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**(1) In what sense do you find it meaningful to talk about "living technology?"**

THERE is no doubt that our World has evolved to be complex, with life having emerged as the ultimate manifest of self-organized superior structure. There are certain unique properties of living systems that we are seeking to imitate in the quest to design systems and organizations with high agility, which can dynamically change, exhibit emergence, and self-organize to adapt, reconfigure and quickly respond to unexpected societal and environmental demands. Applications for such technology abound in a large variety of problem domains in our ever-changing world, since several critical problems are due to the rigid structure of our social, political and economic systems. These systems do not allow for adaptation and agility of response to unexpected, emerging needs, but rather act as roadblocks on the path to implementing effective necessary solutions. In our quest to make our world more sustainable and resilient, we need to acknowledge the limitations of our legacy of (institutional and critical) infrastructures, which were built in the industrial age. A deep understanding of the intimate mechanisms behind the properties that make a living technology "alive" will point to the need to change the cultures in our organizations and revolutionize how we live and work through a radical shift in the way we interact with (and within) our socio-politico-economic systems, as well as with the natural environment: from being constrained and dependent on technology and institutional structures to having them fuel our creativity and innovative potential in a proactive, anticipatory manner.

Several emerging technologies related to the pervasiveness of information and communication technologies (ICT), combined with advances in nano- and biotechnology, enable spontaneous linkages between people, systems, infrastructures and "things" to create "living" ecosystems that can configure and reconfigure as needed. Such technology can offer process and production continuity in all areas and aspects of life and work. In an ever-growing system of systems linked by intelligent communication networks, *softbots* (autonomous software robots that emulate human abilities, such as making decisions, discovering knowledge and performing tasks on behalf of the user in cyberspace) and *nanobots* (autonomous nanomachines exhibiting human-like behaviour to perform tasks in environments inaccessible to the human, such as carrying drugs to various parts of the body through the blood vessels) start interacting to create "societies in Cyberspace." These Cyber-Physical Ecosystems exhibit a life of their own in an emerging parallel universe, bridging the physical and the virtual, merging us with our "things," transforming the way we live and work, and augmenting our abilities in unprecedented ways. Examples range from self-reconfiguring manufacturing plants and self-stabilising energy grids to self-deploying emergency taskforces, all relying on myriad mobile devices, software agents and human users that would build an ecosystem bringing the right skill, tool, or competence at the right time for the right task on the sole basis of local rules and peer-to-peer communication. In such opportunistic ecosystems, distributed systems at various levels of resolution, ranging from single devices to spaces, "living" in an "Internet of Things" connected via communication networks and enterprises, are brought together into a larger and more *complex* “system of systems,” in which the individual properties or attributes of single systems are dynamically combined to achieve an emergent desired behaviour of the synergetic ecosystem.

The dramatic progress of Cyber-Physical Ecosystem technologies is envisioned to reach unanticipated levels of complexity, beyond the boundaries of the disciplines that conceived their components. This challenges the traditional engineering school of thought in disruptive ways, given that, by their very nature, these technological ecosystems cannot be defined a priori, but rather *emerge* from the interactions between individual systems (and people), interactions facilitated by the communication networks. The unanticipated levels of complexity exhibited by these ecosystems are transcending the boundaries of the sciences under which these artefacts were conceived and incrementally crafted. This requires drastic revision of the traditional top-down perspective on system design and control, which aimed at imposing order *exogenously*, telling each element of the system what to do at every step through predetermined strategies, and assuming that all possible situations the system might confront are knowable in advance. Living technologies offer inspiration from natural systems for a new way of designing and engineering such digital ecosystems that are being interwoven into our world’s infrastructures, from governance structures to critical infrastructures, endowing them with an intrinsic ability to self-replicate, evolve and adapt to support us respond to the demands of an ever-changing, unsafe and convoluted world.

