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In this article the notion of Probiotic Architecture is proposed as a way of framing the shifting understanding of health in architectural design.

# Living with buildings, living with microbes: probiosis and architecture

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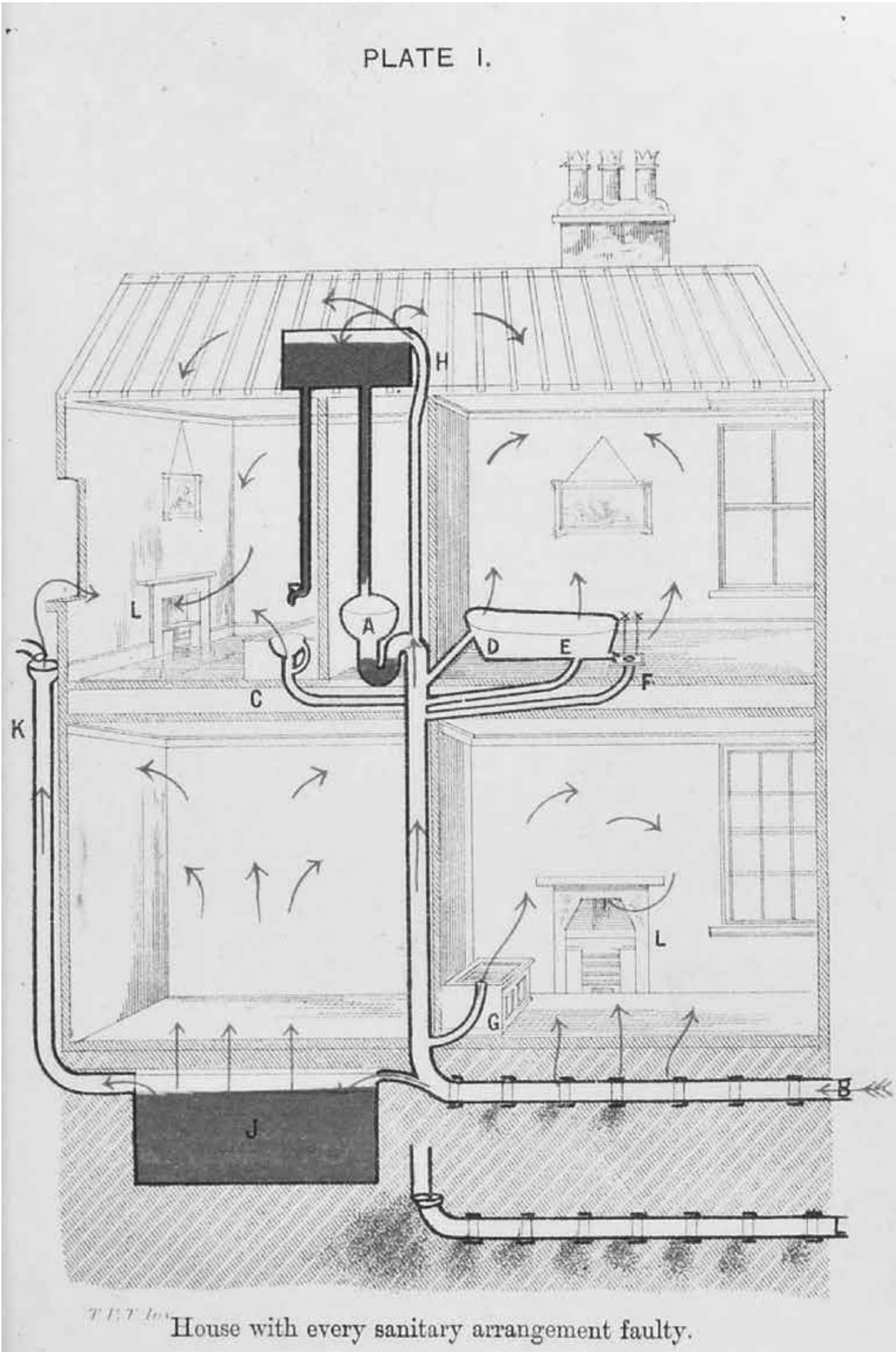
In 1943, Erno Goldfinger designed a pair of posters for 'The Nation's Health', an exhibition organised for the Army Bureau of Current Affairs. Each poster is arranged on a 68 x 48 cm board and composed as a regular grid containing six black-and-white photographs. The first poster includes 'Bad Environments': slums, unemployment, bad schools, bad sanitation, bad factory building, under nourishment. The second works as the opposite: good housing, full employment, good schools, good sanitation, good factories, and balanced diet. The posters each carry one half of a slogan set in condensed, all caps, sans serif typeface: '*BAD ENVIRONMENT CAUSES ILL HEALTH; GOOD ENVIRONMENT IS THE BASIS OF HEALTH*'. The diptych was one of the highlights of 'Living with Buildings' (2018), an exhibition by the Wellcome Trust that charted the way design and architecture shapes our mental and physical health. The exhibition was arranged chronologically, starting with Victorian efforts to improve sanitation, through to the creation of the welfare state in the mid-twentieth

1 Engraving by Gustave Doré included in *London: A pilgrimage*.

century, and finally leading into a review of contemporary challenges in understanding the intersection of architecture and health. Curator Emily Sargent suggested the exhibition did not set out to provide simple answers about the relationship between architecture, health, and well-being, but to reconsider 'some of the structures we take for granted and noticing more the things that contribute to health such as colour, light, and nature.'[1]

Here we establish a dialogue with 'Living with Buildings' to contextualise NOTBAD (Niches for Organic Territories in Bio-Augmented Design), a multidisciplinary design research project at the intersection of architecture and microbiology sited within a wider historical discourse connecting architecture and health. Taking its cue from artefacts in the exhibition, this article traces the rich tradition of exchange between architectural thought and medical science from the eighteenth century onwards, which is articulated in three key phases: miasma theory, visual impermeability, and the antibiotic turn. We argue that our current understanding of healthy architecture assumes all microbes to be detrimental to human health. Contemporary medical thought suggests this not to be the case and so following the tradition of exchange between medicine and architecture, we




2 Plate I of *Dangers to Health: A Pictorial Guide to Domestic Sanitary Defects*. Teale concentrates on the dangers of smells generated by waste pipes.

propose a fourth stage in the evolution: Probiotic Architecture. Basing our discussion on contemporary theories of the human and built environment microbiome, we explore how buildings influence human health and well-being. Microbiome describes communities of microbial organisms that develop in and around human bodies and assist them in digesting food and developing their immune system. We suggest that the microorganisms that colonise humans and our built environment have the potential to influence our health and the resilience of our buildings. Against the backdrop of NOTBAD, we suggest the need to 'live with microbes', reversing notions that all microbes are bad to propose materials that encourage benign and potentially beneficial microbial growth in buildings.

