Scientific strategic plan

Human-centered digital world

Multiscale everywhere

Augmented intelligence

Reliable connected world

2018

2019

2021

2022

Inria
inventors for the digital world
1 Inria and its scientific strategy

2 Researching the digital world

Algorithms and Programming
Data Science and Knowledge Engineering
Modeling and Simulation
Optimization and Control
Architecture, Systems and Networks
Security and Confidentiality
Interaction and Multimedia
Artificial Intelligence and Autonomous Systems

3 Societal and Transverse Issues

Questions posed to digital sciences by social expectations

Personal data and privacy
Verifying information
Computer science education for everyone
Sustainability
Transparency and neutrality
Contributing to grand societal challenges involving scientific progress
Health and Well-being
Agronomy
Understanding society
Inria’s approach in contributing to an open digital society

4 Scientific Challenges

Computing tomorrow
Post Moore’s law computer
Ever-running software
Extreme-scale computing for data intensive science
Quantum technologies and algorithms
Augmented intelligence
Trusted co-adaptation of humans and AI-based systems
Data science for everyone
Connected autonomous vehicles

Reliable connected world
Distributed systems without central authority
Formal methods for cyber-physical systems
End-to-end verified cryptographic protocols
Towards a trustworthy Internet of Everything

Multiscale everywhere
Bridging time and space scales
Predictive systems biology
Digitizing energy
Modeling and simulating the environment

Human-centered digital world
Lifelong adaptive interaction with humans
Digital learning for education and training
Improving rehabilitation and autonomy
Integrative computational medicine

An external testimony

5 Inria’s research centers

Bordeaux – Sud-Ouest, Grenoble – Rhône-Alpes,
Lille – Nord Europe, Nancy – Grand Est, Paris,
Rennes – Bretagne Atlantique, Saclay – Île-de-France, Sophia Antipolis – Méditerranée
Inria and its scientific strategy
Inria is the unique French public research organization devoted to digital sciences. It is placed under the dual supervision the ministry in charge of research, and the ministry in charge of industry. Inria's aim is to promote “scientific excellence for technology transfer and society”. In particular, the institute develops a strong policy of partnerships with all sorts of economic and societal players, from startups to medium-sized companies to large corporations, or research and educational institutions.
This document presents the scientific strategy of Inria for the upcoming five-year period.

Previous “strategic plans” of Inria, including the previous one, presented in a single document the strategy of the institute in all domains (science, technology development, industrial transfer, international development etc.) as well as operational aspects for the implementation of these strategies. A recent evolution in the governance of public research institutions has resulted in the creation of an “Objectives and Performance Contract” (in French: COP, for “contrat d’objectifs et de performance”) jointly signed by the institute and its parent ministries, and Inria signed its COP in 2015 for the 2015-2019 period. Since the development and management strategies of the institute are covered in this COP, Inria made the deliberate choice to focus the present document only on questions pertaining to its scientific research. Its purpose is therefore to describe important research directions, to identify important societal expectations that impact our scientific activities, and finally to present a set of challenges taken up by Inria in the next five years. Naturally, and through its many contacts with industry, Inria is always taking in and embracing the evolving needs of the economy. The present document has been discussed with the many industrial partners of Inria to ensure that their scientific expectations are well covered, but it does not attempt to provide a roadmap for technological developments or industry priorities.

Inria’s research covers most aspects of digital sciences, with around 180 project-teams each having a well-defined focus and a multi-year scientific roadmap, as well as specific application areas and partnerships. These project-teams are created after a thorough review process involving Inria’s management as well as international experts, in order to assess the relevance of the scientific objectives, the positioning within Inria’s portfolio of activities, the perspectives of impact and transfer (be it industrial or societal), and the adequacy of the proposed set of team members. As part of its scientific strategy, Inria is therefore committed to helping each of these teams to progress towards its objectives. We begin this document with an overview of the current promising research directions existing in our project-teams portfolio across the fields of digital sciences, and declare an ambition to support research on all these topics.

However, looking beyond the advancement of science in computer science and mathematics, we also aim to connect our activities to the evolutions of society: firstly in terms of applications and scientific challenges for other sciences, secondly by promoting an integrated reflection about societal transformations brought by our disciplines in our research teams. A section of the document therefore reviews a number of timely questions and issues raised by society or external environments, and that have to be addressed in Inria’s positioning.

Finally, Inria has selected a number of scientific challenges for the period: these are typically expressed as specific directions in which the institute declares its ambition to make progress, generally by combining competences in several topics. These challenges have been selected after extensive discussion in the Inria research centers and project-teams, and have been presented to, and discussed with, Inria’s academic and industrial partners. They are therefore endorsed collectively at all levels of the institute. The second element of Inria’s scientific strategy consists in taking up these scientific challenges as a guide in the evolution of our research project-teams and their activities.

Researching the digital world
Most aspects of our society are already deeply impacted by the digital evolution, and will be even more transformed in the near future. Simply consider a few of the main challenges lying ahead of us, and how they call for digital sciences:

<table>
<thead>
<tr>
<th>Domain</th>
<th>Challenge</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HEALTH</strong></td>
<td>aging population and health systems organizations; personalized medicine based on data analysis; drug design; etc.,</td>
</tr>
<tr>
<td><strong>ENERGY</strong></td>
<td>optimizing available energy sources, controlling the energy footprint of digital tools,</td>
</tr>
<tr>
<td><strong>SECURITY AND RESILIENCE</strong></td>
<td>building safe and robust infrastructures and mechanisms while respecting individual rights and privacy,</td>
</tr>
<tr>
<td><strong>ENVIRONMENT</strong></td>
<td>understanding the evolution of our environment through the complex interplay of phenomena, in order to limit negative impacts and promote sustainable activities,</td>
</tr>
<tr>
<td><strong>CLIMATE</strong></td>
<td>understanding and controlling the impact of human activities on climate change,</td>
</tr>
<tr>
<td><strong>TRANSPORTATION</strong></td>
<td>providing accessible, efficient, safe and sustainable solutions for all transportation needs and scales,</td>
</tr>
<tr>
<td><strong>CULTURE AND ENTERTAINMENT</strong></td>
<td>new forms of arts creation and sharing, media evolution,</td>
</tr>
<tr>
<td><strong>ECONOMY</strong></td>
<td>transformation of industry and services with extreme personalization and flexibility, new economic models based on intermediation and collaboration,</td>
</tr>
<tr>
<td><strong>FINANCE</strong></td>
<td>risk modeling and control, for quantifying and regulating purposes,</td>
</tr>
<tr>
<td><strong>FOOD AND AGRICULTURE</strong></td>
<td>quality, efficiency and traceability of food production for the planet,</td>
</tr>
</tbody>
</table>
Clearly, expectations are exceptionally high on digital sciences to provide new visions and solutions in all these domains. Inria promotes scientific excellence for technology transfer and society, therefore explicitly incorporating in its mission the desire to have a sizable impact on the real world.

Inria’s approach is to combine simultaneously two endeavors: understanding the world, the issues and the systems, and acting on them by providing numerical models, algorithms, software, technologies and solutions. This involves developing a precise description, for instance formal or learned from data, adequate tools to reason about it or manipulate it, as well as proposing innovative and effective solutions.

This vision has developed over the 50 years of existence of the institute, favored by an organization that does not separate theory from practice, or mathematics from computer science, but rather brings together the required expertise in established research teams, on the basis of focused research projects.

Identifying the major research issues for digital sciences

The notion of “digital sciences” is not uniquely defined, but we can approach it through the dual goal outlined above, to understand the world and then act on it. The development of “computational thinking” requires the ability to define, organize and manipulate the elements at the core of digital sciences: Models, Data, and Languages. The development of techniques and solutions for the digital world calls for research in a variety of domains, typically mixing mathematical models, algorithmic advances and systems.

Therefore, we identify the following branches in the research relevant for Inria:

- Algorithms and programming,
- Data science and knowledge engineering,
- Modeling and simulation,
- Optimization and control,
- Architectures, systems and networks,
- Security and confidentiality,
- Interaction and multimedia,
- Artificial intelligence and autonomous systems.

As any classification, this presentation is partly arbitrary, and does not expose the many interactions between topics. For instance, network studies also involve novel algorithm developments, and artificial intelligence is very transverse in nature, with strong links to data science.

Clearly, each of these branches is a very active area of research today. Inria has invested in these topics by creating dedicated project-teams and building strong expertise in many of these domains. Each of these directions is considered important for the institute. The scientific challenges listed in Section 4, as well as the interactions with industry, will act as opportunities to orient or focus some of these activities, as well as creating synergies across domains.
The ever-increasing impact of computers, ubiquitous networking, and massive storage capabilities, makes it ever more crucial to develop our understanding of algorithms and their complexity.

