Nanomaterials: Invisible Structures, Visible Performances

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Abstract: Nanotechnology is the study and manipulation of matter at the molecular or subatomic scale. Advancements in this diverse and vast field of science are rapidly producing innovative materials and processes with a wide range of applications. Despite the diminutive scale of nanotechnology, the influence of the field is far reaching and is poised to exert a profound effect on the built environment. Beyond self-cleaning surfaces and anti-fog coatings, nanotechnology suggests an extension of the scalar range at which architecture operates. Challenging its modes of fabrication, emerging research within this micro-science confronts energy intensive modes of material production in favor of ostensibly effortless processes that emulate nature. This paper considers the potential for research in the growing field of nanotechnology to instigate a new generation of performative materials made possible through the design of customized molecular structures that remain veiled from the naked human eye. Through a review of current nanotechnology research, it queries a series of shared principles between science and design in an attempt to identify productive areas for future collaborative research in architecture. Furthermore, it confronts the premise of *visibility of research* through the exploration of a state of materiality that is naturally imperceptible in its formal organization, yet strikingly conspicuous in its active and situated processes.

KEYWORDS: biomimicry, innovation, materials, nanotechnology, performance

INTRODUCTION

Nanotechnology is a broad field of study that spans chemistry, biology, physics, materials science, and others. The most widely accepted definition of the field identifies it as the manipulation of matter that is 100 nanometers or less in at least one dimension, a measure that is one thousand times smaller than the thickness of a sheet of paper. The prefix 'nano' is derived from the Greek word *nānnos*, which is translated as one-billionth. Put simply, the nanoscale is exceedingly small. The minute scale of matter associated with nanotechnology might lead one to believe that the ramifications of this science are proportionately trivial to the processes that occur at the human scale. To the contrary, the science of nanotechnology reveals the relationships between energy and forces at the nanoscale to the complexity of formal and structural logics at the macroscale, thereby broadening the lens of inquiry within the field of architecture. The advancements of scientific knowledge of the nanoscale suggests opportunities to embed material aptitude within the molecular structure of matter, revealing new opportunities for a performative architecture that persists in synergetic existence with its surrounding environment.

1.0 BACKGROUND

1.1 Scientific provocation

> Biology is not simply writing information; it is doing something about it. A biological system can be exceedingly small. Many of the cells are very tiny, but they are very active; they manufacture various substances; they walk around; they wiggle; and they do all kinds of marvellous things – all on a very small scale. Also, they store information. Consider the possibility that we too can make a thing very small which does what we want – that we can manufacture an object that manoeuvres at that level! (Feynman 1960, 25)

Enthusiastic over the future potential of the field of nanotechnology, physicist and Nobel Laureate Richard P. Feynman envisioned the prospect of manufacturing bespoke nanomaterials with advanced properties. In his famed 1959 speech entitled *There's Plenty of Room at the Bottom*.[1] Feynman challenged the scientific community to develop the mechanisms by which materials can be designed, manufactured, and evaluated at the nanoscale. Through simple mathematical calculations, Feynam posited the practicality of manipulating nanoscaled materials and hypothesized on the means by which his theories might be realized. Over 50 years later, the science behind Feynman's suppositions has been significantly advanced as research in the field of nanotechnology is now producing new materials with radical and innovative properties.

Projecting outside of the boundaries of his own discipline, Feynman theorized about the vast potential of this fundamental research to be applied to a multitude of innovations in all areas of science and technology. First and foremost, he identified critical gaps in scientific knowledge necessary to study, create, and manipulate matter at the molecular scale, also connecting this research to potential advancements in the digital realm. He goaded his peers in physics to vigorously pursue research in this field, personally offering monetary awards for those that were successful in meeting his challenges. Feynman cited the most critical apparatus necessary for the advancement of science to be the invention of a more powerful electron microscope capable of viewing nanoscale matter. Modestly, Feynman correlated the ability to *see* matter at the nanoscale with a resultant ability to *discern*, *analyze*, and *synthesize* new scientific knowledge of biological processes, chemical analysis, and the physical structure of atomic particles.

