Building science to advance research in the microbiology of the built environment (MoBE)

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Workshop Report and Meeting Transcript

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Executive Summary

Recent advances in DNA sequencing techniques that allow rapid, high-throughput characterization of taxonomic marker genes (e.g., 16S/18S rRNA and fungal ITS) and whole genomic DNA from environmental samples, coupled with the recognition that the majority of people in the developed world spend most of their lives indoors, have led to a rapid increase in the number of studies exploring microbial diversity within the built environment. Much of this recent work has been ignited by approximately $35 million in research funding from the Alfred P. Sloan Foundation's program on the Microbiology of the Built Environment (MoBE). While these recent studies have greatly increased our understanding of microbial community structure and composition on surfaces and in air within the spaces in which we live and work, most have been driven and led primarily by microbiologists with the building science community playing a supporting role. There remains a need to solicit input from expert building scientists, engineers, and other disciplines that make up the building science community on the overall effectiveness of these previous studies for advancing knowledge of microbial communities in the indoor environment, to identify existing gaps in these studies, and to inform a research agenda for future studies of the microbiology of the built environment that stems from deep knowledge of how buildings are constructed, operated, and occupied. Therefore, the workshop described herein, ***Building science to advance research in the microbiology of the built environment (MoBE)***, was designed to bring together a group of experts in building science and engineering with a smaller number of microbiologists and microbial ecologists to discuss existing gaps and future opportunities for research on the microbiology of the built environment. Goals of the workshop were to advance the MoBE program's research goals and ultimately work towards increasing efficiency and impact among grantees by facilitating interdisciplinary discussions.

While the details of the workshop are described in full in this report, resultant recommendations from the workshop for future research in the Sloan MoBE program can be generalized as follows:

- There remains a need for better methods for microbial ***quantification*** and the identification of other quantitative ***metrics***, particularly those that may be more relevant to health (e.g., viability, metabolic activity, allergenicity, etc.)
- There remains a need for smaller sample size ***intervention and controlled environment studies*** that focus on ***fundamental processes*** (e.g., emission and survival) and transport and dispersal mechanisms, which can also be used to elucidate impacts of important built environment factors (e.g., ventilation, environmental conditions, filtration, occupancy characteristics, and others)
    - More broadly, there is a need to ***improve study designs*** in terms of achieving specific goals for informing building applications
- There remains a need to begin engaging ***other sources of funding***, including those in the building design, construction and operation fields and public health
    - Including NIH, NIOSH, HUD, ASHRAE, DOE, AHRI, and others (including piggy-backing with existing health studies where appropriate)
    - This may also benefit from starting to increase knowledge transfer and awareness in these communities
- There remains a need to continue to ***increase communication*** between microbiology and building science communities, as well as to begin integrating with ***health scientists***

    - More interdisciplinary workshops should be pursued, including potentially:
        - A cross-disciplinary hands-on workshop where fields learn each others' methods, terminology, and tools
        - A similar workshop to the one described herein, albeit with more engagement with practitioners and other important stakeholders
- There remains a need to continue to ***improve standardization in sampling methods***
    - Includes microbial methods for both air and surface sampling and built environment data collection
    - Standardization must include flexibility for study design and future method developments and applications
- There remains a need to explore connections between ***indoor microbiology and chemistry***

While not an exhaustive list, beginning to address these broad priority areas is expected to lead to increased efficiency and usefulness of MoBE studies and better elucidate the connections between building design, operation, and occupancy, indoor microbiomes, and human health.

1. Introduction

Recent advances in DNA sequencing techniques that allow rapid, high-throughput characterization of taxonomic marker genes (e.g., 16S/18S rRNA and fungal ITS) and whole genomic DNA from environmental samples (Wooley et al., 2010; Su et al., 2012), coupled with the recognition that the majority of people in the developed world spend most of their lives indoors (Jenkins et al., 1992; Farrow et al., 1997; Klepeis et al., 2001; Xue et al., 2004; Brasche and Bischof, 2005), have led to a rapid increase in the number of studies exploring microbial diversity within the built environment (Humphries, 2012; Kelley and Gilbert, 2013; Konya and Scott, 2014). Recent studies have characterized microbial diversity using these culture-independent techniques in offices and other commercial buildings (Tringe et al., 2008; Hewitt et al., 2012), university buildings and classrooms (Hospodsky et al., 2012; Qian et al., 2012; Meadow et al., 2013, 2014; Kembel et al., 2014), healthcare facilities (Lee et al., 2007; Rintala et al., 2008; Kembel et al., 2012; Poza et al., 2012; Hewitt et al., 2013; Oberauner et al., 2013), homes (Kelley et al., 2004; Medrano-Félix et al., 2011; Adams et al., 2013a; Dunn et al., 2013; Flores et al., 2013; Jeon et al., 2013), public restrooms (Flores et al., 2011), and transportation environments (Korves et al., 2013; Robertson et al., 2013), all of which represent indoor environments where people spend much of their time. These recent studies have greatly increased our understanding of microbial community structure and composition on surfaces and in air within the spaces in which we live and work.

These studies thus far have revealed several important findings related to the microbiology of indoor environments, including:

1. Culture-based methods vastly underestimate the abundance and diversity of microbial communities in air and on surfaces indoors
2. Bacterial communities in occupied environments are often dominated by human sources (Hospodsky et al., 2012; Hewitt et al., 2013)
3. Fungal communities appear primarily dominated by local outdoor environments with few indoor sources in most buildings without a history of moisture problems (Amend et al., 2010; Adams et al., 2013a, 2013b)
4. Building characteristics such as outdoor air ventilation strategies and human occupancy patterns can also influence the diversity and abundance of microbial communities found indoors (Frankel et al., 2012a; Kembel et al., 2012, 2014; Meadow et al., 2013)

Many of these recent studies, particularly those funded by the Alfred P. Sloan Foundation's program on the Microbiology of the Built Environment (MoBE), have been driven and led by microbiologists and microbial ecologists. Perhaps as a byproduct of this arrangement, these previous studies have varied widely in their characterization of key building details and in the overall implications of their findings in relation to how buildings are designed, built, and constructed. In particular, many recent studies of the microbiology of the built environment have insufficiently or inadequately characterized important building operational and environmental characteristics that could influence microbial communities. For example, indoor environmental conditions such as air temperature, relative humidity, and light can influence the growth rate, survival, and composition of many microbes indoors (Aydogdu et al., 2009; Tang, 2009; Frankel et al., 2012b); however, these parameters are often not measured over relevant time frames in recent MoBE studies (e.g., Flores et al., 2011, 2013; Hewitt et al., 2012; Poza et al., 2012;

Oberauner et al., 2013). Additionally, methods to measure influential building factors such as airflow rates and air exchange rates in those recent MoBE studies that have attempted to characterize building operation unfortunately have not always utilized robust, standardized methods (e.g., Kembel et al., 2012; Meadow et al., 2013). Insufficiently documented building characteristics can limit our ability to compare microbial ecology results from one indoor environment to another or to use the results to assess how best to control indoor microbial communities (Corsi et al., 2012).

Only recently has a systematic effort been made to better inform indoor microbial investigations with the development of the MIxS-BE package, which describes "minimal built environment metadata" that should be collected in microbial ecology studies (Glass et al., 2013). However, this package does not specify the types of instrumentation to use, specific methods that should be used to make these measurements, or the time scales over which data should be collected in order to best capture important changes that may influence microbial communities indoors. Additionally, many broad findings from recent MoBE studies have been highly intuitive and often expected (Konya and Scott, 2014), informed by many years of research using culture-based methods for biological sampling as well as investigations of the fate, transport, and control of indoor particles and gases. For example, findings that microbial communities in indoor air are more similar to those in outdoor air during periods of high outdoor ventilation rates are highly predictable given an understanding of ventilation rates and pathways (e.g., Kembel et al., 2012; Meadow et al., 2013). It is not clear how results like these will inform actual building design or operation. Building scientists and engineers – particularly those that have been investigating indoor environments for much of their careers – can therefore bring a unique perspective to ongoing research needs in the MoBE program. In fact, there is a long history of research on moisture and microbial growth in buildings, much of it led by teams of building scientists working with other disciplines (e.g., Andersson et al., 1997; Gravesen et al., 1999; Goh et al., 2000; IOM, 2004; Fisk et al., 2007; Mendell et al., 2011), although they have not yet had a strong presence in many of the recent MoBE studies.