**(2) How does your research relate to living technology, and why were you initially drawn to do this work?**

During the early 1990s the Japanese government indentified a clear need to create intelligent manufacturing systems endowed with agility and resilience able to quickly reconfigure in response to unexpected customer production demands. To implement such systems, the Holonic Manufacturing Systems (HMS) consortium took inspiration from Arthur Koestler’s seminal book *The Ghost in the Machine*, which introduced a generic paradigm for designing self-organizing systems at all scales by emulating general principles of how the universe self-organized in a manner that enabled the emergence of life. The ultimate goal was to discover the laws that can create the premises for “living” manufacturing systems endowed with self-* abilities (which denotes a series of self-reflexive phenomena: e.g., self-replication, self-movement, etc.), that can self-repair and self-configure around dynamically changing production needs. In conjunction with this project, the HMS consortium was concerned with the design and development of intelligent robotic systems that emulated human abilities and could create autonomous “societies” “living” on the manufacturing shop floor, which could replicate and repair themselves and each other. High-level coordination was necessary through production planning within the manufacturing enterprise, and in turn production depended on the supply chains managed with outside partners, which also had to be implemented in an ecosystem-like manner. The principles of living systems were applied at all scales, to create the premises for the manufacturing technologies themselves to become “living production ecosystems.” Specifically, production processes are information-rich, and the dynamics of the information infrastructure is the tool for carrying it out both at individual locations and across the global environment. The electronic linking implies that work matter (or critical parts of it) is being transferred across virtual locations via the dynamic service environment, which supports organizational information that in turn can mirror social organization.

For the implementation of this technology, the latest advances in distributed artificial intelligence were used, namely software agents coupled with the latest ICT advances, which resulted in the creation of a dynamic service environment of intelligent mobile agents regulating production in a distributed manner by mirroring how the nervous system regulates a living organism. As member of the HMS consortium I collaborated with the Foundation for Intelligent Physical Agents (now part of the IEEE standardisation efforts of the IEEE Computer Society) to design this dynamic service environment as a standard for the implementation and deployment of distributed autonomic manufacturing systems. The mobile agents that were carrying the command and control function across the manufacturing plant, being gradually equipped with more and more intelligence and human-like abilities, began having a life of their own in cyberspace, thus creating "living" societies from which the concept of an "eSociety" resulted. The result of my five-year quest as the Canada Research Chair in eSociety (2005-2010) was a generic methodology for designing self-*-distributed systems for coordinating various activities, ranging from manufacturing production and energy distribution to online community building and virtual organizations that dynamically link the right skill at the right time at the right place for the coordination of streamlined and agile emergency response and business operations.

**(3) How is living technology related to overlapping or nearby research areas, such as nanotechnology, molecular biology, cloning and stem cell research, genetic engineering and synthetic biology? How is it related to social and technological systems such as social networks or information networks, such as the World Wide Web, cell phone networks and electronic banking networks?**

Implications of such broad-scale, networked, independent yet collaborative agents for societal functions such as trade, commerce, military applications, energy, transportation, health, education and entertainment are arguably extremely significant nowadays. Such progress in networked systems has transformed our world to the extent that it can be argued that very large numbers of entities (mostly modelled as software agents) now exist virtually in a universe of networked information, with distinct parallels to the universe we can normally apprehend through natural and extended human senses. Implementing an organizational structure (modelled after a real-life, complex adaptive system) into software using the multi-agent systems framework opens the perspective of regarding the Internet as the equivalent of multiple societies of agents comprising a virtual (digital) ecosystem that emulates different contexts of the real world, cloned in software by abstracting various functions and abilities of real entities as needed to fulfil the specific contextual purposes addressed by the ecosystem..

Such digital ecosystems are built on advances in: sensor, wireless and optical networks; secure software design; models for social networks and economic behaviour; resource management and cloud computing; and complex systems theory to address fundamental challenges in the design and operation of new, massive-scale, complex computing and communications systems and apply these new systems to enable the seamless and ubiquitous interconnection of diverse environments and smart infrastructures. In such hybrid, complex and convoluted systems, agents acting on our behalf make the best decisions, for example finding the best deal on a travel package or making us aware of opportunities and available choices in a plethora of areas, such as “discovering” that there is no milk left in the fridge and ordering it, suggesting changing to a more ecologically friendly energy supplier, managing financial systems or materials and supplies in storage, or finding the best partners to help a company get that highly demanded product on the market sooner than the competitor can manage.

