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- status 1 October 2010-

Autonomic Network Computing Science

Brief explanation – *Towards a theory of Autonomic Network* Computing

ICT beyond limits – based on Autonomic Network Computing Science

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Autonomic Network Computing (ANC)

Ambition:

- ICT is at the heart of our society and is totally reliant on the design of electronic information processing systems. The solution will be accomplished by a novel design paradigm, which is based on the principals of the autonomic nervous system (ANS) and which is "**beyond traditional thinking**."

ANC is inspired by the Autonomic Nervous System:

- The organs of our bodies, such as the heart, lungs and others, are regulated by a part of the nervous system called the **Autonomic Nervous System (ANS)** which is part of the peripheral nervous system. It does this without any ***conscious intervention***. In most situations, we are unaware of the workings of the ANS because it functions in an unconscious (involuntary), reflexive manner.

Building ANC:

- **Internet and multicore tera-devices chips** are extremely complex systems with a dynamic behaviour due to the continuously changing environment. Building a complex computer system, such as Future Internet and tera devices-chips, having similar properties to the ANS is a **very complex interdisciplinary problem.** However, the current state of the art does not yet lead to a practical *autonomic computing paradigm*.

The Promise:

- *ANC will allow us to create a FUTURE INTERNET and massively-parallel tera-devices chips as complex systems with a dynamic behaviour in a continuously changing environment (anomalies (faults, failures, attacks, congestion, traffic loads, power consumptions, device variability) that are controlled in an **"unconscious" reflexive manner.*** The Autonomic Computing initiative has defined the following functional areas as the cornerstone of an autonomic system: **self-awareness, self-reconfiguration, self-healing, self-optimization, self-regulation, self-organization and self-protection.** The self-healing property refers to the automatic prediction and discovery of potential failures and the automatic correction to possibly avoid downtime of the computer system. This leads to the vision of "**computers that heal themselves**" without dependence on a system manager.
- While there has been some interesting work on self- healing techniques or mission-critical systems we are a long way to achieving that goal in the Future Internet and tera devices-chips. The Future Internet may not be able to achieve its functional goals because of certain anomalies (node and link failures, performance failures and DoS). Such anomalies will be considered as "normal" properties of Future Internet. However, the Future Network may counter these anomalies by protection mechanisms.

Autonomic Network Computing (ANC) - Why?

- In many cases, the population cannot trust systems processing sensitive personal information to conform to public policies in the realms of **health care, banking, e-commerce, and government without fear of sudden disruption by cyber attacks**. In particular, the vision motivating Future Internet is to enable scalable, available, secure and transparent resource sharing (data and computing) across a widely distributed dynamic heterogeneous network environment.

- The major autonomic properties **self*(awareness, organization, optimization, reconfiguration, regulation, healing and protection**) that will be guaranteed by ANC, will provide uninterrupted service to millions of Internet users if a given event is not tied to one box necessarily or one storage disk. Once you get that kind of leverage, you can build the set of functions that relate to the **self* properties of the Future Internet**. The essential new design paradigm has to **holistically** deal with the fact that the overall environmental is strongly dynamic.

- The question is how to shield that from the end user, keeping the application running. As one of the objectives is to design and develop effective solutions for *virtualised infrastructures*, which are relying on two level virtualization (node and network overlay level) in support of flexible, dynamic, dependable and scalable provision of advanced services for the future Internet (e-Services, software as a services (SaaS), resources as a service (RaaS) and other approaches.) The nodes and the overlays will be defined as a service platform that can be used by any applications and as a consequence, that will be able to support flexible, dynamic, and dependable sets of communication, computation or data services.

- As a result of this, these services will define a basic generic support for a large set of new advanced applications that will get very strong and transparent self* properties. However, future autonomics is not just about self-* functions that relieve the burden on network operations, but is also about implementing self-*functions for self-adaptability, context or situation driven behavior changes in systems, services or applications. A very important notion, implicitly infused to such distributed and adaptive operation is that of *awareness*, at different forms and levels. Awareness is meant in the form of self and environmental knowledge that provides an entity with the required information on one hand and on the other with the mechanisms that adapt quickly and efficiently to variations of the topology and system state. The fundamental concept, behind realizing self-* functions for self-optimization and self-adaptation of an autonomic system, is a *control loop(s)*. Being able to quickly move workload is a critical vehicle for that. ANC will be used to provide a trusted access to information via the Internet. In order to exhibit sustainable behavior and to be able to quickly react to anomalies, the networked system should be able to predict, based on machine learning techniques, its status or anticipated load or anomalies (failures and attacks).

  ANC will allow the creation of **massively-parallel tera-device chips**. Technology scaling has enabled tremendous growth in the computing industry over the past few decades. However, recent trends in power dissipation, reliability, thermal constraints, and device variability threaten to limit the continued benefits of device scaling and curtail performance and energy improvements in future technology generations. The temporal and spatial scales of these effects motivate "holistic " solutions that span the circuit, architecture, and software layers. ANC proposes a "holistic" solution that encompasses self* (awareness, monitoring, healing, regulating, reconfiguration and optimizing) properties of massively-parallel tera-devices chips at different levels of abstraction (from the circuit up to the interconnection & system level). The solution will be accomplished by a novel design paradigm, which is based on the principals of autonomic nervous system (ANS) and is **" beyond of the traditional thinking".**

Autonomic Network Computing (ANC)

- In order to build tera devices massively-parallel systems in nano-scale technologies, the ANC proposes a new paradigm shift towards autonomic complex systems that continuously use self *(monitoring, healing, regulating, reconfiguring, protecting and optimizing) mechanisms during normal operation in the field, without external intervention.
- The interconnection network in autonomic massively-parallel tera-devices chips has a profound effect on their autonomic properties. Low-power on-chip interconnection network is needed, or it will be a key stumbling block for the realization of the tera-device chips. On-chip interconnection network should not just handle communications, they should also drive and shape it.
- Key optimization drivers will be the cost-effectiveness of the "**holistic**" approach, and the minimum impact of the solutions on the system performance and power efficiency. To guarantee autonomic behaviour of tera devices chips several challenging tasks must be solved in order the self-properties to be guaranteed.
- **<u>Impact</u>**
- The results of this will contribute to the realization of many aspects of the long-term vision in the ICT domain by allowing all ICT users, in all disciplines to use and rely on ANC. This will lead in a long run to a potential high pay-off by restoring and increasing the trust of a large number of users into processing sensitive personal information in the realm of health care, banking, e-commerce, e-science and government. Finally, ANC offers one step ahead to define more efficient theory to manage the computing resources.
- **<u>Plausibility</u>**
- The *“**holistic**”* approach for ensuring the autonomic properties of the Future Internet and massively-parallel tera devices will be the intellectual focal point of scientists and university researchers to collaborative efficiently. The level of complexity of these tasks is extremely high and a single team is not capable of solving them, since the ANC is *“**intrinsically interdisciplinary**.”* Therefore, the collaboration work will be established for providing higher availability, QoS and security of the Future Internet and massively-parallel tera devices and will be for mutual benefits of all parties and millions users. ANC will provide *sustainable* services of such large companies in the area of Network/Cloud Computing and drastically improve their level of services.
- ANC will offer a basic platform to achieve greener and more available Internet services because, ANC looks for a better resource management and utilization according to the status of the system. It is not the current main goal of ANC but it is in the long term vision of this theory, which is taking into account the maturing issue in our society nowadays: ***becoming Green Computing systems***
- ***Tera-devices* chips, with autonomic behaviour**, will achieve unprecedented computing power and may have a profound impact on all computer application domains (Internet infrastructure and utilization, network &cloud computing, embedded systems, telecommunication networks, …), and ultimately on science, technology and the society as a whole.

Autonomic Network Computing (ANC)

Work programme topics from FP7 ICT addressed :

Challenge 1: "Pervasive and Trustworthy Network and Service Infrastructures"

•*Objective ICT-2009.1.1.a: "Future Internet Architectures and Network Technologies".*

• ICT-2009.3.6: Computing Systems

•ICT-2009.3.1: Nanoelectronics Technology

Integration :

• *Computational Perspective*: Convergence of Internet and Multicore systems in the future. The Future Internet will be driven by multicore based modules (blades) for the Data centres and transport layers. *Operating Systems (OS), controlling Internet and implemented on multicore systems (tera devices - chips), will drive the Internet .*

•*Mathematical perspectives:* ANC objectives aim to contribute to further development of important scientific areas by formulating new problems to be solved in: algorithm complexity, graph theory, queuing theory, effective learning and prediction, non-linear optimisation techniques and game theory.

• *Social Science Perspective* : ANC will drastically increase the level of thrust of the millions users over the world into the Services provided by Internet – e-commerce, e-science, banking , health records.

•*Economic Perspective*: ANC will guarantee significant increase of the availability, QoS and security of the Internet. As a results of this, maintenance and management costs the of Internet services for million users will be significantly reduced.

•The above underlying framework is required to support: Modelling and simulation transformation for European Growth (including design by simulations and scalable software), Evolution of the Web, Modelling complex economic and social systems and evolutionary social behaviours, Scale free collaboration in large-scale Communities, Ubiquitous complex event processing, Computational Socio-Geonomics, Social Networks.

Comments : (Academic scientists and labs who already occupy this community and are potentially interested in developing the area include) : LAAS CNRS Toulouse-France, ATOS Research Barcelona -Spain, University of Virginia-USA, IRIANC Munich-Germany, TIMA CNRS Grenoble -France, IBM Research Haifa, University of Luebec(CEI) - Germany, University of Klagenfurt & Research Institute on Self-Organizing Systems - Austria, University of Messina-Italy, University of Coumbra-Portugal, National Technical University of Athens-Greece, Carnegie Melon University-USA, Research Centre for Communications Viena-Austria, University of Roma-Italy, University Magdeburg- Germany, Fraunhofer FOKUS- Germany.

FET Flagship Proposal - Pilot Description

FuturICT will form the core of a new revolutionary 21st Century Science, developing information and communication technologies (ICT) to create a decision support system aimed at tackling humanity's grand challenges. FuturICT will accelerate our understanding of social and economic systems and their interplay with our environment. It will do so by integrating sophisticated planetary scale computer simulations with massive real-time data, illuminating paths towards a sustainable future.

A brochure describing the aims of the projects is available at
http://www.futurict.ethz.ch/data/flyer/FuturICT-Flyer-to-view.pdf

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Key partners:
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Steven Bishop *(University College London - UCL, UK; Coordination)*
Tassos Bountis *(Patras, Greece; Complexity-Net and Complex Models)*
Anna Carbone *(Politecnico di Torino, Italy; Smart Energy, Econophysics)*
Rosaria Conte *(ISTC-CNR, Italy; Social Simulation, in particular Corruption)*
Andreas Flache *(Groningen, Netherlands; Social Science, Agent-Based Models)*
Dirk Helbing *(ETH Zurich, Switzerland; Modelling and Managing Complex Systems)*
Carlo Jaeger *(PIK, Germany; Climate, Sustainability, Economics and Policy)*
Janos Kertesz *(Budapest University of Technology and Economics, Hungary; Network Theory, Analysis of Large Socio-Economic Datasets)*
Jörn Kohlhammer *(Fraunhofer Institute, Germany; Visualisation)*
Paul Lukowicz *(Passau University, Germany; Data Mining and Computer Architectures)*
Thomas Lux *(Kiel Institute for the World Economy, Germany; Economics Modelling)*
András Lörincz *(Eötvös Loránd University, Hungary; Education, Privacy and Ethics)*
JB McCarthy *(Cork, Ireland; Business Practices and Stakeholder Engagement)*
Eve Mitleton-Kelly *(London School of Economics, UK; Policy-Maker Engagement)*
Kai Nagel *(TU Berlin, Germany; Supercomputing and Traffic Modelling)*
Björn Ola-Linnér *(Linköping, Sweden; Interfaces for Policy-Makers and Citizens)*
Andrea Scharnhorst *(Virtual Knowledge Studio, Netherlands; Innovation and Social Change*)
Thomas Schulthess *(ETH Zurich, Switzerland; Supercomputing)*
Alex Vespignani *(Institute for Scientific Interchange, Italy; Social Systems, Health and Wellbeing)*

As befits a major project, we are expecting to have around 40 signing partners and a further 115 associate partners. All partners will benefit and be involved with the project, either by organising events or helping in the writing of the final proposal. The ones listed here merely indicate some key areas and connections. Another 200 researchers have declared their support for the project, and are listed on the project website, alongside a number of institutional letters of support. Senior figures will act as members of the Advisory Board. The project will organise widely advertised open workshops and events to facilitate involvement of any interested parties from ICT to the natural, engineering and social sciences. There will be open competition for the Flagship funds, such as international stipends, awards/prizes, and travel grants, irrespective of this list.

http://www.futurict.eu/

Mission
The overall mission of the project is to bring the fields of computer science, mathematics and engineering together with the fields of social science and economics to develop a new **planetary scale data science** and **planetary scale models**. These advances will enable humanity to tackle the urgent and profound global challenges ranging from environmental change and shortages of natural resources to financial and economic instability. These challenges all derive from difficulties in managing our collective global activities and their consequences.

Vision
The planetary scale models developed by FuturICT would be not only massive in scale, but also wide in scope, considering the interactions between the social, economic, technological and environmental systems of our world. Such groundbreaking models can only be constructed by pushing ICT systems beyond their current limits and creating a new planetary scale data science. This new science will encompass real-time acquisition, analysis and interpretation of massive volumes of data from sources ranging from mining of the web and social networks through to infrastructure sensors and personal mobile devices. This data will be used to drive and verify the models and simulations at scales previously unattainable. The new data science will also include novel methods for quantitative and qualitative interpretation and visualisation of both raw data and simulation output, to transform this massive scale data into information that humans can understand and act on.

The primary goal of the FuturICT project extends beyond the scientific desire to understand the operation of our society and economy, and lies in the creation of tools that will be invaluable to policy makers and citizens alike. Specifically, the project will initially focus on the application of the models in three core areas:

- **Crisis mitigation and avoidance**: real-time analysis of raw data input and simulation output to detect early warnings of impending crisis events, including instabilities in the financial system, to enable successful counter-action.
- **Policy exploration:** simulation powered multiple scenario testing of different policy options, in areas such as energy, climate, transport, recycling and waste, health, education and the design of future cities; creation of large interactive multimedia arenas for policy makers, and of online tools and programmable simulation interfaces for citizen interaction.
- **Advancing of science, technology and innovation policy:** accelerating research, development, and the creation of new business opportunities.

State of the art and challenges
To achieve this vision, we must vastly increase the scale and scope of current scientific models and technology. The core challenges can be roughly broken into four areas: a) planetary scale data acquisition and analysis, b) computer architectures and processes for planetary scale modelling, c) human interaction with planetary scale data and models, and d) development of complex models of planetary scale and scope.

Past work has brought advances in data acquisition both from the Internet (texts, search queries, and social networks) and sensor data (data from infrastructures, such as traffic sensors and CCTV cameras, or data from mobile devices). However, current technology does not provide the scale and scope of data required in order to build models of the massive scale and scope proposed by FuturICT. To enable the construction of such models, we need to simultaneously gather data from all of these sources, and do this on a planetary scale. Previous work has also largely focused on offline data analysis. To implement real-time crisis detection and response functionality, we need to achieve real-time analysis of the data. It is also vital that technologies are developed to protect privacy and confidentiality in data mining, storage, and processing.

It is clear that vast computing power will be required to run models of this size. Much past scientific research has focused on developing faster high performance computers. However, the peak performance of such computers is only achieved for particular applications for which they have been optimised. No research so far has focused on optimisation of supercomputers for real-time interactive social data-analyses and simulations. Some social simulations are based on differential equations, and related research in this area may be applicable. However, we expect that new research will be required to optimise architectures for the execution of other modelling approaches such as large-scale agent-based models. Development of the models themselves will also present a challenge. Software engineering methods must be established to ensure model reliability and that changes to the models and their relationship to generated data are reliably recorded. A final challenge lies in the development of programming methodologies to allow social science experts with little experience in programming to quickly code complex simulations.

The recent onslaught of data in our world has led to great interest in interaction and visualisation of this data and models based on the data. The core aim of such work is to transform vast quantities of numbers into information which is comprehensible to humans and can be acted upon. However, the volume of data which will be collected by FuturICT, and generated by its models, far surpasses the size of data sets which have gone before. Equally, the models themselves will be of an unprecedented scale. For FuturICT to be successful, systems will need to be developed which allow users to ask questions and receive answers from these planetary scale data sets and models in a language and form, which is intuitive to the user and conducive to action upon the information. A principal challenge lies in making the FuturICT tools usable in a way similar to today’s web search engines. This will facilitate creation of applications targeting not only political decision makers but also interested citizens alongside broad consumer, business and public service markets.

In complexity science we have seen systems which change in unexpected ways. Emergent phenomena fall into this category. Systems whose structure and dynamics can be represented nonlinearly often exhibit catastrophes, bifurcations, and phase transitions. These kinds of dynamics provide one of the baselines for complex systems science. So far, this focus has been largely developed in direct correspondence with physical systems, where rapid and surprising change is relatively easy to define and simulate. Progress, however, in understanding such change in human systems has been slow. Yet rapid, unexpected change in human systems is not unusual. Indeed, recent discoveries suggest that changes may occur frequently, and that the task of the social sciences is to define systems of interest in ways that reveal such change. The idea that catastrophic socio-economic change is due to the interaction of bifurcations through cascading effects, occurring in parallel and simultaneously, is a helpful metaphor, and it is this thinking that we believe is useful for the development of a science of complexity that is applicable to many global crises contemporary societies face.

Impact

Science and technology

The FuturICT project will lead to substantial progress and major innovations in science and technology. The achievement of planetary scale modelling of human society and its interaction with the environment will represent a landmark scientific victory, a major advance in social science and hence a dramatic step forward in understanding the world we live in. This scientific progress will be made possible through major technological innovation, in the shape of the creation of a new planetary scale data science. This will drive progress across the breadth of Computer Science, in areas such as sensor networks for planetary scale data acquisition; software engineering and supercomputing architectures for planetary scale analysis and simulation; and machine learning and human-computer interaction for informative interpretation and visualisation of these vast volumes of data.

Progress in data science is needed not only in academia but also in business. Here, the recent surge in data available on consumer behaviour and preferences offers desperately needed opportunities to boost profits and fight against the current economic downturn. The scale up in data science that the FuturICT project will bring will lead to both a vast increase in the data available for businesses to analyse, and substantial improvements in their ability to locate and understand the relevant data patterns within this sea of information.

Society

Equally importantly however, the FuturICT project will bring clear and unprecedented benefits for society. The ability to detect upcoming crises will open up a possibility of avoiding them. The ability to explore the outcome of applying different policies in different scenarios will permit well-informed, evidence-based policy-making and allow us to work towards a sustainable society. FuturICT has the potential to move policy forward in a number of areas, including energy, climate, transport, recycling and waste, health, education, and the design of future cities. In particular, the project will focus on informing and improving policy and practice for science, technology and innovation, offering a large boost to the productivity of our society.

Dissemination

To maximise the impact of the project on FuturICT, there will be a strong focus on dissemination of the outcomes, to scientists, business people, policy-makers, and citizens alike. Planned activities include the establishment of a new cross-disciplinary journal; major workshops for business associates, and particularly for start-up companies, for whom insights into new innovation approaches would be of particular interest; media activity, including a strong web presence, but also extending to involvement with the BBC and film makers with whom relationships are already being developed; and arts and technology exhibitions explaining issues around the FuturICT project and its latest discoveries, designed to be accessible to a general audience. Workshops will be organised to assess effectiveness of qualitative methods and in particular the use of narratives for the transmission of ideas to policy makers. The idea here would be to engage with people active in chosen fields but then bring to the table experts from outside the field to share experiences and develop new ways to tackle the global problems.

Ethical considerations

FuturICT will be designed to benefit society as a whole. To achieve this goal, FuturICT will dedicate research resources to investigating ethical issues from the outset, considering a range of issues from privacy of the individual to transparency of policy-making and availability of data and simulations to citizens as well as policy-makers. Furthermore, likely impacts of current and future ICT systems on societies and economies will be studied. A specific committee will be set up to arrange this and expert advice from outside, including legal advice, will be sought.

Integration

The FuturICT project will gather scientists from more than 25 countries, within Europe and beyond, with associate partners joining from the US, Singapore, China, Israel, Japan, amongst others. These scientists are drawn from a range of leading universities including University College London, Oxford, Imperial, London School of Economics, ETH Zurich, Bologna, Politecnico di Torino, Warsaw University and Warsaw Technical University, the Santa Fe Institute, MIT, and Harvard University and institutions such as the Fraunhofer Institute, the Potsdam Institute of Climate Research, CNR (Italy) and supercomputing centres in Switzerland, Germany, and Spain. Links have also been established with existing European Commission projects and initiatives such as Complexity-net, Climate-KIC, PEER, Global Systems Dynamics and Policies, ESSA (European Social Simulation Association), e-Governance, ICT4Peace, and COST (European Cooperation in Science and Technology). The project will also engage with other communities working in social systems, including the Complex Systems Society.

At an unprecedented scale, the FuturICT project will bring together expertise in understanding humans (sociology, cognitive science, anthropology), the systems we have built (economics, political sciences and law) and the environment we live in (geosciences, biology and ecology) with technological expertise (computer science, engineering) and expertise in modelling complex and interrelated systems (mathematics, physics). Input from technological and modelling experts will lead to more advanced models and understanding of human society, and the challenge presented by such large-scale modelling of human society will drive exceptional progress in technology and simulation techniques.

Leadership
The FuturICT project will be coordinated at UCL, ranked fourth in the world in the 2010 QS World University Rankings. FuturICT is strongly in line with UCL's 'Grand Challenges' in Global Health, Sustainable Cities, Intercultural Interaction and Human Wellbeing. UCL is actively establishing mechanisms whereby its expertise and analysis of these challenges can be brought into public fora to engage funding agencies, opinion-formers and legislators. Institutional support means that the FuturICT project receives the backing from a vast array of world leading research experts. Project coordination at UCL will be further supported by expertise from UCL's specialist European Office, where they have vast experience in project management and coordination of major EU projects.

Professor Steven Bishop (Maths, UCL), who will be coordinating the management of the project, has a strong track record of successful collaborative research projects and conference organisation. A recent EC funded grant (GSD) awarded to him together with partners across Europe investigated how a complex systems approach can be used within a policy-making context. Many contacts were made in both industry and government. This experience of crossing into the policy and decision-making domains together with the many contacts gathered will be vital in the research proposed here.

The project will be scientifically led by Professor Dirk Helbing of ETH Zurich, Continental Europe's leading university according to the QS World University Rankings.

Milestones
July 2010 – Open Kick-off meeting, followed by WP think tank meetings, London
July 2011/12 – Formation of Flagship consortium
Jan 2013 – Project commences
2015 – Design of new simulation and data collection concepts, prototype decision arena
2016 – First data collectors and crisis observatories in operation
2017 – First version of a reputation-based quality evaluation platform for innovation
2018 – Parallel world modelling and scenario simulation
2019 – Demonstration of reality mining (new zero-delay sensing applications)
2020 – Visualisation of demonstrator areas
2021 – Theory and concept of sustainable economies
2022 – Planetary scale simulations running

Appendix: Work packages

WP1 Data and Models (led by Paul Lukowicz)

- Planetary Scale Reality Mining (data collection, interpretation, management, etc)
- Architectures and Processes for Social Supercomputing (supercomputing, cloud and grid)
- Human Centric Design for a Comprehensible World (privacy models, user participation, visualisation, tools for building applications)
- Multi-scale Comprehensive Heterogeneous Complex Models (agent-based, analytical, mixed, coupling, etc)
- Crisis Observatories

WP2 Decision Arenas (led by Bjorn-Ola Linner)

- Prototype system
- Interface with technology
- Link to serious games, second life and living labs

WP3 Innovation Accelerator (led by Dirk Helbing)

- New ways of publishing, evaluating, and reporting scientific progress
- Analysis of scientific productivity and emergent fields
- Community detection
- Reputation platforms
- Customized information services
- Co-creation, coordination and collaboration tools
- Turning innovation into practice

WP4 World of Realistic Systems Modeling and Crisis Observatories (led by Janos Kertesz and Thomas Lux)

- Financial Markets and Global Economy
- Social Crises
- Migration and Integration
- Conflicts and War
- Crime, Corruption and Security
- Health Risks and Disease Spreading
- Energy and Green ICT
- Transport, Logistics and Evacuation
- Smart Cities
- Environmental Change
- Scarcity of Resources (water, energy, rare elements)
- Infrastructures (e.g. waste removal and recycling)
- ICT Systems: Security and Societal Impact

WP5 Ethics (led by András Lörincz)

- Privacy issues
- Access to knowledge gained from planetary scale data mining

WP6 Complexity and Governance (led by Steven Bishop)

- Innovative Management of project:

  Complete structure for Flagship; Advisory Board, Scientific Board, Management Committee, Ethics Committee, Conflict Resolution Committee, Training Section, Mobility Section

  Organise 'Kick-off' Meeting open to all to disseminate aims and upcoming events

  Manage links with media and website activities (WP5)

Coordinate regular virtual and physical meetings of the Management, Scientific Committees and Advisory Board.
Coordinate Funding

- Integrative System Design and Institutional Design
- Managing and Embracing Complexity
- Link with e-Governance
- Personalised Education
- Dissemination, Media, Arts, and Citizen Engagement
- Business practices and Stakeholder engagement
  Highlight long term drivers, challenges and policy implications for the EU
  Uncover Emergent Service Enabled Businesses
- Collaborations outside Europe
- Contacts with Policy-Makers
  Think tank meeting to refine strategy
  Liaise with EC NPCs, EC Commissioners and politicians

WP7 Media and Web Presence (led by JB McCarthy)
- Re-design website so as to be open for discussion
- Create extended animated title sequence for increased visibility
- Create short clips to explain the project focusing on the public and younger viewers
- Develop presentations suitable for scientists, policy-makers and the general public – both young and old
- Work with journalists to increase press coverage
- Work with BBC to create documentary for general output
- Science meets art exhibitions for general public

WP8 Collation of Final Flagship Proposal (led by Steven Bishop and Dirk Helbing)
- Liaison between all other work packages to ensure timely and coherent compilation of the the final Flagship proposal

For each work package, signing partners will be commissioned to identify the key challenges and opportunities, as well as the people and business partners best suited to move this forward. In most areas, the work package will start with a one and a half day think tank to scope out the area, followed by typically a two day, open meeting (a Hilbert-type workshop). These meetings will involve the wider community, for example taking place during the European Conference on Complex Systems 2011. Outcomes from a final summarising think tank will be published on-line.

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Consortium

39 partners from 38 countries

eurozone partners

AUSTRIA, BELGIUM, CYPRUS, FINLAND, FRANCE, GERMANY, GREECE, IRELAND, ITALY (COORDINATOR), LUXEMBOURG, MALTA, THE NETHERLANDS, PORTUGAL, SLOVAKIA, SLOVENIA, SPAIN

additional european partners

BULGARIA, CZECH REPUBLIC, DENMARK, ESTONIA, HUNGARY, LATVIA, LITHUANIA, POLAND, ROMANIA, SWEDEN, UNITED KINGDOM

associated partners

ALBANIA, CROATIA, ICELAND, ISRAEL, LIECHTENSTEIN, FYR OF MACEDONIA, MONTENEGRO, NORWAY, SERBIA, SWITZERLAND, TURKEY

institutional partners

FOOD AND AGRICULTURE ORGANIZATION
OF THE UNITED NATIONS (FAO)

Project coordinator

The project coordination will require adequate geographical location and administrative support from the host institution, and thus the host will be agreed within the consortium.

Contact person

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FEDERAL WATER ADMINISTRATION

DRAFT PILOT DESCRIPTION
15 SEPTEMBER 2010

Mission

The continuing mission of the project is to use Information and Communication Technologies to defend the human right to water [4]. The vision of the project is to strive to reach the next level of safety, efficiency and environmental responsibility, being ultimately accountable to the people.

Moral rights and moral duties inform the mission. The moral rights inspire the following measurable impact on people as users of the service: 1. sensibly higher quality of life for partners suffering water scarcity; 2. guaranteed delivery of a minimum amount of safe water at low cost; 3. transparent, ethical business; 4. lower cost of water as a service; 5. uniformly high quality of service among partners; 6. education on efficient use of water; 7. e-Government service.

The moral duties inspire the following measurable impact on people as managers of the service: 1. Establishment of the *Federal Water Administration* (FWA) from the local water authorities of partners; 2. Establishment of the FWA *Standard*: (a) harmonization of local policies; (b) harmonization of local implementation of policies; (c) harmonization of the costs of water as a service; (d) real time monitor of performance and accountability; (e) real time detection and containment of leaks; (f) annual report on performance, accountability and financial results; (g) annual report on the economic impact of water on the economy (see, for inspiration, the report by the Federal Aviation Administration [3]); (h) e-Government service. 3. Establishment of the FWA *Recognised Organization* certification, to state that the named organization meets the FWA Standard.

The *Investor in People* international standard inspires the bottom line impact of the project: 1. embed strong change, culture and leadership; 2. reduce cost and wastage; 3. deliver improved skill levels and flexibilities; 4. increase commitment, effort and results; 5. improve competitive edge, reputation and performance; 6. keep challenging and reaping the rewards.

Motivation

"Water is an essential resource for life and good health. A lack of water to meet daily needs is a reality today for one in three people around the world. Globally, the problem is getting worse as cities and populations grow, and the needs for water increase in agriculture, industry and households. [The *World Health Organization*] urges everyone to be part of efforts to conserve and protect the resource." [5]

In 2003 I proposed to consider as a human right the minimum water quantity for short term survival, as indicated by the *World Health Organization*, and proposed to do so by amendment to the *Universal Declaration of Human Rights* [8, 1]. Water became a human right the 26th of July 2010 [4].

Still in 2003, at the same congress held in the island of Sardinia, I described the mismatch between the state of water emergency in Sardinia [12] and the leaks from its network, with local losses up to 80% [10] and 200% [14], and average losses of 62% across the island [13]. To those who have experienced water scarcity, wether not the complete absence of water, the problem is now perceived as a personal offence. As water is now a human right, class actions and criminal charges are likely to follow. Still concerning leaks from hydric networks, the most recent report to the Italian Parliament literally states that "the situation appears generally out of control, both in terms of awareness and containment measures" [15, p. II]. An old report suggests average losses of 30% across the planet [11]; its results may not be fair to the facts, being Italy part of the survey. "At the beginning of the twenty-first century, the Earth, with its diverse and abundant life forms, including over six billion humans, is facing a serious water crisis. All the signs suggest that it is getting worse and will continue to do so, unless corrective action is taken. This crisis is one of water governance, essentially caused by the ways in which we mismanage water." [2, p. 4]

We need *materials and methods* to deliver court-safe water management.

Materials and Methods

The project will replace all human activities currently involved in water management, eventually leading to an autonomous system. The project will gradually bridge the gap, with measurable progress on the state of the art.

To set off in the quest, we shall first build a geographically distributed system of sensors and actuators, with a logic and numeric management system at its core. The resulting system is a non-humanoid robot.—Concerning the method to achieve this specific aim, we build directly upon our experience. Our scientific modelling of human causal reasoning led to the introduction of a symbolic logic whose range of correct applicability is adequate to control the above non-humanoid robot [6, 9]. On the engineering side, we invented a method of water management that builds upon twenty years of experience and solves the problem of network leaks [7]. We experimented the method in a residential area suffering water scarcity, reducing leaks from 30% to 7% in just five months. Our engineering method of water management uses our scientific model of human causal reasoning.—Concerning the materials, we need sensors and actuators that are both reliable and sufficiently inexpensive to cover the European hydric infrastructure. Our experience to date shows limitations of available technologies, necessary research and related business opportunities.

Further or concurrent research will focus on robots with sufficient dexterity to dig, lie and repair pipes, to name the simplest of duties.

The establishment of the Federal Water Administration, as described by its impact, requires legal help from the Commission. The core of the FWA's back office consists in the above mentioned logic and numeric management system, being the mind of the eventually autonomous system. The project is open to competing approaches, welcoming its partners to engage in relevant research, development and experimentation.

COMPUTED MEDICINE (CompuMed)

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Carlos Díaz	Synapse Research Management Partners, Spain [*project manager*]
Heinz U. Lemke	Technical University of Berlin, Germany
Molly Maleckar	Simula Research Laboratory, Norway
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Our vision encapsulates a new and revolutionary ICT infostructure that will unlock the potential of 21st century healthcare by making completely personalised, and dynamically optimised medical knowledge and guidance transparently available to doctors, patients, and many other stakeholders. The concept entails a modular trans-national unifying architecture that provides appropriate access to diverse sources of information, with principal functionalities based upon constantly improving/evolving probabilistic graphical models (PGM) of disease entities, individual patients, and medical processes. This elegant and feasible solution will solve the innate complexity challenges of today's and tomorrow's medicine, such that medicine will never be the same again.

CONSORTIUM

This proposal reflects the combined wisdom and strategic vision of four high-profile biomedical communities that work actively on advanced ICT challenges in biomedicine and healthcare, and interact closely with policy makers, national and regional healthcare authorities, regulatory bodies, and funding agencies, all of which will benefit or contribute to this endeavour:

G2P: Genotype-to-Phenotype Databasing
VPH: Virtual Physiological Human
CARS: Computer Assisted Radiology & Surgery
AMEE: Assoc. for Medical Education in Europe

Together, these communities comprise well in excess of 200 organisations and companies that explicitly support the CompuMed vision, with direct extensions into many hundred other collaborating projects and groups worldwide.

