ICT Beyond Limits: Computing reality, materializing simulations

The goal of this project is to design future information processing technology that will take ICT beyond the current limits of energy requirements and performances. In order to realize this ambitious goal, the project will require and enable anticipation, insight and validation via simulation through a multiscale approach, from atomic scale including quantum features up to complex system level design. Such simulations will themselves make extensive use of today's most performant supercomputers and distributed computing infrastructures.

Ambition

Information and Communication Technologies have opened up new and unprecedented possibilities for businesses and citizens alike, and have lead to an exponential increment in our wealth and welfare. Also, it is widely recognized that ICT will play a major role in the next decades, where it will be an enabler for the structural changes that our society will undergo in order to become the sustainable society of the future.

Until now, ICT has ensured constant progress due to the scaling down of its building blocks, the consequent increase in computing power as well as the scaling up of the number of interconnected processors leading to massively parallel/distributed computing. But limits are now very clearly in sight that threaten the further development of a number of applications. Those limits are related to heat dissipation and energy efficiency, and also to hitting the “atomic wall” where the components size reaches nanoscale and below.

In this context, the goal of the ICT BEYOND LIMITS flagship is to open new avenues for future information processing technologies to go far beyond the current limits of performances and energy requirements.

To reach this ambitious goal, ICT BEYOND LIMITS addresses the most pressing scientific and technological demands arising from the way technologies, systems and products are and will be designed. It works in two strongly interconnected strands: Emerging hardware and Emerging Simulation.

The part “Emerging Hardware” addresses the following issues in

- **Supercomputer Technology Beyond the Exascale**: The development of supercomputer technology towards the Exascale and far beyond requires the creation of innovative components on all aspects of architectural design, and a mastering of both the limitations and the novel possibilities opened by working at the nanoscale;
    - Immense progress will be achieved in ultra-scalable hardware architectures, optimized energy efficiency and highly scalable storage;
    - The transfer of HPC technologies from the lab to information and communication technologies for business and society in order to sustain the exponential increment in our wealth and welfare. Championing supercomputing at the forefront will be pushing and propagating innovation to all other levels;
    - The development of European ICT technology will reduce dependence and foster cooperation with USA and worldwide;
- **Quantum Technologies**:
    - The exploitation of the full potential of quantum mechanics in information processing,

    - by engineering quantum behavior at the level of logical degrees of freedom;
    - The use of quantum coherence to perform tasks in information processing, communication, sensing, imaging and metrology unattainable by systems behaving classically;
    - The transfer of these quantum technologies from the lab to the real world, leading in the mid- to long-term to entirely new fields of economic activities, and having an impact on everyday concerns like, e.g., security, privacy, data protection and health care;
- **The solution of the power dissipation problem for current and future ICT devices in quantum and supercomputing by answering fundamental questions** on 1) basic mechanisms behind heat production; 2) the way to take advantage of the fluctuations instead of avoiding them and 3) the mean to merge the physics of heat and charge transport with the phonon engineering in order to advance computing tasks.

The technology fields Supercomputing and Quantum Technologies represent the fundament of the Emerging Hardware part of the initiative, complemented and supported by the resource area Phonons and Fluctuations, and deeply connected with the other areas described below.

The part “Emerging Simulations” in turn addresses the following issues:

- The increasing importance of simulations of nearly all real-world problems concerning real, virtual or conceptual complex systems: this requires to rethink models and algorithms. A revolution is expected in the way systems are designed that will rely on simulation on a 10-15 year time horizon;
- The demand for system simulations of ever increasing complexity calls for the development of scalable application codes as well as scalable system software to exploit the full power of supercomputers and distributed computing facilities. Completely novel programming paradigms, program development processes and programming tool chains to address technical challenges of (Exascale) multi-core computing are needed;
- The contributions will come from four operative research areas: three well-developed fields (Quantum Technologies, e-Design and Supercomputing) where maturity and critical mass have already been attained, and an emerging and promising one (Phonons and Fluctuations) where the same progress is to be expected over the next years;
- Quantum Technologies will develop the most radical and promising ideas and technological platforms to bypass the scalability limits of conventional ICT, resulting in:
    - New components and devices that will be elements in the long term in high-performance computing facilities;
    - completely new technologies (quantum communication, quantum metrology, entanglement based technologies);
    - new models of quantum dynamics that will constitute physical input for the e-Design simulation environments.
- Supercomputing Technologies will deliver most innovative all-purpose leadership supercomputing hardware and software technology for key applications, resulting in:
    - Rapid progress in computational power (high performance computing facilities and cloud computing) enabling the simulation environments needed by e-Design;
    - Pushing the transfer of leadingIC-technologies from the lab to business and society;
    - A common software architecture through the development and exploitation of advanced computing facilities to simulate real systems.
- e-Design will revolutionize the way scientific support is addressed, products, systems and technologies are designed, resulting in:
    - Efficient and realistic multi-scale, multi-physics, multi-technologies algorithms and Exascale simulation codes;
    - New computation/simulation capabilities using post-Exascale and quantum technologies;
    - A universal and distributed database at the atomic scale;
    - Innovative CAD tools and intuitive Human Machine interfaces.
- Phonons & Fluctuations will develop a new understanding of basic mechanisms of information transport and energy dissipation for a greener computing technology, resulting in:

