really annoying"), but not the solution.

Amazon One customer identification. No two palms are alike; truly contactless interaction; enhanced privacy compared to, e.g., facial recognition; in use today by Amazon and many third parties.

The day concluded with a panel on human-AI interaction—broader than human-robot interaction—with Maya Cakmak and Jamie Morgenstern from UW's Allen School, Ryan Calo from the UW School of Law, and Meredith Morris, director and principal scientist, People + AI Research at Google Research, moderated by **Ed Lazowska** from the Allen School. The advances in AI are remarkable, with tremendous positive impacts, but they also create a number of challenges, including the ethics of autonomous decisions, the impact on jobs and the economy, privacy, security, the safety and robustness of autonomous systems, and issues of fairness, bias, and transparency.

The meeting was organized by Ed Lazowska and Sidd Srinivasa. Russell Allgor assisted with the program, and Kelly Warren from Amazon expertly handled the logistics.

RPI-NAE Regional Meeting: Engineering Solutions to Grand Challenges—From Computing to Biotechnology and Beyond

by Shekhar Garde and Georges Belfort (NAE)

The NAE's Northeast Regional Meeting, held April 27–28 at Rensselaer Polytechnic Institute, presented perspectives on solving grand challenges facing humanity. A sense of history coupled with an eye toward the future provided the context for the meeting.

Over the past 2 centuries, technological revolutions have helped improve the quality of life for most people. Many measures of human well-being—such as life expectancy, health care, infant mortality, ability to travel, communicate, GDP per capita—have shown remarkable improvements around the world. Engineers, including many graduates of RPI, have played a major role in driving the technological revolutions that have been the engines of growth and prosperity.

Yet despite the impressive advances, humanity today faces many significant challenges, including health and disease mitigation, energy and sustainability, climate change, water, and security of cyber, physical, and biological infrastructure. We believe that engineers and scientists will play a key role in addressing these challenges through inventions and discoveries, by influencing the development of sensible policies, and by educating the public. As the first and oldest technological institution in the United States, Rensselaer Polytechnic Institute was an ideal venue for the NAE regional meeting to discuss and present engineering perspectives on solving grand challenges.

There was palpable excitement about the meeting, the first in-person event at RPI in more than 2 years because of the pandemic. After numerous online lectures, conferences, classes, and research group meetings, we were reminded of the joy of in-person meetings, free exchange of ideas, and the power of random collisions with colleagues and friends.

The event began with an after-dinner speech April 27 by physician and *New York Times* bestselling author Matt McCarthy, of Weill Cornell Medical College and New York-Presbyterian Hospital, titled “Overwhelmed: Lessons from the front lines of the covid-19 pandemic in New York City.” We heard a firsthand account from the emergency room doctor responding to a highly dynamic pandemic, and the need for communication and collaboration among scientific experts, practitioners, and policymakers to respond to fast-changing challenges.

The next day the meeting opened with welcome addresses by NAE president **John L. Anderson** and Shekhar Garde, dean of engineering at RPI. The meeting included talks by three world-renowned experts in the areas of computing, human health, and advanced materials. **John E. Kelly III**, executive vice president of IBM (retired), looked at “The future of computing: Accelerated discovery,” explaining that we are entering a new era of computing that is moving from bits to include “neurons” (today) and qubits (in the near future), as artificial intelligence (AI) and quantum computing take on larger roles addressing complex problems and accelerate discovery. **Samir Mitragotri**, Hiller Professor of Bioengineering and Hansjörg Wyss Professor of Biologically Inspired Engineering at Harvard University, delivered a talk titled “Engineering solutions to future health challenges,” which expertly combined results from exceptional research at the frontiers of drug delivery with innovation and entrepreneurship that translates ideas from laboratory to the marketplace. **Angela Belcher**, James Mason Crafts Professor of Biological Engineering and Materials Science & Engineering, and head of the Department of Biological Engineering at MIT, spoke about “Giving new life to materials for energy, the environment, and medicine,” demonstrating the power of understanding and harnessing nature’s processes to design technologically important materials and devices for the three areas, with applications to solar cells, batteries, medical diagnostics, and single molecule interactions related to diseases.