For algorithms, many questions arise, of combinatorial, geometric or topological nature, and attention must be paid to the incursion of uncertainties in the data and the computation processes. Representations (e.g. geometric) evolve towards high dimensionality, as triggered by the emergence of big-data, but clever algorithms should recognize opportunities to reduce the required computations, either by adapting precision or by detecting lower-dimensional patterns.

New forms of computation are emerging, stemming either from physics with quantum computing or from biology, e.g. with DNA computing. These new technologies create new research avenues, either for understanding their potential impact when the complexity of computation is crucial (as is the case for quantum computing in cryptology or optimization applications) or for understanding what new computing applications can be invented (as is the case for DNA computing).

Research in algorithms is needed to adapt to new questions in the design of massive computers, pertaining to the localization of computation in multi-core systems, energy savings, adapting precision to avoid extraneous computations, etc.

A central aspect of all this research on algorithms is the question of algorithms for algebraic computation, which will have an impact for geometry, cryptography, robotics, number theory, or high-precision numerical computation.

Computers in large numbers and in all compartments of human activity also challenge our capacity to make them do exactly what we expect.

For several decades already, we have advocated tools that help verifying that the programs are correct and trustworthy, either by analyzing their behavior abstractly, or by performing proofs whose consistency can be checked. Future investigations will focus on designing languages that are adapted to this proof activity, making it efficient for large formally verified libraries (in domains such as numerical computations in mathematics, robotics, or cryptography) and for complex systems (such as autonomous vehicles, compilers, online commerce networks etc.).

The integration of computer- and network-intensive systems in our society, where structures and social habits undergo constant change, also raises more questions concerning software engineering. The objective is to build complex systems by integrating multiple components, supporting a long-lasting lifetime (several decades) following constant changes in requirements and technology, and constructing systems that provide continuous service without interruption in spite of service evolution. Computer technologies can also be adopted in many and various aspects of human activities, thanks to domain-specific languages, which help capitalize knowledge concerning each activity and disseminate best practices. Research is needed on efficient approaches for the design of such domain-specific languages.

Computers in large numbers and in all compartments of human activity also challenge our capacity to make them do exactly what we expect.
Data, taken here in a broad sense ranging from raw data to information to knowledge, has always been at the core of computer science.

As a research field, data processing witnesses a tight collaboration between academic research and industry, and a perpetual renewal of research topics, together with a cross-fertilization with other areas in computer science and mathematics: programming languages (object databases), distributed computing (concurrency control), verification (data-centric workflows), mathematical logic (dependency theory), probability theory (imprecise data), AI at large, including e.g., knowledge representation (semantic web), and statistics and statistical machine learning (from data mining to big data).

New issues arise today from extreme applications with large-scale distribution of massive data (aka big data), with the challenges posed by poorly-structured and imprecise data (e.g., text, tweets, commercial web sites, ads), though balanced by the advent of large-scale computing (from grid/cloud computing to GPUs) and ad hoc approaches for data analysis and machine learning. This leads to a variety of “big data” scenarios: for the semantic web; for scientific applications; for data integration, visualization, and analysis...

Noisy, incomplete, or inconsistent data can be tackled using probabilistic approaches, calling upon statistical methods to unveil the most likely data (e.g., recommendation systems, community discovery, and leader identification). But ethics comes into play when the «noise» is adversarial, calling upon fact-checking to identify fake-news or biased/opaque/disloyal web services.
Data visualization, whether for manipulation or exploration, faces new challenges due to the size of data but also to their highly complex or, on the contrary, poor underlying structure.

Data visualization, whether for manipulation or exploration, faces new challenges due to the size of data but also to their highly complex or, on the contrary, poor underlying structure. New tools have to be designed to discover the hidden structures. In this context, data mining and symbolic machine learning are being revisited to exploit human knowledge, or properties of underlying substrates carrying the data (e.g., networks or graphs).

The gap between such symbolic approaches and more traditional statistical methods is slowly being filled, as on the other hand, new statistical inferences and models are proposed to tackle large heterogeneous complex data. Beyond discriminative models, generative models pave the way to new applications, exploring the data distribution rather than simply deciding if a data point belongs to a given cluster, thus being more robust in front of huge data spaces.

Machine learning methods, agnostic with respect to data type and structure, have also adapted to big data, using kernels to abstract data types, and improving optimization algorithms in both the convex and non-convex contexts. Deep learning in particular has gradually been recognized as the tool of choice in some application areas where high-capacity models are needed. But the ‘big data’ hegemony should not hide the radically different challenges posed by ‘small data’, when only few examples are available in complex spaces of very high dimensions, as is the case for many applications in Social Sciences and Humanities, or industrial scenarios such as predictive maintenance.
Mathematical modeling and simulation are not only unavoidable paths to better understand the world’s complexity: they also provide us with fantastically efficient forecasting tools. Numerical simulations are very helpful to supply a priori information on phenomena that cannot be reproduced in laboratory experiments. While digital models are increasingly used to help in decision-making (e.g. in government), scientists from all disciplines also rely on them to understand the evolution of complex phenomena, in particular relying on data. Moreover, companies including small and medium-sized enterprises now include the exploitation of numerical software packages in their R&D activities.

These simulations involve combining very different skills including mathematical analysis, digitalization, linear algebra and high-performance computing (HPC).

More and more software packages simulating realistic phenomena that are governed by complex systems of equations have been released in recent years and will continue to be in the future. These simulations involve combining very different skills including mathematical analysis, digitalization, linear algebra and high-performance computing (HPC). This is a considerable challenge that must in particular exploit the tremendous advances in computational architectures. These should be accounted for in the design of numerical schemes — meshless approaches or model reduction techniques are good examples —, so that HPC methods and numerical modeling take advantage of one another.

Nowadays, mathematics along with computer science have greatly improved and are prepared to tackle realistic problems involving coupling and interactions. Examples of recent important developments include numerical medicine and climate studies (including for instance developments used by members of the Intergovernmental Panel on Climate Change), as well as virtual testing in many industrial domains. By addressing environment, energy, transport, health, security issues, etc., researchers impact on major industrial and societal challenges. Hence the need to design mathematical models accounting for the wide range of scales and physics representing the world’s complexity. These large-scale models push the limits of existing numerical methods and require progress in this field.

It is also worth noticing that the next generations of computing architectures are rather complex, progressing to computational platforms in which mathematical algorithms and possibly programming should be reconsidered. Another important aspect is uncertainty that has to be taken into account both for mathematical modeling and simulations: On the one hand, randomness has to be taken into account in the models in order to define the degree of confidence that one is willing to place in a mathematical model, while on the other hand simulations should be combined with statistical methods to quantify simulations accuracy.
The virtuous circle [modeling – simulating/predicting – optimizing – controlling] relies on models of the phenomenon under study. As discussed in the previous section, models for real-world systems have been gradually refined, taking into account more heterogeneous variables, and more interactions or dependencies between different components or subsystems, in order to reach acceptable levels of accuracy (e.g., biological systems, high energy physics, chemical processes, material sciences, environmental models, or systems involving human interactions such as transportation or financial systems). Similarly, artificial systems become more and more complex, involving an ever-increasing number of (heterogeneous) items, e.g., sensor networks, the Web and the internet of things, and power grids.

However, making a model as accurate as possible is not necessarily the best route, an alternative lies in combining a rough model with a robust control law: there is a compromise to be reached between the time spent for modeling (which may tend to infinity) and the expected performance quality (which will stay bounded). Control techniques that were used for small dimension systems (a few loops governed by ODEs) need to be redesigned so as to handle Systems of Systems (SoS), in which systems of different nature (ordinary, distributed, event-based or non-smooth, with delays, involving differential inclusions or high dimensional data) are interconnected. Whatever the size or complexity, there is a clear need for enhancing control capabilities, for instance with stochastic parameters or constraints.

Interdisciplinarity is a key to progress: information theory to handle hyper-connected systems; network science to derive scale-free (i.e., low-complexity) control algorithms for specific systems, such as urban road networks; abstract mathematics (geometry, topology, algebra) as a design language, possibly reinforced by symbolic computation; distributed data management and computing for decentralized real-time decision making.

Along similar lines, optimization techniques also need to scale up, in the dimension of the search space (e.g., the challenge of PDEs comes from their infinite dimension) as well as in the number of objectives and constraints. Traditional numerical approaches have been complemented at Inria with discrete Operational Research techniques, stochastic optimization, and (meta-)heuristics. Here too, hybridizations with other domains are necessary for further progress, both in the continuous (decomposition-based and model-based optimization), in the discrete and combinatorial settings (e.g., Lagrangian and polyhedral theory, graph theory), and more generally for complex domains (game theory and multi-objective optimization). The choice of the right algorithm, together with its parameters, has also become a research topic on its own.