    - Lower energy and higher efficient components;
    - Noise-tolerance computational strategies based on fluctuations.
- ICT BEYOND LIMITS targets bridging breakthroughs in science and innovative applications through strong synergies between its components:
    - Energy efficient technologies will develop thanks to advances in theoretical nanoscale thermodynamics, quantum technologies and computing system design;
    - Conversely, e-Design will benefit from advances in physical modeling of nanoscale processes both at classical and quantum levels, allowing "quasi-zero approximation" simulation;
    - Quantum technologies will take advantage of extensive simulations for the design of new components and devices;
    - Supercomputing development will require breakthroughs in computing power and in energy management, possibly benefiting from new computational approaches both at classical and quantum level.

Impact

Due to the comprehensive breadth of the research areas interconnected within the ICT BEYOND LIMITS flagship, a very large leverage effect on European research, funding and economic activity is to be expected.

- First, this initiative will enable the coming of a Second Quantum Revolution which will be responsible for key physical and technological advances for the 21st Century. The hallmark of this Second Quantum Revolution is the realization that humans are no longer passive observers of the quantum world that Nature has given us. In the First Quantum Revolution, quantum mechanics is used to understand what already existed. The difference between science and technology is the ability to engineer your surroundings to your own ends, and not just explain them. In the Second Quantum Revolution, quantum mechanics is actively employs to alter the quantum face of our physical world— developing a quantum technology. Thus, although quantum mechanics as a science has matured completely, this initiative will make possible the emergence of the quantum engineering as a technology;
- Second, this initiative will foster the rise of a new era in the knowledge-based economy where Europe will be leader. In eighteen/nineteen centuries Europe led a cultural and social revolution that changed forever the way people have considered their way of working and living. The invention of heat engines and progresses in thermodynamics were the two faces of the coin that bought such a major advance in human history thanks to the discovery of the laws of heat and work’s transformation. Today we face the opportunity for a new, similar change. The discovery of similar laws at atomic / nano scale might ignite the progress leading to invention of unprecedented nanoscale machines for sensing, actuation and communication;
- Third, this initiative will clearly foster an even stronger structuring of the European research communities involved, leading in particular to a new organized and identified HPC users community (such as those that already exists in the research areas on Climate or Fusion). Also the new components, devices, tools and simulation environments developed within the ICT BEYOND LIMITS will noticeably accelerate research in basic and applied sciences by providing an easy access to up to date simulation means to the research community at large;
- Fourth, it will have important implications for the future European economic competitiveness in areas ranging from wholly new and innovative technologies to improvements in everyday concerns like, e.g., health care, security and privacy of information, data protection. Energy efficiency will be also thoroughly addressed through the understanding and control of thermal properties. ICT BEYOND LIMITS will strive for turning these promises into reality, strengthening at the same time the industrial dissemination of these new technologies and thus helping in bootstrapping the market for their commercial exploitation;
- Fifth, a new service providing business will be developed (providing a return on investment on a pay- per-connect basis), that will allow a large number of SMEs to access up to date

design tools and allow them to do in–house design without unaffordable database costs of ownership. In addition, a number of large scale industry players specialist in system integration will also directly benefit and accelerate the implementation of the ICT BEYOND LIMITS goals.

More generally, it should be noticed that:

- The next few decades will witness the birth of many architectures with homogeneous multicores and accelerator hardware that promise huge performances but will require new efforts to port applications, rethink algorithms and develop flexible software infrastructures. The new multicore era will have a tremendous impacts not only on supercomputing, but also on all scales of computing like departmental or even personal computing; ICT BEYOND LIMITS will ensure not only that the European competitiveness is enhanced by deploying the full power of the next generation of HPC, but also that Europe will be a developer and a provider of these facilities;
- European industry will depend on non-European simulation and database technologies on a 10-15 years horizon: with ICT BEYOND LIMITS, the databases and the simulation environments (including quantum simulators) will become European, thus supporting a European strategic independence;
- Many quantum technologies have gone past the proof-of-principle phase and it is expected that the will reach the market in the ten-year framework. These include: quantum metrology and sensors, clocks based on entangled atoms, nanometer sized rods and cantilevers, quantum imaging, frequency entangled photon pairs for sub-micron biomedical imaging, quantum simulators, quantum communication protocols and networks, and finally quantum processors and computers.