The ultimate configuration of the Flagship Consortium will be determined by the profiles and expertise needed to successfully undertake the enabling tasks in the project, and many others will be engaged as we leverage a range of national and international funding. The project will therefore emphasize flexibility, openness, dynamism, and efficiency, to enable so many players to interact and synergise effectively.

IMPACT AND UTILITY

The CompuMed solution will exploit the totality of relevant biomedical and patient specific knowledge to enduringly benefit European societies in short, medium, and long terms, by enabling:

- Healthcare to change from being generalised and reactive to **personalised and preventative**
- **Reductions in national healthcare costs** by promoting more effective & earlier interventions
- All individuals to **live longer and healthier**
- The **transfer of best practices** and evidence-based successes across national boundaries
- **Improved training** for medical doctors

Key stakeholders will be empowered and benefit from the system, as follows:

- **Healthcare Institutions** will assess and optimize medical procedures for substantial outcome and cost improvements on the basis of PGM evidence
- **Medical Societies and authorities** will establish validated standards and/or guidelines for medical activities of physicians, patients and the healthcare community at large

- **Industry** will respond with innovative ICT systems integrating patient-specific PGMs and clinical process/workflows based on cutting edge hardware, software, and application technologies
- **Physicians and Patients** will interact and communicate on the basis of a unified representation of the patient-specific PGM and its transparency features realized through ICT systems
- **Physicians** will employ simulation technologies to deliver objective and reproducible medical procedure analysis, understanding, learning, prediction and decision making
- **Patients** will take advantage of a wide spectrum of functionalities for their healthcare planning
- **Learners and Educators**, via interactive patient simulations, will revolutionise medical education in ways that place the patient at the centre of students' decision-making and safe practice, whilst also advancing shared European objectives in medical competencies.

'WHAT' WE AIM TO ACHIEVE

We aim to rapidly and progressively deliver a new, personalised, information-rich, and self-optimising, approach to healthcare. This will provide doctors, citizens, policy makers, and many other stakeholders, with real-time access to the best possible information and guidance on disease entities, set in the context of each specific potential patient.

We therefore propose a practical infostructure which employs information and knowledge integration technologies (web services and workflows, semantic web linked data, federated and central databases, syntax and semantic standards, etc) in conjunction with probabilistic graphical models (PGMs) adapted for healthcare settings. Mathematical modelling has previously driven major advances in science and engineering, and it is now the time to do the same for medicine. In particular, understanding specific patient situations and medical processes will benefit from a solid foundation of modelling methods, and so CompuMed will:

- provide a simple and intuitive way to create, visualize and manage 'knowledge constructs' of the patient and the medical workflow process,
- assist in gaining new insights into the multiplicity of (probabilistic) variables and properties surrounding patients and medical processes,
- provide complex computational functionalities, such as simulation, decision making, intervention and validation to enable advanced inferencing and learning.

The ICT system underlying this will also provide access to a wealth of information sources that feed, contextualise, substantiate, and explain the PGM-based outputs (e.g., literature, database entries, information sites, Electronic Healthcare Records (EHR), real-time and stored patient biometrics, environment, outputs from diagnostic devices, etc). Indeed, the absence of any such information brokerage capability today already creates an 'information overload' for doctors, causing real-world medical care to be inconsistent, uninformed, and biased by subjective opinion (see Figure 1).

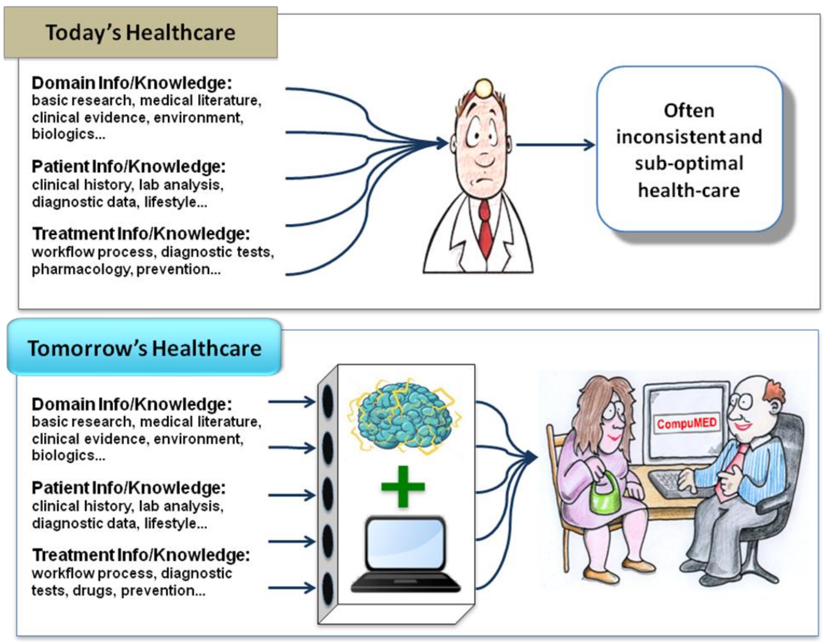


Figure 1.

Critically, however, our proposed 'ICT mediated' strategy for enhancing the practice of medicine is explicitly not aimed at replacing the role of the doctor. On the contrary, it aims to assist the medical professionals who are impossibly burdened by trying to be all-knowledgeable in the face of rapid and overwhelmingly large and complex advances in diagnostic and interventional procedures as well as in biomedical knowledge produced by 'omics' and other advanced technologies.

The infostructure we have conceived to achieve all the above is based upon 'Gateways' and 'Navigators' (see below for further details of these elements), which together not only provide the functionalities described above, but also enable multiple stakeholders (health professionals, patients, healthy citizens, etc) to contribute 'crowd-sourced' updates to the system's knowledge base and its PGMs, thus influencing and optimising the computed decision options for disease prevention, prognosis, diagnosis and therapy. This important dimension means that the systems utility and accuracy will thus steadily improve as a direct result of its own usage and feedback loops built into it to enable it to learn!

'WHY' THE PROJECT IS NEEDED

Many ICT-based projects are underway, contributing towards the goals of understanding and/or manipulating life, health, and disease. This ICT landscape includes such things as research on Personal Health Systems, Biomedical Informatics (spanning bioinformatics through to integration and exploitation of EHRs), and the Virtual Physiological Human, with modelling and simulation being increasingly considered. But these piecemeal activities alone will not suffice to transform medicine in the way or pace at which it needs to be transformed. Critically, there is still a structural 'gap' between potentially useful research and actually used research results in healthcare settings, a gap that will only widen as current medical practice is progressively unable to deal with the rapid growth in size and complexity of extremely varied, relevant knowledge. There also needs to be a definitive plan for achieving the universal deployment and operation of any proposed solution.

There is therefore an urgent and definitive need for:

1) an ambitious, unifying, and yet practical ICT vision that engages all the key research communities towards one common, concrete solution;
2) a strategy that is designed from the outset to harness all of the most relevant biomedical and ICT advances, to securely orchestrate all the background information and knowledge, and to deliver PGM-based optimised healthcare to all citizens; and
3) an ICT based educational support layer for the infostructure, tackling issues such as increasing training constraints, the lack of consistency in standards and competency, and the need for training that mimics as closely as possible the role of the practitioner whilst providing students with self-directed personalised learning opportunities.

'HOW' THE PROJECT WILL BE EXECUTED

Many of the raw materials needed for CompuMed are already emerging, or are on the horizon. Our task will entail innovating ICT mechanisms to tie them together and exploit the consequentially emergent functionalities relevant to our objectives. For example, internet protocols are continually improving, linked web pages are giving way to linked data networks in the semantic web, grid and cloud computing are becoming a reality, bioscience databases are growing in number, sophistication, and uniformity/interoperability, EHRs are becoming widespread and increasingly powerful, genotype-to-phenotype relationships are being elucidated, wearable, implantable, and remote biosensors and devices are being developed and implemented, multi-scale computational models of human biology are emerging, and PGM languages are taking shape.

We will exploit all of these resources, via a globally distributed and locally enacted information management architecture (see Figure 2) that will organise discrete categories of extant subject matter via ‘**Information Gateways’** and ‘**PGM Gateways**’. Content will be channelled via these Gateways into software applications that provide various ‘**CompuMed Navigator’** functions supporting many possible use cases.

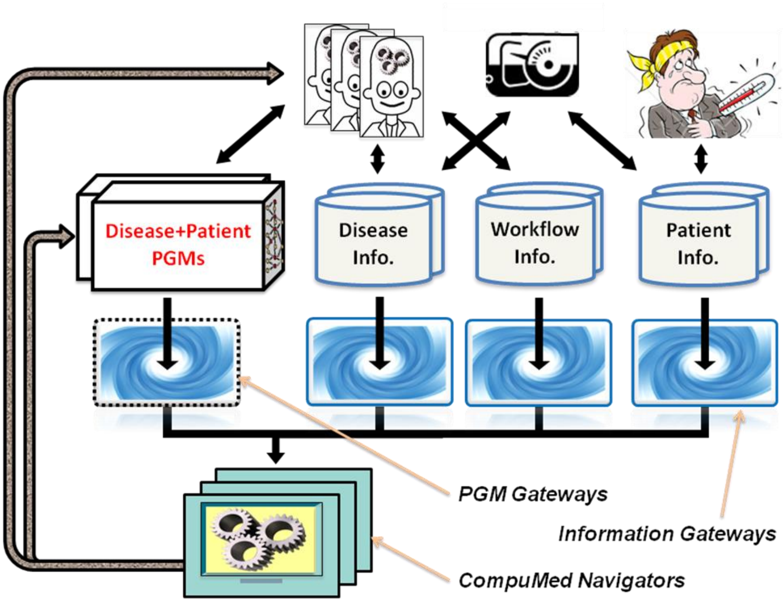


Figure 2.

Stored and real-time content relating to the ‘Disease’, the ‘Workflow’, and the ‘Patient’ (whether generated by humans or by a diagnostic instrument, and whether locally or remotely located) will be made accessible to humans and other computers via the Information Gateways. The all-important PGMs themselves will be stored in dedicated repositories, and accessed through PGM Gateways. CompuMed Navigators, tailored for different user types (citizens, doctors, researchers, authorities, etc), will then pull required content from the Gateways to present it to users and/or to use it to calculate healthcare options. Thus, for example, doctors and patients alike would be able to seek personalised guidance regarding a specific disease diagnosis, prognosis, and treatment options. Concomitantly, users could reach through the Gateways to determine the detailed basis for that guidance, and navigate on to seek further relevant knowledge.

Information availability and Automatic Optimisation of the System: Large amounts of non-personal research and biomedical data, information, and knowledge, will be placed online, and hence made available to the CompuMed ICT infrastructure. To maximise this resource, we will bolster our existing joint efforts with e.g., DataCite for data publication, semantic web initiatives for linked-data promotion, the OBO Foundry for biomedical ontology coordination, HL7 and other data modelling efforts, web services developers, and creators of healthcare workflows. Digital IDs for human actors online will make it possible to unambiguously track who is making online contributions, so that such activities can be recognized and rewarded, and hence promoted. Anchor IDs for this are soon to be enabled by the ORCID initiative in which we play a leading role, providing a starting point for us to build upon.

Importantly, however, it is not essential that all non-personal biomedical information be accessible online for CompuMed ICT functionality to become operational; the system's ability to generate guidance itself is the critical factor - and this depends primarily upon the global biomedical community steadily contributing to the different repositories (as described above) according to their domain-specific knowledge and experience.

The final category of information that the system will typically need to access would be person-specific biometric, diagnostic, and health-related data. This will include such things as EHR content, information entered manually by individuals (stored and interactional), diagnostic test data (in real-time), and outputs from various kinds of health monitors. Ultimately, much of this will be organised into purpose built, highly secure repositories. Once everything is fully in place, radical new capabilities become possible, such as; the automatic re-assessment of an individual’s healthcare status each time a new relevant biomedical discovery is made; and real time, holistically integrative evaluation of data feeds from biometric sensors to detect early disease indications.

Further than that, as the system becomes more pervasive and widely used, it will enable a wealth of clinical outcomes and experiences that can and will be fed back into the underlying disease representation constructs to make them more complete, precise and useful. This self-optimising behaviour of the system will eventually become largely automated as the ICT underpinnings of the system become increasingly sophisticated.

Security and ELSI Considerations: The core ICT system described above will make biomedical information and knowledge potentially exploitable in ways never before possible. However, that exploitation must be undertaken in a manner that ethically and legally respects and protects all stakeholders - not least the patients themselves. Hence, an additional layer of ICT based security solutions and innovations will be an integral part of the total system. Security components will include advanced encryption mechanisms, remote interrogation protocols, anonymisation procedures, and federated authorisation strategies, deployed according to the differing sensitivities of the various structural and information elements. The use of federated digital identities for each human actor in the system (patients/public through to doctors and researchers) will ensure that unambiguous and equitable access policies and security functions can be applied in seamless ways across the globe. Clearly, the ethical and legal aspects in all of this will be paramount, and so the project will instigate a dynamic and pro-active panel of experts to guide on such matters.

EDUCATION

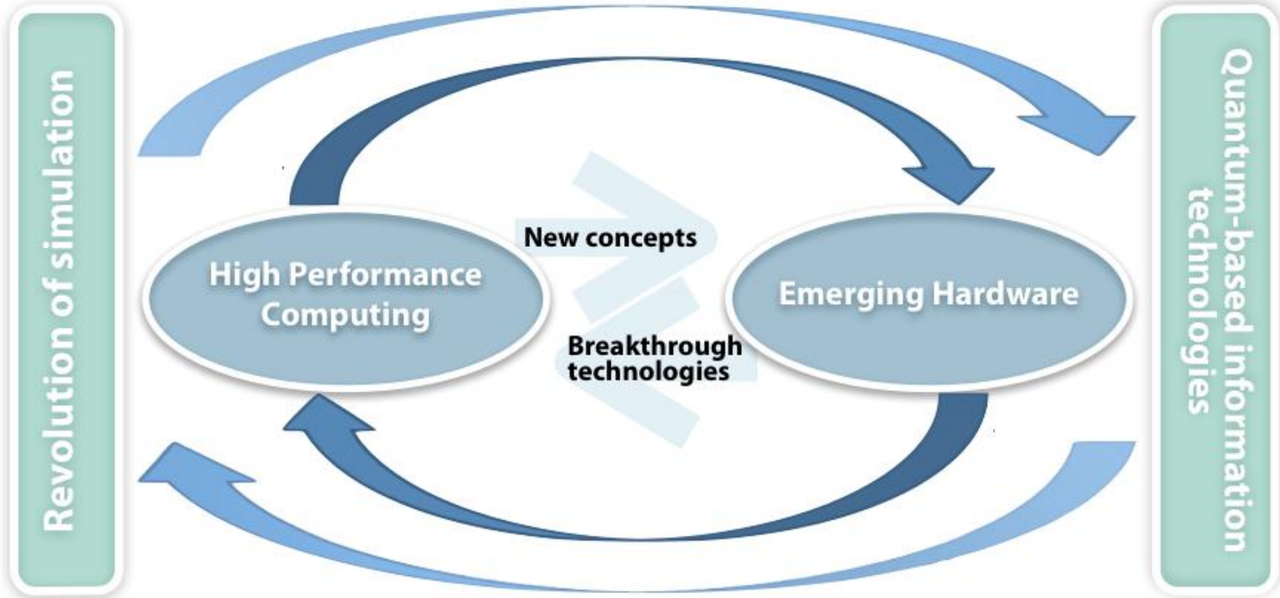
The CompuMed ICT approach will additionally emphasise the opportunity to research and develop multi-scale patient modelling systems capable of instructing students in all aspects of medical training, from clinical sciences to clinical procedures and management. These anatomically and physiologically interactive simulations, will be made able to access existing EU EHRs to mimic management of individual patients. These models could form the core components of a common medical curriculum framework adapted to recognised healthcare standards and competencies for Europe. Real-time clinical data (authenticated and anonymised) from distinct European states can provide regional Model-Based Medical Evidence (MBME) to harmonise learning and reflect national cultures and priorities.

GOVERNANCE & MANAGEMENT, COMMUNICATION, CO-FUNDING

The size and complexity expected of a FET Flagship demands sound, flexible and dynamic structures and procedures underpinning the initiative on all levels, and professional project management capacity has been already involved in the early scoping stages of the proposal. The primary approach in CompuMed is based on the application of accepted international project management standards, modulated according to the specific needs and characteristics of the endeavour, so as to ensure maximum efficiency without distorting the scientific creativity by means of an exaggerated bureaucratic overhead. Flagships will necessarily have an "open" philosophy that allows for participant change, with flexible work plans and financial flows. It is therefore anticipated that, aside from 'traditional' scope, schedule, cost and quality processes, change control will occupy a key position, and dynamic evaluation procedures (guiding selection and approval of the optimal tasks, contributors, methods, quality levels and resources needed at each step) will have to be innovated through careful design. As significant funding is expected to be leveraged complementing the core FET contribution, raising of funds will be subject to specific attention – involving proactive communication with all stakeholders, particularly authorities and industry. Actually, and as a high-impact initiative, CompuMed will need to be incredibly permeable to the outside world, so communication will be one of the core processes. The uncertainty inherent to any research activity is maximised in the case of visionary undertakings, and as a consequence risk management will also be reinforced so as to rapidly adapt to ever-changing circumstances. Although a preliminary plan for governance and management is already in place, it is expected that the Pilot action will serve as test-bed for any potential approaches to management.

ICT Beyond Limits

Quantum-based Information Technologies



The ICT Beyond Limits concept. Current simulation capabilities will enable designing disruptive hardware, leading in turn to revolutionary simulation potential with which new hardware can be developed, in an endless loop.

Barcelona Supercomputing Centre, Barcelona, Spain

Bull, Bois, France

Centre Européen de Calcul Atomique et Moléculaire (CECAM++)

Centre National de la Recherche Scientifique (CNRS), France

Chalmers University of Technology, Gothenburg, Sweden

Commissariat à l'énergie atomique (CEA), France

Consorzio Interuniversitario per il Calcolo Automatico (CINECA), Italy

Dassault Systèmes, France

Delft University of Technology (TUDelft), Delft, Netherlands

ECT* - Fondazione Bruno Kessler, Trento, Italy

Edinburgh Parallel Computing Centre, Edinburgh, UK

European Laboratory for non-Linear Spectroscopy, Firenze, Italy

European Theoretical Spettroscopy Facility (ETSF), Louvain-la-Neuve node, Belgium

Finnish IT Centre for Science (CSC), Espoo, Finland

Fyzikálny Ústav Slovenskej Akadémie Vied, Bratislava, Slovakia

IBM Deutschland GmbH, Böblingen, Germany

Institució Catalana de Recerca i Estudis Avançats (ICREA), Barcelona, Spain

Institut National de Recherche en Informatique et Automatique (INRIA), France

Juelich Supercomputing Centre, Juelich, Germany

Karlsruhe Institute of Technology, Karlsruhe, Germany

Leibniz Rechenzentrum (LRZ), Garching, Germany

Niels Bohr Institute, Copenhagen, Denmark

Noise in Physical Systems (NiPS) Laboratory, Perugia, Italy

Österreichische Akademie der Wissenschaften, Austria

Poznan Supercomputing and Networking Centre (PSNC)

QUITEMAD Consortium (Universidad Politecnica, Universidad Complutense, Universidad Carlos Tercero and Consejo Superior de Investigaciones Cientificas), Madrid, Spain

Swiss Center for Scientific Computing (CSCS), Manno, Switzerland

The Chancellor, Masters and Scholars of the University of Oxford, Oxford, UK

University of Geneva, Geneva, Switzerland

Universität Ulm, Ulm, Germany

VTT Microsystems and Nanoelectronics, Finland

MISSION

Information and Communication Technology (ICT) has opened new and unprecedented possibilities for businesses and citizens alike, and has led to an exponential increment in our wealth and welfare. Evidently it will also 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. But limits are now very clearly in sight, and threaten the constant progress ensured up to date by the scaling down of its building blocks and the consequent increase in computing power, as well as the scaling up of the number of interconnected processors and the resulting massively parallel/distributed computing. Those limits are related to heat dissipation and energy efficiency, and also to hitting the "atomic wall" where the components size reaches the atomic scales.

The aim of the ICT Beyond Limits Flagship initiative is therefore to design disruptive quantum-based information technology that will take ICT beyond its current limits of performances and energy requirements. This ambitious goal will be realized through

- The development of ICT from atomic scale and quantum features up to complex systems delivering unprecedented solutions both in terms of performance and efficiency;
- A revolution in simulation capabilities via a multi-scale approach, involving extensive use of today's best High Performance Computers (HPC) and distributed computing infrastructures.

STATE of THE ART

A radical evolution of the way technologies, systems and products are designed is underway in many industrial sectors. High Performance Computing (HPC) is a base technology, an instrument enabling progress in nearly all areas of science with ever increasing impact as enabler of technological progress as well. For example, pharmaceutical companies are increasingly using HPC to design new drugs in silico before attempting to synthesize them, improving significantly the process efficiency. Also, supercomputers have become indispensable instruments for the theoretical understanding of quantum computing devices, research in error corrections or the prototyping of actual devices; similar examples can be found in the domains of Materials Science, Nanoelectronics and New Technologies for Energy.

Multi-scale simulations will profoundly change the scientific and technological practices. In order to fulfill the promise of digital engineering of materials and products, nanoscale building blocks must be transferred in a series of hierarchical simulations at much larger scales. Products and systems design requires completely rethinking modelling-optimization-simulation chain including multi-physics, multi-scale and multi-model environments and access to standardized large-scale databases.

The need for always more computing resources requires in turn mastering heat exchanges at the nanoscale. In this domain, a unique convergence of knowledge from different fields, enabled by development in concepts, theories, experimental techniques and novel materials, allows to understand in a comprehensive manner the role of confined and coherent phonons and fluctuations in nanoscale thermal transport, coherence, non-linear phenomena and energy-efficient communication technologies.

For many years the performance of supercomputers has been increased in a twofold manner, coupling more and more processors up to the few hundreds of thousands in today's largest systems, and by increasing the clock frequency. Having hit the power wall that stalled the increases in frequency, the current progress solely relies on the increase of the density of integration both on processor and system level. Reducing the device feature sizes enables the integration of many cores on one chip. Meanwhile, the continuous reduction of the feature size is approaching the limit where quantum effects start to render current devices unreliable. Ensuring that devices can continue operating properly at finer feature sizes is an extremely important research challenge for the future. Here, interdisciplinary joint research of computer science with experts in quantum computing will soon become mandatory to achieve progress.

Even though the multi and many core evolution is still providing significant improvements in peak performance (with heterogeneous systems with power efficient components for specific problems being designed, and many more appearing probably in the near future), all progress towards the Exascale comes at a significant cost in terms of programming complexity and difficulty, ensuring the efficient use of the resources. In the near future however it will even be impossible to simultaneously power up all the components in a chip. Huge research efforts are required to identify what will be the best combination of component types and functionalities and how to efficiently schedule operations, while ensuring that programming is kept simple to be handled by computational scientists efficiently.

One possibility to bypass these problems is to change today's digital model physically underlying computation/execution for those components (cores). For instance, quantum computing models and devices exploiting fundamentally new modes of computation and communication may help drastically changing the time complexity for solving some important problems.

Indeed, Quantum Information Processing and Communication (QIPC) is a vigorously active cross-disciplinary field drawing upon theoretical and experimental physics, computer science, engineering, mathematics, and materials science. Its scope ranges from fundamental issues in quantum physics to prospective commercial exploitation by the computing and communications industries. Most QIPC platforms fall roughly into two major categories: atomic, molecular and optical (AMO) systems and solid-state systems. Hybrid QIPC systems and interfaces between different platforms can be expected to gain a decisive role in the next ten years for quantum repeaters as well as for truly scalable quantum processing architectures.

European research is currently at the leading edge in QIPC, which has the potential to revolutionize many areas of science and technology, because it is based on the physical laws of quantum mechanics instead of classical physics. It holds the promise of immense computing power beyond the capabilities of any classical computer, it guarantees absolutely secure communication, and it is directly linked to emerging quantum technologies, such as, for example, quantum based sensors.

IMPACT

A very large leverage effect of ICT Beyond Limits on European research, funding and economic activity is to be expected on the basis of the comprehensive breadth of the research areas interconnected within the initiative as well as the following observations:

- The next few decades will witness the birth of many architectures with homogeneous multicores and accelerator hardware at all scales, from HPC facilities to desktop PCs. These promise huge performances but will require new efforts to port applications, rethink algorithms and develop flexible software infrastructures. 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 its strategic independence.
- Many quantum technologies have gone past the proof-of-principle phase and it is expected that they will reach the market in the ten-year framework (e.g., quantum metrology, sensors, clocks, sub-micrometre biomedical imaging, simulators, communication protocols and networks, as well as small quantum processors and computers). ICT Beyond Limits will provide Europe with a leading edge in the future market where the quantum limits will define the performance of industrial applications.

The impact of the ICT Beyond Limits flagship can thus be hardly overestimated; in particular it will

- Enable the coming of a second Quantum Revolution, responsible for the key physical and technological advances for the 21st Century. Quantum mechanics will cease to be only a mere explanation of Nature's law, as in the first Quantum Revolution of the 20th Century, and actively deployed as a means to engineer our world, leading to the development of disruptive quantum-based technologies.
- Foster the rise of a new era in the knowledge-based economy where Europe will be leader. In the 18th and 19th centuries the invention of heat engines and progress in thermodynamics were two faces of the same coin - a major advance in human history. Today we face the opportunity for a comparable change. The discovery of new laws at the atomic and nm scale may ignite the progress leading to invention of unprecedented nanoscale machines for sensing, actuation and communication.
- Foster an even stronger structuring of the European research communities involved, leading in particular to new HPC user communities (e.g., bioinformatics, health and medicine), such as those that already exists in the research areas on Climate or Fusion. The new components, devices, tools and simulation environments developed within the ICT Beyond Limits will also noticeably accelerate research in basic and applied sciences by providing an easy access to up to date simulation environments to the research community at large.
- 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, energy efficiency, security and privacy. ICT Beyond Limits will foster the adoption of these new technologies at the industrial level, and bootstrap the market for their commercial exploitation.
- Develop a new service providing business (with 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 for affordable in-house

design. In addition, a number of large scale industry players specialist in system integration will also directly benefit and accelerate the implementation of the flagship goals.

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. 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.

The federation under the common ICT Beyond Limits initiative, will give rise to an unprecedented critical mass that will ensure Europe's leadership in the ICT field for the next decades, when the foreseen limits of micro- and nanoelectronics will be hit. In addition, ICT Beyond Limits will heavily rely on the intensive use of European integration centres, specialized laboratories and clean room facilities for nanotechnologies, large scale research instruments and HPC infrastructures. At the same time it will gather participants from the following industrial sectors:

- "Traditional" sectors such as energy, electronics, 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 control;
- High tech sectors, including highly specialized SMEs 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/Nanoscience, Supercomputing and Quantum Technologies, including:

- 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, clusters of projects on nanophotonics and nanophononics, and, possibly, initiatives addressing atom chips and atom lasers, spintronics, single nano objects and similar topics.

ICT BEYOND LIMITS: FLAGSHIP PILOT CSA IMPLEMENTATION

WP1. Governance, Legal issues, Exploitation and Internal monitoring and Evaluation

This WP has several parallel and interacting tasks.

Governance. We will explore models of governance to build in the ICT Beyond Limits structure and procedures. The objective is to promote a dynamical process of integration and, simultaneously, to enable internal progresses monitoring an internal and external evaluation. Researchers, funding agencies and members states participating in the initiative will be consulted with a particular attention on governance models in comparable initiatives (EIT, ETP & JTI, etc.).

Governance will be considered at two levels:

- At the flagship level for the coordination of the different technical parts towards the unifying goals and the policy aspects;
- At the technical subprograms level for the to-be-decided real or virtual clustering of scientists.

Legal issues. Intellectual property, strong deviations of the agreed milestones and legal aspects of the FF consortium agreement, will be discussed from the start. This is particularly important if the flagship takes the role of an advanced research funding agency of projects contributing to the overall objective, running calls and evaluations. A benchmark of good practices in similar ambition initiatives will be used as a starting point.

Exploitation. ICT Beyond Limits is expected to generate substantial innovation which needs to be assessed for its transfer to stake holders. Methods will be explored to come up with a suitable periodic exploitation plan and optimal coordination with the Dissemination WP.

Internal Monitoring and Evaluation. Evaluation of the research and its relevance towards reaching the stated goals will be crucial to ensure convergence towards unifying goals. Thus, mechanisms for a timely internal and external evaluation will be considered and discussed at the project design stage. A key issue here is to strengthen motivation and integration as well as scientific excellence and reactivity.

WP2. Feasibility, Financial plan and Sustainability

This work package encompasses support activities designed to prepare a comprehensive financial and sustainability framework for the launch of the ICT Beyond Limits flagship. The first objective will be to analyse the economic and administrative requirements for ICT Beyond Limits, taking into consideration the objectives and the RTD long term strategy and operational plan developed in parallel within the Research Agenda work package (WP3). During the analysis we will identify and approach potential complementary funding sources including the different national and European administrations as well as other sources and/or revenues coming from the project's activities. We will evaluate the balance between estimated costs versus assured and foreseeable investments and include a risk analysis identifying situations in which the objectives of the project can be compromised. The latter will be done taking into account not only the 10 year duration of the flagship but also the general viability of the actual exploitation of the technology in the future. The outcome of these considerations will result in a financial and sustainability plan for the actual launch of the ICT Beyond Limits flagship.

WP3. Research Agenda

The main purpose of this WP is to develop a comprehensive, visionary yet feasible research agenda to approach the flagship's unifying goal of bootstrapping the quantum-based information technology era. This will start from the existing deep synergy between the different research components and the corresponding scientific communities. Existing roadmap documents[1] will be screened, reviewed and reshaped to match the ICT Beyond Limits vision, while at the same time a novel long-term strategy and action plan to reach the flagship's common objectives will be elaborated. To assist in this ambitious task, task forces composed by renowned experts in the various fields will be set up and actively involved during all preparatory phases.

WP4. Outreach, Visibility, Dissemination and Industrial/International links

This WP is divided into several parallel though intertwined tasks.

Outreach, Visibility and Dissemination. We aim to implement various dissemination measures in order to maximize the impact of the CA and to promote the ICT Beyond Limits concept. In particular, we plan to address the following audience:

- *RTD community* who can benefit from the scientific outcomes and technological progress achieved by the project (e.g., via publications and/or conference presentations);
- *Industrial groups*, to raise the awareness on the emerging quantum-based information technologies;
- *Policymakers*, to showcase how quantum-based technologies open up new horizons for solving pressing scientific, industrial as well as social problems by offering qualitatively new computational and communication resources for dealing with complex problems;
- *General public and sciences writers*, to appreciate the transformative role of modern quantum-based science and technology.

Industrial links. The project will directly interact with industry, in the context of both developing quantum-based information technologies and exploring the market base. In particular, it will organize an "Industrial Forum of Quantum-based Information Technologies" with the purpose of making potential industry partners aware of presently available and oncoming quantum-based technologies solutions.

International links. With the goal in mind of establishing Europe as the world-wide focal point of the activities in the field of quantum-based technologies, we will:

- Establish close links with research groups in our field world-wide, setting up where possible bilateral agreements leading to scientific collaborations/partnerships (closely addressing IPR issues);
- Contact funding agencies in USA, Japan, Australia, China, BRICS countries with the aim to establish large joint research facilities (e.g., integrating projects) that would allow for faster progress in the field.

[1] For example the HiPEAC vision www.HiPEAC.net/roadmap, the report by the NSF blue ribbon panel on Simulation-Based Engineering Science www.nsf.gov/pubs/reports/sbes_final_report.pdf, or the QIPC roadmap qurope.eu/content/Roadmap

ROBOT COMPANIONS FOR CITIZENS

A 5-PAGE ROADMAP TOWARDS A FLAGSHIP PROJECT

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This document anticipates a proposal for a CA to be submitted by 2 Dec. 2010. It is a follow-up of a paper presented at the Brussels FET-Flagship presentation June 9-10, 2010. That paper was supported by as many as 95 European experts working across multiple research disciplines. These include, roboticists, neuroscientists, social neuroscientists, psychologists, to name just a few. During the last 3 months, support has increased from many additional organizations and individual experts.

For a complete list of supporting organisations and individuals, see:

www.robotcompanions.eu

Encouraging contributions to this Roadmap came also from many colleagues, experts, researchers, industrialists, and politicians from almost all member states in Europe.

MANIFESTO OF "ROBOT COMPANIONS FOR CITIZENS"

A NEW GENERATION OF SOFT-BODIED SENTIENT MACHINES WHICH ACT AND INTERACT WITH THEIR PHYSICAL AND SOCIAL ENVIRONMENT

THE ORIGINS

Over the past 50 years, robotics has enabled worldwide economic and social progress by allowing large-scale production of many goods at lower prices and better quality. In addition, it has liberated humanity from many dangerous and tedious tasks. Robotics has a vital role to play in humanity's future. Indeed, humanity is facing new critical challenges including: the aging of the population, increasing urbanization and an expanding need to maintain the environment. Furthermore, new wealth generating industries are also vital to support a changing European and World economy. In fact, in 40 years from now, *nearly 35 per cent of the population of Europe is projected to be 60 years or over and* we should consider now how to evolve toward a society where this part of the population will remain creative, productive, autonomous and independent. Furthermore, the existing healthcare systems will not be able to support the elders at the level they do today. Another trend in worldwide demographics is that the *population will tend to live in urban centres that will continue to grow in size and density*. This creates great challenges for a broad range of adaptive real world technologies including waste disposal, infrastructure maintenance (sewage, wires, structures, etc.), quality of air, and transportation. A third and related challenge, that is a major liability for our current welfare state, is *the deteriorating state of our natural environment* which demands a completely new approach towards monitoring, preservation and management of natural resources; once again, we believe that robotic technologies can come to the help of humans.