Given some of these challenges, there remained a need to solicit input from expert building scientists, engineers, and other disciplines that work extensively in buildings on the overall effectiveness of these previous studies for advancing knowledge of microbial communities in the indoor environment, to identify existing gaps in these studies, and to inform a research agenda for future studies of the microbiology of the built environment that stems from deep knowledge of how buildings are constructed, operated, and occupied. Therefore, this workshop, ***Building science to advance research in the microbiology of the built environment (MoBE)***, was designed to bring together a group of experts in building science and engineering with a smaller number of microbiologists and microbial ecologists to discuss existing gaps and future opportunities for research on the microbiology of the built environment. Goals of the workshop were to advance the MoBE program's research goals and ultimately work towards increasing efficiency and impact among grantees by facilitating interdisciplinary discussions. Other recent workshops have successfully addressed other key issues within MoBE research, such as the workshop on challenges of microbial sampling indoors (led by Yale University and co-sponsored by NIST), the workshop on data visualization, imaging, and repositories for the MoBE program (led by the University of Chicago), and the symposium on MoBE at Indoor Air 2011 (led by the University of Texas at Austin), among others. These workshops and symposia have been crucial

to setting the MoBE program's research agenda, and it is now a crucial time for building scientists and other related disciplines to contribute more meaningfully to the discussion and advance research within the MoBE program.

This report describes the proceedings of the workshop and synthesizes priority research needs generated during discussions at the meeting.

2. Transcript of Workshop Proceedings

This invitation-only workshop brought together a group of experts in building science, engineering, and related fields (including those with expertise in architectural engineering, environmental engineering, architecture, aerosol science, environmental health, and exposure science) with a small number of molecular biologists and microbial ecologists in order to discuss existing gaps and future opportunities for research on the microbiology of the built environment. The workshop was held at Illinois Institute of Technology in Chicago, IL, beginning with a group dinner on May 22, 2014 and a full-day workshop on May 23, 2014. A list of participants and their affiliations is included in Appendix A.

2.1 Workshop Agenda

The workshop began with introductory and overview presentations to provide motivation and set specific goals for the workshop. This included five invited presentations given "through the lens" of the particular fields that each presenter represented. A short group discussion followed, followed by the assignment of smaller breakout groups tasked with identifying both specific and overarching research needs and priorities. Finally, the entire group reconvened as group leaders summarized their breakout discussions and the entire group worked to synthesize and prioritize these recommendations. A detailed agenda is provided in Appendix B.

2.2 Summary of Morning "through-the-lens" Talks

Paula Olsiewski, Alfred P. Sloan Foundation, Program Director

Paula Olsiewski began by introducing the Sloan MoBE program to the workshop attendees. The MoBE program began about 10 years ago as an offshoot of their original bio-security program initially by funding world-renowned life scientists such as J. Craig Venter and Norman Pace to apply their culture-independent molecular biology methods for use in indoor environments. The goal was to launch a multidisciplinary field focused on the microbiology of the built environment that may serve to change the way we design buildings. The effort would initially be funded by Sloan (which has since invested about $35 million in this program), but ultimately would be funded by federal agencies, industry, and other groups beyond the Sloan Foundation after the initial investment period. Sloan now envisions a remaining four-year window of grant making in this program before they expect other funding sources to continue funding this kind of work. At this point there have been two major gaps identified in the Sloan MoBE program: (1) a lack of focus on indoor fungi and (2) better integration with building science to inform their funded research and increase knowledge transfer. The latter is one of the primary reasons for this workshop.

Brent Stephens, Illinois Institute of Technology, Building Science

Brent Stephens followed by introducing the workshop agenda and the Sloan MoBE program generally. Then he presented his view of recent findings in the field from two particular

perspectives: (1) that of an "objective observer" who is attempting to interpret what the major findings in the field have been, and (2) that of a "building scientist" who is attempting to interpret how these findings may influence building design and operation, or more accurately in the absence of this relationship, what has been lacking in previous studies.

Introduction to the Sloan MoBE program

Continuing with Paula Olsiewski's introduction, Brent Stephens introduced the primary goals of the Sloan MoBE program, highlighting the large amount of time we spend indoors, the large number of microorganisms with which we come into contact, the large number of microbial cells on our bodies relative to human cells, and that the advent of new molecular tools, techniques, and cost reductions have dramatically increased our ability to detect microbes in indoor environments. For those not intimately familiar with the Sloan MoBE program (estimated at around one-third of the attendees), Stephens then described that the Sloan MoBE program has been steadily growing since 2004, with approximately 75 projects funded to date (as seen in Figure 1).

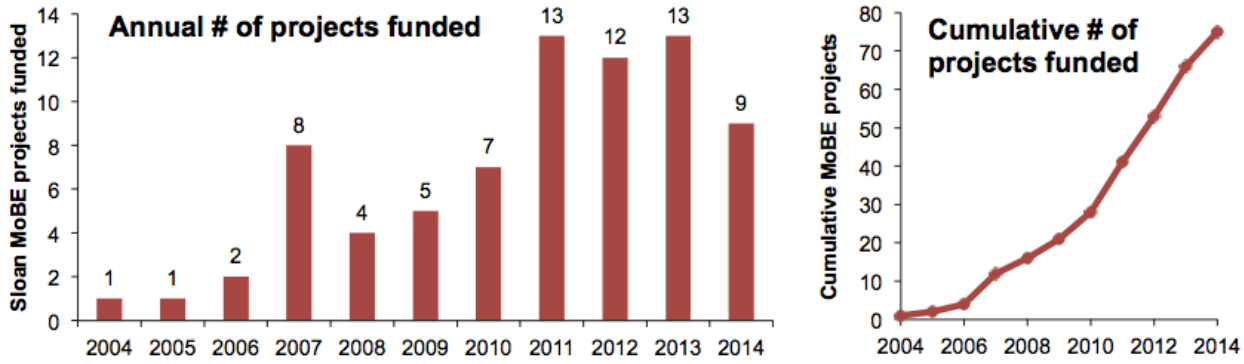

Figure 1. Summary of Sloan MoBE program funded projects

These projects have occurred in three distinct phases, according to Stephens:

1. **2004-2008 initial studies (16 projects)**
   - Several early projects primarily demonstrated the utility of new molecular methods for applications in indoor environments and began to elucidate differences in microbial communities among various locations between and within buildings (PIs: Venter, Thaler, Pace, Williamson, Handelsman, Eddington, Sieracki, Borisy, Sogin, Fox, Lasken, Peccia, Bruns, Seifert, Samson)
2. **2009-2011 (25 projects)**
   Within the next few years, 25 more projects were funded, including a number of core research centers, continued tool developments, workshops, an annual conference, and specific investigations into several new environments. These projects included:
   - BioBE: Biology and the Built Environment Center (Green)
   - microBEnet: microbiology of the Built Environment network (Eisen, Levin)
   - BIMERC: Berkeley Indoor Microbial Ecology Research Consortium (Bruns, Nazaroff)
   - Continued tool/method development (various PIs)
   - Viral explorations (Kelley)
   - Homes (Fierer, Gilbert)
   - NICUs (Banfield, Morowitz)

- Indoor bioaerosols (Peccia, Nazaroff)
- Water delivery systems (Pace)
- Several workshops/symposia (various PIs)
- First annual MoBE conference (Hernandez)

3. **2012-present (34 projects)**
   The last three years have seen even stronger growth in the number of projects funded, with much more focus on investigations in a wide variety of indoor environments and the development of the MoBE postdoctoral fellowship program:
   - Continued work on homes
     - Homes across global cultures (Dominguez Bello)
     - 1000 homes in the US (Fierer, Miller)
     - Pre and post weatherization (Angenent)
     - Fungi in dust (Lynch)
     - Flood damaged homes (Fierer)
     - Insect infestations (Schal) and arthropods (Madden)
     - Interactions with phthalates (Dannemiller)
   - Hospital Microbiome Project (Gilbert)
   - Plumbing systems (2) (Pruden, Bibby)
   - Office surfaces (Caporaso)
   - Building materials
     - Test methods (Scott), moisture (Peccia), pH (Kolter)
   - Public transportation (Huttenhower)
   - ICUs (Banfield)
   - Daycares (Prussin)
   - Wine and cheese making facilities (Mills)
   - Bioaerosol transport and control (Kunkel)
   - Built environment metadata (Schriml)
   - Open sensor building science sensors (Stephens)

As expected, the number and diversity of Sloan MoBE projects have both increased over time, from initial tool development and proof of concept studies to larger scale studies of particular building types, materials, and systems.

