An epistemology of information technology models for pervasive computing

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Abstract — **The present paper introduces the digital realm as a dynamic, Darwinian ecosystem, then analyses the emergence of the concept of pervasive computing, and finally develops an account of information and communication technologies (ICT), their evolution, and a roadmap for their potential future development. The paper then examines the constraints and the evolutionary pressures acting upon ICT through an analysis of the subconscious representations that model the domain in the current discipline of information technology, as applied to pervasive computing. The investigation examines the principles of its conceptual models along with the conditions that permit these models to arise and flourish. The paper concludes by proposing a number of novel representational concepts for communications that show future promise as well as an exploration of possible new models of the Internet of tomorrow.**

Keyword: pervasive computing, Internet of Things, security, computing model, Future Internet.

I. Introduction

At the outset of the French film *Pierrot le Fou* [1] by Jean-Luc Godard, actor Jean-Paul Belmondo (playing the role of Ferdinand, a.k.a. Pierrot) starts reading an extract from an art history by Élie Faure [2] in front of a bookstore named "The Best of All Possible Worlds" (*Le meilleur des mondes*), before ending up at home lying in the bathtub, reading to his daughter this passage on Diego Velasquez, a painter who came to prefer depicting the relationships between objects, rather than the things *per se*. He reads:

"Velasquez, after fifty years, no longer painted anything with definition. He wandered among objects, through the air and the dusk, capturing in the shadows and the transparencies of backgrounds the many-hued palpitations which he made central to his silent symphony. He no longer grasped anything in the world but those mysterious exchanges that make shapes and tones penetrate one another, through a secret and continuous motion in which no collision, no abruptness, interrupts the flow. Space itself reigns supreme […] It is like an airy wave that strides upon surfaces, impregnating itself with their visible emanations in order to define and model them, then spreading everywhere else like a perfume, like an echo dispersed throughout the surrounding spaces as an intangible powder…"

By analogy, this paper attempts in the area of information and communications technology (ICT) to explore a novel approach to the concept of pervasive computing via a renewed vision of space, objects and subjects, and to effect a change in point of view, focussing more on the relationships between entities than the character of the entities themselves. In the recent evolution of the ICT sector, one can observe that there has been a destabilisation of architectures and styles, a shortage of models, a lack of certainty surrounding objects in terms of their design, and a loss of identity by conceptual objects. If the Internet was indeed fairly innovative in the decade after 2000, with the spread of multimedia content, then pervasive computing, a notion that is still in its infancy, should prove itself an advance beyond preceding models of communication achieving a more refined engineering of the relationships between communicating objects.

II. The ubiquity of the digital realm

A The digital realm

The digital realm, born some sixty years ago, now clearly occupies a central stage between the animal, vegetable and mineral worlds. It is a new realm that has been more or less domesticated, and which has not yet claimed its independence. The technological constraints and ethical unease in the evolution of this fragile and invasive "Frankenstein-like" creation are the focus of this paper.

The digital realm takes concrete form as a series of dynamic, mobile objects, which themselves obey the laws of a rapid evolution, a natural selection in their uses on an IT time scale. It delivers services adapted to computers, but also to the environment, to people and to other physical objects, and all of these are provided in a context-sensitive manner. The computer is no longer an autonomous tool for calculating, or for automated workflow processes. Networks are no longer simply cabled meshes of computers able to transport bits of information back and forth and to link them altogether. The digital urbanization has become a new entity, furnishing a totality of *in situ* services, deriving its richness from relationships between the digital realm and the physical and living world. These ever-increasingly complex and rapid interactions between the digital realm and the physical and living world (spreading through the invention of a variety of new sensors and actuator devices), will be the major issues at stake in this explosion of services and tools in the economy of this sector in the years ahead.

B The morphogenesis of the digital world

In the ICT sector, there are radically different yet coexisting forces and speeds at play.

- Hardware obeys Moore's law, with its doubling of power every 18 months, as a consequence of which there is a constant readjustment of structural equilibria between hardware and software, approximately every three years: renovations in corporate IT installations, novel developments in the portable electronic devices of individuals, and a progression of versions in application packages.
- Network infrastructures (2G, 3G) tend to cycle every 10 years, and network usage turns over every 5 years or so. There are changes in network equipment, improvements in end-to-end transmission rates, the appearance of new services and multimedia content, and changes in the types of attacks made by pirates.
- Software is progressing much more slowly: a new generation of different services, programming languages, development environments, software management tools – these arise only once a decade. Software engineering has encountered difficulties industrializing, if not a total failure to innovate, since the 1980s.
- Physical infrastructures and base software have hardly evolved at all: the TCP and IP protocols are 40 years old; the SQL query language dates back to 1980; and Bell Labs' and AT&T's UNIX, like the Linux kernel it inspired, have hardly changed.
- Relevant legislation evolves in a 10-year cycle, as evidenced in the examples of European directives on digital signatures, the respect for private data, and ISP obligations to retain personal traceability data.

These ongoing lacunae between vastly different rates of innovation are causing frontal technological collisions, not to mention new constraints, which are resulting in the appearance of new fault lines in the IT landscape. These differing rates of evolution are discombobulating the synergies between various technologies, disjointing the various architectures, and defying the norms now in place - a situation which necessitates the appearance of new, more stable forms. Moreover, actual uses often differ significantly from the concepts inventors expect to see, which leads to the creation of new markets where no one had anticipated them.

Beyond these structural readjustments, there are profound movements of an economic nature, such as digital convergence, leading to a constant retooling of the digital landscape – efforts toward optimization, the standardization of protocols, formats and architectures, the harmonization of hardware and software resources, and the ability to expand into new services, and to new users. Norms and standards have had a crucial role in the digital convergence of computing, telecommunications and audiovisual technologies. For example, the JPEG and MPEG multimedia standards for the compression of images and sound have overflowed their boundaries, and can now be distributed equally over the three media types, thus becoming digital consumer goods in their own right.

In the end, these appropriations made by end-users, and more generally their concomitant acceptance by society, dovetail into several patterns: there are sudden victories (e.g. mobile phones, Facebook); slow acceptance (computers in every home); and the gradual adoption of ICT by certain sectors (health, distance learning).

C A Darwinian ecosystem

The Darwinian theory of evolution, by virtue of its process of selection, may be interpreted in terms of an information technology-based reading. All populations of computer-related species (models, languages, architectures, protocols, products, equipment or hardware, software, modules, functions, non-functional properties), whether they are in direct contact with the end-user, or embedded within another entity, are exposed to individual requests from their environment; there are rival technologies of differing composition, the economics of competition with other similar products, and finally societal preferences to consider. The result of this is the existence of an endless intrinsic capacity to foster variation (flexibility, the ability to adapt). These entities evolve (generally as new versions) and adapt themselves constantly to their environment, which more specifically consists of the subjective preferences of end-users, the marketplace (price, availability, publicity) and easy pirating (as a number of products which could originally simply be copied produced a sense of dependency among users). The selection of the best-adapted candidates signifies the simple fact that the properties that favor the survival and the spread of an entity see their resilience and their "value" increase from one generation to the next. Thus the Darwinian evolution of digital entities, which promotes a diversity of form via de-standardization or differentiation, rests upon three principles [3]:

- The principle of variation, which explains how "copies" of an entity differ from one another (duplicated clones end up being modified) or how entities in competition differentiate themselves from each other.
- The principle of adaptation (products or copies that are the best adapted to their niche survive and find greater deployment) and
- The principle of heredity (or of descent), which posits that advantageous characteristics in a line of products, an architectural family or a conceptual philosophy are transmitted as a hereditary characteristic (with ascendant compatibility).

While Darwin did not discriminate between the interior and exterior of beings, in IT it is definitely a requirement to distinguish between the internal and closed parts of products (the invisible and interdependent innards that are often under permanent reconstruction) and the public part, the interfaces that are so fundamental to their usage, as well as to their ergonomics and interplay with the existing milieu. The internal part that brings heuristics into play intercedes as a question of survival in the quality of construction, in the confidentiality of entities covered by secrets of manufacture, in moving to the industrial scale. The public interface must be simple, efficient, and constant.

D The heterogeneous urbanization of abstract entities of varying granularity

The digital realm consisted in the past of great transversal species, which were both conceptual and concrete: Dichotomies between hardware and software, between the computer and the network, between the private and public cyberspaces, between the interior and exterior of the information system, between the different layers of communication. Yet a strong burst of progress (from around 1997 to 2003) has recently altered these antitheses, and has in effect ended the black-and-white character of the distinctions they represented. A conceptual wave has submerged these natural species and invaded the digital landscape. It has been reclaimed by the mobility of living entities, the massiveness of content and the huge end-to-end throughput, seeing the old duality swept away by the winds of globalization, mutating towards the most primitive, structuring abstractions.