In addition to the intellectually stimulating expert presentations, attendees enjoyed a session with brief presentations by junior RPI faculty: Helen Zha on “Bioinspired materials for sustainability and human healthcare”; Karyn Rogers on “Planetary perspectives on life’s emergence”; and Shayla Sawyer on “Reflections on the role of improvisation: The jazz of engineering,” in which she considered what engineering pedagogy and engineering design could learn from jazz and improvisation to become more inclusive, open, and creative. It was a treat!

EngineerGirl 2022 Writing Contest Winners

This year’s EngineerGirl writing competition asked students in grades 3–12 to write an essay about how engineering can help humanity meet one of the United Nations’ Sustainable Development Goals (SDGs). In addition to the prizes awarded to students based on grade level, essays were selected regardless of grade for “special topic recognition” based on their excellent treatment of a given SDG. Winners were chosen from among nearly 800 essay submittals.

First place among 3rd to 5th grade students was awarded to Isha Gupta, a 5th grade student at Daves Creek Elementary School in Cumming,

Georgia, for her essay on using hydroponics as a solution to the global food crisis. Eighth grade student Chloe Weng from Fort Settlement Middle School in Sugar Land, Texas, won first place in the 6th to 8th grade category for her essay on engineering's role in creating diagnostic devices in health care. Megan Haubrich, an 11th grade student at Fred C. Beyer High School in Modesto, California, won first place among entries from grades 9 to 12 for her essay on engineering developments to pull water from air.

The 2022 EngineerGirl writing contest was sponsored by Oracle and North Carolina State University's Kenan Institute for Engineering, Technology, and Science. Awards are $500 for first place, $250 for second place, and $100 for third place. Honorable mention winners received EngineerGirl sweatshirts, and authors of essays given special topic recognition received EngineerGirl T-shirts.

All the winners and their essays are posted at https://www.engineergirl.org/146898/2022-Contest-Winners.

New NAE Youth Voices Campaign

The EngineerGirl Ambassadors program is a unique and powerful opportunity for high school girls to engage directly both with the NAE and with like-minded peers while mentoring upper-elementary and middle school girls in engineering design. Girls who have participated in this program have said their experiences as near-peer mentors were "life-changing."

The NAE now proposes to create a dynamic outreach program for underserved youth that will engage them in engineering, help develop their skills, and recognize their achievements, all with the aim of building a new generation of diverse leaders in engineering.

The program will welcome girls and boys for participation over several years. Students will design and implement an engineering outreach project connected to their school and community. They will also participate in an online leadership training program that will encourage middle and high school students to work collaboratively to improve awareness of and interest in engineering. To help fund their projects each year the NAE plans to make minigrants available to participating youth/schools.

To learn more about this proposed program, please contact Simil Raghavan (SRaghavan@nae.edu), director, Inclusive, Diverse, and Equitable Engineering for All (IDEEA) Program.

Joanna Livengood Joins NAE Program Office

JOANNA LIVENGOOD, a senior advisor to the Office of Science in the Department of Energy (DOE), is beginning a 2-year assignment as a senior visiting fellow with the National Academy of Engineering. For the past 12 years she was the DOE Argonne site office manager and senior federal executive responsible for oversight of Argonne National Laboratory. She previously held similar responsibilities for 5 years as the DOE Fermi site office manager at the Fermi National Accelerator Laboratory. Her extensive technical background spans science, energy systems, environmental controls, energy-efficient technology, and nuclear safety and security. Joanna spent her early career as a researcher in air pollution control technology at the Pittsburgh Energy Technology Center (now NETL), a project manager in the DOE Clean Coal and Environmental Management Programs, and a team leader managing public-private partnership projects in energy efficiency and electric transmission/distribution. She earned a BS in chemistry and mathematics from Mary Washington College and an MS and PhD in chemical engineering from Carnegie Mellon University. Honors include the 2012 Secretary of Energy's Achievement Award, the 2015 Secretary of Energy's Excellence Award, and the 2017 Presidential Meritorious Rank Award for sustained distinguished service as a senior federal executive. Joanna can be reached at JLivengood@nae.edu.