Designed following the natural laws of evolution, which merge self-organization and natural selection, these socially embedded information infrastructures can adapt to fulfil various needs as their environment demands, enabling the sharing of information, services and applications among suppliers, employees, partners and customers via:

- deployment of automated, intelligent software services (e.g., internet-enabled negotiations, financial transactions, advertising and bidding, order placement and delivery, automatic order tracking and reporting, etc.);
- complex interactions between such services (e.g., compliance policies, argumentation and persuasion via complex conversation protocols, bargaining, etc.);
- dynamic discovery and composition of services to create new compound value-added services (e.g., dynamic virtual clustering of synergetic partnerships of collaborative organizations aiming to achieve a common goal, finding and accessing an unknown service that is available on the Web, matching of different templates from different sources to design a product optimally, etc.).

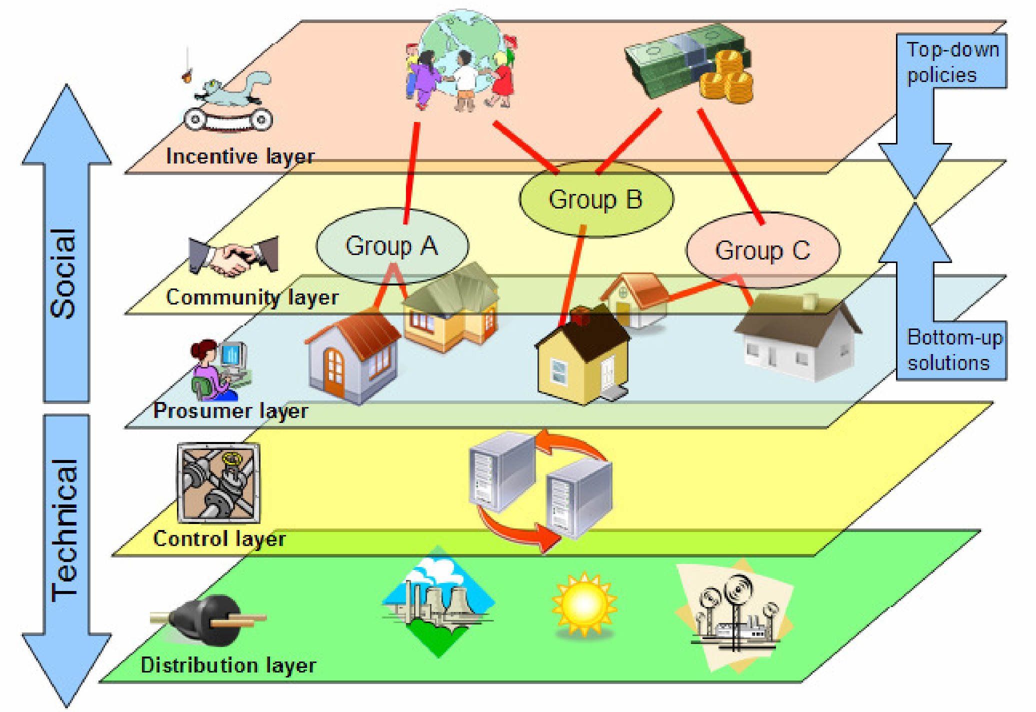


**Figure 1**. The EnergyWeb, integrating the cyber-physical and social dimensions.

Such digital ecosystems are envisioned also as an enabling technology for the "backbone" and "central nervous system" of the future smart infrastructures (e.g., Smart Grids, Smart Transportation Systems and Vehicles, Smart Buildings, Smart City) that will craft organic sustainable regions and enable the shift to a green and environmentally sustainable economy in low-carbon cities of the 21st century. In particular the Smart Grid is expected to have robustness, adaptability, self-healing and self-protective capabilities to support highly dynamical networks of power producers and consumers ("prosumers") through advanced ICT infrastructures, incorporating into various interdependent critical infrastructures the benefits of distributed computing and communications to deliver real-time information and enable the near-instantaneous balance of supply and demand. Along these lines the EnergyWeb concept (see Figure 1) is envisioned as a multi-layered large-scale socio-technical system in which industries, cities, communities or individuals will become part of a global socio-ICT "ecology," in which they can negotiate the energy they produce and consume. They will obtain direct financial benefits while promoting at the same time the growth of renewable energy sources. Since energy consumption by users and energy production by renewable energy sources are by nature unpredictable, utilization of the energy produced can be optimized by applying the idea of self-organization at the control level, influenced by the social network resulting from real-time involvement of prosumer communities in the operation of the grid.

Living digital ecosystems also offer a unique opportunity to address the crucial challenges related to the global nature of the Internet, which exacerbate the already critical global security risks facing our world. Besides the potential conflicts stemming from global warming, the possibility of "cyber war" adds an additional risk, threatening to destabilize interdependent critical infrastructures from finances and logistics to electrical and transportation grids on a large scale. The weaving of ICT into every critical infrastructure at a global scale across regions, countries and continents tremendously exacerbates the risks threatening business continuity