The first of these high-level abstractions is the ecosystem. Today it is difficult to differentiate between programs and data: Documents contain macros, HTML pages include scripting code, and programs themselves become the data in saves. It is an inextricable tangle to unwind – between the executable threads on machines and the massive content, in the amalgamated form of implementations, machinations between two different species of one-dimensional strings, like manuscripts written with a feather-pen:

- Executable strings, active computing machines that accomplish something with meaning, in other words, abstract Turing machines which are actually automated applications that execute themselves as function of time, and
- Static strings, passive information which is acted upon by executable services, in other words user data (sequences of zeroes and ones that obey the laws of information theory): these are files, static documents, video flows, texts, images and words, Voice over IP.

In practice, the connected mass of manufactured objects now surrounding us, featuring its IT scarce resources, tends to provoke a loss of measure and in fact reinforces the gigantism of open digital meta-systems. These two opposite penchants are manifested in turn as two opposed yet extremely fecund IT concepts, virtualization and embodiment.

The idea of virtualization is not new. It consists of juggling information entities of differing kinds in order to produce new, more efficient species of IT entities, while reducing the complexity of the transformed system, from the point of view of its handling by applications and services. Just as the object-oriented approach changed the way programs were made, the virtualization approach has transformed the treatment of information-technology architectures. Virtual memory has changed the writing of programs that hogged RAM. The Java virtual machine has facilitated the encapsulation and filtering of distant programs in HTML pages on the Web, which is what accounted for its initial success. Virtual private networks (VPNs) have brought about a trench phenomenon in public networks, which has created a sense of intimacy within a form of global no man's land, and has allowed businesses to deploy their trades further on the Internet. The VLAN technology has allowed for a separation of the infrastructure of the local logical network from the physical infrastructure of the business network, which has greatly contributed to the success of this type of network. Virtualization has thus permitted the borders to be erased between hardware infrastructures, and between hardware and software. This is to bridge between the forms and standards of different databases, to enter into new territory in terms of information management policy, to route different types of packets, and to issue passports between heterogeneous networks and technologies. On top of J. von Neumann's hardware vs software distinction, a virtual plane is being constructed for the long term over all IT architectures. Overlay structures, like all overlay networks, are also paradigms derived from this operation of virtualization.

Embodiment is the notion opposite to virtualization, although it is less widespread. Whereas virtualization aims to annihilate any rebellion against transparency and a seamless world, embodiment allows for the invention and revelation of dynamic forms, while at the same time creating local intelligence where none existed before. Robotics and artificial intelligence are now producing useful innovation, notwithstanding their rather premature claims of revolutionary success in the 1980s. A New School that is both efficient and pragmatic is pointing the way forward with the fundamental idea that knowledge is not merely the result of information and calculation [4]. Intelligence is not merely a computation; it requires a body in the physical sense of the term. The first successes in the field of robotics are able to recognize their surroundings, ascertain their situation, and even assist people with domestic chores. It goes without saying that this powerful concept will have considerable impact in the distributed world of sensors, middleware and surveillance, useful for the securing of unpopulated locations, and in IT in general, once the concept has been more fully developed.

While there exist today both distributed and embedded systems, this panoply will be complemented in the future with overlays corresponding to virtualizations, and independent confined systems corresponding to embodiment. Virtualization and embodiment are the two most powerful forces in 2010 for encapsulating, separating and abstracting more primitive IT concepts. The idea of virtualization has been extremely productive in recent years, no doubt because the concept of virtualizing data storage, networks, hardware and files has finally matured to the point of being much more easily implemented than self-organizing structures.

The second high-level abstraction for harmonizing this patchwork is thus virtualization. "Seamless" digital technologies are working their way into the lives of individuals. It is weaving a tight meshed sheath around them and creating a digital urbanization that is changing the way things are done, even overturning the values of our civilization. It is the creation and interaction of three complementary "ubiquities", that of calculation (in programs executed here and now), that of communication (access anywhere, anytime, using the best available pipelines) and finally that of storage (collected knowledge and information, stored, represented and visualized, available anywhere and at any time). The value of digital assets may soon overtake that of material goods, whether one considers those made by or for individuals, enterprises or government agencies. Virtualization is a robust paradigm for relations in the presence of heterogeneity. It represents a world without visible seams, yet it is in fact sewn of invisible virtual threads: overlay structures, the cross-layer mechanisms of protocol stacks, and underlay or landmark structures are in fact logical and virtual IT relationships that serve to link together, in a masked manner, several distinct entities, thus reducing the complexity of services.

The third abstraction is the taking of power by new entities whose life cycle, being entirely autonomous, is characterized by self-organization. Embodiment is adapted to interacting with the physical and informational environments. Stand-alone systems are independent entities in direct relationships with their environment. These liberated, miniaturized systems communicate over a network under the constraints of temporal resources, in particular those of energy.

E Pervasive computing

Pervasive computing [5] is built upon ubiquitous information infrastructures. This is a concept that signifies an "intelligent area", meaning a digital urbanization, a spatiotemporal (3D+1D) milieu that provides both sustenance and interdependent evolutionary power to a digital ecosystem of individuals, organizations, and States, but also to nature, which surrounds them. We are therefore witnessing the creation of a 3D world of communication, the birth of a digital ecosystem of multiple granularity, on a global scale, in short the emergence of a pervasive computing.

A pervasive system is constituted by infrastructures equipped with specific entities that form an integral part of the network, and which provide intermediation services assisting with communication (bandwidth broker, localization manager, commitment of node topology to memory) or facilitate the functioning of terminals (configuration, service discovery).

A pervasive network can also utilize external services provided by another available infrastructure (e.g. for the management of time, space, radio resources). The pervasive computing attached to the walls of physical buildings, which supports the infrastructure in terms of computing or communication will co-operate with the actual functions of communication, by facilitating transmission. It will also be used to configure applications as a function of their geo-positioning usage.

The pervasive computing systems an individual uses in an apartment and on campus are different. They adapt themselves to the environment, the services and the uses required. Their semantics vary and grow according to the granularity of their niche in the digital ecosystem. The substitution of a common language by modified and better-adapted dialects, while enabling the adaptation of the system as a whole, does not occur without raising other potentially insurmountable obstacles at the same time.

Pervasive computing, consisting of networks of sensors, multitudes of un-powered computer chips like smart tags, are made with the informational mutualization of mobile communicating objects of rare computing and network power. This "smart dust" spreading throughout the urban landscape raises real security questions.

The domain of pervasive computing is not a homogeneous world of free robots around us to offer their help with difficult or painful tasks. Pervasive computing is a "situated computer science", meaning an IT that depends on function, on the local environment, on context, on the size of the cyberspace in question. It can constitute forms of intelligence on any scale that of :

- the planet, to observe, analyze, detect, identify, alert, decide, and act;
- human communities, to collect data in real time;
- a city or neighborhood to assist citizens;
- a transport infrastructure to facilitate travelers' trips;
- a house, to inform, educate, or for domestic controls, daily life;
- a person, to monitor individual health, via control mechanisms, through digital prostheses attached to the human body yet connected and interacting with the outside world, connecting the patient with a care-giver at home, or a doctor via telecommunication.

Pervasive computing is therefore a crossroads of multidisciplinary research resting on an IT foundation. It is situated side-by-side with microelectronics and software, as well as the human sciences and even legislation, as the behavior of the principal actors plays a capital role in the evolution of this digital realm, which surrounds our manufactured objects, that covers our walls, that decorate our public places (stations, airports) and our means of transportation (trains, cars).

However, it seems that beyond the slogans and mottos of mercantile jargon, no one has pierced the veil and gone all the way in identifying the consequences that these phenomena entail in reality. This is particularly so in terms of models of communication, computing, storage and interactions with physical reality (through robots), or with living reality (such as cellular information, bioinformatics), or the invisible reality of the extremely small (nanotechnology).

Pervasive computing has not had quite the expected success following investments made through several research projects (e.g. Eureka, European Union Framework Programmes for Research and Technological Development) that have been financed by the private and public sectors. This was an "industrial order" at the outset, fostered in particular by Philips Research, to modulate light levels in the living room, and computerize the home, the refrigerator, household objects, even electric razors. While successive European research projects put the concept of pervasive computing at the forefront, meaning simply a wireless IT programme on a small scale, they developed, on the level of actual use, into a nearly opposite IT, meaning peer to peer applications, a distance IT capable of bringing together far-flung isolated web users by the virtualization of resources.

The challenges of pervasive computing are:

- Mobility (persistence and continuity of communication), the movement (intermittent connection) of communicating entities, the contextualization and learning of the milieu (discovery services, adaptation) with pervasive computing, remote presence of physical persons, or the expanded presence of the body;
- The identity and ID-management of various objects, including their mass extension, considering that outside a certain set cardinal, element identity can lose their effectiveness;
- The primordial properties of communicating objects: safety, transparency of function, non-intrusion, non-addiction for the end-user;
- Multi-mode interfaces, heterogeneous interactions in the assemblage of the urbanization of the whole, and the composition of the different aggregates of architectures of different systems, and their negotiation;
- Integration, cooperation (spontaneous or opportunistic), even collusion, and the capacity to learn, on every level of granularity, in niches that overlap, and the management of this complexity;
- The transversal aspects of uses, including multidisciplinary ones.

