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Coordination and Support Action

EUINCOOP
Cooperate Collaborate Connect

EU-India Fostering COOPeration in Computing Systems

D3.2: Research Challenges for Europe and India

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Executive Summary

This deliverable describes the computing systems research challenges that are shared by Europe and India, along with the trends, strategies and opportunities in each region that are behind these research challenges. While there is a wide spectrum of shared interests in technology research between Indian and Europe in many different scientific domains, the EU-INCOOP project has a specific focus on computing systems technologies and the opportunities for shared innovation and technological advances described in this deliverable are concentrated in computing systems challenges.

This deliverable utilises knowledge gained from several tasks that have been carried out within the EU-INCOOP project. In particular, the project has carried out a regional analysis of computing systems research activities and roadmaps in both Europe and India and has prepared a catalogue of key actors involved in European and Indian computing systems research projects along with an analysis of the projects and topics being addressed in each region. Technology roadmaps from both regions were also researched to identify common interests in desired technology innovations. These tasks have been complemented by interactions amongst experts group and organisation of brokerage events to help prioritise and provide a more complete view of the technologies that have greatest potential to be addressed by joint research initiatives between India and Europe.

The process of gathering inputs from Indian and European experts is ongoing and further validation of the shared research challenges described in this deliverable will be carried out, which will culminate in the publication of a joint Research Roadmap at the end of the EU-INCOOP project.

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1 Introduction

1.1 Purpose of this deliverable

This deliverable has been developed by the EU-INCOOP Project to identify the computing systems research challenges that are shared by Europe and India with a focus towards areas of potential collaboration that could be addressed through jointly funded projects. The research challenges that are described result from several tasks that have been carried out earlier in the project:

- analysis of government funded computing systems research activities and topics in Europe and India, published in deliverable D2.1 – Regional Analysis of Computing Systems Research Activities
- analysis of various technology roadmaps from Europe and India identifying main areas of focus in India and how they map to European technology roadmaps, published in deliverable D2.2 – Preliminary Research Roadmap
- analysis of the key actors in computing systems research in both India and Europe, published in deliverable D3.1 – Catalogue of Key Actors
- collection of inputs from experts groups at project sponsored brokerage events in Europe and India, summarised in deliverable D4.1 – Brokerage Event Report 1

The interactions amongst experts groups and the organisation of brokerage events has helped to prioritise and provide a more complete view of the computing systems technologies that have greatest potential to be addressed by joint research initiatives between India and Europe.

The process of gathering inputs from Indian and European experts is ongoing and further validation of the shared research challenges described in this deliverable will be carried out by the project, which will involve an even broader set of European and Indian experts. The validation process will culminate in the publication at the end of the EU-INCOOP project of a joint Research Roadmap.

1.2 Structure of this document

This deliverable is structured as follows:

- Section 2 identifies the technology and industry trends in computing systems that impact research and development challenges in each region
- Section 3 provides an overview of the objectives of the government funded research programmes in each region
- Section 4 describes the industrial strengths in computing systems in each region and provides an analysis of technology disruptions and associated opportunities for each region
- Section 5 highlights the importance placed on international cooperation in each region and the specific provisions that are included in the regional plans

- Section 6 describes the computing systems research challenges shared by each region, including the specific technical topics that could potentially be jointly addressed
- Section 7 describes further aspects to be considered when coordinating the formation of joint funding for projects between India and Europe

Additional information is available from the references provided in Section 9 and the EU-INCOOP project partners welcome further comments and guidance from experts in Europe and India by visiting the project website at www.euincoop.eu.

1.3 Scope

This deliverable has been developed to achieve specific objectives within the EU-INCOOP project under the FP7 ICT Programme, and in particular related to the computing systems objective within the European Commission's ICT Work Programme. The research challenges identified have a time horizon of 2013-2020 in line with Horizon 2020, which is the next Framework Programme of the European Commission for funding advanced research.

The EU-INCOOP partners note that there are limitations in describing India government funding priorities when compared to those of the EU as there has been less public consultation on prioritisation of research funding in India. The research technology challenges have been identified based on a combination of information provided by published Indian government sources, consultation with leading Indian research actors, and through the personal contacts of the EU-INCOOP partners.

While there are many shared interests in technology research between India and Europe, the EU-INCOOP project has a specific focus on computing systems technologies and the opportunities for joint initiatives in government funded research. The targeted technological advances described in this deliverable are therefore concentrated in computing systems topics that are of shared interests in both India and Europe and that are aligned with the strategies and the funding mechanisms for government funded research in each region.

1.4 Contributors

The deliverable was prepared with contributions from all of the EU-INCOOP partners, each playing an important role in preparing the contents:

- IISc investigated the research priorities of the Indian government and organised local groupings of leading Indian experts to provide advice and guidance on research opportunities and priorities
- CDAC investigated the research challenges facing India related to high performance computing, which represents one of the largest focus areas of computing systems research in India
- ITSMA investigated the topics being addressed in India by non-government funded actors involved in computing systems research
- KYOS facilitated the brokerage events and collected contributions and guidance on computing systems research priorities from leading actors both in Europe and India

- FORTH and TOG gathered inputs from leading EU actors on computing systems research challenges, promising technological approaches and potential opportunities for joint research initiatives with India
- TOG provided the overall structure, coordination and editing of this deliverable, while FORTH carried out reviews and quality control

In addition, this deliverable reflects the technological and societal insights, challenges and expertise from the following:

- Participants to EU-INCOOP brokerage events conducted both in Europe and India providing important contributions and guidance in preparing this deliverable
- Participants to European Commission sponsored advisory groups, workshops and concertation meetings who have contributed to establishing the technological vision and challenges for the Horizon 2020 Framework Programme in Europe
- Participants to the working group established by the Department of Science & Technology who have contributed to establishing the Twelfth Five Year Plan in India

The preparation of this document was made possible through a close collaboration amongst the project partners and with the kind support of leading actors in computing systems research from Europe and India.

2 Technology trends

In preparation for describing the opportunities for collaboration between India and Europe in addressing computing systems research challenges it is useful to consider important trends that are occurring within the broader Information and Communication Technology (ICT) sector that are affecting both regions. Many of these trends also appear in various roadmaps and planning documents from each region and are described here to provide the context and motivations behind the specific research challenges shared between India and Europe.

One overarching trend that is impacting multiple areas of computing is the advent of parallelism within mainstream computing systems. Parallelism is impacting the entire spectrum of computing systems from personal systems (smartphones, tablets, PCs) to large-scale data centres and high performance petascale computing systems. Parallelism is becoming pervasive as it is currently the only viable alternative for significantly increasing the performance of computing systems while providing improved autonomy for small devices or keeping the energy profiles at lower levels for data centres and high performance computing (HPC) systems. This trend fundamentally impacts software technologies since parallelism has to be largely managed by software rather than hardware technologies.

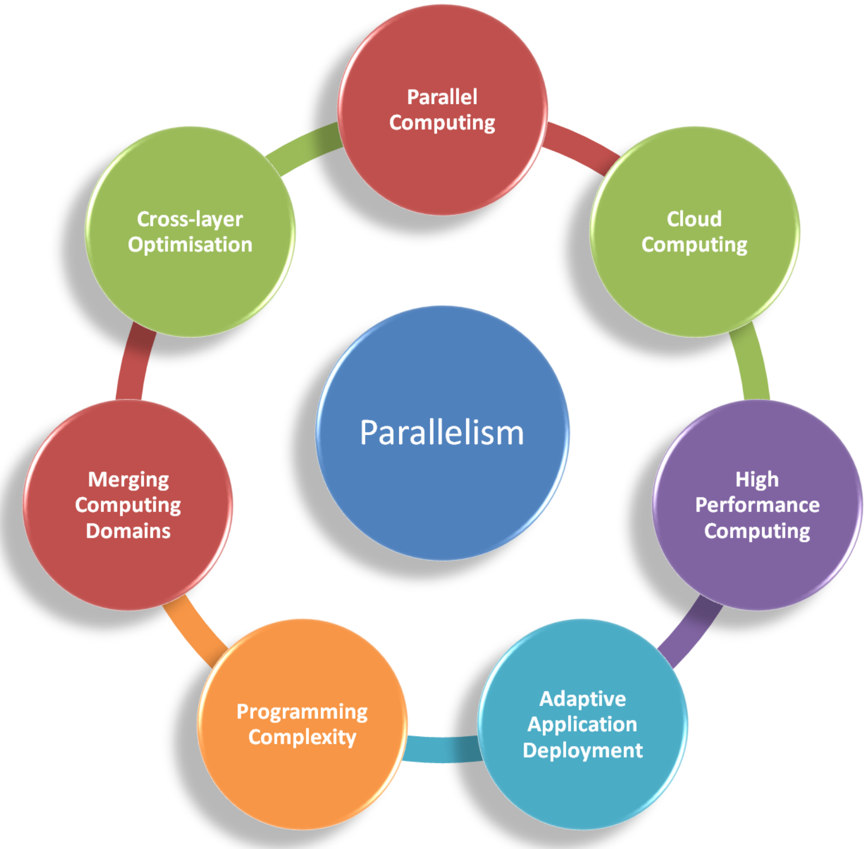

Figure 1: Computing Systems Technology Trends

In addition to this major overarching trend, there are important technology trends for computing systems technologies that will bring about changes in technology uses and pose new challenges for computing systems research. These include the following:

- Parallel computing
- Cloud computing
- High performance computing
- Adaptive application deployment
- Programming complexity
- Merging computing domains
- Cross-layer optimisation

The following sections describe these trends and the challenges and opportunities that are associated with each.