Making a model as accurate as possible is not necessarily the best route, an alternative lies in combining a rough model with a robust control law.

Another difficulty comes from the uncertainty of the environment in which the system lives (e.g., finance, neuron assemblies, interacting particles, low-cost sensors, biology). Uncertainty handling requires brand-new approaches, be they set-theoretic (parameters and variables described by sets instead of points, used for robust control and estimation) or stochastic (used for prediction and optimization), in turn requiring new optimization and control mechanisms.

More and more research domains involve control and optimization, in diverse fields such as the emerging quantum technologies, fluid mechanics and complex mechanical structures, energy management, transportation, aerospace, defense, and robotics. Among those,
biological and health applications are gaining momentum, and possess most of the characteristics described above in terms of size, connectivity, and complexity. Control theory is pivotal to e.g. understanding the dynamic behavior of intracellular networks and to guiding their optimal control and experimental design for biotechnological or medical purposes. These efforts have extended to the control of ecosystems, the optimization of biological programs to control pathogens and pest invasions, and optimization to understand molecular structure-function relationships in structural biology, or genome rearrangements in molecular evolution.

→

Architecture, Systems and Networks

The digital ecosystem is constantly evolving and growing both in size and heterogeneity with billions of individual devices. This evolution leads to new challenges involving a strong convergence between the architecture, system and network research domains.

The spectacular increase in the use of digital objects and platforms is changing the way infrastructures are designed. From huge centralized data centers located in few locations, the future will see the spread of highly distributed and heterogeneous platforms. These novel architectures will integrate both small objects (smartphones, tablets, connected objects) and medium to large-scale data centers interconnected by networks. This will favor the evolution of current cloud computing infrastructures towards a massively distributed federation of small and heterogeneous data centers placed at the edge of network backbones, called Fog/Edge Computing. Reducing electricity consumption is also a priority to deploy such cloud infrastructures, prompting for the design of new energy models and algorithms.
Operating systems need to adapt to new architectures such as mobile (ad hoc) networks, sensor networks, robot networks, peer-to-peer systems, cloud infrastructures, tiny objects of the Internet of things (IoT) world, and multicore processors. The various constraints of these architectures include resource allocation, management of concurrent access to data, limited energy and storage for small objects. The challenges cover memory management in large-scale multicore architectures, interconnection of small objects, management of dynamicity for large-scale distributed architectures and management of the architectures' virtualization.

Major improvements made in virtualization pave the way for the elasticity paradigm, which refers to the capacity of a system to scale up and down its own resources and adjust them as required. If elasticity can provide more agility in cloud computing, new approaches have to be proposed to identify the proper strategy for making a given system elastic.

The Internet ecosystem will face a denser and denser interconnected environment of communicating machines (sensors, appliances, actuators, robots, and drones). Research challenges include the design of adaptive routing protocols using local information, end-to-end reliability and latency guarantees, the building of “intelligent” devices with storage and processing capabilities and detecting and characterizing users’ behavior in a big data context.
the development of adapted protocols to make them cooperate in an efficient and secure manner, the measurement methods to monitor and predict quality of experience in real time, the strengthening of privacy protection.

Another key aspect of today’s networks is their softwarization combined with virtualization that provides more programmability and flexibility. So, a network operator can offer dedicated and customized services to its customers, and even offer its own network to other customers (network as a service). This business model will allow major over-the-top actors to lead the service sector without managing the network infrastructure. Dynamicity and adaptability in deployment, resource consumption and security have therefore to be addressed through a global approach about resource management. This requires a better abstraction and integration of network resources in virtualized environments as well as knowledge-driven networking.

Security and Confidentiality

Our growingly interconnected world calls for building trust and thus for more research on securing computations, commercial exchanges, and personal data, especially in cryptography and security.

Cryptography offers guarantees such as confidentiality or authenticity. It is also a crucial means to provide protection of our democracies against the growing threats coming from malevolent uses of the web: surveillance, fake news and calls for violence, interference in electoral processes, etc. Computer devices that come into play range from minuscule devices to large computing facilities with formidable computing power. While some cryptographic primitives have been in use for a long time, research also addresses more recent primitives or functionalities which are suited to new constraints such as minimizing the deployment costs, the increasing need for performance, or the ability to withstand the advent of a quantum computer. Well-established primitives also require continued scrutiny by cryptanalysis: newly discovered flaws might make these primitives obsolete so that their replacement becomes urgent. Based on fundamental expertise in mathematics, algorithms, implementation constraints, using approaches such as algebra, number theory, lattices, codes and algebraic curves, this research is crucial to maintain the capacity to provide new cryptographic primitives as needed and to assess their relevance.

Beyond the robustness of cryptographic primitives, questions of security appear in more elaborate systems such as group communication and cloud environments. Additional vulnerabilities may arise from inappropriate information dependencies, or from the misuse of primitives. This calls for an accurate control of the information flow and for end-to-end security analyses, based on precise definitions of systems, adversarial behavior and the kinds of attacks that one should deflect. Mathematical proofs are sought, aiming at quantifying risks and checking whether promised security guarantees are really offered. Formal models and computer-aided analysis and proofs are becoming the norm. Several levels of scrutiny must be envisioned, some levels working on abstract models and some levels relying directly on program verification.

Security analysis and security proofs are made with a model of the attacker, but the attacker does not play with predefined rules.
predefined rules. This model is by essence incomplete as unknown attacks are likely to happen. Besides, complex inter-connected systems are rarely entirely modeled. Therefore, both preventive and reactive security approaches have to be addressed. Preventive security consists in doing the best efforts to eliminate all sources of security holes in the protocols and their implementations, as well as in the different components of the global system. Reactive security makes the assumption that the attacker may still find a breach to bypass security guards and thus monitors the networks and systems to detect intrusions or malware as early as possible, and respond appropriately. Since cybersecurity attacks may propagate extremely fast, the initial response should be automated, in order to deploy the appropriate countermeasures at the right time, making sure that the cure is not worse than the disease. The attacker and defender play a cat-and-mouse game, which forces them to continuously learn new techniques. This challenging research combines traditional approaches based on formal methods with new approaches based on statistical analysis, data mining, and machine learning, which are needed to explore the large amounts of security data for suspicious patterns and for the orchestration of countermeasures. This research may require performing experiments in confined environments, where malware can be collected, studied while operating, and where countermeasures can be tested. Inria has set up “high-security laboratories” for this purpose.

Web applications are exploding, while new applications and services are emerging in mobile and Internet-of-Things (IoT) contexts, considerably increasing the attack surface and creating a growing number of security problems. We observe violations of users’ privacy as they browse the Web, use mobile apps, and deploy IoT artifacts exposing personal data. Tracking data and controlling its usage through associated permissions is a promising direction. Inria has been tackling these problems through large-scale measurements, user-centered studies, and verification of Web, mobile and IoT applications. This research requires trans-disciplinary efforts, from designing languages for safer development of security policies and concurrent security-aware programs.

→

**Interaction and Multimedia**

Audio and visual sensors are now everywhere, with the increasing availability of more powerful vision sensors such as high dynamic range and 3D panoramic devices. In fact, it is hard to imagine a discipline in society not affected by digitally sensed data, be it medicine, assisted living, games including serious games, environmental modeling, industrial inspection, robotics, efficient communication, cognition, or social media. Depth sensors are also coming into widespread use, as the quest for 3D information is developing. While offering unprecedented opportunities for a deeper understanding of the world around us and for expanding the wealth of interactions with the digital environment, the data captured by pervasive vision sensors is not only large in volume but also overwhelming in many other aspects, e.g., privacy, reliability, need for processing power. Wearable unobtrusive sensors measuring a variety of physiological signals (pulses, skin conductivity, movement and posture) are also developing in telemedicine for health and wellness monitoring, more generally for quantified-self applications e.g. in sports, for safety and personal rehabilitation at home.
Given the very large volumes of high dimensional data produced by new imaging modalities, **compression** for communication and storage is a necessity. The design of data dimensionality reduction methods, of sparse models and compressive sensing techniques are important issues for further progress in this area, involving advances in signal processing, computer vision, image analysis and coding.

