A Living Architecture for the Digital Era

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The history of architecture has been punctuated by transformations sparked by sudden technological leaps. During the mid-1400s, into the context of a craft-based architectural tradition, Leon Battista Alberti introduced a mathematical approach to graphic representation. In doing so, he paved the way for Renaissance classicism: architecture focused on precision and representation through drafting rather than approximate construction by artisans. Four centuries later, steel and glass enabled engineers like Isambard Kingdom Brunel, Sir Joseph Paxton, and Gustav Eiffel to design daring and innovative structures that shattered the limits of what could be constructed. Soaring feats of technological prowess became a new aesthetic at the nexus of architecture and engineering. A generation later, at the crest of the mechanical era, Le Corbusier appropriated the tools and forms of mass production, and concluded that the house is a machine for living in. Architecture was optimized not only from the standpoints of design and structural engineering but also from those of mass production and social function.
Technological upheavals are the lurching steps of architectural progress, its driving force. Le Corbusier dreamt of "realiz[ing], harmonically, the city that is an expression of our machinist civilization." Yet our civilization today has transitioned from mechanization to computation. The digital revolution–the convergence of bits and atoms–is poised to be the most radically disruptive change that has ever recast the design, construction, and operation of our built environment. Just as machines brought standardization and high output, digital tools can bring dynamism, variation, and responsiveness. The question now becomes, how will architecture evolve in the digital era?

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Fig. 1. Digital Water Pavilion (image credits: Claudio Bonicco). The Digital Water Pavilion, made for the 2008 World Expo in Zaragoza, Spain. The design teams at the MIT Senseable City Lab and Carlo Ratti Associati (CRA) created a reconfigurable space, with walls composed of digitally-controlled water droplets.

Fig. 2. Future Food District: (image credits: Delfino Sisto Legnani). A 7,000 sq. m. thematic pavilion exploring how digital technologies can change the way that people interact with food for the 2015 World Expo in Milano, by CRA and supermarket chain COOP Italia.

Initial attempts to address this question–to create dynamic architecture for the digital age–were form-based. Designers created evocative architectural sculptures that shout distinctive visual identities: Frank Gehry's iconic Guggenheim Museum Bilbao, for example, and the similar projects he has scattered around the world. These have ushered in a new aesthetic regime of irregular and organic buildings, often called "blobby" architecture. This new formal language was enabled in large part by parametric design software: digital tools that allow the architect to script an internal logic, input data values (objective contextual factors, zoning, or functionality requirements), and run an algorithm to negotiate those constraints and produce formal, often extraordinarily complex artifacts. Rather than detailing intricate specificities by hand, the architect writes parameters, and the computer churns out highly elaborate results.
Parametric software opened a new arena where designers could radically question inherited formal assumptions about architecture. They explored the boundaries of possibility eagerly and productively, assuming that–given an opposition between rational and organic–non-gridded and complex forms have a more vibrant quality. Early theorists of parametric architecture characterized a new sensibility that aimed for "maximal emphasis on conspicuous differentiation" [Schumacher 2008].
The highly visible 2004 Venice Biennale of Architecture, titled Metamorph, explored the "fundamental changes under way in contemporary architecture, both in the theoretical and practical design field, and in the use of new building technologies." The event brought together architects, academics, researchers, and critics at the forefront of computational design. Individualism and experimentation defined the collective rhetoric, but a more cynical view of the menagerie of projects found the differentiation to be superficial. "The computer has finally made possible forms that are different, at the same cost as the standard forms of old. A newness of very similar forms though, more sculptural than radical, buildings and structures with sensual folded, twisted and curving surfaces. It looks more like an international computer art festival […] and the most important theme to come out of the biennale was the question of redundancy." Under the guise of novelty, the common denominator that emerged was predictable manipulations of complex geometry rather than meaningful dynamism.
Parametric tools have granted architects an unprecedented power to generate space using algorithmic functions and to appropriate a rhetoric of vibrancy. As the trend

Fig. 3. Vertical Plotter (at Future Food District) (image credits: Delfino Sisto Legnani). The Vertical Plotter was the world's largest plotter, which painted on the facade of the Future Food District, a project by CRA and COOP Italia at the 2015 World Expo in Milano in 2015.