Without ever naming the field of study that he described, Feynman posited that the extension of our sense of sight into the nanoscale would provoke considerable advancement within the entire scientific and technological community. Ultimately his speech provoked significant scientific research in nanotechnology - later termed as such by Japanese scientist Norio Tanaguchi, including the development of molecular electronics, the discovery of buckyballs, and perhaps most importantly the development of the scanning tunneling microscope (Jain 2008). Returning to the conference theme of *visibility of research*, I will make a comparison here between modes of inquiry within design and science; in both the act of surveillance, close observation, is equally vital to the process of innovation. Therefore, it follows that architecture has also gained much through the consequent advancement of the field. I will expand on this proposition later.

1.2 The structure of living matter

To add historical context to Feynman's provocations, it is worth noting that six years prior to Feynman's speech, American geneticist James Dewey Watson and British biophysicist Francis Compton Crick, discovered the physical and chemical structure of DNA and revealed the processes by which living organisms replicate and grow (Johansen 2002). This breakthrough emanated from the observation of the molecular pattern and physical shape of the DNA molecule. The double helix structure of DNA molecules consists of two single polymers that store genetic information while also serving as a template for growth when divided into two single strands. The arrangement of DNA also carries information in the form of a genetic code that governs its growth and behavior in detailed and precise ways, such as the type of cell that it will become, its rate of growth, size, color, etc. Logical, efficient, and structurally stable, the DNA molecule exemplifies the efficiency and complexity of nature.

1.3 Biomimicry and synergetic relationships

Grounded within natural processes of form, biomimicry has emerged as a field of applied science equally as broad as nanotechnology. It is important to avoid misinterpretation of the science of biomimicry as simply providing creative inspiration for technological innovations that *mimic* the form of nature without significantly exploiting the underlying logic it embodies. Beyond a creative muse, biomimicry is the application of biological processes and systems to the research and design of technological innovations. As is the case with nanotechnology, biomimetic research extends across the boundaries of discrete disciplines as it is utilized within chemistry, materials science, engineering, agriculture, ecology, architecture, and many others.

Furthermore, as an applied science, biomimicry informs the field of nanotechnology serving as both a limiting schema and a motivating force. Recalling the words of Feynman, one might be led to believe that anything will be possible as the nascent science of nanotechnology matures. However, biologist and bimimetic expert, Janine Benyus, caution against such fallacious assertions noting, “We are still beholden to ecological laws, the same as any other life form” (Benyus 1997, 5). As knowledge of the processes, structures, and complexity of natural life is uncovered, this information must be used to avoid innovations that continue to threaten the overall viability of the natural ecosystem. To that end, biomimicry guides science and technology toward more integrated relationships between our built and natural worlds.

2.0 NANOTECHNOLOGY AND ARCHITECTURE

2.1 Towards new theories of materiality

The influence of scientific discoveries in nanotechnology and biomimicry has been wide reaching and has exerted influence on design thought for over 50 years. The capacity to view, fabricate, and manipulate matter at the molecular scale, suggests an altered approach toward materiality within architecture. The prospect of replicating natural processes of organic life within synthetic materials and virtual environments has been an area of particular interest. Evidence of the coding of genetic information and the processes of growth within nature offer a nexus between form, performance, and materiality, providing a basis for much of contemporary research in digital technologies and the production of smart materials.