The non-technical scope of pervasive computing also covers a large spectrum:

- Simplicity, friendliness: intuitive interaction, which is more general than ergonomics;
- Psychology: the phenomenon of rejection of apparatuses for assistance to the aged;
- Legality: the safety of the use of robots, the area of intellectual property, the right of access to a digital entity, the right of oblivion of records saved by these objects, the regulation of physical objects;
- Ethics: respect for the private sphere of individuals, digital dignity in infrastructures for monitoring purposes.
- Politics: The freedom of expression of citizens within semi-private areas.

III. A ROADMAP TO THE DIGITAL WORLD

From a digital perspective, up to the year 2050, one can divide the technological near future into three stages. The three distinct periods do not, however follow neatly one after the next, but rather they appear, co-exist and fade away at separate rhythms, at times overlapping with one another. Nanotechnology already exists; and quantum communication (which is never just one quantum computer with a single quantum bit) is already operational; it has been here since 2008 (FP6 Secoqc Project), and will soon flow into current infrastructures.

A The waning of the concepts and the digital convergence: 1995-2015

Digital convergence, thanks to the success of open interfaces and interconnections (as well as progress in optics, and the mastery in a near field of the Maxwell equations), is continuing inexorably toward demolishing the demarcations between IT, telecommunications and audio-visual media. Its goal is to create and harmonize an end-to-end chain of value with interoperable infrastructures, configurable architectures, adaptable services and compatible terminals. This is materializing through the emergence of a universal virtual network to which users connect to obtain services, but it is also driven by a fierce confrontation between standards, a ferocious combat in the marketplace, a revolution in behavior and practices and a profound alteration of the economic rules.

The current digital convergence, which is an all-out war between three industries aiming to dominate the standards and paradigms of the numerical science of bits of information, is manifested essentially as a relentless advance by the Internet, now an unavoidable yoke for education, media and families. The three devices (the Television, the Computer and the Telephone) are not going to dissolve into a single communicative object, but will become more compatible with each other, at the cost of a dangerous uniformity, a source of fragility, and the fact of becoming mundane, a source of vulnerability. The three infrastructures will cohabit with a mere quasi-compatibility. The protocols, formats and standards will draw nearer, overlap and become uniform.

Digital technology has been characterized in the current decade by a period of respite. This has meant doing some housekeeping, including touching up our computers, televisions and phones to make them more interconnected and interoperable. Human interfaces are now operated with a keyboard, mouse, screen, microphones, speakers, and increasingly, with the voice and fingers, and even gestures, blinks of the eyes, movements and thoughts (there are indeed products that can measure the electromagnetic energy flow in the brain). In telecoms it has been established that the mass of data sent by a piece of equipment depends directly on the richness of the interface used. This digital technology has very little connection to physical reality, utilizing a few networks of sensor-activators, and a very few robots. IT still appears mired in the mud.

B The coming effervescence: 2010-2030

Moore's Law, already at the atomic threshold, has turned its approach away from the repeated miniaturization of transistors, and will continue its march in the direction of an increasing parallelization of components: Intel gave up on the erstwhile goal of a 4GHz clock speed in 2009, in favor of new multiple-core processors. A layover for technological retooling is likely to give rise to a new period of frenzied effervescence which will reconcile the virtual and the physical, thus merging IT with reality. We are witnessing the spread of radio-frequency ID tags (e.g. in the logistics of parcels in transit, in tagged and tracked animals), networks of sensors in the city (surveillance cameras of every kind), in nature (forest-fire and earthquake detection for instance), in home networks, in cars, service robots designed to assist people, and remote-diagnostics. If the current Internet connects 1.5 billion computers, and the mobile telephone 4 billion persons, the coming Internet of Things will likely connect billions of objects. Their inevitable malfunction, and the black-hat attacks they will fall victim to, will provoke distributed catastrophes with multiple aftershocks.

Architectures are constantly tested and renewed only to re-establish new, semi-stable equilibria between (on the one hand) the complexity of digital urbanization, its heterogeneity, its highly distributed character, and (on the other hand) the mobility of entities as well as the continuous evolution of this technological moving target, both in terms of the technologies and their uses.

The appearance of new infrastructures (from RFID chips to label real objects to the constellations of new Galileo GPS satellites able to track give the time and position of these labeled entities), the massiveness of the networks and the constant reduction in size of their nodes, the diversity of interactions, these factors demand a redistribution of the intelligence in these urbanizations. All these nodes will possess the capacity to calculate, communicate and store, but they will also be aware of their location and context, and will be able to react to their environment, after sophisticated reflection.

The innovative services of the future will be hosted by these poly-infrastructures, and the new digital economy will begin a decisive expansion fuelled by the richness of these virtual, spontaneous hybrid services, which will fully exploit their resources, wherever they are available, in the pervasive computing milieu. The Internet and cellular networks will no longer be the only two pillars of the digital world. We will enter into a world that is post-Google, post-3G and post-TCP/IP, with multiple services and architectures, which will be grafted on to this universal network, with more Spartan protocols than IP for the irrigation of sparsely fed networks, less gluttonous operating systems than those we are familiar with, and more open mobile infrastructures than those offered by today's telecoms operators.

Penetrating into the connected domestic space (in the broad sense) is the next royal road on the direct line pervasive computing is following in its advance. But this world still belongs to electricians, not yet to the world of telecommunications. There is still no agreement on the footbridge that will allow entry into the home and make the house communicate with other devices (telephones, contactless chips, bank cards, IoTs, RFID, TVs). It may be necessary to forge a consensus between electricians, mobile and fixed telecom firms, cable companies and mass-market electronics manufacturers, in order to bridge the gap separating these players.

The sheer size of networks means they require a capacity to self-organize, to adapt to context, to analyze, to diagnose and to repair themselves (self-healing). Finally the trust, the security, the privacy, the dependability must be ensured, in order to avoid gigantic outages that are in danger of appearing in infrastructures for satellites, the Internet, cellular networks, peripheral access networks and in networks of sensors and actuators, down-time which can cripple economic activity and even threaten social stability.

C NBIC technologies and attoscopic science: 2025-2050

Within 20 years we will cross the "atomic Rubicon" and enter into the nano-scale world. A new era will arise with the reunification and metamorphosis of scientific disciplines around nanotechnologies, which will make the atom the veritable scale of work, and will see Mendeleev's periodic table of the elements become the new horizon for innovators (particularly the elements in the upper middle of the table, H, O, C and Si, but also Ga, Ge, In and As). Networks and IT will necessarily undergo radical changes in nature, as it will become necessary to connect to the massive world of the invisibly small.

When digital convergence is complete (around 2015) another inexorable confrontation is likely to occur some ten years later, a battle to see which technology will guide and direct the advance of civilization from then on. It will either be nanotechnology, in a kind of atomic-level Lego that assembles atoms into new "manufactured" (or 'nanofactured') products, or bio-genetic technologies capable of manipulating (or 'nanofacturing') cells as a branch of bio-engineering, that will win and take all. We will be swallowed in a digital crepuscule, as traditional IT will become a technology at rest. Classical IT will go up in sputtering flashes and leave the field open to research into quantum IT. The industrial quantum computer might see light as early as 2020, able to execute many calculations (though not all) with a speed a thousand million times superior to today's computers. For "specialists," this date of 2020 is the latest prediction for the creation of a quantum computer of some fifty quantum-bits, which may be able to crack all current asymmetric cryptography (and all electronic signatures will become obsolete).

This period of crossover with living reality should last 10 to 15 years, then a new digital era will appear, that of Nano, Bio, Info and Cognitive (NBIC) technologies, where humankind will finally be able to work at the scale of the atom (nanotechnology), the living cell (bio-genetic technologies), and photons (with quantum computing). This will mean a radical revolution in our whole civilization. The Zeroes and Ones of IT will slide in among atoms and living cells. Vulnerabilities and threats of an entirely new order should arise in this nano-world: nano-warfare, a marketplace for living cells, a quantum war to break the secret codes of national governments, in short a new battlefield on the scale of the atom. Countries wishing to safeguard their pre-eminence will need to attain mastery the science of the attometer (10^{-18} m) on the scale of quarks, and the technology of the angstrom (10^{-10} m) on the atomic scale. Humanity, having assimilated the space-time theories of Einstein and Minkowski, will surpass its 4-dimensional vision and expand its horizons into theoretical universes of more than 4 dimensions (some of which are nanoscopic) and having more than four fundamental forces. The first theories of Theodor Kaluza [6] were written in 1921!

Yet they remained virtually unknown for more than 50 years. String theory, along with gauge-field, brane and super-symmetry theory, will all likely become much more solidly developed over the next 20 years. The world of quarks mandates non-Hilbertian spaces with heterogeneous dimensions. It is in mathematics that we face shortfalls today, whereas the physicists of the last century had all the mathematical theory they needed for their models (General Relativity in 1916, then Quantum Mechanics in 1925).