We envisage that in order to maintain the quality of life of the population, we require a new class of machines and linked technologies that will fulfil a variety of assistive roles: *the robot companions for citizens*, a *new generation of "soft", sentient machines* which will help and assist humans in activities of daily living, in workplaces like factories and hospitals, in infrastructure maintenance and environment monitoring and preservation, thanks to their capabilities to *act and interact physically, emotionally, socially and safely with humans.* Robot Companions will give us the chance of *improving our **quality of life** and will be the key tools for the foundation of a new affordable welfare for all citizens*. They will be ubiquitous and user-friendly; they will preserve and augment human capabilities and experience and *extend the active, independent life of citizens*; they *will maintain our planet*. Thanks to Robot Companions, social services will pass from *information-based* to *action-oriented* paradigms with physical (not only "mental") support: Robot Companions will promote the paradigm shift from "Information and Communication Technologies" (ICT) to "Information, Communication and Robotic Technologies" (ICRT).

Furthermore, these technologies will promote *new industries and opportunities for worldwide commercial exploitation* and, most importantly, provide Europe with actively linked science, technology and industrially connected communities to exploit future emergent opportunities. These technologies arising from new disruptive scientific findings have, if achieved, a huge potential social and economic transformative power: comparable to the introduction of the steam engine, the radio, the automobile or more recently the Internet.

ROBOT COMPANIONS ARE SOFT, SENTIENT AND PREDICTIVE MACHINES

Robot Companions will be radically different machines; needing bodies made of purposively designed new materials, implementing a novel conceptual integration of solid articulated structures with flexible and compliant properties (soft-bodied robots) and new levels of perceptual, cognitive, emotive and behavioural capabilities including advanced social intelligence based on internal cognitive models of themselves and the environment based on our understanding of their natural analogues. These advances will allow reaching a new level of gentle, graceful interaction of robots in our physical and social environment based on safe and dependable physical contact, mutual understanding and anticipatory behaviour. We call the machines based on this blending of physical and behavioural compliance "soft robots". This approach will require not only to develop new scientific knowledge and to solve formidable technological challenges but also to implement solutions which are economically sustainable, socially acceptable and industrially attractive and feasible.

Robot Companions and humans *will mutually understand and adapt to each other*. They will symbiotically interact and communicate through multiple-channels of communication deployed by us and other animals, including gaze, shared attention, natural language, physical interaction and gestures. Robot Companions will not simply be tools (like a manipulator or a calculator) helping the human to execute 'routinizable' tasks, but they will be interactive partners sharing goals with humans and be participants in an extended mind. They will not be limited in shape to humanoid robots (they could be a wearable robot, animaloid, or have a completely new shape), and actively observe and sense the environment and understand humans' physiological and psychological state and will adapt their operation and act accordingly. We envisage Robot Companions as an "ecology" of compliant sentient machines of *extreme sophistication* developed at the levels of their *single components* up to their *behavioural, assistive, social* and *cognitive skills*. The range of robotic assistive technologies is nearly limitless and devices will be employed in all areas of human activities including maintenance of personal, social, domestic, business, leisure, physical and industrial environments, providing medical assistance in the care of patients and improving the quality of life for the healthy, elderly and disabled persons - robots will continuosly accompany and support us in our daily personal and social lives.

Robot Companions will be *sentient machines*. Indeed, while operating, they will not execute their tasks in a stereotyped way. On the contrary, they will be cognizant of the scenario, and of its human factor, in which they operate, and will shape their motion, their actions, their communication, and their expression, in a way that they are appropriate to the situation, in other terms, they will be able to "understand" humans, other animals, physical systems and each other and act accordingly.

Robot Companions will have *predictive and decisional capabilities* based on their experience. They will operate with completely new algorithms for shaping their own experience of the world and form their *memories and interpretations of real world scenarios*: they will use their experience to continuously enrich and strengthen their skills of problem solving, of perceive what other agents want from it and of predicting the consequences. In order to proper behave in all possible scenarios, Robot Companions will have to continuously "decide". However, its knowledge source is also humans and their actions and advice, web technologies and other robot companions.

We should not imagine Robot Companions as the result of the *current robotics design principles*. Rather, ***Robot Companions will be disruptively new kinds of robots employing adaptive and self-organizing technologies based on new scientific, technological and social objectives***. Their body shall not be limited to a rigid metallic frame; their joints to be ball bearings; their sensing apparatus to force and position sensors; their actuation to electrical, pneumatic or hydraulic actuators; their transmission system to steel cables; their "intelligence" to digital centralized computing units; their energy source to electro-chemical batteries. On the contrary, for Robot Companions we intend to explicitly and systematically address the discovery and use of: novel integration of lightweight, solid, articulated structure with soft, compliant, multifunctional new materials; distributed and intelligent sensory, actuation and transmission systems; light weight and silent actuators; migrations between embodiments; new joints mimicking human articulations and distributed neuromorphic control systems. Robot Companions will take energy from metabolic-like chemical pathways and will implement biomimetic energy-harvesting strategies. Robot Companions will have superior, refined perceptual, cognitive and motor skills: they will be capable of an emotional, social, and even emphatic, interaction with humans. Machines featuring these variety of novel physical and cognitive properties can emerge only from a completely new design process. Instead of the current CAD/CAE systems, human designers will need the massive use of computational resources for generating concepts, for their iterative evolution and for the selection of optimal solutions. There is again a lot to learn from Nature in this area, e.g. for scaling down the evolutive process that allows to develop the same capabilities we wish to embed – and embody – in Robot Companions. This vision provides the necessary springboard for the creation of new European industries – not only for complete systems but the design and creation of the myriad new sub-assemblies and processes from which robots are constructed.

Needless to say, to realize this kind of artefact, a new scientific and technological paradigm is required, and its related communities, have to be formed, supported and networked to commercially exploit these new technologies and ideas by existing European industries and new ICRT branches.

FROM STATE OF ART ROBOTICS TO THE GRAND SCIENTIFIC CHALLENGE

Nowadays robotics has reached a great level of advancement. Robots are accurate, fast and dexterous in unstructured environments. They can perform many tasks, such as: effectively produce goods, perform surgery, explore Mars, or serve humans as prostheses. Nevertheless, robots are only modestly able to meaningfully and safely interact with humans, to autonomously realize tasks at any level of complexity, to experience and explore unknown environments, let alone to blend seamlessly into the complex, social everyday world of humans. On the other hand living organisms, from human beings to so-called "lower animal species", can perform complex tasks, such as: simultaneously executing and coordinating multiple motions, effectively exploring their external environment, adapting to novel situations, expressing individual and collective intelligence, surviving injuries, adapting to external and internal changes (e.g. aging) and self-repair. They are able to accomplish these tasks in spite of the nervous system's long delays as compared to silicon-based computational systems in transmitting and processing information, stringent physical world constraints and unexpected events, and energy rationing.

The logical consequence of this analysis is that the development of the Robot Companions for Citizens is **definitely not just a technological challenge**. Rather than the progressive advancement of the current ICT technologies, "Robot Companions for Citizens" asks for new scientific avenues and findings. At the core of this approach is the belief that the development of this new generation of robot companions should be grounded in our understanding of the most advanced machines we know: animals. This will range from the highly effective and specialized solutions to specific tasks found in insects and mammals to the general purpose adaptive and predictive capabilities of perception, cognition, communication and action found in humans. The fundamental point is that the identification of the key design principles underlying biological sentient machines will allow us to engineer a wide range of synthetic ones that might be biomorphic, anthropomorphic or express fully novel body-brain configurations. The engineering of these systems will not be a blind copy of biological solutions but will advance **our understanding of the general design principles which evolution has generated to build bodies and brains and will exploit this understanding to build a new generation of robots: robot companions**.

Furthermore, this Flagship forces the pace of new technologies to realize these concepts. The detailed investigation of natural psychological and social systems will also lead to a better understanding of the key features that can make a machine a companion: that is **really effective** in helping humans, collaborative and cooperative within the real world. Robot Companions for Citizens is a **science-** and **engineering-driven** initiative, whose scientific mission is **complex** and **broad.**

As a result of this analysis, the key question is: "*which features of living beings do robot companions need*?", and more specifically, "*which features of living beings would we like to see in our robot companions?*", finally we can ask "*which features would we like to see in our robots that living beings do not have?*". Furthermore, more central to the present proposal is the identification of the kind of scientific knowledge we need to gather and jointly develop to answer these questions, which disciplines we need to bring together, which new ingredients that have not be explicitly considered so far, will give us a solid opportunity to solve these formidable problems.

By answering these questions and attempting a new roadmap, we can define the GRAND scientific challenge of this FET Flagship initiative "Robot Companions for Citizens", which is: **to unveil the secrets of embodied intelligence of natural sentient systems (such as humans) that makes them capable of acting, interacting and adapting effectively to their physical and social environment and of being cognizant and sentient of this relationship to the world**.

This grand scientific challenge subsumes that we aim at understanding: the principles underpinning the *mind-body* (or *structure-function*) *relationship*, (or in other terms the role of "matter" in building the mind), the principles of *neuroscience*, and the principles, which make living beings *cognizant* and *sentient*. Eventually, by investigating the "mind-body relationship", "neuroscience" and "sentience", Robot Companions for Citizens will pave the way to the new **"science of companionship"** and in general of emerging social processes in networks of cognitive systems (natural and artificial). The essential ingredients of this new scientific paradigm are: soft robotics in its "mindware" and "bodyware" components, the fundamental design principles underlying biological brains that allow them to operate in complex physical and social environments, soft-materials sciences addressing structure, sensing, actuation, mechanical and signal transmission, and last but not least energy production, storage and scavenging. Indeed, within the Robot Companions framework, several specific scientific challenges will be investigated in the following research fields:

- *Robotics and the morphology-behaviour relationship in living beings*, to understand how adaptive, anticipatory behaviour emerges in humans and animals from the complex and dynamic interaction between the body morphology, the sensory-motor system, and the environment;
- *Neuroscience and the organizing principles of the sensory-motor system at any scale* (i.e. cell-scale, tissue-scale, system-scale), to understand the strategies for the information processing and fusion of the redundant and distributed animals sensory system and understand how the brain efficiently, acquires, analyses, memorizes and retrieves sensory information (from various sources) for orchestrating coordinated and complex actions and to explore the human biomechanics and human motion control strategies, with a focus on the mechanism underpinning "graceful behaviour" (motion gracefulness);
- *Systems Neuroscience* with the goal of understanding the generic design principles of brains and the processes that allow their development, adaptation and maintenance in the real world;
- *Social Neuroscience, cognition and principles of human-human, human-robot and robot-robot interaction* in order to make it possible that robot companions can interact in a natural way with humans (e.g. gesture, gazing and language interpretation; shared attention), recognize human emotions and empathy, experience the feeling of body ownership, in other terms, be sentient machines based on the brain's capabilities to be sentient;
- *Energy storage, production and harvesting*, to investigate biomimetic solutions for energy generation, harvesting and management;
- *Soft/flexible/adaptive material sciences* in order to identify the fundamentals of the body softness, at any body level: skin, muscles, joints, realize components based on soft materials; to develop biological-artificial hybrid systems (i.e. bio-hybrid and bio-artificial actuators and sensors, e.g. artificial muscles);to catch the ultimate physical-chemical properties of the biological materials constituting the sensory motor system;
- an integrated approach towards the development and implementation of the architectures of robot companions that includes *Principles of Knowledge accumulation*, to identify means whereby knowledge gained from various fields, e.g. robotics, neuroscience, material science, social sciences, psychology, energy can be appropriately integrated into the implementation of the robot companions;
- *Human and Social Sciences*, to favour the social acceptability of the robot companions and the human robot co-existence and to develop new areas of the engineering of the psychological and social capabilities of robot companions.

THE METAPHOR OF THE "DANCING ROBOT" AND THE OTHER COMPANION EMBODIMENTS

The metaphor of the chess player has been a source of inspiration for artificial intelligence and as such has been a fundamental challenge in the early years of the discipline. Nowadays computer programs can successfully compete against chess masters and, even if these programs have only contributed marginally to our understanding of how human intelligence can be reproduced artificially, they have certainly contributed significantly to the advancement of information technology. Since the golden years of the chess player challenge artificial intelligence has evolved toward a more embodied view leading to the current approach of cognitive robotics in which the main view is that intelligence must develop inside a physical body.

Within the Robot Companion we are proposing to raise the level of embodiment by considering explicitly the kind of physical matter used to build the body and to consider it as an integral, intimately linked aspect of intelligence. In addition we want to move beyond "intelligence" and "computation" to the more inclusive notion of sentience that subsumes perception, cognition, emotion and action. In humans and other biological systems, sentience is a multi-technology and multi-level achievement and our ability to interact softly with the environment and with each other is based not only on the operations performed by the brain (our neural components supporting "mind") but also on the elasticity of our muscles, the lightness of our bones and the flexibility of our skin and sensors (our "matter" ingredients). We intend to demonstrate that only through a blending of such ingredients in a new science of robot companions, which has never been attempted systematically, it will be possible to unveil the secrets of embodied sentience of human beings and animals and to realize artificial systems with the mental and physical softness found in these biological systems.

In other words **we want to move from the brittle AI of the chess playing machine metaphor to that of the adaptive, predictive and socially intelligent "dancing partner robot". Such an embodied intelligence is able tolearn from and also to teach humans how to dance using the multi-modal communication channels which humans employ intuitively. A robot with such capabilities and properties provides us with an exemplar of the ultimate expression of safe physical and intelligent social interaction embedded ina compliant body:the symbolic expression of the science of companionship** and, in its complexity, of a representation of the *Man-on-the-moon*-like scientific and technological ambition underpinning this FET Flagship initiative. With the "dancing partner robot" we mean *systems of different shapes able to learn and perform physical activity also in physical contact with a human partner relying on their multimodal communication (e.g. gestures, haptics, voice, gaze, emotions…) and their ability to learn and adapt.*

The metaphor of a dancing robot, capable to learn and teach, to gracefully dance with a human partner a romantic waltz (or a passionate tango), requires the development of new hardware and software components and subsystems. New hardware components, such as new artificial muscles (e.g. biohybrid muscles), new artificial joints (e.g. bone-like conjugate contours), distributed sensors (e.g. artificial muscle-spindles, artificial flexible skins, acoustic sensors), neuromorphic hardware processing units, will be needed for the Robot Companion bodyware. New theory and models, such as models of visual, touch, gesture and haptics agent-agent interaction, models of distributed cognition and sharing of perception and decision, models of shared intention and attention, new models of graceful motion and control (synchronized in case of the dancing robot metaphor by music), will be the basis for the mindware of Robot Companions. New hardware and software components will be combined to develop new multi-purpose subsystems: new artificial limbs, algorithms for high-level cognitive skills (e.g. motion learning trough multichannel interfaces and sentience), biomimetic processing units emulating the human peripheral and central nervous system, biomimetic energy sources, strategies for energy harvesting.

Within the 10-years framework of the FET Flagship initiative and with this metaphor as our beacon, Robot Companions for Citizens will target the development of a demonstrator in the form of the dancing partner robot and several, application oriented, embodiments. *The dancing partner robot* will be an implementation of our proposed metaphor to be used as a test-bed and proof of concept demonstrator of the flagship's achievement. In 10 years 'a dancing partner robot' and a human will dance together for one hour. They will perform publicly a 'passionate tango' and 'a romantic waltz'. At the beginning, by relying on its multimodal communication with humans (e.g. gestures, haptics, voice, gaze, ...) the dancing robot will learn how to dance, and will become an expert dancer.

More practically, several application-oriented embodiments will be implemented, among them are:

- *the robot companion "collaborator" will be a robot for personal, domestic, medical, industrial and urban assistance with an "all purpose" humanoid shape and/or different, dedicated embodiments*; this robot companion will help, assist and cooperate with all: healthy, adults, children, elderly and disabled people in performing activities of daily living: work, care, leisure; it will operate in houses, factories, urban and hospital environments; it will be "personal as my closest friend", "trustworthy as my mother", "functional as my personal assistant", or "dexterous as my best worker";
- *the robot companion "suit" will be a wearable robot for body power extension;* this robot will be a compliant suit easy to wear and to work with; it will be mainly aimed at helping people to perform "heavy" jobs or "assist the motion of disabled and elderly people";
- *the robot companion "explorer" will be a small robot*(as it could be, for instance, a "robotdog") *with morphing capabilities for environment maintenance and monitoring*; it will be able to walk, swim, and fly, will be able to leverage on social and cooperative intelligence found in advanced animal societies, and will be able to cooperate with humans in tasks of rescue, and exploration of hostile environments; this robot will become the "best friend" of mankind in case of floods, forest fires, earthquakes or other catastrophes;
- *the robot companion "body augmentation system"* will leverage the morphing capabilities of biomimetic materials and neuromorphic design principles of sensing and control to develop and deploy a new generation of adaptive prosthetic systems that share massive bi-directional information exchange between the biological body and the nervous system; leading to new ways to replace and augment the human body and brain.

Although we envisage developing these four embodiments of Robot Companions in 10 years, we would remark that this FET Flagship will give *many intermediate S/T results* (that will be the milestones of this FET Flagship) which will include engineering of all the hardware and software components, as well as all the outputs from the-science-of-companionship research activities. These intermediate results will stimulate and be usable for new ICRT industrial opportunities as well as to enhance the worldwide scientific and technological progress.

OVERVIEW OF THE STRUCTURE OF THE COORDINATED ACTION

To successfully prepare a structure as complex as a FET-Flagship, the 'Robot Companion for Citizens' Coordination Action (CA) is set out to effectively integrate a large set of research issues, diverse scientific communities, a broad range of stakeholder interests, collaborating research organisations across Europe, enhancing the international co-operations, and to define a complex managerial, contractual, and financial structure.

To achieve this challenge within 12 months, the following consortium structure is suggested including 8 key elements, each reflecting a key-feature of the CA, as well as a substantial component of the future Flagship: **1) The Vision**, to motivate and federate researchers across various research communities, in creating S&T scenarios of future Robot Companions and a Roadmap; **2) Science and Integration**, to develop a concrete but flexible workplan and to provide effective mechanisms to help integrate the trans-disciplinary research within a flagship; **3) Participation & Outreach**, to proactively inform all relevant target groups of the Robot Companions for Citizens initiative, increasing its visibility to greater audiences; **4) Acceptances and Social Aspects**, to investigate issues related to the introduction of future Robot Companions for Citizens and their operation in future society for the benefit of all; **5) Competitiveness**, to investigate mechanisms to close the innovation loop with the industry to help make Robot Companions successful ICT "Robot-Inside" products; **6) Sustainability**, to organize funds from various sources and set up a financial structure enabling the continuous leverage of the resources required for a Flagship and beyond; **7) Governance**, to work on a managerial structure including legal, contractual, and financial terms that will help effectively bring into a full operation of a steering and management structure for the later Flagship; **8) Management & Coordination**, to support the CA consortium in its work.

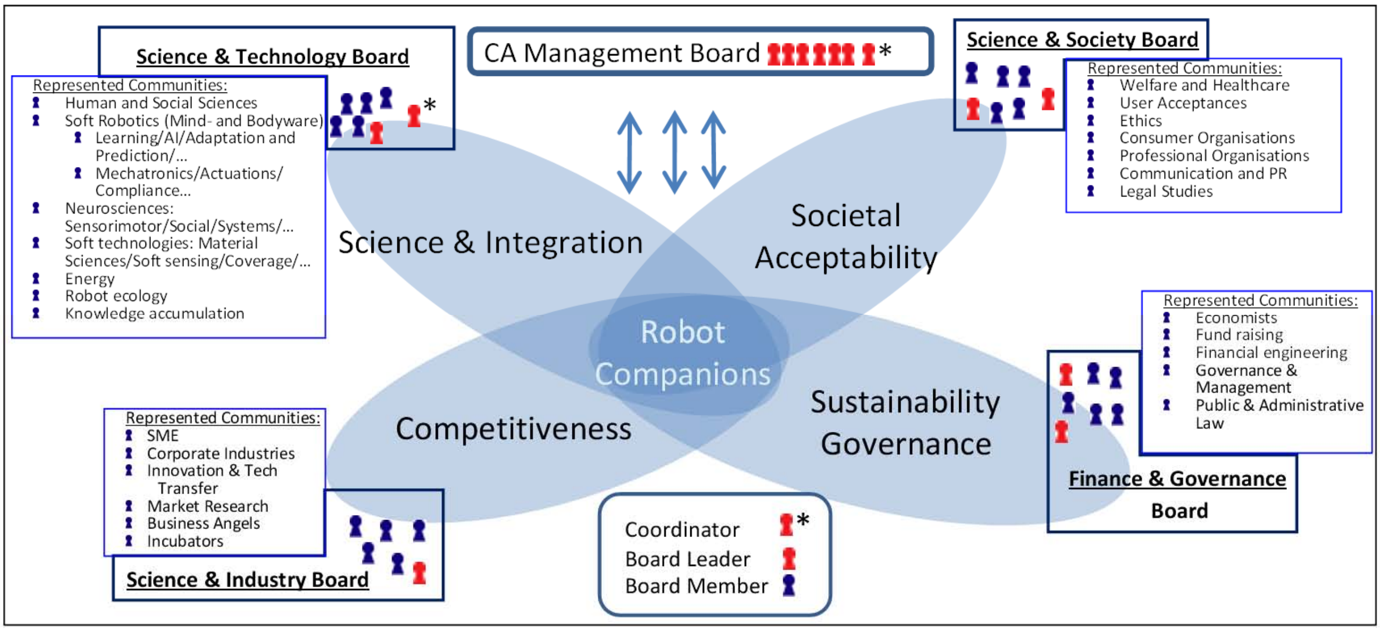

Figure 1.Overview of the CA structure.

In order to bring the wealth of existing experience into the Robot Companions for Citizens Flagship, the CA will make use of area related advisory boards which are associated with each of the key topics outlined above. They include specialists (the board members) with various expertise who support and oversee the work done and formulate their recommendations on a consensual basis, and many of them have been contacted already. The main purpose of the advisory boards is to include a representative range of stakeholders in the working process and to open the CA to the interests of **Science, Society, Industry and Funding** bodies. During the preparation of this document, a Provisional Board has been organized with experts with a large number of different research communities and expert researchers backing the proposed CA and being ready to work on the challenges for a future Flagship.

Establishing Milestones. The detailed workplan of the FET Flagship will be defined within the CA framework. It will include usual checkpoints and evaluation methods but considering the size of the Flagship, it will define means of verification that go beyond the standard in order to guarantee multidisciplinary integration, proper definition of standards, internal competition to achieve subgoals efficiently, etc. The milestones shall fully reflect on the overall management, internal funding rules and contract types, as well as industrial liaison.

A growing support. The document presented to anticipate a proposal for the CA is a direct follow-up of a paper presented at the Brussels FET-Flagship presentation June 9-10, 2010. That paper was supported by as many as 95 European experts working across multiple research disciplines. These include, roboticists, neuroscientists, social neuroscientists, psychologists, to name just a few. During the last 3 months, support has increased from many additional organizations and individual experts.

The Social Computer: Internet-scale human problem solving [1]

The problem

In the coming decades, the Internet will provide society and all citizens with an increasing amount of data and opportunities for communication and social interaction. In addition, a significant part of all the financial, economic and logistic transactions will be performed (semi-) automatically "in the cloud". The virtual world on the Web will increasingly mirror and merge into the real world, providing all sorts of activities and interventions that will provide new and powerful ways to address societal problems such as sustainability, health care and social integration.

However, although intelligent ICT tools and methods can to a certain extent handle and interpret the growing amount of data and connectivity, they are still not able to use this information in a socially acceptable way. They are not able to really interpret the very diverse social contexts of applications nor, among other things, to take into account human values such as integrity, privacy, solidarity, and so on. Furthermore, ICT methods are not able to perform algorithmically on a pair with humans on general problem solving and strategic decision making. In order to address the grand challenges of the coming decade, both large scale and small scale, we need an infrastructure that benefits from the growing power of ICT but that also harnesses these growing possibilities in a more socially acceptable way, providing a good balance between machine and human "social" intelligence. The journey towards the development of this infrastructure will lead us to the construction of the "**social computer**".[2]

The kind of problems and solutions we want to tackle is well described by the following example.

"A severe acute respiratory syndrome is spreading all across the world. The disease is carried around by humans and by a specific kind of birds; it is transmitted via the respiratory system, it is highly infectious and possibly lethal to humans. No cure exists and, furthermore, the virus causing the disease keeps mutating depending on the local environmental conditions. The risk of the situation going out of control is high."

The social computer will address this problem by minimizing the spreading of the disease and by optimizing the countermeasures of the cure, as follows:

1. By assessing in real time the position of birds, despite the fact that there are thousands of them and that they migrate in an unpredictable way and in many independent directions. This minimizes the probability of infection from birds.
2. By discovering new cases and forms of the disease when the first symptoms appear or as soon as the conditions for a new infection arise. This minimizes the probability of infection from humans.
3. By immediately enabling the people who have to deal with similar forms of the disease to share this information, worldwide, each time new conditions arise (e.g., a new mutation, a new symptom, a new cure). This minimizes the reaction time.
4. By globally using all the data collected locally to do real time simulations, for instance, to evaluate the impact of the different cures and activities. Achieving this, despite the different data conventions and management processes, minimizes the time needed to discover the cure.

In performing these tasks, the social computer exploits a set of capabilities of the current Internet and computers, which are far beyond human capabilities, and which are at the basis of their success:

1. **Their storage capabilities:** which are needed to store very large amounts of data collected across the various sites worldwide. This supports step 4 above.
2. **Their computing capabilities:** which allow them to perform large scale computations in a time which is orders of magnitude smaller than those needed by humans. Again, this supports step 4.
3. **Their networking capabilities:** using computer networks to transfer data, information, and knowledge between any two places in the world in close-to zero time. This supports steps 1 and 3.

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1 Written by Fausto Giunchiglia after many great discussions and feedback inside the mailing lists of the Social computer FET Flagship proposal. The site at http://socialcomputer.eu contains the names of the community of people who is supporting this proposal and who was involved in the discussion.

2 *"The social computer – combining human and machine computation"*, by F. Giunchiglia and D. Roberston (http://eprints.biblio.unitn.it/archive/00001851/01/036.pdf) contains an early definition of the Social Computer which embodies many intuitions and motivations.

4. **Their sensing capabilities:** relying on the pervasiveness of sensors, cell phones and PDAs. This supports steps 2 and 3.

However, existing computers and the Internet cannot solve any of the four sub-problems identified above. Let us consider them in turn.

How do we keep track of the flying birds? Tracking down single flying birds is impossible for any image analysis algorithm. Computers show good performance in image analysis only in limited domains and with dedicated training or *a priori* knowledge describing the context of application.[3] This is an instance of the general problem that **there are tasks where computers perform worse than humans.** Our proposal is to **involve humans.** Work in this direction is emerging under the heading of **human computation**, see for instance the reCAPTCHA Project (Science, 321 (5895): 1465-68), or the work on ESP games ("Games With a Purpose", www.gwap.com). However, in human computation a single person is engaged in each task. Most often we need to involve lots of people in order to achieve the goal, in our example, geographical coverage. This is the idea beyond the work on **social computing** (see, e.g., the Darpa Balloon challenge (https://networkchallenge.darpa.mil/Default.aspx), the Human Flesh Search engine (http://en.wikipedia.org/wiki/Human_flesh_search_engine) or the new US NSF funding program on social-computational systems (http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=503406&org=IIS&from=home). These are examples where people overcome the limitations in the **sensing capabilities** of computers. Another task where people have proved to be better than computers is related to **general problem solving and creativity**, for instance applied to scientific reasoning, see, e.g., FoldIt (http://fold.it/portal/).

How do we put in place, locally to a specific site, all the necessary activities by which any new possibility of infection is immediately detected? The techniques described above are not enough to solve this problem; the actions of people and computers are temporally and functionally separated; computers are used to activate human action which then goes on independently and reports to the computer only when a task is accomplished (e.g., in the DARPA challenge, when a balloon is found). But there are situations, like the one in our motivating example, where **computers and people must interact in far more complicated ways**, at various levels of nesting. One possible approach is to model computer activities as Web services and to integrate them with human provided services, modeled themselves as Web services (see, e.g., "Programming Human and Software-Based Web Services," by D. Schall, S. Dudstar, M. Brian Brake, IEEE Computer, 2010) thus allowing for some kind of **intermixed distributed human and machine computation**. This work goes in the right direction, but in a departure from Web services, the **potential services available thanks to human problem solving are not necessarily exposed in advance, and need to be dynamically discovered and composed** on the basis of suitable knowledge of available resources, capabilities and constraints. Moreover, a major difficulty is that **people have often proved very resistant to a tight integration of their activities with those performed by computers**. This problem grows enormously when we move outside the work environment. In this latter situation it often becomes practically unfeasible to convince people to change their behavior via some kind of Business Process Re-engineering (BPR), and, in turn, this often becomes a sufficient condition for failure in the uptake of new technologies: *why should we adapt to the malfunctions of machines whose main goal is to help us?* The work on crowd-sourcing, see, e.g., the Amazon Mechanical Turk (http://mechanicalturk.blogspot.com/2007/02/you-can-help-find-jim-gray-from-home.html), goes in the right direction as, here, people voluntarily accept to have their work scheduled and coordinated by a machine. But this work is still in its early stages and suffers from the same problem of "simplicity" (from a social and organizational point of view) as the work on human computation and social computing.

How do we know who else in the world is facing a similar problem in real time? We need novel methods for finding, on an internet scale, people who fulfill very specific conditions and are willing and able to take on very specific tasks. Some kind of intermixed human and machine computation, as suggested in the item above, when successful, might work partially, but we are left with the still unsolved **Long Tail problem** (http://en.wikipedia.org/wiki/Long_Tail). How do we find those small niches (e.g., data, people) which are of very high value to a small set of persons?

How do we globally exploit data and information which are generated locally and according to the local culture and rules, which can change quite radically from region to region and even more from continent to continent? Worldwide data integration is impossible. The partial success of the Semantic

[3] A similar argument can also be made for other kinds of sensory input, e.g., in speech recognition and natural language processing.

Web efforts shows that the **homogenization of semantics under some kind of global schema does not scale** in general or outside specific applications domains. The problem applies to data and knowledge and also to (computer and human) services, as also discussed in the paper by D. Schall et al. In practice, this is one of the main difficulties towards Internet-scale distributed problem solving.

The last two problems are two sides of the same coin. **People and the knowledge they produce are profoundly diverse.** This diversity is not only unavoidable, but it is also a feature, a local maximum, which takes advantage of the local conditions and that, as such, should be exploited to get better results. Each person is different from every other person and this diversity is distributed over a continuum. There are many dimensions because diversity arises, and they are connected to the local **context**. There are many kinds of context, e.g., culture, local needs or goals, school of thought, mood and opinions, geographical location, and so on. Time is maybe the most difficult source of diversity to manage, at least from an ICT point of view, as at any moment in time, we have no way to predict how the world will evolve. Thus, on one side, diversity can create islands of very specialized knowledge and expertise which are of potential high value, possibly only for a small set of people (the long tail), but at the same time, it creates a barrier which makes any global attempt of standardization and homogenization bound to fail.

Computers are not people, they are profoundly different; they do not "live" and have no understanding of the world and society. The **context acquisition and exploitation problem** is one of the major stumbling blocks towards any strategy aimed at a major integration between human and computer activities. The work on Social Signal Processing is a very promising first step towards the solution of the context acquisition problem, see for instance the EC NoE SSPNET (http://sspnet.eu/).

Ambition

The main conclusions which can be drawn from the previous section are:

1. Computers and people complement each other as there are problem solving activities which are hard or impossible for one and easy or very easy for the other. The current pervasiveness of ICT suggests that we **concentrate on finding ways for integrating them in a way to maximize their strengths and complement their weaknesses.**
2. The main difficulty towards the above strategy is **that it is very hard, and also not desirable, to force humans to adapt to computers beyond a certain limit**. We need to better understand the differences between what people can do and what computers can do within an integrated service perspective, taking into account their role in a larger social system where physical, legal and ethical constraints apply. There must be an upper bound to the level of organization and standardization that we impose on ourselves and society in order to complement the computer's rigidity (and consequent inadequacy and inability to adapt to the complexity of the world).
3. A key challenge towards achieving the complementary integration of people and computers is the **real time context acquisition and exploitation problem**: because the "right" context is in the mind of the current user at any given moment, a computer has no access to it (like any person in the world). How can we make sure that the computer understands most of this context and makes maximum pragmatic use of it? Notice that the problem is made even harder and somewhat circular by the fact that the computer needs to understand context in order to **exploit** it and fully integrate with humans, but at the same time it needs humans to help **understand the context**.

Our solution and proposed approach is to build **social computers**, namely future computational systems which are **embodied in society**. By this we mean that social computers work in symbiosis with their users (by being able to understand the intended context) and inside society (by having some understanding of the rules, norms, regulations, … to which people must comply). Notice that the kind of embodiment we are aiming for, and that we call **social embodiment**, is orthogonal to the kind of physical embodiment which is the goal of robotics. It is possible to foresee a new generation of computer systems which will be physically and socially embodied in the world but at the moment the two problems can be dealt with independently.