Integration

ICT BEYOND LIMITS builds on fundamental purpose-driven basic-science and technology-oriented research, which truly is of transformative nature, in the sense of leading to exceptional and unprecedented outcomes (the nurturing of this type of research representing clearly the FET mission).

It is multidisciplinary by nature and integrates diverse scientific and technological communities:

- Basic traditional science disciplines such as experimental and theoretical physics, chemistry, mathematics, statistics, engineering and computer science;
- A diversity of disciplines of computer science such as design and implementation of high performance and power-efficient computers, resource and power management, programming models, resilience, performance tools, CAD systems, adaptive databases, artificial intelligence, Human Machine Interfaces, resource and power management, programming models and runtimes, resilience, performance tools and architectures.

All these outstanding communities and disciplines will be federated under the common ICT BEYOND LIMITS initiative, thus forming an unprecedented critical mass that would be needed to ensure Europe’s leadership in the ICT field for the next decades, when the limits on the traditional electronics will be hit. It should be stressed that the theoretical communities in all the aforementioned areas will play an important role in the ICT BEYOND LIMITS flagship: they will push the knowledge of fundamental science topics (quantum physics, and nanoscale thermodynamics, to mention a few) beyond the state of the art, will investigate fundamentally new models and algorithms, protocols and approaches to ICT and in general they will guide and support experimental activity and covering a wide range of physical systems and technologies.

In addition, the ICT BEYOND LIMITS Flagship initiative will heavily rely on the intensive use of European integration centers, specialized labs and clean room facilities for nanotechnologies, large scale research instruments and HPC centers; at the same time it will gather participants from the following industrial sectors:

- "Traditional" sectors such as energy, nanoelectronics, health, materials, transport, aeronautics which, as end-users will be actively involved in specifying the necessary contents and applications to come from the expected revolution of the e-design and the use of breakthroughs coming from quantum/phonon/fluctuation control;
- High tech sectors, including highly specialized SME providing innovative solutions by leveraging the tremendous capabilities offered by novel classical and quantum technologies.

Finally, ICT BEYOND LIMITS will federate and transcend several European research efforts on the subjects of e-Design, Supercomputing, Quantum Technologies and Phonons & Fluctuations, in particular:

- The EMBL, House of Simulation network, ETSF, CECAM++, HM research, JRC PETTEN, GENESYS;
- The Supercomputing E-Infrastructure “Partnership for Advanced Computing in Europe” (PRACE) and PROSPECT, where industrial and academic partners aim at developing HPC technologies, as well as HIPEAC and EESI aiming for Exascale software;
- The FET Proactive Initiatives Quantum Information Foundations and Technologies, NANO-ICT and Molecular Scale Devices and Systems, Zero-Power collaborative projects and communities, Nonlinear-stochastic-dynamics European networks, and, possibly, initiatives addressing atom chips and atom lasers, spintronics, single nano objects and similar topics.

Plausibility

The plausibility for such an ambitious initiative as the ICT BEYOND LIMITS flagship derives from a number of various green indicators and ongoing progress which relates to the different components (e- Design, Supercomputing, Quantum Technologies, Phonons & Fluctuations) of the initiative. These include

- The current irruptive situation generated by the arrival of the multicore era and the prospects of Exascale computing has given opportunities to find ways to attack what otherwise might be a very static industrial dominance position in ICT technology. Championing supercomputing technology at the forefront will be pushing innovation on all other levels. Europe has a privileged position in terms of application and industrial software developers. It also has numerous SMEs and highly recognized research teams providing excellent technologies in areas of system software like storage, programming models, tools;
- Constant progress in the quantum technologies area has allowed many of its branches to go past the proof-of-principle phase; further advancements will be ensured by the integration of the scientific base in order to encompass the full range of quantum information processing from conception to development of devices and from computation and communication to other technological applications of quantum effects;
- Convergences of technologies that are allowed by mastering matter at the quantum level and the nanoscale; this convergence is accelerated by the development of nanosciences and of strategies of technological integration;
- Maturity of the large scale instruments and of their capabilities to validate models of unitary processes;
- Recent progress in theory and simulation both at the nanoscale and for multiscale integration to describe complex systems;