Calendar of Meetings and Events

August 18–19	Symposium on Extraordinary Engineering Impacts on Society Virtual
September 21–23	The Grainger Foundation Frontiers of Engineering 2022 Symposium Seattle
September 23–24	EngineerGirl Ambassadors Training Meeting
September 30–October 1	NAE Council Meeting
OCTOBER 2–3	**NAE ANNUAL MEETING**
October 20–22	EU-US Frontiers of Engineering Symposium Bled, Slovenia
November 15	FOCUS: Delivering on Engineering Megaprojects: A Virtual Exchange
December 5–6	FOCUS: Synergies Between Evolutionary and Engineering Analyses of Failures Webinar

All meetings are held in National Academies facilities in Washington, DC, unless otherwise noted.

In Memoriam

Klaus D. Bowers, 92, retired vice president, AT&T Bell Laboratories, died July 7, 2022. Dr. Bowers was elected in 1985 for contributions to and management of solid-state optical, magnetic, and semiconductor research and development.

Alan C. Brown, 92, retired director of engineering, Lockheed Corporation, died May 25, 2022. Dr. Brown was elected in 1992 for pioneering developments in stealth technology and their successful blending with other aircraft technologies into the F-117 aircraft.

John T. Christian, 85, retired professor of civil and environmental engineering, University of Massachusetts, died June 5, 2022. Professor Christian was elected in 1999 for leadership in geotechnical earthquake engineering, computer methods in geotechnical engineering, and engineering education standards.

Alexander G. Fraser, 85, president, Fraser Research, died June 13, 2022. Dr. Fraser was elected in 2005 for contributions to the development of packet-switched networks, including virtual circuit switching and window flow control.

Richard J. Fruehan, 80, US Steel Professor, Carnegie Mellon University, died July 3, 2022. Professor Fruehan was elected in 1999 for research in iron and steel making.

Noel C. MacDonald, 81, professor, University of California, Santa Barbara, died May 18, 2022. Professor Brown was elected in 2000 for contributions to the development of the scanning auger microprobe and micromachined micro-instruments.

George C. Maling Jr., 91, managing director emeritus, Institute of Noise Control Engineering of the USA Inc., died June 9, 2022. Dr. Maling was elected in 1998 for noise-control engineering and the development of international and national noise standards.

D. Bruce Montgomery, 89, chair, Magplane Technology, died July 1, 2022. Dr. Montgomery was elected in 1998 for the development, design, and construction of high-magnetic-field devices for conventional and superconducting applications.

Joel Moses, 80, institute professor, professor of computer science and engineering, and professor of engineering systems, Massachusetts Institute of Technology, died May 29, 2022. Professor Moses was elected in 1986 for pioneering accomplishments in symbolic algebraic manipulations by computer, and for outstanding leadership in engineering education.

Alan W. Pense, 88, professor emeritus, ATLSS Engineering Research Center, Lehigh University, died May 11, 2022. Professor Pense was elected in 1993 for interdisciplinary research in weldability, deformation, and fracture of metals and for leadership in engineering education.

Richard H. Petersen, 87, director, NASA Langley Research Center, died June 18, 2022. Mr. Petersen was elected in 1993 for contributions to aeronautical engineering in all flight regimes.

Karl S. Pister, 96, dean and Roy W. Carlson Professor of Engineering Emeritus, University of California, Berkeley, and chancellor emeritus, University of California Santa Cruz, died May 14, 2022. Dr. Pister was elected in 1980 for contributions in the use of advanced principles of mechanics in understanding the behavior of engineering materials.

Pravin P. Varaiya, 81, professor, Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, died June 10, 2022. Professor Varaiya was elected in 1999 for contributions to the theory of systems and control.

Raymond Viskanta, 90, W.F.M. Goss Distinguished Professor of Engineering Emeritus, Purdue University, died December 27, 2021. Professor Viskanta was elected in 1987 for pioneering contributions to thermal radiation transport and general heat transfer engineering.

Irv Waaland, 94, retired vice president and chief designer, Northrop Corporation, died May 16, 2022. Mr. Waaland was elected in 1991 for contributions in aircraft design and aeronautics ranging from early commercial craft to the B-2.

Invisible Bridges

The Grind Challenges

Guru Madhavan is the Norman R. Augustine Senior Scholar and senior director of programs at the National Academy of Engineering.