2.1 Parallel computing

Future processor performance increases will be mostly driven by an increasing number of cores, either homogeneous or heterogeneous, sometimes offering multithreading capabilities. To be able to exploit performance increases, applications will have to utilise much higher degrees of parallelism than is generally exhibited today. Programming languages will have to provide mechanisms, through either parallel constructs or annotations, to express concurrency within applications and find ways to maintain portability while still exploiting performance aspects of the underlying hardware architecture. Technologies will be needed such as dedicated runtime systems that are capable of scheduling threads across the available homogeneous or heterogeneous cores while managing data transfers and maintaining data coherence. Developing the most appropriate architecture and applying new technologies of manycore and parallel computing appropriately and effectively will soon become prime competencies widely required in Europe and India.

2.2 Cloud computing

Cloud computing has emerged as a new paradigm for providing advanced information processing as a commodity. One of the fundamental aspects of Cloud computing is to provide elasticity and scalability. These two intrinsic properties impact not only the way resources are managed but also require programmers to design applications so that they can be run on an unknown set of resources that may fluctuate during execution. Elasticity is provided through virtualisation where virtual machines can be migrated and can use specific parallel programming models for distributing and parallelising tasks. Programming models will need to interact effectively with data management systems to process and analyse large, heterogeneous and dynamic data. Cloud computing raises an important challenge in how to manage energy consumption, which has a strong societal impact. Proliferation of data centres for Cloud computing will significantly increase electricity consumption unless new technologies can reduce energy profiles in a global way, including the network infrastructures and mobile devices. New initiatives have been established focusing on “Green IT” to raise awareness and share best practices in reducing energy consumption of large data centres. These issues will grow in importance as access to Cloud computing services will support new computationally intensive or highly distributed innovations from SMEs as well as encourage the growth of large scale and possibly global Cloud services providers.

2.3 High performance computing

The next frontier of high performance computing (HPC) will be the design of exascale computing systems by 2020 with an accompanying 1000X increase in performance over present HPC systems. Although such an increase has been achieved in the past moving from terascale to petascale, current software technologies are not suitable for the forthcoming high-end HPC systems due to the high degree of concurrency required to reach exascale performance. Current estimates indicate such systems will need between 100 million to 1 billion cores and will consume up to 100 MW. Although dedicated hardware such as the new generation of low power consumption processors might help to keep the energy envelope within reasonable bounds, a tight cooperation between hardware and software technologies, including the operating, runtime systems and applications, is necessary to address the energy challenge.

Programming exascale machines represents another challenge due to the complexity of these machines: core heterogeneity (CPU & GPU); deep memory hierarchy (cache, local memory, remote memory); and communication and synchronization mechanisms (messages, shared memory). New programming models must be invented providing a high level of abstraction while allowing application programmers to focus on their research fields rather than managing low-level technical details that are dependent on the target architecture. Such programming models will have to ensure "performance portability" on the whole range of exascale systems. Exascale systems will also provoke a data deluge with applications generating tremendous amounts of information. Rapidly storing this data, protecting it, and analyzing it to understand the results will be significant challenges.

2.4 Adaptive application deployment

It's likely that by 2020 the paradigm of software programs being developed for a specific hardware platform or operating system will be obsolete. Programs will likely have no knowledge of their runtime environments as commodity computing systems will range from smartphones to the Cloud, with each of these platforms featuring hardware parallelism and hardware heterogeneity. The efficiency of applications will become highly dependent on the ability of computing systems providers (from the smartphone manufacturer to the Cloud manufacturer) to provide software technology that tailors applications to the underlying hardware at deployment and run-time. The challenge will be to allow portability of both functionality and performance on a whole range of hardware platforms. New run-time technologies are expected to enable both research and industrial applications to be developed fully independent of the target hardware, while innovations in system software will enable such applications to fully exploit the performance capabilities of the underlying platform.

2.5 Programming complexity

Productivity of development and maintenance of software for advanced computing systems is becoming increasingly effort-intensive. Efficient programming of advanced computing systems from embedded to HPC has not evolved as fast as hardware capabilities and network capacity and requires dual expertise, both on the application side and on the system side. The joint targets of high performance, ease of programming, and portability will lead to radical improvements in programming frameworks, languages and tools and increased automation in software engineering for advanced computing. For 20 years the predominant paradigm in programming parallel systems has been message passing and OpenMP, having been most recently combined to establish a hybrid programming model. The complexity of code optimisation is increasing exponentially where past approaches to optimisation focused on performance (Gflop/s), is giving way to new priorities such as energy consumption. Looking forward, a broad spectrum of optimisation parameters will become equally important including locality of data, cost, dependability and security, depending on the application. These more varied requirements will help define the programming models used for future advanced computing systems.

2.6 Cross-layer optimisation

Most computing initiatives around the world are hardware driven, usually not reaching beyond the system software level. This traditional bottom-up approach starting from the evolution of the hardware will need to be enlarged to enable applications to fully exploit parallelisation and hardware configurations involving dedicated accelerators and customised FPGAs. The situation becomes more tenable if the target for the software tools providing parallelising functionalities is an abstraction layer comprising parallel algorithms with which individual application codes can be constructed. The automated mapping of parallel algorithms to the underlying system software and hardware infrastructure should prove to be a viable approach to simplifying the costs and necessary expertise involved in creating application software for tomorrow's advanced computing systems.

2.7 Merging computing domains

One of the key structural changes that are emerging in computing systems is the migration towards a computing continuum that will likely see:

1. the same key technologies and players acting across all computing segments: embedded, mobile, desktops, servers, data centres, clouds, supercomputers; and
2. application usage of computing resources cutting across the computing spectrum such as embedded systems utilising HPC functionalities and HPC systems used in time- and safety-critical applications.

Embedded computing is going through many transitions: from single core controllers to multi to manycore systems; from local buses to switched and open embedded system networks; from single application contexts to application integration and from individually maintained systems to autonomous, self-X systems. This brings new challenges in programming, validation, systems integration, system dynamics and guarantees, mixed critical systems, system maintenance and in autonomous system platforms and functions. Power consumption has an increasing influence on both the hardware and software architecture, while timing, safety, reliability, availability and security are of increasing importance at the core of critical systems. As the functionality of embedded systems increases, HPC capabilities are combining with embedded requirements: low power, low cost and mixed criticalities. HPC will no longer be the province of specialist supercomputing centres. While, HPC for big scientific challenges will always need dedicated supercomputers, this may be a shrinking market. The advent of low cost clusters powered by multicore CPUs and GPUs takes HPC capabilities to a much wider audience. But while that new audience has the appetite to use HPC to develop better products, it generally lacks the skills and experience to do so.

3 Regional research programme objectives

Europe and India each have multi-year frameworks that provide government funding for research and development. The European Commission in collaboration with all of the European member states has established the Horizon 2020 Framework Programme which defines priorities and instruments for funding European research over the next seven years. In India, the Twelfth Five Year Plan published by the Indian government also sets out priorities and new initiatives for government research funding over the next five years.

The following sections provide an extract of the main objectives and priorities that are identified in the planning documents that will be guiding government funded research and development in India and Europe.

3.1 European research programme objectives

The European Commission has established the Horizon 2020 Framework Programme for funding research and development which has a focus on successful mastering and deployment of enabling technologies by European industry as a key factor in strengthening Europe's productivity and innovation capacity and ensuring Europe has an advanced, sustainable and competitive economy, global leadership in high-tech application sectors and the ability to develop unique solutions for societal challenges. Within the Horizon 2020 Programme innovation activities will be combined with R&D, as an integral part of the funding.

Horizon 2020 provides funding for a wide range of European science and technology domains. Computing systems research falls under the part of the programme focused on industrial leadership where Europe aims to speed up development of the technologies and innovations that will underpin tomorrow's businesses and help innovative European SMEs to grow into world-leading companies. This part of Horizon 2020 focuses on three specific objectives:

1. Leadership in enabling and industrial technologies shall provide dedicated support for research, development and demonstration on ICT, nanotechnology, advanced materials, biotechnology, advanced manufacturing and processing and space. Emphasis will be placed on interactions and convergence across and between the different technologies.
2. Access to risk finance shall aim to overcome deficits in the availability of debt and equity finance for R&D and innovation-driven companies and projects at all stages of development. Together with the equity instrument of the Programme for the Competitiveness of Enterprises and SMEs, it shall support the development of European Union-level venture capital.
3. Innovation in SMEs shall stimulate all forms of innovation in SMEs, targeting those with the potential to grow and internationalise across the single market and beyond.