IT will therefore become intermingled on every level with every tiny vein of reality, and of nature, thus creating a new reign. The new IT of the 21st century will govern this artificial invisible realm, a massive, ubiquitous world.

IV. THE PRINCIPLES AND MECHANISMS OF EVOLUTION

A A stable theoretical foundation

Digital technologies like computers and networks are not evolving in any fundamental way. They see spurts of episodic progress, through ever-increasingly efficient manufacture and the inexorable miniaturization of transistors. But it is above all else thanks to their broad adoption by individuals and businesses using them to automate tasks and for practical IT uses, that our daily life has been transformed. This success has placed IT at the vanguard of forces advancing Western civilization over the last 50 years. Yet this cannot last.

The penetrating models of the pioneers of IT, which make up a part of pure and abstract science, are finally ubiquitous in today's hardware: The Turing machine (1936-1938), von Neumann's computer architecture (1944-46), Shannon's information theory (1948-49), von Neumann's working storage concept (1949), and the languages and compiler of Backus (1953-57). Here we have a good example of the virtuous implementation of fundamental knowledge:

- One must recall that Alan Turing [7] "invented" the computer in 1936-38, starting out by demonstrating a mathematical conjecture devised by David Hilbert.
- Claude Shannon [8, 9] transposed the kinetic gas theory of molecules in an enclosed space (developed 50 years earlier by L. Boltzmann) to a linear string of 1s and 0s. The publications of 1948-49 are already foreshadowed in his M.A. thesis in 1936.
- John von Neumann [10] conceptualized the current computer, first by inventing the workspace essential to a machine that automatically executes algorithms, and later, with the notion of the software program, using a "volatile electronic circuit" to modify its instructions more easily, thus avoiding spending all his time patching circuitry hardware.
- In 1954-55, John Backus [11] created Fortran and the compiler. In 1959, he invented the notation that describes the syntax of a high-level language. It has been called the Backus-Naur form (BNF) after Peter Naur's improvements.

These theories are all over 50 years old, and nothing new and essential has come by to shake their foundations.

B Respiration in the ICT universe

The variable architectural cursor between distributed and stand-alone system

There seems to exist a blueprint on a temporal horizon covering around 15 years for successive expansions and re-concentrations of digital infrastructures, like the movement of an accordion, between (on the one hand) architectures that are flat, reticular, and interconnected, during periods favoring distributed computing, and, (on the other hand) forms which are hierarchical and centralized, during periods of respite, favoring stand-alone computing.

The enormous success of autonomous applications (eBay, BitTorrent, YouTube, Facebook) appears to contradict the necessity for a consensus on norms for IT, and has done so for a number of years. Moreover, to the benefit of the implementation of the concept of the virtualization of IT resources, the recent birth of Cloud Computing is going against the currents of the modern period in terms of networks (e.g. peer-to-peer networks, largely distributed architectures, Skype). This favors a return to the previous proprietary and divided IT concept, where users connect to their IT account (via Internet but this can be on specialized lines, as before), hosted by a provider of resources and services, on just one computer (or a server farm). Will this paradigm of Cloud Computing, and, in the future, the concept of protocol virtualization within the Internet of tomorrow, become part of a new organizational concept favoring a respite, a break in the deployment of distributed IT, which will therefore prove to have been over-used or abused? What are the consequences on the norm evolution practices?

The versatile requirements of the properties of openness and interoperability

The properties of digital systems are highly dependent on their morphology. Depending on whether a system is distributed or stand-alone, its non-functional properties will be different in terms of security, interoperability, administrative ability, and evolvability. Openness, transparency and interoperability are essential for distributed applications and for networked morphologies. According to whether or not the functionality of a system or service is integrated and autonomous, or on the contrary depends on other applications or is associated with other services (in workflow for example), the requirement that it must be interconnected or composited is not the same.

While we have been in the digital period of networking since 1995, it seems that we have returned to a time of recentralization, a concentration seeking a confined computing power, an anti-Internet period of producer-consumers now following after the over-expansion of the Internet. Indeed, all the new information technologies that are intended to pleasure users are in fact feigning ignorance both of openness of services (public interfaces to applications in order to be able to be interconnected), transparency (since the originality of a service and its industrial secrets can exert a pressure toward opacity of algorithms), and of interoperability (since the applications are independent and cannot contain or call one another). This demands neutrality, which in reality translates into the right for these applications to enter any network and cross them all, free of charge. Can this total denial last, given the economic imbalance it encourages between the providers of network infrastructure (optical and wireless) and providers of services and content? Will the volatility of Internet users who are fanatical about the free-as-in-beer model finally put an end to the virtuous circle engendered by the expansion of the Internet and its variety of innovative services?

The debate between conventions and de facto standards

If one must choose between official norms and *de facto* standards, the ICT world is characterized less by the former, and more by the latter. The PC standard (in hardware and software) is an industry success story, led by the Intel-Microsoft pairing, which succeeded in overthrowing the IT giant that was IBM. There are thus two distinct approaches. One of convention-creation results from a strategic approach to needs. It states goals, defines work programmes, then finds and mobilizes experts. In contrast, the *de facto* standards approach consists in enlisting or implementing those technical solutions that experience uncovers in the wild. This is really what the various forums and industrial groups aim to do. Therefore there are two opposing attitudes, one advanced by the adoption of norms and the other by the emergence of standards, which co-exist today in the evolution of the canons of IT:

- A rational vision in which considered norms are agreed after lengthy consideration by consensus-seeking, independent experts. "Objective" maturation demands a robust lay conception, an agnostic description of forms (protocols, network architectures, compression and cryptography algorithms, base services, man-machine interface styles) or the engineering of eminently stable product lines (routers, firewalls, encryption key servers, biometric ID). We have seen, for instance, the widespread adoption of the MPEG-2 image compression standard, P3P privacy on the web, the interoperable XML interface for databases, the TCP/IP and DNS protocol suite on the Internet, and the new 3G LTE in mobile telephony.
- A spontaneous, dynamic, voluntary jumble of work through which standards impose themselves via the initiative of corporate groups (e.g. Bluetooth, essentially a creation of Nokia and Ericsson), of a few persons belonging to a single company (Multi-protocol Label Switching was developed by Cisco, Java by Sun, Peer-to-Peer architectures by Napster), or according to market forces and commercial usage (Web 2.0 applications like Second Life, download applications like BitTorrent). What wins in these cases is the opportunistic implementation of innovative yet proprietary services (e.g. the Windows OS, Oracle databases, SAP groupware), along with new products that simply meet existing needs (e.g. Intel's x86 microprocessor architecture), or an ability to respond to users' wishes (mobile devices like the iPhone), all of which constitute de facto standards, and have avoided any long deliberations by experts.

Conventional norms shape the IT landscape by tracing, as time progresses, a genealogy of canonical forms which organizes it and governs its evolution. If such conventions can prove their relevance, they resist the erosion of time, they survive transformations in their usage, and they absorb any technical conflicts spawned by the emergence of newer innovations. If such standards are heavy or overly complex, they have difficulty adapting to the changing IT landscape, and fall into obsolescence. Standardized norms are now especially relevant in the development of network infrastructure specifications, where a long-term perspective, solid foundations, backward-compatibility and interoperability with adjacent concepts all continue to be crucial properties for the numerous implementations that will take form after major investments. Examples of this are GMPLS, IMS, 3G+ and grids. These norms are well justified, particularly when they consist of base algorithms that transcend numerous applications, and when product competition intercedes residually, as with turbo-codes, compression heuristics, Advanced Encryption Standard algorithms, and X509 certificates.

De facto standards frequently thrive in areas where there are extremely tough constraints in technology or its use. They then introduce revolutionary change – both through reductions in complexity, and via architectural simplifications that bypass poorly performing assemblages that have become too convoluted. Competition amongst standards generally gives rise to leaps of progress in IT. Java, thanks to its standardized libraries, was able to attack a flabby C++; HTML was born from a simplification of SGML; and the Adobe PDF format for text documents, while entirely proprietary, took over in the area of document exchange, thanks to a morass of incompatible word-processor file formats.

C Factors inhibiting progress

Toward new paradigms for rationalizing complexity

The present and future state of technological and scientific chaos in the ICT field is due to a conceptual impasse regarding the coupling of models, difficulties managing complexity (the folds, the ripples and semantic tissues of different disciplines) and problems ensuring the continuity of certain scales (in time and space) within certain contexts (meaning physical and economic conditions). The mechanisms, limitations and constraints observed in ICT today are all functions of granularity. It is thus the articulation of the various scales that is problematic. We are not doing well in weaving different semantics for different modules in different complex systems. We are having trouble progressing in the physical sciences, in mathematics, in computer sciences, the sciences of systems and symbols, because of the complexity of multidisciplinary questions that we are unable to disentangle, along with the opposite problem of disparate archetypes we are unable to combine.