Recognizing objects, understanding scenes and behaviors, extracting higher-order semantics from visual data are among the objectives of **image processing** and **computer vision** research. The rapid increase in the amount of visual data is giving momentum to the development of **machine learning** techniques that are taking a considerable importance in computer vision research. One important topic in **audio research** is the separation of different sources of sound captured in complex environments with non-calibrated and non-synchronized sensors. **Augmented reality** technology and applications have become a major topic within the visualization and human computer interface communities. Progress in this field is feeding on advances in both audio analysis and vision-based methods for object localization and 3D modeling. Transparent and better **interaction between people**, including people with disabilities and pervasive digital systems requires exploring novel interaction modalities, novel human-computer interfaces such as brain computer interfaces. Research in interaction and visualization also requires leveraging perceptual psychology and cognitive science to better understand how people perceive information and how to use animation and feedback to their best advantage.

The analysis and interpretation of sensory audio and visual information is still ahead of us with a broad potential impact in science and society.
Within the last two decades, the field of **Natural Language Processing (NLP)** has made dramatic advances on several long-standing problems. Achievements have been fueled by the intensive use of big text data and statistical machine learning. But the continual emergence of **new communication media** (such as online forums and micro-blogging platforms) has created a much wider diversity of text data in terms of domains, languages, and styles. With this diversity comes the need for much deeper linguistic analysis, that also involve recovering structures spanning an entire document or a collection of documents. NLP has to undergo both a paradigm shift towards systems that rely on less human supervision, and a thematic shift towards better modeling for semantic and pragmatic phenomena. This clearly also raises the machine learning objectives to deal with very high-dimensional input (and output) structures.

**Computational techniques** for realistic modeling of physical objects, for animation of models, for enabling data to take part in virtual scenarios while rendering the computing tool invisible in the interaction are central to the research in computer graphics with applications in virtual reality. Biomechanical models compatible with real-time simulation are useful, for example for medical simulation based on augmented reality. Computational techniques for modeling complex shapes, for processing geometry and optimizing structural properties and material consumption, are key enablers of the emerging 3D printing technology turning digital geometric objects into physical artifacts.

→

**Artificial Intelligence and Autonomous Systems**

Artificial Intelligence enjoys today a great popularity, thanks to some highly visible and easily understandable
Researching the digital world

achievements: IBM Watson and Google AlphaGO beating world champions, Siri-like assistants and efficient machine translators, development of autonomous vehicles, to name only a few. This has raised very high, sometimes unrealistic expectations in the public as well as among decision-makers. In addition, different societal risks (from threats on privacy to autonomous lethal weapons, loss of decision control for humans, or job cuts) place an extremely high pressure on AI research. As a consequence, AI is facing today critical scientific challenges regarding scaling up, understandability and explainability, interactions with humans, and, maybe more importantly when considering the acceptation issue, validation and certification by the society.

AI is a transverse domain, impacting many research areas.

AI is a transverse domain, impacting many research areas, although the AI part of the successful realizations is often the visible part of the iceberg. AI has de facto become ubiquitous in the digital world in general, from data-intensive application areas, where knowledge engineering and machine learning have become unavoidable, to model-intensive domains where AI has started to be a complementary approach to first principles. This movement is clearly observed at Inria, as shown in its recently published ‘white paper on AI’.

These aspects of AI research are particularly prominent for autonomous systems, that need to tackle perception, control, planning and decision-making challenges, such as for instance autonomous computing and software bots (often naively called “AIs” in games and other artificial environments). This is even more so for autonomous vehicles and physical robots, that have to meet hard constraints, from mechanical issues to interaction with humans, and, as a consequence, safety.

Research in robotics evolves in the direction of drastic increase in complexity, handling of more dynamic environments, especially human-populated environments, and the necessity to cope more robustly with uncertainty. The increase in complexity stems from larger numbers of degrees of freedom and configurations, either because single robots use more articulations, or because research considers multi-robot systems, larger numbers of sensors, and the target of long-lasting missions. This increase in complexity is well illustrated by two extreme examples. First, soft robots where the number of configurations is infinite, and methods based on finite elements are expected to help tame the computational complexity of modeling and controlling the objects. Second, continually-learning robots, where either they adapt to human-populated environments or they cope with damage in their hardware.

The necessity to handle more dynamic environments rises as autonomous systems are introduced in environments with human people, whether to serve frail people in a medical setting or as a part of autonomous driving on roads. In particular, in order to handle the interaction with humans, there is a need for research providing predictive knowledge of the human behavior, so as to maximize satisfaction, avoid accidents, and improve acceptability. Research also has to consider interruptions and handovers in collaborative tasks between intelligent systems and humans, where systems have to explain their decisions and the current status of the task, as well as being able to understand the input of (non-expert) human beings, together with their feelings, through natural language and non-verbal communication.

Here also, efforts are needed to improve the handling of uncertainties arising from dynamic environments at various levels: at the time of receiving data from sensors, at the time of predicting the behavior of dynamic components of the environment, and at the time of predicting the effect of robotic actions or computer decisions.
Societal and transverse issues
Besides advancing knowledge and technological abilities, the progress on all the issues of the previous section will also facilitate advances in other sciences, societal transformations and new applications. In terms of applications, Inria is committed to working with existing and emerging companies to assist innovation using its research results. In addition, we consider it very important, and part of Inria’s responsibility, to identify the societal evolutions and the many questions they bring to digital sciences, so as to address these questions while the research is being conducted and disseminate the results in society. In most cases, the questions mentioned below will be opportunities for Inria researchers to work with other partners (e.g. researchers from other fields, social scientists and economists, philosophers and legal scientists, etc). Inria’s aim is to root its research in society and encourage researchers to think about these questions, in an open approach.

We begin this section with a set of questions representing strong expectations of society, associated to its digital transformation, that require careful consideration in Inria’s research. We then present a few challenges that combine major societal issues and scientific challenges, to which Inria is committed to contribute although it cannot claim a leadership role. We then identify several challenges of a more methodological nature, that will impact Inria’s activities and approach.
Questions posed to digital sciences by social expectations

[1] Personal data and privacy

The fact that ever-greater quantities of personal data are collected by various private and public entities is a serious threat to individual rights (privacy breaches, discrimination, etc.) but also to collective rights (manipulation, chilling effect, etc.) and ultimately to democracy (Orwell’s and Huxley’s dystopias).

However, data is also often collected for genuinely valuable purposes. The challenge is therefore to provide the means to analyze the risks and benefits of data processing, as well as tools to reconcile conflicting objectives (when possible) or to restore more balanced relations between citizens and data collectors.

Examples of relevant research on this topic include anonymization techniques (to reconcile big data analysis and personal data protection), peer-to-peer architectures and cryptographic techniques (to reconcile global computation and local control) and explainable AI (to reconcile precise prediction and intelligibility).

To make a real impact on this topic, Inria is committed to work in close collaboration with other disciplines (law, social sciences, political sciences, etc.), policy makers, supervisory authorities and industry.

[2] Verifying information

Our time is characterized by an informational abundance: sources have multiplied, the rate of production of information, often by replication, has accelerated; we are confronted with an information deluge. Inaccuracies, mistakes, and lies are spreading on the web, attempting to manipulate, destabilize public opinion, sometimes with significant negative consequences. With fake news, we are witnessing a weakening of democracy. In response, new open data practices have flourished, as well as fact-checking initiatives sometimes based on crowd sourcing, or data journalism.

Technical solutions must be developed to support journalists and citizens confronted with the considerable task of assessing the quality of the masses of information. Inria will contribute by its research to develop tools notably including data analysis and web monitoring.

[3] Computer science education for everyone

Computer science and the digital world are everywhere, in our cities, our sciences, our private lives... As we had to learn to live in an industrial world in the nineteenth century, we must learn today to live in a universe of algorithms, digital data and networks, learn to master new tools and new uses.

Beyond the scientists and engineers, we must all, without exception, acquire a culture of this new science, and the techniques that were born from it.

Inria therefore has to intensify its science outreach activities and its participation in the education of the entire population. This involves strengthening partnerships with actors on the ground that mesh the territory, and including digital sciences in lifelong learning and professional training curricula.
Sustainability

Today, humanity faces unprecedented challenges. On the environmental front, we have to face the scarcity of resources (water, soil erosion, minerals, etc.) and serious pollution problems (GHG, plastics, persistent organic pollutants, etc.). As illustrated by global warming or the collapse of biodiversity, the impacts are likely to be irreversible and global, and dislocations may be very violent. Via simulations and the multiplication of sensors, digital technologies allow us to better understand these phenomena, to follow their evolutions, and to make predictions. They can improve resource management and help the development of clean technologies. However, the benefits generated by these technologies are still very limited by the “rebound effects”, in which efficiency gains are offset by increased demand.