The activities under this part of the Horizon 2020 programme shall follow a business-driven agenda. The budgets for the specific objectives 'Access to risk finance' and 'Innovation in SMEs' will follow a demand-driven, bottom-up logic, without predetermined priorities. These shall be complemented by the use of financial instruments and a dedicated SME instrument following a policy driven logic.

Horizon 2020 will take an integrated approach to the participation of SMEs, which could lead to around 15% of the total combined budgets for all specific objectives on societal challenges and the specific objective 'Leadership in enabling and industrial technologies', which includes computing systems technologies, being devoted to SMEs.

The specific objective 'Leadership in enabling and industrial technologies' shall follow a technology-driven approach to develop enabling technologies that can be used in multiple areas, industries and services. Applications of these technologies to meet societal challenges shall be supported.

A major component of Europe’s vision for achieving leadership in enabling and industrial technologies are Key Enabling Technologies (KETs), defined as micro- and nanoelectronics, photonics, nanotechnology, biotechnology, advanced materials and advanced manufacturing systems. Many innovative products incorporate several of these technologies simultaneously, as single or integrated parts. While each technology offers technological innovation, the accumulated benefit from combining a number of enabling technologies can also lead to technological leaps. Tapping into cross-cutting key enabling technologies will enhance product competitiveness and impact. The numerous interactions of these technologies will therefore be exploited. Dedicated support will be provided for larger-scale pilot line and demonstrator projects. This will include cross-cutting activities that bring together and integrate various individual technologies, resulting in technology validation in an industrial environment to a complete and qualified system, ready for the market.

Strong private sector involvement in such activities will be a prerequisite and implementation will therefore notably be through public private partnerships. To this extent and through a dedicated governance structure, a joint work programme for cross-cutting KETs activities will be developed. Taking into account market needs and the requirements of the societal challenges, it will aim at providing generic KETs building blocks for different application areas, including societal challenges.

Innovation activities will include the integration of individual technologies; demonstrations of capacities to make and deliver innovative products and services; user and customer pilots to prove feasibility and added value; and large-scale demonstrators to facilitate market take-up of the research results. Demand-side actions will complement the technology push of the research and innovation initiatives. These include making the best use of public procurement of innovation; developing appropriate technical standards; private demand and engaging users to create more innovation-friendly markets.

For nanotechnology and biotechnology in particular, engagement with stakeholders and the general public will aim to raise the awareness of benefits and risks. Safety assessment and the management of overall risks in the deployment of these technologies will be systematically addressed.

These activities will complement support for research and innovation in enabling technologies, which may be provided by national or regional authorities under the Cohesion Policy funds, within the framework of smart specialisation strategies.

Strategic international cooperation initiatives will be pursued in areas of mutual interest and benefit with leading partner countries. Of particular, but not exclusive, interest for enabling and industrial technologies are

- the development of global standards;
- removing bottlenecks in industrial exploitation and conditions for trade;
- the safety of nanotechnology-based and biotechnology-based products;
- the development of materials and methods to reduce energy and resource consumption;

- industry-led, collaborative international initiatives within the manufacturing community; and
- the interoperability of systems.

A number of activity lines will target ICT industrial and technological leadership challenges and cover generic ICT research and innovation agendas, including notably:

- A new generation of components and systems: engineering of advanced and smart embedded components and systems – where the objective is to maintain and reinforce European leadership in technologies related to smart embedded components and systems. It also includes micro-nano-bio systems, organic electronics, large area integration, underlying technologies for the Internet of Things (IoT) including platforms to support the delivery of advanced services, smart integrated systems, systems of systems and complex systems engineering.
- Next generation computing: advanced computing systems and technologies – where the objective is to leverage European assets in processor and system architecture, interconnect and data localisation technologies, cloud computing, parallel computing and simulation software for all market segments of computing.

Horizon 2020 is structured around the objectives defined for its three major parts: generating excellent science, creating industrial leadership and tackling societal challenges. Particular attention will be paid to ensuring adequate coordination between these parts and fully exploiting the synergies generated between all specific objectives to maximise their combined impact on the higher level policy objectives of the European Union. The objectives of Horizon 2020 will therefore be addressed through a strong emphasis on finding efficient solutions, going well beyond an approach based simply on traditional scientific and technological disciplines and economic sectors.

Cross-cutting actions will be promoted between Part I 'Excellent science' and the societal challenges and the enabling and industrial technologies to develop jointly new knowledge, future and emerging technologies, research infrastructures and key competences. Research infrastructures will also be leveraged for broader usage in society, for example in public services, promotion of science, civil security and culture. Furthermore, priority setting during implementation for the direct actions of the Joint Research Centre and the activities of the European Institute of Innovation and Technology (EIT) will be adequately coordinated with the other parts of Horizon 2020.

Furthermore, in many cases, contributing effectively to the objectives of Europe 2020 and the Innovation Union will require solutions to be developed which are interdisciplinary in nature and therefore cut across multiple specific objectives of Horizon 2020. Particular attention will be given to responsible research and innovation. Gender will be addressed as a cross-cutting issue in order to rectify imbalances between women and men, and to integrate a gender dimension in research and innovation programming and content. Horizon 2020 includes specific provisions to incentivise such cross-cutting actions, including by an efficient bundling of budgets. This includes also for instance the possibility for the societal challenges and enabling and industrial technologies to make use of the provisions for financial instruments and the dedicated SME instrument.

Cross-cutting action will also be vital in stimulating the interactions between the societal challenges and the enabling and industrial technologies needed to generate major technological breakthroughs. Examples of where such interactions may be developed are: the domain of eHealth, smart grids, intelligent transport systems, mainstreaming of climate actions, nanomedicine, advanced materials for lightweight vehicles or the development of biobased industrial processes and products. Strong synergies will therefore be fostered between the societal challenges and the development of generic enabling and industrial technologies. This will be explicitly taken into account in developing the multi-annual strategies and the priority setting for each of these specific objectives. It will require that stakeholders representing the different perspectives are fully involved in the implementation and in many cases, it will also require actions which bring together funding from the enabling and industrial technologies and the societal challenges concerned.

3.2 Indian research programme objectives

The research and development (R&D) base in India is currently undergoing transformational changes. Various advisory councils have made recommendations to step-up R&D investments and the Prime Minister of India has committed to double public spending on R&D. Whereas Indian outputs from the science and technology sector continued to grow, but at a relatively slow pace during the 1985 to 2000 period, other emerging economies like China and Korea invested heavily in science and technology and grew their outputs much more vigorously. Consequently, the relative position of India with respect to scientific output indicators slipped to ranks below 15 by 2003.

On account of several promoting measures taken by the country, there are some positive trends with respect to science and technology output indicators during the last few years. The relative position of India with respect to scientific publications has improved from 15th in 2003 to 9th in 2010. However, there remains a concern that the global share of high impact making discoveries in science is relatively small. This issue could be best addressed only by broadening the R&D base of the country and the attraction of talent to careers with research, and increasing significantly the Gross Expenditure on Research and Development (GERD) as a percentage of GDP.

In order that GERD increases significantly, engagement of the private sector into R&D must be quantitatively increased over the Twelfth Plan period (2012-2017). Such increases would be forthcoming only when indigenous research leads also to intellectual products which are globally competitive in market and knowledge economies. Although there have been substantial increases in growth rates of patents filed in India during the last decade, the share of patents filed for work in India through indigenous research is less than 20% of total patents filed. Policy interventions are necessary for stimulation of private sector engagement and investments into R&D.

Supply side approaches for promotion of advanced basic research should be further enabled with tools for demand-side planning for innovations and technology development. A few approaches to be considered within the Twelfth Plan period are given below:

- Current individual investigator centric models need to be expanded for consortium funding systems.
- Possibilities of funding Indian basic research with other nations with control of Intellectual Properties through international S&T cooperation

- Mega facilities for basic research are being built and created through International consortium type of funding and plan for participation in global research consortia.
- Capability to build new instruments needed for basic research outside the strategic research sector.
- Offer a new scheme to institutions aspiring to gain listing among the top 300 universities in the world by making higher investment with changed governance structure.
- Investment in long-term goal oriented Basic Research in national priority areas such as Water, Energy, affordable Health Care etc, as well as for impact making discovery research.

The Science Advisory Council to the Prime Minister has prepared a Science Vision for the country. It is expected that during the next twenty years, the Indian economy would have emerged as a major global economy with economic prosperity leading to better access to education and health care for larger sections of the population which would live with hope and security. It is envisioned that science would be at the heart of strategies for meeting the next stage of national developmental demands.

India is now poised in the 21st century to usher in an 'Innovation' phase where technology can lead a sustainable development that minimizes India's environmental footprint, enables distribution of wealth, and creates equal opportunity, sustainable food supply and affordable health care. India cannot afford the luxury of waiting for industry to embrace technology and lead this innovation phase. Whilst the Indian government develops ways of working with industry to maximize the impact of technology, it also needs to identify ways of bringing science to market. Here India is helped by the innate enterprise of scientists and technologists who with some support and mentoring are capable of developing viable businesses starting from the laboratory. The biggest barrier for technology transfer is often the risk averseness of established industries who feel that there is an unacceptable level of uncertainty in new technology. This is where start-ups play a critical role.