Towards new models for it interfaces

The fundamental constraint on computer sciences and network technologies remains the continual bottleneck strangulating the junction between the computer and the network, a last-centimeter syndrome in IT, analogous to the last-mile syndrome in fiber-optical telecoms. With the emergence of recent paradigms (overlay structures, web services, active networks, middleware, P2P, grids), and protocols that are still quite young (Session Initiation Protocol) the sacrosanct separation between applications and communications has finally fallen apart. One of the causes of this is obviously the success of packet networks, which do not guarantee quality of service standards sufficient for rudimentary classical services such as the transmission of voice over telephone lines. Yet the most fundamental reason for the glut is that we need to transmit bits of information from one point to another. This process is efficient across an optical fiber, but it is around 1000 times less efficient via wireless, and this transport is run by a specific manufacture (or protocol factory) peculiar to electronic devices, which translates into a requirement for packeting through cumbersome logistical set-ups. The entire field of protocol engineering is trying to reconcile all these factors with a single, rigid protocol stack that is not only not configurable, but which is buried under a "protecting" OS, and which is in danger of overgrowing the stack through non-existent preoccupations with current communications.

Toward new models of hybrid interrelations

The interplay between physical reality and distributed information systems is a major constraint on the development of pervasive computing. This question has been under-estimated again and again. What is impeding the implementation of pervasive computing is wireless communication. The development of methods for the management of the electromagnetic spectrum is a problem that is neglected, or even ignored. Access architecture, the protocols of the transmission layer, security, and radio bandwidth have all been treated in a centralized, hierarchical manner, within a culture of subscription to an operator, via networks originating in the telecoms industry, and related to a family of cellular networks (GSM, GPRS, UMTS, HSDPA, or LTE); moreover, in a very specific and delocalized fashion, these have arisen within IT culture through networks originating in the world of IT (*viz.* the IEEE 802.11 and 802.16 family). We need these constraints to be removed by abstraction (virtual cells attached to devices), in order to reconcile or bypass both the excessively rigid architectures of cellular networks and the simplistic ones from the IEEE family. Pervasive computing will not work until wireless digital communications are adapted and built specifically for the real functions to which they are to be dedicated. New research must concentrate on the underlying communications infrastructure of peripheral networks of femto-cells, self-organizing networks, webs of communicating devices, sensor networks and those of NFC and RFID tags, with a specific mandate to rationalize their management and their interconnection with larger infrastructures (like 3G, the Internet, and the new Galileo GPS system). Moreover, if wireless is to become the physical medium of transmission of tomorrow, governments must open the breach in the spectrum wall that is currently sliced into under-utilized sections, and plan for an audacious and dynamic usage of the spectrum on a global level. We must stop this static allocation of sets of frequencies to specific operators, to finite military and civil applications, and for broadcasting and communication, because the currently allocated electromagnetic spectrum, if we examine in detail the spatiotemporal dimensions of the frequencies actually used, is far from saturated. Research into cognitive radio has also been slow to deliver results. Investigative work on cognitive networks is still quite modest as well: discovery sensors in the multi-radio environment, radio interference problems and both inter- and intra-system collocation, all remain problematic.

Towards new models of representation for software

The last of the constraints, and not the least, is a set of limitations in software engineering: the objet-oriented languages, software components by contract, are still too poor, and yet too cumbersome, to manage any synthesis of different architectural styles and configurations. This essential difficulty arises at the level of architecture modeling. The software intensive systems have their own architectural styles at every level of granularity. This can be seen for instance in object-oriented, client-server, P2P, tier-architectures, agent systems, automatons, and processing algorithms, and all these idioms intermingle in borderlands with which the systems architect must grapple. If one scrutinizes any system in depth, one inevitably discovers a multiplicity of architectures, each adapted to local issues. These architectures are not interconnected in a nested manner like Russian dolls. On the contrary, they are entangled, and this tangled mass is the reason systems are so complicated. Systems engineering is not a science, it's an ad-hoc know-how allowing us to translate awkwardly between techniques belonging to different job descriptions, a way of coherently working together disparate functions of every granularity, which together make up the system. The methods and the tools used depend on the state of the art in many different fields. The difficulty is thus the requirement of juggling these different jobs and domains.

D The engines of evolution: principles for progress in it

In IT, there are governing principles and factors affecting progress, which are seldom spoken. These principles owe their existence to the Darwinian evolution of architectures and devices. They encourage diversity and yet favor a certain regulation of populations coexisting in the ecosystem. These are the principles of enrichment, imitation, separation, fragmentation, plasticity or play (in the sense of latitude), action and reaction. And they have corollaries: separation and play allow the creation of diversity within the fishpond of new solutions that then enter into competition with one another.

The principle of enrichment

In order to grapple with complexity and proceed with the construction of edifices, it is essential to create new abstractions. But to invent new, more efficient paradigms, one must create new models, manufacturing tools with new programming languages, protocols with new techniques for modeling, simulation and dynamic verification. In IT, the enrichment life cycle of a given model sees it successively born, transformed, enriched and made more complex, aged and then mutated in order to survive its own swelling complexity, until being shattered and fragmented into several distinct parts. The successive transformations of systems, software, and products enrich them all, broadening their capabilities with forward compatibility throughout their life cycle. It is the economy of versioning, and now on-line improvement, just-in-time deployment (in the form of patches) that sees them improve, albeit in fits and bursts.

The principle of imitation

When a new procedure or innovative form is healthy, it is emulated immediately, since imitation, with its cutting-and-pasting, is a real part of the consubstantial IT ideology. As an example one can take the new phenomenon of twinning in computer sciences and networks. One can no longer imagine research and development in communications without addressing its IT aspects, just as one cannot analyze perspectives in IT research without examining questions related to communications. The two disciplines of IT and networks are inextricably linked, since IT is now essentially distributed, and the communications field has diversified in terms of its semantics, nature and form: it now includes programs, texts, voice, data, synchronous-asynchronous, point-multipoint, online-offline and broadcasting.

Application-layer IT can no longer even be conceived of without a consideration of communication between apps, a result of the input-output linkages necessary to execute them (via intermediation and P2P architectures, and via computing grids). The classical operating system manages local memory and time for local peripherals; I/O, and in particular client connections (xDSL, LAN, Internet) as well as wireless ones (Wi-Fi, Bluetooth) between computers are becoming far more important than before, in the new methods of work in factories, offices, homes and in travel. Sooner or later it will be necessary to renovate the specifications and priorities of operating systems, and to revise their security to allow for the integration of the newest concepts of nomadic operation, configurability, virtualization and openness in communication, and in particular the secured management of attributes of applications to the various links, something that no OS is really capable of doing today.

In the context of dual convergence (voice/data, mobile/fixed), which is taking more time than initially foreseen to concretize and organize, communications and networking are tackling the new dimension of multi-services. Architectures and network protocols are increasingly using the semantics of applications and services to improve communication performance.

The principle of separation

When an entity becomes too large or complex, it is broken into several pieces and re-organized. These bits are not necessarily of the same order as one another; the metamorphosis of reconstituted parts always gives off ballast, often increases degrees of freedom, and sometimes brings about interesting changes. IT needs to be as simple and efficient as possible. It has a tendency to create minimalistic solutions, the simplest tools that will allow entities to survive and multiply. Yet novice users usually prefer integrated, all-in-one services. This leaves us in a perpetual balancing-act between initial concepts and deployments on the one hand, and the tendency toward feature-creep and complexity on the other. In order to separate tools into modules and simple entities, the use of dichotomies is a powerful principle. This principle is indeed the origin of all the great divides in IT: hardware vs software, computer vs network, and the layer model. In the American project, for a future Internet financed by the NSF, GENI (Global Environment for Network Innovations, www.geni.net), the concept of slicing and segregating the main networking functions of the future Internet obeys this principle.

The principle of fragmentation

As infrastructures spread and begin to age, they have a tendency to break up. They then organize themselves into networks or hierarchies of smaller structures. The IT systems of the 1980s, organized into local networks, were closed, inaccessible fiefdoms. Later they opened up to become interconnected and interoperable. They were then given wireless peripherals with Wi-Fi, and this process will proceed with swarms of RFID.

Tearing the wide electronic board: the web

One can also illustrate fragmentation through the history of the web. Contrary to what people are saying here and there, the Web did exist before 1989. At the time it was a unique, great white board (the word web was in fact an acronym for Wide Electronic Board) that IT professionals used to make appointments and send information in short messages, a sort of universal postal forwarding service. It was then that Tim Berners-Lee tore up the white board by breaking it up into web pages to display on the web's servers. These pages themselves were then cut up into portions to be reassembled on the end-user's computer (with syndication and feeds, in Web 2.0), and there is no reason to believe that these shredded pages will not be further subdivided into a thousand more pieces.

The tools for reconstituting an ephemeral book from these pages are the search engines, with which one can situate oneself in this Inquisition-like book-burning of shredded articles. This tendency will continue along several axes: the deep web of forms that randomize XML, and the Web split into geographic zones around each nomadic user, will regionalize indexations, and the Internet of Things will end up seeing to it that each connected device will have its own blog.