has developed since Metamorph, however, architects have been hard pressed to find meaningful data to feed into algorithmic design processes. A cruise ship terminal in Japan, for example, was informed by the geometry of waves in traditional paintings, specifically "the Hokusai Wave." The designers were inspired by "a drawing from a local painter that we had been toying with while we indulged in geometric manipulations and construction hypotheses during the design phase of the competition entry" [Zaera-Polo 2005, p. 80].
Furthermore, the application of parametric software, in many cases, goes no deeper than the skin of a building. Algorithms can compute thousands of unique elements to compose a dazzling facade on an otherwise standard structure. Parametric design promises a certain novelty, whether it is driven by geospatial data or by complex matrices of associations.
The virtual dimension that now blankets physical space is burgeoning with data, some of it appropriated by designers to plug into scripts as they seek "to grow or evolve new formal configurations in response to specific forces and constraints: structural, climatic, or programmatic. While this has produced compelling formal results, there are conceptual and procedural limits. The design techniques used to generate these new buildings may be dynamic, but the buildings themselves are static" [Allen 2011]. Architects can generate an almost infinite number of formal solutions in a given situation, but complexity and magnitude are not inherently meaningful or living. "The forms generated may resemble nature, but they retain little of the performative or adaptive complexity of life itself."
Algorithmically generated architecture is a static visualization of larger complexities. To evoke the fluidity of digital space in an inert physical object is to freeze a dynamic process, as if pressing Pause to find a single frame in an action sequence. Even the climax of energy and vibrancy, caught in a still frame, will convey only a shadow of the dynamic whole.

Fig. 4. Patrick Henry Commune (image credits: CRA graphic team). The Patrick Henry Commune is a project by CRA for a center for co-living, co-working and co-making in a former American military village on the outskirts of Heidelberg, Germany.

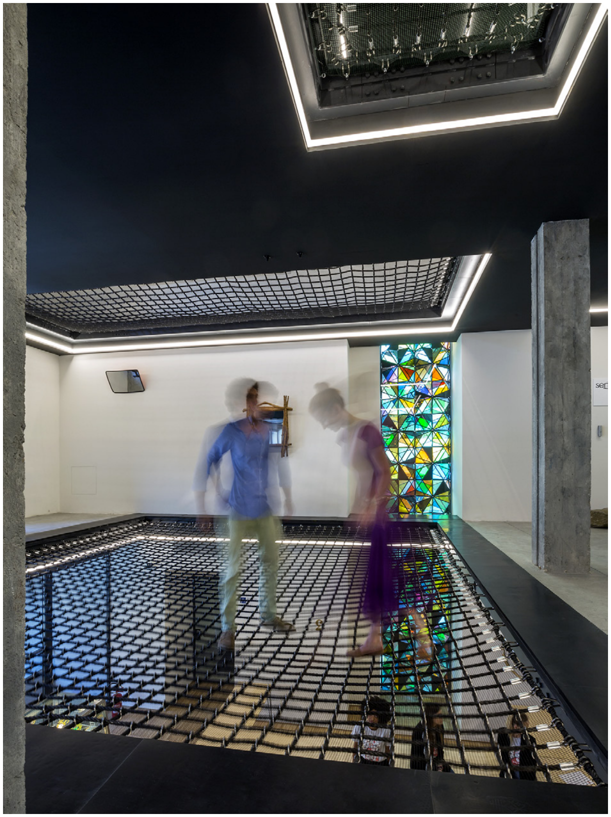

Fig. 5. Agnelli Foundation HQ (image credits: Beppe Giardino). For the redesign of the Agnelli Foundation headquarters, CRA equipped the century-old edifice with hundreds of sensors that monitor different sets of data, transforming it into a co-working space for the Office 3.0.

Fig. 6. Agnelli Foundation HQ (image credits: Beppe Giardino). CRA's intervention also added elements to open the building up to the city, and to make it a more light-filled and fun space.

Visual complexity can be computed, but can it deliver anything more than curb appeal?

And is that even desirable? The digital age has already suffused our world with innumerable flows and layers and intricacies, and formal plasticity only adds visual chaos to the ambient complexity. Could digital tools be integrated with architecture, beyond veneer or gloss? How, then, to integrate digital systems to achieve true dynamism? "Being digital is not primarily about using a computer in the design process, nor about making this use visually conspicuous. It is an everyday state that goes in hand with gestures as simple as being called on a cell phone or listening to an mp3 player" [Picon 2006]. That is, architecture should become an integral and responsive part of human life. Architecture must do more than just look like a living organism: it should perform as a living system.