Based on the above, we can provide the following three informal definitions of the main objectives of the proposed research.

The social computer: it is a new kind of computer. There are two sides to it. On the one hand, it is your **social computation assistant,** helping you to dynamically launch, compose and control **social computations** on the basis of your actual needs, preferences and constraints. It is networked with other social computers, it connects you with other people and social computers, and with the world at large. On the other hand the social computer relies on a large scale worldwide infrastructure which enables social computers and people to interact via **social communications**, proactively promoting social awareness and proposing that the user get involved in social computations satisfying larger societal needs. The parallel is with the current PDAs and computer networks; the key difference is that people, social computers and society are part of the enabling infrastructure.

Social computation: it results from a composition of **distributed social computational steps**, where each social computational step is a service deployed by people or social computers. Social computation steps change the internal state of social computers, as a representation of the change of state inside people or in the world. Social computations enable the combination of the problem solving and actions of people and social computers.

Social computational system (also called a **computational society):** a society of people instrumented by social computers and social communications. It has all the usual properties of societies (an identity, a boundary, a time and a location span ...). It is the **infrastructure** (as introduced in the definition of the social computer) enabling those social communications which enable social computers to work.

A new foundations of ICT through the integration with Humanities

The three pragmatic goals defined above lead us to the ambitious goal of **rebuilding the foundations of ICT.** A mechanical notion of computation, as that provided by Turing Machines cannot provide the foundations for social computations, and the involvement of people, at least from a modeling point of view. The problem of rebuilding the foundations of ICT has three facets, all highly **interdisciplinary**:

The science of the social computer: namely the study of social computers and computational societes as manifestations of concrete social interactions, developing on top of the existing Humanities. The relevant disciplines include cognitive science and psychology (in order to study the symbiosis between a person and her social computer), sociology and political science, management and organizational science (in order to study the social embodiment of the social computer), criminology (for the study of deviance), economics (in order to study quantitative models of, e.g., collaborations people - social computers via incentives), law (in order to study the effects of norms and laws) and, last but not least, ethics (providing us the foundations for the creation of a better society).

The engineering of the social computer: on one hand, the engineering will be based on the science and requirements produced by the humanities and on the consequent validation methodologies. On the other hand, it will build upon a large set of existing ICT sub-disciplines, including: languages and semantics, design (e.g., software design, interaction design, society design, system design), modelling and simulation, data (including media) and knowledge management, distributed systems (including services and networking), and computer systems (including High Performance Computers (HPC) and large scale, possibly distributed, storage systems).

The engineering for the development of the science: the current Humanities are nowhere close to providing the kind of specifications that are needed in order to provide requirements for the social computer. A big effort will have to be made in making sure that ICT will support the development of the new science of the social computer (building upon the existing efforts in, e.g., Web Science and Internet Science). This will include the development of large scale, real time user and society centric testbeds and corresponding evaluations. In turn, it will require the development of new engineering and new science. Here HPC and large scale time-aware digital archives will play a fundamental role.

Challenges

The “new” ICT will have people and society at its core; we are interested in **improving human, rather than computer, problem solving**. In this perspective, social computations and communications are a new enabling capability whose main goal is to improve what people can do **towards a better society**. This consideration leads to a first set of **socio-economic challenges and goals**, namely:

Improving the quality of life: by bridging the gap and managing the continuum from well-being to health, aging and inclusion. The physical and psychological status of a person will be at the core of the project as the key enabling factor for globally improved quality of life, as also supported by the other socio-economic challenges introduced below.

Learning, design, innovation and creativity: Learning will be improved by the new networking and design capabilities provided by social computers. These capabilities in turn will support creativity as an important step towards innovation. Personal creativity, and the enhanced interaction capabilities will be an enabling factor for a new attitude towards innovation which, in turn, will make society as a whole more capable of innovation.

Reconstitution of the public sphere: by bridging the gap and managing the continuum from private to increasingly public data, information, knowledge and opinions. This will apply to previously generated data (e.g., text, media) as well as to personal and social interactions. It will provide forums and arenas for the articulation and expression of societal differences and conflicts, and for their mediation.

Establishing more efficient and effective means for production for goods and services: thanks to the automation, integration and composition of steps performed in part by humans, the social computer will provide cost effective means to create whole new products and markets.

Sustainability: at the individual and societal level, in terms of resourcing, environmental protection and energy consumption, as it applies to social computers, people and world logistics. We will also have to consider how to resource participants in social computations.

Approaching the above challenges and goals will require the exploitation of **interdisciplinary domain knowledge** (e.g., health, logistics). But, in turn, as described above, the proposed solutions will have to exploit knowledge coming from the human sciences. We will approach this by identifying and tackling a set of fundamental **interdisciplinary, scientific and technological challenges** as a necessary step towards the construction of the social computer. At the moment we foresee the following challenges:

Human - social computer symbiosis: the main goal is to enable the social computer to understand and exploit the user mental and physical context. It will be achieved via a seamless multi-media multi-modal interaction deeply rooted in the person (explicit and implicit) way of thinking and behaving. It must handle, for instance, emotions, persuasion, behaviours, incentives as the way of interaction.

Enabling computational societies, including governance: the main goal is to enable the social embodiment, thus enabling the social computer to support people in their activities; for instance in their capabilities of being autonomous and, at the same time, of participating and interacting with other people and social computers. The solution includes dealing with issues such as trust and reputation, coordination, cooperation and conflict, emotions, persuasion, incentives, and so on.

Managing diversity and its impact on social computation: as described above, social computers and computational societes must adapt to and exploit the unavoidable diversity of people, society and the world. They must handle it as a feature not as a bug, as the mirror of the richness in diversity of society, as it appears in the huge amount of data and services that are available to each and any person.

Managing time and its impact on social computation: because of the diversificaton in time (via, e.g., learning, adaptation and evolution) of people, social computers, and computational societies.

Privacy: the social computer will require, as a prerequisite for functioning correctly, a converged identity in the real and virtual world. This will require full control of all privacy related issues in the continuum from fully private to fully public.

Web and Internet Science: the goal is to develop a science of the Web and the Internet, to be studied as natural phenomena whose comprehension is a necessary means towards the science of the social computer. This will require input from the humanities and, at the same time, the development of dedicated technologies and testbeds exploiting the knowledge coming from all the ICT sub-areas.

The teams working towards all challenges will all be highly interdisciplinary. The **work on the interdisciplinary challenges** will concentrate more on the design of the enabling technologies and science, while the **work on the socio-economic challenges** will exploit this previous work and will apply its results to a set of key case studies by adding the required interdisciplinary domain knowledge.

Workplan and Impact

The output will consist of scientific results, not restricted to ICT, and new ICT technologies. Impact will be ensured by careful design of the work-program. The **short term plan** (two-three years) will encompass a first definition of the theoretical framework, the creation of the enabling infrastructures for large scale testbeds, together with a first set of exploratory case studies. In **the medium term** we will produce the first versions of the enabling technologies (two-five years) and we will deploy them in full fledged case studies (three-seven years), some of which will run on the testbeds. This will allows us to have large scale evaluations and simulations (four-eight years) which will drive us in an incremental, spiral **long term** approach of successive refinements and extensions.

In the long term, the development of the social computer will lead to a radical departure from the current practice in ICT and in the other disciplines. The future ICT will go beyond the barriers which now exist among the ICT sub-disciplines and the other disciplines. The integration will not see ICT as a simple instrument, nor as a cause of a simple change of approach. We see a process of bi-directional, interdisciplinary **mutual convergence which will change all disciplines**, including ICT.

The main impact will come from Europe's increased capability of generating innovation and, therefore, social and economic value. By putting the interdisciplinary studies at the **beginning and at the end of the research/ innovation pipeline** (rather than only at the end, and mainly concentrated on the domain knowledge, as is mostly the case now) we will increase the capability of transforming research results and technological innovation into **service and social innovation**. Systems will be constructed with the requirements and specifications for the societal deployment embedded in their design.

Unravel the human brain

Expression of interest from organisations within the ELAt[1] region

Mission and goal

Neurological diseases make up a significant portion of the ***global disease burden*** and healthcare spending. Data collected by the WHO suggest that brain diseases are responsible for 35% of Europe's total disease burden. The proportionate share of the global worldwide burden of disease due to neuropsychiatric disorders is projected to rise to 14.7% by 2020. According to the WHO, cerebrovascular diseases and Alzheimer/dementias together account for 91.28% of all deaths caused by neurological diseases, and unipolar depressive disorders are expected to become the leading cause of burden of disease by 2030.

It is further estimated that the annual ***economic burden*** by these diseases amounts to 2 trillion USD worldwide, which will increase sharply when no anticipated action is taken. This huge (future) socio-economic impact of the burden of neurological disorders, makes them high priority globally and calls for extended actions to handle them in a better way. To come up with treatment and solutions towards these brain-disorder related diseases, understanding the functioning of the brain is therefore crucial.

Unraveling the mechanisms of the integrated activity of the human brain is without question one of the greatest ***scientific and ICT-relevant challenges of today*** and comprises major consequences for humanity and society. The mammalian brain consists of billions of neurons connected into circuits by trillions of synapses. The ultimate goal in this respect is to understand the neuroscientific principles organizing these complex circuits and thereby decipher how they process information and guide behavior. The capabilities within the ICT field and the knowledge in the scientific field have to shift far beyond current frontiers to encounter this challenge.

ICT-based solutions, such as external brain stimulation, artificial memory extensions, and automatic and selective *in vivo* drug delivery systems are necessary in order to solve different types of neurological diseases. In addition further mapping between the brain (dis)functioning fields and different kind of neurological diseases will result in appropriate drug development and effective stimulation approaches.

Finally also the ***societal, human, and legal aspects*** of brain manipulation will be taken into consideration along the trajectory such that the solutions coming out of this research will actually be able to be applicable in real life.

Impact

Understanding the complete brain activity and its effect on human behaviour will have the same effect on our society as the human genome project. Impact will be created in different directions.

Societal impact

[1] ELAt, the Eindhoven-Leuven-Aachen triangle, is a geographical area of high-tech activity in the Dutch, Belgian and German cross-border region.

- Patients with severe neurological disorders can be (re)integrated in normal life when on-line monitoring, stimulation and controlling will be possible.
- Disabled persons will have control over their daily life using brain mind recognition systems.
- Ethical questions on brain mind, security, and legislative issues will rise; answers will have to be provided.

Impact on ***science and technology***

- Understanding brain activity will request new developments within the field of medical imaging, neuro-electronics, neurology, monitoring systems (sensors, neuroprobes), (data) mining, etc.
- The ICT sector and operator systems will have the tremendous task to analyse, connect and distribute data from the patient – independent from where he/she is – to nurses and doctors and vice versa in a secure way.

Economic impact

- Advanced neuro-ICT developments will reduce the costs for internment and continuous, intensive follow-up of neurologically disabled people.
- New developments of (implantable) brain sensors, probes and actuators, analysis tools, monitoring systems, secure data transfer operator systems and advanced imaging technologies offer new market opportunities to (European) companies.
- Novel reimbursement systems need to be developed when using neuro-ICT devices in hospitals or at home.

Educational impact

- Advanced knowledge and developments related to the functioning of the brain and treatments systems, combined with the ethical and security aspects, have to be taken up in the curricula of universities.

Novelty

For the first time in history, our knowledge has reached a level of resolution that allows it to take full advantage of micro- and nano-scale electronic engineering and of understanding biological molecular interaction at the scale of nanometres.

During the last 10 years the Eindhoven-Leuven-Aachen region (ELAt) has built up significant expertise in the field of neuro-ICT. It is unique in the world by having centers of excellence in ***biotechnology and nanotechnology***, combined with the presence of academic hospitals, renowned universities and world leading top-technology companies in a wave of 80 km. Collaborations among these partners have already created leverage towards neuro-ICT developments.

Ambition

As indicated, the ambition of the proposed research program is to come to a deep ***understanding*** of the functioning of the brain and to develop solutions to ***prevent or treat*** neurological diseases.

This overall ambition can be translated into a number of specific scientific-technological goals that go far beyond the state-of-the-art:

- understand the complete ***electrical*** stimulation – and the ***molecular*** mechanisms behind it – of a single neuron and neurons in a network *in vitro* and *in vivo;*
- develop devices, processes and tools for patients with diseases of the brain:
    - (wireless, implantable) ***devices*** for monitoring, drug delivery and stimulation with special attention to power consumption, security, miniaturisation, radiation minimisation/orientation, and communication with the outer world
    - (server-run or embedded) ***algorithms and tools*** for analysing brain behaviour, mining and combining different sources of information (images, EEG signals, documents)
- trigger brain cells of patients in order to ***control and monitor patients*** with neurological disorders and to enhance ability and functioning in stressed or traumatized conditions;
- create an experimental environment for ***drug development***, where the influence of specific drugs can be measured and evaluated using new and advanced tools, devices and techniques;
- identify barriers obstructing the social and economic uptake of technology (e.g. ethical issues, acceptance by patients, legal aspects).

Interdisciplinary approach

Neurobiology stands today at very exciting cross roads. A large number of approaches – from genetics, electrophysiology and imaging to behavioural sciences – are ***converging*** to unravel the secrets of brain formation and function. Although each of these approaches alone has already contributed significantly to our understanding of the brain, it is the integration of these different disciplines that is yielding exciting results at ever increasing rates.

Different organisations therefore have to work together, such as (university) hospitals, universities, research centres, industry, SMEs, and social partners. Interaction is necessary, fostering ***integrated teams*** of engineers, biologists, chemists, brain imaging specialists, cognitive science specialists, experts in security/privacy, neurologists, neurosurgeons, (neuro)psychologists, specialists in legal and ethic affairs, health economists, ...

Resources within the ELAt region

- ***Belgium***

  Within the region of Leuven three partners are in the driving seat: ***IMEC*** (Interuniversity Microelectronics Center), ***Katholieke Universiteit Leuven*** (+ University Hospitals Leuven) and ***VIB*** (Flanders Interuniversity Institute for Biotechnology). Their joint NERF initiative (www.nerf.be) provides a solid foundation for their participation in the current FET Flagship initiative. The mission of NERF is to unravel the anatomical and functional fundamentals of neuronal circuits. It does so by using and integrating neurobiological and nano-electronic approaches. The research groups of NERF are integrated in the research community of the founding institutions and have full access to their research, technology and service facilities. Other potential partners at local level are DSP Valley, Capricorn Venture, FMTC, and City of Leuven.

- ***Netherlands***

  Within the region of Eindhoven, the ***TUe*** (Technische Universiteit Eindhoven), ***Philips Research*** and ***Philips Healthcare*** have a broad range of research activities in the area of neurological diseases. Imaging approaches, in particular various forms of MRI (imaging, spectroscopy, functional) and nuclear imaging are key elements in diagnosis of neurological disorders. Multimodality-based approaches are being developed to increase the diagnostic power. With the advancement of new interventional treatments, such as Deep Brain Stimulation, which rely on accurate placement of electrodes, therapy planning approaches become essential components of the neurosurgeon's repertoire. Potential partners at local level are Brainport Development and City of Eindhoven.

Within the region of Maastricht ***MUMC+***, including Maastricht University (FHML MHeNS, FPN M-Bic, FHS Computer Sciences) plays a key role. The recently developed "Brains Unlimited" project, in which Maastricht University develops an ultra high field MR facility and the "Neuropartner" neuroscience business incubator, will attract industry partners, partially to be hosted at the Maastricht Life & Science campus.

- ***Germany***

  RWTH Aachen and ***Universitäts-klinikum Aachen*** cooperate in several research areas, under which neuroscience, with Belgian and Dutch partners based on bilateral cooperation agreements. There is a growing industrial participation in these projects. A potential partner at local level is Forschungszentrum Jülich.

The consortium welcomes proposals for collaboration.

The Web Time Machine: Understanding the Past and Present to Build the Future

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Consortium

The Web Time Machine effort will leverage the existing research laboratory network of the Web Science Trust and build on current research that is underway under its auspices. Academic scientists and labs that already occupy this community and are expected to be interested in participating or contributing to this project include:

- Europe
  - Stefan Decker, Digital Enterprise Research Institute, National University of Ireland, Galway *
  - William Dutton and Helen Margetts, Oxford Internet Institute, University of Oxford *
  - Nigel Shadbolt and Wendy Hall, Electronics and Computer Science, University of Southampton *
  - Ioannis Antoniou, Mathematics, Aristotle University of Thessaloniki
  - Paul Spirakis, Computer Science, University of Patras
  - Guus Schreiber, Computer Science, Free University of Amsterdam *
  - Steffen Staab and York Sure, Web Science and Technologies (WeST), University of Karlsruhe *
  - Wolfgang Nejdl, L3S Research Centre, Leibniz University, Hannover
- US
  - Tim Berners-Lee, CSAIL, Massachusetts Institute of Technology *
  - Noshir Contractor, Engineering/Communication/Management, Northwestern University *
  - Joan Feigenbaum, Computer Science, Yale University
  - James Hendler and Deborah McGuinness, Tetherless World Constellation, Rensselaer Polytechnic Institute *
  - Manuel Castells, Annenberg School of Communication and Journalism, University of Southern California *
  - Ramesh Jain, Information and Computer Sciences, UC Irvine
  - Ben Shneiderman, Human-Computer Interaction, University of Maryland
- South America
  - Daniel Schwabe, Brazilian Institute for Web Science, Rio de Janeiro, Brazil
- Asia
  - Wu Jianping and colleagues, Shenzhen Web Science Laboratory, Tsinghua University/University of Southampton *
  - Hong-Gee Kim, Biomedical Knowledge Engineering Laboratory, Seoul National University

*Indicates current member of WSTNet

Brief explanation

The World Wide Web has been revolutionary in terms of impact, scale and outreach. It has evolved to be many things at the same time: a network, a repository of collective intelligence, a service, a means of social interaction, and an archive of human activity. Yet we do not understand how it succeeds or how exactly it affects individuals and societies, thanks to the lack of sound theoretical understanding, detailed archives and predictive models. The Web Time Machine will provide all these essential functions.

Mission

The relation of emergent macro scale phenomena to micro scale technical development is a particularly difficult challenge, yet important for assessing the web and ensuring that it develops in socially benign ways. It cannot be simply one of cause and effect, as the web and society are actively changing each other. Such a complex system involving multi-conditioning factors cannot be understood in the frame of the presently available methods and formalisms. Furthermore, the Web is changing at a rate that outstrips our ability to observe it without relying on efficient analytic tools based on new formalisms relating to a novel blend of evolutionary modelling of complex systems, graph theory and game theory.

The creation of a 'Web Time Machine' is a visionary and ambitious undertaking that will record the state of the Web over time, and combine interdisciplinary research efforts on analytic instruments to assess and explain its evolution and to highlight future trends, especially in connection with policy decisions. It will draw on advances in areas such as evolutionary modelling of complex systems, graph theory and statistics, game theory and, at the same time, it will have a significant impact on developments in these areas. This project is expected to provide us with new insights on Internet economics, social networks, privacy and trust, Internet infrastructure, biomedical networks and provide the tools to assist policy makers and legislative bodies to ensure the safeguarding of privacy and of European societal values.

The 'Web Time Machine' project will leverage the extensive network and scientific expertise of the organisations related to the Web Science trust and will build on the interdisciplinary research methods and current research results. The project envisages the establishment of a number of centres co-located with European research laboratories to coordinate efforts on the Web Time Machine.

Integration

The Web is 20 years old but there is very little written about its state and development over this period. Much of the current research relies on fragmented data and to some extent personal perception and often limited speculation about its evolution. However, its impact on everyday life has been significant and its analysis has been challenging given the current theoretical background and formalisms.

The vision of creating a 'Web Time Machine' that will model the Web, record and analyse its structure, identify future trends and detail its impact, necessitates:

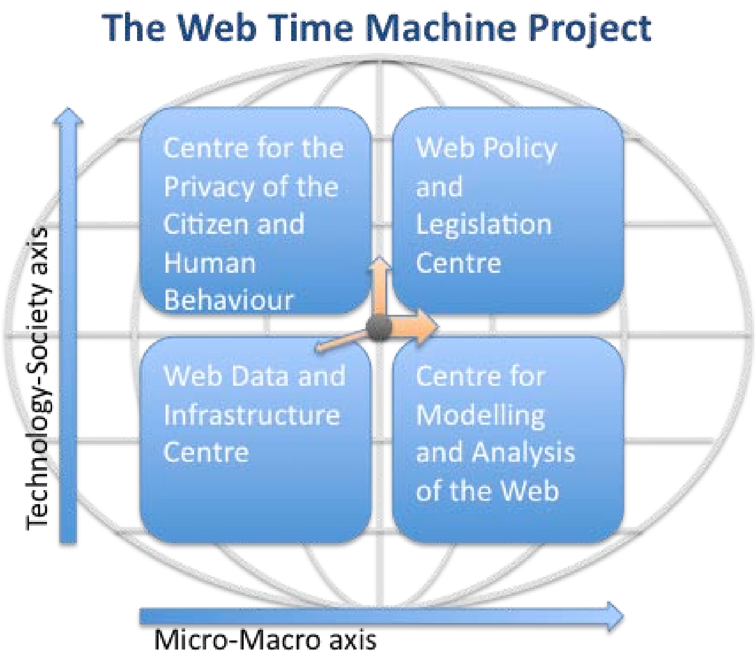
- Interdisciplinary research methods
- Statistical Processing Tools and Formal models of the Web and Web dynamics
- Innovative analytic tools to show how the Web influences society and the economy
- Predictive models on Web evolution and future impact
- Large-scale archives of the Web and Web-based activity
- Advanced visualization techniques
- Repositories with research results
- Liaison with the society, the industry and government
- Specification of industrial exploitation cases

The development and operation of the Web Time Machine will be fully compliant with the data protection directives of the European Commission and the consequent legal requirements.

Creating the 'Web Time Machine' will require collaboration among different laboratories in Europe and across the rest of the world, which will act as Centres of Competence in areas such as Mathematics, Computer Science, Social Science, Economics and Law.

Apart from the participating laboratories, the project will establish four different centres to coordinate activities for the implementation of the Web Time Machine. It is expected that these centres will be based at participating research labs in the European Union, making use of existing infrastructure:

- *The Web Data and Infrastructure centre*
  This is the core centre for the Web Time Machine implementation activity. It will coordinate the creation of a distributed repository across participating sites that will record the state of Web over time and will be able to reproduce its state at a given time. It will provide the infrastructure to observe the evolution of Web and to establish provenance of Web resources. Advanced visualisation techniques will be researched and deployed for these purposes.
- *Centre for Modelling and Analysis of the Web*
  This centre will build on the infrastructure operated by the Web Data and Infrastructure centre and will provide Data Processing Tools and formalisms to describe the Web and to model human activity on the Web. It will work on simulations and predictive models on how the Web could involve in the future as well as analytic models to better understand its past. This work is expected to inform and support policy makers and to establish further requirements for Web infrastructure development.
- *Centre for the Privacy of the Citizen and Human Behaviour on the Web*
  The main mission of this centre is to research more thoroughly how individual behaviour affects other individuals and Web evolution. It will identify risks for citizen privacy at an early stage and potential issues of data usage and transparency, addressing the balance of privacy versus transparency. It will also establish and quantify opportunities for citizen empowerment (such as lifelong learning).
- *The Web Policy and Legislation Centre*
  The development of the Web has already necessitated the introduction of policies and often legislation in order to address issues faced by society or enable further development of the Internet/Web economy. Very often these changes were introduced after the consequences of these problems affected society or too late to foster emerging business models and economic activity. Based on the modelling and analysis activities, this centre will develop the part of the Web Time Machine that will inform policies and legislation in this respect.



The above diagram illustrates the activities of these centres for the implementation of the Web Time Machine

Impact

Implementing the Web Time Machine would give Europe a significant competitive advantage. It would help to advance its position in ICT research significantly with anticipated major contributions in graph theory, in game theory and in evolutionary dynamics in complex systems. For this reason, it is also expected to attract top scientists from around the world to its research labs and address issues of 'brain drain' from European research centres.

This project would benefit European industry significantly by providing it with access to innovative analytic tools and new insights into Internet economics. It would help to safeguard the privacy of its citizens. It would inform its policies and, when necessary, initiate legislation activities in a timely manner.

The impact of the project can be detailed from the following perspectives:

- Computational and Mathematical
  - Building an archive of the Web is a significant challenge in itself not only in terms of storage but also on modelling the Web and its activities. Addressing challenges on storing, querying and visualising the Web over time is expected to drive significant innovation in these areas.
  - Complex systems modelling and graph theory provide the framework for studying interrelations, links and multi-conditioning. Within this framework new formalisms will be necessitated to model the Web functions and evolution.
  - Game theory is an area on which the project will draw to model societal interaction and Web economics
- Systems biology and systems medicine
  - The many common structural, functional and evolutionary features between the Web and genetic networks, (genome, proteome, metabolome), disease phenotypic networks (phenome), and the brain as a global distributed workplace (connectome), lead to significant cross-fertilization of these fields.
- Social Science
  - Developing insights and new models of human interaction
  - Collective intelligence processes
  - Virtual community lifecycles
- Privacy and trust for citizens
  - The changing nature of privacy and trust in the light of the evolution of social networks and cloud-related developments
  - Alerts on privacy, data protection, national security, etc
  - Legal limitations and transparency of data usage
- Human activity on the Web
  - Identification and quantification of opportunities for lifelong learning and the development of the citizen
- Legal sector
  - Greater understanding of the impact of legislation on conduct online
  - Models of the relative roles of regulation, architecture, market incentives and social norms on behaviour
  - The application of predictive models within the legislative process to ensure regulation incorporates future risk
- Business sector
  - Business models for the digital economy
  - Understanding of online incentives for productive & collective activity
  - Early identification of business opportunities in fast moving areas like Web 2.0
  - Early anticipation of risk for the consumer

Why this is timely

The importance of Web Science has been argued for in detail by many distinguished scientists and leaders of industry. Understanding and assessing the Web will have wide reaching implications and is on a par with other great scientific challenges of our time such as understanding the climate, our biological nature or the larger Universe. Web Science is a new and emergent discipline that is developing its own methods and techniques. Web Science is not only a new frontier it is an endeavour that will bring together a new generation of enquiring minds.

The Web is only 20 years old, but has penetrated virtually every aspect of individual and social life, while revolutionising scientific and social-scientific research, and human communication at all levels. Yet the predictive and descriptive tools needed to understand the most complex piece of human technology ever devised are still not in place. The Web Science initiative has begun to fill this lacuna with a vibrant and diverse research community, but now is the time to build on these early results and consolidate future developments.

This is the right moment for the Web Time Machine. The early research in Web Science, dating from the birth of Web Science in 2006, has provided a basis for development, both in terms of data about the Web, and in terms of the networks of excellence in both natural and social science, which did not exist before, and which is beginning to reach maturity. The Web Time Machine will accelerate the development of data, models and theories, thereby leveraging the networks already in place and allowing them to develop synergetically to address the research and governance issues that the Web is raising all the time.

The FET flagship pilot

The flagship pilot will leverage existing networks, such as the Web Science Trust network of research labs, and the work of existing research centres. A major focus of this effort will be on the documentation of existing interdisciplinary research methods and the exploration of new ones. In addition, the Web Time Machine pilot will investigate requirements and structures for building archives of Web data, Web Science research data and results. The pilot project will also provide the necessary toolsets for the analysis and the deployment of predictive models based on the current work of the participants. The pilot will also involve the elicitation of requirements for privacy protection on the Web, for transparency, for policy and legislation recommendations, and Internet economics models and forecasting.

The success of the Web Time Machine project relies on the collaboration among *Centres of Competence*, laboratories well established in Europe and in the World for their research in areas such as Mathematics, Computer Science, Social Science, Economics, Law, Cloud computing, Web Technologies, Psychology and Systems Biology. The success of the project depends on the rigorous specification of the requirements for its infrastructure. In addition, success will also depend on the elicitation of scenarios that will drive the development of the infrastructure, of analysis and modelling techniques, of the privacy and transparency practices, and of policy and legislation.

The Web Time Machine pilot project will aim at the following specific outcomes:

- Identification of Centres of Competence and of their involvement in the Web Time Machine Project centres.
- Detailed specification of the technological requirements for the infrastructure of the Web Time Machine project.
- Specification of the mission, structure and operation of the four project centres.
- Elicitation of scenarios that will drive initial developments in the Web Time Machine project centres and detail their mission.
- Deployment of repositories with relevant current research data from the centres of competence.
- Deployment of repositories with relevant modelling and analysis tools currently available or developed by the participating centres of competence.

Ubiquitous powering: Energy Aware Nanoelectronic Personal Companions (Nano-PCo)

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Position : Associate Professor, Director Nanoelectronic Devices Laboratory
Did you read the agreement : Yes
Country : Switzerland

Partnership:
CEA-LETI, CEA-INAC, CSEM, EPF Lausanne, ETH Zürich, IBM-ZRH, IMEC, IMEP, KTH, Infineon, ST Microelectronics, Tyndall, University of Bologna, Université Catholique de Louvain, University of Cambridge, University of Geneva, University of Pisa, University of Udine, University of Lund

ABSTRACT

A ubiquitously powered personalized computational and communication system, called **Nanoelectronic Personal Companion (nano-PCo)**, is the result of the convergence between future zero-standby power mobile computing, mobile communications and disruptive integrated powering/scavenging technologies. This flagship will uniquely combine the development of novel power aware integrated circuit technologies (exploiting revolutionary device concepts and nanotechnology) with the integration of energy conversion layers, inspired by biology, in advanced nano-PCo's.

In general, the novel system architectures will be significantly inspired by biology and nature evolution in terms of energy efficiency and exploits most advanced computing and storage technologies, including both digital and analog principles. Nanotechnology will permit to provide synthetic man-made versions of available energy conversion principles existing in nature. Battery-free Nanoelectronic Personal Companions could find their own energy in the environment using seaming-less novel integrated technology inspired by microbial light-driven proton pumps (like bacteriorhodopsin which has become the object of scrutiny for an entire branch of science in last 30 years) or leaf photosynthesis (converting light and CO_2 in electrical energy). Exploitation of other energy sources in a fully integrated way, like thermal energy from various computational processes and/or from environment is another research alternative.

The technologies developed in this proposal will also enable the large scale deployment of battery-less Wireless Sensor Networks and, in general, of embedding invisible advanced nanoelectronic functions in the human environment. The impact on the society will be tremendous; the project will define a series of five demonstrators to reach after periods of two years.

AMBITION

The ambition of the project in terms of disruptive technologies is threefold: (i) develop energy efficient computing and communication technology based on the emerging nanoelectronic technologies including novel materials and spin-based devices, (ii) devise system and circuit architectures inspired by biology and exploiting energy efficient thermodynamic principles, (iii) develop a completely novel integrated energy conversion technology for Nano-PCo. Based on the three categories of disruptive principles, technologies and system architectures mentioned before, the **very first demonstration of a fully operational hand-held battery-less Nano-PCo** will serve as a measure of success.

IMPACT

Understanding the limits of digital computation at device and architecture levels, find alternative energy efficient solutions to present power hungry high-performance digital computation and storage, exploit spin and novel nano-materials for the universal memory, understand biological energy efficient processes and translate them in effective electron/ion technology for ubiquitous powering of the nano-PC are the elements that could create a huge impact in the computing and communication technologies. The proposed Nano-PCo is a personalized device that has no equivalent in today's available or projected tools. It will be equipped not only with unique energy aware technologies but will have personalized sensing interfaces and communication interfaces, adaptable to the existing natural in-door or outdoor environment. The Nano-PCo is a smarter extension of all-in-one-device, respectful to the environment. It will exploit self-learning technology and could offer specialized advice in extreme conditions and finally, serve in hazard situation as a guardian angel for people. Guardian Angel (GA) functions enabled by Nano-PCo will help old people with their main problems: loss of memory, loneliness, reduced mobility and feeling useless in an ageing society. It will also help to monitor their medical condition and call help if necessary. Voice and/or face recognition interfaces, fall sensor and some other basic medical monitoring, with data transmitted to a watch centre could be personalized in the Nano-PCo. Furthermore, the emerging integration of heterogeneous technologies such as nanosensors with intelligent substrates on ever-smaller volumes are enabling an increased functional density that may bring about new paradigms for truly autonomous and highly miniaturized devices able to continuously monitor, store and transmit on demand data about molecular targets. The application of autonomous molecular sensing is wide and beneficial on several targets supporting the GA paradigm providing ubiquitous in-vivo and in-environment sentinels where molecular targets are recorded on multi-point platforms for body monitoring or for deep ambient surveillance.

INTEGRATION

The heterogeneous integration (including emerging 3D techniques) of computation, communication, sensing and energy supply technologies, and novel user interfaces, is key for this project. Even more important is the integration of a large variety of fundamental knowledge and synergies in electrical engineering, biology, computer science, energy conversion as enabler of the battery-less companion. These synergies will create opportunities for new industries and for novel innovation at the frontiers between disciplines and sciences. The hardware integration will be particularly enabled by ongoing efforts in More-Than-Moore nanoelectronic technologies where Europe has international leadership. Hardware-software will be part of the project. Key semiconductor, design and end-user companies in communication, sensing and medical domains will be involved in the project. The project is built on selected excellence in ENIAC and Swiss Nano-tera initiatives, and their extension to integrate specialized research know-how in biology and energy conversion at small scale. Even if great advances have been achieved in low-power systems, energy autonomous molecular systems need great technology challenges to be solved: i) heterogeneous integration of nanotechnology devices on microelectronic substrates; ii) exploitation of new devices for miniaturized energy harvesting (advanced optoelectronic, thermal, vibrational systems); iii) shift of paradigms from low-power to energy-wise systems, memories and logic devices and from power to energy management. vi) new concepts ultra-low energy short-range transmission systems.