From the perspective of an "objective observer"

Stephens then introduced the motivation for this workshop from the perspective of an "objective observer." In this portion of the talk he described general findings that he had observed in the literature stemming from the aforementioned studies (and a few others funded outside of the MoBE program). Early work showed that microbes in indoor air are primarily bacteria that are not necessarily random transients from surrounding outdoor environments, but rather tend to originate from indoor niches and sources. Indoor microbial diversity was shown to be much less diverse than water or soil, but still had large differences between indoor air and indoor dust (Tringe et al., 2008). Differences in bacterial communities were shown to be larger between buildings than seasonal differences in single buildings (Rintala et al., 2008). In more recent findings, indoor fungal communities were shown to be largely driven by outdoor fungal communities (Amend et al., 2010; Adams et al., 2013b). Other work showed that humans often

dominate indoor bacterial communities in public spaces, including restrooms (Flores et al., 2011) and university classrooms (Hospodsky et al., 2012). Similar work also showed that humans often dominate indoor bacterial communities in homes (Flores et al., 2013), albeit with modifications by other factors such as presence of dogs (Dunn et al., 2013). Additionally, building *design* has been shown to influence microbial communities, including how ventilation air is delivered (Kembel et al., 2012) and how well spaces are connected to each other (Kembel et al., 2014). So too can building *operation* influence microbial communities, including ventilation rates, ventilation sources, and human occupancy (Meadow et al., 2013; Kembel et al., 2014).

From the perspective of a "building scientist"

Subsequently, Stephens then described what he thought was lacking in many previous MoBE studies from the perspective of a building scientist by paying particular attention to the level of assessment of building characteristics in these studies. While this work has greatly increased our knowledge of microbial ecology of the indoor environment, the number of studies collecting robust, long-term data using standardized methods to characterize important building operational characteristics, indoor environmental conditions, and human occupancy remains limited. Insufficiently described built environment metadata (or perhaps more appropriately built environment *data*) can limit our ability to compare microbial ecology results from one indoor environment to another or to use the results to assess how best to control indoor microbial communities.

Stephens grouped recent studies utilizing culture-independent analyses of microbial communities in indoor environments into three general categories based on their level of detail in documenting built environment metadata (Ramos and Stephens, 2014): (1) those that did not include any building descriptions or building environmental measurements; (2) those that included some *basic* information about building characteristics, heating, ventilating, and air-conditioning (HVAC) systems, outdoor air ventilation strategies, occupant behaviors, and/or environmental conditions during the time of testing; and (3) those that included *detailed* information about HVAC systems, environmental conditions, and/or human activities in the sampled space. He then described examples of each of these study types in order to demonstrate how robust built environment data collection can be used to generalize results from one indoor environment to another.

As an example of a study lacking information about the buildings in which sampling occurred (and thus limiting our ability to understand consequences for building design or operation), Hewitt et al. (2012) found that bacterial diversity on several surfaces in office spaces in Tucson, AZ were clearly different from those found in New York, NY and San Francisco, CA (which were indistinguishable from each other) (Hewitt et al., 2012). Additionally, bacterial abundance was significantly lower in San Francisco compared to both Tucson and New York. However, with samples in three very different climates, a lack of information on human occupancy or building design and operational characteristics limit our ability to further interpret these results beyond basic geographic differences. These results were interesting, but why were they interesting? We simply can't know without more detailed built environment data collection.

In studies that characterized at least some basic information about qualitative building characteristics, HVAC systems and ventilation strategies, occupant behaviors, and/or basic

indoor environmental parameters such as air temperature (T) and relative humidity (RH) during testing helped to better explain findings, albeit with some limitations. For example, Kembel et al. (2012) quantified airborne bacterial communities and environmental conditions inside patient rooms of a hospital that were occupied only by researchers during testing and in outdoor air on the roof near the outdoor air intake of the HVAC system (Kembel et al., 2012). The rooms were classified as "exposed to mechanical ventilation" or "exposed to window ventilation." The mechanically ventilated rooms had ventilation air supplied by the HVAC system and removed by a return duct and a bathroom exhaust duct. The window ventilated rooms had ventilation air supplied directly from the outside through a window and removed through a return duct, bathroom exhaust, and by any outflow through portions of the same window. The phylogenetic diversity of airborne bacterial communities was lower indoors than outdoors overall, although the mechanically ventilated rooms were less diverse than window-ventilated rooms. However, bacterial communities indoors contained many taxa that are absent or rare outdoors, including those potentially related to human pathogens, suggesting humans were significant sources in these particular rooms. Other building environmental parameters such as the source of ventilation air, airflow rates, and indoor T/RH were also correlated with the diversity and composition of indoor bacterial communities. The relative abundance of bacteria closely related to human pathogens was higher in rooms with lower airflow rates (used as an imperfect surrogate for air exchange rates) and lower relative humidity (although some of these factors were also correlated with each other so it is difficult to reveal the true influencing factors). Results from this study clearly demonstrate that the source of ventilation air is an important determinant of indoor microbial communities, which suggests that at a minimum this kind of basic built environment data should be collected in future studies.

Paying closer attention to occupancy characteristics, Adams et al. (2013) assessed the pattern of fungal diversity and composition in airborne dust that settled onto suspended petri dishes both indoors (in the kitchen, living room, bathroom, and bedroom) and outdoors (on a patio or deck) at a university housing facility (Adams et al., 2013b). The authors also noted several details about the construction of the housing complex units (e.g., age of construction, exterior cladding material, and interior wall material). Each building had its own forced-air ventilation system with heating but no air-conditioning. A short survey was given to occupants inquiring about unit age, the number of various types of rooms, and the frequency of cleaning by the occupants. Indoor air T/RH were also measured during sampling. Some of these factors were significant predictors of fungal community composition across units in single-factor models, including floor level and frequency of cleaning; however, only geographic distance from each other remained significant predictors in multifactor models. Adams et al. (2014) also examined the bacterial component of the same residential samples mentioned above and found that, as with fungi, bacterial richness was higher outdoors than indoors (Adams et al., 2014). It was also higher in units that reported some humidifier use, which suggests that moisture-generating indoor activities are important built environment related data to capture. Bacterial composition varied by residential unit and room type, while fungi varied by season and residential unit. Indoor samples had a large amount of human-associated taxa not found outdoors, indicating humans as a greater indoor source of bacteria than fungi.

Finally, Stephens made the case that when studies focused more on gathering very detailed information about building characteristics, environmental conditions, and/or human activities in

their sampled environments, results from microbial ecology investigations could be uniquely generalized to other environments. Perhaps most important for demonstrating this, Qian et al. (2012) estimated size-resolved emission rates of airborne biological (bacterial and fungal) particles from people using staged measurements in a classroom (Qian et al., 2012). Emission rates are crucial to characterize because they allow for direct extrapolation to other environments via models and direct comparisons between source strengths. The authors were able to calculate emission rates because they sufficiently characterized detailed building operation, including air exchange rates, HVAC operation, and the number of occupants during sampling. They also performed size-selective aerosol sampling using an 8-stage impactor, allowing for a deeper understanding of particle dynamics. Optical particle counters were also used simultaneously to measure size-resolved number concentrations in the room.