and public safety, making risk and uncertainty even more integral parts of our lives. At the same time this becomes an opportunity to inject resilience and agility into critical infrastructures by designing the future networks with embedded autonomic self-* properties. Our "design for resilience" paradigm is using the ICT backbone endowed with self-healing, anticipatory and recovery capabilities; it presents a unique perspective on the implementation of global security strategies via a holistic approach which makes the security and trust of the ICT-infused interdependent critical infrastructures an integral dimension of public security.

**(4) What do you think are the most important open research questions about living technology, and how you think they should be pursued?**

In what we refer to as "digital ecology" theory and practice our research aims to understand and advance the interweaving of humans and ICT to create a world with social, physical, and cyber dimensions, enabling a kind of social network in which humans are not just "consumers" of data and computing applications. Actors in the social network operating within the new digital ecosystem are much more: They are producers, "players," and "inputs" whose interactions use the "invisible hand" of the market to steer complex, interdependent global-scale systems linking hybrid sectors of the economy and society. We are looking for the principles of management and engineering of these emerging complex large-scale systems that will infuse them with the ability to discover a variety of potential solutions in their repertoire, when confronted with a problem-rich environment.

Based on concepts having to do with distributed networked multi-agent systems with a variety of purpose-built capacities (e.g., sensing, reporting, acting, and collaborating), our quest belongs to the novel area of "emergent engineering," which aims at solutions that can be selected through an evolutionary adaptation process to produce progressively better (and continuously improving) solutions. Our long-term goal is to rephrase the classical concepts of engineering design and systems control respectively in terms of the evolvability and emergence found in natural systems, to propose a breakthrough approach to the architecture and control of future digital ecologies. The uniqueness of our approach stems from our regard for self-organization as a paradigm for designing, controlling, and understanding complex distributed systems, fundamentally challenging the traditional engineering school of thought in its core principles.

We believe that it is now essential to develop a "living technologies toolbox" of methods and techniques that address the architecture of digital ecologies and the control of smart infrastructures for a sustainable world spanning production, agriculture, defence, finance and the economy as a whole. As an example, for the deployment of the Smart Cities of the 21st century we can see immediate applications within three interwoven areas:

**a. Green Cloud Computing** concerns management systems for the dynamic and distributed allocation of computing load to cloud computing resources powered by carbon-free sources, e.g., hydropower, wind farms, solar farms, and tidal power. Our objective is to address challenges that relate to scalability, management, service models, quality of service, ease of use, scope of applicability and relation to pervasive ICT infrastructure, business models, and power and carbon emissions.