2.2 Material aptitude

Architect and industrial designer William Katavolos conducted early research on the implications of the emerging field of nanotechnology within architecture. In contrast to the more metaphorical interpretation of science by architects such as Wright, Sullivan, and Le Corbusier, Katavolos proposed a notion of a "chemical architecture" that more directly considered the relationship of architecture to emerging research in the area of molecular nanotechnology (Johansen 2002). As co-director of the Center for Experimental Structures at the Pratt Institute since the early 1960s, Katavolos predicted that scientific discoveries would soon make possible the fabrication of materials embedded with "… a specific program of behavior built into them while still in the sub-microscopic stage" (Braham 2007, 149). He and his contemporaries theorized that the invention of synthetic chemical processes suggests new means of fabricating materials and assemblies in architecture. Within his manifesto essay entitled "Organics," Katavolos speculated that this new science would provoke an architecture that grows with "… ceiling patterns created like crystals, [and] floors formed like corrals…" (Braham 2007, 149). Directly related to current inquiry into smart materials, these theories suggest a correlation between the reduction in size of matter and a corresponding increase in material aptitude.

2.3 Science and digital technologies

> The modelling of these complex natural processes requires computers, and it is no coincidence that the development of computing has been significantly shaped by the building of computer models for simulating natural processes. (Frazer 1995, 13)

Scientific research into natural processes and behaviors has also pervaded the discourse surrounding digital processes in design. John Frazer, a British computer technician at the Architectural Association in London, conducted research on the development of an *evolutionary architecture* through the use of computational technologies beginning in the late 1960s. Suggesting an architecture that does more than imitate the formal gestures of nature, Frazer's research explores the notion of computer systems that embody "… the inner logic of [Nature's] morphological processes" rather than external form (Frazer 1995, 10). His research sought to formulate a "genetic language of architecture" comprised of a set of "responsive instructions" that are based on nature's processes of generating form (Frazer 1995, 11). Frazer's work investigated the interaction of exogenous forces of nature and concepts emanating from architecture.

Similar to Frazer's research, the Genr8 tool was a genetic algorithm developed by a team of architects and computer scientists at the Massachusetts Institute of Technology in 2001. This digital tool modeled natural processes of growth in a virtual environment with simulated environmental forces (Holland 2010). However, the Genr8 tool also allowed the designer to manually intervene in the automated process of simulated growth. In this case, the objective forces of the virtual environment are augmented by the subjective preferences of the designer. Collectively, both Frazer's work and the efforts of the M.I.T. team is exemplary of a body of research that explores forms of computational intelligence based on the scientific principles that explain the persistence of life through the organization of its genetic code at the molecular scale. These theories have laid a foundation for future applications of nanotechnology and other areas of science within the discipline of architecture.

3.0 PRINCIPLES AND PERFORMANCES

3.1 Shared tenets and performative principles

> Natural ecosystems have complex biological structures: they recycle their materials, permit change and adaptation, and make efficient use of ambient energy. By contrast, most man-made and built environments have incomplete and simple structures: they do not recycle their materials, are not adaptable, and they waste energy. An ecological approach to architecture does not necessarily imply replicating natural ecosystems, but the general principles of interaction with the environment are directly applicable. (Frazer 1995, 16)

Theories emanating from nanotechnology and related areas of physical and applied science have already had a measureable effect on architectural discourse. In addition to providing fertile ground for the research and development of smart materials and motivating advancements in areas of digital computing, the field of nanotechnology offers a compendium of shared tenets between architecture and the sciences. In lieu of replicating nature, these principles intimate a more synergetic coexistence between environments conceived by humans and those propagated by nature. In so doing, they suggest an evolutionary model of materials that is moving away from energy intensive means of material production towards modes that emulate the interactions within natural ecosystems. While the technology to apply all of these principles is not yet fully mature, the science motivating these developments suggests a course that departs from many currently accepted notions of materials. This section interrogates fundamental tenets of nanotechnology for the suggestive potentials that they embody for future advancements within the field of design. In contrast to the paradigm of materials as static and inert objects, these tenets incite a *performative* archetype of materials as dynamic, responsive and variable elements within the built realm.