The earliest glimmers of this possibility date back to experimentation with moveable structures in the mid-twentieth century. A group of young Japanese designers, the Metabolists, imagined living architecture for the growing population of postwar Japan. Buildings, they proposed, could be shaped dynamically by the pushes and pulls of socio-dynamic forces. Metabolist structures used biological models, attempting dynamism through, for example, spine-and-branch arrangements or cellularly subdivided megaforms. The architect would establish a master program (or "DNA") that could propagate itself according to a patterned structural system. Few of their structures were ever built. One notable exception–Kisho Kurokawa's Nakagin Capsule Tower, located in central Tokyo–is a paradigmatic example of Metabolist theory. It is conceived as a central spine, onto which individual housing pods can be attached and rearranged. In theory, infinite combinations of pods and connections between them allow residents to create larger or smaller spaces in response to different families, budgets, or changes in housing demand over time. Yet the Capsule Tower reveals a deep conceptual flaw: since the building's completion in 1972, not a single pod has been shifted or combined.

Fig. 7. MIND (image credits: CRA graphic team). MIND is a master plan to reimagine the former site of Milan World Expo 2015, designed by CRA in collaboration with Australian real estate group Lendlease. It features a one-mile long linear park and the world's first neighborhood planned for self-driving cars.

The twentieth century is dotted with similar attempts at mutable architecture–from Gerrit Rietveld's Schröder House to Archigram's Plug-In City–but they invariably fall into stasis or remain unbuilt. An entirely flexible structure still requires inspired occupants to take agency. In practice, mutable buildings go largely unchanged.

Flexible structures may not spark active participation, but it is here that digital technologies reenter the playing field, enabling a more gentle, intuitive, and responsive interaction between humans and the built environment. Far outside the discipline of architecture, pioneering computer scientists and mathematicians of the mid-twentieth century started developing a theory of cybernetics. The emergent discipline sought to explore networks, focusing on communication and connections between interdependent actors in a system.

Cybernetics, according to Gordon Pask, the academic responsible for popularizing it among architects, is "how systems regulate themselves, reproduce themselves, evolve and learn. Its high spot is the question of how they organize themselves." This conceptual framework could be productively applied to architecture. As a

practical design strategy, cybernetics is about negotiating a set of interrelated factors such that they function as a dynamic system. "The design goal is nearly always underspecified and the 'controller' is no longer the authoritarian apparatus which this purely technical name commonly brings to mind. In contrast the controller is an odd mixture of catalyst, crutch, memory and arbiter. These, I believe… are the qualities [the designer] should embed in the systems (control systems) which he designs." The architect becomes a choreographer of dynamic and adaptive forces rather than scripting outcomes in a deterministic way.
Around the same time, architects at the fringe of the discipline took the idea of interactivity and sensationalized it. Architecture became loud, fun, hip, and constantly evolving. Buildings were thought of as venues for action and interaction, as dynamic scenes that could incite events and connections and evoke delight. The Generator Project, by the architect-provocateur Cedric Price, was a clear example of this new attitude. An unbuilt concept for a retreat and activity center, the project consisted of a system of 150 prefabricated cubes, each twelve feet per side, that could be shifted and reconfigured–much like the pods in the Nakagin Capsule Tower–but, crucially, would also interact in a dynamic way. A primitive digital software detected inactivity, and if the building remained static for too long, the software automatically executed "The Boredom Program" to reconfigure its own structure and incite (or perturb) users. The architecture itself took an active role as provocateur, with the aim of enhancing human experience. This was a system for dialogue and mutual reaction, beyond the Metabolists' linear user-changes-building idea. In many ways, this work was an application of cybernetic ideas to the field of architecture: it created systems that would dynamically self-organize in response to inputs and actions.
If the first industrial revolution was concerned with creating machines optimized for a specific task, cybernetics, in contrast, was concerned with a new kind of (perhaps nonmechanical) "machine" that could satisfy an evolving program. "We are concerned with brain-like artifacts, with evolution, growth and development; with the process of thinking and getting to know about the world. Wearing the hat of applied science, we aim to create […] the instruments of a new industrial revolution–control mechanisms that lay their own plans" [Pask 1969]. Translated into architecture, cybernetics means buildings