The division of the internet into segments

While the Internet was at first a homogeneous graph, it rapidly became subdivided into autonomous systems talking via BGP through systems of contracts (peering, transit) - to such an extent that the Internet is now a vast assemblage of connected networks, a rough kind of articulated skin like the scales of a snake. Before the advent of too many autonomous systems, we must sooner or later either amalgamate or virtualize the concept of autonomous systems, in order to restrain and secure the relationships between them, by retooling and rejoining the far too divided landscape of the many small and dangerous bits of real estate.

The principle of plasticity

A newly created model or entity introduces something slack, a bit of "softness" into the interfaces used to assemble the modules, a degree of play in the cog wheels, a bit of incompleteness, in order to create the degrees of freedom necessary for innovating during the creation of the application. A model that is too rigid will impede both the construction of applications and the deployment of connections. John von Neumann, for instance, separated hardware from software when he invented his eponymous computing architecture, in order for it to have the essential flexibility necessary to create a free platform, thereby mixing the operations and data, and storing applications. It is the invention of this workspace that spurred the rise of IT.

The principle of action and reaction

When a phenomenon first appears, it causes an inverse phenomenon that provokes opposite effects. When a deployment is made via one channel, there exists an inverse phenomenon of retreat via another. This principle applies today to the appearance, right alongside the Internet, of the Anti-Internet that is Cloud Computing. Indeed, the ability to connect computers and networks has allowed their deployment everywhere. Yet, this interconnectivity has produced a simultaneous counter-reaction, a concentration of computers that has caused a weakening of the role of the network, or at least a radically different use of it, as though conceptually, people were only connected to a single computer. While the Internet is extremely broadly based, we are now witnessing the suffocation of its principal skeleton. All other things being equal, the great arteries of the network are narrowing, and we are seeing an increasing concentration of operations on vast sites of server farms.

Currently the big success stories belong to the Anti-Internet: Facebook subscribers connect to a huge computer on which they have created an IT account with a username and password. From this computer, they send messages and chat live with friends who are connected to the same computer. This is reminiscent of the stand-alone IT architectures of the 1970s, client-server networking over Ethernet, or VAX780 and VT100 alphanumeric screens!

E Two historic parallels

This section briefly describes a history of IT models, reinterprets them through a reticular reading and re-analyses the history of networking models. Through this type of hermeneutics, one discovers a homology between two distant stories, rather like a score with two voices for a fugue written as a canon. This asynchronous parallelism permits one to grasp what might become of future communications in the pervasive digital ecosystem.

The history of the semantics of programming languages: the increasing complexity of abstract data types

1) The invention of the compiler: J. Backus's Fortran

In order to facilitate the writing of scientific programs, what was needed was a simple language and a compiler. IT pioneer John Backus invented the Fortran language in 1953-54 for the IBM 704. He created the programmer's entire job, by inventing Fortran and the compiler: he separated the task of designing computer architectures from that of creating algorithms and formulae, which could now be done by non-electronic engineers. His high-level language allowed the engineer who was unfamiliar with the arcane secrets of memory and registers to abstract his work from the hardware plane and focus instead on the scientific problem he aimed to resolve. The engineer could define and identify the variables of his problem, and conceptualize the flow and subroutines of its execution, while the compiler took care of allocating memory to variables and routing the operations to the registers in the right order. The language distinguishes sequential declarations from the scientific application, and the translation network from loading and execution, a graph of nodes of calculations and links created with the branching of algorithms.

2) An organization of memory: L. McCarthy's Lisp

Lisp was conceptualized and developed in 1956-58 mostly by John McCarthy at MIT [12]. He broke the rules separating the naming and routing of variables when he implemented his Lisp language on the IBM 710 computer of the era. In both the mantissa and the exponent fields for floating-point numbers in the computer's memory, he audaciously placed an integer in the first field, referring to an abstraction in his language and the memory address of the next in the list in the second. In this way he created homogeneous lists and an operational management of these lists, and gave them semantics with operations (CAR, CONS, CDR) in the language for processing the lists. He also introduced meta-programming, making the program and the data more symmetrical: a program written in Lisp could create data that would eventually become a new Lisp program, and programs could now modify themselves during their execution. In brief, this was the great hope of artificial intelligence [13], which has proved so disappointing: the idea of a program capable of writing another program, passing the torch to this spontaneous new generation.

3) The manipulation of pointers and structures: D. Ritchie's C language

The C programming language was created in 1972 by Kenneth Thompson and Dennis Ritchie [14] at the same time as UNIX, to process, according to its philosophy, a sequence of characters (which also required the creation of a text editor). The genius of the C language was to create the notions of pointers and structures: a memory address at the top of a static list and a heterogeneous list of IT entities (integers, floats, tables, or other structures). Without reading and writing numbers, one can therefore make calculations, just by making operations with pointers or with pointers to other pointers. This is the factor that historically contributed to the effectiveness and acceptance of C: the possibility of managing memory in an abstract and efficient way. This capacity for writing tricks is now banished from the methodologies of the software engineering today. The C programmer writes an imperative text and can directly intervene by treating heterogeneous groups of entities, even in a recursive fashion.

4) The abstraction of local programs: the object-oriented class language of A. Kay

Object languages (Simula-67, Smalltalk71, Eiffel, C++, and Java) were the next to appear. Rather than a static structure, they point to the encapsulation of another little program, an autonomous object that is executed with its own attributes and methods and which models an entity of the problem to resolve. A problem is therefore treated in two separate steps, with a singular degree of liberty, as the general program unleashes an encapsulation of thousands of other generic bricks that only take existence as they become reified by spontaneous generation, after being called by an event or a message.

The parallel history of network thinking: link types become more complex

We shall now transpose the philosophy of these languages to the later historical context of networks in order to construct a roadmap of the Internet of the future.

1) The network before 2000 was a grid of nodes and links

For nearly all formalizations, a network is a graph-like grid of nodes connected by links. Graph theory is therefore used to model a network of computers, whether a LAN, the Internet or a telephone network. The underlying tools of graph theory are queues, as governed by Poisson's law [15], and Markov chains [16] for modeling event sequences and finite-state machines. Circuit networks (whether virtual or not) and packet networks are treated in the same manner with these tools, and we obtain Erlang's laws for example to dimension a network. With this concept of the graph, poor yet effective, the network model that is simplest and most efficient is a flat EEG, a fallow field composed of copper wires, fiber-optic cables and the atmosphere, through which electromagnetic waves flow. The nodes are not computers but switches or routers that store, process and forward, and the links are likened to pipes that merely transport bits of information without meaning. One already remarks the distortion that exists between the pipe and a radio wave modulating between two points.

This conception of the network has become obsolete. So much so that every attempt to prolong its use will meet with failure: the naked graph turbocharged into a valued graph, IPv4 simplistically prolonged into IPv6, the old web extended into a semantic web, all trying in vain to concretize rigid ontologies which are by nature ambiguous.

2) The network organized to create homogeneous topological links

During the decade following 2000, the network model has no longer referred in practice to a graph. The search engine, with its success at indexing web pages, has become the entry portal, the yoke beneath which one must bend one's back in order to access the network, which no longer plays its meshing role. Moreover, peer to peer applications construct, beyond the physical network of connection cables and the logical network of routing algorithms, a new virtual network, a topology of computers, disks or pathways, for sharing calculations, files, flows and traffic, beaming computing, storage and communication resources to the virtual level. The link is often defined and provided by a hashing function that fine-tunes the allocation of distributed resources. The hashing table, which identifies the entities and gives the address of the next in the P2P geometry, strangely resembles the homogenous-list memory implementtation seen in John McCarthy's Lisp language.

Furthermore, search engines, which locate resources (web pages, images or video) associated with a series of words, often function based on the popularity of the links associated with the resources themselves. A web page is therefore taken here as a structure that points to similar subsequent structures, and these first links to an applied page allow for the statistical ranking and selection of the pages in question.

Above the physical interconnections of the graph of their material resources and the logical transport governed by IP, we are thus organizing a new dynamic interconnection of entities, rather like that seen in the Lisp programming language. Current IT, considered virtual, functions as though a modern McCarthy had implemented Lisp dialects on the whole internet network, taken as a single memory, with applications (Skype, Napster, BitTorrent, Chord, CAN, Freenet, eDonkey2000) that are concurrently executed on the network, with distinctive list management systems, like giant garbage collectors swallowing up the available resources.

3) The network organized to create heterogeneous links

In the future, in order to reach geographical regions with weak wireless density or poor data rate, it will become necessary to send information using the capillaries of every available pathway (hierarchical routing, radio diversity). To respect the private sphere of a person or a home, it will no doubt be necessary to employ a gateway, a public node (with an IP address known to all). Next, the mobile telephone of the person or the ADSL box of the domicile, serving as a secured gateway, will route the information privately to the private device (a prosthetic control centre or domestic apparatus) using the appropriate routing and security protocols, a lightweight virtualization allowing the creation of a continuous linkage for end-to-end communication.