- Recent progress in realization of nanoscale devices and experimental investigation of physical properties at the nanoscale;
- Recent development in atomic and nanoscale science including non-equilibrium thermodynamics and associated basic statistical sciences as well as quantum physics;
- Proactive development of HPC in Europe leading to a large increase of the available computing power (Petaflop-class computers) and of the simulation expertise, following the existing PRACE agenda and the initiatives around Petascale software development;
- Development of distributed computation by cloud computing;
- Acceleration of the research agenda on adaptive databases and HIM;
- Experience of European CAD industry, to master numerical centers and simulation environments;
- Increasing interest in energy efficient ICT for the future reduction of the ICT originated Carbon footprint (SMART2020 report).

In fact, in the past twenty years, with a limited resource available, the e-Design, Supercomputing, Quantum technologies and Phonon & Fluctuations communities have been able not only to elaborate individual research strategies, but also to meet all the timelines identified for the various goals and proofs of principle. From this track of record it is to be expected that the leap in invested effort as well as the federation that ICT BEYOND LIMITS would ensure, will have an extremely high return on investment, with a new wealth of advanced technologies capable of unprecedented tasks being thought, developed and finally commercialized for the benefit and wellness of the whole European society.

Backing from different experts and/or organizations

From the Supercomputing initiative:

The proposal has been in discussion between major partners of the PRACEconsortium. A strong support will be given by the community of computer science research institution, the supercomputing centers and the very large community of users.

From the e-Design initiative:

CAD vendors, PLM providers Large integrating systems industry players Design Houses Physics, chemistry, biology, computing sciences research communities.

From the Quantum Technologies initiative:

QUROPE Governing Board

- Rainer Blatt, Institute for Quantum Optics and Quantum Information, Innsbruck, Austria
- Harry Buhrman University of Amsterdam, Netherlands
- Vladimir Buzek Institute of Physics, Slovak Academy of Sciences, Bratislava, Slovakia
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- Anton Zeilinger University of Vienna, Austria
- Peter Zoller Institute for Quantum Optics and Quantum Information, Innsbruck, Austria

Some of the industrial stakeholders for Quantum Technologies in Europe:

- ARC Seibersdorf, Atos Worldline, Belgian Defense, Bell Labs, Lucent Technologies, BookhamBSI, Bundesamt für Sicherheit in der Informationstechnik Corning, Crescendo Ventures, D-Wave Systems Inc., DANTE, Elsag, ETSI - European Telecommunications Standards Institute, FTTH Council Europe GCHQ, HP Labs, IBM, Zurich Research Laboratory - Identity Management and Privacy Group, id Quantique SA, Infineon Technologies, JDSU Optical Communications groups, JENOPTIK AG, MagiQ Technologies, Inc., Meriton Networks, METAS, NEC, Omnisec, Ovum RHK - Network Infrastructure, Philips Research, Pirelli, QuTools, Senetas, Siemens AG, Smals-Egov, Smart Quantum, STMicroelctronics, Technology Strategy Board, Thales, Toshiba Research Europe Ltd, Zetes PASS, Zurich Research Laboratory

From the Harnessing fluctuations initiative:

- Luca Gammaitoni, Noise in Physical Systems Lab, University of Perugia, Italy
- Jouni Ahopelto, Microsystems and Nanoelectronics, Technical Research Centre of Finland, VTT, Finland
- Bruno Michel, IBM Zurich Research Lab GmbH - Sebastian Volz, Laboratoire d'Energétique Moléculaire et Macroscopique, Combustion, Ecole Centrale Paris, France
- Alejandro Martinez, Universidad Politécnica de Valencia, Nanophotonics Technology Center, Valencia, Spain
- Fshin Ziaei, THALES Research & Technology France
- Francisco Gamiz, Dept. Electronics, University of Granada
- The Catalan Institute of Nanotechnology (J. Pascual, Clivia M. Sotomayor Torres, Sergio Valenzuela and Adrian Bachtold)
- José Sánchez-Dehesa, Universidad Politecnica de Valencia, Department of Electronic Engineering
- BahramDjafari-Rouhani, University of Lille
- Adnen Mlayah, Centre d'Elaborationde Matériaux et d'Etudes Structurales CEMES/CNRS, Toulouse, France
- Lukas Worschech, Technical Physics Department, University of Wurzburg (Germany)
- Fabio Marchesoni, Università di Camerino (Italy)

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