3.2 On the matter of material efficiency

Long before the proliferation of nanotechnology research, 15th century Greek philosopher Democritus hypothesized that all materials were made of indivisible particles, which he named *atomos*, meaning "unbreakable" in Greek (Rogers 2008, 5). Democritus' theory on atoms was based on the fundamental belief conveyed by his famous expression, *ex nihilo nihil fit* - translated as "nothing comes from nothing." Today, knowledge of the structure and relationships between atoms is a cornerstone of science used to explain much of the universe. All materials consist of atoms. Therefore, it follows that all materials are affected by nanotechnology. Nanotechnology interrogates the fundamental properties of materials in order to discern the ways in which these properties shift as the amount of material approaches the atomic scale. Furthermore, it queries whether materials can be used in new ways if they are comprised of smaller pieces.

Nanotechnology proposes a "bottom-up" approach in which materials are made by the arrangement of atoms in specific locations, thereby proposing a process that produces very little raw material waste. This method suggests a significant shift away from the current paradigm within architecture of "top-down" engineering, in which larger sections of materials into smaller parts. The efficiency of "bottom-up" processes reveals perhaps the most significant tenet of nanotechnology, which is equally relevant to architecture−"*Do More with Less*" (Rogers 2008, 17). With obvious application to the physical processes whereby materials are fabricated into products used in the built environment, this principle supports current materials research into ultra-lightweight and high performing materials. It also suggests more ecological processes of fabrication that negate the need for post-industrial recycling by replacing current industrial processes with less wasteful means of production.

3.3 On the matters of energy and material fabrication

In nature, atoms are held together through inter-atomic forces, akin to molecular "glue," which exert attractive and repulsive forces on matter. At a particular distance, these forces balance each other creating a condition of equilibrium separation. At this distance, energy is required to move the atom in any given direction. The successive interactions of atoms to create molecules and ultimately solid materials operate on a fundamental principle of energy conservation. Nature operates with inherent efficiency; "*Energy is never wasted when a more efficient option exists*" (Rogers 2008, 97). For example, crystalline structures exist through the natural process of energy efficiency. With repetitive lattice structures that can extend in any direction, crystals sparingly utilize energy packing their unit cells into a complex three-dimensional array of points.

Working in normal ambient conditions, nature constructs materials without harming its environment using simple materials that are readily available. Current biomimetic research in nanotechnology queries such potentials for more efficient means of material fabrication of synthetic materials. Nacre, a naturally occurring nanomaterial that lines the inside of abalone seashells, is a composite of a hard and brittle inorganic material with a soft, but tough organic material. This extraordinary example has inspired research into polymer-clay nano-composites that are strong, tough, and easier to recycle than conventional reinforced plastics. Chemical engineering professor Nicholos Kotov of the University of Michigan has created nacre-like composites utilizing a layer-by-layer assembly process of clay and a polyelectrolyte, a specialized polymer (Berger 2007). Such materials utilize methods of production that will continue to produce more advanced and environmentally sustainable materials.

Nanotechnologists are developing numerous mechanisms of fabrication and material production that take advantage of the propensity of matter to judiciously utilize energy. For example, methods of self-assembly have been developed as autonomous processes where individual units of a material organize and assemble as stimulated by desirable environmental conditions, templating themselves to form a densely packed, yet thin layer of material. Such processes are currently employed to functionalize a surface, altering its properties. As many physical interactions are limited to the surface, the deposition of a thin layer of nanomaterials can modify and improve the performance of materials by increasing material efficiencies, decreasing friction and surface tension, and improving overall resilience and durability.