This description in two stages strangely recalls the pointers and static structures of the C language. This is what already exists on wired connections with bridges and firewalls between enterprise intranets and NAT mechanisms for IP addressing: a more fundamental enrichment of these procedures using the characteristics of wireless communication seems ineluctable and very promising.

4) The architecture of the network will be programmable

In a not too distant future (2020), the network will be "programmable" rather like an application written on the network of an object-oriented language. Tables and routing algorithms will be software object-classes instanced as a function of context, in order to optimize the routing of information and flows between bridges and pathways, which will serve as pointers like the launch address of a class in an object program. We will thus have forgotten the static hashing tables of peer-to-peer applications and will have entered into a dynamic world where the user (or an agent in his service) will be able to transit flows on his own territory, on every scale. The user could even be a telecoms operator if the territory is an autonomous system. The virtual topological architecture of linkages will no longer be constituted by squares, circles, tori, or simple and deterministic geometric forms, it will be a veritable private program, which will allow the formidable issues involved in the safeguarding of private data and digital privacy to be addressed.

V. Toward more transversal concepts of representation

A Toward a complex recursiveness and non-fractal architectures

Progress in microprocessor technologies, new ICT paradigms and the emergence on every scale of networked sensor-activators all permit us to envisage a new age for information processing in daily life. Nevertheless, there are major errors in the exploitation of IT and frequent setbacks in software implementations that contrast starkly with the successes of a few avant-garde IT leaders (e.g. Google and Skype).

IT is not a discipline governed by the equations of nature. It is a pure creation of the mind, with all the resultant advantages (inventiveness, originality) and all its concomitant faults (errors of strategy, prediction, conception, monetization, and usage). The orientation of ICT research is currently situated in the absorption of complexity, the articulation of multiple scales, the betterment of interaction models and the convergence of multidisciplinary approaches.

In order to edify the architectures of these great evolutionary systems (composed of independent, context-aware, adaptive elements which address the issues of mobility and security), the first requirement is research new models of calculation, communication and information. The second requirement is to inject semantics into these systems, for in a mobile and changing world, information must be locally validated. These models need to be adaptable – moving back and forth from being discreet to continuous, from deterministic to probabilistic – in order to be able to envisage the future and explore the environment. The third requirement is to create models of interaction and knowledge for these autonomous devices so that they can be able to learn and interact optimally throughout their life-cycles, along with models for the creation, acquisition, distribution and sharing of knowledge as well as trust models. All these models follow a deeply intermingled growth pattern, one of complex recursiveness allowing them to be tailored correctly for each scale, as computer science is not fractal in its structures.

Next, there are necessities regarding the languages and tools. What is needed is a new conceptualization of programming languages, and languages of interactivity, new data structures for information stored in immense archives, in order better to grasp the relationships between data and IT applications, and better to apprehend the validity, quality and degree of certainty of this information. It will also be necessary to design much more flexible and decentralized network protocols, in order to break the monotony and the symmetry of network nodes, with algorithms of cooperation, coordination and autonomy, to regulate the constraints of scale.

It will ultimately be necessary to develop techniques for verification and validation.

B The great strata of IT

In his book *The Order of Things, an Archaeology of the Human Sciences* [17], Michel Foucault analyses the major currents traversing the human sciences in our age. Foucault deconstructs the human sciences through an archaeological inquiry. In it he distinguishes three strata: the Renaissance, with its system of knowledge based on resemblances, the Classical age, with its ordering of representations, and Modernity, which is centered on humankind.

In computer science there exist similar strata within the ICT world. Thus, in an analogous manner, one could re-read the history of IT and construct an archaeology of IT models, in order to shed light on the various intermingled layers. IT is the science of the organization of symbols: At various times in its history, structural and operational symbols, along with tools for manipulating them, are in harmony, moving in resonance in such a way that technologies are rapidly implemented; at other times, the models, standards and usages are in friction with each other, and impede one another, and one must wait for a change of concepts in order to reform the architecture of the thought system.

A reductionist distillation: the transparent model's paradise lost

There was, in the 1970s and 80s, a veritable flourishing in research and development into languages (e.g. Pascal, ADA, etc.) as well as machine architectures (both scalar and vector). This effervescence was stopped, on the one hand, by the application of UNIX, an operating system that was open between machines and applications and which reconciled hardware and software through its starkness (everything is a file, even the printer is the file /dev/lpr), along with the arrival, on the other hand, of the C programming language, making it very simple to manipulate files (a file is a sequence of characters). A golden age of transparency reigned for a few years among IT professionals, who were delivered from the labyrinth of proprietary machines and from the shackles of dialects and exotic software developments. It was an empowerment of the IT expert. Still today, the promoters of free software are inspired by this bygone world. The reconciliation of hardware and software by the concept of the file has healed the wound opened by John von Neumann. Software engines have been able to spread and become commonplace at universities. This homogenization occurred at the time the elementary Ethernet protocol emerged, when the simplifying architecture of the RISC processor came along, when person-machine interfaces like the screen, keyboard and mouse deepened and personalized the relationship between the programmer and his machine. This sunny spell within the never-ending IT storm has never returned.

Pragmatic and opaque representations: the era of suspicion of a cover-model

That bright era of transparency darkened, at the beginning of the 1980s, with the arrival of the proprietary world (*viz.* Apple, Microsoft) and the idea of the document. This was a period of confrontation between usage models for the general public in which the end-user was supposed to take power. A document is an opaque file for which only one on-screen representation is visible. In order for IT to move into the enterprise, it was necessary to fog the transparency of files in favor of displaying finalized reproductions for office automation in enterprises: The word-processor and spreadsheet, with their board-based presentation, would exert an irreversible influence on the course of IT. The files and folders on desks became images of files and folders on disks, ordered into neat directories. The arrival of the Internet in the enterprise could only extend the office by pulverizing folders (on web servers) and papers (on web pages), spreading them across the network. In order to make this powerful move succeed, it was necessary to open and strip down the notion of the document (via HTML). It was also at this time that IP (Internet Protocol) slowly but surely established its hegemony, thus hiding the underlying heterogeneity of physical transmission methods, with its superior connection principle, which favored the growth of the web, at the very moment that the fiber-optic cable would make its debut, allowing for pure transmission. The success of this model of opacity constituted a closing-off, even a blockade against wired networks, with the triumph of hermetic proprietary routers. A network that was supposed to be open and transparent, boasting a simple and unique protocol suite (HTTP, TCP/IP, and SMTP) became, as time passed, the guarded treasure of a few manufacturers.

A broken representation: the sorcerer's apprentice explodes on the net

A new conceptual stratum appeared in the years after 2000, a universal conquest exploiting democratized local wireless networks and the massive invasion of high-speed end-to-end data transfers. The closed-source program was distributed on the network, took power and created an explosion of data on that network. On the one hand documents, enriched by multi-media, were unlocked and copied across the web through peer-to-peer applications (like BitTorrent). On the other hand, certain documents themselves became software: the Jini concept of Sun Microsystems defined a local network of hardware as a collection of Java programs (a printer here is a Java method that can print a file), and so a PostScript document is a program executed on a particular type of computer which is actually a printer. Active networks even transformed IP packets into programs that run on a specific computer, the network router.

This general disintegration threatened the robustness of the entire system. The unmanaged interdependencies of this fragile edifice risked disrupting society's entire organization. The question of the legitimacy of data transmission can even be asked; net neutrality, the transparency of the network, and the governance of infrastructures are the battlefield of a struggle between economic and political actors. The real freedom of the citizen-consumer and the respect of privacy are no longer certain, thanks to the merchandising of personal data and behavioral profiling. Predators are the great beneficiaries in this chaotic regime. The mastery of this ecosystem escapes all players, like the Frankenstein monster escaped into the north, and the ethical questions are becoming more arduous: fraud, piracy, spying and the destabilization of economic models.

C Toward new models for protean communications

The urbanization of networks is becoming more dense and diverse as digital technologies spread into the daily lives of individuals, businesses and institutions. The networks of tomorrow will without doubt be an interconnected federation of digital ecosystems each having its own methods of computing, communicating and storing information, a fusion that will constitute a kind of reconciliation with physical reality. The heterogeneity of communication technologies, the massiveness of communicating objects, and the diversity of needs, shall all require differing properties for infrastructure, security and management. On the periphery of the networks, it will be necessary to inject versatility into the layers of communication, as well as configurability and adaptability, in order to interact with this physical reality. They will be required to deal with extremely dynamic environments and changing resources, and will have to evolve toward a more implicit and proactive interaction with human users. Content providers will have a decisive role in this context.