**b. Smart Power Grid** concerns the development of a management system that integrates sensor and communication technologies with the power grid to produce a system that encompasses generation, transmission, and distribution as well as end users and appliances. By leveraging real-time information, the management system will provide higher efficiency, reliability, and flexibility. The central role of micro grids and plug-in hybrid electric vehicles, as well as smart meters, applications in the home, and incentives to influence consumption behaviour will be considered.

**c. Intelligent Transportation Systems** concerns the development of a large-scale, distributed mobile networking and cloud- computing architecture to network and harness the power of millions of cars and public transportation vehicles. We seek novel approaches to designing digital ecosystems for networked vehicle infrastructure that can manage the flow of people and goods in an integrated private and public transportation network, to produce dramatic improvements in performance and reductions in environmental impact. There is a very high need for large-scale management systems that monitor and control the flow of vehicles for efficient movement of people and goods in an integrated road and public transit system. This integrated system will include dynamic pricing mechanisms and networked vehicles, as well as the interactions that will result between smart grids and the intelligent transportation systems mediated by the digital ecology.

**(5) What do you consider to be the most interesting and important human or societal implications of research and development in living technology?**

Taken together, interconnected grids of communication, electricity, and transport amount to what we call “organic infrastructures” whose integrated and reliable operation will undergird development of this century’s energy-efficient and sustainable cities, hosting the institutions and technologies of transformed low-carbon economies. Living technologies will enable the deployment of such organic infrastructures for the transition to a post-manufacturing, innovation- and knowledge-based green economy and society. We envision that such constructive organic organizations designed as “living systems” merging power grids, cloud computing, smart buildings and transportation networks will advance the state of the art in the rigorous design of resilient and robust management systems for the control of resource usage in massive-scale complex systems, targeting a “clean” and “green” world. We envision that living technologies will be at the forefront in the deployment of digital ecosystems that promote energy efficiency and reduce carbon and greenhouse gas emissions in homes, offices, factories, cities, and entire urban regions; and in extremely large-scale distributed data centres that will support the next generation of cloud computing.

Above all else, however, the enormous potential stems from the lessons that we can transfer from life's successful principles to revolutionize our governance structures to reset the current dynamics of our world from its perilous (market-and-conflict-oriented) trajectory, onto a prosperous one that is sustainable and focused on human needs. Such a shift in governance is required for fuelling the generation and adoption of innovation, in all sectors and at all levels of social, and institutional and organizational structures. There is an acute need to (re-)define new indicators of wealth and social well-being that will enable this critical paradigm shift from risk governance to resilience governance. Due to the lack of adequate policy frameworks, the obstacles in implementing innovative solutions at all levels are the limited capacity of social processes to manage rapid change in institutional design, planning and public services, rather than technological innovation. Lessons from life's processes are priceless in restructuring the organization of our social processes into more fluid and organic structures that enable the manifestation of creativity through social innovation generation. Among the most critical issues that must be addressed without delay are:

- how to facilitate the *transition* from the currently disabling rigid governance structures into the necessary enabling agile policy frameworks that will transform our coercive institutional frameworks into agile, responsive and fluid ones, capable of fostering creativity and supporting innovation;
- how to design *engaging control mechanisms* that stimulate rather than oblige, transitioning the current work organization processes from contract to commitment by fuelling performance through visceral engaging architectures of participation, which, in an online gaming-like manner, infuse blissful productivity into work activities, giving an epic-like meaning to the purpose of work;
- how to design *validation frameworks* that reveal the impact of policies on the work ethics, culture and productivity in our organizations;
- how to redefine *indicators* that expose the impact of the convoluted effects of interdependent socio-political-economic factors on the current global dynamics, negatively affecting the overall wellbeing and sustainability of life on Earth;
- how to anticipate the evolution of society and the course of life under the influence of the transformative forces that change us as individuals – who in turn change our environment, which changes us – on the ever-mysterious trajectory of mankind's destiny as part of our "living," self-organizing universe.