For realizing the science vision of India, conscious efforts to synergize various programmes of the country in both private and public funded institutions are essential. Agencies like the Department of Science and Technology (DST) must play a critical and changing role during the Twelfth Plan period, if the science vision for the country for emerging as a leader in global science is to be realized.

The science vision of India demands that science should be able to play a more centric role and forge linkages with the developmental programmes of the country and the basic research programmes of the Indian science sector should be enlarged. Some roles of DST for promotion of Indian science sector in the wake of changing context of the country have been mapped and are summarized as follows:

1. Policy formulation for the science sector with a stronger focus on enlarging the role of private sector into Research and Development.
2. Strengthening of Human Capacity with a vision to broaden the R&D base of the country while promoting excellence in science education and research.
3. Strengthening of institutional capacity with a focus on rejuvenation of research in the university sector and multiplying the number of centres of excellence.

4. Establishment of Technology Platforms with a special emphasis on convergent technology solutions in key areas of national importance like water, homeland security, fertilizers, solar and clean energy.
5. Promotion of new mechanisms and structures for national S&T partnerships among academia, research and industry for technology development, developing and strengthening bilateral, multi-lateral and regional S&T cooperation of India with other countries for technology diplomacy, technology synergy and technology acquisitions and Public-Public-, Public-Private- and Public-People- partnerships for innovations and technology deployment.
6. Serving and servicing the social contract of Science and Technology for increasing living choices to people.
7. Coordinating the establishment of large R&D facilities in cooperation with other agencies in the country.

Designing and developing an enabling innovation ecosystem is considered a national priority. DST is expected to assist the development of such an innovation system through both policy and programmatic support. The Department has adopted an approach to the planning process based on the: a) expressed stake holder aspirations, b) alignment of planning to the Results Framework Document enunciated by the Government of India to monitor the delivery of outputs, and c) changing role of DST along the growth trajectories of the Indian Science and Technology systems.

4 Regional strengths and opportunities

In support of understanding the computing systems research challenges shared by India and Europe, it is helpful to understand the industrial role of computing systems technologies in each region. Each country has computing technology areas where they are competitive at a global level and each seeks to fortify and improve these global positions. In addition, both India and Europe seek to invest in technologies that create opportunities for their respective industries in other areas.

Historically as technological gaps or disruptions in technology evolution have occurred, opportunities present themselves for actors who have next generation technologies or who utilise innovative business models or provide innovative products. Both Europe and India seek to invest in technologies that will exploit disruptions in technological evolution creating new opportunities to excel and be competitive in global markets.

The following sections provide an overview of the industrial strengths of Europe and India in computing systems technologies, along with an analysis of the disruptions in technological evolution that are occurring or will soon occur and the opportunities these present for each region.

4.1 European industrial strengths

Europe is strong in computing systems technologies and sees opportunities in exploiting more powerful computers to provide the next generation systems and products. More sophisticated computing systems technologies will deliver a broader range of features, which will help European industry be competitive in global markets. Europe has a wide range of technology providers who develop, manufacture and integrate computing systems technologies in key European industries such as automotive, aerospace, energy, health, finance, and many others. Europe is particularly strong in computing systems technologies for embedded systems where large multinationals like Bosch, Continental, Thales, Siemens, and many others are recognised globally as technology leaders. European automotive and aircraft manufacturers have been able to exploit this strong European embedded systems ecosystem to strengthen and extend their market position.

In Europe, there has been an established HPC community for more than two decades. The first HPC centres appeared in Europe in the mid to late 1980s and these centres have cooperated in many ways over the years. Much of this cooperation has been focused around scientific and industrial collaboration (some financially supported by the European Commission and industry), and involvement in international standards. For example, the development of MPI and OpenMP involved a number of European HPC experts. Europe has an acknowledged strength in HPC applications, and has many world leading Independent Software Vendors (ISVs).

Most of the system integrators for HPC and server farms come from multinationals with headquarters outside Europe, though many of them have significant research and development in Europe employing a respectable work force. Teaming up with European or multinational actors, European actors such as Bull, Materna, Eurotech, Transtec, or upcoming start-ups are reinforcing their profile as integrators in the HPC, server farm, or embedded markets.

Europe has excellent parallel processing skills at both a systems and an application level. For example, Allinea has produced the most scalable debugger for HPC systems, scaling to hundreds of thousands of cores, and CAPS is a leading global provider in compiler technologies & engineering services for parallel hybrid computing. Europe’s research establishments such as Fraunhofer and INRIA also have a proven track record of delivering advanced algorithms and simulation technologies for industrial applications.

The European market for advanced computing systems is very large. The market can be characterised as consisting of two large segments:

1. Primary market – industrial actors producing and marketing software, providing software as a service, or providing services using software products; and
2. Secondary market – actors producing their own in-house software.

There are many European suppliers of enterprise applications, including SAP (one of the world’s largest software companies) and Germany’s Software Cluster of 170 partners. With nearly 100,000 employees in the Rhine-Main-Neckar region, these partners represent a 30% world market share of the enterprise software market.

In markets such as engineering, energy, health, and electronics, there are some very large European actors like Dassault Systemes, Philips, and Siemens, who are world leaders in their segments, plus a large number of service providers and smaller companies including many SMEs. They will all need to update their software for next generation systems in order to maintain their leading positions.

Software is a key driver for the European economy. However, the European software industry has a substantial position in global markets only in a few segments such as Embedded Systems and Enterprise Software. It lags behind its US competitors in important segments, like the traditional packaged software and as a consequence, US vendors dominate the world Top 20 software vendor list.

Whilst the European software industry lags behind its international competitors, recent trends in technology such as those for Future Internet, Mobile Computing and Cloud Computing offer a window of opportunity for Europe to improve its competitive position in software. The European software sector employs more than 2.75 million people and is projected to grow to €383.5B by 2020 – this rate of growth is twice the projected growth of the overall economy amongst the 27 member states.

The commoditisation of software and infrastructure inherent in the move towards Cloud Computing and the continued advances in Open Source and mobile applications should help to foster greater innovation. Europe must ensure that the younger generations are equipped with the appropriate technical and business skills to exploit these opportunities.

Non-functional features such as reliability and security are expected to become more important differentiators and are areas where Europe has developed leading technologies. Increasingly software will be automatically produced and Europe needs to ensure that the appropriate production methods are employed to ensure that the European software sector is market leading in these aspects.

4.2 Indian industrial strengths

India has invested substantially in High Performance Computing (HPC) over the years and has announced a €767M grant to create next generation super computers and invest in HPC. The US is a clear leader in the HPC segment with 253 of the 500 systems, followed by Europe with 107 systems. Dominant countries in Asia are China and Japan with 68 and 34 systems respectively. India has a supercomputer in the top 100 ranking and a few in the top 200 band. While a country's economic success is often not defined by who has the fastest computer, building the required capabilities and ecosystems to use these capabilities, and develop solutions for applications in different domains will nevertheless strengthen its position in any given area. Going by this dictum, India is keen to invest in the high impact area of HPC.

The need for HPC is more pronounced in the modern day than it was a few decades back. The demand for high computing power is seen in almost all major sectors, from government to individuals, from scientific applications to small businesses; from climate modelling to energy exploratory missions, HPC plays a major role in Indian society. In India, government led initiatives such as the universal identification for all the citizens, providing affordable health care to the rural masses through telemedicine are in need of HPC systems. HPC applications to enable efficient transportation systems impact the automotive and the transportation sector.

Health care devices for improved health care delivery systems provide major breakthroughs to the health care industry. Scientific and life sciences related applications will revolutionize science and technology of the nation, consumer electronics and retail businesses related applications bring in large economic benefits to the society in direct and indirect ways and a common thread to achieve substantial improvements in these sectors is HPC technology, which can bring about the much desired success.

India has expertise and research interests in many new technologies related to HPC such as cloud computing, multicore and manycore architectures, and FPGA programming models for these technologies. For example, the cloud computing market in India is expected to grow by 50% by the end of 2013 and will maintain similar growth rates for the next three years, driven by cost and performance efficiencies[1].

India with its proven strength in software, can leverage its strengths to become a leader in HPC systems software and applications that are scalable and able to exploit processors in numbers that are several orders of magnitude higher than today.

India has well-established academic and research centres with a proven capability of designing and assembling supercomputers. Most of these supercomputers serve the scientific community with centres having substantial expertise in the provision of HPC services. Key strengths for India in the area of HPC are the following:

- With India's proven expertise in software, it has the potential to pursue global leadership in rewriting software codes required for petascaling and exascaling of HPC applications code. This is a major business opportunity for the Indian ICT industry.
- India has a vast pool of talented workers; strong research groups working on almost all computing systems aspects spanning from embedded systems, grid computing to cloud computing and large scale distributed computing.
- With developed R&D expertise in future HPC technologies, India can lead in providing HPC training and education. The world will badly need this type of service in near future and this can become a major business opportunity for India.
- Focused development groups like CDAC, C-MMACS and computational research labs who have the capability of developing system software stack and support, and have strong domain expertise in diverse HPC applications.