A critique of Shannon's model

Writing about digital communication in the context preceding Claude Shannon's theories, Jacques Lacan [18] lamented the situation as early as 1955: "It is about determining the most economical conditions that will permit the transmission of words that people can recognize. No thought is given to their meanings." He may have been a visionary, for the constraints on pervasive computing subsist precisely where the meanings of these abstractions constitute a general failure. The restitution of meaning in the digital world is essential. The key to the deployment of pervasive computing most certainly lies right here. It will be by overcoming the rift between the single biological entity (the body of the end-user) and the volatile, infinitely-reproducible and vulnerable digital realm (the applications, the data, the interface prostheses of the responsible person), and thus by virtue of a grand synthesis between the physical and logical (or real and virtual) planes, that IT will ultimately triumph, putting behind it once and for all the current crisis it is passing through, bogged down as it is by a disparate assortment of complicated solutions that are only accessible to the ordinary user with great difficulty. Information security, as the synthesis of a profound dialectic, will have to surmount its obligation to be ubiquitous and quasi-transparent in order to simplify and facilitate its integration with scientific methods, along with a nearly unavoidable requirement to disappear into the background in order to make IT interactions with human beings less arduous and less hazardous.

Roland Barthes [19] described communication by introducing the concept of an enunciator with an ethics (capable of ἔ θος), transmitting a message with meaning (or λόγος), to an addressee able to interpret it with emotion (given a capacity for πάθος). One can take inspiration from these reflections by Barthes and propose new models of communication that might prove far more adequate for current communications than models lacking semantic dimensions. These new Barthesian- and Lacanian-style models would not be assumed to completely replace the Shannon model, which in any case will always persist on the level of data transmission, but the new models may prove to be of interest on the level of the communication layer, where bits and bytes will not suffice for decision-making processes, when it is necessary to inject semantics into the pipelines. The semantic dimensions will either come from the wireless environment (cognitive radio, cognitive networks) or flow transmissions (such as highly protected banking transmissions, extremely secure surgical commands over the network, and video transmissions in real time).

The current obstacle holding back pervasive computing is the lack of audacity in the evolution of communications and interactions with the environment. IT objects, in the final analysis, are still very isolated, and are not yet able to meld with the ambient space. The process of connecting them to the physical world is fraught with difficulty. Robots have yet to be liberated and are still largely slaves to constant human input. And communication between objects is more confounded still. Pervasive computing must redefine the models of communication between the very nodes of IT. This essentially means a wireless world, as these objects are often moveable (and thus connecting intermittently), or mobile (connecting even while in motion). It is therefore a heterogeneous confederation of cyberspheres of various radically different sizes that will cohabit and coexist, all communicating using protocols that have yet to be defined.

Darcy's laws for porous digital media

One can imagine the ambient digital edifice, rather than overgrowths of computers connected by invisible wires, as a porous 3D environment. We must therefore model the network of its capillaries not as a graph of nodes and links but as a permeable space, of varying textures and viscous shapes, rather like a porous and permeable rocky landscape, and the flows of data that would circulate on it would not then be temporal series or stochastic processes, but like a set of multi-phase fluids (texts, voice, video) that would take multiple pathways, and would percolate through every possible route.

In order to model this network, one must therefore abandon Poisson's laws on the appearance of discrete events and Markov's chains, which formalise the appearance of sequences of characters, in order to seek out new laws governing the permeable flows of text, sound and video according to an information theory of percolation [20], instead of standardizing ordinary sequences of 0 and 1 as packets of information and attempting to mix them all together with a highly uneven quality of service.

If we are to progress, a conceptual leap must be made starting with a "clean slate design". It appears more economically feasible to view IT in terms of fields of pores and to stop thinking of information merely as packets or circuits, but rather flows, on the level of the network and the routers. Darcy's law [21] gives the flow speed of porous environments by defining porosity and permeability in terms of a geometric variable of a space having a viscosity or a texture. It is written $Grad\ P = \mu/k\ u + \rho g$ (where u is the mean rate of discharge or flow, and $Grad\ P$ is the pressure gradient at the extremities of the system under consideration). In place of the traditional web of scales, networks will resemble porous media [22], where the laws of permeability will replace the laws of queues. But these physical laws were obtained through the measurement of physical reality. These are models based upon empirical observation, whereas bits of information are not constrained by gravity or material resistance to movement. In order to obtain an adequate law, Darcy measured the flux in the rocks and fountains of Dijon, and inferred a generalization regarding the universe. IT knows thousands of instances, with their different laws, and there exist models, counter-models and alter-models, according to usage. It will therefore be necessary to conduct research into laws of permeability that are regionalized according to usages and configurations, as there is no providential, fractal and universal law that applies everywhere.

The inertia of the players in question in Europe

Still today, in the perspective of the Internet of the future, tinkering with IP (the Internet Protocol) remains a taboo subject. European executives are opposed to it. Researchers who have built their entire careers upon the paradigm of the Internet are less than enthusiastic about conceiving things any other way, and have no intention of abandoning it. Moreover, research is influenced, as a result of financing, by short-term innovation. What results from this is progress in tiny steps, along with a desire to avoid transgressing industry orientations in any move toward an Internet++. Computer Science, a science driven by the market, needs to protect its freedom in the long term. Unfortunately it is heretical even to think of a post-IP era. Yet it will be necessary to redesign the architecture of communication in general, in a more radical and audacious manner, liberated from the confined realm of current projects.

In Europe, particularly in France, a vicious circle of ideology in the ICT domain researching better digital consumer products, the conservative nature of researchers and the conformity of research institutions have coalesced. They now all contrive to prevent any transgression against current representations, in order not to rock the boat of existing disciplines, and not to disturb traditional organizations (conferences, journals and the gatekeepers of finance). It will nonetheless be absolutely necessary to lay siege to the castles of the Establishment, to clean away the overgrown cobwebs between the silos of mutually isolated disciplines and to wash away the mildew of compromises, if we are to advance at all on a conceptual level along the narrow pathway of ICT's innovative researchers, if we are to stop wandering along the avenues of the consumer-researcher. Yes, research in IT demands audacity, courage and intelligence from the illustrious few [23, 24, 25, 26 and 27], but it also demands validation and industrial implementation along with heavy investment. It is imperative in Europe to reform the public financing of research in the digital domain. We must stop allocating all of the money to those who are reticent and averse to change; we must no longer thoughtlessly transfer funds to docile research centers full of dogmatic and sclerotic experts who are more concerned with their careers than advancing knowledge. Otherwise the resources will be wasted. The former group will asphyxiate innovative SME projects and thereby block progress, and the latter will swallow public funds bureaucratically and continue to nip any debate in the bud regarding projects promising concrete implementations or innovative products that might be based upon frightening new ideas hatched by their impertinent rivals.

D Toward a multilateral governance, with models, counter-models and alter-models

In this paper, we have examined the concepts and underlying conditions for the modeling of pervasive computing as a space-time continuum where one can observe the gravitation of moveable and mobile communicating objects, and indeed an interplay of relationships between the different objects. Perhaps it will someday be necessary to revise this approach once again and to envisage, in a green computer science, a brand new IT that starts with a *tabula rasa,* sweeping away the linear thinking of the old strings of symbols, an information science capable of imagining symbolic machines in three dimensions (morphological computations) and even an analogous "3D thinking," but that is another story altogether.

The geostrategic stakes of geo-localization coverage, which is so important to pervasive computing, are essential here, as the infrastructures of geo-localization allow surveillance, the synchronization of clocks, localization and mapping. The different continents are all attempting to reassert their independence around new constellations of geo-navigation satellites. In any international collaboration, an international thought process will be required. The world's schools of thought are localized, and we shall thus need to begin thinking differently, with other models. With globalization, we shall have to accept new inventions and innovations, and along with them the diversions and renewed successes of various entities. We will therefore need to seek out new frames of reference (models, counter-models and alter-models) and find bridges between these models, especially following the arrival on the IT scene of China and India. A certain audacity will be needed – not to prevent balkanizing communications, but on the contrary to enable the coexistence of aggregates of increasingly autonomous virtual systems with conflicting models, which themselves will be housed within virtualized resources (packets, channels, routes and sessions). Europe, lacking industrial champions, is being excluded from the digital Yalta conference dividing the planetary village into neighborhoods, as Asia takes care of the manufacturing of the hardware while India and the USA take charge of the creation and design of the software. But this future is not written in stone. Rather than some idyllic vision of a future Internet pre-written by marketing professionals, let us count on our own intellectual capacities to reverse this tendency and invent, in a multi-polar vision, the polymorphous Internet of tomorrow. In this ecosystem, there will be cohabitation between entities born in the models of yesteryear, and those born in counter-models from other continents, but there will also be a place for our very own information systems, arising from conceptual alter-models compatible with our democratic values and delivered by our own mathematical culture.

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Beyond the horizon: http://cordis.europa.eu/ist/fet/strategy.htm : technology roadmaps

SecurIST: http://www.ist-securist.org/: ICT trust and security roadmap

Inco-Trust: http://www.inco-trust.eu/: International Cooperation in ICT Trust and Security

ThinkTrust: http://www.think-trust.eu/: ICT Trust and Security Think Tank

Panorama: http://www.perada.eu/: FET Project on pervasive adaptation

FIRE: http://cordis.europa.eu/fp7/ict/fi re/: Future Internet Research and Experimentation

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