## Architects and doctors: medical science and architectural design

### Architecture of smell

In 1872 journalist and playwright Blanchard Jerrold published *London: A Pilgrimage*, the result of a four-year collaboration with Gustave Doré. The book, included as part of the opening section of 'Living with Buildings', contextualises efforts in the nineteenth century to improve health in the city. The engravings produced by Doré depict the human cost of the industrial revolution; rapid urbanisation, unprecedented population density, and living conditions of squalor and neglect *[1]*.[2] The Dante-esque atmosphere served as a backdrop to the development of the hygienist movement, which drew on Miasma theory to define cleanliness in terms of smell. Miasma theory suggested that bad smells and odours were the origin of disease and so many of the strategies towards cleanliness involved masking or removing bad smells – a deodorisation of the city's smells that was also a quest to clean society of disease and vices.[3] The use of water for bathing and washing the body – uncommon at the time – was promoted as the solution for combatting disease, yet was resisted by many: the skin was believed to be permeable to smells and vapours and washing would expose the body to disease.[4]

Miasma theory highlighted the importance of architectural design in creating healthy living conditions. Combined with the emerging science of hygiene, it was used to medicalise architecture as physicians began to reconsider the boundaries between the body and the dwelling – seeing buildings as an extension that enhanced the physiological functions of the body. Doctors and surgeons extended their assessments of human health to that of their patients' houses, identifying sick buildings (in terms of domestic sanitation) and, following diagnosis, proposing strategies to treat and heal unhealthy buildings. In a move that was hugely damaging to the established architectural industry, the so-called 'building doctors' of the time defined a new form of expertise in building design that was lacking in existing architectural practice. There was a shift towards public acceptance of these new approaches – partly due to the state of public health but also to the perceived security of scientific advance and notions of 'systems'. Dr T. Pidgin Teale, one of the most vocal building doctors of the late nineteenth century, regularly lectured across England to raise awareness of how design and building defects, especially in drainage, endangered health. His *Dangers to Health: A Pictorial Guide to Domestic Sanitary Defects* analyses the potential sources of 'bad smells' generated by defective waste pipes *[2]*.[5]

### Visual impermeability

Rituals of purification soon extended to buildings and built surfaces within the city. Limewater as a chemical disinfectant was used to wash paving stones daily; building exteriors, especially those of the poor, twice yearly; and their interior, at least once. The Plan for Cleansing and Purifying the Metropolis (1811) argued that 'external cleanliness would lead to increased neatness in the houses, dresses and habitats, of the poor, and consequently to an improvement in their moral condition'.[6] This shift from olfactory notions of hygiene (linked to Miasma theory) to a more visual code of hygiene saw the architectural aesthetic become medicalised (and the medical aestheticised in architecture). For Mark Wigley, architectural cleanliness 'joins the doctor's white coat, the white tiles of the bathroom, and the white walls of the hospital'.[7] The principle translated to plastering, coating, and whitewashing, strategies that served to present a visible aesthetic of 'impermeability' that kept bad smells off buildings, but also exhibited the purity of water through the use of glazed ceramics, varnishes, and glazing.[8]

These principles of cleanliness and health also influenced building form. Urban illnesses of the time such as tuberculosis and rickets led to the development of new spatial and building typologies and technologies based on exposure to the elements. First came design approaches to administer sunlight (heliotherapy), based on its antibacterial properties, but also its representation of purity. Second was the need for clean, fresh air within buildings.[9] The benefit of fresh air in buildings was observed in hospitals, where wards with open windows demonstrated improvements in patient health and quicker recovery from illness compared to wards with no or closed windows. A good example is the Peckham Pioneer Centre, established in London in the 1930s as an experimental facility to promote preservation of health and self-care. The photographs and drawings of the centre show the glass-fronted façade of the family club providing generous exposure to sunlight and a range of open-air activities that take advantage of the 'fresh' air of Peckham. Later architectural experiments included the open-air school and the tuberculosis sanatoriums, which championed exposure to nature and its benefits to health, prefacing architectural discourses linking hygiene, milieu, and climate. Alvar Aalto's drawings for the Paimio Sanatorium illustrate these principles in designing terraces and windows that maximised the exposure of patients to sunlight.[10]

### The antibiotic turn

A key historical moment missing from 'Living with Buildings' is the transformative effect that antibiotics had on architectural thought. The widespread acceptance of Pasteur's germ theory towards the end of the nineteenth century raised awareness of the presence of bacteria in building, which were quickly seen as the locus of disease. Domestic surfaces became the focus of microbial inspection to try to detect germs and their origins and dust and infill materials were identified as the main breeder of pathogens. This thinking, in part, led to the emergence of the vacuum cleaner with its ability to actually remove dust and other home cleaning routines that are familiar today.[11] In response, engineers of the time specified asphalt floors and impermeable walls in an attempt to hermetically seal spaces from the outdoors and so too came the practice of disinfecting indoor spaces with chemicals. Fears of airborne microbes drove technical advances in mechanical ventilation and air purification to produce confined atmospheres that could overcome the limitations of the natural environment, providing optimal temperature, humidity, and sterility. For the first time the isolation of indoor spaces from nature was thought healthier than exposure to it.

The discovery, and then widespread use, of antibiotics in the mid-twentieth century alleviated many of the health problems associated with living in urban environments. A new wave of confidence over the threat of infection facilitated a shift in focus in building design from health and exposure to nature, to that of comfort in mechanically controlled environments. With a new confidence that microbes were no longer deadly, the mechanised approach to hygiene and thermal control switched away from air purification and climate neutralisation towards the idea of 'self-climate'. New technologies and the principle of the 'well-tempered environment', as articulated by Reyner Banham, led to a preference for a more artificial indoor climate, sealed from the outside, which tried to replicate and improve on nature with clean air and comfortable thermal control.[12] This has led to indoor environmental design to become dominated by thermal control – controlled temperature and humidity – that controls the physical parameters of indoor atmospheres and inevitably influence occupants' perception.

### Living with microbes: Probiotic Architecture

'Living with Buildings' calls for reflection on the myriad ways that buildings have an effect, good and bad, on our health. The brief summary above affirms that evolutions in architectural thought have been connected to advances in medical research and practice, an exchange that does not occur in a vacuum but results in people and institutions promoting and advancing a better understanding of medical research. The exhibition showed the association of philanthropists and activists to create a widespread understanding of what a healthy architecture looks like. Goldfinger's diptych, for example, was part of a movement to increase awareness of how much architecture can influence health and promote the development of a welfare state in postwar Britain that, we suggest, largely continues today. But does architecture's role in mediating health require some calibration given recent medical research on microbiomes?

Aalto believed that buildings can become 'medical instruments' in the way they can be used to improve the health of their inhabitants.[13] Architecture, however, finds itself at a crossroads. Although there is a growing understanding of how much it influences our well-being, architectural thought still clings to the antibiotic turn. Walls and floors are still considered potential sources of infection, and there is an overall approach to generating impermeable, sterile spaces that look to remove any and all microbial presence as the default healthy condition. Both physically and aesthetically, we employ strategies that ward off impurity and filth. Medical thought, however, has shifted its understanding of the interaction between the human body and microorganisms, creating a more nuanced picture of their role in promoting and preserving health. It is now understood that microbes generate communities that assist in digesting food, train the immune system to resist attacks, and crowd out other pathogenic microbes.[14] The potential of these communities, known as microbiomes, has triggered a new area of research and innovation around 'probiotics', expected to revolutionise the way that conditions such as obesity, diabetes, cancer, and immune diseases are treated. The notion of probiotics suggests that, in addition to institutions, philanthropists, and medical researchers, architects will need to create new alliances with microbes in the ongoing quest to improve health and well-being. We argue that nature extends beyond parks, greenery, and plants and that we should live with microbes.