When asked what form he would take if he could come back to Earth again, Othmar Hermann Ammann answered, "An eagle."[1] In 1964, the 85-year-old civil engineer would often stand at the window of his Madison Avenue high-rise looking through a telescope at six of his New York bridges—each a sonata of steel and stone, born from bolts, beams, burns, and blisters. As he told a reporter for *Life* magazine, he believed it "a crime to build an ugly bridge."

The Bayonne Bridge, which Ammann designed with architect Cass Gilbert, opened over the Kill Van Kull strait in November 1931. The lacy steel crescent, 325 feet tall and 85 feet wide, became an emblem of elegance and economy. With a 1675-foot shore-to-shore span, the busy connector between New Jersey and Staten Island was the world's longest through arch bridge at the time, although its fame is now overshadowed by its thicker twin, the Sydney Harbour Bridge.

In the early 2010s, the widening of the Panama Canal created a problem for the Bayonne Bridge.[2] A new generation of post-Panamax megaships, built to suit the canal's new dimensions, could not fit under the Bayonne Bridge's 151-foot vertical clearance. The Port Authority had three options. First, remove the bridge and replace it with a new tunnel, at a cost of at least $3 billion over 15 years. Second, retain the original arch but rebuild it with a higher cable-stayed model—also expensive, and this approach would produce an odd-looking bridge. The third option was deemed the best although it was the most complicated: install a new road deck closer to the arch's apex, which would compromise the bridge's elegance but create the necessary 215-foot vertical clearance.

Raising the roadway on a bridge while keeping it open to traffic was an extraordinary engineering challenge, drawing comparison to conducting open-heart surgery on a running patient. Building a bridge-within-a-bridge also required safe staging of the transit and crane operations. More than that, it entailed attempting (not always successfully) to minimize disruption to the lives of the residents of the surrounding neighborhoods and ecosystem.[3] The price tag for the elevation was $1.3 billion—six times higher, when adjusted for inflation, than the original cost of building the bridge.

The Bayonne Bridge reengineering illustrates something common to all projects involving infrastructure upkeep and upgrades. I call them the "grind challenges."

Unlike the grand challenges that transfix communities with big, bold targets that push the frontiers of achievement, grind challenges are the myriad interlocking tasks that keep our highly engineered world functioning. They involve testing, inspections, standards, compliance, quality work, care work, and all the nuances of negotiating to move load-bearing bureaucracies.

Inspired by the name of this quarterly, this column reflects on the practices and uses of engineering and its influences as a cultural enterprise. This issue's column also appeared as a feature essay in the summer 2022 issue of *Issues in Science and Technology*.

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[1] Rockland MA. 2008. *The George Washington Bridge: Poetry in Steel*. New Brunswick: Rivergate Books. p. 53

[2] Several articles—including by Kate Asher (*New York Times*, Mar 21, 2014), Dustin Racioppi (*northjersey.com*, May 2, 2017), Ian Frazier (*New Yorker*, Nov 13, 2017), Paul Berger (*Wall Street Journal*, Dec 6, 2017), Dan Ronan (*Transport Topics*, Mar 3, 2020), Daniel Israel (*Bayonne News*, Apr 8, 2020), and Vitali Ogorodnikov (*New York YIMBY*, Apr 22, 2016)—provided useful background.

[3] US Coast Guard, Environmental Assessments; Availability, etc.: Modification of Bayonne Bridge Across Kill Van Kull Between Bayonne, Hudson County, NJ, and Staten Island, Richmond County, NY (Federal Register Publication), USCG-2012-1091-0009.

Essential though these tasks are, few people besides the workers who regularly wrestle with the details are aware of them. Despite their low profile, such challenges are tremendously important, and they are defined not by their blue-sky idealism, but by how well they accommodate nearly impossible constraints on—and in—the ground.

In the 1930s Ammann had few restrictions on his engineering vision, enabling him to deliver the Bayonne Bridge months ahead of schedule and under budget. No seismic requirements, concerns about infringing on residential areas, or even consideration of environmental impacts impinged on the construction of the bridge. By contrast, in 2009 the impact studies required to raise the roadway involved consultations with over 300 organizations and 50 Native American tribes. The resulting 5000-page report cost over \$2 million to complete. It revealed that the Kill Van Kull, one of the most heavily industrialized zones in the country, is a possible breeding location for about six dozen bird species, including the endangered peregrine falcon.[4] Rebuilding Ammann's road in the sky was rife with potential roadblocks.