Moreover, digital technologies themselves generate significant pollution and are currently unsustainable in terms of resources (energy and materials). They are also partly responsible for the explosion of the complexity of the contemporary society (source of inertia and growth of costs) and its acceleration (loss of control, headlong rush). It is fundamental that Inria be committed and has a global vision of these issues.

[5]

Transparency and neutrality

Net neutrality is a very sensitive debated topic concerning the regulation of Internet infrastructures and uses. This concept stipulates that traffic should not be discriminated between different applications, contents or end-user devices. Strengthening a non-discriminatory Internet is very challenging as more and more stakeholders with conflicting goals contribute to provide data and services. Inria’s scientific expertise could help policy makers, governments and other decision-makers, and citizens in general, by giving them a more accurate and reliable basis for decision-making at an individual scale (privacy strategies) or at a collective scale (legal norms).

The transparency of algorithmic systems used by digital platforms is also very crucial. A lot of questions remain unsolved and need to be addressed: what is the origin (resp. destination) of input (resp. output) data? How are the results produced? There is a great imbalance between consumer’s and digital platform’s knowledge; this situation must be redressed.
Contributing to grand societal challenges involving scientific progress

Our society faces a number of global, systemic challenges, such as maintaining the population’s health, feeding the world, setting up stable and harmonious citizenship and government systems… while these issues have been constant challenges throughout history, some of their parameters are greatly amplified by modern-day fast-paced evolutions (rise of the global population, climate change, global economy and digital communications...). Digital sciences will play an important role in confronting these challenges, in terms of simulating and understanding their constituents or their impact, as well as developing models, tools and solutions in cooperation with the relevant parties, and Inria is strongly committed to this effort.

[6]

Health and Well-being

Information and communication technologies have revolutionized the health field, for the benefit of both the healthy and the sick. Needs are as diverse as the recording of physical activities (number of steps taken, heart rate) for the well-being and athletic performances; the management of chronic diseases like the recording of blood sugar levels by diabetics; or the remote surveillance of sick patients through video conferencing consultation and recording of patient information. Electronic health also seeks to achieve social equality, by enabling access to health services and training of the health workforce for remote populations and underserved communities. These novel health-care practices owe a lot to current developments in IoT, big data technologies, and electronic devices - from mobile phone applications to connected objects and surveillance devices for measuring physiological data. Based on its solid expertise in these fields, Inria will pursue and amplify its action alongside its institutional (INSERM, clinical and research hospitals) and industrial partners to contribute to the well-being and health of populations. A key aspect of this research should be a constant attention to the actual benefits brought by the proposed innovations in terms of health issues, both for patients and the public good.

[7]

Agronomy

More than ever agriculture is under pressure to be sustainable while feeding a rising world population. After decades of R&D on increasing yields of crops per acre or conceiving smart tractors, a digital transformation is pervading agronomy to help farmers and industrials making decisions for protecting crops, optimizing operations, increasing yields, and tracing products from the farm to the table. The real-time monitoring and analysis of field-level data through sensors, combined with satellite and weather data, and aerial photography, feed algorithms allowing one to adapt farm processes: e.g. robotization and remote control through the cloud allow efficient irrigation of fields, adjusting to rain conditions. Sensor networks, big data technologies, IoT, and cloud computing are hence at the forefront of this revolution. With its expertise in these domains, Inria has committed itself to stand up with its institutional partners in agronomy (INRA, CIRAD, IRD, and IRSTEA) to help them face the major challenges of a responsible and sustainable agriculture. Clearly, these issues are also related to major environmental challenges (decline of insect populations) as well as societal challenges (models of agricultural value chain with an emphasis on stable farmer income).
Understanding society

The humanities are significantly impacted by digital sciences, enabling one to reconsider long-studied topics and defining new ones. In sociology, economics, geography or history, the tedious gathering of data is substituted by large-scale open-ended information retrieval from the wealth of digitized documents. On the other hand, new topics, behaviors or phenomena (bitcoin, social networks, ...) are readily observable and allow for large-scale natural experiments.

While data mining and information retrieval can provide many answers from large corpora, not all answers are new, relevant or interesting for the social/human science researcher. Interdisciplinary work is mandatory to make sense of statistical regularities and to assess conjectures, taking into account available background knowledge or integrating the expert in the loop.

At the crossroad of natural and social phenomena, simulations have the potential to support new policy design. Such simulations should be fed by theories, and refined using data assimilation for a more fine-grained analysis (see e.g., Piketty's simulator of tax policies1). But actual policy design requires more advanced reasoning modes, including "what-if" scenarios and counterfactual hypothesis testing. Considering the utmost toxic impact of such abilities if put in Big Brother's hands, safeguards must be integrated in Computational Humanities.

[9] Ethics

The explosive development of digital sciences and technologies calls for a deep reflection on ethics, both at the individual and collective levels. This process is required in all scientific domains, and much has already been exposed on the philosophy and ethics of science, and how to understand the meaning of our research, the social framework of their development, and the impact of their results. Inria has worked on these topics for the last decade, and created its first operational ethics committee in 2012. In addition, the institute contributes to general reflections on the ethics of digital science and technology, through the ethics committee of the ALLISTENE alliance. Our objective is to work on large-scale issues (such as the responsibility of autonomous systems, or the duality between privacy and surveillance), as well as to accompany researchers on very practical matters such as confronting the ethical issues raised in their research projects.

However, digital advances also impact the existing ethical frameworks: new capabilities such as large-scale computing, big data, machine learning, models of reasoning, modify our investigation capabilities and therefore the very basis of our ethical reflection. Ethics then becomes a research topic for digital sciences: for instance, how can we formally describe the notions of values, dilemmas, conflicts, and ethical reflection? Advances on these difficult topics potentially impact all scientific disciplines and society in general, even though they cannot claim to “solve” ethical considerations that are by nature extremely subtle and complex.
The challenge of reproducible research

Reproducible research (RR) aims at facilitating the exploitation and reuse of research processes and results by advocating the use of computerized procedures and laboratory notebooks, the full disclosure of code and (meta-)data, as well as standardized and well-controlled experimental test beds. It is an essential step of modern science that has become increasingly complex and error-prone.

A challenge lies in the development and the adoption of RR methodologies so that the whole computer science community improves their daily practice. Hopefully, this effort will also impact other domains of science.

Carrying out RR is obviously not a one-size-fits-all effort: teams working in relation with biology or physics have a strong need for ensuring that the software implementing a particular model is numerically correct, can be faithfully compared, understood and is capable of evolving; teams working on distributed infrastructures (HPC, cloud, sensor networks, IoT) have strong needs for open and configurable large scale platforms to faithfully compare competing approaches. These issues will be addressed through the following efforts:

**Dissemination and adoption**

The practice regarding data/software distribution and the use of modern laboratory notebooks allowing researchers to easily integrate notes, code, data or figures, is quite variable. Inria teams will be highly encouraged to systematically use such tools that facilitate the production of reproducible scientific articles. Inria teams already involved in RR will both disseminate the techniques and tools they use or develop and promote good practices through lectures, summer schools, webinars or even MOOCs.

**Powerful laboratory notebooks and mutualized experimental test beds**

Electronic notebooks have started becoming a standard way of addressing reproducibility in computational science and experimental platforms such as Grid5000 allow for conducting experiments with an unprecedented level of control. Yet, these techniques currently come at a high cost in terms of expertise and it is often easier for researchers to have their own custom (but limited) test bed or methodology. Lowering the adoption cost of mutualized test beds and notebooks for newcomers is thus a priority. Furthermore, the combination of RR tools with complex experimental or computational infrastructures remains very cumbersome, which calls for better integration and ultimately for the convergence of experimental test beds in terms of software infrastructure and practice (security, account management, isolation, ...).

**Preserving and exploiting software/data**

The advent of huge repositories such as Software Heritage or of large sources of information that result from open laboratory notebooks lead to radically novel questions about software (e.g., error detection or correction propagation) and research (e.g., scope extension or meta-studies). The exploitation of such repositories raises many technical, algorithmic and semantic challenges.
“The first appearance of the term “reproducible research” in a scholarly publication goes back to 1992 (J. Claerbout at the meeting of the Society of Exploration Geophysics). But the goals set 25 years ago are still unmet. Now that the top scientific institutions around the world recognize the issue as urgent, research communities must work together to establish standards, tools, workflows, and educational needs. The impact of such concerted efforts will be accelerated progress in science, and enhanced credibility of science findings, both decidedly needed today.”