PLAUSABILITY

The modern society has come to depend not just on basic functionalities of computing and communication but on their increased capabilities that have been made available each year at given cost and power budget. The applications covered by advanced silicon CMOS technology are enabled by the aggressive scaling of the MOS transistor (MOSFET) and the reduction of the cost per transistor by the amazing factor of 10^6 in more than 40 years, a level never reached by any other modern technology. However, among many other fundamental and technology barriers, power density and consumption appears to severely limit the future evolution of silicon CMOS. This project is built on achieved progress in nanoelectronics, which revolutionized already the modern society make today possible mobile computing and lowering the cost of a transistor to value less than the cost of a printed letter in journal. This industry is today looking at new challenges related to power consumption and the energy crisis, based on its extraordinary accumulated know-how and technology facilities. In Europe, we are particularly well placed for the challenges of ultra-low power and for the interaction between bio and nano for building complex power-aware systems. Therefore, there is a high probability of success despite the ambitious targets of bio-inspired battery-less Nano-PCo. Europe is also leading in communication technologies and bio-pharma industry; it is highly plausible the interaction between these industries and nanoelectronics will create novel opportunities for applications in an energy hungry, ageing society.

COMMENTS

This flagship project will find unique matching support in Switzerland through the Nano-Tera program extension that is perfectly aligned with its goal and ambition. Moreover, in Switzerland the project will be coordinated by a joint committee of the two Federal Schools, EPFL and ETHZ, in strong collaboration with CSEM and IBM Zürich.

Other matching initiatives will be provided by some key partners, including involvement of leading semiconductor and communication industries. The Consortium includes key European Research Institutes with access on the most advanced technology platforms, like IMEC and CEA-LETI, and top level universities well connected to many other end users. ST Microelectronics, Infineon and IBM Zurich will provide concrete industry support for efficient management, visionary products and milestones for applications with high societal impact. Biologists from EPFL, ETHZ, University of Geneva and University of Bologna will be deeply involved in the bio-inspired scenarios concerning the energy conversion using artificial photosynthesis or on-chip ion pumps.

Other concrete collaborations will be planned in US (with partners applying to NSF program enabling collaboration with Europe) and Japan for complementary needed know-how. The project is clearly goal-oriented and will identify various application scenarios and explore for adapted configurations of the Nano-PCo's.

Graphene Science and Technology for ICT and Beyond

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Project Outline

This Flagship will establish a coordinated European research platform on graphene, with two main core activities. It will connect the leading national initiatives in Europe, cross-link European research excellences, and build a pathway for the newly accumulated strategic knowledge to impact European industries and society. The Flagship will foster the emergence of foundational breakthroughs in graphene science and technologies and develop new engineering concepts to exploit the unique opportunities offered by graphene and its derivatives.

The large technological potential of graphene makes us confident that the Flagship will have a profound effect on the competitiveness of European industries, and create wealth in the form of environmentally friendlier technologies, new business opportunities and new jobs.

The exceptional development of graphene also clearly holds promises in economically strong markets such as high-frequency devices, reinforced composites for aeronautic/automotive applications, or nanoelectromechanical and sensing devices. Significantly, this material could also serve as an information and communication technologies (ICT) platform for fostering the innovation in information data storage and processing devices, complex molecular-based circuits, as well as disruptive computation and communication protocols, driven in particular by the anticipated outstanding capabilities of graphene-based ultrasensitive nanoelectromechanical, electromagnetic, as well as spintronics and energy-harvesting devices.

We will integrate the research chain from fundamental science, through developing new engineering concepts, to commercializable applications. Due to the unique structure of graphene, many of the possibilities it offers are still poorly understood, and their analysis requires highly sophisticated methods; to quote the Nobel Laureate Frank Wilczek from the Nobel Symposium on graphene held in Stockholm in May 2010, « *graphene is probably the only system where ideas from quantum field theory can lead to patentable innovations* ». In this Flagship we will address the bottlenecks associated with materials production and develop new facilities that provide a reliable and versatile supply of high-quality graphene. Building upon a rational materials supply, we will develop graphene electronics that can sustain ICT devices and technologies evolution beyond the limits achievable with silicon. By exploiting the unique electrical and optical properties of graphene, we will develop novel electronics systems with ultra-high speed of operation and electronic devices with transparent and flexible form factors. We will advance methods to produce cheap structural materials, with embedded electronics, in an environmentally sustainable manner. The Flagship extends beyond mainstream ICT to incorporate novel sensor applications and composite materials that take advantage of the extraordinary chemical, biological and mechanical properties of graphene.

Presently, the large graphene research community in Europe is fragmented in a several national and international programs that cover a wide spectrum of activities from basic science to production technologies and applications. The consortium behind this Flagship is still evolving; at this moment, it includes more than 80 research groups representing over 50 academic and industrial partners in 17 countries.

Introduction to graphene and graphene research in Europe

Graphene is an atomically-thick layer of bonded carbon atoms in a hexagonal array and stands as the thinnest conducting material ever studied with unique mechanical, electrical and optical properties, governed by unusual and fascinating physics. It can be fabricated r by mechanical or chemical exfoliation of graphite, thermal decomposition of SiC, or epitaxial growth on catalytic metals. The last three techniques allow mass scale production of graphene. Additionally, although sharing some common chemical and physical properties with carbon nanotubes, graphene offers substantial advantages in terms of engineerability and ease of integration: it opens unprecedented horizons to revolutionize low-dimensional nanoelectronics and related ICTs.

Since the discovery of graphene in 2004 in Manchester (onnes.ph.man.ac.uk/nano), the European scientific community has led the initiatives to gather research efforts and foster networking activities. As a matter of fact, the main international conferences series fully dedicated on graphene was launched in Europe under the support of ESF (GRAPHENE weeks 2006-11) and the Phantoms Foundation (GRAPHENE 2011-, www.imaginenano.com). Additional European research networks include several EU projects (GRAND, [www.grand-project.eu]; ConceptGraphene; RODIN, GRE-NADA) with a total funding of well over 15 M€, ESF Eurocores program EuroGraphene (7 M€ in 2010-13, www.esf.org/eurographene), the GDR GNT (France, 200 k€ in 2009-13, www.graphene-nanotubes.org), different projects funded by the ANR (France, 2.2 M€ in 2009-13), DFG Specific Priority Program (Germany, 15 M€ in 2011-16, www.graphene.nat.uni-erlangen.de/spp1459.htm) and EPSRC Infrastructure Science and Innovation Awards (United Kingdom, 15 M€ in 2009-14). These projects aim at advancing expertise in graphene devices, material characterization, or simulation, and at the development of functionalities such as composite materials and spintronic or photonic applications.

However, worldwide competition has become fierce and countries such as Korea, China, Japan, Singapore and USA have massively enhanced the incentives to transfer graphene-based materials to industrial applications. As a matter of illustration, IBM received significant financial support by American funding agencies to achieve in 2010 wafer scale integration of graphene-based high-frequency devices; at the same time a large international research consortium was launched in Korea, including leading scientists in Japan and USA, and reinforced by SAMSUNG corporation's strategy and industrial strength. In 2010, this consortium demonstrated roll-to-roll production of large graphene sheets and device integration, pinpointing the emergence of medium term applications (in, *e.g*., tactile electronics displays). *It is thus of strategic importance for Europe to implement a long term vision of graphene research, and foster the networking between academic research with industrial innovation.*

Fundamental science

The term 'graphene' stands for an atomically thin layer of graphite: monolayer (MLG) or bilayer (BLG). It is a truly two-dimensional (2D) material, one of its kinds. While studies of electronic properties of graphene have become the hottest topics in Physics, according to *ScienceWatch - Thomson Scientific*, so far, its chemical and thermomechanical properties, and the qualitatively new extremes of engineering it is able to generate when added into composite materials, remain largely an unexplored territory.

Both MLG and BLG are gapless semiconductors, with highly mobile carriers suitable to build field effect transistors (the development of a universal resistance standard based on the quantum Hall effect phenomenon in MLG is already under way). Due to Klein tunneling (a feature of electrons in pristine MLG where charge carriers behave as relativistic particles), achieving the pinch-off requires controllable patterning, chemical functionalization, or nanofabrication of ribbons with controlled edges – another area where coordination between physicists and chemists will play a crucial role. Alternatively, the band structure of BLG can be changed using electrostatic gates, with a gap – as large as 200 meV – opened in its spectrum by a transverse electric field. This determines the challenge for chemists and materials scientists to find methods for mass production of BLG.

Using MLG and BLG as interconnects in hybrid circuits opens the possibility to create new types of hybrid electronics: superconducting proximity effect transistors; electrostatically operated spin valve transistors; integrated circuits with graphene-based nanoelectromechanical elements, from GHz to THz range. For this, a detailed understanding of electron-electron correlation effects, interaction of electrons with disorder and deformations of the 2D crystal will be needed, which will be achieved by bringing together nanofabrication, electronic transport measurements from room temperature down to the mK range, STM studies, and theoretical modeling.

Fast optical studies of graphene (from femto- to picosecond range) will aim to understand mechanisms of photo-excited carrier relaxation in graphene and charge transfer from graphene to metallic contacts, polymer environment, dyes, or intercalating layers. This will pave the way for graphene applications as a saturable absorber (in conjunction with high-n polymers), as transparent conducting component in flexible displays and photo-emitting diodes, as active element in photodetectors, and – possibly – as conducting element in energy harvesting cells. Optical and vertical tunneling studies will be extended onto atomically thin films of insulating materials such as boron nitride, $NbSe_2$, and MoS_2.

Due to sp^2 hybridized bonds between carbons in the honeycomb lattice of graphene, graphene is an extraordinary strong flexible 2D crystal (it has a specific strength, *i.e.* breaking force per unit area per density, of 48,000 $kNmkg^{-1}$, compared to best steel's 154 $kNmkg^{-1}$), and it has, quite uniquely, a negative thermal expansion coefficient. Adding graphene into polymers has potential to create strong lightweight materials, which requires research in chemistry and physics of graphene-polymer coupling, understanding mesoscale continuum mechanics of graphene-polymer composites, and their thermomechanical properties using AFM, near field scanning, STEM, and theoretical modeling.

Graphene production and characterization

Emerging technologies, no matter how revolutionary they are, initially face significant cost barriers to compete with established technologies. Thus, the cheap production of large amounts of graphene with controlled electrical, chemical and structural properties is fundamental for graphene to have a significant impact on society. A main advantage of graphene over other nanostructured materials (such as nanocrystals or nanotubes) is that graphene sheets can be directly obtained in large quantities and at low cost by exfoliation of graphite, which is a cheap and abundant mineral. Graphene can be considered as a way to overcome the limits and burden of molecular synthesis; instead of assembling polyaromatic structures starting from small polycyclic molecules, we can cut the piece we desire from a large sheet of graphite. Large quantities of graphene can be produced by chemical exfoliation in solution with organic solvents, surfactants or molecules that intercalate between the layers of graphite, yielding suspensions or stable solutions in organic solvents.

The exfoliation process has many drawbacks that lower graphene quality, both as defects in the graphene lattice and contaminations that are difficult to remove. A major challenge will thus be the production of single graphene sheets with outstanding electrical and mechanical properties, with good yield, controllable size and low cost.

A great advance in this field is the recently reported bottom-up fabrication of graphene nanoribbons with uniform widths of the order of 1 nm. As discussed above, nanoribbons are one possible route to introducing a gap in the electronic spectrum of graphene, which is of great interest for electronic applications.

While solution processing is suitable for bulk applications, continuous and defect-free wafer size graphene layers are needed for electronic applications, where the highest electrical performance is required. Homogeneous mono-layers of graphene can be obtained with epitaxial growth of graphene on SiC, or by Chemical Vapour Deposition (CVD) on different metal surfaces (Cu or Ni). In this way uniform, large transparent electrodes with monolayer thickness and lateral size over 70 cm have been obtained, which can be applied to roll-to-roll fabrication of graphene-based flexible devices.

Thanks to their large lateral size, even monoatomic graphene sheets can be visualized with a standard optical microscope, exploiting interference effects on silicon or fluorescence quenching on different substrates. Graphene samples can be routinely characterized by electron and scanning probe microscopy, X-rays diffraction, Raman spectroscopy, *etc*.. However, a complete characterization of graphene's chemical and electronic structure, especially in the case of functionalized graphene such as graphene oxide (GO), is still missing and more experimental and theoretical work will be needed to fully exploit all the potentialities of this material.

Overall, different techniques allow production and characterization graphene with quality high enough for applications ranging from electronics to plastic composites. The challenge is to transfer the techniques already demonstrated in laboratories to industrial production, and to make the performance and cost of graphene-based materials competitive with established technologies. Graphene commercial production is already emerging with a production of more than 15 tons of various kinds of graphene in 2009 by several companies, mostly based outside Europe. A major effort is needed to keep Europe at the forefront of the development of this revolutionary technology – according to recent information, first Korean-produced graphene-based consumer products are expected to enter the market in a few years.

Graphene for high frequency and digital electronics

The idea of using graphene for high frequency applications and digital electronics was born already in 2004 after the first realization of a graphene based field effect transistor by the group of A.K. Geim, driven mainly by three extra-ordinary properties of this new material: a high carrier mobility reaching values of more than 10.000 cm^2/Vs at room temperature; an enormous current carrying capability of over 10^8 A/cm and the fact that graphene, a single layer of carbon-atoms, is the thinnest material conceivable.

The latter is in particular relevant for silicon dominated digital electronics, where the increase in computation power was mainly realized by miniaturizing the individual transistors. However, with decreasing gate lengths, parasitic short channel effects become more and more important, which can be avoided by using ultrathin silicon channels. Graphene as the thinnest conceivable channel material would enable scaling beyond the limits of silicon, which is thought to be the so called *11 nm node*. As graphene is a zero band gap material, the on/off ratio is rather poor and not sufficient for logic operations. Therefore, a major research focus is to convert this semi-metal into a semiconductor to reach on/off ratios larger 10^4. This still remains an unsolved problem although two approaches have already been proven to work in principal: Cutting graphene to nanoribbons with a width below 10 nm, or using bilayer graphene with a perpendicular applied electric field might open the way to a digital graphene transistor world. Therefore, the main challenges are at the moment: Introducing a band gap in graphene reproducibly on the wafer scale, exploring new device concepts such as tunnel FETs or single-electron transistors, where a rather small band gap can be tolerated or is even beneficial, and the large scale synthesis of high quality graphene. For first industrial entry points hybrid silicon/graphene devices will also require the integration of graphene into the established silicon CMOS technology, which will no longer be a limitation in the all graphene era.

Using graphene in RF transistors is made attractive by the extremely high carrier mobility and the fact that RF applications do not have as strict requirements for the on/off ratio as logic applications do. Graphene transistors operating at frequencies up to 100 GHz were demonstrated in 2010 (IBM), and very recently over 300 GHz (UCLA); the material has the potential to pass the THz-border in the near future. High frequency applications like low noise amplifiers are currently dominated by III/V semiconductors, which have major drawbacks in that they are hard to integrate into silicon technology and that they have often relatively small transconductances. These two drawbacks can be eliminated by using graphene as channel material. The main challenges for RF applications are similar to the ones for logic applications: The integration of graphene devices in silicon technology and the increase of their trans-conductance by, *e.g.*, introducing a band gap, and ensuring sufficient voltage gains and output currents so that components can be integrated to circuits.

Although the route for introducing graphene in RF and digital electronics is specified quite clearly after 6 years of research on graphene electronics, the remaining challenges are still high, requiring a joint effort of leading European institutes and industry to exploit the great potential of this remarkable material in future ICT devices.

Other graphene electronics

It can be foreseen already that the main impact of graphene for future ICT technologies will come from its unique combination of properties, instead of just as a replacement or improvement over current materials. Its high mobility and ambipolar conduction combined with transparency, flexibility and chemical stability will enable novel electronic devices, with drastically new form factors, user interfaces and usage scenarios.

Already now graphene has been demonstrated to meet the electrical and optical requirements for transparent conductive electrodes used in touch screens and displays, but in contrast to indium tin oxide (ITO) presently in use, graphene is flexible and mechanically more robust. The other alternatives for transparent and flexible electrode materials, such as carbon nanotube networks and silver nanoparticles, are currently more cost-effective, but when mass manufacturing methods for graphene develop further, cost will come down radically and quality will improve. This alone may be enough to drive graphene to consumer electronics products. It is clear that a replacement for ITO is urgently needed due to limited indium supplies – this is reflected by a tenfold rise in indium prices over the last decade.

A more intriguing possibility is to use graphene not only for conductors, but also for the active electronic and even optical elements: transparent conductive films with embedded optical and electronic functions, all consisting of graphene, could be the ultimate goal for future ICT systems to be studied in this project. All the required components such as transistors, memory elements, chemical and biological sensors, photovoltaic and light emission devices have already been demonstrated in research laboratories, but are still far from practical applications. The most demanding effort lies in combining the components to functional systems. Integration requires a thorough understanding of component properties in realistic environments, and their variations in mass manufacturing. Once these are understood, system integration and system level modeling is needed to combine components and subsystems into functional devices. This requires a large scale research project, with expertise ranging from various fields of basic sciences, to systems engineering and manufacturing.

Nonlinear optical devices based on graphene are rapidly emerging as a new application area. Graphene's ultrawide broadband capability opens the route to high-speed, transparent and flexible photosensitive systems, which can be functionalized to enable chemical sensing. The combination of graphene photonics with plasmonics is expected lead to novel advanced devices.

Graphene composites

Apart from its outstanding electronic properties, graphene has high mechanical strength, excellent thermal conductivity, and can be used for the fabrication of high-performance composites. The application areas of graphene composites extend from aerospace and automotive industries to medical implants and prostheses. Based on experience with a similar disruptive technology, carbon nanotubes, we predict that composite materials will be among the first commercial applications of graphene.

Single sheet graphene is 300 times stronger and five times stiffer than steel, has an electrical conductivity of 6000 S/cm and a thermal conductivity of 5000 Wm^{-1} K^{-1} (better than copper). Transferring these exceptional properties to a graphene-based composite material requires proper preparation. Graphene or graphene oxide (GO) can be mixed with polymers in solution, or directly in melt. Mixing graphene with suitable monomers followed by *in situ* polymerization has also been tested.

As example, a 76% increase in tensile strength and a 62% improvement of Young's modulus have been achieved by addition of only 0.7 wt% of GO to a PVA matrix. A striking 33% enhancement of elastic modulus for graphene loading as low as 0.01 wt% has been found in graphene-PMMA composites.

Polystyrene-graphene composites exhibit a charge percolation threshold of 0.1 volume per cent for room-temperature electrical conductivity, the lowest reported value for any carbon-based composite except for those involving carbon nanotubes. Hence, graphene-based materials are among the leading candidates for electrically conducting composites, which open many new application areas. A major advantage with respect to nanotubes is that graphene sheets, because of their shape, do not form entangled bundles.

Enhancement in thermal conductivity has also been observed in graphene-polymer composites, but with higher loadings compared to electrical conductivity, probably due to poor heat conduction through graphene-organic interfaces. Furthermore, graphene has a very low permeability to all gases including helium, making it an interesting additive for polymers in packaging.

A future major challenge will be the development of efficient, reliable ways to attain good dispersion of graphene in the composite, avoiding sheet re-aggregation and stacking. For this, strong and well-defined and controllable interactions at the graphene-polymer interface are needed. Many of the results obtained up to now cannot be explained using the available theoretical models; a complete understanding of graphene's role and of the highest performance attainable in graphene-based composites requires more detailed studies of their structure at the nanoscale, and of the chemical and physical interaction of graphene with organic materials.

Environmental and medical applications

Graphene is particularly well suited for engineering complex chemical and biological functionalities. Inspired by earlier research on fullerenes and carbon nanotubes, graphene-based materials have been anticipated as candidates to design ultra-sensitive and ultra-fast electronic sensors, particularly due to low electrical noise material. Indeed, graphene (being a one atom thick sheet) comes in direct contact with a substrate, so that the interface states play a crucial role in sensing. Selective sensing properties for gases such as NO_2, NH_3, H_2O, CO have already been demonstrated, as well as simple and scalable fabrication methods for practical devices. The sensor response is usually consistent with a charge transfer mechanism between the analyte and graphene with a limited role of the electrical contacts. Suspended graphene sheets can be also mechanically resonated using laser or electrostatic methods. The optimisation of the Q-factor of graphene will be a key to maximise the mass sensing capability of related devices.

Grafting (bio)-molecules to graphene substrates could open interesting directions for innovation. In particular, the link with biological applications could be developed based on DNA-graphene hybrid materials. Possible applications for a DNA-graphene biosensor include diagnosing diseases such as cancer, detecting toxins in tainted food and detecting pathogens from biological weapons. Some recent results have suggested that single-stranded DNA attached to graphene is less prone to being broken down by enzymes, which makes graphene-DNA structures especially stable. This could lead to drug delivery for gene therapy.

Recently, double-stranded DNA translocation through nanopores in single-layer graphene was demonstrated, which represents a step towards single-molecule nanopore analytics. In future, this may lead to single-base detection, and ultimately sequencing.

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The Human Brain Simulation Project (HBSP)

A proposal under the FET-Flagship program
September 15th, 2010

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Goal

The Human Brain Simulation Project (HBSP) will build a supercomputer-based infrastructure and lead global cooperation to simulate and understand the human brain from genes to behavior, to accelerate the development of diagnostic tools and treatments for brain disease, and to generate new brain-derived technologies.

Mission

The mission of the HBSP will be to (i) *build a European Facility for Simulation-Based Brain Research,* providing scientists throughout the world with a unique integrated research environment, including exascale data storage and computing capabilities, remotely accessible virtual laboratories, and other tools and infrastructure required to integrate their data and knowledge in biologically detailed models of the brain; (ii) drive the development of new genetic, optical, electrical, telemetric, and nano- technologies to "screen the brain"; (iii) create a design center for High Performance Computing (HPC) driving the development of exascale and larger facilities for brain simulation and other simulation-based applications; (iv) build *Neuromorphic* and *Neurobotics Facilities* with the capabilities to design and build a new generation of brain-derived, low energy technologies for computers and robots; (v) use these facilities to derive the molecular, cellular and systems basis for emergent functions of the brain, including higher cognitive functions such as learning and memory, perception, action, decision making, reasoning and emotion; (v) simulate brain diseases, develop a new generation of diagnostic tools, and develop new treatments.

Background

The industrial-scale neuroscience of the 21^{st} century is producing a rapidly escalating volume of data and knowledge on every possible level of biological organization. The result is a data deluge. The grand challenge in the post-genomic era is to integrate this fragmented information, to find the patterns within and across different levels, and ultimately to understand the causal chain of events leading from genes to complex behavior and intelligence.

Several recent life science projects are already using industrial-scale approaches and informatics to collect and organize huge volumes of basic and clinical data on the brain. This is a crucial step. Informatics and advanced data analysis are becoming ever more effective at exposing correlations and other patterns in the data and extracting general organizing principles, but are not as effective at proving causal relationships. It is these relationships we have to find to understand how the genome "unravels" to produce an organism and a brain, how the interactions between the different elements support emergent behavior, and how their breakdown leads to brain disease. This requires new strategies.

In many fields of engineering, it is now standard practice to build simulations of physical systems (e.g. a car or an aircraft) as accurate as data, knowledge and computing power allow. Unlike high-level conceptual models, these detailed, simulation-based models allow engineers to explore the contribution of individual components to the properties and behavior of the system. Neuroscientists have the same need. Supercomputing-based simulations of the brain have the potential to reveal the complex chains of causation leading from genes, molecules, cells and connections, to behavior and disease.

In the past, the main obstacle to this kind of simulation-based research has been complexity: a complete simulation of even a small part of the brain has to solve trillions of simultaneous equations. Today, however, supercomputers are approaching the critical mass where this is possible. In other areas of the life sciences, these developments are leading to a new kind of *ICT-based Integrative Biology*. The time is ripe for neuroscience to seize the opportunity and trace a roadmap for the simulation of the human brain.

Simulating the brain will be a grand challenge not only for neuroscience and medicine, but also for HPC. Although recent growth in computing power has been driven by scaling up existing technologies, modern supercomputers are quickly approaching the maximum practical limit on energy consumption and face other serious barriers in terms of memory, computing speed, data transmission, programmability and reliability. Necessarily, the attempt to simulate the human brain will drive radical innovations in the design of supercomputers and HPC facilities. But it can also do far more. Every day, human brains perform tasks too sophisticated for even the most powerful of today's supercomputer or robots – all with a mere 30 Watts. Understanding the physical basis for these abilities can open the door to brain-derived computing technologies, driving genuinely intelligent computers, devices and robots completely unlike those we know today.

The Project

The Brain Simulation Facility

The *Brain Simulation Facility* will consist of an integrated research environment, including an HPC infrastructure and a full range of tools, data and services accessible remotely to scientists throughout the world. The Facility's *simulation cockpit* will integrate a broad range of capabilities and information including standardized data from neuroscience experiments and industrial-scale screening covering a range of species; clinical and experimental data on brain disease; geometric and computational models describing all levels of brain organization; advanced informatics and data analysis tools making it possible to mine this data and derive organizing principles; software to build, simulate, and analyze brain models and to visualize them in 3D; an Internet portal allowing researchers to access models and model-building tools; software making it possible for scientists, clinicians, companies and educators to build customized experiments, virtual laboratories and teaching facilities; software and experimental setups coupling brain models to virtual and physical robots for cognitive and behavioral experiments.

To meet the needs of the Facility, the Project will design and implement an exascale supercomputer, optimized to meet the requirements of human brain simulation. The design will co-evolve with the design of applications software, maximizing end-to-end value for scientists. Key design issues will include the selection of components for heterogeneous architectures, the management of exascale volumes of data, *in situ* visualization, and the configuration of the final facility. The facility will include an *HPC cockpit,* making it possible to monitor and optimize the performance of HPC hardware and software, not only for brain simulation but also for applications in other domains of science and technology.

Modeling and Simulation

The project's strategy is to build biologically accurate models, starting at the most elementary levels of brain organization. Models will be validated against experimental data describing the emergent properties of neurons, neural circuits, and the whole brain. The ultimate validation will come from evaluating emergent behavior and advanced cognition in robots interacting with real environments under the control of realistic brain models.

The biggest challenge facing the project will be to build biologically accurate brain models for humans and other higher species, using mainly non-invasive data. To achieve this goal, the project will begin with lower species and derive the principles determining the individual steps leading from genes to the brain. This will require a cyclical workflow beginning with data, continuing through informatics and advanced data analysis, to simulations that attempt to replicate biological experiments and test hypotheses of causality, back to experiments to validate predictions and meet new requirements for data. The results from this process will allow us to build generic *template* models covering all levels of biological organization, to update the models as new data and principles emerge, and to gradually approach biological realism.

The project will establish a roadmap specifying a sequence of models at various resolutions (cellular, subcellular, molecular, genetic), at various scales (micro-, meso-, macro-level circuitry, whole brain) and in various species (rat, mouse, cat, monkey) leading towards simulation of the human brain. The project will not aim at a single model for each species, but at the *capability* to build as many models as scientists need, at ever higher resolutions and scales.

The HBSP recognizes that the human brain is enormously complex and that it is not certain when a complete simulation will be feasible. However, envisaging Human brain simulation as *on*, rather than *over* the horizon, makes it possible to identify the key technological, informatics, experimental and clinical challenges *en route* to understanding the brain and its diseases. Even if simulating the human brain takes longer than the initial ten years of the HBSP, it will inevitably deliver a vast spectrum of biological insights at each step along the way.

The Diseasome – Simulation-Based Clinical Research

The HBSP will collect large volumes of data describing all recognized diseases of the brain (the *diseasome)*, developing new informatics approaches to understand their differences and similarities at different levels of biological organization. These insights will be used to identify new diagnostic indicators and to derive organizing principles needed to simulate the human brain. Scientists will be able to use the *Brain Simulation Facility* to model brain disorders such as Alzheimer's and Parkinson's Disease, schizophrenia, and depression, and to test hypotheses of causation. Detailed computer models of diseases will allow them to simulate the action of candidate drugs, speeding drug discovery and development.

Brain-Derived ICT

The HBSP will convert detailed brain models into novel software applications and neuromorphic hardware devices. To do so, it will set up two research facilities. A *Neurorobotics Facility* (NRF) will couple brain models to robotic agents, testing the emergence of cognitive capabilities as these agents meet the challenges of real or virtual environments. Successful models will provide blue prints for novel cognitive architectures. An advanced *Neuromorphic Computing Facility* (NCF) will implement these cognitive architectures in novel software and in neuromorphic hardware, driving a new generation of intelligent devices and robots for health, entertainment, industry and the home. The new technologies will not be just inspired by but directly derived from the brain

Society, Ethics and Education

The HBSP will have major societal and ethical implications, some controversial. The project will thus follow the lead of the Human Genome Project, dedicating substantial resources to research, discussion and informed debate on ethical and societal issues. In parallel with this effort, the project will develop a program of education, designed to spread awareness of brain processes and brain disease to the general public and to all levels of the education system. The program will include *Virtual Education Centers* for post-graduate students who wish to pursue transdisciplinary research crossing the traditional boundaries between ICT, science and medicine.

Impact

Neuroscience & Medicine

The first sign that biologically detailed brain models can support even the simplest form of cognition would be a major breakthrough for the project and neuroscience, making it possible to trace the genes, molecules, cells, synapses, connections, pathways, and brain areas involved. Models displaying more advanced functions, such as goal-oriented behavior, intelligence and language, will help unravel the elementary steps that lead to higher cognition and the multiple factors responsible for brain disease. As the project assembles the diseasome, studying the commonalities and dissimilarities among brain diseases, it will contribute rapidly to medical diagnostics. As it expands its capabilities, particularly in molecular modeling it will become possible to test hypotheses of disease causation and candidate treatments. Simulating drug effects will provide a firm foundation for rational drug design. Shortening the design cycle will have far-reaching effects on medicine, industry and society.

High Performance, Low Energy Computing

The grand challenge of simulating the Human Brain will drive and guide the evolution of supercomputing and supercomputing-based simulation in the life sciences and elsewhere. New insights into the way the brain computes, stores and transmits information will generate novel solutions for efficient use of energy, memory, data movement, resilience and self-repair. The project will actively drive new concepts for cluster-based supercomputing and for visually steered, interactive supercomputing guided by these insights. The possibility of remote real-time visualization holds the potential to make supercomputing accessible to the general public, creating opportunities for mass-market applications including e-medicine, and virtual environments for schools, business and entertainment.

Brain-derived ICT and Neurorobotics

In the longer term, the HBSP will lay the foundations for a paradigm shift in computing itself. Brain models with cognitive capabilities will provide a basis for intelligent systems suitable for implementation in software or in neuromorphic hardware. In this way, the project will open the road to completely new forms of brain-derived computing, with valuable new capabilities (e.g. learning, adaptability, flexibility, self-repair, low energy consumption, automated posing of problems and finding solutions, goal-oriented behavior, decision making) largely absent in current systems. These capabilities are a precondition for the development of genuinely intelligent robots. Such robots will have a huge range of applications in industry, health, education, research and the home.

Hightech and Biotechnology

The HBSPs need for industrial scale, high quality data will drive high throughput screening technology, and will have a major impact on European hightech and biotech SMEs. New technologies from this effort (e.g. new techniques for genome analysis, single cell transcriptomics and proteomics, cellular resolution whole brain scanning, molecular level whole brain functional imaging) will have a major impact right across the life sciences.

The Consortium

The project is proposed by a group of partners from Switzerland, Germany, Sweden and a broad range of other European and non-European countries, including representatives of existing large-scale initiatives in neuroscience, supercomputing, medicine, brain-inspired ICT and robotics and a broad range of computing, hightech, biotech and pharmaceutical industries, and many major hospitals, healthcare centers and clinics around the world.

Contacts

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Torsten Wiesel, Chairman of the **Scientific Advisory Board**

A number of other leading scientists are at the center of the HBSP initiative; Jean-Piere Changeux, Collège de France, **France**, Ethics & Society; Javier DeFelipe, UPM, **Spain**, Neuroscience; Yadin Dudai, Weizmann Institute, **Israel**, Ethics & Society; Seth Grant, Sanger, **UK**, Large-scale Neuroscience; Andreas Herz, Bernstein Center, **Germany**, Modeling; Sean Hill, EPFL, Neuroinformatics, **Switzerland**; Alois Knoll, TUM, **Germany**, Neurorobotics; Thomas Lippert, JCS, Germany, HPC; Jose Pena, UMP; **Spain**, Data Analysis; Danny Porath, Hebrew U, **Israel**, Brain Probes; Alois Saria, Innsbruck, **Austria**, Education; Thomas Schülthess, CSCS, **Switzerland**, HPC; Felix Schürmann, EPFL, **Switzerland**, Simulation; Idan Segev, Hebrew U, **Israel**, Modeling; Alex Thomson, U of London, **UK**, Neuroscience; Antoine Triller, CNRS, **France**, Neuroscience.