### Probiotics

The term 'probiotic' is used in medical science to describe non-pathogenic organisms, generally yeast and bacteria, which have a beneficial effect in human hosts. The word is derived from Greek, meaning 'for life', and was originally coined in 1910 by Elie Metchnikoff whose late research linked senility with a form of human cells known as phagocytes, mobile cells used by the immune system to swallow harmful microbes and debris. Metchnikoff hypothesised that senility is caused by phagocytes, which shifted their protective function with age and became responsible for deterioration of healthy tissue. Inspired by the diet of rural communities in Russia and the Balkan States, Metchnikoff proposed the use of probiotics: bacteria found in yoghurt and soured milk which, he believed, manipulated the intestinal microbiome and countered the negative effect of phagocytes on healthy tissue.[15]

The early work of Metchnikoff on probiotics quickly lost legitimacy in the medical world following its coverage in popular media as an 'elixir' of eternal youth. The notion resurfaced in scientific debate in the 1990s, signalling a shift in the way medicine understands relationships between microbial communities and the human body: from a general understanding of microbes as potential sources of disease, to a more nuanced view that includes interactions that are beneficial to human health. We know now, for example, that there are less than one hundred species of bacteria that cause disease to humans, yet their gastrointestinal tract contains over five hundred species of bacteria and their number vastly surpass that of human cells. These organisms group in localised communities along the gastrointestinal tract, specialising in tasks that range from breaking up nutrients to producing vitamins and minerals missing in our diet to neutralising toxins. Beyond their direct, chemical interaction with nutrients, the gut microbiome is also thought to be connected to mental health. Recent research has suggested the existence of a gut-brain axis creating a direct link between disorders such as dysbiosis (the imbalance of microbial communities in the human body), anxiety, and depression and giving rise to treatment that involves the use of probiotics to restore gut microbial balance and treat mental health disorders.[16]

### Architecture and the microbiome

Recent research on the human microbiome shows that interactions occur not only inside but also on and around the human body. Because these interactions are often mediated by artefacts and the built environment it is more pressing that architects understand the way buildings generate specific microbial communities and how they have beneficial or harmful effects on humans. The indoor microbiome is influenced by humans and pets, the materials used within the building, and the spatial layout and there are clear differences due to building typologies and geographical locations.[17]

Research in the field of microbial biogeography, an emerging field that studies the temporal and spatial distribution of biodiversity, suggests that human occupants dominate the bacterial communities on both interior surfaces and in the air.[18] A person travelling away from home for a short period results in their bacterial communities rapidly declining, then sharply increasing when returning home. Results from the Home Microbiome project have also shown that after a family moves in to a new house, its microbiome rapidly converges towards the communities found in their former home.[19] The Home Microbiome Project was developed by US Department of Energy's Argonne National Laboratory and the University of Chicago and followed seven families (and their pets) for six weeks, asking them to 'swab' (take a sample) of their hand, feet, and nose daily to analyse the composition of the microbial communities on their bodies. Occupants and surfaces have also been shown to interact in both directions, and results from the Hospital Microbiome Project suggest that when patients enter a new room they initially pick up the room-associated bacterial taxa that predates their stay, but their own microbial taxa (a bacterial community with common characteristics) slowly influence the room taxa back. The project was conducted over the course of a year to analyse the bacterial diversity brought about by staff and patients in the newly constructed Center for Care and Discovery at the University of Chicago.[20]

The relationship between indoor microbiome and occupants is also mediated by design through material application, spatial layout, and building ventilation. While microbial communities are brought in from outside, it is the building design which seems to play a key role in determining whether indoor or outdoor sources dominate. These patterns are determined by the building ventilation type: mechanical ventilation tends to result in human oriented taxa with a lower diversity, while natural ventilation introduces outdoor microbes, increasing diversity and closely mirroring the biome of the outdoor air.[21]

### Probiotic Architecture

Probiotic Architecture involves an understanding of the interaction between built environment, artefacts, humans, and their microbial communities resulting in design strategies that actively shape the environmental microbiome to promote well-being and human health. The dynamism between building and microbiome suggests a rich area of opportunity and we suggest that the microorganisms that colonise humans (the human microbiome) and our built environment (the built environment microbiome) have the potential to influence our health and the resilience of our buildings. A probiotic approach to building design draws an analogy, initially, to medical techniques that aim to manipulate gut microbes. It proposes that benign and potentially beneficial bacteria might be encouraged, even purposely inoculated in our buildings and urban spaces, as a direct approach to making healthier buildings. Probiotic Architecture works on two key principles. The first is to reduce human exposure to infectious microbes through the use of beneficial bacteria that can protect against the colonisation and proliferation of pathogens (including those demonstrating drug resistance). The second aim is to actively encourage the proliferation of beneficial microbes that can act as modulators to prevent or reduce disease.

The probiotic approach proposed in this article shares the conceptual background of other proposals in the field but uses different strategies to encourage microbial growth and diversity. A good contrast is the recently published *Microbiomes of the Built Environment*, a report prepared by the US National Academies of Sciences, Engineering, and Medicine to propose strategies to modify the built environment to promote health and reduce disease. The report follows what can be described as an indirect probiotic approach, making two core suggestions: indirectly add microbes by having pets or animals nearby, and increase outdoor biodiversity, in the form of vegetation. Although such approaches are sound in their biological thinking, they are difficult to apply to a wide enough range of buildings to be effective. There are, for example, financial, social, cultural, and moral complexities, which might prevent some people from having pets. Similarly, increasing vegetation is challenging, especially in urban environments. More green spaces in cities has been a predominant agenda for the sustainability movement yet has proved difficult to implement widely due to lack of space, cost, and maintenance issues.[22] Here we propose probiotic design as a material strategy to directly add beneficial microbes to buildings so that walls, floors, ceilings, and surfaces might become active sources of microbial diversity. This is explored primarily through designing materials by optimising their physical and chemical properties to support the growth of selected microbes.

The approach proposed here has precedent in previous work in the field of bioreceptive design, which has explored strategies to colonise building materials with cryptogams (non-seed bearing plants), and in parallel work within the field of biodesign that utilise microbes in beneficial ways. In his research project 'Probiotic Donuts', Taylor Caputo modifies an industrial strain of yeast used in golden bread, to alter the taste and colour of dough, a strategy that is combined with the use of genetically modified bacteria mixed in the icing to produce different aromas. Another good example is Seed, a company described as an ecosystem of scientists, innovators, and poets collaborating in products that harness the potential of the human microbiome. Their current offer includes Daily Synbiotic, pills containing nutrients and bacterial communities thought to contribute to gastrointestinal and cardiovascular health. Although probiotics are often associated with food and supplements, there is an ongoing exploration of the different interfaces between humans and microbes. Mother Dirt, a set of spray and cream products, are developed by Jasmina Aganovic to improve skin health by reintroducing ammonia-oxidising bacteria, which are thought to have disappeared from human skin as a result of changing hygiene practices in the last century.[23]

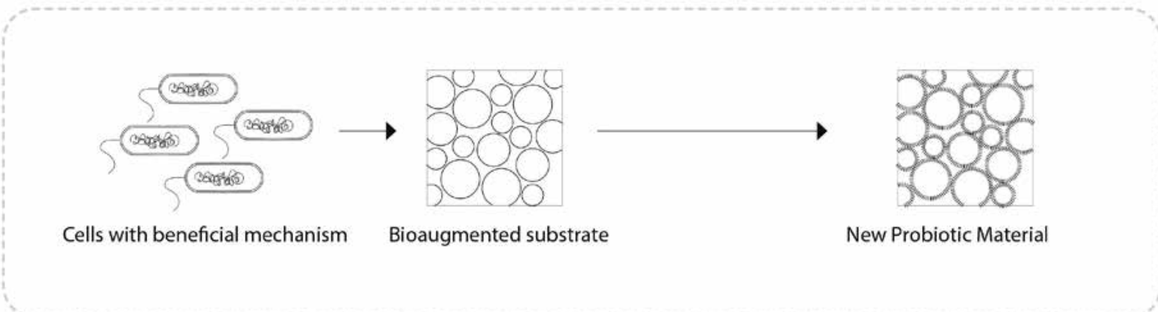
Here we define a host of strategies that involve key material properties, such as porosity/permeability, surface roughness, and pH as well as the geometrical form of objects being important for microbial growth and survival to occur. Our notion of probiotic design builds on principles of bioreceptive design where the materiality and micro scale geometries of wall, floor, and surfaces can be designed to support microbial growth and aims to find and design niches within buildings where we might propose to purposely grow beneficial bacteria.