Fig. 8. Scribit (Image credits: Avocado studio). Scribit is a small write&erase robot that can safely draw, cancel and re-draw content on almost any vertical surface, developed by CRA in 2018.

that function as adaptive learning entities living in a kind of dialogue with their inhabitants.
Active and networked architecture is starkly opposed to recent form-focused attempts at dynamism and may illuminate an alternative path forward. "Today, many designers have turned several late twentieth-century infatuations on their heads, for instance with speed, dematerialization, miniaturization, and a romantic and exaggerated formal expression of complexity. After all, there is a limit beyond which […] complexity simply becomes too overwhelming" [Antonelli 2008]. Rather than using digital tools to mathematically calculate complexity for the visual sense, interactive spaces can use digital tools to generate a new form of complexity: experiential complexity. A shift away from elaborate structures and toward structural dynamics entails buildings that perform as (rather than appear to be) living organisms.
Computation will not be used only to define intricate shapes according to parameters but will also become an integral part of the building, interacting with users according to a program. This interface functionality points to embedded rather than generative technology. In addition to plans and sections, architects in this future will be free to specify a system of interrelated sensors, operations, and actions–loops that bring architecture to life, based on a dynamic set of experiential and functional requirements. Grounded in communication and learning systems,

Fig. 9. The Dynamic Street (image credits: David Pike). In collaboration with Alphabet's Sidewalk Labs, CRA developed The Dynamic Street, a prototype of a modular and reconfigurable paving system hinting at the possibility of the future streetscape seamlessly adapting to people's needs.

Fig. 10. CapitaSpring (image credits: BIG). CapitaSpring will be a 280m tall high-rise on 88 Market Street, Singapore, jointly designed by CRA and BIG-Bjarke Ingels Group. The tower will be one of the tallest in Singapore, blending urban life with tropical nature.

sensor networks can transform buildings into intelligent agents with the capacity to learn from and coexist with their occupants. The dream of dynamic spaces can finally be fulfilled as buildings weave together humans, environment, infrastructure, and personal devices.

Just as mobility networks are taking advantage of ubiquitous sensors (as with crowdsourced maps or pothole detection), so too will buildings take advantage of the human flows running through them. We will shift from living in a home to living with a home. Architecture becomes a form of interface, playing an active role in the human environment, both digital and physical. "The goal is to facilitate as seamless a movement as possible from fast to slow, virtual to physical, cerebral to sensual, automatic to manual, dynamic to static, mass to niche, global to local, organic to inorganic, and proprietary to common, to mention just a few extreme couplings" [Antonelli 2008]. Integrating digital elements will allow the built environment to become a connective tissue between the distinct but coexisting realities of bits and atoms–an interface that enables spatial cybernetics.

The built environment is becoming a physically habitable Internet, a Hertzian space–one that is inextricably intermeshed with digital devices. "Hertzian space is […] a way of linking things, of sending information and content, etc. But [architecture] is an environment that can be inhabited, enjoyed, and explored" [Dunne, Raby 2013]. In the newly interactive, digitally laced architecture, detail and dynamism and complexity (formerly the ambition of parametric scripting) are the experiential consequence of design, not the justification.

Architecture takes on life through response–it becomes shocking or vibrant in time rather than in its external visual character.

Just as smartphones are a portal to larger systems, architecture can function as a mediator between daily, human-scale functions and vast, humanity-scale networks. "For millennia architects have been concer-

Fig. 11. CapitaSpring (image credits: BIG). The indoor space of the CapitaSpring tower will be characterized by an array of hi-tech solutions, including sensors, Internet-of-Things (IoT), and artificial intelligence, as well as a tropical forest at the core of the building and greenery throughout.