These strengths are leading to a growing interest and expertise in India on HPC and related technologies. India has vast experience in software applications and can build upon these strengths to adapt to newer programming models.

4.3 Technology disruptions and regional opportunities

Advanced computing systems technology is driving new markets and creating new opportunities for researchers and industry in both Europe and India. Computing systems technologies power many industrial and societal applications such as forecasting, automotive systems, manufacturing, energy and mobility, ageing and health, and have application in many other domains. The recent advances in new computing system technologies and how they are being used has created technological gaps or disruptions, which provide new opportunities for organisations in both Europe and India.

[1] Announcement in Indian financial daily 'The Economic Times' of IDC forecast

In preparation for Horizon 2020, a European Commission hosted workshop on advanced computing systems identified key disruptions in technologies and the opportunities these present for Europe. An updated version of this analysis is provided in Table 1, which has also been extended to show the potential opportunities these disruptions present for India.

Disruption	European Opportunity	Indian Opportunity
Energy efficiency is becoming as important as performance where components increasingly come from the low power mobile world rather than the more power hungry desktop world. Tablets and smartphones are driving new innovation and markets.	Europe has significant strengths in low power, low cost processing for battery powered devices.	India has strong expertise in system software to develop new features for energy awareness and to exploit these at application design and deployment.
The data deluge and the end of the increase in processor clock speeds for powering hardware innovation are leading to a new generation of computing systems, which are increasingly parallel and heterogeneous.	Europe has the skills in parallel processing and the ability and expertise in both embedded and supercomputing technologies which when combined provide opportunities for capitalising on this technology revolution.	India has substantial skills in addressing large data challenges in several scientific disciplines and years of experience in parallel processing that can be applied to scale applications to exploit new heterogeneous architectures.
There is a trend towards a computing continuum with the same key technologies and players acting across all computing segments, and application usage cutting across current computing disciplines.	Europe can expand from its strengths in embedded, mobile and high performance software.	India can extend from its strengths in HPC computing to further develop world class expertise in embedded and mobile software.
A new era of enterprise software given the emergence of ground breaking technologies such as cloud computing, multi- and manycore processors, and main memory database technology. In addition, the Internet of things has become reality generating massive data volumes.	Europe has world leading capabilities in enterprise software and expertise in developing system software that exploit new platform architectures especially in areas related to mission or safety-critical domains.	India has world leading capabilities in enterprise software and expertise in exploiting new technologies for developing enterprise applications and adapting technologies to many different industrial domains.
High bandwidth networks based on the widespread deployment of broadband – fixed and mobile – enables promising new business models leveraging the cloud computing paradigm.	Initiatives such as the GÉANT 100 Gbps European network and 4G for mobile opens access to advanced computing resources and application services to European actors to who these were out of range in the past, in particular SMEs.	Networking advances create new opportunities for India's large base of software suppliers to access and exploit new HPC technologies for innovative applications and services.
The cost of developing new hardware approaches in silicon is dropping due to the use of FPGAs for prototyping and novel ASIC manufacturing methodologies.	Europe has world leading expertise in integrated circuit design through its embedded systems community.	India has world leading expertise in developing applications that exploit new hardware designs and lower cost platforms.

Table 1: Technology gaps and regional opportunity analysis

The analysis demonstrates that both India and Europe are well posed to exploit opportunities that are being presented due to range of technology disruptions.

5 International cooperation interests

Europe and India each have made public their interests in international cooperation. The multiyear plans that have been established in Europe (Horizon 2020) and India (Twelfth Five Year Plan) setting out priorities for funding of technology research and other programmes also include specific references to international cooperation. Both regions identify interests in collaborating with other countries on science and technology initiatives and make clear that such actions further the objectives set out in their respective plans. The interests in international cooperation from each multiyear government plan are described in the following sections.

5.1 European interests in international cooperation

The Horizon 2020 plan prepared by the European Commission indicates the importance Europe places on international cooperation with partners in third countries to effectively address many specific programme objectives. This is the case for all the societal challenges addressed by Horizon 2020, which are global in nature. International cooperation is also considered essential for frontier and basic research in order to capture the benefits from emerging science and technology opportunities. Europe sees promoting researchers and innovation staff mobility at an international scale as being crucial to enhance global cooperation. Activities carried at the international level are equally important to enhance the competitiveness of European industry by promoting the take-up and trade of novel technologies, for instance through the development of worldwide standards and interoperability guidelines, and by promoting the acceptance and deployment of European solutions outside Europe.

The focus of international cooperation in Horizon 2020 will be on cooperation with three major country groupings:

1. industrialised and emerging economies
2. enlargement and neighbourhood countries
3. developing countries

Where appropriate, Horizon 2020 will also promote cooperation at regional or multilateral level. International cooperation in research and innovation is a key aspect of the Europe's global commitments and has an important role to play in the Europe's partnership with developing countries, such as progressing towards the achievement of the Millennium Development Goals.

Horizon 2020 includes a specific article that sets out the general principles for participation of organisations from third countries and international organisations. As research and innovation in general benefit largely from openness towards third countries, Horizon 2020 will continue with the principle of general openness, while encouraging reciprocal access to third country programmes.

In addition, a range of targeted actions will be implemented taking a strategic approach to international cooperation on the basis of common interest and mutual benefit and promoting coordination and synergies with activities in European countries. This will include a mechanism for supporting joint calls and the possibility of co-funding programmes together with third countries or international organisations.

5.2 Indian interests in international cooperation

India's Twelfth Five Year Plan spanning 2012-2017 has specific provisions for international cooperation in scientific research. In particular, the plan seeks to establish international cooperation on science and technology under both bilateral and multi-lateral arrangements based on the principle of reciprocity and parity. The Five Year Plan suggests an approach of mapping and profiling of opportunities and benefits of international science and technology engagement through strategic planning. India intends to proactively increase its engagement in science and technology cooperation with selected countries and regions by increasing the number of external science counsellors in its planning committees from 4 to 20.

The Five Year Plan also recommends support of select bilateral and multilateral projects with funding for developing the cooperation based on mutual and global interests. India's participation in the creation of large R&D infrastructures and mega science is also strongly supported and the creation of Technology Acquisition as well as Science and Technology Assistance Funds and the establishment of a Global Innovation and Technology Alliance have been proposed. India sees a need for promoting Private-Public Partnerships (PPP) in R&D through a holistic approach.

Adequate provision for funds for deployment into pan-India S&T missions on key sectors identified by the Planning Commission has been suggested. Alignment of the programmes and schemes of DST to several cross-departmental programmes and linkages has been suggested as a better means of implementation. The suggestions include:

a) enhancing capacity for growth in partnership
b) Technology and Innovation
c) securing technology future for India
d) improved access to quality education
e) managing the environment
f) enhancing skill and employment generation

Wide scale increase in Science and Technology communication and enlargement of on-going programmes have been recommended. Several new partnerships and alliances for reaching out to the community various science based developments have also been suggested in the Five Year Plan.

6 Common research challenges

Europe and India have similar motivations for funding new innovations in computing systems technologies. However, as previously shown in Section 3, there are differences in strategy between India and Europe that must be considered when identifying common research challenges. One of the most distinguishing characteristics is that Indian research funding has an emphasis on applied research where new technologies are often developed to address specific scientific, societal or economic problems. European research is also very much concerned with ensuring research is applied and directed at similar European problems, but is also more willing to fund visionary or technological advances that are more exploratory, which may also have higher risks but also greater potential for dramatic impact in Europe or in global markets.

Identifying computing systems research topics that provide a balance between direct applicability while also being sufficiently visionary was an important consideration of the EU-INCOOP project in order that the identified research challenges would likely to garner both Indian and European government support for joint funding.

A further distinguishing characteristic is that Europe provides substantial funding for research in hardware components and platform technologies, while very little government research funding in India is directed towards these areas. India relies predominately on industry funded research for advances in hardware components. These differences means there is a strong emphasis on software technologies and exploiting underlying architectures amongst the challenges that are common between India and Europe.