**Niches and Organic Territories**

NOTBAD – Niches for Organic Territories in Bio-Augmented Design – is an ongoing, AHRC-funded research project in which we set out to develop the notion of Probiotic Architecture. The project is based at The Bartlett School of Architecture and brings together expertise in microbiology and infectious diseases, with Dr Sean Nair as co-investigator, and our expertise in architectural research and material development and research. It explores the challenges of integrating microbes in materials and maintaining their viability over time, and questions how these materials might be received by users and in wider cultural contexts. The project uses an interdisciplinary approach, combining epistemologies and techniques from biology and design, and operates in the context of contemporary efforts to tackle the growing threat of Antimicrobial Resistance (AMR), which describes microorganisms that cause diseases and have evolved to develop resistance to medicine and antimicrobials commonly used to control their spread. The emergence of drug-resistant organisms, often referred to as 'super-bugs', is estimated to cause hundreds of thousands of deaths each year by conditions such as pneumonia and urinary tract infections, which should be otherwise treatable. The proliferation of drug-resistant microbes, combined with existing problems in pharmaceutical research and development, is expected to outpace the current reserve of antibiotics.[24] Leading researchers and medical practitioners have warned that the trend risks a return of now eradicated diseases and complication of ones that are routinely treated.

NOTBAD aims to develop materials that contain living microbial communities with a natural antimicrobial effect, reducing the opportunity for super-bugs to develop. This work frames itself as a departure from existing approaches to create antimicrobial surfaces or applications for surfaces whereby the aim is to prevent any bacterial presence – a so-called 'kill-all' approach. The project involves two phases. The first, now completed, prioritises development of materials, especially porous ceramics, which are designed to support and proliferate the growth of benign bacteria. The challenge of producing probiotic materials is not exclusively technical and expands into cultural and semiotic concerns. The second phase, yet to be

3 Diagram of probiotic material development.

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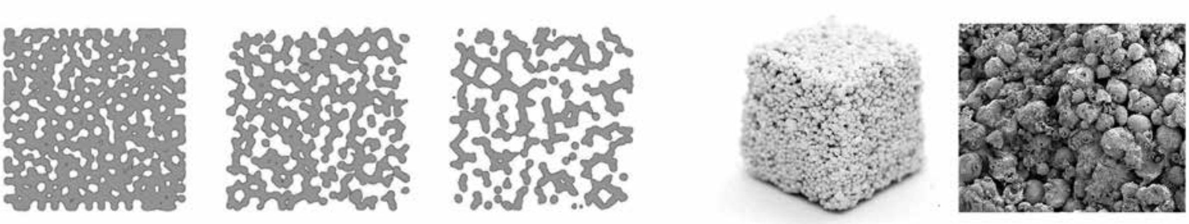


4 Microbial-led material development: a range of chemically inert, porous indoor materials were produced and developed through laboratory testing for bacterial viability.

5 Varying pore size distribution through computational approaches for 3-D printed materials (0.2, 0.4, 0.6 mm macro pore size) and mix design/ fabrication strategies for concrete and ceramic materials.

developed, attempts to respond to this expanded understanding of probiotic materials and revolves around the application of seeded materials in a specific design and cultural settings. Here we report on our experience in developing the first phase of the project, reflecting on the challenges ahead as we embark on the second phase to integrate materials in design context.

### Microbial-led design: seeding materials

The first phase of the project addresses the challenge of embedding viable bacterial strains in materials and is developed in three stages *[3]*. Microbial viability, an initial process to identify and select materials that were suitable for bacterial integration; microbial survival, an assessment of the long-term survival of bacteria in these materials; and probiotic activity, a final step where selected materials could be tested directly against a known pathogen in order to validate its probiotic action. The desired result was to generate a palette of microbial mechanisms and strategies that enable safe embedding of benign microbes – ensuring that potential pathogenic strains cannot proliferate while avoiding the negative side of microbial growth which can contribute to Sick Building Syndrome (SBS).

Seeding materials, our term to describe the introduction of bacterial communities to materials, requires optimisation of material porosity and chemical properties in order to promote bacterial growth and survival. To do this we employed a materially driven process whereby physical and chemical properties were determined by the niche requirements of Bacillus subtilis DSM15029, a benign bacterial strain commonly found in soils and the gastrointestinal tract of animals. We selected the species due to its use in food processing, probiotic potential, ability to produce antimicrobials with multiple modes of activity and to generate molecules that prevent the adhesion and accumulation of other microorganisms. Furthermore, B. subtilis bacteria are able to form spores that can remain dormant for hundreds of years and are highly resistant to alkaline pH, heat and other environmental stresses such as dehydration.[25]

### Microbial viability

This approach draws on both scientific and design epistemologies, including iterative material design and geometrical studies that were then tested under laboratory conditions in terms of their potential for microbial growth and survival. We explored a range of porous ceramics, concrete mixes, plastics, and 3-D printed metals, which were fabricated into 1 $cm^3$ cubes in order to facilitate microbiological testing *[4, 5]*. Samples were sterilised in the microbiology lab, and then seeded with a nutrient rich solution of B. subtilis spps *[6]*. Cube samples were then left at room temperature for one week before they were re-plated onto agar plates in order to assess whether the microbes were still viable.

These initial experiments suggested that a range of the materials had potential for further testing. At this point, 3-D printed materials were not selected due to cost and limits in regards to ease of scaling up.


6

6 Inoculation in the laboratory and assessing bacterial viability after one week.

Both concrete and ceramic exhibited good capacity to host microbial activity and so were taken forward for further evaluation into long-term microbial survival.

### Microbial survival

The second stage involves experiments to quantify the amount of bacteria that survive in material samples at room temperature and without nutrient restock. Samples were again fabricated into 1 $cm^3$ samples in the studio and taken to the laboratory for testing. Samples were sterilised and seeded with a nutrient-rich solution containing a known amount of B. subtilis. Following this they were incubated and crushed into small fragments following an extraction protocol we created to retrieve and count cells that survived without nutrient restock (the optimal nutrient requirements for bacteria), which gives an indication of how optimal each material is for microbial survival in indoor environments *[7]*. At this point concrete samples were proving harder to crush and analyse than ceramic, so we decided to narrow our material investigation to ceramic.