Size-resolved microbial emission rates during human occupancy were then estimated by considering the room as a well-mixed reactor and using a time-averaged mass balance to quantify the indoor concentration as the sum of a fraction of the outdoor concentration (measured during vacant periods) plus a contribution from indoor emissions (which is a function of individual emission rates, the number of people present, the volume of the space, the outdoor air ventilation rate, and size-resolved particle deposition rates). Size-resolved particle deposition rates were assumed from previously measured values in existing literature (Thatcher, 2002). Emission rates of bacteria or fungi were assumed to be the same for each person in the room, for simplicity. Bacterial genomes showed a strong peak in indoor concentrations during occupancy for particles in the 3-5 μm aerodynamic diameter size range. Fungal genomes peaked near 2-5 μm and >10 μm, corresponding well with typically cited aerodynamic diameters of unicellular and multicellular fungal spores, respectively. These aggregate emission rates include both contributions from resuspension from the carpeted floor and other surfaces as well as direct shedding of microorganisms from humans. The indoor occupied aerosol microbial ecology showed a distinct signature of human skin microflora in addition to outdoor air and resuspended dust. These important results demonstrated that human occupancy results in significant emissions of airborne particle mass, bacterial genomes, and fungal genomes. Detailed knowledge of particle size distributions in this study offers a unique ability to extrapolate from measured airborne microbial communities to the overall fate, transport, and control of indoor bioaerosols. The usefulness of this particular study was confirmed by at least one other participant who teaches building science (Harriman).

Stephens finished his talk by suggesting a number of built environment data collection recommendations, including paying closer attention to the influence of:

1. Detailed building characteristics and indoor environmental conditions
    - Such as temperature, relative humidity, absolute humidity, and light
2. Human occupancy and activity
    - Using a variety of methods including proximity IR, IR or LED trip wires, CO_2 measurements, RFID tags, acoustic measurements, Bluetooth activity, or video cameras
3. HVAC system characteristics, airflow rates, and ventilation rates
4. Surface characteristics and conditions
    - Such as temperature, water activity, pH, porosity, qualitative details, and frequency of cleaning

5. Standardized air sampling and quantifying aerosol dynamics

Discussion after Stephens' presentation revolved around questions about built environment data collection, including:

- What is meant by "long-term" measurements?
    - High temporal resolution and longevity
- Is it more difficult to perform quantification rather than qualitative diversity/structure analyses?
    - Yes. It is difficult (Adams)
    - But it's not all that difficult to get a good estimate (Hospodsky)
        - Seems to the author and others that this difference among microbiologists may have more to do with familiarity with techniques in particular labs
- On characterizing human occupancy, what exactly is important to capture?
    - Could be as much as age, diet, activity, interactions, history – there are so many different factors that we need to come up with plausible mechanistic reasons why they might be important (and this number is probably more than we could characterize in most studies) (Fisk)
- We should probably work towards classifying metadata to collect based on the type of study
    - It will differ depending on study type
- There are a large number of built environment data that we have the ability to characterize and may want to for any number of study types
    - There is a lot of complexity in buildings that isn't often captured in current MoBE efforts (Levin, others)
    - Some attendees tended to view the large number of complex measurements available too much to overcome in that if everything might be important but there aren't resources to measure everything, things will be missed (Levin)
    - Others suggested that we not give up just because of complexity and that standards can play a role in informing these choices (Walker)

Jeffrey Siegel, University of Toronto, Building Science

Jeff Siegel then presented from the perspective of a building scientist, with a focus on the "Why, what, how, when, and where?" Siegel was wary of studies that were making building science measurements for the sake of building science; that is, he is most interested in better understanding buildings, suggesting that we don't actually know that much about how buildings operation, surprisingly. Siegel divided "what" we should be measuring/assessing into four distinct areas: (1) surfaces, (2) air, (3) systems, and (4) people. There are many approaches to measuring many of these items. Siegel discussed "how" to make some of these measurements by focusing on two particular parameters in order to highlight how many different means of measurement there can be for a single parameter. First, to answer the question "how often does a residential forced air HVAC system run?" (which may be useful for quantifying collected air volumes passing through passive HVAC filter samplers) one would think it is straightforward, but there is an incredible lack of data in the literature. There are also many ways to measure this, including electromagnetic state monitors, current transducers, air velocity meters, and temperature sensors in supply ducts. Each has their own advantages and disadvantages, including costs, accuracy, and others.

As another example of a potentially important parameter, Siegel noted that water drives much of indoor chemistry and biology. Siegel couldn't find much information on air RH being important for microbial growth, but surface water seems likely to be far more important. However, Siegel has not found any study that measured 'equilibrium relative humidity,' which is a surrogate for surface water activity, in any real buildings for any amount of time. There are limited ways to make this measurement but Siegel suggests we pay particular attention to this parameter.

Another important question to consider in built environment data collection is "When?" Siegel emphasized the need for long-term data collection. Siegel personally doesn't think measurements in buildings that are shorter than about a year are likely to be helpful or meaningful. He suggested that we need more long-term data until we get more of a sense of what scales are important. Short-term measurements can often give a very different picture of an environment than what would be revealed with long term measurements, as he demonstrated with measured data from his own projects. For example, exploring person-hours as a metric of occupancy in the Hospital Microbiome Project, the time frame over which you sample will yield a very different estimate of occupancy. Siegel suggested we continue to consider other aspects of "when" including what is the frequency of sampling that is important for built environment data? And how does this compare to response times of the measured variable itself versus sensor response times?

"Where" is another important consideration introduced by Siegel, although he doesn't think we have a good sense for what level of spatial resolution we need yet. Additionally, your choice of measurement may change how many sensors you need and thus change where you can even measure, and budgets and sensor availability obviously dictate what is feasible.

Finally, Siegel introduced a few future thoughts, including:

i. There are complex and fantastic visual and statistical tools that MoBE microbiologist use for exploring their data. Siegel thinks we should leverage those tool developments for exploring building science data and differences in spatial and temporal patterns within and between buildings. These tools could also be used to explore the rates of changes of both microbial communities and building science parameters.
ii. Siegel also mentioned that there would be a lot of helpful information gained on some fundamental parameters by digging into old building science reports that never made it into peer review publication. Siegel would like to see a project combining literature review and new measurements of HVAC system runtime.

Discussions after Siegel's presentation continue for a few minutes. Nest thermostats (and other similar technologies) may offer an opportunity to collect some of the runtime data Siegel mentioned, although people using Nests are not going to be representative of the entire population. There was also interest in details such as observed lag times between air RH and equilibrium RH, although others suggested that we could spend a large amount of time on parameters like equilibrium RH, but what may really be needed is stronger hypotheses and goals in mind when you decide what you're going to measure and how to reveal what is important.

Hal Levin, Building Ecology, Architecture/Building Science

Hal Levin then presented through the perspective of an architect by training, with interests and expertise in building science and indoor air quality (IAQ) as well. Levin started with a short architectural history of Chicago, making the point that there is a large diversity of buildings in any environment and that diversity in building characteristics should be appreciated. Levin gave some more perspective on where, how, and what you measure in an indoor investigation, particularly by focusing on the evolution of IAQ measurements. That is, when a new field is started, how things are measured tends to evolve over time. There is a long history of this in IAQ, as the better job that is done characterizing environments with newer, more sophisticated measurements, the better the questions tend to become and lead to a positive feedback loop.

Levin personally thinks that recent MoBE program work hasn't taught us that much more than what we didn't already know, other than that there are a large abundance of microbes that we didn't know were there before. However, Levin also highlighted the importance of this field, from the potential for preventative medicine to architecture to energy to bio-defense. Levin described three inter-related areas of investigation for MoBE studies similar to what had already been introduced, including (1) environmental conditions, (2) occupants, and (3) indoor air and surfaces, which are full of microbes from many places. Levin also mentioned time scales of built environment data collection, highlighting the fact that even long-term averages might not be as important as extremes (making the analogy that when a building is being designed, one actually doesn't design around the averages but the extremes). Levin asked the question, "Can we just continue to massively catalogue what's in buildings?" Sure. But "do we know enough to ask better questions?" Yes we do (informed by a long history of IAQ investigations). Finally, Levin finished by describing how trade-offs are an essential part of any architectural design process and that conflicts among various goals and designs are normal, but that understanding the whole system is essential to understand the indoor microbiome, providing some motivation for finding an appropriate balance (in terms of resources) between microbial and building measurements in future projects.