ned with the skin-bounded body and its immediate sensory environment [...] Now they must contemplate electronically augmented, reconfigurable, virtual bodies that can sense and act at a distance but that also remain partially anchored in their immediate surroundings" [Mitchell 1996]. Pre-digital humans navigated their immediate physical surroundings, but today's cyborg (with prosthetic smartphone) inhabits space in profoundly different ways. Scales and contexts are blurred as we slip elastically between them. At any given moment, we may be standing in a room with three other people, but now the digital-spatial network can also reveal two close friends in a restaurant next door or a potential love interest only a block away. People and physical space are still a central anchor, but the upper and lower bounds of human reality have exploded outward, and architecture must encompass this breadth of spaces–in all of their active dynamics–while still relating to humans. Picon sets forth the question. How should the designer cope with an electronic and informational reality that seems to possess a dynamism and an expressive quality? The advent of the digital represents an even greater challenge for design than what the early stages of mechanization had meant for modern architecture. For the first time perhaps, architecture has to confront itself with a profoundly non-tectonic reality. Given these premises, how can the designer be in deep accordance with the invisible flows of information that constitute the bones and flesh of the digital world?

The very process of creating architecture could become an iterative chain rather than a directly linear process. Today, design, documentation, construction, and inhabitation are distinct phases in the life of a building, each carried out by a different specialist using different tools. As each step of the architectural production chain transitions to digital systems, the whole process will be unified. Integration will happen in-

Fig. 12. Science for Citizens (University of Milan's Scientific Campus) (Image credits: CRA graphic team). CRA is collaborating with Lendlease to develop the schematic design for the University of Milan's new Science Campus, Science for Citizens, which will include robotically-assembled brick facades.

crementally, by streamlining information, enabling the different phases to inform one another, structuring a codependent feedback system and, ultimately, a full merger. Initial steps have been taken in this direction–for example, with project-specific smartphone apps that organize the fabrication, shipping, and installation of complex facades with tens of thousands of unique components. Implicating inhabitants in all stages of the design, construction, and operation chain will graft the development and inhabitation of architecture together into a single experience. The Internet of Bodies and active architecture will be symbiotic. "All evolution is co-evolution; individual species and their environments change and evolve on parallel courses, constantly exchanging information" [Allen 2011]. What was formerly defined by a clear separation between mind, body, population, and environment is now entangled, "supplanted by a more complex and non-linear pattern of urban development in response to the spread of new information technologies" [Gandy 2005]. Each choice we make has ramifications in digital space that, in turn, shape our physical environment. The Internet of Bodies, grounded in our cyborg condition, may ultimately realize the concept of the built environment as a social and relational process.

The most important implication of radically integrating digital systems into architecture will be to refocus technology and the built environment on humans. A living, cybernetic program in spaces of dynamic interaction

Fig. 13. The Circular Garden (Image credits: Marco Beck Peccoz). For Fuorisalone 2019, a part of Milan Design Week, CRA, in partnership with global energy company Eni, developed an architectural structure made of mycelium, the fibrous root of mushroom.

will make architecture more like an extension of the body–and it is cyborg "tools" that enable the environment to respond. Augmented or "living" architecture is the large-scale hardware that digital-physical cyborgs create, plug into, and interact with. Active buildings are at once an environmental life support, a social catalyst, and a dynamic set of experiences. While congenital digital systems integrate seamlessly with human biology, the same prosthetic devices interface with the digitally augmented environment through real-time information flows. The Internet of spaces and the Internet of Bodies enable and co-create each other–each is the interface to the other.
Ultimately, technology recedes into the background, and interaction is brought to the fore. Buildings can be simple–rather than voluptuous and shocking–but even more integrally vibrant and living.
The result of digital networks, and more bottom-up processes, can ultimately lead to what we can call open source architecture. Open source architecture relies on all interested parties being involved in the design process. In the past (for instance, in the case of Gothic cathedrals) this emerged naturally in local communities. In this sense, open source architecture is really a re-visitation of a timeless way of building, of forms of production that yielded anonymous or vernacular architecture. The idea of bottom-up, locally-adapted, copied typologies, produced by citizens using their social capital as well as their financial capital, is the opposite of new. In many ways it is bringing tech-

nology to pre-open source industrial "barn-raising" approaches. Open source architecture is presented as an innovation, but it is really just the vernacular with an Internet connection.
The challenge is looming, goals are clear and technologies for achieving them exist. The task, then, is to reflect on the potential implications that "future vernacular" will have on economic development, social justice, resource scarcity, labor economies, planning systems, and the role of professionals. The discipline cannot remain hermetically sealed forever – there is a critical mass of people, ready and willing to work in a bottom-up way.

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