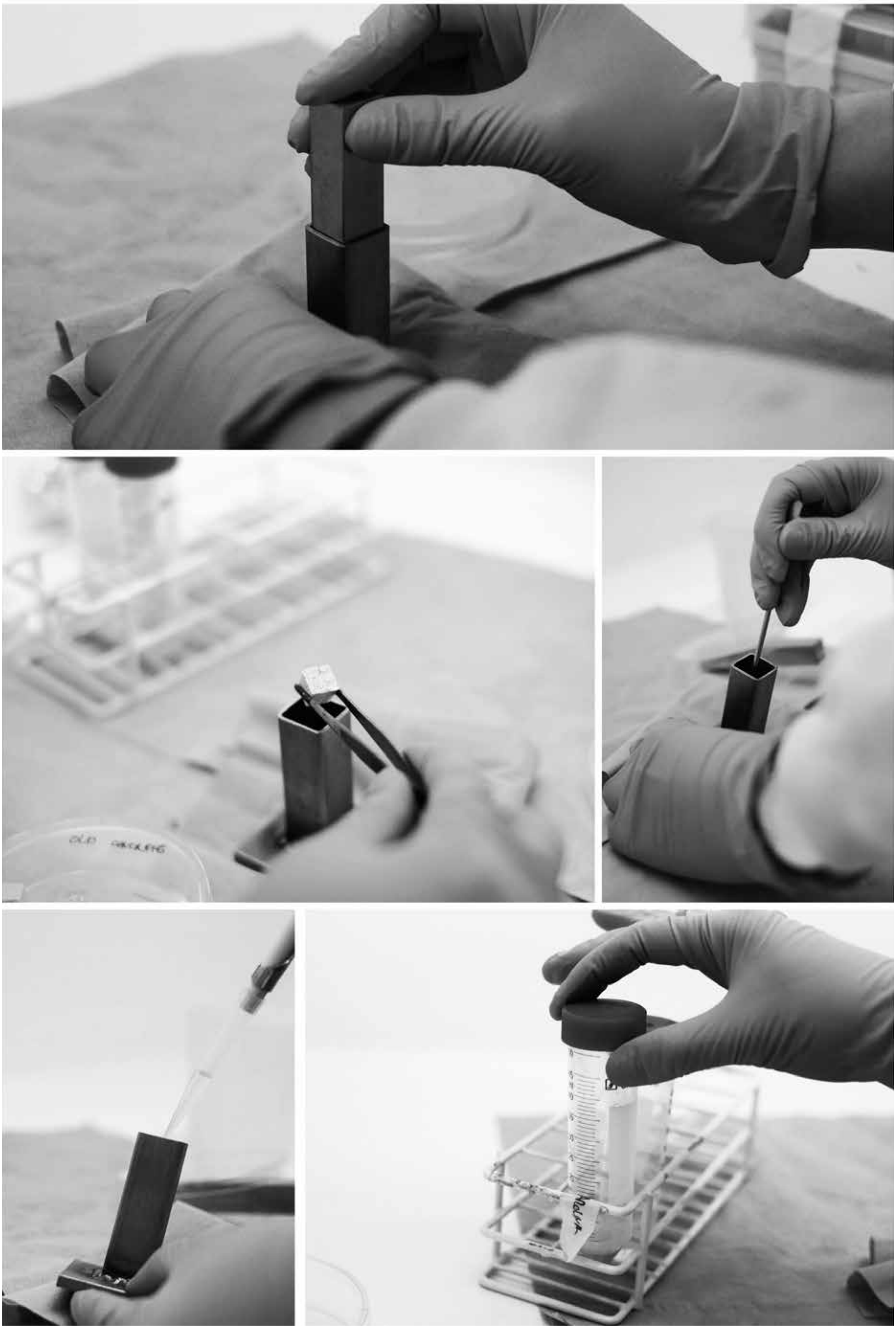
Ceramic samples were tested for survival following six, twelve, eighteen, twenty-four, and thirty days of incubation. The statistical analysis of the data gave positive results suggesting that the number of viable cells remains relatively constant for a period of thirty days, indicating that the porous ceramic has a high capacity to host microbial activity. Samples were assessed under a Scanning Electron Microscope (SEM) to observe the microbes within the material, as shown by *[8]*, where microbes can be seen attached to a single pore at the eighteen-day time point. The image appears to show the bacteria in their sporulated form and while no testing was undertaken to quantify this, the cells in this condition are likely to be able to survive for an extended period of time beyond the thirty-day timeframe of this experiment.

### Probiotic activity

Once the suitability of ceramic for microbial survival was established, the third stage involved experiments to test if the probiotic material had any antimicrobial effect on pathogenic microbes. In this phase, we tested the material against the multi-resistant pathogenic bacteria Staphylococcus aureus JE2 *[9]*. Analysis from the data collected suggests that this probiotic ceramic material is capable of inhibiting the growth of the pathogenic strain and has the potential to prevent the spread of pathogens on building surfaces, making buildings healthier by reducing risk of exposure to pathogens. Although promising, our results are provisional and further experimentation is needed to understand the scalability of these materials, further colonisation and interaction with other microbes, the need for maintenance at longer periods of time, the way that age and change overtime affect the material viability, as well as the resulting material aesthetics.

### Conflicting narratives – probing micro-imaginaries

The second phase of the project will look at the use of seeded materials as they intersect with social and cultural contexts. One challenge in implementing probiotic design strategies is in understanding the symbolic dimensions in which seeded materials operate. ‘Good Germs Bad Germs’, a research project based at the School of Geography University of Oxford, surveyed the microbial composition of fourteen households in Oxford. Their preliminary results have shown not only the highly diverse ecology of microbes within the kitchen, but also the conflicting narratives and imagination that the public has of microbes – while the participants of the study were happy to consume probiotic food, they felt anxious learning the amount and diversity of bacteria living in their sinks.[26]



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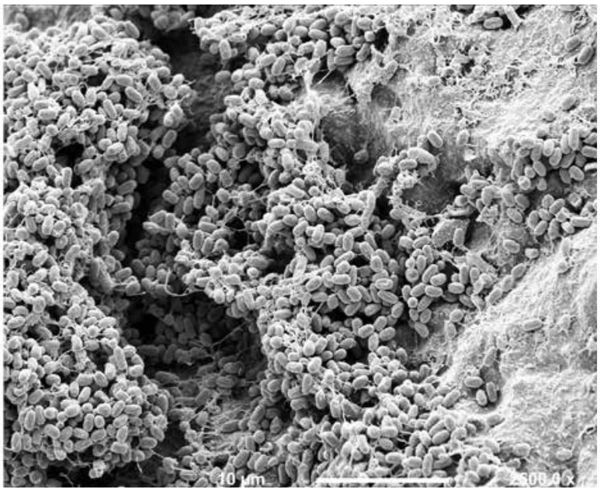
7 **Extraction protocol: material samples are crushed to facilitate bacterial cells extraction and analysis.**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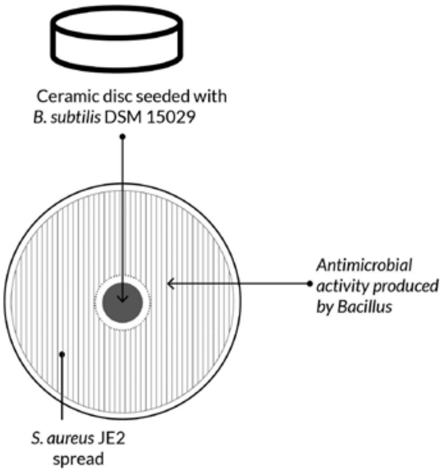
8 SEM images showing material porosity at 100x magnification (left) and B. subtilis cells within an average pore at 2500x magnification.