Shelly Miller, University of Colorado, Environmental Engineering

Shelly Miller introduced her talk by focusing on the importance of indoor air, which motivates her to study indoor and outdoor air quality in context. Miller also spoke from the perspective of an environmental engineer, in that she "thinks like an engineer" and tends to ask the question, "What's the problem with the microbiome?" That is: What do we need to be doing? Do we need to be getting rid of harmful microbes or altering buildings to take advantage of 'good' microbes? The approach is fundamentally an engineering approach – what is given, what is the problem, what is the solution? Miller then showed data from some of her own work, showing that in a recent study of the indoor microbiome in homes the only stand-out built environment parameter to date (albeit using preliminary data) was that the number of carpeted rooms showed a correlation with the fraction of skin bacterial taxa in indoor air, inner trim, and HVAC filters in homes. However, Miller also proposed a "want ad" for a consistent description of the indoor environment (for homes), which led to discussion about whether or not many built environment parameters are really important to capture (Gilbert)? There were thoughts that there are challenges with scale – for example, how do air exchange rates really impact small swipe sample? (Perhaps they don't). But others (Fisk) argued that we can take cues from how building factors affect health in that there is a lot of prior knowledge from this field that can inform this

list and narrow it down (e.g., Mendell and Smith, 1990; Mendell, 1993; Daisey et al., 2003; Fisk et al., 2007; Mendell and Mirer, 2009; and others).

Then the discussion turned towards some confusion about microbial *metrics.* For example, there seems to be a lot of confusion on diversity metrics (e.g., relative abundance or composition) versus quantitative metrics (e.g., concentrations or emission rates) that seems to be at the heart of discrepancies between the two disparate fields. It is clear that building scientists and engineers need to be informed by microbial ecologists on what their microbial data can actually tell us; similarly, microbial ecologists could likely benefit from understanding the perspective of building scientists, engineers, and exposure scientists, to whom quantitative results are extremely important for determining concentrations, exposures, and doses of any indoor constituent.

Finally, other building scientists (e.g., Francisco) brought up the importance of detailed qualitative construction details such as foundation type and foundation connections (and perhaps more importantly where are the leakage areas relative to the foundation in a home, which may be very important for microbial communities). Also, how important is duct leakage in terms of total leakage area? The gaps between building science and microbial ecology became apparent, with both groups asking helpful questions of each other's fields and revealing a need to continue these discussions on a regular basis and when designing experimental research plans.

Rachel Adams, University of California Berkeley, Microbiology
Rachel Adams began by clarifying that a "microbial ecologist" is very different from a "microbiologist," as many in the room were not quite aware! Adams gave her unique perspective as a microbial ecologist and helped identify what questions she asks when approaching an indoor environmental investigation. Her primary questions are "What species are indoors and why?" The house (or building) is primarily considered a new biome that ecologists can explore, with direct applications not necessarily in mind.

Adams also introduced the four fundamental principles in ecology that are explored:

i. Dispersal, or movement across space
ii. Selection, or fitness differences
iii. Drift, or stochastic changes (i.e., randomness)
iv. Speciation, or evolution of new species in new environments

These four considerations are the closest that microbial ecology gets to a "formula," according to Adams.

Adams then described the tools that she and her colleagues use to assess microbial communities in easily identifiable terms for the building science audience, mentioning that diversity patterns and taxonomic identities are the two primary tools they use. Beta diversity is an assessment of the turnover of species, and Alpha diversity is an assessment of how many species are in a sample. She then showed data using this framework, including her data showing that fungal communities looked in a mycology lab were very different from other microbiology labs, as would be expected. Adams offered thoughts on how building science parameters can impact microbial communities under this framework, suggesting that microbial composition is likely influenced by stochasticity, geography, connectivity to outdoor environments, and occupancy (in likely decreasing order of importance for fungal communities). She showed that she had some

predictive ability of indoor fungal composition in her university buildings (temperature, age, floor, number of bedrooms, unit, distance individually), but only distance/geography was linked in multi parameter models.

The group discussion turned towards metrics and intent of MoBE studies, getting productively tense at times. There were several helpful questions, including what is the right microbial parameter to look at? Is it microbial diversity? Composition? How do we link these (or other metrics) to health related issues and impacts? What about pathogenic or inflammatory potential as important metrics? There was also some concern about using current methods to say some factors are or are not important – there is a risk of losing those measurements/descriptions if the problem actually lies with insufficient metrics. This was the first kind of discussion between these two fields that this author has been a part of, and it was obviously constructive.

There were also questions about whether or not we even know how to design a study to look at other metrics at this point? (Waring). Since there are no known health effects linked to particular taxa (other than for infectious diseases), it is not clear. Gilbert responded that for modern environment questions, it's probably not the 300 or so organisms we normally track but that tools are working moving towards helping this. Adams mentioned that the idea of a diversity or composition measure is very generic. She wondered what are the variants in microbial composition that can be tracked? Maybe only a subset is driving the differences; for example, maybe 98% are irrelevant, 1% beneficial, 1% harmful, but microbial ecologists don't know that.

Along these lines, Harriman proposed a focus for the next four years: that is, should we just find out what problem and non-problem buildings have in terms of microbial ecology, and what are the differences between them? Levin generally agreed that much of the IAQ field developed from problematic buildings and that MoBE should follow suit. However, Olsiewski mentioned that Sloan thought about this originally but chose to study ordinary environments not limited to problematic or harmful buildings. Miller mentioned that flood damaged homes are obviously very important building types. The clear difference of opinions between the usefulness of studying problematic buildings versus non-problematic buildings seems to be an important gap to close.

Fisk mentioned that there are a lot of lessons to be learned from the IAQ field. For example, we don't learn that much from simple IAQ measurements. A key point unfolded: Fisk (generally representing the building science community) mentioned that he would like to see more hypothesis-driven work. However, Gilbert (generally representing the microbiology community) retorted that they "always have hypotheses." It is the opinion of this author that they are in fact both correct, but the way in which hypotheses are defined varies greatly between the two communities! One has to do with application, the other more basic science. This is another important gap between two fields to identify and work towards closing.

Before turning back to finish Adams' presentation, Waring suggested that we generally all have the same end goals, but it is unclear how we can move to the next level of investigation. It may start with well-defined study questions from the combined perspective of building scientists and microbial ecologists in ways that haven't been done before.

Finally, Adams offered more thoughts on metrics for both microbial data and building data. For example, Adams wondered how precise do space connectivity and human occupancy need to be characterized? It's unclear to her (and we assume to other microbial ecologists) that crude information may be helpful enough for answering some questions. In terms of microbial selection, temperature and water are key parameters, according to Adams. A discussion of randomness also followed, with the building science community (represented by Singer at this point) wondering if stochasticity simply meant that there are some things that you can't really measure or assess so it's somewhat random? (Yes). Adams explained that ecologists see beauty in the noise; on a good day she has a model that explains 40% of variance. A bad day is 1%. These statistics are woeful in an engineer's eyes and represent another important gap between the two fields and their expectations.

On the microbial side, Adams wondered, is the concern not about microbial composition (DNA) but microbial particle size and/or concentration (suggesting more quantification)? Most of the engineers in the room were much more familiar with quantification and size rather than some more qualitative composition, and thus tended to agree.

Finally, Adams mentioned the divide among engineers and ecologists in terms of methods development and standardization. For one, what ecologists are looking for in a sampler may be quite different from an engineer and lead to issues with sample collection biases that were previously unknown to an ecologist. Additionally, time scales are different; for example, particle measurements can work on a time scale that biological work can't. At least two hours are typically needed for biomass, which is far too long for capturing dynamic particle response. A recent study compared four air samplers and found that a 1000 L/min allowed for the richest microbial perspective, but this is simply not practical in most environments. Finally, there were questions around accuracy of quantitative microbial assessments, as a lot of data on qPCR shows that uncertainties can be high.