Lorena Barba (George Washington University)
Inria will approach these issues in the following manners:

→ By encouraging work on complexity as a scientific subject.
Several definitions or descriptions of societal complexity, for instance, have been proposed in humanities and social sciences, such as those by Edgar Morin or Joseph Tainter. How to formalize such notions? How to quantitatively take into account their multidimensional character?

→ By developing digital tools and services aiming for the emergence of new models of collective organization.
For example, complementary to the current vertical and centralized structures, the logic of horizontal governance resonates well with architectures and models (technical and economic) of network-based, peer-to-peer, or cooperative character produced by digital science research. This change of philosophy applies to many other fields of society. It has already started to transform numerous habits, such as in the political field through civic apps and citizen platforms, in economy by intermediation platforms, in manufacturing by fab-labs, etc. What will be the position, relevance, and limits of these new philosophies and tools, relative to the challenges posed by complexity? What risks may they entail? It is indispensable to take into account existing and emerging requirements in order to assess already available tools and to identify their main insufficiencies. More generally, scientific communities have to explain the issues, discuss solutions, and generally influence social debates, especially considering society’s ever-growing dependency on digital technology.

→ By tackling the complexity directly generated by the digital world itself.
Which software development methods and which data formats would enable more flexible, open, and easily usable digital tools and services? How to better take into consideration the final users in their specification and design?

→ By supporting research activities taking into account the different facets of current society in a systemic and transdisciplinary approach, in particular with the humanities and social sciences.
In this perspective, the co-construction of research questions and tools, transversal across scientists, stakeholders and citizens, appears as a structuring element and a challenge in itself. Consequently, the institute will encourage participative science and action research.
The approaches described above will be promoted in Inria’s activities, in an effort to continuously improve the relationship between science and society in the digital domain.

“How do complex socio-environmental systems emerge, evolve and decay? What is the role of unintended consequences of earlier actions in driving a complex socio-environmental system to a tipping point? How to cope with the radical unpredictability of complex systems in a situation in which the acceleration of the digital revolution renders the need for anticipation of potential future more and more urgent. How to improve our insight into such systems? What don’t we know about complex systems, and what don’t we know we don’t know? Those are striking questions for an institute as Inria”.

Prof. Sander van der Leeuw (Santa Fe Institute, Arizona State University).
Scientific challenges
This section presents a set of specific scientific challenges that have been selected by Inria as particularly timely and relevant for the upcoming five years. These challenges were chosen by Inria’s management board, drawing upon a number of proposed topics from various origins: some were identified through Inria’s analysis of its discussions and partnerships with industry, others were suggested by (groups of) project-teams through a large-scale consultation process, and some were suggested directly by Inria’s science department. The selection process involved the entire management board of Inria, and an initial list was refined over the course of several months by an internal discussion with all interested project-teams (leading to a slight evolution in the proposed challenges).
The resulting set of challenges is therefore a collective vision of the institute’s ambition for the upcoming five years: it does not necessarily reflect all of the active or “hot” topics of digital sciences, but rather presents a set of directions in which Inria believes it will contribute to significant progress. This belief is supported by the particular mix of competences brought by Inria: many of these challenges require the combination of advanced mathematics, statistics, computer science tools, systems expertise, and a taste for interdisciplinarity. By combining project-teams specializing in each of these topics, Inria is able to assemble ad hoc expertise. Yet most of these challenges also require a strong interaction with other sciences (physics, earth sciences, biology, medicine, human and social sciences, to name a few), or interested parties (e.g. physicians and clinical researchers in the medical domain, schools and e-education specialists in the education domain, industrial actors for the validation and deployment at real-world scale). The development of interdisciplinary projects is a clear, transverse objective of Inria.

The creation of this scientific strategic plan involved a thorough consultation of our industrial partners of all scales (large corporations, some having a long-term partnership with the institute, smaller companies, and startups). The clear message from economic actors is that they expect Inria to pursue both challenges with immediate industrial applications (think of autonomous vehicles or complex software systems) and challenges with longer-term perspectives that require further research before reaching the market (think of quantum computing). This is entirely consistent with Inria’s choice to present challenges of diverse nature and size, some of them concerning a large set of project-teams in most of our research centers while others involve a small, focused set of project teams together with relevant external partners. All of the challenges presented below have been considered relevant by most of the consulted companies.

We now present our 19 scientific challenges, organized in 5 main themes:

**Computing tomorrow**
1. Post Moore’s law computer
2. Ever-running software
3. Extreme-scale computing for data intensive science
4. Quantum technologies and algorithms

**Augmented intelligence**
5. Trusted co-adaptation of humans and AI-based systems
6. Data science for everyone
7. Connected autonomous vehicles

**Reliable connected world**
8. Distributed systems without central authority
9. Formal methods for cyber-physical systems
10. End-to-end verified cryptographic protocols
11. Towards a trustworthy Internet of Everything

**Multiscale everywhere**
12. Bridging time and space scales
13. Predictive systems biology
14. Digitizing energy
15. Modeling and simulating the environment

**Human-centered digital world**
16. Lifelong adaptive interaction with humans
17. Digital learning for education and training
18. Improving rehabilitation and autonomy
19. Integrative computational medicine
Computing systems have been the invisible (and often ignored) key enablers for all Information and Communication Technologies (ICT) innovations of the past decades. Until recently, computing systems were sitting under a desk or in a machine room. But devices are becoming ubiquitous, from Internet of Things to Cloud computing. More than ever, following this fast pace requires fundamental research on many fronts to advance the state of the art and define the essential computing platforms of tomorrow.

Parallel computing is now mainstream, even for embedded systems. It has re-boosted the interest for research on architectures as well as on techniques to exploit their benefits. Yet, computing systems in the coming years will become considerably more complex and heterogeneous.

Energy consumption has become a key concern for computing systems, yet most processor architectures are optimized for speed rather than energy. High-level programming abstractions necessitate architectural support (e.g., coherent shared memory models) that is again not very energy efficient. Substantial energy savings can be envisioned by revisiting current computing architectures. The time has come for heterogeneous manycores in which processors coexist with specialized energy-efficient hardware.
However, these emerging heterogeneous architectures will only succeed if they offer enough software-level programmability, therefore also requiring new compiler and run-time support.

With the end of Moore’s law, the relative portion of a chip capable of switching at full frequency is diminishing. This “dark silicon” opens new opportunities for integrating hardware accelerators, either static or reconfigurable at runtime. Seamlessly deriving this specialized hardware from high-level software is a major challenge for heterogeneous computing systems.

Moving data requires orders of magnitude more energy than computing. Therefore, moving data closer to their computation is a key issue for energy efficiency. Processing directly in the memory, recalculating to avoid data transfers, or real-time compress-decompress units are very promising approaches.

Moreover, thanks to new non-volatile memory (NVM) technologies, we foresee a kind of universal memory that combines fast random access with non-volatility. Existing programming models, compilers and operating systems are not designed for main memory computation. There is a need to completely redefine the computing stack to take advantage of non-volatility and hide memory latency. NVM is also relevant for next-generation intermittently powered sensor platforms for future low-power internet-of-things devices with infinite lifetime.

Future technologies bring the constraint to deal with more and more transient or permanent hardware errors. Innovative designs are needed, that can intrinsically resist faults or aging. Many traditional or emerging applications are inherently resilient to errors and inexact computations. Computing with approximation provides significant energy gains by trading energy for application quality of results. Choosing the adequate accuracy, at compile or run time, while preserving application functionalities, is therefore a promising, if challenging, approach to improve energy efficiency.

The task of programming itself has to evolve, to cope with the current and future challenges regarding hardware and software complexity. Taking advantage of next-generation platforms is only possible if proper parallelizing, optimizing compilers and run-time environments support them. The software development chain must provide ways of interacting between the programmer, the software and the hardware. Hardware extensions and runtime systems must facilitate the monitoring of software execution, regarding correctness and performance.

The ever-growing dependence of our economy on computing systems also implies that security has become of utmost importance. Protection has a cost in terms of performance and energy and making hardware and software resistant to attacks is a key issue.

“The next generation of computer systems are facing enormous challenges. The computer industry is in the midst of a major shift in how it delivers performance because silicon technologies are reaching many of their power and performance limits. Inria has identified and is in many cases uniquely equipped to tackle many of these challenges in end-user programming, compilers, and computer architecture.”

Kathryn S. McKinley (Microsoft Research)
Ever-running software

Nowadays, typical software systems run in rich and complex environments, leveraging such resources as information systems, distributed services, and various kinds of sensors. These systems range from small to large scale, spanning smart phones, automated buildings, railway systems, and energy distribution systems. In all these contexts, software must run continuously, while maintaining its ability to evolve, thus addressing new needs and requirements, technology changes, and bug fixes. Conversely, when software cannot evolve while running, significant business opportunities can be missed.