Engineering tends to valorize the lofty ideals of grand projects, but it is in the daily grind that the deeper pact between engineering and society plays out. Adapting any older system to a newer reality comes with a Gordian tangle of considerations. And it is in these tangles, where proper social accountability for the consequences of the work resides, that we can find an accurate and grounded view of engineering.

Consider each grind challenge as a dot in a pointillistic painting—with distance we can see their shades, depths, patterns, and connections to the larger whole. But only up close can we see the real art that connects the grimy gears of multiple layers of technology to the smooth running of servers, sewers, and subways. True appreciation of the grind challenges leads us to reflect differently on the allure that characterizes other aspects of engineering. Many of these aspects advance a vision of engineering that resembles Ammann's description of the energy of New York: "Everyone rushes and pushes, everything is in a busy excitement and everyone is working for a goal without caring about the rest of mankind."[5]

Indeed, Ammann's gorgeous bridges arose in reaction against grand plans. Until his early 30s, Ammann worked as chief assistant to the showy bridge builder Gustav Lindenthal, whose Hell Gate Bridge, the rigid rainbow over New York City's East River, opened in 1916 and served as an inspiration for the Bayonne Bridge. In 1922 Lindenthal, in his 70s, advanced a grandiose structure for a span over the Hudson from Hoboken to downtown Manhattan. It was a nonviable idea, but it evolved into an even more impractical proposal: a dazzling double-decker with a dozen train tracks and almost twice as many road lanes. The plans imagined a veritable Asgardian bridge with concrete towers that were taller than the tallest skyscraper of the time, costing over \$300 million in 1924 dollars.

Society celebrates the light bulb but not the vast electric utility system that makes illumination possible.

Ammann critiqued his mentor's plan as overblown and extravagant. Lindenthal exploded, scolding the younger man for his "timidity" and "shortsightedness," while the older engineer claimed to be looking a thousand years ahead. Lindenthal's refusal to "bring moderation into his gigantic plan" led Ammann to split with him. Ammann put forward a competitive proposal for a stronger and slimmer bridge, resisting "the unlimited ambition of a genius that is obsessed with illusions of grandeur."[6] When his George Washington Bridge opened in October 1931, just three weeks before the Bayonne Bridge, it was immediately acclaimed for its engineering and elegance. The legendary architect Le Corbusier called it the "most beautiful bridge in the world.… It is the only seat of grace in the disordered city."[7] The final cost of the bridge—under \$60 million and ahead of schedule, with both decks and built-in features for expansion—was a fifth the cost of Lindenthal's proposal.[8]

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[4] From Sam Roberts, *New York Times*, Jan 2, 2014, and Brian Budzynski's "Riveting Work," *Roads & Bridges*, Nov 5, 2019.

[5] Rastorfer D. 2000. *Six Bridges: The Legacy of Othmar Ammann*. New Haven and London: Yale University Press, p. 2.

[6] Rastorfer, pp. 14–15.

[7] Le Corbusier. 1947. *When the Cathedrals Were White* (trans. Hyslop F Jr.). McGraw-Hill paperback ed, 1964, p. 75.

[8] Miller DL. 2014. *Supreme City: How Jazz Age Manhattan Gave Birth to Modern America*. New York: Simon & Schuster. pp. 480–81.

To be clear, grand goals can have value in mobilizing passions and bringing about social benefits. The management scholar Bent Flyvbjerg has referred to such passions as the "four sublimes."[9] The first is the "technological sublime," which excites engineers to push the boundaries of what's possible in infrastructure—the longest-tallest-fastest (and often most expensive) types of projects. The second is the "political sublime," which politicians seek by promoting monumental constructions to generate visibility and votes. The third, the "economic sublime," delights businesses, trade unions, developers, bankers, lawyers, and their networks with jobs or income. And the fourth is the "aesthetic sublime," which can supply the pleasure that creators and communities derive from visually striking designs. But a focus on the four sublimes alone distorts engineering, which is centrally defined by its dedication to details and disconnects.