Adams summed up her talk with the phrase, "Ecologists think nature is noisy and messy," suggesting both that this makes their way of thinking fundamentally different from engineers. Adams also suggested that continued replications across time and space are important to capture for now (rather than larger sample sizes) until the data suggest otherwise.

Seema Bhangar, University of California Berkeley, Exposure Science

Finally, Seema Bhangar gave her perspective as a combination environmental engineer and environmental health scientist, or perhaps more accurately, an "exposure scientist." In a modified graphic of the 36 views of Mt. Fuji, Bhangar provided a summary of the things that people care and think about in MoBE research. The 36 views analogy was largely intended to point out that the same field can be viewed by a variety of disciplines in a variety of ways, and in many ways they are all correct and still representative views of a field. Bhangar also used Lioy and Smith's recent article as a framework for thinking about exposure science; that is, one starts with the source, then understands dynamics, then behavior, then exposure and dose, and finally outcomes (Lioy and Smith, 2013). These are the important considerations of an exposure scientist (representing many other disciplines), particularly if MoBE research is to be used to inform and improve human health. She discussed how these important determinants vary in different environments and with different sources. For example, human activities are highly dynamic and

non-deterministic. There are gradients in time and space. Emitted biomass is relatively low, and ultimate and proximate sources can differ.

Continuing on this line of thinking, Bhangar offered the following guiding principles in MoBE research from her perspective:

i. Emission rates are more useful than concentrations
ii. We must design and test interventions
iii. We must always understand the influence of underlying processes across environments (the reason for (ii) above)
iv. Investigation time scales should match process timescales
v. Quantity matters!

She then described her recent work using the UV-APS, showing that it could be used for quantifying interesting dynamic bioaerosol responses and estimating emission rates, although the jury is still out on the overall usefulness of the UV-APS as a bioaerosol sensor (Bhangar et al., 2014). Bhangar demonstrated that emission rates could certainly be used to compare across very different environments, as previously mentioned in this report. She also mentioned previous work defining different built environment metadata time scales, from static to pseudu-static (on/off) to dynamic (i.e., 1-min) (Sreedharan et al., 2011), suggesting that we work towards understanding the importance of these scales in built environment data collection and in understanding microbial dynamics in the indoor environment.

Bhangar then provided her perspective on specific MoBE research needs, suggesting the following are needed at this time:

i. Source characterization
ii. Need to push the envelope on measurement methods (time resolution, particle size, quantification, composition, standardization)
    - Also making a call for humility (i.e., what can we and can we not say based on our data?)
iii. Ecology linkages (who's there where are they from what are they doing?)
iv. Environmental health linkages
    - Healthy and sustainable buildings; population exposures, impact of life styles, who is vulnerable; does the 'outdoor-ness' or 'human-ness' of a building matter for health?
v. Comparative risk assessment

2.3 Breakout Discussion Groups

Following the initial presentation period, workshop participants were then divided into smaller groups to participate in breakout discussions. Team leaders were assigned and participants divided as follows:

Group 1	Group 2	Group 3
Rachel Adams	Seema Bhangar (**notes**)	Paul Francisco (**leader**)
Parham Azimi (**notes**)	Kyle Bibby	Jack Gilbert
Ian Cull	Edoarda Corradi (**notes**)	Denina Hospodsky
Rachael Jones	Bill Fisk (**leader**)	Hal Levin
Stephanie Kunkel (**notes**)	Lew Harriman	Shelly Miller
Bill Rose	Ben Stark	Atila Novoselac
Jeff Siegel (**leader**)	Iain Walker	Tiffanie Ramos (**notes**)
Brett Singer	Michael Waring	

Their tasks were assigned as follows:

1. Answer starter questions (provided below)
2. Develop a list of specific research questions
3. Group these into smaller list of thematic/overarching areas
4. Work on a parallel list of 'guiding principles'

The following starter questions were provided to initiate conversation (although not universally answered):

Q1. In what areas should MoBE be working that it currently is not?
Q2. What are the key barriers or challenges remaining in the MoBE field?
Q3. How should these recent MoBE results impact building design and operation (R2P)?
Q4. What are the most important unanswered questions related to indoor microbiology in your specific field?
Q5. Are we more concerned about microbial communities in indoor air or surfaces?
Q6. How can the MoBE program help address questions about remediation when we have problems in buildings?
Q7. What disciplines would you like to see involved in every MoBE study?
Q8. What should the Sloan MoBE program goals be over the next 5 years?
Q9. How do we link MoBE work with risk analysis?
Q10. How do we better link MoBE methods and results to practitioners?
Q11. How can we work towards greater standardization of methods (including microbiology, air sampling, built environment metadata, and others)?
Q12. Will we be able to resolve fundamentally what built environment parameters really do impact microbial communities?
Q13. How will MoBE be influenced by climate change?
Q14. What are the best angles to stimulate external funding in this area?

2.4 Summary of Breakout Discussion Periods

A full description of individual breakout group discussions is not included here. Rather, we summarize the larger group discussion led by individual breakout group leaders.

Group 1

Group 1 answered a few starter questions, and then transitioned to developing research questions and finding overarching themes. Their summary is presented below.

Q1: In what areas should MoBE be working that it is currently not?

- Health and health-related outcomes – but how do you interpret the microbiome data?
    - Motivations: Health concerns and building design

Q2: What are key barriers/challenges to the MoBE program?

- How do we market the research in direct quantitative effects?
- Need to better understand methods (both biological and building science)
- Maybe the larger picture macro (insects) and chemical (gases) are important to capture (not just the microbial community)
- Maybe more integration with health disciplines are needed in order to understand sensitization and the characteristics of people that are getting sick
- Are there particular environments of utmost importance? (e.g., crowded environments like prisons or shelters)
- What about odor / microbial VOCs?
- Do we know whether quantification or speciation is most important? Both?
- What about viable versus non-viable quantification?
- Time scale that people find interesting is not always biologically possible
- Standardized methods for sampling and extraction. Consistency should yield good results.
- Limitations? Number of buildings, number of samples collected, cost, time
- Are there biological measurements that we aren't measuring that we should be?
- Cost of sampling and time to analyze data
- Leverage against other studies
- Need a standardized checklist for sampling

Specific research questions identified:

- How can we start narrowing down the specific areas of standardization?
- What is the connection between the indoor microbiome and modes of infectious disease transmission
- What other metrics should we be working with?
    - Potential infectivity versus viability?
- When are we going to start seeing practical implications? Is it worthwhile to focus on some small set of practical questions in order to make a bigger impact?
- Do we really understand how the indoor microbiomes in humans interact with each other?
    - How does touching a surface affect the surface and the human microbial community? Can we start to establish functional relationships on this?
- Do quantitative assessments tell a different story than community assessments?
- What can we learn from measuring effects rather than causes? Can we use this to guide our research?

Overarching themes identified:

- Do we study every characteristic in a damaged building or just one characteristic?
- We NEED standardized methods!
- Infectious disease transmission
    - Probably should have made more progress than we have

- Cost/time of analysis
- We can currently send a sample to a commercial lab and ask for a count of a few dozen particular species present in the sample. But does it mean anything in microbiological view?
- Need quantitative assessments vs. community assessments
    - It seems logical that quantity matters a lot, but what are the barriers to doing quantitative assessments?
- Is the goal ultimately to enhance healthy microbes or get rid of toxic ones? The field seems divided

Group 2

Group 2 jumped to the final three given tasks, and first identified two very different goals of research that can and have occurred in this field:

- Understand microbial ecology (typically what has been done)
- Application oriented: Research to inform policy, building design, health protection (typically what has not been done)

Group 2 also proposed some general ideas for future research:

- More hypothesis-driven research with identifiable application(s)
- Longitudinal, case-control, and intervention studies (that may include controlled environment or chamber studies)
- Investigate microbial dynamics, time scales of responses
- Investigation time scale should match process time scale
- Spatial scales for microbial community and environmental measurements will match
- More focus on source strengths
- More complete assessment of built environment (BE) parameters to complement measurement of microbial communities
- Finer-scale outcomes than total microbial diversity or composition; focus on the portion of the microbial composition important to health (microbial *activity*?)
- Make program results more visible to building and health professionals, possibly via microBEnet
- Consider human health consequences in research prioritization
    - Positive and negative
    - Immune system development
    - Inflammation
    - Infectious respiratory diseases, especially those with pandemic potential (influenza)
- Abundance (not just relative abundance) as well as diversity
- Viral diversity and abundance
- Built environment metadata recommendations will vary among study types
    - Consider filtration, AC, humidification, T/RH, water damage, material type, foundation type, occupants, occupant activity, demographics, indoor detailed location
        - How precise does a microbial ecologist need to be?
            - Depends on study, size, type, hypothesis;