9 Antimicrobial test. Probiotic ceramic disc tested against a pathogenic bacteria S. aureus JE2.

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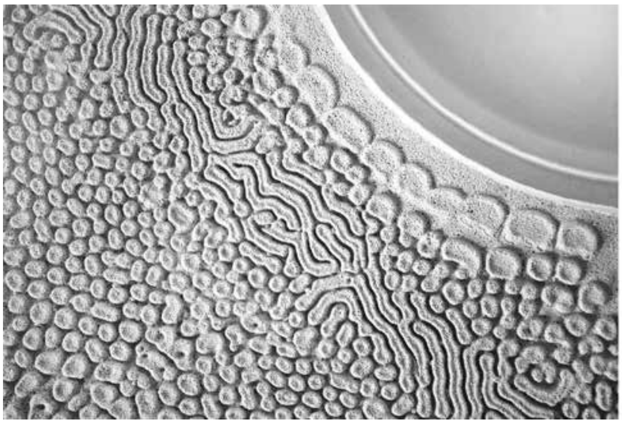
As we have shown in our dialogue with 'Living with Buildings', microbes have been historically linked to notions of disease and decay. Seeded materials participate in this narrative and risks being perceived as detrimental to health, despite medical evidence to the contrary. In the second phase of NOTBAD, we are interested in how materials and surfaces can elicit the production of new actions and meanings that contribute to the production of a healthy microbiome – how the aesthetics of materials, for example, can be used to promote the use of specific surfaces, or the way in which objects can be inscribed in activities that encourage building-to-host transmission of beneficial microbes. We have started our experimentation with a series of 1:1 prototype tiles, which we have exhibited as part of the 'Life Rewired Festival' (2019) at the Barbican Centre in London *[10, 11]*. With these prototype tiles we aim to explore the interfaces of the human body with different surfaces around the home, including splashback areas, tiles, walls, floors, and ceilings. The prototypes intend to produce a catalogue of material strategies that raise awareness of how design can contribute to human health, and to develop new ways in which designers can engage with the microbiome. More importantly, we hope that the prototypes are the first of a series of instruments to change the imaginaries that users have of microbes, and as a provocation to engage with other architects and designers.

## Conclusions

When Goldfinger designed Good Environment, he was tapping into a collective effort to create an optimistic outlook for the future. Like many architects of his generation, Goldfinger had been conscripted to the Army Bureau of Current Affairs during the Second World War.[27] In keeping with the mission set out by Sir William Emrys Williams, Goldfinger's posters were part of a series of exhibitions intended to educate British troops in current affairs. Read in the context of 'Living with Buildings', the poster represents a crucial point in the gestation of the postwar welfare state: it is a reminder of the association of unlikely political actors that were required to bring about a new way of understanding the connection between built environment and health.

But the exhibition misses a key piece, a crucial link in understanding the evolution in the understanding of health from the Victorian era, the garden suburbs, and high-rise dwelling such as Balfron Tower and Pepys Estate. In 2003, art-medicine collective Pharmacopoeia presented 'Cradle to Grave', a medical-art installation featuring hundreds of pills, capsules, and their packaging sewn into a large piece of fabric. The work showed the medical history of a man and a woman, using medicines as their physical trace.[28] A modified installation, showing exclusively the amount of antibiotics a person takes over the course of a lifetime, could be the missing exhibit at 'Living with Buildings'. As we have suggested, widespread use of antibiotics in the mid-twentieth century resulted in a wave of confidence over treatment of infections and facilitated a shift in focus away from health and exposure to nature to a mechanically controlled, well-tempered environment.



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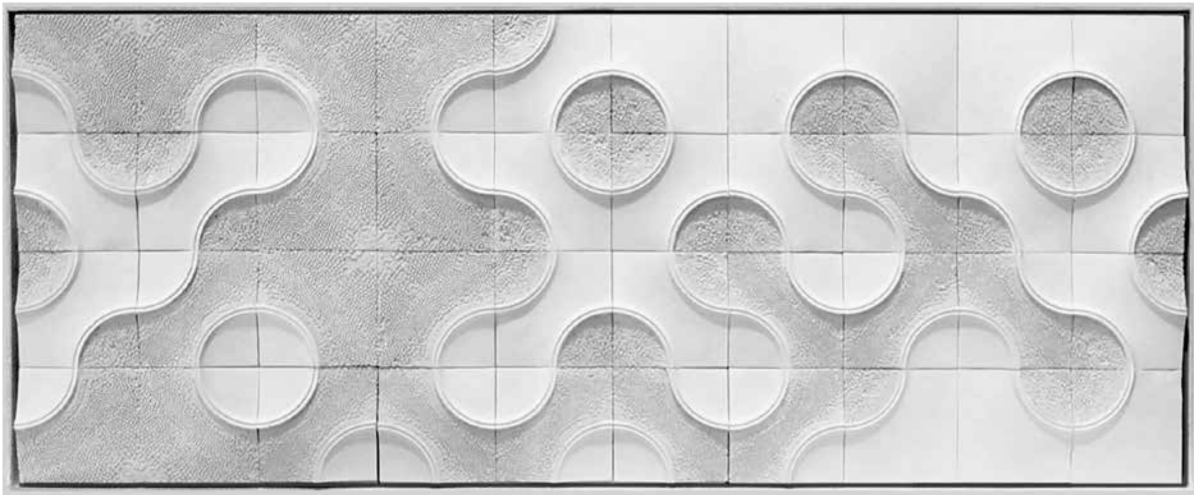

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10 Probiotic Tiles 150 mm x 150 mm, with growth areas defined by geometry and material porosity.

11 Probiotic wall surface: Ceramic Tiles tessellated.

Here we have suggested that contemporary challenges facing health and well-being require architects and designers to actively engage in understanding the way that architecture shapes the human microbiome which, in turn, influences human health in both positive and negative ways. We started writing this piece a year before the COVID-19 outbreak of 2020, convinced there was a sound argument in favour of reconsidering our relationship with microbes when designing buildings. As we edit and review our conclusions, we believe there is now a stronger case for architects to engage with the way that buildings affect the microbiome and become instruments of (ill) health. If the welfare state was constructed through association of philanthropists, medics, architects, and politicians, then the future of healthy environments, especially in the post-pandemic world, will require new alliances with microbes. Current research shows an often-intimate connection between buildings, humans, and their microbes and we have presented an historical argument suggesting there is an overdue shift in the understanding of health in architecture to align to current research and thinking in medical science. Although we generally appreciate that 'good environment is the basis of health', the way that the principle is implemented is conceptually and practically connected to the antibiotic turn. Walls and floors are considered potential sources of infections, and healthy environments often suppose materials that are impermeable and which, on a semiotic level, ward off impurity and filth.

A probiotic approach to architecture aims to draw on contemporary research on the human microbiome, which suggests a sophisticated community of microbes that connect to human beings through associations that facilitate nutrition and immunity. Not all microbes are bad, many are benign and essential to health and so architectural strategies that can not only reduce exposure to pathogens, but also increase our exposure to beneficial microbes should be pursued. Doing so, however, involves material and semiotic challenges that we aim to tackle in NOTBAD: seeding microbes require understanding and developing strategies to optimise chemistry and porosity of materials while being mindful that these materials operate in a cultural context where cleanliness and purity need to be slowly redefined and reframed when talking about microbes.