Ever-running software systems raise a number of critical challenges across scientific, technological, economical and societal dimensions. These challenges are due to the complex production environments targeted, the mechanisms needed to let software evolve dynamically, and the reliability and security constraints required by such systems.

Because ever-running software systems are bound to disseminate widely in our society, they need to ensure stringent constraints, including scalability, security, privacy, performance, and reliability. To achieve these constraints throughout their lifecycle, research is needed to address the following questions:

- How to express ever-running software systems (specification, programming language, integrated development environments, etc.)?
- How to process their definitions (compilation, verification, instrumentation, etc.)?
- How to run them (monitoring, libraries, runtime support, etc.)?
- How to make them evolve (introspection, runtime code generation, self-adaptation and autonomic computing, reconfiguration control, etc.)?

This research has far-reaching impact. Citizens can be impacted when computing-based, society-wide services are critical and need to evolve. The IT industry can have a competitive advantage to successfully digitalize a range of areas across society and industry sectors.

The nature of ever-running systems requires a new software development lifecycle, to account for continuous runtime evolutions of possibly large-scale systems. Three major breakthroughs are required.

Program analysis

Drastically new analysis approaches should be developed, blending static and dynamic aspects that
1. are non-disruptive (i.e. preserving behavior and minimizing overhead),
2. can handle the relevant languages and runtime supports,
3. scale to high-frequency, monitoring events of realistic systems,
4. provide certification of domain-critical properties.
Infrastructure

Ever-running software requires new generation runtimes (virtual machines, reflective kernels, etc.) that support hot updates. Furthermore, these runtimes should be subjected to feedback loops and regulation techniques from control theory to enforce safety conditions and strive for optimality in QoS or resource management.

Usages

Ever-running software requires a human-in-the-loop approach to supporting evolution operations. This approach entails domain-specific tools to support key tasks, including visualization, decision making, and maintenance.

“To cope with rapidly changing demands, companies need to continuously evolve and realign themselves with the market. Ever-running systems will allow addressing the resulting challenges by producing developable systems that are based on heterogeneous technologies and environments at minimal cost. Customers will be confident that their requirements are addressed while service quality is preserved.”

Nabil Djarallah (R&D and Open Source Exploitation Director at Scalair)
High Performance Computing (HPC) and Data-intensive processing (Big Data) today follow separate approaches: HPC supercomputers gather millions of computing cores aggregated through a dedicated network, and run numerical simulations to address major scientific and engineering challenges. They run highly optimized parallel simulations and performance (compute time, energy) is a major concern. In contrast, Big Data analytics runs in elastic environments built on cost-effective commodity components (Cloud), with the objective to analyze, extract knowledge and make decisions based on huge data corpora. It relies on generic paradigms (Map/Reduce, machine learning) to process large static or streamed datasets, while trading performance for productivity and programming simplicity.

The challenge is to jointly leverage the know-how and existing solutions from both domains to build next generation tools. Performing transversal research is expected to foster the emergence of original solutions to answer the upcoming needs in both domains.

Big Data applications are expected to move towards more compute-intensive algorithms for descriptive (data
aggregation and mining) and predictive (statistics and forecasting) analysis. Prescriptive (decision-making and optimization algorithms) analytics should be added to provide a feedback loop across the full decision-making process.

To process the massive results of HPC numerical simulations or to feed numerical models with complex data produced by other scientific tools, the HPC ecosystem will need to integrate a full-fledged scalable data analytics software component. Many real-life examples arise in industry, for instance when a new physical process must be optimized, by combining:

1. **Data generated from large-scale simulations** requiring exascale computing (e.g. PDEs solved on billions-points meshes in the physical space and thousands of dimensions in the stochastic space),
2. **Experimental observations** from several sensors.

Beyond obvious hardware distinctions, HPC and Cloud/Big Data infrastructures distinguish themselves on two major aspects:

1. **Resource allocation strategies** give exclusive node access to applications (HPC) versus time-sharing through virtualization or multitenant applications (Big Data).
2. **Supercomputers** rely on external dedicated storage while clouds may hold data (replicated) on disks distributed on the compute nodes.

**Breakthroughs** are needed on these two aspects to move toward a unified infrastructure that could support both types of applications as well as hybrid ones. For instance, on-node persistent storage is expected to become more prevalent in both domains with the emergence of non-volatile memory.

Traditional parallel programming achieves high performance but requires a strong expertise. Map/Reduce-based frameworks favor ease of programming through high-level data parallel operators on specific distributed data structures. There is a need to better reconcile accessibility and performance, for instance through task programming or high-performance runtimes supporting dynamic load balancing, elasticity and resilience to cope with hard-to-predict resource availability.

**Data modeling** and **storage** are key components for data-intensive processing in both domains. But simulation data differ in structure and nature from the ones Big Data stacks are designed for. Should we converge towards universal software architectures based on common abstractions, or rather bridge and integrate various specialized abstractions? For instance, on-the-fly data analysis is present in both domains but currently relies on divergent approaches: streaming (Big Data analytics) versus in situ/transit processing (HPC). Inria’s investment and support of flexible test-beds such as Grid’5000, provides a sound base for developing cross domain solutions.

> “Advances in computational methods can create the potential for obtaining data of higher scientific quality from experiments, and conversely, better experimental data can result in advances in the physical models of the simulation codes. On the computation side, accommodating such use cases may require rethinking operational practices at HPC centers. On the data acquisition side, closer collaborative relationships between experimental and computational scientists create the potential for rapid adoption of new methods and practices.”

E. Wes Bethel (Senior Computer Scientist, Lawrence Berkeley National Laboratory)
Quantum technologies and algorithms

We live today a second quantum revolution, which promises to deeply impact our society of information and communication. These developing quantum technologies will profoundly impact our cryptographic protocols, will allow us to simulate large quantum systems to predict material properties, to perform computations for problem size not accessible to classical processors and to improve sensing capabilities beyond what is classically possible.

Here are some of the major challenges:

**Quantum error correction (QEC) and protected qubits**

The major obstacle towards full exploitation of quantum features resides in the short coherence times of quantum systems such as quantum bits. QEC is considered as the major breakthrough needed to remedy this obstacle. Its practical realization remains extremely challenging for three main reasons:

1. **important hardware overhead** for a single protected qubit,
2. **difficult fault-tolerance thresholds,**
3. **presence of correlated error channels** breaking the protection in standard architectures.

**Proposing and realizing applications and algorithms reachable today without requiring full QEC.**

At a hardware level, this boils down to developing quantum control tools that are robust to a certain type and amount of noise. This requires the development of efficient and universal tools for multiple time-scale analysis of open quantum systems to achieve efficient adiabatic or optimal control algorithms. At a software level, we need to propose new computation or simulation problems where a quantum speedup is reachable with a small number (50 to 100) of physical qubits and coherence times achievable with state of art qubits. Progress in this area strongly relies on the development of tractable, yet physically relevant models and numerical methods for simulating many-particle quantum systems, as well as quantum nano-devices with several temporal and spatial scales. This should enable the simulation of different components of a complex quantum computation or sensing device, therefore allowing a more efficient design and optimization process.
As a longer-term challenge, we prepare the society of tomorrow where such quantum machines will be functional at a large scale.

Three main directions are to be explored:
1. **quantum cryptanalysis** analyzing the potential quantum attacks against cryptographic protocols,
2. **systematic methods** for benchmarking the potential speedup provided by quantum machines,
3. **efficient representation and optimization** of quantum algorithms for transition towards implementation.

Relevant approaches include the development and implementation of hardware-efficient QEC protocols, the development and analysis of Low Density Parity Check (LDPC) codes, optimal and adiabatic open-loop control of quantum systems, quantum filtering and feedback, quantum and classical cryptography and cryptanalysis, quantum algorithmics and software, modeling, analysis and simulation of classical and quantum multiscale systems. Existing collaborations with theoretical and experimental physicists will be further extended, in particular in the framework of the upcoming European quantum flagship program.

“Major IT companies such as IBM, Intel, Microsoft, Google in the US and Atos-Bull in France consider quantum information processing as a potentially disruptive technology in HPC and communications. As a result, they develop in-house research and/or strong academic partnerships in this strategic domain where many national initiatives have popped up and a European flagship has been launched. A core mission for Inria, no doubt.”