A much larger circle of scientists have expressed their interest in participating. They include: Wanda Andreoni, CECAM, **Switzerland**, Modeling; Alim-Louis Benabid, Grenoble, **France**, Diseasome; Driss Boussaoud, CNRS, **France**, Diseasome; Raymond Campagnolo, Grenoble, **France**, Brain Probes; Angelo Egidio, U Pavia, **Italy**, Neuroscience; Sue Denham, U Plymouth, **UK**, Modeling; Marcus Diesmann, Riken, **Japan**, Modeling; Hans-Ulrich Dodt, TUW, **Austria**, Large-Scale Neuroscience; Gregor Eichele, MPI, **Germany**, Large-Scale Neuroscience; Mark Ellisman, UCSD, **USA**, Neuroinformatics; Tamas Freund, HAS, **Hungary**, Neuroscience; Dario Floreano, EPFL, **Switzerland**, Neurorobotics; Fernando Ferri, Trier, Germany, Visualization; Lyle Graham, CNRS, **France**, Modeling; Michael Hausser, UCL, **UK**, Neuroscience; Allan Jones, Allan Brain Atlas, **USA**, Large-Scale Neuroscience; Mira Marcus-Kalissh, TAU, **Israel**, Brain Body; Marcus Kaiser, Newcastle U, **UK**, Data Analysis; Edvard Moser, NUST, **Norway,** Neuroscience; David Lester, U Mancester, **UK**, HPC; Yusuf Leblebici, EPFL, **Swizerland,** Neuromorphics; Enrico Macil, Polito, **Italy**, Neuromorphics; Corinne Mestais, Grenoble, **France**; Brain Probes, Pierre Magistretti, EPFL, **Switzerland**, Neuroscience; Johnny Ottesen, RUC, **Denmark**, Neuroscience; Guy Orban, Leuven, **Belgium**; Franco Pavone, LENS, Large-scale Neuroscience, **Italy**; Alain Prochianz, CNRS, **France**, Neuroscience; Claire Prummel, Grenoble, **France**, Brain Probes; Ranolfo Romo, UNAM, **Mexico,** Neuroscience; Terry Sejnowski, Salk, **USA**, Modeling; Bernd Stahl, Simone de Monfort U., **UK**, Ethics; Leslie Smith, U Sterling, **UK**, Neurorobotics; Paul Verschure, Pompeu Fabra U., **Spain**, Neurorobotics; Robert Williams, UT, **USA**, Neuroinformatics.

A number of existing consortia and companies in HPC, ICT, Hightech, Biotech, Bioservices, and pharmaceuticals have also expressed their interest in contributing to the project.

Sustainable Personal Living Technology (SPLiT)

Vision for the public: "The personal computer, along with the world-wide-web, has revolutionized personal productivity of informational content. The next giant leap is to the personal production of the complex things we need, with the help of a personal fabricator hooked to your PC like a printer. Using information on the web, you will be able to design and build unique smart devices and systems at home, with inbuilt integrated computing, sensors and moving parts, with the help of millions of online users and a vast repertoire of evolving modular designs, spanning personalized health care to smart photovoltaic devices. The production is sustainable through smart recycling of materials, and on site operation and accountability. This is a world in which changing individual, social and environmental requirements can come first even for those with special needs currently missed in our mass-production society. This is a world where both information processing and material production evolve by individual choices. Welcome to the personal fabricator network."

1 Participants

To create and deploy the personal fabricator network, the consortium will bring together computer scientists (web, languages, CAD, robotics, embedded systems, evolutionary computation, artificial life & intelligence, complex systems), chemists, synthetic biologists, physicists, electronics-, production- and automation engineers, social scientists, educationalists and policy advisors. The consortium is not yet complete.

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2 Flagship mission

We propose to bring ICT to life with novel adaptive manufacturing for a creative society by developing the Personal Fabricator Network (PFN). This network, with the architecture of living systems, will allow individuals to create and deploy human-scale intelligent material devices in a socially responsible, informed and sustainable manner. Programmable personal manufacturing will provide individual access to cumulative expert design and evolutionary optimization, enabling, for example, customizable household devices, the printing of adaptive interfaces (to microbes, renewable energy sources, sensor networks etc), microscopic chemical processing for the personalization of diagnostics and pharmaceuticals.

Society needs this technology in the aftermath of the industrial revolution of the 19th century, which achieved mass production in factories, and the information revolution of the 20th century, which culminated in information processing with personal computers and the internet. By enabling individual digital manufacturing and deployment in an informed self-organizing social framework, the PFN will enable novel individually inspired services, rapid and cumulative propagation of innovations, foster wealth creation and provide transparent personal accountability, creating a new foundation for a sustainable society.

The Personal Fabricator Network will finally realize a founding vision of computer science and bootstrap construction complexity via von Neumann's famous *second machine*: a programmable construction engine. Beyond von Neumann's vision, this flagship project will exploit the evolutionary potential of interconnected human innovation through ICT infrastructure. Further, the PFN will bridge the current bio-silicon gap between ongoing construction and fixed hardware.

The Personal Fabricator Network will eventually reach the level of personalization and popular utilization we know from the PC and internet. The flagship federal effort will provide the critical investment of multidisciplinary research, spearheaded by ICT, to initiate in society a measurably growing and maturing PFN with increasing functional information density. By leveraging individual participation in the manufacturing process, global deployment of the PFN will lead to genuinely useful manufacturing output with integrated ICT that will better fit local needs and the regional environment. The net result will be to remake the manufacturing profile of the world, with Europe returning to its former leading position.

3 Living Technology: why now?

Living Technology is technology that exploits the core properties of living systems[1]. Central to life is the general-purpose construction process that allows the creation of diverse functional organisms from a common communicable (genetic) description language. Such a universal production language will form the core architecture of the PFN that will render its technology communicable, flexible, adaptive, and evolvable; making it both sustainable and appealing to live with, just as evolution and life are intimately connected.

We are already witnessing an increase in personal productivity supported by personal computers. This increase is mediated by progress in social ICT infrastructure (the internet, the world wide web, etc.). Individuals however are still insulated from technological production creativity by mass production – by the remoteness, size and complexity of factories and their management, proprietary information and logistics – and by the massive development times for profitable mass production. This limitation is reminiscent of some of the barriers to computation in the age of mainframe computers, but it is significantly more serious because of the economic and environmental impact of miscalculated mass production. Overcoming the distance between production and deployment will catalyze responsible involvement and creativity.

For the first time now, the microscopic scale can be programmed to allow a vast repertoire of novel useful artifacts to be designed, produced and deployed by individuals. Technological evolution is already progressing in the direction of personal fabrication: Gershenfeld[2] has already advocated desktop personal fabrication combining circuit board synthesis with computational numerical control (CNC) machines; Bill Gates has argued that computers will be replaced by a plethora of distributed intelligent devices. Already, for restricted materials, 3D-printers[3] are available that can make many of their own parts, and electronic devices are being extended to more and more common materials, including paper and plastics. The SPLiT flagship aims to lift this progress to a competitive personal network fabrication platform in Europe, with the clear goal of achieving increasingly high information density processing in products right down to the molecular level (enabling intelligent and life-like properties) with socially-evolvable digital designs, and with a priority on sustainability and the integration of human needs into the local construction process.

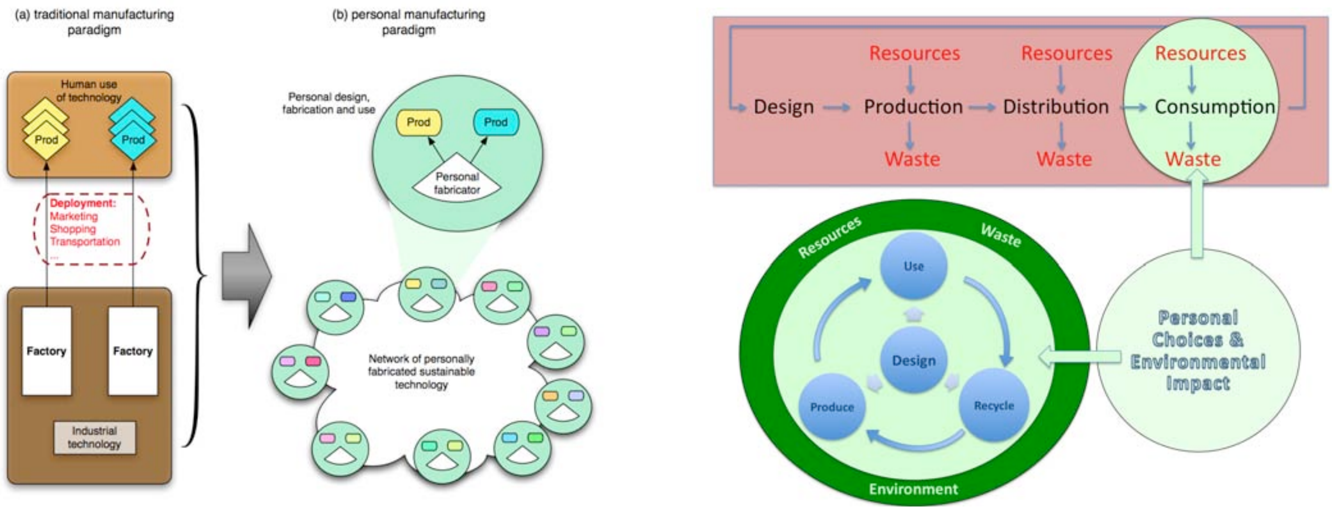


Figure 1. (a) Traditional organization of centralized technology production via factories, compared with (b) the Personal Fabricator Network, where participants use the network to communicate using genetic specifications of technology. The right figure compares traditional manufacturing (upper) with the PFN (lower), where design, production, and consumption are localized; distribution is eliminated. With the PFN, production and deployment are locally rooted and need driven, but globally informed, and therefore both efficient and sustainable and agents for social community building.

Personal fabrication will provide the basis for a new internet of ongoing material processing, and will benefit from a parallel development of living technology middleware to create value as illustrated in Figure 1.

4 The Personal Fabricator Network

Society increasingly depends on complex artifacts that function by processing information. In addition to electronic devices, these also include smart materials and integrated sensor and actuator networks. By enabling individuals to design, fabricate and deploy complex artifacts, a Personal Fabricator Network will enable individuals to create personalized solutions to the perceived needs in their communities, and thereby complement and augment existing networks of complex artifacts.

Biological organisms provide sophisticated problem solutions based on a high information content technology that reaches up from molecular to macroscopic scales. Compared with our engineered artifacts, this functional information density in biology is used to ensure scalable self-construction, self-organization, growth, communication, self-maintenance, ambient self-powering, flexibility and adaptive functionality. A clear goal of the SPLiT flagship is to redirect manufacturing towards an investment in high information content distributed construction infrastructure reaching down to the molecular scale. Although the first personal fabricators will function with microscopic rather than molecular scale detail, both chemical engineering and synthetic biological engineering are already defining new paradigms for programmable construction down to the molecular scale. The SPLiT flagship will link up these levels with a technology prioritization that focuses on hierarchical and scalable architectures, construction processes down to the molecular scale, and the early inclusion of molecular information level prototype research.

The PFN will build on existing technology for chemical systems, combinatorial materials, synthetic biology, reconfigurable hardware and microfluidics, moving from 3D-printing to self-assembling architectures. Personal fabricators will be universal as in protein translation, with particular fabricators able to fabricate any functional device within its material domain. The PFN will embrace digital evolutionary, morphogenetic and neural network design, as well as engineering based on self-assembling and self-organizing systems. ICT middleware will provide access to an internet of material designs, objects, and systems, and allow individuals to create and share in a growing wealth of information on how to design, construct, and use complex artifacts in a responsible and sustainable manner. This PFN will be designed in consultation with industrial ecologists.

The SPLiT flagship initiative will use at least six classes of metrics for completion and success:

- total potential product diversity
- complexity/cost/functional information density
- programmable product reproducibility
- construction time and manufacturing bandwidth
- sustainability of raw materials, waste and CO_2 footprint (LCCI, see in Sec. 6 below)
- requisite education time for effective use (see in Sec. 7 blow).

The successful completion of the SPLiT flagship will involve the establishment of a European wide network of personal fabrication for several key generic manufacturing niches. It will seed an initial user community that will contribute designs, evolutionary optimization procedures, products and testing, and deployment information to the open internet integration repository. The successful completion will also involve establishing a hierarchy of personal fabrication down to the molecular level, with the completion of personal fabricator prototypes at this level, with a clear roadmap for achieving cost effective integration of molecular information processing in personal fabrication.

5 Flagship Sails (work packages)

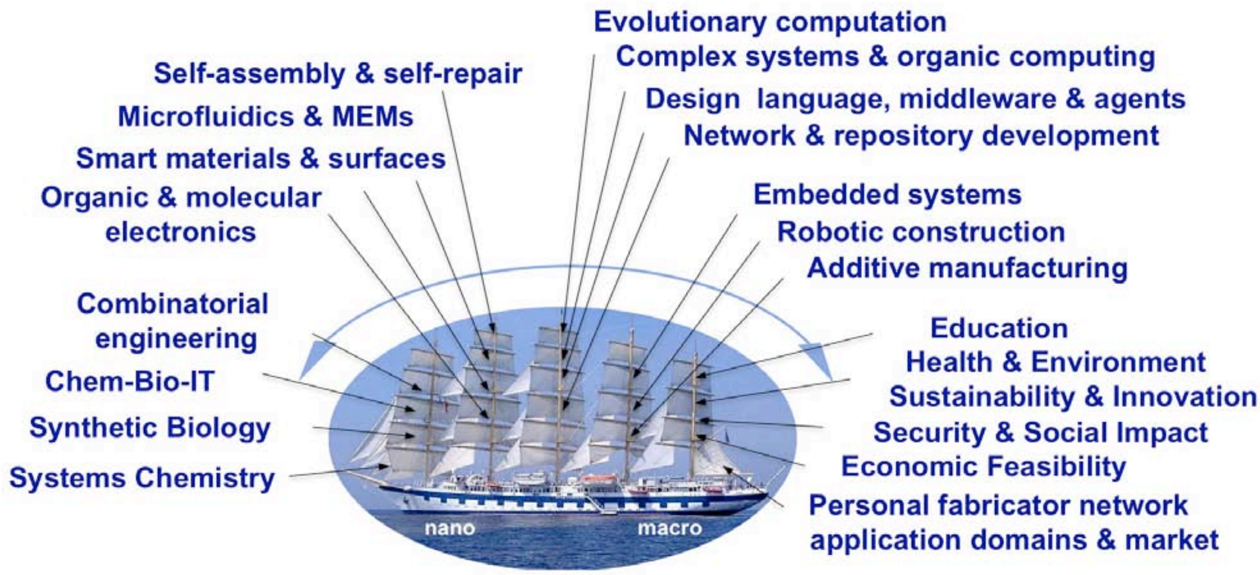
The SPLiT flagship will aim at personal fabrication based on bottom-up semi-autonomous construction processes like the self-assembly of specified components, moving from 3d-printing to increasingly embedded construction with higher information density and finer scale functionality. Initial personal fabricators will be domain specific, but able to produce a broad range of different high information content functional devices or systems, under the control of a digital program.

The implementations will be propelled by the sails listed below (Fig. 2) and will focus on four main thrusts:

- Smart surfaces with novel surface functionalization
- Three dimensional functional devices via programmable self-assembly, programmable fold-up and functionally extended 3D-printing
- Chemical and biological personal fabricators for custom material diagnostics and manipulation including personal medicine
- Personal fabrication of personal fabricators

A cornerstone flagship goal is development of a universal construction production language and implementation, carried by multiple technologies at various scales – including electronics, mechanics, fluidics, chemistry, biochemistry, computing and communication. The greatest scientific challenge for the flagship is to build a bridge between the amazingly efficient and useful biochemical production and -structuring and the networked- and personalized mesoscopic manufacturing.

As part of the implementation of the PFN, we envision the establishment of *ca.* three new European centres focused on the critical cross-cutting scientific, technological, sustainability and societal integration issues. Examples for such centres could be (i) Multiscale Production & IT Integration Centre, bridging information processing and production from the nano to macroscale and from fixed to growing systems (ii) Sustainability PFN Centre, developing



Living Technology Flagship Sails

product recycling technology and network tools in the PFN (iii) Manufacturing integration of prototype PFN components. In addition, we propose to refocus and expand core activity in the critical research directions defined by the PFN vision, where it presently exists in select academic departments and centres, and industrial laboratories.

Ties will be made with appropriate existing design and manufacturing approaches, e.g. additive manufacturing, modular manufacturing, and axiomatic design. The SPLiT flagship will work together with existing and future European Consortia such as JTI's and PPP's. Explicit ties will be formed with (i) the European Nanoelectronics Intitiative Advisory Council (ENIAC), particularly the part of their roadmap that is concerned with design platforms and manufacturing science relevant to compact systems, (ii) the ARTEMIS embedded computing initiative, particularly with regard to distributed information processing, (iii) the Innovative Medicines Initiative (IMI), particularly with regard to efficacy and safety of medical treatment via personal fabricators, and (iv) the Factories of the Future Public-Private Partnership (FoF PPP), particularly MANUFUTURE, with its components Clean Environmental Technologies (CET), Micro Nano Manufacturing (MINAM) and Rapid Manufacturing (RM). In addition, connections have been established with many other EU projects and CAs including COBRA and COST Systems Chemistry will be established.

6 Sustainability

The flagship coordination of the development of the personal fabricator network technology will enable research to secure autonomous sustainability as a consequence of the infrastructure provided. For example, energy and material (carbon) accounting can be made transparent as part of the enabling ICT infrastructure. This, together with the reduction distance between producer and consumer to zero, means that a larger fraction of decisions regarding production (including cost / benefit decisions) will come to be made in immediate consultation with need, deployment and impact information.Recycling of used objects can easily be incorporated in the economy of personal fabricators. Because the PFN becomes an important part of any regional sustainability solution each deployment region will estimate a Low Carbon City Index (LCCI), which can be followed yearly and be used as a benchmark.

Social and political controls (e.g. taxation, regulation of production of particular materials and substances) may easily become a part of the ICT infrastructure.

7 Education

Just as the revolution of personal computing has moved into the classroom, at an ever earlier level, so will personal fabrication. A primary goal of the project will be to design the initial curricula for migrating personal fabrication to educational institutions. By the end of the project, a snowball effect will be measurable, whereby both demand and exploitation of personal fabrication becomes fed by a growing user base. The SPLiT flagship will help educate many technology illiterate sections of society: the young, the old, those without formal education, those in remote areas and developing countries.

8 Flagship Landmarks, deliverables

Flagship landmarks are constructed in a progression, with a portfolio of several personal fabricator technologies being explored initially, focusing to the few most successful by the end of the project.

Year 0 (Coordination Action) Establish six major technologies that will be explored in the project for personal fabricator implementations.

Year 3 Prototypes of initial implementations in each of the six fields. Prototype of ICT middleware for building the world-wide-web of fabricated objects. Prototype ICT platform for educational deployment

Year 6 Decide focus on three major target technologies for remainder of project. Begin migration to industry for production of personal fabricators. Deploy educational ICT infrastructure in initial target institutions. Deploy initial version of ICT middleware for version 1.0 of the "personal construction web".

Year 8 First personal fabricators designed in the project emerge on the consumer market

Year 10 Personal fabricators for all three of the target technologies emerge on the consumer market.

9 Impact

Achieving the final goal of integrating programmable construction down to the molecular-scale will functionally bridge the bio-silico gap: integrating information processing with the construction of information processing systems. Coarser scale generic fabricator technologies will be stabilized by a major research effort so that they may already be brought to market.

The project will also extend our understanding of living systems and their organization and evolution, by establishing a biological organization for technology that integrates the construction process and establishing a foundation for the genetic description of technology. Scientific experimentation with novel materials, devices and systems will be accelerated by the rapid transferability and reproducibility of achievements.

Society: Traditional organization of technology production and use is illustrated in Figure 1(a). Some of the problems society currently faces within this technology paradigm include

- Long, costly, inefficient pathways (i) between technology production at factories and personal technology use, (ii) between technology use and the corporate technology decision processes, and (iii) between corporate technology decision processes and factory implementation.
- Formation of a corporate utility function that may lead to undervaluation of or disregard of risk and social cost, in favor of profit.
- Limited personal choice, and limited personal participation in determining the range of possibilities for one's ecology of personal technology.

Figure 1(b) illustrates the flagship vision for technology deployment and use: centered on the migration of fabrication from the ecology of industrial technology to the ecology of personal technology.

The advantages of the PFN include:

- Enabling of personal engagement in the creative process of technological innovation, with Wikipedia like access to construction information and deployment experience.
- The transparent accountability of individuals for the high tech products that will continue to transform society, providing an enabling technology for sustainability
- A vast increase of society's input into the creative process of design and engineering intelligent artifacts, including an enabling technology for the participation of our creative youngsters and for the increasing and wise community of elderly people.
- The economic viability of individual problem solutions: even "products for a market of one". Thus enabling product development by remote communities with minimal resources and rapid technical adjustment to local needs.
- Reproducibility and transferability of construction between communities through the reduction of construction to digital recipes on the personal fabricator machine. This provides a kind of societal genetics for manufacturing.
- All of this will lead to an amplification of value created by local production, both in terms of products, and even more in terms of knowledge production from designs that emerge from the user community.

With the development of the PFN, society faces a variety of novel issues and opportunities. It enables the implementation of a personalized industrial ecology, which ensuring sustainability via accountable material and energy flows. This includes, for example, the transition from linear to closed-loop flows, reducing waste and bi-product problems. Fabricator material and energy efficiency must be strongly optimized during increasing distribution, and emission of hazardous substances avoided from the start. Separable production steps may still be performed at larger facilities. Further, the replication and evolution in synthetic biology and personal fabricators, raises the real and perceived ethical, environmental and safety issues[4]. These issues will be addressed with a thorough public, stakeholder and expert engagement, supported by the user community.

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[1] M. A. Bedau, J. S. McCaskill, N. H. Packard, S. Rasmussen, "Living Technology: Exploiting Life's Principles in Technology". Artificial Life, Vol. 16, pp. 89-97 (2009).

[2] N. Gershenfeld, "Fab: The Coming Revolution on Your Desktop--from Personal Computers to Personal Fabricators", Basic Books, Cambridge MA (2005).

[3] T.Wohlers. "Additive Manufacturing State of the Industry Annual Worldwide Progress Report" ISBN 0-9754429-6-1 (2010).

[4] M. A. Bedau, E. C. Parkeo, U. Tangen, B. Hantsche-Tangen "Ethical guidelines concerning artificial cells" in "The PACE Report" http://www.istpace.org/Web_Final_Report/the_pace_report/Ethics_final (2008)

Further information at SPLiT website: http://split.ecltech.org/

MATRIX REDONE

SYNTHETIC ENVIRONMENTS FOR THE MODIFICATION OF THE BODILY SELF-CONSCIOUSNESS AND IMPLICIT MOTOR TRAINING

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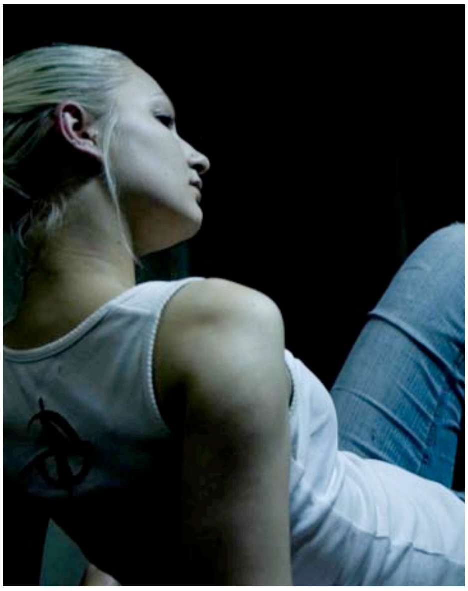
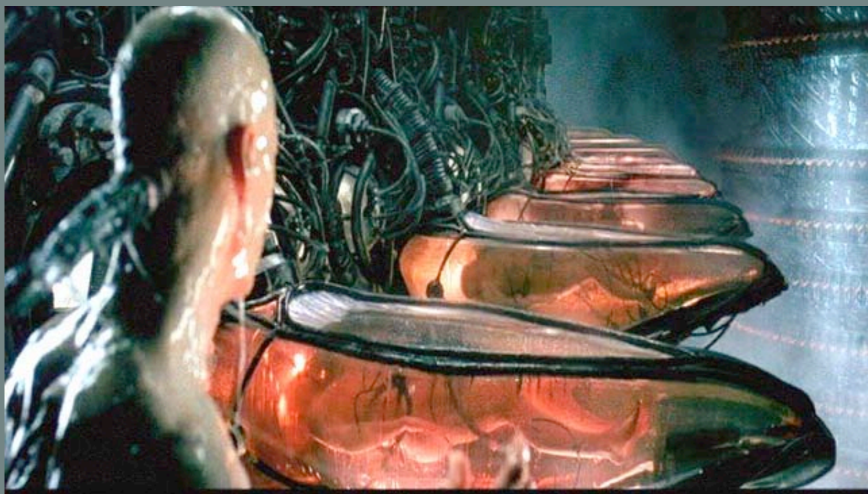
MATRIX REDONE CONCEPT SUMMARY

Up to now different methods and technologies are used to simulate the "external" world: from mental images to virtual reality (VR).

This proposal aims at a radical shift to this approach: its goal is the design and development of a method and/or a tool able to modify and simulate our most "internal" experience: bodily self consciousness.



In the science-fiction thriller **The Matrix**, the heroes "plugged in" to a new generation virtual world for training. While their bodies rested in reclining chairs, they learned how to fight martial-arts battles, drive motorcycles and helicopters in a virtual world.



Click here to see the original Matrix scene (http://www.youtube.com/watch?v=6AOpomu9V6Q)

Differently from typical virtual environments, that simulates reality, the Matrix environment simulates bodily self consciousness: a subject can acquire a complex behavioral skill – *mastering martial arts or driving a plane* – by experiencing through a somatic simulation (passive interaction) the behavioral processes related to the skill.

Main objective of this proposal is to replicate this approach without the need of "jacking in" the brain: its goal is - **through the understanding of the cognitive processes related to it** - the design and development of a tool able to modify and simulate our most "internal" experience: bodily self consciousness.

To reach this goal the project will integrate:

- robotic and haptic devices (to provide sensorimotor information);
- virtual and augmented realities (to provide visual information);

with the outcomes of a recent branch of cognitive science: embodied cognition and its analysis of the link between representations, action and perception.

The project aims, in the short/medium term, to understand the cognitive processes involved in the emergence of bodily self consciousness (1-3 years). The data and the experience gained could allow, in the long term, both the simulation of the experience of a given body (3-5 years) - e.g., an obese subject could experience a thin body to increase his/her motivation to change – and the development of Matrix-like motor training tools (5-10 years). Specifically, the goals of the project are:

- Investigating both the characteristics of somatic awareness and the features of actual tool and experiences that can influence these characteristics.
- Developing an embodiment procedure or device able to modify the actual body experience of the subject. Simulation and haptic tools will be used to produce a controlled sensory rearrangement able to simulate, even a distance, a different passive and active body.
- Exploring the possible use of the embodiment procedure/device for real world applications. In particular three possible areas will be investigated: health care, training, and entertainment.
- Evaluating the efficacy of the embodiment device in user trials.

RATIONALE OF THE PROPOSAL

THE EXPERIENCE OF THE BODY

Even if the body is usually considered as the most personal part of our perceptive experience, our perception of the body is not direct. In fact, evidence from studies of brain-damaged individuals suggests our bodily experience is mediated by a cognitive representation of the body, not used for representing other objects, that is spatially organized, supramodal, and used for representing other bodies as well as one's own.

Evidence that this body representation can exist independently of sensory input is found with the phantom limb phenomenon: it is the subjective sensation, not arising from an external stimulus, that an amputated limb is still present. After amputation, many subjects still experience sensations of movement, position, and pain, as if the limb still existed. Because there are no sensory receptors, any kinesthetic sensations that an amputee may associate with voluntary attempts to flex or extend a phantom joint must arise internally from some form of bodily representation.

SENSORY REARRANGEMENT: WE CAN USE TECHNOLOGIES TO MODIFY THE EXPERIENCE OF THE BODY

The adaptive capabilities of the human experience of the body are well known. As underlined by Lackner & DiZio (2005), the control and adaptation of body orientation and motion are the result of multiple sensory and motor mechanisms ranging from relatively simple, peripheral mechanisms to complex ones involving the highest levels of cognitive function and sensory-motor integration.

For instance, if you watch an experimenter stroking a shoe or a table surface while he simultaneously, in perfect synchrony, strikes and taps your knee hidden from you under the table, you will experience the touch sensations as emerging from the shoe or table. If the experimenter then hits the shoe or table with a hammer, you will register a strong galvanic skin response, as though the object was now part of your body. But if the shoe (or table) and your hand are stimulated out of synchrony, no illusion occurs and no galvanic skin response is seen (so the response is not just due to startle).

It is well known that in immersive virtual reality (VR) systems the human operator's normal sensorimotor loops are altered by the presence of distortions, time delays and noise. Such alterations that are introduced unintentionally and usually degrade performance, affect body perceptions, too. The somesthetic system has a proprioceptive subsystem that senses the body's internal state, such the position of limbs and joints and the tension of the muscles and tendons. Mismatches between the signals from the proprioceptive system and the external signals of a virtual environment alter body perceptions and can cause discomfort or simulator sickness.

A BASIC PROTOTYPE: SCIENCE ARTICLES (24 August 2007)

As underlined by different papers published in the past (Biocca and Rolland, 1998; Castiello et al., 2004; Riva, 1998; Riva et al., 2001), it is possible to use virtual reality to induce a sensory rearrangement able to modify the bodily experience.

Two teams of cognitive neuroscientists independently reported on Science Journal (24 august 2007) methods for inducing elements of an out-of-body experience in healthy volunteers.

- The Experimental Induction of Out-of-Body Experiences, H. Henrik Ehrsson (24 August 2007), Science 317 (5841), 1048. [DOI: 10.1126/science.1142175];
- Video Ergo Sum: Manipulating Bodily Self-Consciousness, Bigna Lenggenhager, Tej Tadi, Thomas Metzinger, and Olaf Blanke (24 August 2007), Science 317 (5841), 1096. [DOI: 10.1126/science. 1143439].

Both groups used head-mounted video displays to give people a different perspective on their own bodies. Each team also drew upon the sense of touch to enhance the illusion.

It is also well known that key biases can distort perception of the location and orientation of objects and surfaces in virtual environments. While virtual environment interfaces may be argued to be "natural" in principle, there are many features that can disrupt or distort the natural coupling of actual reaching and walking, to create problems of stability and disorientation, lessons that have been well learned in the flight community.

To take account of these capabilities, the concept of sensory conflict has been extended into a theory of sensory rearrangement (Reason and Brand, 1975) which states that: "all situations which provoke motion sickness are characterized by a condition of sensory rearrangement in which the motion signals transmitted by the eyes, the vestibular system and the non-vestibular proprioceptors are at variance either with one another or with what is expected from previous experience". In general, sensory rearrangement is a change in the normal relationship between body movements and the resulting inflow of sensory stimuli to the central nervous system. It can also result from discoordination of one sensory inflow pattern with that of another sense (e.g., a mismatch between vision and touch).

BEING PRESENT IN ANOTHER BODY OR IN AN EXTENDED BODY

The two experiments discussed in the previous page box show that humans systematically experienced a virtual body as if it were their own when visually presented in their anterior extra-personal space and stroked synchronously (see also the book “The Ego Tunnel” by Thomas Metzinger, 2009):

In sum, the experience of being localized within the physical body was determined by the visual perspective in conjunction with correlated multisensory information from the body.

As indicated by the author of the proposal (“Virtual Reality and Telepresence”, Science 318: 1240 [DOI: 10.1126/science.318.5854.1240d]) these experiments suggest that subjects were no longer present in their real body but were instead “present” in a synthetic body produced by VR.

More recently, new experiments showed that:

- A first person perspective of a life-sized virtual human female body that appears to substitute the male subjects' own bodies was sufficient to generate a body transfer illusion (Slater et al., 2010);
- Synchrony between visual and proprioceptive information along with motor activity is able to induce an illusion of ownership over a virtual arm (Sanchez-Vivez et al., 2010);
- Galvanic vestibular stimulation (GVS) interferes with the mechanisms underlying ownership, touch, and the localization of one’s own hand in healthy participants by using the “rubber hand illusion” paradigm: left anodal GVS increases illusory ownership of the fake hand and illusory location of touch (Lopez et al., 2010).
- The subjective illusion of ownership of a virtual hand can also be induced by the imagination of a motor act followed by movement of a virtual hand (Perez- Marcos et al., 2009).

In short, the experiments showed that is possible to use virtual reality and eventually touch technology (haptic tools) to induce an experience of “telepresence”, the feeling of “being there” (presence) by means of a communication medium: We want to exploit and further expand this concept with this FET FLAGSHIP initiative.

VIRTUAL REALITY

AN ARTIFICIAL REALITY THAT PROJECTS THE USER INTO A 3D SPACE GENERATED BY THE COMPUTER.

VIRTUAL EMBODIMENT

AN ARTIFICIAL REALITY THAT PROJECTS THE USER INTO A BODILY SELF-CONSCIOUSNESS GENERATED BY THE COMPUTER.