        - Even qualitative assessments can be helpful
        - One deliverable should be a 3-5 page guide on identification of systems and qualitative things to assess in a building
        - Be very cautious about having time scales in built environment metadata
        - Whose job is to convince whom in terms of building science metadata?
- Investigate locations with frequent direct human contact (e.g., beds, faucets), including dynamics
- Investigate storage of samples for future analysis (bc analytical techniques are advancing)

Group 2 also offered some specific project ideas:

- Relate microbial community in BE with microbial community in human respiratory system (including lung)
- Longitudinal studies of how introduction of new person or pet influences microbial community in BE and of how exposure to a new BE influences microbial community in a person
- Develop a list of target indicator organisms for controlled studies
- Detailed spatial mapping of microbial communities, possibly over time
- Compare microbial communities of urban built environments to rural farm built environments where occupants have animal contact (motivated by evidence of protective effect of farms)
- Microbial changes in homes, including time response, as a response to:
    - Temperature or humidity change intervention
    - Ventilation or filtration intervention
    - Chemical pollutants
- Longitudinal or intervention study focusing on probiotics
- Factors that forces induction or incorporation of viral phages in bacterial genome

Group 2 offered one final thought, "This type of multidisciplinary meeting very helpful for definition of priority directions."

Group 3

Group 3 answered several of the starter questions, as follows.

Q1: In what areas should MoBE be working that it currently is not?

- Defining problem buildings versus non-problem buildings
    - Microbiome
        - Key species and their significance to health?
        - Repetition of results
    - Causal factors
        - Moisture, air leakage, ventilation?
        - Occupancy?
            - Including social factors (socioeconomic status, cultural traditions, etc.)
- Exploring fundamental processes
- Need to piggy-back on health focused studies
- Work on eliminating confounding factors

- Answer the question "what are the microbes doing?" (i.e., activity)
- Need more long-term studies (and need to define this)
- Combine with chemistry (e.g., mold odor)

Q2: What are the key barriers or challenges remaining in the MoBE field?

- Linking chemistry to microbiology
    - Reactive MVOCs
- Measurement needs
    - Temporal and spatial resolution
    - Detection limits
    - Development of real-time measurements for environmental control
    - Need to apply atmospheric chemistry measurements to indoor environment
- Interdisciplinary communication
    - Microbiologists, building scientists, and health professionals (e.g., medical doctors)
    - Need more cross-training between disciplines
- Need to determine what exactly should be measured? (both building and microbiology)
    - For example, what is our best metric for water?
    - What is the best metric to use for characterizing microbes?
- Need to standardize these metrics

Q3: How should these recent MoBE results impact building design and operation (Research to Practice)?

- We're not there yet – still a lot more work to do

Q4: What are the most important unanswered questions related to indoor microbiology in your specific field?

- "What does it all mean?"
    - That is: what are the practical implications of this work? Has it or will it do anything to influence building design and/or operation? (unlikely)

Q5: Are we more concerned about microbial communities in indoor air or surfaces?

- "Both"
- Surface: longer term, seems to be more relevant to health (transfer to humans)
- Air: important for respiratory conditions
    - Lots of interplay

Q6: How can MoBE address questions about remediation in problem buildings?

- We're not there yet

Finally, Group 1 suggested that their research priorities are largely outlined in their response to Question 1.

A combined group discussion period followed each individual breakout group discussion summary, as described below.

Full Group Discussion Period
The full group discussion period grouped around the following topics.

1. Future funding sources
Are there any practical limitations for getting interdisciplinary work like this funded?

- Seems like there are some plausible funding agencies for the future (e.g., NIH, HUD)
    - But may need to be led with the right health leaders
- Beware: Publication can be tough to do cross-disciplinary (Siegel)
- There may be potential risks in NIH type research proposals based on too broad of hypotheses (i.e., "characterization studies")
    - Likely has to be a "zero risk" study probably for NIH (Fisk)
- Other potentially less stringent opportunities may include NIOSH R21 or R01 (Jones)
- The two most important areas for partners are likely *public health* and *building design, construction, and operation*, as suggested after the conference by one attendee (Harriman)
    - Engaging these institutions early is important for attracting research partners
    - On the building side, this may include the following:
        - DOE Building America Program
        - California Public Interest Research (PIER) Program
        - New York State Energy Research and Development Authority (NYSERDA)
        - ASHRAE
        - AHRI

2. Study designs
Are there any previous study designs (using culture based methods) that you'd like to see replicated with new methods?

- There were several with counts, glucans, endotoxins and their relationship to respiratory health and asthma outcomes (Fisk)
    - Although by and large they haven't shown many associations with indoor air and health
    - But would like to see that kind of study with a much more powerful assessment techniques
- EPA BASE study of 100 office non-problem buildings (Cull)
    - BASE study was biased, only looked at a minority of office buildings with particular criteria for number of people (Levin)
        - Then just improve statistical representativeness of sample (Cull)
- What can we do to improve indicator organisms?
    - How can we enhance some of the measurements we're taking to get a little more information?

3. What are research priorities?

- Low-hanging fruit may be to piggy-back on current epidemiological studies (Olsiewski)
- We need better quantitative methods – but what are those? (Miller)
    - Can be quite difficult to do from a microbiology standpoint
    - But desperately wanted by the building scientists and engineers

    - One suggestion submitted after the workshop (by Stark) is that since both microbial ecologists and building scientists probably have useful approaches for categorizing microbes indoors, the two fields should work together to propose new tools
        - One proposed example may be to change the way diversity measures are used: Perhaps they can be used to identify relative abundances of species in a sample using 16S rRNA sequencing, which is then used to inform traditional culture based methods and plate counts to explore a correlation between 16S rRNA gene *relative* abundance and *actual* live cell numbers
            - This kind of thinking may also necessitate other measures that capture biochemistry, physiology, and inter-relatedness of metabolic strategies of all the members of the community identified in a sample in a more comprehensive way
    - Another suggestion submitted after the workshop (by Harriman) is to engage others who are familiar with quantification, such as:
        - Mark Mendell (California Public Health)
        - David Miller (Carlton University)
        - Jean Cox-Ganser (NIOSH)
        - Carl Grimes (ISIAQ)
        - Don and Lan Chi Weekes (AIHA)
        - Andrew Rozak (NACCHO)
- Much of the MoBE work has experience long times to publications (Levin)
    - Need to improve
- We probably need some cross-education – that is, microbiologists and building scientists should get hands on experience with the opposite disciplines tools and techniques to increase understanding (Hospodsky)
- We need smaller scale, targeted intervention studies
    - Explore fundamental processes
    - Explore transport mechanisms
    - Explore impacts of built environment factors
- We probably need better standardization on microbial sampling
    - Are swab samples as reliability and effective as we think they are? (Jones)
- We need to characterize dispersal
    - To what extend does transport of microbes between places you in habit happen through air or surfaces (clothes, shoes, etc.) (Bhangar)
    - Could investigate employees in an office, at home, and in transport (Waring)
    - Perhaps compare to study groups who consciously try not to track things into their home (e.g., by removing shoes) (Bhangar)
    - The success of a study like this may depend on locations for sampling (Jones)
- The microbiologists and microbial ecologists need a list of fundamental building science parameters to increase their knowledge (Adams)
    - We have some versions of this for existing home inspection protocols (Francisco)
        - Examples of these include the Healthy Housing Inspection Manual (CDC and HUD, 2008) and the National Healthy Housing Standard (NCHH and APHA, 2014), among others

- Finally, it was suggested that building scientists initiate a research proposal to Sloan (Stephens)
    - Or if Sloan needs to release an RFP they will

4. Other input from the building science community

After the workshop, Lew Harriman forwarded a number of observations and suggestions, which are valuable to provide here.