> *It is telling that the very epitome of the grand challenge, the literal moonshot, was undergirded by so many interlocking grinds.*

It is telling that the very epitome of the grand challenge, the literal moonshot, was undergirded by so many interlocking grinds. The Apollo program required the contributions of more than 300,000 people, 2000 contractors, and 200 universities. To empower this collaboration, NASA managers adopted military systems management techniques to focus procurement and guide project teams and requirements in the nitty-gritty details, such as cleanroom protocols and safety-critical maintenance checks. Europe's space agency took the opposite approach, starting with an existing "missile searching for a mission," as aerospace historian Stephen Johnson has written.[10] Lack of attention to quality and safety details and the pursuit of parochial interests doomed the European effort, while the US project famously made it to the moon. As Johnson points out, many of the solutions for the technical problems of rocketry turned out to be social and organizational.

In other words, reaching what astronaut Buzz Aldrin described as the moon's "magnificent desolation" first required a heroic commitment to mastering the magnificently mundane. In deploying moonshots as metaphor and motivation, though, we must acknowledge that many of the things that are necessary in life aren't moonshots. Society celebrates the light bulb but not the vast electric utility system that makes illumination possible. Such biases drive hyperbolic discounting, the inclination to value immediate over delayed rewards: attention paid to maintenance and other longer-term concerns diminishes to the vanishing point.

Science and technology policy often gravitates to megamissions focused on flashy innovation, but there are many other things that require equal attention. Developing and distributing novel vaccines to abate an airborne infection are crucial, but so is the grind of redoing outdated heating, ventilation, and air conditioning systems to improve air quality in buildings and transit. When reaching for the sublime, the quotidian may be what sparks the revelation. As Apollo 8 engineer and astronaut Bill Anders famously quipped, "We came all this way to explore the Moon, and the most important thing is that we discovered the Earth."

All the grind challenges associated with care and conservation are at the core of the bargain between engineering and society—they distill the essence of accountability, values, and humility into professional practice and ethics. Ask systems engineers about timely repair, refurbishments, replacements, renewal, retrofitting, and recycling. They will point out the often unappreciated and unmeasured benefits: avoided failures, faster recoveries, extended performance, reliable networks, and planned sunsetting of obsolete systems.

Recognizing and rewarding those who manage the grind challenges is not a priority of today's incentive systems. Still, such responsibility should be at the very heart of sharpening equity considerations through engineering. Moreover, a grind challenges sensibility can provide a more mature vision for conceiving and communicating engineering. What is engineering, what should it be, how do the practices work, and who do they benefit? Not everything in engineering—or life—is exciting or needs to be made so.

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[9] Flyvbjerg B. 2014. What you should know about megaprojects and why: An overview. *Project Management Journal* 45(2):6–19.

[10] Johnson SB. 2006. *The Secret of Apollo: Systems Management in American and European Space Programs*. Baltimore: Johns Hopkins University Press (1st ed. 2002), pp. 4–8 [quote: p. 6].

In 1964, just a year before his death, Othmar Ammann's final bridge opened. Five years in construction, the Verrazano-Narrows Bridge contained three times the steel of the Empire State Building.[11] At the ribbon-cutting ceremony, Robert Moses, a public official noted for his bulldozer mentality, said the bridge was built by one of the "significant great men of our time."[12] He didn't mention Ammann's name—or any of the construction engineers, architects, trades people, and laborers who brought the bridge into existence.

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[11] Talese G. 2003 (1964). *The Bridge*. New York: Walker Publishing Company.

[12] Talese G. 1964. Verrazano Bridge opened to traffic, new landmark greeted with fanfare in harbor. *New York Times*, Nov 22.

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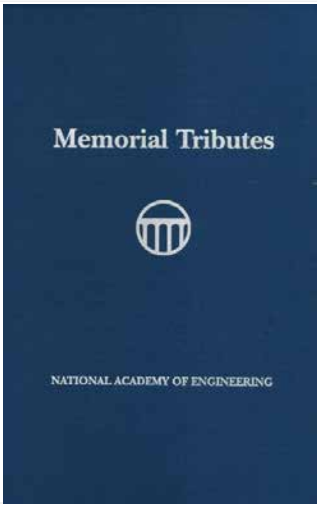

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This is the 24th volume in the Memorial Tributes series compiled by the NAE as a personal remembrance of the lives and outstanding achievements of its members and international members. We greatly appreciate the efforts of the NAE members and others who have commemorated these outstanding engineers. The tributes are inspiring and heartwarming.

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