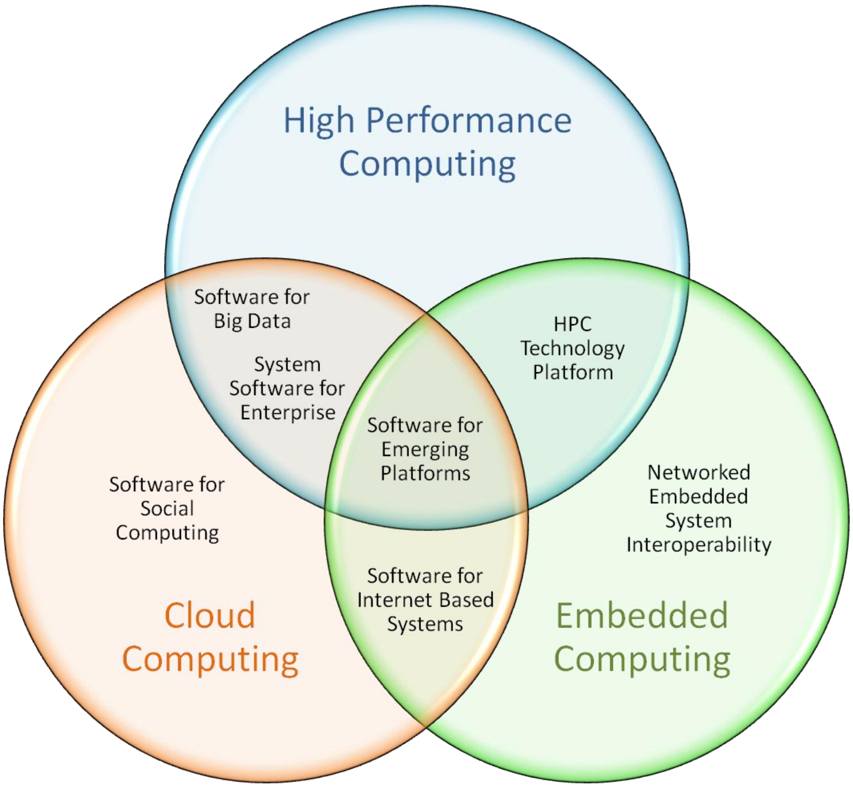

Figure 2: Common Research Challenges and Computing Domains

The most substantial computing systems research and technology challenges that have been identified as being common to both Europe and India are the following:

- Software for emerging platforms
- Software for internet based systems
- Software for Big Data
- System software for enterprise
- Network embedded system interoperability

- Software for social computing
- HPC Technology Platform

These challenges span the main computing systems domains of high performance, cloud and embedded computing technologies. Figure 2 provides a representation of where each of these common challenges is positioned within the three dominant domains for computing systems research and development.

The following sections describe the common research challenges in more detail and suggest new technologies that could be jointly developed by organisations in Europe and India to address these challenges.

6.1 Software for emerging platforms

Hardware platforms are increasingly becoming heterogeneous presenting new and substantial challenges for European and Indian software developers in addressing high levels of parallelism, new memory, storage and connectivity configurations, which are all leading to increased complexity. Software development for advanced hardware platforms is becoming a barrier to productivity both in research and commercial application domains and new innovations are needed in automating software development for highly parallel and heterogeneous environments. New technologies that automate new systems development on advanced heterogeneous platforms are essential, but equally important are technology innovations that make it economically feasible to migrate and extend existing software forges to exploit parallelism, new memory architectures and other platform innovations. New technologies that seek to find a balance between ease of programmability, portability and exploiting performance of new multi- and manycore platforms are research challenges that would benefit both European and Indian industries that rely heavily on software systems.

Several possible threads of research could be explored jointly between Europe and India including:

- Use of algorithms as an abstraction layer, combined with automated parallelisation based on that abstraction
- Model-based engineering technologies that better address properties related to parallelisation during design combined with new transformation technologies to automate exploitation of parallelisation at deployment
- Increased run-time intelligence to dynamically adapt software to better exploit parallelism of the platform
- New languages that aid in the expression of parallelism and that provide better mapping or automation of algorithm design

Special emphasis should be placed on portability and scalability so that investments in transforming existing software to exploit parallelisation and advanced platforms need not be repeated as future platform advances emerge. Research actions that bring together communities of research knowledge as can be found in Europe for embedded systems and in both India and Europe for HPC hold promise for addressing specific application domain level challenges. Projects should use these real world challenges to focus innovations that solve specific societal needs both in India and Europe.

Research into human aspects is also critical where better understanding is needed as to how people should program software for new multi- and manycore platforms as they become ubiquitous in HPC, the enterprise and embedded systems. In particular, University and professional curricula needs to be adapted or developed to provide the skills needed to address ever greater levels of parallelism and to transform current sequential approaches to application design to the use of efficient and effective programming practices suited for advanced platforms.

Future manycore architectures will require both a higher degree of design and deployment automation as well as greater parallel programming efficiency and both Europe and India face a similar and significant skills gap. Too few universities teach parallel programming at an undergraduate level and new paradigms are needed to help software programmers better understand and conceptualise parallelisation. The challenge being faced both in India and Europe is that advances in high performance platforms are outpacing advances in software development technologies for effective exploitation.

6.2 Software for Internet based systems

Both Europe and India have a strategic focus on the evolution of telecommunications technologies that will enable innovative applications and services that exploit mobile computing and the Internet. Telecommunication networks and services are in fact large scale software systems that are distributed across wide geographic areas, and are highly complex due to the dynamic nature of the services they support. The behaviour of such systems is nonlinear and can even exhibit chaotic properties where the software part of each individual component can be mastered by a single actor but the overall architecture can lead to new emerging phenomena that are difficult to understand, model and control. Both Europe and India have a high dependency on their telecommunication and IT infrastructures and new technologies are needed to address challenges related to security, quality of service, resilience and resource optimisation across service platforms based on telecommunications and the Internet.

The availability of manycore computing platforms enables a wide variety of technical solutions for large scale distributed systems involving nodes that range from the embedded to high-performance Cloud Computing domains. However, large scale manycore based systems are notoriously hard to design and manage – choices regarding resource allocation alone can account for wide variability in timeliness and energy dissipation (up to several orders of magnitude). These challenges coupled with the dynamic nature of Internet based communications and services need to be addressed by new technologies for distributed systems that focus not only on traditional properties of resilience and quality of service, but also on energy usage and adherence to real-time constraints on timing and resource utilisation.

Recent trends in devices and web services where there is a clear independence between software and hardware will happen for network infrastructures as well. Technologies for virtualization, management of manycore platforms, development tools, and web standards are expected to be core technologies that will lower the capital expenditure in Europe and India on telecommunication infrastructures and shorten time to market for new applications and services.

Several possible threads of research could be explored jointly between Europe and India including:

- modelling the architecture and behaviours of large scale distributed software systems using separation of concerns and other techniques that reduce the costs of verification and provide mechanisms for guaranteeing behaviour at run-time
- dynamic resource allocation in manycore embedded and high performance systems while providing appropriate guarantees on performance and energy efficiency
- different types of cloud-like resource management infrastructures aiming to harmonise the approaches to dynamic allocation across the complete spectrum between systems with little flexibility and strict performance guarantees to highly flexible systems with soft performance guarantees
- resource allocation techniques that are sufficiently lightweight to be applied during runtime, and that are able to take into account performance guarantees for timing and energy use
- scalable resource allocation techniques that are capable of supporting different kinds of cloud-like infrastructures including embedded clouds, micro clouds and high-performance clouds
- extensions to existing system software (OS, virtual machines, middleware) to support predictable runtime migration of tasks and virtual machines, with monitoring and back-propagation for dynamic optimisation

Both Europe and India need to reach a position where software for real-time service systems such as telecommunication systems is predictable in different configurations in order that these highly distributed and dynamic systems can continue to evolve for decades after their initial deployment. Compositional techniques are needed to provide automated verification and testing of updated systems based on component or subsystem level verification such that the behaviour of systems with many different components, especially involving real-time systems is predictable.

Another growing opportunity in both Europe and India centres around Internet of Services concepts where business services will be built upon new innovations in Internet based system services. A collaborative approach to addressing large scale distributed systems that support new Internet based services would greatly benefit markets in both India and Europe.

6.3 Software for Big Data

In India and Europe both commercial and research organisations are experiencing an explosion in the quantity of data that is being produced. New computing systems technologies for extracting value from this data are needed as both Europe and India have industries seeking to build new products and services, government organisations seeking to better support citizens, and research organisations envisioning major steps forward through the analysis and mining of large data stores.

New technologies are needed to address Big Data challenges from several different perspectives:

- diversity of information to be analysed as data may come in a variety of forms from very structured (tables in relational systems, XLS, HTML, PDF) to semi-structured (XML, web services, RDF) to unstructured (sound, image, etc.)
- data may be distributed between a large numbers of devices, of which many may be mobile, with different systems and formats, different models and ontologies
- quality issues with imprecise data, inconsistencies, and incompleteness along with capturing not only the data but indicators or metadata enabling the assessment of the quality and reliability of data
- identifying and adapting to external trends and changes amongst data providers that might affect the precision or reliability of data mining and analysis

The challenges presented by Big Data in analysing from many dimensions, using complex aggregations, and in some cases applying probabilistic techniques to address gaps or precision, introduce new challenges in computing systems technologies. Specifically, this includes techniques for the analysis of multidimensional, geo-referenced, unstructured data like text, and streaming data involving the integration of different formats and data types, and in many cases to do so within specific real-time constraints.

Several possible threads of research could be explored jointly between Europe and India including:

- Data centric system software exploiting manycore parallel computing platforms
- Asynchronous computing and distributed data focused run-time environments
- Scalability of open data management platforms and support for new approaches to analysis and visualization
- Optimisation through balancing or delegating work using techniques such as moving algorithms to local data stores
- Improving interoperability of data, techniques, and methods across tasks and scenarios

An overarching challenge in the development of new technologies for Big Data is scalability as the volumes of data stores are expected to increase at substantial rates in the coming years. New technologies need to include capabilities for continuous scaling and adaptation to data volume increases. Specific applications that are driven by Big Data can be drivers for research but application-specific technologies should be avoided and research should focus on innovations that are widely applicable to large classes of Big Data related applications.