MEDIUM TERM APPLICATIONS:

Health
Persuasion
Sport Training
Entertainment

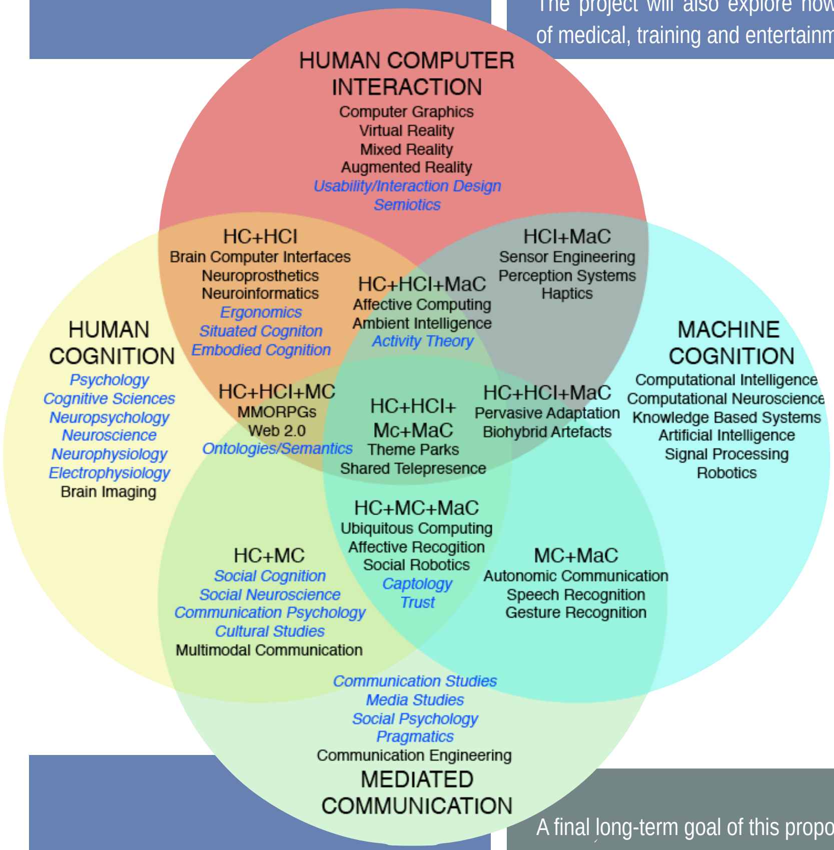
The medium term goal of this proposal is the understanding of the processes of presence and telepresence to modify in a controlled way our body experience. In this activity we will integrate neuroimaging (fMri and/or evoked potential mapping), psycho-physiological and behavioral indexes (Observer, Theme). Specifically, the process should work at three different levels (Biocca, 1997) :

- sensory engagement: the degree to which the senses are connected to the interface/simulator;
- motor engagement: the degree to which interface/simulator sensors map the motion of the body;
- sensorimotor coordination: the degree to which changes in body position correlate immediately and naturally with appropriate changes in sensory feedback.

The final outcome will be a full body simulation tool, able to produce the experience of a totally new body, altered in shape and size - e.g., an obese subject could experience a thin body to increase his/her motivation to change.

This approach can be considered the ultimate form of "Somatic Displacement" (Holopainen & Meiers, 2000) - the ability of a person to project the mental model of his or her own identity into another physical form

The project will also explore how to use the modifications induced to the somatic awareness across a range of medical, training and entertainment applications.



A MULTIDISCIPLINARY APPROACH:

FROM COMPUTER SCIENCE, TO HAPTICS AND ROBOTICS, TO COGNITIVE SCIENCE

LONG TERM APPLICATIONS:

Implicit Motor Training

A final long-term goal of this proposal is developing new approaches to training.

It is known that the body is integrated with the mind as a representational system, or as the neuroscientist Antonio Damasio puts it, "a most curious physiological arrangement ... has turned the brain into the body's captive audience" (Damasio, 1994, p. xv). In some ways, the body is a primordial display device, a kind of internal mental simulator. The body is a representational medium for the mind. Some would claim that thought is embodied or modeled by the body. Johnson and Lakoff (1980) argue against a view of reasoning as manipulation of prepositional representations (the "objectives position"), a tabulation and manipulation of abstract symbols. They might suggest a kind of sensory-based "image schemata" that are critical to instantiating mental transformations associated with metaphor and analogy. In a way virtual environments are objectified metaphors and analogies delivered as sensory patterns instantiating "image schemata."

In his book, Decartes' Error, the neuroscientist Damasio explains how the body is used as a means of embodying thought:

"...the body as represented in the brain, may constitute the indispensable frame of reference for the neural processes that we experience as the mind; that our very organism rather than some absolute experiential reality is used as the ground of reference for the constructions we make of the world around us and for the construction of the ever-present sense of subjectivity that is part and parcel of our experiences; that our most refined thoughts and best actions, our greatest joys and deepest sorrows, use the body as a yardstick" (Damasio, 1994, p. xvi).

Thinking of the body as a kind of simulator for the mind opens new possibilities for training. From the “learning by doing” approach we can move to the “learning by experiencing the simulation of the doing” approach.

In particular the final long term goal could be the MATRIX training: as in the Matrix movie, a subject could acquire a complex behavioral skill – mastering martial arts or driving a plane – by experiencing through a somatic simulation the behavioral processes related to the skill.

NPC

Non-deterministic Polynomial Computing

ABSTRACT. Information technology is a key utility to any current progress: not only does modern day manufacturing and engineering depend on computing capabilities to build and test complex machinery, but most current research builds on calculation and simulation of complex systems through supercomputers. In fact one can subsume almost all of the current research and development challenges as being obstructed by computing limitations: modelling and predicting behaviour of social systems, virtual physiological humans, astrophysics, brain emulation etc. all require hardware and in particular software that can deal with a larger scale than currently possible. The major problem thereby however consists in the fact that the resource requirements do not scale linearly with the problem scope, but in fact exponentially, according to the NP problem. The essence of current computing models, namely the (parallel) Turing machine, is however incapable of addressing non-determinism in a polynomial scalable fashion.

A joint effort to dealing with the NP problem more effectively is therefore essential for making lasting advancements in ICT. Non-deterministic alternatives to the Turing model have thereby been suggested from various research fields, including biology, chemistry, physics etc. To realise the long term sustainability of computing in research and development, a flagship such as the one suggested here is mandatory, to investigate extensions and alternatives to the Turing model.

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WHAT

about the mission and relevance of the flagship

The amount of required computational resources grows exponentially with the complexity of the problem.

Modern day research faces serious obstacles – and even though it is often presumed that they are mainly due to our lack of understanding and knowledge in the respective area, the major challenge actually arises from somewhere else: the limitations of computing capacities. Given the current boom in system scales, ranging from many-core processors to large scale supercomputers, this may sound like an odd statement. But when analysing current research proposals and projects, a shared goal towards development of soft-/ hardware capable of dealing with the increased scope, scale and complexity of the respective research environment becomes notable. This is due to the growing interest in larger problem spaces and more accurate processing results in all areas of research and development. It is acknowledged by all research communities that the resource requirements grows exponentially with accuracy or size of the problem set, in other words any (linear) improvement in simulation leads to an exponential increase in required computing resources to satisfy the calculation complexity needs. This exponential requirement growth is grounded in the intrinsic characteristic of the respective problem domain, which is essentially non-deterministic in nature and belongs to the domain of NP (see [SCH10] for more details).

Scalability of applications and hardware is naturally limited

The limitation of (number of) resources is not the only obstacle towards solving such computational problems, though – instead, the limitation of software scalability, due to messaging overhead, synchronisation misalignment, jitter, Amdahl's law etc. play another crucial role. By analysing the impact of Amdahl's law and other overhead, it can be clearly shown that the speedup achieved through an increase in scale reaches a natural saturation at which point memory wall etc. actually lead to a decrease in efficiency – only embarrassingly parallel problems have a chance of circumventing this restriction [REFS]

Growth of computation, and implicitly *all* research and development therefore faces two major obstacles: the exponential need for resources due to the nature of these problems, which is further impacted by the natural limitations of scalability. To compensate the impact from these two factors, current HPC developers and research projects focus on increasing the scalability of their respective code by reducing the communication overhead, improving the synchronisation and distribution, increasing scalability by better subsegmentation, through multi-level coupled applications, approximations etc. – in effect they all try to reduce the NP problem to the P space. At the same time, this makes development of applications and in particular porting the logic to new problem areas more difficult. Most researchers are therefore building on future hardware, whilst hardware manufacturers more and more push the problem to the software developers.

In summary this means that

a) The growth of resource scale is too slow for (all) future (and even current) research & development simulation challenges

b) Software scalability is limited
c) All attempts to increase the scalability lead to linear / polynomial improvements, whilst the resource need grows exponentially due to NP

The classical computing model is insufficient to deal effectively with non-determinism

At the heart of all these problems is therefore *not* the scale of the system (i.e. the number of resources), but in particular the underlying computational model which bases on the concepts established by Turing. Whilst the Turing machine model has been extended to cater for parallel execution, i.e. on multiple tapes at the same time, it is still very deterministic in nature and therefore subject to the impact of NP. As can be shown, the limitations of a deterministic machine must lead to an exponential need for scalability that cannot be fulfilled by it [SCH10]. In other words, the Turing model has become obsolete for modern requirements put towards soft- and hardware.

In fact, the whole mathematical basis on which both computing and programming model are based needs to be re-evaluated, in light of addressing the NP problem at its root.

Only in this way can long-term sustainability of computational performance be guaranteed, and accordingly research and development of tomorrow be enabled. The NPC flagship therefore proposes to initiate joint, collaborative efforts to investigate new means, i.e. a new computational foundation, to address the non-deterministic problem scope. As elaborated below, it will thereby extend on existing approaches and principles that improve the impact of NP onto overall computing – however, no feasible and complete model exists as yet. Furthermore, even though this problem seems to be essentially restricted to theoretical computer science, we will show that approaches to improving and dealing with NP have and are being approached from a large variety of research domains and communities, but as of today remain purely speculative and have not been investigated to their full potential, respectively regarding their limitations. This lack of interest is mainly originating from the strict industrial drive to exploit existing manufacturing strategies and extend on widely accepted concepts, rather than disrupting the according development.

It should be noted here again, that the goal of the flagship is *not* (1) to reduce NP problems to the P space, (2) to solve all NP problems, (3) to realise a "faster, bigger, better" machine. Instead, it focuses at reiterating the computational model, so as to improve the capabilities to deal with NP per se and to reduce its impact on compute complexity. This may equally involve tools & languages for usage, models & concepts for computing and architectures of systems.

Any improvement in dealing with NP in general will impact on the whole computing usage landscape

It is quite obvious that the realisation of a computing system that can deal with NP would implicitly revolutionise the whole ICT landscape and all its directly and indirectly associated communities. The according decrease in computational complexity would lead to a huge range of benefits in this domain, amongst which count:

a) More problems can be solved in less time and
b) With only a fraction of currently needed resources
c) Reduced power consumption for computation
d) Higher correctness of simulation results
e) Linear and therefore sustainable growth in future complexity requirements

WHY

about the basis and feasibility of NPC

Non-deterministic polynomial (NP) problems have been subject to computing theory for more than 40 years by now [GAR90] and there still has been no generally reusable solution to dealing with NP problem space. There has been little industrial (or financial) support for addressing this problem, as long the benefits from deterministic computing were still obvious. What is more, NP may actually be identical to P. For industry this serves as a justification that even highly complex problems could still be solved on deterministic machines – nonetheless, *any* attempt to reduce an NP problem to P space implies a large degree of effort with only slow and little incremental improvements in execution time. In general, it can be stated that the effort exceeds the benefit by far.

In particular this discrepancy has led to many communities addressing the problem as a side issue to their normal research. As noted, this is due to the fact that all communities and research topics typically have to deal with problems that are non-deterministic in nature. Besides for theoretical computer science and mathematics, we can highlight the following domains that have already investigated into solving NP through different computing models (non-exhaustive):

- Chemistry: almost all chemical reaction is subject to strict (mathematical) laws that can be employed to execute computational tasks (see e.g. [TOM07]). Non-determinism is a common aspect of chemical behaviour [VLAD86]. Beigel and Fu show in [BEI99] how molecular computing can principally be exploited to deal with bounded non-determinism.
- Biology: includes many aspects that can be exploited for computational purposes, as for example visible in the process of RNA translation, which has already been shown e.g. by Adleman [ADL94][ADL96].
- Sociology & Anthropology: social systems of any kind are essentially non-deterministic of a very high order. Even though networks constructed of individuals should in theory not work as a single system (lack of direct common purpose), they typically very quickly show an emergent goal-oriented behaviour which tolerates error and fuzziness, yet is still capable of solving complex problems (see e.g. [KOH82]). This is true for tightly coupled systems such as brains [YAN07][KEL95], as much as very loose ones such as swarms [GUE07][DEN83] and people [LEY01][FUC02][FLA02][KEL95]
- Physics: with chaos theory and quantum mechanics, non-determinism has become intrinsic to physics. Whilst the determinism of quantum mechanics is still mostly up to philosophical debate, it is obvious that it is subject to causal effects, which simply are not fully known as yet [GRE09]. LaPlace demon remains unsolvable, therefore physicists use different means to describe system behaviour including mechanisms based on non-determinism [GIS91].

Non-regarding these efforts, there is no solution as yet to dealing with NP problems, let alone to realize non-deterministic machines. But the results of these attempts show that the problem is principally solvable, or at least can be improved considerably. Over recent decades serious advances have been made both technologically and theoretically that make the attempt more realistic than 20 years ago. By now, the theoretical and practical knowledge about computing, but also about chaos theory, indeterminism, system modelling etc. have advanced considerably. Following the results achieved so far (see above) and further indicators from the development of theoretical and mathematical computer science, we can particularly highlight the following basic principles that support addressing the NP problem (again non-exhaustive):

- Cloud Computing
  Enabler: IT
- Cellular Systems
  Enabler: Biology, Biochemistry
- Swarm Intelligence and Neural Networks
  Enabler: Sociology, Neurology, Biology
- Functional Programming
  Enabler: Mathematics, IT
- Miniaturisation
  Enabler: Physics, Chemistry
- Quantum Mechanics
  Enabler: Physics, Philosophy, Mathematics
- Etc.

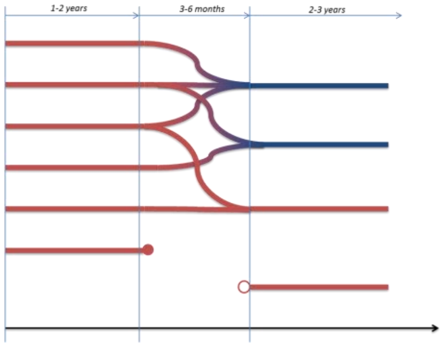
HOW

about the challenges of and the way towards NPC

At the moment, a rough plan for exploiting commonalities in order to achieve maximum convergence, whilst maintaining a high degree of individuality so as to allow maximum progress in these domains could look as follows. We can distinguish between three major phases, which however may be repeated according to need:

(1) Individual Elaboration: investigating the problem in the individual strands with little to no integration or cross domain exchange. This phase focuses on approaches, problems etc. in the area of NP that have not yet been elaborated before.
(2) Exchange and Integration: common or at least cross-domain exchange of results, problems etc. for the purpose of discussing approaches from other strands and identifying other solutions. Due to the interdisciplinarity of the problem on the one hand and the relationships between disciplines on the other, the approaches, problems, results identified in (1) can be verified and elaborated through other disciplines, thus extending the results.
(3) Integrated Elaboration and Convergence: once commonalities and approaches across domains have been identified (2) they may have to be elaborated commonly rather than in separate strands as in (1). This is already common practice in biology and chemistry, where a common field of its own – biochemistry – has emerged due to this overlap.

Considering the scope of the individual tasks, this prescribes a timeline for the phases roughly along the line as follows:



Individual strands thereby may have run-time of 1-2 years, whilst joint strands due to their extended complexity may last up to 3 years. The time needed for discussing and reaching convergence is considerably short in comparison (estimated 3-6 months). It may be noted that the following events may occur during the transition phase (2): (i) the strands identify a commonality to work upon; (ii) only parts of the strands identify a commonality or a related issue to work upon together; (iii) this may even lead to the result that further work in an individual strand needs to be pursued; (iv) in some cases the results may indicate that no further work along that line should be followed or (v) that a complete new strand needs to be opened.

As *milestones* we can accordingly identify the results of the according phases, whereas for the overall flagship we can specifically highlight: I) identification of relevant strands and approaches; II) results from the individual strands; III) integration and elaboration of these results; IV) identification of joint strands; V) elaboration and examination of these results; VI) derivation of new "computational" models.

The core areas to address thereby consist in tools, new computational models and formalisms, whereby we can distinguish between different communities' contribution along the line of their focus area.

The basic project structures follows (1) a core coordination team; (2) a set of experts & advisors in particular from the theoretical computing science to validate correctness and completeness of the models and (3) the range of researches and contributors from the range of communities identified above. Interest was expressed from multiple stakeholders of all different areas, including all EC countries and also US, Russia and China. In order to reduce the size of this document, a full list may be provided on explicit request.

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Uncovering the Human Cell Lineage Tree in Health and Disease

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Preliminary composition of team as of September 17th, 2010.

Institute	Country	Participants	Disciplines
Weizmann Institute of Science	Israel	Ehud Shapiro – *Coordinator* Nava Dekel Tsvee Lapidot Elchanan Mossel Michal Neeman Eldad Tzahor	Computer Science, Biology Fertility Immune system Mathematical foundations Vascular system Heart, skeletal muscles
CHiBi	Canada	Carl Hansen	Microfluidics, Single cell transcriptome
Ontario Cancer	Canada	John Dick	Hematopoietic and immune system
Helsinki University of Technology Tampere University of Technology	Finland	Harri Lähdesmäki	
Aalto University	Finland	Samuel Kaski Kai Puolamaki	
CNRS-LIRMM	France	Olivier Gascuel	Algorithms
Institut Curie	France	Daniel Louvard	Morphogenesis, intracellular signalling
Pasteur	France	Margaret Buckingham Shaharagim Tajbakhsh	Vascular system Skeletal muscles
Fraunhofer	Germany	Thomas Berlage	
EMBL	Germany	Takashi Hiiragi	Embryonic development
Max Planck Molecular Genetics	Germany	Bernhard Herrmann Hans Lehrach	Development Molecular biology and biotechnology
Max Planck Heart and Lung Research	Germany	Thomas Braun	Heart
DKFZ Heidelberg	Germany	Hellmut Augustin	Vascular system
University of Regensburg	Germany	Christoph Klein	Dormancy and origin of metastasis / Transcriptome characterization
University of Trento	Italy	Themis Palpanas	Data mining
Technion	Israel	Karl Skorecki Shlomo Moran	Kidney and urinary tract Algorithms
Hebrew University	Israel	Yuval Dor	Kidney
Tel Aviv university	Israel	Dafna Benayahu Benny Chor Shai Izraeli Ron Shamir	Stem cells Bioinformatics, algorithms Paediatric leukaemia Data analysis, algorithms
IBM	Israel	Haim Nelken Michal Rosen-Zvi Yaron Wolfsthal	Medical and genomic data Medical and genomic data Storage and system

Institute	Country	Participants	Disciplines
Google	Israel	Yossi Matias	Computer science & systems
Sheba Medical Center	Israel	Gidi Rechavi	Cancer
Hubrecht Institute	Netherlands	Hans Clevers	Gastrointestinal tract
Erasmus University Medical Center	Netherlands	Gerard Wagemaker	Hematopoietic and immune system
University of Canterbury	New Zealand	Mike Steel	Mathematical foundations
CNIC	Spain	Miguel Torres Sanchez	Development
Karolinska Institute	Sweden	Jonas Frisen Kirsty Spalding	Renewal/ Carbon dating Renewal / Fat tissue / Carbon dating
University of Geneva	Switzerland	Pedro Herrera	Pancreas
Belfast City	UK	Alexander Peter	Kidney and urinary tract
Imperial College	UK	Ilpo Huhtaniemi	Reproductive system
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Sanger Institute	UK	Seth Grant	Brain
Microsoft	UK	Stephen Emmott	Computational biology
Stanford University	USA	Stephen Quake	Biotechnology, Microfluidics
University of California	USA	Shimon Weiss	Biophysics

Introduction

Every human being starts as a single cell – the fusion of an egg and a sperm – and progresses via cell division and cell death through development, birth, growth, and aging. Human health depends on maintaining a proper process of cell division, renewal and death, and humanity's most severe diseases, notably cancer, auto-immune diseases, diabetes, neuro-degenerative and cardiovascular disorders, and the multitude of inherited rare diseases are all the result of specific aberrations in this process.

The history of a person's cells, from conception until any particular moment in time, can be captured by a mathematical entity called a *cell lineage tree*. The *root* of the tree represents the fertilized egg, the *leaves* of the tree represent the person's extant cells, and branches in the tree capture every single cell division in the person's history. Science knows precisely the cell lineage tree of only one organism – a worm called *Caenorhabditis elegans* that reaches its full size of 1 millimetre and 1,000 cells in 36 hours. By comparison, a newborn mouse, weighing only a few grams, has about 1 billion cells. An average person has about 100 trillion cells.

Understanding the structure and dynamics of the human cell lineage tree in development, growth, renewal, aging, and disease is a central and urgent quest of biology and medicine. The challenge of uncovering the Human Cell Lineage Tree is reminiscent, both in nature and in scope, to the challenge faced by the Human Genome Project at its inception and, in fact, its results will decisively contribute to the functional translation and ultimate understanding of the genome sequence. A technological leap of a magnitude similar to the one that occurred during the Human Genome Project is required for the success of the human cell lineage project, and the biological and biomedical impact of such a success could be of a magnitude similar, if not larger than that of the Human Genome Project.

Mission

The unifying goal of the Human Cell Lineage Flagship initiative is to develop a high-throughput, large-scale, accurate, multidisciplinary, science-driven, collaborative cell lineage analysis infrastructure and apply it to uncover the structure and dynamics of the Human Cell Lineage Tree in health and in disease.

Mission Rationale

Central open problems in biology and medicine are in effect questions about the human cell lineage tree: its structure and its dynamics in development, growth, renewal, aging, and disease. Consequently, knowing the Human Cell Lineage Tree would resolve these problems and entail a leapfrog advance in human knowledge and health.

When cells divide each of the two daughter cells accumulate a small number of random mutations. These random somatic mutations accumulate independently in each body cell, and constitute an effectively unique "genomic signature" for each body cell. Our Human Cell Lineage Tree is implicitly encoded by the genomic signatures of our body cells, as cells with similar signatures must reside near each other in the cell lineage tree and cells with very different signatures must be far from each other, much the same way as people with very similar genomes must be near each other in the human family tree. Hence uncovering the genomic signatures of human body cells will reveal the Human Cell Lineage Tree. As reconstructing a cell lineage tree utilizing somatic mutations is non-invasive and retrospective, it is ideally suited for the study of human development, growth, renewal, aging, and disease.

Therefore, the proposed Human Cell Lineage Tree Flagship initiative is to build a collaborative cell lineage analysis infrastructure by a large federated multi-disciplinary effort of leading partners in ICT and biotechnology; to engage a large number of leading research groups in a wide range of branches of biology and medicine to resolve key open problems using this collaborative infrastructure; and to integrate piecemeal cell lineage data so far obtained into a global and coherent view of the Human Cell Lineage Tree in health and in disease, thus causing a leapfrog advance in biology and medicine.

Impact

The Human Cell Lineage Tree Flagship initiative will drive major innovation in medicine, biology, biochemistry, biotechnology, bioinformatics, computational biology, computer science, and computer systems. The goal of high-throughput and complete characterization of large numbers of individual cells from multiple biochemical and biological aspects will drive all known technologies for single-cell isolation and analysis to the limits and necessitate innovation to go beyond, driving competitiveness of all parties involved. These high-throughput and broad-spectrum single-cell assays will generate very large volumes of data. The need to handle such unprecedented volumes of single-cell data and extract the relevant biological and biomedical knowledge will necessitate bioinformatics and computational biology to generate new algorithms and new computational methods. At the same time, supporting the entry, storage and access of this data, and the computations to be carried out on it, will put to the utmost test the most advanced approaches to large-scale computer systems, storage, and networks.

The ability to place high-quality single-cell information in the context of the Human Cell Lineage Tree would enable a critical advance in biology and medicine, answering many pressing open questions in biology and medicine. Thus, the Human Cell Lineage Tree initiative will promote human health and the quality of life by elucidating the genomic causes of aberrations and thereby reveal new therapeutic avenues for a wide variety of acquired and

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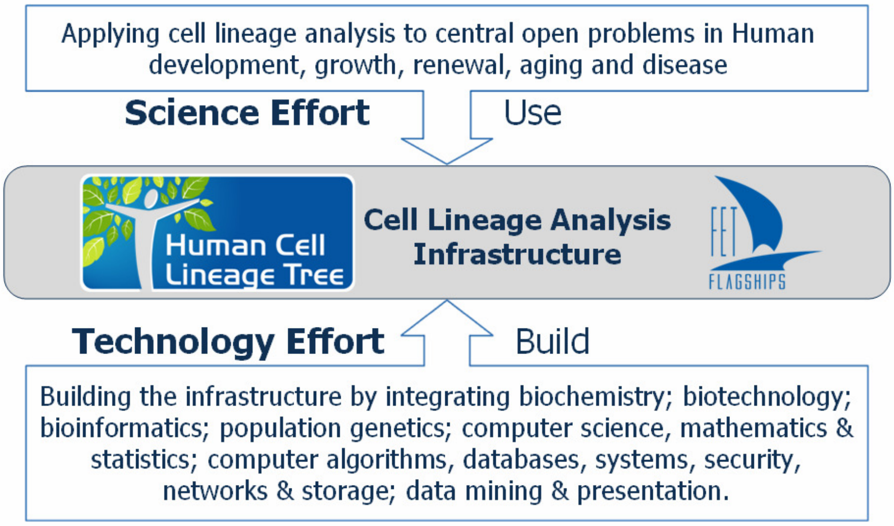
inherited disorders, such as cancer, diabetes, fertility, neurodegenerative disorders, in compliance with the European Strategy (COM(2002)27 final) which focuses on “Life Sciences and biotechnology”.

Integration



Uncovering the human cell lineage tree would require a unifying approach that relies on a large federated effort of developing and integrating methods from many scientific disciplines, as described in the attached table of Scientific Disciplines and Research Topics, which is also available online (www.weizmann.ac.il/lineage).

The initiative consists of two major efforts: (1) A very broad Science effort in biology and medicine, to apply cell lineage analysis to central open problems in human development, growth, renewal, aging and disease (in particular cancer and inherited disorders), in all organs and systems, giving rise to an ever more coherent and accurate view of the human cell lineage tree, in health and in disease. (2) A large federated multi-disciplinary Technology effort, to build the cell lineage analysis collaborative infrastructure, integrating research and development in biotechnology, computer science, computational biology, bioinformatics, mathematics, statistics, and computer systems. The biotechnology task is to generate data from individual cells, providing accurate genome, transcriptome, proteome, and metabolome profiles of cells at key ramifications of the Human Cell Lineage Tree. The computational and mathematical task is to turn data into knowledge. The computer systems task is to support the entry, storage, access and presentation of data and knowledge. Successfully addressing an ICT challenge of this magnitude requires massive industrial involvement currently exemplified by large-scale companies such as IBM, Microsoft, and Google.

Plausibility

Theoretically, cellular genomic signatures could be gleaned by sequencing the cells' genomes. Prices of whole-genome sequencing are going down rapidly and will soon cross the 1,000 Euro per Human genome. At these prices, reconstructing the entire cell lineage tree of one Human would cost 100,000 trillion Euro. Therefore much more efficient ways of cell lineage reconstruction must be sought.

Fortunately, analyzing even a fraction of the genome of each cell can provide sufficient signal for meaningful lineage reconstruction. The technology challenge is architecting an accurate high-throughput cell lineage analysis

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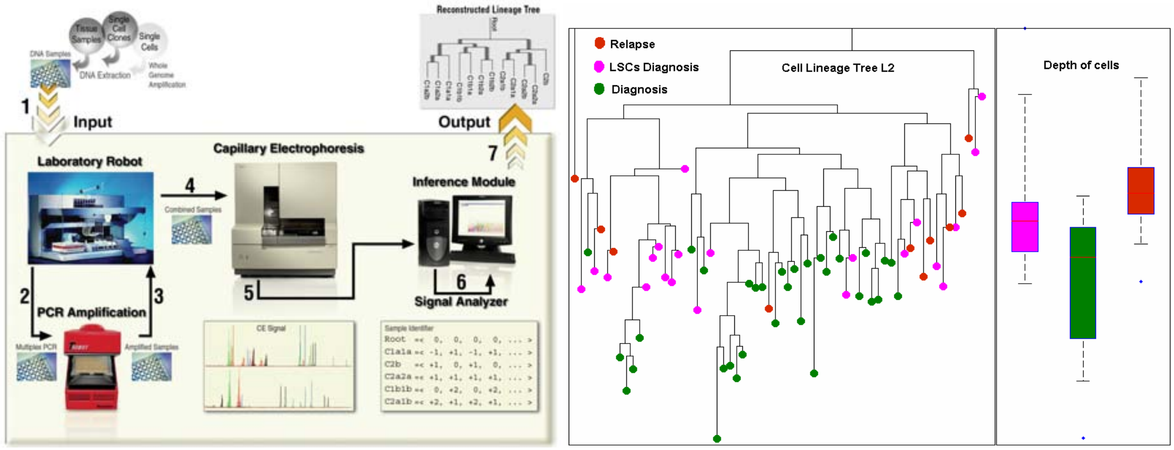
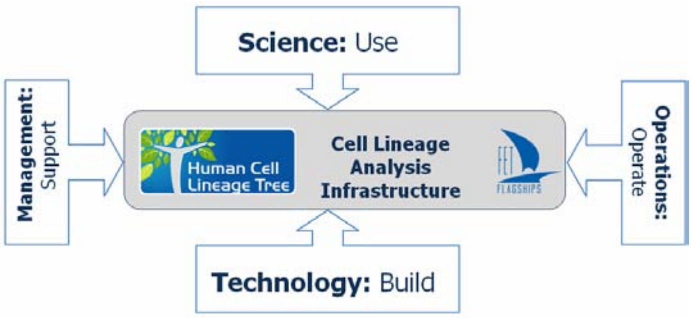
infrastructure initially building on available technologies and driving technological development to get maximal signal from each cell at minimal cost and maximal speed.

The plausibility of the proposed approach has been demonstrated by a cell lineage analysis project that started at the Weizmann Institute 7 years ago, and expanded into a national Israeli consortium 4 years ago, to include Hebrew University, Tel Aviv University, Technion, Sheba Medical Center, and Rambam Medical Center. Preliminary results of this work are startling (PLoS Computational Biology 2005, 2008, PLoS One, 2008). We confirmed in mice that cancer indeed starts from a single aberrant cell (Cancer Research 2008), and more recently that leukemia relapse after chemotherapy is initiated by rarely-dividing leukemia stem cells, as illustrated in the figure below (showing leukemia cells sampled from a patient at diagnosis and at relapse after chemotherapy, and leukemia stem cells isolated at diagnosis; manuscript under review). The Human Cell Lineage Tree initiative will expand on this foundation and use complementary approaches for lineage tracing for control and validation.



Organisation



The Human Cell Lineage Tree initiative is organized around of two main efforts and of two secondary efforts: a Science effort and a Technology effort explained above. An Operations effort will operate several regional cell lineage analysis centres serving the Science effort as well as an international data and computing cloud that coalesces the data and supports turning it into knowledge. Management will support the entire operation, also addressing specific ethical and legal questions arising from the new science and technology efforts, as well as pursuing scientific, industrial and public dissemination and educational activities, with a keen eye on the IPR aspects of the project and marketing opportunities.

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Overview

World Society Modeller (S-GAIA) is a long-term visionary proposal for a new kind of social modelling toolset. Its initial foray will be called SMART SOCIETY, and will be a pilot FI proposal for a 'User' UseCase. This strategy underlines the vision of S-GAIA: it is a pragmatic modelling framework for people to get right the societal component of our future seen as science engineering, innovation and determination of what our world needs to look like if we are to survive, thrive, and ensure a sustainable world future. The backbone of the toolset is ICT, but equally the social process, that together mark both the summit of mankind's efforts to do things differently, better but also can be marked by failure at a personal, institutional, and societal level. Integrating these two domains is required. The ICT and social science will be a radical new paradigm in both social and computational thinking and practice. The core innovation is society will drive it, leading to a new conception of socially-enabled computation, meaning and purpose. This is computational socio-geonomics; its realisation called Metaloger is a pervasive new platform embedded in society, its systems, and processes. But only people can choose to deploy new thinking and tools to bring about *change.*

Whilst the FuturICT Flagship (with which S-GAIA is federated) is a visionary concept to re-engineer the global social domain described briefly above, there are powerful reasons for starting by considering S-GAIA separately initially because:

- It is a living process going on all the time *now* in the multitude of ICT systems in use pervasively across the institutions, enterprises, personal domains built up over the past half century. These are a here-and-now heuristic process that needs enlivening with new science, principally complexity science; we need therefore to engage people who are in the thick of it now so that the science is leavened by society and vice-versa
- There are dramatic changes ahead in society in the near future so that the time for this initiative is not merely 'right' but urgent so that the opportunity is not lost or seriously compromised by the failure to align thinking and action. The principle area pointing up this message is the Future Internet initiative.

We need to recognise that any societal based initiative needs to enable, empower and engage with society if it is to succeed. This is even truer where the underlying need is critical and urgent. A key imperative of S-GAIA and of SMART SOCIETY is to put in the hands of the people the new toolset it needs and Future Internet lacks now. This ambition supersedes the pre-eminence of science, technology, or new ideas. Indeed it is a pre-requisite for true innovation and its application to a better world society. The alternative is an alienated society that perceives coercion and reacts against it – the same dynamic that leads to extremism, organised crime, and war. It is better to engage, solve problems, and choose the best tools to enhance human societal potential.