**Notes**

1. A review of 'Living with Buildings', including quotes by Emily Sargent, the exhibition's curator, can be found in: Pamela Buxton, 'Plain Speaking on Buildings and Health from the Wellcome Collection', *RibaJ: The RIBA Journal* (London, October 2018) < https://www.ribaj.com/culture/exhibition-review-living-with-buildings-wellcome-collection-london-iain-sinclair-pamela-buxton> [accessed 25 January 2019] (para. 7 of 7).
2. William Blanchard Jerrold collaborated with Gustave Doré to produce a survey of the living conditions in London. Starting in 1869, the duo took four years to walk the streets of London, from slums and opium dens to dinner parties and resulted in the book: William Blanchard Jerrold and Gustave Doré, *London: A Pilgrimage* (London: Grant & Co., 1872).
3. Scott Drake analyses how modern architecture associated with new theories of disease transmission to remove the 'mephitic air' of the cities of Europe. He argues that the project to deodorise cities had less to do with disease and more with what he calls a 'bourgeois' project to clean the city of the poor: Scott Drake, 'The Architectural Antimephitic: Modernism and Deodorisation', *Architectural Theory Review*, 2:2 (1997), 17–28.
4. A contemporary rebuttal of *endosmose* and *exosmose*, the passing of fluids through a membrane and one of the principles thought to be central in the transmission of disease through 'miasma', can be found in: François Magendie, 'On Endosmose and Exosmose, and the Permeability of Tissues by Vapours', on *The Lancet London: A Journal of British and Foreign Medicine, Surgery, Obstetrics, Physiology, Chemistry, Pharmacology, Public Health and News* (1835). On 'building doctors' and their historical context, see: Annmarie Adams, *Medicine by Design: The Architect and the Modern Hospital, 1893–1943*, Architecture, Landscape, and American Culture Series (Minneapolis: University of Minnesota Press, 2008).
5. Thomas Pridgin Teale, *Dangers to Health: A Pictorial Guide to Domestic Sanitary Defects* (London: J. & J. Churchill, 1878). The bad smells described by Teale are connected to the sewer gas scare of the late nineteenth century, which, in the popular imagination, reached a peak in 1871 when the Prince of Wales suffered from typhoid. The event caused sanitary audits of the royal water closet as well as of the soil and sewer pipes connecting to the Prince's residence, and later led to a national sanitary reform. The spatial implications of the sewer gas scare are analysed in: Barbara Penner, 'The Prince's Water Closet: Sewer Gas and the City', *Journal of Architecture*, 19 (2014), 249–71.
6. More about the Plan for Cleansing and Purifying the Metropolis can be found in Geo B. Whittaker and Ave-Maria Lane, 'Plan for Cleaning and Purifying the Metropolis', *The Monthly Magazine*, 1 May 1811, p. 311.
7. Mark Wigley, *White Walls, Designer Dresses: The Fashioning of Modern Architecture* (Cambidge, MA: MIT Press, 2001), p. 5. Mark Wigley's thesis, that the white wall of architectural modernism should not be understood as a 'naked' feature but as a form of clothing, is the more relevant in understanding the double process of the architectural aesthetic becoming medicalised and the medical aestheticised in architecture. See chapter 5, 'The Antifashion Fashion'.
8. Drake, 'The Architectural Antimephitic: Modernism and Deodorisation', p. 24.
9. Simon Carter explores the cultural understanding of the sun and the way it has been incorporated to our material and social culture in often-contradictory ways, seen both as dangerous and as source of health. One of his case studies is the use of sunlight in the treatment of tuberculosis and rickets in the early twentieth century: Simon Carter, *Rise and Shine: Sunlight, Technology and Health* (Oxford, UK: Berg Publishers, 2007).
10. For the (then) revolutionary ideas of the Peckham Pioneer Health Centre, see: Robert Furneaux Jordan, 'Peckham and Architecture: A Drama of Building and People', *Bulletin of the Pioneer Health Centre*, 3 (1949). Drawings and photographs of the Paimio Sanatorium, alongside a contextual description can be found in Ellis Woodman 'Revisit: "Aalto's Paimio Sanatorium Continues to Radiate a Profound Sense of Human Empathy"', *Architectural Review* (2016) <https://www.architectural-review.com/buildings/revisit-aaltos-paimio-sanatorium-continues-to-radiate-a-profound-sense-of-human-empathy/10014811.article> [accessed 10 February 2019].
11. The complex and often-slow process by which architecture absorbs and reflects medical notions of disease and their transmission is described in great detail in: Annmarie Adams, *Architecture in the Family Way: Doctors, Houses, and Women, 1870–1900*, McGill-Queen's/Associated Medical Services Studies in the History of Medicine, Health, and Society (MQUP, 1996); Sarah Schrank and Ekici Didem, *Healing Spaces, Modern Architecture, and the Body*, Ashgate Studies in Architecture (Taylor & Francis, 2016). On rituals of cleanliness understood in architectural thought and praxis, see: Adrian Forty, 'Hygiene and Cleanliness', in *Objects of Desire: Design and Society Since 1750* (London: Thames and Hudson, 1992).
12. Architectural historian Reyner Banham was one of the first to systematically survey the mechanical and electrical systems used in generating interior atmospheres. Banham observes the supposed ugliness with which these systems are often associated and argues for 'frankness' and a celebration of the technologies that make spaces liveable: Reyner Banham, *The Architecture of the Well-Tempered Environment* (Chicago: Architectural Press, 1969).
13. In designing the Paimio Sanatorium, Alvar Aalto placed great care in understanding specific design strategies that might alleviate the pain and discomfort of patients. He described how 'The main purpose of the building is to function as a medical instrument [...] One of the basic prerequisites for healing is to provide complete peace.' Cited in Peter Reed and others, *Alvar Aalto: Between Humanism and Materialism* (Museum of Modern Art, 1998), p. 29.
14. When describing the complex interactions in the microbiome, it is important not to draw hard borders between 'benign' microbes and 'pathogens' and between a 'healthy' and 'unhealthy' microbiome. Science journalist Ed Yong writes of the 'befuddling' complexity of the microbiome: Ed Yong, 'There Is No "Healthy" Microbiome', *The New York Times*, New York, November 2014, <https://www.nytimes.com/2014/11/02/opinion/sunday/there-is-no-healthy-microbiome.html> [accessed 18 February 2019].
15. A general review of the use of probiotics as a medical nutrition therapy, and specific ailments that are currently treated with them, can be found in: Amy C. Brown and Ana Valiere, 'Probiotics and Medical Nutrition Therapy', *Nutrition in Clinical Care: An Official Publication of Tufts University*, 7 (2004), pp. 56–68. A biography of Elie Metchnikoff, concentrating on his work on phagocytes, which

earned him the unofficial title of 'Father of Natural Immunity', can be found in: Luba Vikhanski, *Immunity: How Elie Metchnikoff Changed the Course of Modern Medicine* (Chicago Review Press, 2016). A critical review of the notion of probiotics as understood by Metchnikoff, and the way it has influenced contemporary medical thought can be found in: Philip A. Mackowiak, 'Recycling Metchnikoff: Probiotics, the Intestinal Microbiome and the Quest for Long Life', *Front Public Health*, 1 (2013).