6.4 System software for enterprise

Enterprise software is a key driver of innovation in both Europe and India's business environments. The dynamic integration of business partners is of ever-growing importance in order to quickly react to customers' needs, as are the opportunities for offering new services that exploit intelligence being increasingly embedded within manufactured products. These new services will be made possible through the use of the Internet via cloud platforms and new system level technologies are needed for these service to be efficiently developed at costs that make feasible commercial exploitation. New business models are being introduced in both India and Europe that combine a wide range of components from different product and service providers in a dynamic and flexible manner, in order to fulfil highly complex customer requirements. Innovations in new system software technologies for enterprise also hold great promise both in India and Europe for enabling small companies to access and participate in regional and global markets.

Enterprise software needs to adapt itself dynamically to the changing requirements of the market as well as the business environment and to support many types of service relationships between companies. The intelligent linking of existing offers and the addition of supplementary components and services enables new innovations in the range of offers that can be provided. Companies that make use of such software will be able to establish new business models that go beyond and are potentially more lucrative than those that motivate the original development of the individual components and services. A vision for both India and Europe is that enterprise software systems can be created through the simple composition of standard solutions from multiple providers. This would reduce the costs of maintaining enterprise systems and reduce the investments required to establish new service based systems. Enterprises in both Europe and India will therefore be able to be more innovative in introducing new business models, have greater flexibility in adapting and tuning of business models, and have systems that are more responsive or adaptable to market conditions and opportunities.

In order to provide these capabilities of enterprise software, the current state-of-the-art with respect to Internet of Services and Cloud Computing must be extended allowing for semantically connecting software services across enterprise domains. As of today, there are no suitable software engineering methodologies in place or any appropriate standards.

Several possible threads of research could be explored jointly between Europe and India including:

- automating interoperability of systems between enterprises where existing services are linked efficiently and quickly to new business processes without new interfaces having to be implemented
- automating adaptation of systems to dynamically accommodate changes in circumstances where no overall view of the business process across enterprises is available, including techniques to recognise when adaptation is required
- distributed systems technology addressing the complexities of interfacing, managing and exploiting data from manufacture products with embedded intelligence that may have been sold around the world
- system software supporting real-time data analytics and new enterprise database technologies and related programming and design tools to support rapid adoption
- manycore programming methods and models that transform service oriented architectures to better exploit dynamic service composition, virtualisation and main memory techniques for enterprise software

New system software innovations have to be designed in such a way that they are applicable and adaptable in unfamiliar contexts. An important enabler will be the automated production of semantic interoperability of components and adapters as well as mechanisms for searching, finding, evaluating and configuring components for constructing tailored enterprise systems.

6.5 Networked embedded system interoperability

Europe and India have different visions as to how embedded devices will enable important societal changes. The differences are not technological and result from each region facing different societal challenges and having different targets for global competitiveness. However, both regions share a vision of increased reliance on embedded devices to bring about important improvements for citizens and industry. Governments in each region are investing substantially in research and development of applications that will utilise embedded technologies such as Internet based government services and associated apps for mobile devices, or remote medical services and patient care using sensors and other intelligent devices. Seamless connectivity is essential for the future of these embedded systems based services and applications. Technologies that enable connectivity span middleware, operating systems and other functions required to link the physical world, as seen by the networked nodes, and also the higher layer applications, as well as hardware features needed to support efficient and effective interoperability implementations.

Many emerging embedded applications share networks and components and often the network hierarchies do not correspond to the respective application structures. The expected increase in the number and size of open networks of embedded systems that will couple applications from multiple domains will result in increased levels of system complexity. The emerging use of the Internet for embedded system networking provides new opportunities where applications will seek to exploit the emerging ubiquitous network topology not only for communications but also to gain access to information systems.

The availability of digital information from the physical environment is a unique opportunity for the embedded systems industries in both Europe and India. The information base for systems will be larger than ever before, which if new technologies are developed, could be exploited to provide more optimised, accurate and efficient services from both government and industry. Technologies that enable semantic interoperability are needed, so that users may exploit the different information and knowledge from different domains. These technologies will be able to create smart environments in both Europe and India resulting in increased intelligence, better services and enhanced productivity for all aspects of living.

Several possible threads of research could be explored jointly between Europe and India including:

- operating systems and virtual environments that can be distributed and composed, and are able to support dynamic reconfiguration
- resource augmentation enabling devices to identify resources accessible across a network such as cloud computing, HPC, or simply other more intelligent devices and to exploit these to dynamically improve quality of service and energy usage
- connectivity schemes that support ubiquitous syntactic and semantic integration of heterogeneous sub-systems, under the constraints of minimum energy usage and limited bandwidth
- self-configuration, self-organisation, self-healing and self-protection of computational components to establish connectivity and services, using knowledge acquired from the environment
- monitoring techniques for object and event recognition making possible new control tasks in large-scale systems

Through research and development of technologies for device connectivity, networked embedded systems have great promise to become the backplane of both European and Indian society. Embedded systems technologies should no longer be considered in their traditional isolated or specialised application contexts, but should be seen as core computing systems technologies that will contribute to addressing societal challenges in both Europe and India.

6.6 Software for social computing

Technology factors in both Europe and India such as mobile computing, intelligent devices, and Internet connectivity will lead to hundreds of millions of users exchanging information with billions of devices. Many of these devices will be able to store and process information and extract knowledge from it creating a new paradigm for computing systems where knowledge is pervasive.

Both Europe and India have to reconsider the notion of data, information and knowledge in this social context where the bulk of raw data and information comes from users. Information may come from individual's opinions in tweets, blogs, web pages, emails, or be collected by devices as users move between different environments and contexts. Users may even participate in large-scale data processing via crowd-sourcing and in application building through the new but as yet little understood mechanism of collective intelligence, or exploiting application technologies that enable mashups where new applications are built by assembling web based services. There are also large volumes of information that are drawn from machines observing human behaviours such as what people read, where they go, what they purchase, etc.

New software technologies will be needed to address the deluge of information that will be created because the volume of data and the associated processing tasks. Europe and India need to develop the tools and interfaces to support the interaction with the masses of data surrounding their citizens and system level tools are needed to find, access and manage data so that applications with societal importance for both government and industry can be developed.

Several possible threads of research in system software supporting social computing and societal applications could be explored jointly between Europe and India including:

- Data intensive distributed computing system software and middleware
- Semantic-based data integration and standardisation
- Software optimisations and acceleration for reasoning in a huge-scale distributed environment
- Technologies for discovery, surveillance and managing dynamic and mobile data

One challenge facing researchers in this area is having access to suitable data sets of sufficient size to test the scalability of new technologies. An opportunity exists for Europe and India to collaborate in creating an open, possibly anonymised, shared data set for use in testing advances in system software and middleware in support of new social computing applications. Also, opportunities exist to establish new standards to enable data coming from many different sources to be handled more easily.

There is an increasing trend to set these issues in the wider context of social computing which is concerned with the intersection of social behaviour and computational systems and the development of what might be called social computers or social machines. Advances in this area are also related to the development of open data initiatives and new technologies will create opportunities for innovation in new services and entrepreneurship.

6.7 HPC Technology Platform

One of the largest areas of commonality between India and Europe in computing systems research interests is High Performance Computing (HPC). Each region has substantial programmes for developing new HPC technologies and each region faces common challenges affecting both industry and research organisations:

- continued exponential growth in performance in computational components is facing disruption due to the effect of Moore's Law coming to an end
- future HPC systems if built using current technologies will consume an unacceptably large amount of electrical power
- applications that are critical for biotechnology, mitigation of natural disasters and other societal supporting sciences are already difficult to scale to exploit higher petaflop systems and will need substantial re-engineering for exascale systems

European research advances in devices that use less power are expected to make it feasible to build future systems having exascale performance with acceptable power consumption using manycore technologies. A shared research challenge for both Europe and India resulting from the use of these low power devices is the need for innovative software technologies that will exploit new HPC architectures. Such devices present new programming challenges to enable applications to be sufficiently scalable and to accommodate restrictions on memory and processor bandwidth.

HPC plays an important strategic role in both Europe and India where research advances will support new opportunities for industry to exploit HPC technologies for new services surrounding cloud computing and to address Big Data challenges that have arisen and will continue to increase in coming years. HPC research also presents a societal opportunity as there are skills shortages in HPC in both regions and a need to develop new skills amongst populations well-educated computer engineers to exploit HPC for specific application domains. Many of the companies which can benefit the most from HPC are small and unable to directly invest in the development of HPC platforms. For these companies especially but also for companies of any size, a common Technology Platform for HPC developed jointly between Europe and India could present substantial economies in development and deployment costs that would enable HPC to be more widely exploited in both regions.

Some characteristics of the challenges surrounding HPC that are particularly well-suited to the establishment of Technology Platform are the following:

- problems to be addressed require multidisciplinary science and engineering inputs where knowledge from different disciplines is applied in new and innovative ways
- contributions are needed from a range of different types of stakeholders in defining the solutions from research institutes to industry

- shared vision and leadership will provide substantial economic benefits in terms of the resources needed for research and development
- many real world applications for HPC appear diverse, but the underlying computing systems challenges are shared amongst large classes of applications making it feasible to develop HPC technologies that are applicable to a wide range of industrial and societal applications

Further opportunities will also be created in the area of standardisation of research results that would underpin a common HPC Technology Platform.