Vision and Scope of S-GAIA and SMART SOCIETY

Smart Society is a vogue buzz-word that points to the area of dramatic science and technology changes on the near horizon (in science breakthrough terms). We aim to bring society up to the same level of dramatic innovatory change as will be seen in energy, climate, smart cities, transport, but also needy societies, the disadvantaged of our world and the threatened resources and infrastructures on which our sustainable future is built. This needs to start with *our society.*

We assert that human social dynamics are not only the driver of all progress and problem solving but the key element in enabling the massive achievements of science technology and human thought to be deployed successfully. We emphasise this as a truism from concept to standard process and practice. It is also the driver of all forms of defective action and practice (difficult to define, however). S-GAIA will tackle this problem area head-on by giving organisations, institutions, enterprises and people a toolset to model and instantiate a better society. This will, quite simply take pervasive organisational systems up to a new level of functionality based on complexity science, social engagement, and the ability to chart the direction we take our world-systems in. The dramatic new direction is it will become routinely normal for everyone to say "Yes we compute our world". They will say this because the tool-set will empower enable and engage them; it will be totally immersively built around the human and social cognitive behavioural and purposeful 'way we do things here'.

Science Society, Sustainability and Self-interest

For the first time it has become critically urgent to review and change the hitherto relentless pursuit of 'progress' because it is itself destroying the goals, values, and necessary world conditions for life. The imperative this points to is the need to see what the combination of these can bring about and do things differently where needed. Therefore a toolset to support such new thinking has to be able to take an integrated holistic view which inevitably has a canvas vastly greater than hitherto across specialist domains needing a multi-disciplinary focus. These domains are identified in the title of this section. How can they be joined up? We can list the necessary components which we stress are identified *so far*:

- SOCIAL CHANGE: the partnership between society, science, innovation and progress to choose to change the current unsustainable world order. This is *action research*
- ENTERPRISE SYSTEMS: Societal meta-modelling and systems; their ontologies; information; and elicitation of *designed* emergent properties
- SOCIAL SCIENCE: Personal and organisational behaviour and action viewed as a unique combination of mankind as a social biological and thinking species
- SOCIO-GEONOMICS: Complexity science, dealing with the entirety of resulting world action and behaviour
- ICT TECHNOLOGIES AND ENGINEERING: Massive new social-computational platforms across and integrating with the multitude of pervasive independent organisation and personal systems, able to correlate the history of 'life', viewed as our decisions and actions, their effect on world resources, and the results for our social existence
- COGNITIVE AWARENESS: New paradigms of personal computational engagement, foreshadowed by games virtual reality, and all forms of considering and constructing new approaches to what life is about, what it 'is' and what it means

- THE 'SYSTEMIC' DIMENSION – EVOLUTIONARY SOCIETY AND COMPUTING: representation of the entirety of continuously evolving social 'species' their interactions with the world's resources and especially the abstract entities that are the hidden drivers of social behaviour, and the pointers to sustainability
- METALOGER TECHNOLOGIES: the ubiquitous instantiation and operation of interlinked systems globally or locally to support discovery of the intended or accidental emergent events and dis-continuities arising in evolving world social scenarios, thrown up by the combination of sensor data and wilful human action
- APPLICATIONS AND EXPLOITATION: the huge potential application areas across all those currently existing and new ones emerging from the new paradigm of social-computation and the opportunities to forecast new ways of handling 'life':
  - THE REPOSITORY OF 'LIFE': The tapestry of interacting social/computational worlds will lead to new information age where socially enacted information is the history of mankind tying together 'life' as this embraces, science, culture, society history *and the future*
  - U-CEP: The dynamics are the profound world of ubiquitous complex event processing and interpretation of the significance of their patterns for life, decisions, and action
- GOVERNANCE the raft of new governance systems needed to exploit the new-found complexity patterns of computational socio-geonomic world. Every level of societal structure and institution will want the new tool-set as part of its repertoire of affordances for improving things:
  - Across all sectors of society the tool-set will provide new ways of engaging with the familiar problems of standards methods, quality, achievement and success, but most of all *change*
  - Choice and consequences becomes the driving dynamic of the world rather than *power and coercion*

The above is revealingly and significantly the province of Future Internet, itself the pervasive technology engaging society, and, revealingly showing up societal strains that are the hidden pointers to the need to address social urgencies. We can label this Society needing to be fixed; science needing to support this, and above all people embracing the requirement to pursue a better moral quest – that of a fair and sustainable world. The goal of systems, engineering, science and all progress, defined as 'Fitness for Purpose' needs a further emphasis defined in terms of 'choice and consequences'. The latter is more like a quantum view of world reality than a classic science one of cause and effect. Such a change of viewpoint underlies the ethos of S-GAIA as User driven and user involved: a world where social demand for involvement is pervasive and increasing needs the most advanced tools to render this effective, meaningful, and able to lead to effective decisions and actions. A better world needs all this by consensus because that is more effective, faster of realisation, and better founded in science and societal terms than current authoritarian models or (worse) pernicious structures underlying behaviour, decision and action. The most significant feature of Flagships and the Future Internet is the aim to solve global problems. The scale requires the huge involvement of everyone, because we are asking the world to change and pay for us to do it. We offer opportunities that we want to excite the world with even as we offer it a new toolset and a new Future Internet. This is vitally necessary and it is also do-able.

Method & Way Ahead

We have assembled a core of expert research groups across all of the identified areas of examination listed above. These can only be a starter list and this is not only the nature of Flagships, steadily emerging as the crucial aspect, but the nature of life itself. We will emphasise this as an example of the fact that research is itself a social process. We are fortunate that we are devising just the tool for this discovery: it is *evolution.* For SMART SOCIETY, Future Internet and S-GAIA we would use the term *co-evolution.* We aim to support the social process of Flagship research itself, as well as the ubiquitous systems that are society itself, starting with small prototypes and building up.

The new science of computational socio-geonomics is profound, relevant across many domains of Flagship effort, but paradoxically 'what goes on now'. Only the computational aspect is a new science and has to start by overcoming quite usual and predictable views that it is irrelevant, impossible, and not worth the candle. S-GAIA and SMART SOCIETY are a new symbiosis to put things right and exploit the combined affordances of the new science of complexity, evolutionary computing, societal strengths, and human will. We owe it to our children to get it right.

The fascinating and exciting feature of the S-GAIA world is that the people are the experiment, the model, the simulation, because people do this all the time. The tool-set simply gives them a new affordance in the quest previously the province of the specialist, the elite the privileged, and those at the top of society. Actually we will all work together to devise, understand and apply the new tool-set. This has a number of key advantages:

- It removes the gap- between client and expert because it is immediate, real-life embedded, and actionable. Co-evolution becomes enabled with a profound new tool
- Technically the entire toolset is a living simulation (philosophically all human thought is a gigantic collective model)
- We are all in it together and this is probably the critical element in all change and innovation efforts. We would go further, encapsulated in the Dutch proverb 'we first eat ourselves what we serve to others'
- Science, technology and engineering do not suddenly appear as the claimed answer to everything (thereby setting themselves up for a fall); continuous trial, prototyping, experiment and change is the way of all evolutionary processes, indeed of process itself, now seen as the commanding imperative of the world, science, mathematics, and society
- Everyone will pull together to solve the problems along the way rather than point the finger – the 'I told you so' syndrome. The alternatives are too obvious to need re-stating; better to get it right than fight over the failure and destruction of a sustainable world for all
- The science is becoming well established though not yet any viable computational realisation; we are bringing into the computational frame new thinking previously 'outside'. The good thing is it is all in the human mind and just has to discover what a new toolset can do to enhance the capability of the human mind (whatever that actually *is.*
- As with all paradigm changes they grow like topsy and it is only in retrospect they become actual paradigm changes. People relish what is new even as they look back on a nostalgic earlier age. This happens as people get involved, empowered, enabled and engaged with *change.*

Outcomes

People ask us to define what changes we will deliver. The answer is new science and society but not because we will deliver it but because we will deliver a tool. It is every enterprise, person, organisation and society that will deliver a new and better world. Society's scientists, technologists engineers and certainly the new generation of experts that will be called Metaloger Librarians will deliver the goods. They will be the custodian of the ubiquitous catalogue of models-in-use that will underpin a computational socio-geonomic world. Everyone will know and search this huge repository of dynamic living life; it will be the true societal M word the universe of m ultiple modelled life that enhances culture society people and understanding. It will be a new paradigm of knowledge and meaning – but that is incidental, albeit with huge computational and archiving implications.

Pilot process

From the start of the Pilot, in both FI and Flagship worlds, we will emphasise the on-going discovery process the collaborative nature of innovation, and the economies of shared working, resources, research innovation and practical hints and tips. This is more than a COP; it is a new model for research, society, and the World. We all need to learn about this new social process:

- Shared results, concerns, solutions and contributions puts the emphasis on communications, openness, learning, and knowledge
  - o FuturICT has set out a vision of such a *flagship architecture*
  - o FARO is consulting widely on the modalities of this and we will look for in depth collaboration with FARO; we have set out some preliminary suggestions as to common requirements and *process*
- ▪ B.R.A.I.D is a fundamental meta-model that we think is relevant
  - o We already know many Flagship areas that seek this new dispensation and we will collaborate to make it work:
    - ▪ VPH has invented much infrastructure that potentially seems relevant to us both
    - ▪ Future Internet is the main case this Paper advances
- Our chosen research model is *Action Research* but we do not know if there are other research models that we should be introducing to our portfolio
  - o We do want to consider in depth whether the S-GAIA toolset should offer a prototype instantiation across the flagship world
  - o It is obviously relevant to consider how the FI-PPP model might offer a relevant process to our Flagship (and others)
- Above all we will *question ourselves* continuously as we go along. This is a continuous ethical quest: what are we doing; is it right; can we do it better; should we be doing it this way or even at all. Our quality process will be shared self-examination, documented and acted upon.

Conclusions

We intend to submit a short proposal for a preliminary Pilot that will be a statement of intent as to the way ahead and not a piece of territorial advancement. It will be accompanied by a specific proposal in the FI area as defined for SMART SOCIETY. Both these ideas are taken further in the on-going White paper that is available to everyone FOC as our commitment to an open Flagship research world for the benefit of Society. We look forward to further federated collaborations!

FET Flagship Proposal: The Transition to Real-World Computing

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Sept. 15, 2010

1. The problem and the opportunity

Society's relationship with computing is in a period of flux. Our computing infrastructure today (including the Internet and all other computing devices such as cameras and mobile phones) does most of its complex processing on relatively "clean" data such as text and databases. More complex, "dirty" data such as pictures, sound, and video, are just transmitted and copied, except in a few special-purpose applications. This situation is changing. The computing infrastructure now has enough resources (storage and processing power) to do complex processing on "dirty" data, that is, on raw real-world data with a complex structure. Such data exists in enormous quantities, dwarfing clean data. Most of the 1.2×10^{21} bytes of digital information (as estimated for 2010 by the Digital Universe Report [15]) is raw data of this kind. Doing complex processing of raw data requires enormous computing resources and highly sophisticated algorithms. Today's software technology is just starting to tackle the issues. For example, Google and others are now working on real-time audio language translation, but they estimate several years are needed to achieve a practical application [9]. Nonetheless, the advantages of processing real-world data are so great that we expect society's computing infrastructure to eventually transition to focus mostly on real-world, "dirty" data.

2. The solution: real-world computing

We are at the beginning of a major transformation in the relationship between computing and society. This transformation can be characterized by a focus on computing with raw real-world data, which we call "real-world computing" (it is also called "data-dominant computing", see [21]). The present Flagship will jumpstart society's transition to real-world computing and will ensure that Europe plays a major role in the new computing world that will result. We perceive the first signs of the transformation today: search engines, recommendation systems (e.g., Netflix and Amazon), pattern recognition and language translation, primitive speech recognition and control, primitive visual recognition (e.g., faces), and prototypes of new applications such as real-time audio language translation. By studying these applications, we predict that the transition to real-world computing will be catalyzed by a combination of two disciplines: *machine learning*, which will provide the algorithms needed to process raw data, and *elastic computing* (e.g., clouds), which will provide the computing resources:

1. Elastic computing is the ability to dynamically ramp up and down resources according to dynamic application need. It is the principal structural means to obtain the enormous computing resources needed by data-dominant applications. Applications that process real-world data can absorb arbitrarily great resources. This is not just because of inherent complexity (e.g., NP-completeness) but simply because of the sheer amount of work needed to store and process large quantities of data. The only way to get these resources is through elastic computing. Through elasticity, enormous resources can be made available to applications for short times. This is economical because these resources are amortized among all applications and their users. Elasticity supports applications that need resources in "bursts" (for short time periods), such as Google Search. Fortunately, many data-dominant applications are of this type. Up to now, elastic computing has been provided only by cloud platforms, but we predict that high demand will cause it to be provided in much wider fashion. Because of this demand, all Internet resources will eventually become elastic, and federated or peer-to-peer clouds will make massive computing resources available to any application willing to pay the (low) price.
2. Machine learning is the primary technique to solve problems for which we do not have explicit algorithms. Often it is not possible to write down an explicit algorithm because the problem is simply too large or too complex. This is usually the case for processing of real-world data to extract useful high-level information, such as audio language translation mentioned before. With machine learning, programmers will no longer laboriously write code to process data, but the computer itself will write the code according to a learning algorithm. This will greatly increase programmer productivity as well as allowing programmers to tackle real-world computing problems. Machine learning is now a mature discipline that has far outgrown its early beginnings as part of artificial intelligence. It has many international conferences (e.g., ICML, NIPS, ECML, etc.) and major journals (e.g., J. of ML, J. of ML Research, IEEE Trans. On Pattern Analysis and Machine Intelligence, J. of Pattern Recognition, etc.) and it is already widely used in industry for solving problems that are too complex to program directly. Most of ML's powerful algorithms can take advantage of elasticity because they have learning and

querying phases. Many have not yet been applied to large problems. We predict that in the near future many more machine learning algorithms will be used in applications and that they will be scaled up to use large, real-world data sets.

In what follows we present and motivate this proposal in more detail. We explore the current limitations of elastic computing and machine learning and how they can be overcome. We outline the research needed to achieve the transformation and the kinds of breakthroughs we can expect to achieve along the way. Some of the goals in this vision will certainly be unachievable. But we will only find out if we try to achieve them. Arthur C. Clarke formulated this insight in his Second Law: "The only way of discovering the limits of the possible is to venture a little way past them into the impossible" [9]. According to this insight, the measure of success of projects in this Flagship should not just be based on how many predicted successes are achieved, but also on how many "impossible" goals are attempted.

3. Machine learning: programs that write programs

Machine learning is the discipline that studies how to program computers to evolve behaviors based on example data or past experience [1]. The results are directly useful in many ways: to optimize performance, to improve intelligence, to predict the future, and to aid understanding. The general approach is to suppose that the data has regularities that fit a given general model (the *inductive hypothesis*, also called the *inductive bias*) and to determine the best fit of the data to the model. Machine learning comprises both determining the right model and calculating the parameters for the best fit in this model. The model can define a simple classification (buy or sell a stock) or a complex behavior (how to play a game). The power of machine learning, like the power of the scientific method, depends crucially on the choice of the model. If it is properly chosen, the model is not a limitation. On the contrary, a good model can give essential insights on the phenomena.

Machine learning has long been considered one of the traditional subdisciplines of artificial intelligence [20], but this view no longer corresponds to reality. The modern situation is that ML is also a subfield of statistics, information theory, signal processing, cognitive science, knowledge representation, mathematical optimization, and inductive logic programming, to name just a few [5,19]. ML has made several decades of progress and has matured enough to tackle many real-world problems. We give just three examples. Game-playing programs (for chess, checkers, backgammon, or poker) are at or beyond the level of world-class players. Hidden Markov Modeling is used successfully for real-world speech recognition and other tasks related to sound such as score following. Pattern matching and classification algorithms such as kernel machines and support vector machines and their relatives are used successfully in real-world applications such as recommendation systems and context-sensitive advertising [7]. There are many other promising subareas of machine learning that have developed sophisticated techniques but have not yet been exploited in high-profile applications. One of the goals of the Flagship is to scale up promising areas of machine learning to large data sets.

4. Elastic computing: clouds and beyond

Today's main source of elastic computing is cloud platforms. A cloud is a form of client/server with novel properties that derive from its large scale. Cloud computing uses the memory and processing power of a large number of computing nodes gathered together in facilities called data centers and linked through high performance networks. Cloud users have at their disposal considerable computing resources that are both flexible and modestly priced. For example, many Web applications execute on a cloud instead of on client machines. Cloud computing has three properties that distinguish it from other forms of client/server computing [12]:

1. *Virtualization*: The ability to run applications in customized environments that are insulated from the underlying hardware. Virtualization greatly simplifies software installation and maintenance. Current virtualization techniques have a performance penalty, but they are still practical for many applications such as enterprise computing and support for small networked devices such as mobile phones.
2. *Scalability*: The ability to provide almost any amount of computing and storage resources. This is possible because of the large size of the data center. Because of their size, data centers have an economy of scale. The Berkeley report measures them as five to seven times cheaper than enterprise installations [2].
3. *Elasticity*: The ability of an application to quickly ramp up and down resource usage on demand. Because of this ability, cloud usage is metered: the user pays only for what is actually used, with almost no entry threshold. Furthermore, the actual cost of resources is low because of the economy of scale of the data center and the amortization of its cost over all users.

Of these three properties, the true game changer is *elasticity*. It enables a whole new class of applications that were not possible before, namely applications that need large computing and storage resources for short time periods [21]. Previously such applications could not be run since the resources were simply not available. On a cloud, the resources can be requested quickly through the elastic computing mechanisms, and released when they are no longer needed.

Clouds are currently hosted in data centers, but this will quickly become inadequate to meet the demands for elastic applications. Fortunately, Internet resources outside of data centers dwarf the largest clouds by three orders of magnitude: in Jan. 2010 there were 800,000,000 Internet hosts [16] versus less than 1,000,000 hosts in the biggest cloud [10]. We therefore predict that most Internet hosts will eventually acquire cloud-like abilities (the three properties mentioned above) and be federated into peer-to-peer clouds, to support the Internet's ever-increasing appetite for data-intensive applications. Medium- and small-sized clouds requiring modest investments will complete the picture.

5. Synergy of elastic computing and machine learning

Future applications will use machine learning algorithms on large data sets to learn sophisticated behavior automatically. They will use elasticity to obtain the computing and storage resources needed to achieve this. Instead of programmers laboriously coding the behavior of data-intensive applications, learning algorithms will learn the behavior automatically. What's more, they will adapt their behavior as necessary.

Complex processing of large data sets is already revolutionizing the computing landscape. In artificial intelligence, success can be attained through large realistic data sets, as recent applications and research have demonstrated (e.g., in textual language translation). In scientific research, large-scale data processing has led to a "Fourth Paradigm" for scientific discovery (next to Experiment, Theory, and Simulation) [14]. In these two areas and many others, handling large data sets gives an essential benefit. Unfortunately, this requires enormous computing and storage resources. Fortunately, the computing resources are not needed continuously but in bursts, and the storage resources can be amortized over many users of the application. The canonical example is Google Search: it uses many resources to track changes to the Web and to look up search results. These resources are used in bursts, when a query is done or a new set of Web pages is processed. This "bursty" behavior is supported by the elasticity of clouds.

We observe that as applications become capable of handling real-world data, the computing infrastructure will become much more intimately connected to the real world. Raw data such from real-world sensors of all types will be processed directly. This will increase the amount of digital data even quicker than it is increasing today, giving a positive feedback effect. We therefore expect a strong and increasing demand for more computing and storage resources. One of the goals of this Flagship is to determine how to meet this demand economically and ecologically. For example, small data centers can be installed throughout the world in large numbers and powered locally by wind, solar, or water power. This will relieve the pressure on the electric grid while at the same time increasing the resources available for real-world computing.

We conclude this overview by giving a few examples of what is possible by combining elasticity with machine learning:

1. *Self-* properties*. Typical properties are self configuration, self assembly, self repairing, and self optimization of services. Maintaining self-* properties needs continuous monitoring, deciding what to do, and actuating, all of which are data-intensive. Furthermore, machine learning can be seen as a sophisticated form of self-* maintenance in which the decision process itself is improved.
2. *Intelligent processing of photo and video archives* (e.g., Flickr and Youtube). Many real-time operations on complete archives become possible such as search of the time and place any photo was taken and analysis and synthesis of photo collections. For example, a time-lapse video of the external aspect of St. Peter's basilica in Rome over the last 100 years can be generated in real time by a query, by finding and processing all the photos that have been taken of the basilica during this time.
3. *Intelligent assistants*. The sensory input of a human being can be processed and useful information can be returned to the person in real time. For example, augmented reality can be used to give precise instructions on how to do complicated tasks in real time. Anyone can become an expert car mechanic by following the instructions given by this application.

These applications and others can be envisaged as results of projects funded in the Flagship.

6. Research disciplines involved

Realizing the vision of real-world computing will require enormous investments in research and development in the next ten years in many disciplines. New interdisciplinary bridges and research agendas must be set up and followed through.

1. Research in *data-intensive algorithms*. The algorithms must be scaled up and extended to take advantage of elasticity. The work on MapReduce [11] and NoSQL databases [8] shows the first steps of what can be done.
2. Research is needed in *machine learning*. Currently, only a small fraction of practical machine learning algorithms is being exploited for Internet-scale operations. This should be extended to the whole of machine learning.
3. Research in *distributed and peer-to-peer systems*. Data-center clouds cannot meet the demand for elasticity. Clouds of all sizes must be built and federated. Ideally, all Internet nodes will achieve cloud-like properties and the word "cloud" will cease to have any specific meaning. Note that this does not necessarily need any hardware investment, since existing Internet resources are sufficiently large and can be given cloud-like properties.
4. Research in *complex systems*. Large applications running on clouds can fail in many ways that cannot be predicted from their design in a straightforward way [4]. The global behavior of these systems is an emergent property [3]. Complex systems research can potentially design these systems to have a desired global behavior, but much research is needed to achieve this.
5. Research in *green computing*. Elastic computing has an ecological value. It extends the economy of scale of cloud data centers and can use electrical energy and computational resources more efficiently than traditional computing nodes. For example, small efficient data centers can be made that run on wind and solar power and distributed throughout the environment.
6. Research in *application domains*. Each domain that is a candidate for an elastic application, at all levels, needs to be targeted toward an elastic infrastructure. This includes low level application domains such as networking and routing up to the highest levels close to the end users, such as natural language and visual understanding. There exist many levels in between; one of the tenets of the new data-intensive artificial intelligence is that all these levels must be addressed.
7. Research in many other areas including *virtualization* (the computing environment adapting itself to the application, thus greatly simplifying lifecycle maintenance), *performance* (current cloud virtualization pays a performance tax; future systems should fix this), *middleware and services* (providing a computing environment that supports large numbers of interconnected data-intensive applications), *resource management and security* (using a combination of market-based competitive mechanisms and cooperative collective intelligence mechanisms), *fractal self management* (applications able to monitor their environments and adapt at many scales), and *programming languages* (new programming models and frameworks to take over the laborious task of managing cloud properties, leaving developers to concentrate on application functionality).

The goal of this Flagship is to develop and combine these areas to greatly enhance the intelligence of the Internet at all scales in the next ten years.

7. Size of the flagship; European dimension

The work needed to achieve the vision of real-world computing greatly exceeds what is possible in a single STREP or IP-equivalent size project. We estimate that the development and deployment of real-world computing will take several dozen STREP-equivalent projects. We outline a few of the steps and their sizes.

1. The design, implementation, and deployment of each data-intensive application requires one or more STREPs, because it depends on targeting the expertise of a specific domain. For example, domains such as personalized medicine, computer-aided diagnosis, natural language, social networking, and bioinformatics will all engender applications.
2. Machine learning research, to explore techniques and to make algorithms scalable and elastic, requires work equivalent to around ten STREPS. We estimate the amount of work as follows. A single STREP can investigate part of this domain and make small prototypes. This is multiplied by the large size of the discipline of machine learning (which includes supervised and nonsupervised learning, game theory, reinforcement learning, statistical and Bayesian approaches, non-parametric approaches, prior

knowledge approaches, complete and incomplete approaches, etc. [1,5]) and the technical development of scalable and elastic systems tailored to machine learning [7].

3. Federating cloud infrastructures, to make clouds interoperable and to achieve elasticity on peer-to-peer infrastructures, requires several technological generations of progress. Each technological generation is about three years. Current cloud systems are still immature: each commercial platform is focused on exploring useful functionality for commercial differentiation, and they are not (yet) cooperating on interoperability. Achieving true federation, with standards for virtualization and elasticity approaches and with a standard service architecture, is not achievable in the short term (three years) but will require at least a decade, because the technology must mature enough so that all parties can agree on the common functionality that is necessary.

As a final note, we observe that contributions in this area can be made by small teams. It does not necessarily require large investments by major corporations. There is a large European expertise in all the scientific disciplines involved and a large European expertise in all the important application domains. We mention just bioengineering, natural language, and sound processing (e.g., the IRCAM institute in Paris [17]). A large hardware infrastructure is not needed, since data-center clouds are not expected to remain the main source of elasticity (they are already dwarfed by other Internet resources). Europe can easily develop its own federated clouds, for example by using peer-to-peer technology. We conclude that Real-World Computing is an appropriate Flagship to drive European leadership in the future development of computing and its relationship with society.

Acknowledgements

The author thanks colleagues Pierre Dupont, Seif Haridi, Alexander Reinefeld, Marc Roisin, and Sabri Skhiri for discussions and comments that improved this document.

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Submission for FET-F pilot project Ubiquitous Complex Event Processing

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WHAT the initiative would be about (Mission, integration, impact)

This proposal focuses on the topics of connecting Internet of Services and Things with the management of business processes and the Future and Emerging Technologies as addressed by the ISTAG Recommendations of the European FET-F 2020 and Beyond Initiative. Such FET challenges are not longer limited to business processes, but focus on new ideas in order to connect processes on the basis of CEP with disciplines of Cell Biology, Epigenetics, Brain Research, Robotics, Emergency Management, SocioGeonomics, Bio- and Quantum Computing – summarized under the concept of U-CEP.

In continuation with the edBPM discipline – presented at several international workshops e.g. at the 1st ServiceWave 2008 in Madrid and the 2nd ServiceWave 2009 in Stockholm, this proposal is a thematical enhancement considering the grand challenges defined by FET-F. FET-F initiative is looking for radically new ideas, products and outcomes and U-CEP is a contribution in order to bring together the relevant Future and Emerging Technologies under one umbrella. This will be presented at a 3rd workshop "From Event-Driven Business Process Management to Ubiquitous Complex Event Processing", accepted for the 3rd ServiceWave, 13 December 2010 in Ghent.

The term «Event-Driven Business Process Management» (edBPM) was coined after the 1st CEP Symposion in Hawthorne/NY March 2006 with its first BPM/CEP panel chaired by Rainer von Ammon. edBPM is nowadays an enhancement of BPM by new concepts of Service Oriented Architecture, Event Driven Architecture, Software as a Service, Business Activity Monitoring and Complex Event Processing. In this context BPM means a software platform which provides companies the ability to model, manage, and optimize these processes for significant gain. As an independent system, Complex Event Processing (CEP) is a parallel running platform that analyses and processes events. The BPM- and the CEP-platform correspond via events which are produced by the BPM-workflow engine and by the – if so distributed - IT services which are associated with the business process steps. Also events coming from different event sources in different forms can trigger a business process or influence the execution of the process or a service, which can result in another event. Even more, the correlation of these events in a particular context can be treated as a complex, business level event, relevant for the execution of other business processes or services. A business process – arbitrarily fine or coarse grained – can be seen as a service again and can be "choreographed" with other business processes or services, even between different enterprises and organisations.

This way, processes will be able to change their control flow dynamically and very flexibly according to enterprise internal or external internet services. For this aim a process execution standard like BPEL (OASIS) has to be enhanced by integrating not only simple single, process external events but also complex events. The pilot project will at first discuss a reference model for edBPM and use cases for different, more "traditional" ICT domains like telco, banking, insurance, automotive, logistics, retail, entertainment etc.

First experiences in setting up edBPM-applications have shown that the potential adopters have major problems to adequately define and implement the underlying complex event patterns. Engineering of such applications remains a laborious trial and error process with slow development and change cycles. Therefore the availability of domain specific reference models for event patterns is an urgent need businesses do have nowadays. Adopters and decision makers need a clear understanding of the alternative event patterns and their applicability to solve certain edBPM problems. They should be able to choose the event pattern which is most suitable for fulfilling the properties and objectives of the intended application in a particular domain. The pilot project will also discuss how to find and model appropriate event patterns.

WHY it would be timely (what is the state of the art we start from)

Internet of Things and Services will change the way how the business processes will be performed, by having them in the form of services on the Internet. Consequently, this opens many challenges, but the most important is managing the interaction between services in such an open environment. Indeed, in such a networked services supply chain every service produces many events that might be relevant for other services. It is clear that all these influences, due to their ad-hoc nature, cannot be defined in advance explicitly. Real-world reactivity requires a kind of publish-subscribe mechanism, that enables pushing relevant events to interesting parties. It means that the actual data flow (and not predefined workflows) will determine the reactive nature of a Future Internet system.

From this basis, the pilot project will start and deal with the Grand Challenges of what is summarized under the concept of "Ubiquitous Complex Event Processing" – presented at the FET-F workshops in Brussels in January and June 2010 - and where the concept of Internet of Services is enhanced according to the FET-F Initiative. Hardly anybody would have forecast 10 years ago that the business world would look as it does today. How will the industrial world look in 10 years time? Which products and technologies will we use to produce goods, to do business, to learn, to live and to communicate? To better explore the potential that these technologies can offer, European Commission has launched a high-level expert group on key enabling technologies. Key enabling technologies, such as U-CEP in connection with nanotechnology, micro- and nanoelectronics including semiconductors, Bio- and Quantum Computing, biotechnology and photonics, but also brain research, cell biology, Epigenetics, robot companions for citizens, Cyborgs, Exocortex etc. will provide services in a much broader sense. For the modeling and management of such new event types and patterns as so called "smart dust" we will also need new modeling and execution platforms. In this pilot project we will start a first dialogue between experts and visionary potential adopters.

HOW we intend to achieve the goal (which will be the main scientific challenges)

1) This pilot project will extend the concept of edBPM as actually "commodity" from the perspective of the **scientific State of the Art**, although there are **no real adopters** so far (and we are far from standards of course).
In several international workshops the pilot project wants
- to extend the concept of edBPM
- as ed(B)PM (means: not all processes must be **"Business"** processes)
- to U-CEP (means: **new** application **domains**, new **Services** from the **"Universe")**

2) The pilot project should position U-CEP as an appropriate umbrella for new medium-term Future Internet- and long-term FET-F technologies and identify new ideas and products in more detail.

3) The pilot project should build the bridge between Future Internet and FET-F technologies as a flagship initiative under the umbrella of U-CEP.

4) The workshop should bring together the high potential experts from the related interdisciplinary domains in several domain specific working groups and open public workshops collocated with major well known international conferences like ServiceWave and Future Internet Assembly etc. with concrete results and new product ideas at the end.

5) The pilot project would be the result of a community building process, started already some time ago, in order to build a large and powerful community for the U-CEP based ideas, e.g. at the 5th EPTS symposion in Trento September 2009, at the 9th edBPM expert meeting in Regensburg December 2009, the CEP Dagstuhl Seminar in May 2010, the 5th DEBS in Cambridge July 2010 and nowadays the 3rd edBPM/U-CEP workshop in Ghent December 2010. That preliminary work was the background for the consortium of this pilot project.

Themes of the Pilot Project

Event-Driven BPM: Integrating Internet of Services

- Integrating Complex Events in BPM
- Deterministically managing of a "concert" of collaborating business processes based on complex events
- Non-deterministically managing of collaborating business processes
- Needed enhancements of modeling standards like BPMN
- Enhancements of execution standards like BPEL
- Enhancements of the NEXOF-Reference Architecture based on edBPM

Ubiquitous CEP: Concepts for the integration of a new kind of Services

- New modeling and design approaches
- Unified Modeling Language and enhanced notations/diagrams for modeling complex dynamics
- New Agent Based Modeling approaches
- New application domains like Epigenetics, Cell Biology, Brain Research, etc.
- U-CEP based robot companions for citizens, Cyborgs
- Weather/global catastrophe emergency management
- New Human Enhancement Technologies (HET) and U-CEP related product ideas like Smart Navigation Systems, Intelligent Cars, U-CEP based SmartPhones, Exocortex products…
- Computational Socio-Geonomics and Social Simulation, e.g. in the case of 10 billion human agents
- From energy to matter – Higgs Boson, Higgs field, quantum physics
- Super-Computing, Bio-Computing, Quantum-Computing
- Challenges for Event Processing Languages (EPL) from the perspective of Bio-Computing and Quantum-Computing

Milestones

1) Organisation of International Workshops about U-CEP in order to evangelize the idea and to bring together the high potential interdisciplinary experts with the potential adopters

2) Organisation of a Course of Study U-CEP, curriculum and concept for Live-long Learning, new eLearning concept
3) Set up of first Proof of Concepts according to where edBPM/U-CEP will start from (Conti use case Change Management, Unicredit use case Risk Management according to an edBPM enhanced NEXOF-Reference Architecture ...)
4) Defining explicit interdisciplinary U-CEP ideas and long-term products