In the future, processes of self-assembly could also be used to fabricate materials with customized molecular structure at the nanoscale that generate performative properties and capabilities at the macroscale. For example, liquid crystal displays are comprised of an array of transistors that are printed on organic thin films that are only 20 nanometers thick (Rogers 2008, 108). Similarly, organic light emitting diodes (OLEDs) contain a light-emitting layer made of a flexible organic polymer that can be woven into textiles. Current nanotechnology is not capable of building complex structures directly from atoms and molecules; however, processes utilizing nanoparticles have emerged as a feasible alternative for the assembly of materials at the nanoscale. Nanoparticles can be efficiently produced in sufficient quantity and used to make a variety of products. Other processes, including template particle assembly, simplify the process while providing considerable control over particle positioning. As these fabrication processes continue to mature, the ability to customize the nanostructure of materials to include multi-functional characteristics in both the structure of the material itself and its surface properties is probable.

3.4 On the matter of scale

At the nanoscale, the laws of physics change. Gravity and inertia have little effect. Quantum effects and molecular forces govern material responses over the normative forces that control the macro world. As one of the first materials exploited for its altered properties at the nanoscale, gold demonstrates this fact clearly. At the macroscale, gold particles have a melting temperature of 1,064 Celsius degrees and possess the characteristic yellow-orange color that is commonly associated with the medal. However, at the nanoscale, gold melts at a temperature more than 300 degrees lower and appears red in color. Medieval artisans exploited this early form of nanotechnology, using molten gold to produce stained glass windows with a rich ruby red color.

In addition, the utility of materials changes as their size decreases from the macroscale to the microscale to the nanoscale. For instance, small wires have enabled complex and intricate networks that make possible faster and more powerful computing networks. As the size of wires moves into the nano- dimension, “they acquire new properties turning ordinary wires from passive components into active ones - sensors, transistors, or optical devices” (Rogers 2008, 104). Therefore, a third tenet of nanotechnology reveals that *the properties of a material are relative to its characteristic scalar dimension*.

A material’s scale affects its surface to volume ratio, the means by which it interacts with external forces, and the interaction of its internal molecular energies. Engineers have devised methods to effectually approximate how the characteristics of something will change as its dimensions change. Termed *scaling laws*, these estimates amount to hand calculations that evaluate the effect of scalar adjustments and highlight the ways in which these scalar shift might enhance or impede a material’s performance. Although scaling laws can provide useful information, these approximations can also lead to misleading or inaccurate results. At this time, mechanical systems scale very well even to the nanoscale, while the same is not true of electromagnetic and thermal properties. The accuracy of mechanical scaling laws would be quite useful to architecture and the building sciences to improve the precision of digital simulations that model the effects of energy and material properties among others. Improvements in architectural computational tools would allow for greater translation between the actual behavior of materials and the digital simulation of these effects.

In addition to altered physical properties and scaling effects, nanomaterials also blur the boundaries between material and machine. The diminutive scale of nanomaterials presents opportunities to embed performative capacities directly into matter at the molecular scale. Researcher Kris Pister of the University of California at Berkeley is pursing these potentials in his work with ‘smart dust,’ remote sensing devices that would integrate computing power, sensing equipment, wireless technology, and battery power into a material smaller than a grain of rice (Sutter 2010). Other research in nanotechnology is leading towards the development of nanoscaled materials that self-repair themselves through processes similar to those of living cells. The scalar dimension of nanotechnology suggests a merging of digital and physical realities as advanced materials are increasingly embedded with micro- or nanoscaled computing devices and interactive technologies.

CONCLUSION

Advancements in the science of nanotechnology significantly progress the theories of visionaries such as Richard Feynman and William Katavolos, who anticipated the capacity for materials to approach the complexity and performative capacities of living cells. Though concealed from plain sight, nanomaterials propose an efficiency of raw materials and energy, as they persist in a scalar dimension that is subject to altered laws of physics. Ultimately, the central tenets of nanotechnology collectively reveal the interdependency of materials, energy, and systems along the scalar continuum. The proficiency, economy, and innovative character of biological life suggest the potential for increased collaborative research between architecture and the sciences that is inspired by the creative productivity of the natural world.

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ENDNOTE

[1] Feynman's speech, originally offered in December 1959, was later published in the Engineering and Science in 1960 and remains a seminal work in the field of nanotechnology.