Several possible threads of research could be established in support of a joint HPC Technology Platform between Europe and India including:

- programming models, languages and methodologies for manycore HPC architectures and tools to automate applications and improve developer productivity
- technologies for energy-aware application and system modelling, compilation and run-time environments for building energy efficient HPC systems
- modelling and simulation techniques that scale to expected levels of parallelism in manycore based HPC platforms
- exploiting technologies from other computing domains for mobile, embedded, cloud, telecommunications and sensors to address HPC
- definition of a common access framework for the HPC infrastructures

Research and development for a joint HPC Technology Platform should anticipate new emerging applications that will present new requirements for HPC. Applications which deal with constant operation and monitoring of infrastructure such as electricity generation and distribution, transport control, logistics and industrial processes and decision support in crisis situations will have new requirements for robustness, real-time and reliability to be addressed by HPC technologies. Furthermore, the ability to deal with enormous amounts of data from numerous diverse sources such as continuously connected sensor networks is a clear requirement.

7 Joint programme recommendations

This deliverable brings together information gathered from analysis of government funded computing systems research actions and planning in Europe and India, analysis of the key actors in computing systems research in both India and Europe, and inputs collected from experts groups at project sponsored brokerage events in Europe and India. In carrying out these tasks and also in identifying the research challenges described, the EU-INCOOP partners have identified a set of recommendations for consideration by European and Indian government organisations when formulating a joint initiative for funding computing systems research. These recommendations are listed along with a SWOT analysis providing further guidance in the following sections.

7.1 Recommendations

A set of recommendations have been identified in the course of identifying and describing the research challenges that are common to Europe and India. These may need to be considered when constructing a coordinated call between the regions in order to increase the likelihood of success in achieving the desired impacts:

- The technology challenges in each of the seven areas identified are substantial and could involve investigations in several of the technology topics that have been noted. The approach that is most likely to yield best results would be to support a few smaller joint projects addressing one or more of the noted development topics.
- Many of the research challenges shared by Europe and India are of sufficient importance that they are likely to also be topics for regional projects. Some planning should be taken in each region to avoid a joint initiative between Europe and India being used for closing gaps or addressing topics not addressed by regionally focused funding to ensure jointly funded topics attract leading organisations from both regions.
- The use of pilot projects should be considered where a joint consortium of Indian and European participants would first work together to formulate a detailed research work plan much like a detailed requirements deliverable that is often the first step of European funded projects. This would allow partners to get more familiar and better understand each others' technical capabilities, working styles, and other characteristics before embarking on a longer term commitment of a 2-3 year research project. Successful completion of the work plan should result in further funding of the longer term joint project without a further competitive proposal process.
- Research projects that result in shared platforms between India and Europe such as the identified HPC Technology Platform, or shared project artefacts that can be used for further research and development (e.g. large data sets for testing and validation of scalability) in regionally funded projects are likely to create lasting collaborations that extend beyond the contractual duration of the projects.
- Joint projects between India and Europe will likely need to have specific provisions for ownership of results that may differ somewhat from standard European Framework Programme terms conditions. The disparity in costs between the regions could become a major barrier to exploitation in India after project completion unless specific requirements to include provisions for open source or other low-cost licensing mechanisms are part of the funding arrangements.

Further considerations will likely be identified by the EU-INCOOP project partners as work progresses and further interactions are orchestrated amongst key actors and experts groups from each region.

7.2 SWOT analysis

The greatest successes to date in collaboration between India and Europe for ICT topics have been achieved primarily through India's bilateral Science and Technology cooperation programmes established with many European countries. India's participation in the European level Framework Programmes for research and development in computing systems has not yielded strong results or substantial new collaborations. For example, no Indian organisations have participated in any computing systems research and development projects in the multiyear Framework Programme 7 that is nearing completion.

In 2012, in preparation for the 7th EU-India Joint Working Group meeting, partners from the European Commission funded SYNCHRONISER project prepared a position paper that included a SWOT analysis of the factors that may have been responsible for the limited outcomes achieved to date from EU-Indian cooperation in ICT research. An updated version of that analysis specific to computing systems is shown in Table 2 as a reminder that while there are very promising opportunities for collaboration, there are also weaknesses and threats to EU-Indian collaboration that should be considered and addressed as part of the formation of any joint initiatives between Indian and European government organisations.

STRENGTHS	**WEAKNESS**
• Traditional linkages between EU & India in computing technologies • Favourable policies, mutual interest on international cooperation with a good number of S&T cooperation programmes between both the regions • Existing cooperation mechanism such as bilateral programmes, multilateral programmes with India & EU member states • Capacity of ICT R&D in India is almost on par with EU countries • Existence of ICT NCP support for Framework Programme projects in both regions	• Limited awareness among Indian scientists and R&D organizations regarding EU's Framework Programme opportunities • Inadequate linkages amongst researchers between EU & India • Lack of EC project management skills in India • Lack of participation of Indian R&D organisations in EU computing systems projects • Different levels of research and technological development between both regions • Non-reciprocity of Indian S&T programmes to EU researchers
OPPORTUNITIES	**THREATS**
• Job opportunities between both the regions • Knowledge sharing on Framework Programme project experiences • Planning emphasis in cooperation programmes on future opportunities between both regions • Strengthen of foreign knowledge as well as innovation linkages • Maximising partnerships between both regions will further aid in development of products for world markets • Improve efficiency of public funded R&D and motivate private sector efforts	• Lack of networking programmes between researchers from different disciplines necessary for co-creation in both regions. • Lack of IPR awareness amongst ICT researchers in both regions. • Gap in expectations between EU & Indian researchers • Problems with understanding the difference between research and application areas and activities • Competition with other Indian cooperation programmes such as USA, UK, China

Table 2: SWOT analysis of Indian and European cooperation in ICT research

The SWOT analysis outlines many factors that should be considered in preparation of further joint initiatives in computing systems research between India and Europe.

8 Conclusions

The number and complexity of the research challenges shared by Europe and India provides a clear indication that both regions could substantially benefit from a more collaborative approach to government funded computing systems research. The opportunity for a coordinated effort in computing systems research has perhaps never been greater as both Europe and India are each in the very early stages of implementing new multiyear programmes for funding technology research, are seeing new opportunities to benefit from the changing landscape of computing technologies, and each have referenced the importance of international collaboration as part of their multiyear funding strategies. These new circumstances bode well for being able to establish a genuine joint effort between Europe and India in addressing computing systems research technologies that are strategic to each region.

The EU-INCOOP partners have identified seven areas of shared interests in computing systems research that would substantially benefit Europe and India and are aligned with the strategies of the government funding programmes established in each region. Within each area the EU-INCOOP project has indicated several specific technology topics for collaborative research. The technological and scientific challenges identified are substantial and the resources required to address all of the shared challenges would likely far exceed the combined funding resources that could potentially be allocated for joint initiatives by the two regions.

In view of these limitations, the next steps to be carried out by the EU-INCOOP project are to further prioritise the research challenges in continued collaboration with experts from both India and Europe. The results of this further focusing will be the preparation of a joint Research Roadmap for Europe and India, which will be published at the end of the EU-INCOOP project.

9 References

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- “A Strategic Agenda for European Leadership in Supercomputing” – IDC Special Study
- “A Strategy for Research and Innovation through High Performance Computing” – European Commission funded PlanetHPC Project.
- “ARTEMIS Strategic Research Agenda 2011” – ARTEMIS Industry Association
- “Computing Systems: Research Challenges Ahead, The HiPEAC Vision 2011/ 2012” – European Commission funded HiPEAC: Network of Excellence
- “Establishing the Specific Programme Implementing Horizon 2020 - The Framework Programme for Research and Innovation (2014-2020)” – European Commission Council Decision
- “Final report on roadmap and recommendations development” – European Commission funded EESI Project: European Exascale Software Initiative
- “NESSI Research Priorities for the next Framework Programme for Research and Technological Development” – NESSI: the Networked European Software and Service Initiative
- “Position Paper for the 7th Joint Working Group Meeting” – European Commission funded SYNCHRONISER Project: Synchronising the Research Policy Dialogue to the Indian Dimension
- “Software Technologies – The Missing Key Enabling Technology” – ISTAG: Information Society Technologies Advisory Group, Working Group on Software Technologies
- “Technology-Scalable Datacenters” – Report from a Workshop organised by the European Commission on Next-Generation Datacenters
- “Towards a Breakthrough in Software for Advanced Computing Systems” – Report from a Workshop organised by the European Commission in preparation for HORIZON 2020
- “Twelfth Five Year Plan (2012–2017) – Economic Sectors – Volume 2” – Planning Commission, Government of India
- “Twelfth Five Year Plan (2012–2017) – Faster, More Inclusive and Sustainable Growth – Volume I” – Planning Commission, Government of India
- “Working Group Report for the Twelfth Five Year Plan (2012-17)” – Indian Department of Science & Technology