16. A review of the work of Metchnikoff from the perspective of current research on the human microbiome can be found in: Scott H. Podolsky, 'Metchnikoff and the Microbiome', *The Lancet*, 380 (2012), 1810–11. For a review of the state of the art on medical research on the human microbiome, see: Ed Yong, *I Contain Multitudes: The Microbes Within Us and a Grander View of Life* (New York: Random House, 2016). Statistics on the number of bacterial species on the human body and their role is taken from this book. A review of scientific research on the 'gut-brain axis' the bi-directional communication between the central nervous system and the gut microbiota can be found in: Megan Clapp and others, 'Gut Microbiota's Effect on Mental Health: The Gut-Brain Axis', *Clinics and Practice*, 7 (2017).
17. For a review of current research on environmental microbiome, see: Charlene W, Bayer and Carl Grimes, 'The Indoor Environmental Microbiome', *Indoor and Built Environment*, 24 (2015), 1035–7. For more specific research on the impact of architectural design strategies, especially ventilation, on the bacterial community of buildings, see: Steven W. Kembel and others, 'Architectural Design Influences the Diversity and Structure of the Built Environment Microbiome', *ISME J*, 6 (2012), 1469–79. A study of the composition of microbial communities in household air can be found in: Helena Rintal and others, 'Diversity and Seasonal Dynamics of Bacterial Community in Indoor Environment', *BMC Microbiology*, 8 (2008), 56. A study on the diversity of office spaces can be found in: Krissi M. Hewitt and others, 'Office Space Bacterial Abundance and Diversity in Three Metropolitan Areas', *PLOS ONE*, 7 (2012).
18. A study concentrating on the microbial composition of indoor air can be found in: Susannah G. Tringe and others, 'The Airbone Metagenome in an Indoor Urban Environment', *PLoS ONE*, 3 (2008). A more general review on the current state of the art in research on the indoor microbiome can be found in: Brent Stephens, 'What Have We Learned about the Microbiomes of Indoor Environments?', *MSystems* (2016).
19. A report on the methodology and results of the Home Microbiome Project can be found in: Simon Lax and others, 'Longitudinal Analysis of Microbial Interaction between Humans and the Indoor Environment', *Science (New York, N.Y.)*, 345 (2014), 1048–52. The study is particularly relevant because of its experimental design, which included a wide range of families (three of which went through the process of moving homes while participating). The study suggests that the diversity of homes is connected to the unique microbial 'signature' of the people who live in them.
20. A report of the methodologies and results of the Hospital Microbiome Project can be found in: Simon Lax and others, 'Bacterial Colonization and Succession in a Newly Opened Hospital', *Science Translational Medicine*, 9 (2017), 1–12.
21. A study on the microbial composition of indoor air can be found in: James F. Meadow and others, 'Indoor Airborne Bacterial Communities Are Influenced by Ventilation, Occupancy, and Outdoor Air Source', *Indoor Air,* 24 (2014), 41–8. The study concentrates on ventilation strategy and uses a building at the University of Oregon to characterise the way that natural and mechanical ventilation strategies have an effect on microbial diversity found in air samples.
22. The report by the US National Academies of Sciences, Engineering and Medicine can be found in: *Microbiomes of the Built Environment: From Research to Application* (Washington, DC: The National Academies Press, 2017). A contrast to the strategies proposed in the report can be found in: Katia Perini and others, 'Greening the Building Envelope, Facade Greening and Living Wall Systems', *Open Journal of Ecology*, 1:1 (2011).
23. The work that we develop here has precedents in: Marcos Cruz and Richard Beckett, 'Bioreceptive Design: A Novel Approach to Biodigital Materiality', *arq: Architectural Research Quarterly*, 20:1 (2016), 51–64. Orkan Telhan provides a good overview of the way that different designers have incorporated microbes in their design practice, offering a good description of the work of Taylor Caputo: Orkan, Telhan, 'Design. Bio', *Bio Newsletter* (2016), pp. 33–43.
24. An introduction and overview to the challenges of Antimicrobial Resistance can be found in: Matthew A. Cooper and David Shlaes, 'Fix the Antibiotics Pipeline', *Nature*, 472 (2011), 32.
25. The use of the Bacillus spores, a dormant stage of the bacteria cycle, in food preservation is reviewed in: Srigitha Nath, Silvia Chowdhury, and K. C. Dora, 'Application of Bacillus Sp. as a Biopreservative for Food Preservation', *Journal of Engineering Research and Applications*, 5:4–2 (2015), 85–95. The effectivity of five commercial 'probiotic' products, which use strains of the Bacillus species, can be found in: Le H. Duc and others, 'Characterization of Bacillus Probiotics Available for Human Use', *Applied and Environmental Microbiology*, 70:4 (2004), 2161–71. The potential use of B. subtilis as probiotic in feed products for fish can be found in: Jorge Olmos and Jesus Paniagua-Michel, 'Bacillus Subtilis A Potential Probiotic Bacterium to Formulate Functional Feeds for Aquaculture', *Journal of Microbial & Biochemical Technology* (OMICS International, 2015), 361–5. The use of Bacillus bacteria to produce peptides with antibiotic properties is reviewed in: Chandra Datta Sumi and others, 'Antimicrobial Peptides of the Genus Bacillus: A New Era for Antibiotics', *Canadian Journal of Microbiology*, 61:2 (2014), 93–103. For a similar study on the pharmacological potential of the Bacillus genus, see: Xin Zhao and Oscar P. Kuipers, 'Identification and Classification of Known and Putative Antimicrobial Compounds Produced by a Wide Variety of Bacillales Species', *BMC Genomics*, 17:1 (2016), 882. The ability of Bacillus bacteria to produce 'bio-surfactant', which act as anti-adhesive agents, can be found in: Fabrizio Rivardo and others, 'Anti-Adhesion Activity of Two Biosurfactants Produced by Bacillus Spp. Prevents Biofilm Formation of Human Bacterial Pathogens', *Applied Microbiology and Biotechnology*, 83:3 (2009), 541–53; Hyeri Son and others, 'Inhibition of Staphylococcus Aureus by Antimicrobial Biofilms Formed by Competitive Exclusion Microorganisms on Stainless Steel', *International Journal of Food Microbiology*, 238:Supplement C (2016), 165–71. A similar review can be found in: Xiao-Hong Cao and others, 'Evaluation of a

Lipopeptide Biosurfactant from Bacillus Natto TK-1 as a Potential Source of Anti-Adhesive, Antimicrobial and Antitumor Activities', *Brazilian Journal of Microbiology*, 40:2 (2009), 373–9. Finally, the ability of Bacillus bacteria to reactivate once spores have been formed is reviewed in: Peter Setlow, 'Germination of Spores of Bacillus Species: What We Know and Do Not Know', *Journal of Bacteriology*, 196:7 (2014), 1297–305.
26. A report of the Good Germs Bad Germs projects, focusing on the use of participatory science methods, can be found in: Jamie Lorimer and others, 'Making the Microbiome Public: Participatory Experiments with DNA Sequencing in Domestic Kitchens', *Transactions of the Institute of British Geographers*, 44 (2019), 524–41.
27. A good review of the work of Erno Goldfinger and other contemporaries for the Army Bureau of Current Affairs can be found in: John R. Gold, *The Experience of Modernism: Modern Architects and the Future City, 1928–53* (London: Taylor & Francis, 2013). Particularly chapter 6, 'Projects and Plans'.
28. A good of Cradle to Grave, written for the British Medical Journal, can be found in: Colin Martin, 'Cradle to Grave', *BMJ: British Medical Journal*, 327 (2003), 1233.

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