- There remains a need to engage and inform real-world decision makers on MoBE program research outcomes
    - After 10 years of results, the time is ripe for broader awareness of these efforts
    - In order to target groups like building owners, developers, construction planners, operations staff, contractors, architects, mechanical system designers, and IAQ specialists, it may be time for:
        - A book summarizing research results thus far
        - An ASHRAE seminar at their bi-annual conferences
        - An *ASHRAE Journal* article
        - An *Architectural Record* article
        - A *BOMA* article
- There remains a need to improve awareness and understanding between the two fields of building science and microbiology (and engage practitioners)
    - This can be achieved by webinars, including:
        - Basics of HVAC and/or building design and operation for microbiologists
        - Common microbiological problems in buildings
        - Basic tools and techniques of microbial ecologists for building research
    - And by another expanded workshop with a greater number of stakeholders

3. Summary of Recommendations for Future Research

While much of the discussion and identified research priorities have already been described herein, this section attempts to succinctly summarize the recommendations for future research in the Sloan MoBE program.

- There remains a need for better methods for microbial ***quantification*** and the identification of other quantitative ***metrics***, particularly those that may be more relevant to health outcomes (e.g., viability, metabolic activity, allergenicity, etc.)
- There remains a need for smaller sample size ***intervention and controlled environment studies*** that focus on ***fundamental processes*** (e.g., emission and survival) and transport and dispersal mechanisms, which can also be used to elucidate impacts of important built environment factors (e.g., ventilation, environmental conditions, filtration, occupancy characteristics, and others)
    - More broadly, there is a need to ***improve study designs*** in terms of achieving specific goals for informing building applications
- There remains a need to begin engaging ***other sources of funding***, including those in the building design, construction and operation fields and public health
    - NIH, NIOSH, HUD, ASHRAE, DOE, AHRI, and others (including piggy-backing with existing health studies where appropriate)
    - This may also benefit from starting to increase knowledge transfer and awareness in these communities

- There remains a need to continue to ***increase communication*** between microbiology and building science communities, as well as to begin integrating with ***health scientists***
    - More interdisciplinary workshops should be pursued, including potentially:
        - A cross-disciplinary hands-on workshop where fields learn each others' methods, terminology, and tools
        - A similar workshop to the one described herein, albeit with more engagement with practitioners and other important stakeholders
- There remains a need to continue to ***improve standardization in sampling methods***
    - Includes microbial methods for both air and surface sampling and built environment data collection
    - Standardization must include flexibility for study design and future method developments and applications
- There remains a need to explore connections between ***indoor microbiology and chemistry***

While not an exhaustive list, beginning to address these broad priority areas is expected to lead to increased efficiency and usefulness of MoBE studies and better elucidate the connections between building design, operation, and occupancy, indoor microbiomes, and human health.

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Results from the participant evaluation are provided in Appendix C.

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Appendix A: Participant List

	Name	Institution	Role
1	Jeffrey Siegel	University of Toronto	Building Science
2	Atila Novoselac	University of Texas at Austin	Building Science
3	Bill Fisk	LBNL	Building Science
4	Iain Walker	LBNL	Building Science
5	Brett Singer	LBNL	Building Science
6	Bill Rose	University of Illinois	Building Science
7	Paul Francisco	University of Illinois	Building Science
8	Michael Waring	Drexel University	Building Science
9	Shelly Miller	University of Colorado	Building Science
10	Hal Levin	Building Ecology	Architecture/Bldg Sci
11	Lew Harriman	Mason-Grant Consulting	Building Science
12	Ian Cull	Indoor Sciences	Building Science
13	Seema Bhangar	University of California, Berkeley	Env Eng/Env Health
14	Jack Gilbert	Argonne	Biology
15	Denina Hospodsky	Cornell	Biology/Env Eng
16	Kyle Bibby	University of Pittsburgh	Biology/Env Eng
17	Rachel Adams	University of California, Berkeley	Biology
18	Rachael Jones	University of Illinois at Chicago	Environmental Health
19	Ben Stark	Illinois Institute of Technology	Biology
20	Stephanie Kunkel	Illinois Institute of Technology	Biology
21	Brent Stephens	Illinois Institute of Technology	Building Science
22	Tiffanie Ramos	Illinois Institute of Technology	Env Eng/Bldg Sci
23	Edoarda Corradi	Illinois Institute of Technology	Architecture/Bldg Sci
24	Parham Azimi	Illinois Institute of Technology	Env Eng
25	Paula Olsiewski	Alfred P. Sloan Foundation	Program Director

Appendix B: Detailed Agenda

Friday
May 23, 2014

8:00 am: Arrive Illinois Institute of Technology, Chicago, IL
McCormick Tribune Campus Center (MTCC), 3201 S. State St.
Executive Conference Room

- Light breakfast and coffee

8:30 am: Kick-off presentations

- Paula Olsiewski, Sloan Foundation: Welcome
- Brent Stephens, IIT: Review of recent MoBE studies

9:15 am: MoBE from the perspective of building science and other disciplines (20-min invited presentations)

- Jeffrey Siegel, University of Toronto, Building Science
- Hal Levin, Building Ecology, Architecture/Building Science
- Shelly Miller, University of Colorado, Environmental Engineering
- Rachel Adams, University of California Berkeley, Microbiology
- Seema Bhangar, University of California Berkeley, Environmental engineering and environmental health

11:30 am: Brief group discussion and facilitated brainstorming session

- Assign individual breakout groups and tasks

12:00 pm: Lunch delivered in main meeting room
1:00 pm: Get outside! IIT campus tour
1:45 pm: Breakout discussion groups (groups of 7-8)

- Tasks:
  1. Answer targeted/standardized questions
  2. Identify detailed research questions (RQs)
  3. Synthesize research questions into thematic areas
  4. Prioritize/rank thematic areas and RQs

3:15 pm: Synthesize themes from breakout sessions and pitch a series research goals for the MoBE program (15-min each team)

- Led by group leaders; participation from all team members

4:00 pm: Group discussion leading towards consensus on priority research areas
5:00 pm: End of workshop and departures

Appendix C: Participant Evaluation

The following participant evaluation and survey was given to every workshop participant (with results from the surveys that were returned in *italics*):

Please complete this brief survey designed to objectively evaluate the perceived success of the workshop among attendees.

1. Below please note which event(s) you attended and your perception of the **quality** and **value** of each event. Both are rated on a scale of 1 to 10.

Event	**Attended?** Y or N	**Quality** 1 = lowest 10 = highest	**Value** 1 = lowest 10 = highest
1. Dinner	*7 Y* *1 N*	*Mean = 9.1*	*Mean = 8.7*
2. Kick-off presentations Stephens, Osliewski	*7 Y* *1 N*	*Mean = 9.1*	*Mean = 9.0*
3. "Perspective" presentations Siegel, Levin, Miller, Adams, Bhangar	*8 Y* *0 N*	*Mean = 8.9*	*Mean = 8.8*
4. Break-out sessions	*7 Y* *1 N*	*Mean = 9.2*	Mean = 8.3
5. Research agenda synthesis	*7 Y* *1 N*	*Mean = 6.7*	*Mean = 6.6*

2. Please provide any suggestions for room for improvement to any of the proceedings:

None mentioned

3. Please rate the productivity of this workshop compared to similar workshops you have attended: [Circle or highlight your response]

Least Productive									**Most Productive**
1	2	3	4	5	6	7	8	9	10

Mean = 7.9

4. The goals of this workshop were originally stated as follows:
"This proposed workshop aims to bring together a group of 10 to 12 experts in building science and engineering with a small number of 2 to 4 microbiologists to discuss existing gaps and future opportunities for research on the microbiology of the built environment (MoBE). Outcomes of the workshop are expected to advance the MoBE program's research goals and ultimately increase efficiency and impact among grantees."
In your opinion, did this workshop achieve its stated goals? [Circle or highlight your response]

Failed by a large amount									**Succeeded by a large amount**
1	2	3	4	5	6	7	8	9	10

Mean = 8.1