Daniel Esteve (Head of Quantronics group, CEA Saclay)
Trusted co-adaptation of humans and AI-based systems

Data is everywhere in personal and professional environments. Algorithmic-based treatments and decisions about these data are diffusing in all areas of activity, with huge impacts on our economy and social organization. Transparency and ethics of such algorithmic systems become increasingly important properties for trust and appropriation of digital services. Hence, the development of transparent and accountable-by-design data management and analytics methods, geared towards humans, represents a very challenging priority.
Mastering the accuracy, the reliability and monitoring the behavior of data management and analytics algorithms allows one to build transparent and accountable systems. It makes it possible to address issues such as help in the identification of fake news, enhancing privacy, providing insights for qualifying algorithms’ loyalty and fairness. **Transparent and accountable algorithmic systems** will provide tools for citizen empowerment in the context of the 2016 French *Law for a Digital Republic* with regards to civil rights. Moreover, the objective is to reduce the information asymmetry between digital service providers and digital service consumers, be they citizens or professionals. These properties allow enhancing business-to-consumer trust as well as business-to-business trust. They represent **competitiveness factors** for data-driven innovation.

Several research directions need to be developed toward accountable-by-design data analytics and management. We should develop progressive **user-centric analytics** to allow human control of decision processes using his domain knowledge and know-how. **This will enhance explainability and traceability of algorithmic decisions**, through appropriate expressive specifications and visual representations of the data as well as the analyses performed on them. Online-learning from few examples together with advanced seamless interaction approaches between humans and machines are very promising. **Mastering accuracy through robustness to bias, diversion and corruption fosters trustworthiness of machine learning algorithms.** As data analytics is changing from descriptions of the past to predictive and **prescriptive analytics** for decision support, causal models should be developed to avoid correlation bias. Both data bias and algorithmic bias must be addressed. Furthermore, developing **scalable unsupervised** machine-learning approaches together with **explainable deep learning models** are identified as major challenges in the coming years. Besides, increasing trust in fact-checks requires explicit, verifiable argumentation integrating heterogeneous data sources and explainable reasoning and outputs to facilitate data journalism and society self-awareness. New dynamic information flow monitoring approaches together with **data provenance** and **data usage monitoring methods** will enhance transparency and privacy.

To achieve progress in these research directions, data collections are needed together with real use-cases and evaluation protocols. In this regard, collaborations with third parties providing **exploitable data** are of great interest, in the form of industries, public or civil society organizations, providing domain-knowledge on open-data or proprietary data.

The enlightenment of decision and policy makers with regards to accountable and ethical data management and analytics is among targeted success criteria in addition to the excellence of academic and industrial impact.

“How do our societies want to be calculated? The growing role of algorithms in social life calls for a vigilant and informed audit of their functioning. Due to its expertise in the field, Inria can play a major role in bringing together computer science and social science competencies to conduct those researches”.

Dominique Cardon (Sciences Po/Médialab)
To achieve this ambitious goal, a paradigm shift is required in machine learning and data mining. Currently, most approaches focus on designing a dedicated algorithm for each task: it is necessary to shift to more flexible approaches, that can be used for a variety of problems and evolve with the understanding of the user and the arrival of new data. This requires re-thinking the way models are used in Data Science. Currently each approach has its own fixed model that may yield good results for a given task, but cannot adapt to any other settings. A promising direction is to have representations and models that are learned during the analysis of the data, and adapt their structure through the interactions with the user and the arrival of new data. For example, the analysis may start with a simple model, and as the analysis deepens more complex models are constructed as needed (e.g. non-parametric models). A natural extension of this idea is life-long learning: having a system that is constantly learning and refining its inner models. Being confronted with many different tasks, such a life-long learning system needs to have ways to adapt what it learned for solving a given task in order to solve a new task (transfer learning). Life-long learning of course requires auto-tuning abilities. Such systems will
allow a better cooperation between the human and the computer, by letting the computer handle the tedious tasks of Data Science, and leaving the human focus on higher level tasks such as the formulation of hypotheses and the actual understanding of the results.

These new directions require continued work on scalability, a well-known challenge in Data Science. It will also require investing more efforts on social acceptability of the proposed solutions as in the previous scientific challenge.

“The ability to analyze massive data sets is central to the quest for machine intelligence. But the data science process requires too much expertise and too much labor. Thus it should be facilitated and even automated. Inria is well placed to contribute towards this grand challenge.”

Pr. Luc de Raedt (head of the DTAI group at KU Leuven)
Connected autonomous vehicles

The connected autonomous vehicle (CAV) is quickly emerging as a partial response to the societal challenge of sustainable mobility. The CAV should not be considered alone but as an essential link in the intelligent transport systems (ITS) whose benefits are manifold: improving road transport safety and efficiency, enhancing access to mobility and preserving the environment by reducing greenhouse gas emissions.

Inria aims at contributing to the design of advanced control architectures that ensure safe and secure navigation of CAVs by integrating perception, planning, control, supervision and reliable hardware and software components. The validation and verification of the CAVs through advanced prototyping and in-situ implementation will be carried out in cooperation with relevant industrial partners.

The following issues constitute current scientific challenges:

**Safety and security**

The CAV is a system of systems whose software components will be preponderant in the coming years. Thus, the first challenge is to ensure its safety and security by tackling reliability and fault tolerance, including software optimization and verification, safety by construction, test and validation... Another challenge is the protection of such systems against cyber-attacks in different forms.

**Perception and situation understanding**

Two main hard topics needed to be investigated are advanced fusion schemes involving massive multisensory uncertain asynchronous data, and the elaboration of highly semantic representations with the objective of achieving a perfect scene understanding and interpretation. An important component is to recognize dynamic behaviors from different sensory data and predict possible scenarios.

**Intelligent decision making**

New decision schemes must incorporate:

→ New topics of road users’ behavior models and complex interactions with the CAV (e.g. unsupervised learning techniques and reinforcement deep learning); thus, massive data collection is needed to enable the learning of the models. These data should come from scenarios representing real traffic conditions (big data) or simulations.

→ The validation and creation of models that take into account the integration of CAVs into classical traffic flows

→ Interactions with other road-users. Specifically, data sharing and intelligent HMI’s (Human-Machine Interfaces) will lead to cooperative decision-making such as negotiating crossings, overtaking and priority access.

→ Advanced control sharing between the CAV and the human driver.

**Simulation**

The critical lack of real data, representing various scenarios, sensor data and behaviors, might call for their generation for virtual testing. Therefore, a fundamental challenge lies in the design and development of (co-)simulation tools integrating hardware-in-the-loop approaches. These simulators would feed learning based techniques...
and can be used as a validation tool for upstream certification of system protocols.

**Vehicle communications and networks**

It is important to tackle vehicular communications effectiveness while ensuring **cybersecurity** in two parallel directions:

→ The design of reliable and scalable communication architectures for real time applications
→ Cooperative driving applications integrating the fusion of multi-vehicle/multi-source data, safety critical coordination protocols and cooperative perception/vehicles control.

With recent players in the field coming from the IT sector (e.g. Google, Apple, Intel) the competition with Original Equipment Manufacturers (OEM), transport operators and Tier 1 automotive suppliers has risen, and the value is being reshuffled across the value chains. Addressing efficiently the CAV challenge requires partnerships with all these stakeholders as well as with the public authorities: those in relation with **legal framework** administration and those wishing to promote the implementation of intelligent mobility solutions.

“This is a perfect overview of the open scientific and technical challenges for the CAV. AI will drive the future of Autonomous Driving which will reshape future mobility. Inria will certainly play a leading part in these major breakthroughs, combining human factors, sciences and technologies in a new ecosystem”

Jean-François Sencerin
(Autonomous Vehicle Program Director, RENAULT)
Recent technological improvements support the hope that it will become possible to manage and share information in an open, transparent and dependable way, under the users’ control. This has a high disruptive potential.

Following the peer-to-peer (P2P) expansion and cloud computing lock-in by monopolies, blockchain technologies are making enthusiastic headlines in tech and industry news. A blockchain is an immutable, unfalsifiable public ledger, used in particular in the Bitcoin crypto currency. The technology is promising but immature. Blockchains mix elements of decentralized systems and cryptographic protocols. Furthermore, extensions, such as “smart contracts” that turn blockchain into an open software platform for legal and financial commitments, are not well understood and raise completely novel challenges.

To gain adoption, there are pressing issues in many domains: formalization, security (integrity, confidentiality, proofs, opposability), quality of service (bandwidth, latency, robustness, dependability), and governance (evolution, neutrality).
A variety of security properties are attributed to blockchains: ledger capability, timestamping, trust platform, “unstoppable computer”, etc. These need to be formalized so that one can build **safer high-level protocols**. The blockchain properties need to be decomposed into basic blocks such as mining, consensus, identity, and incentives. This work of clarification and formalization is already underway in the academic world, in order to measure the trustworthiness of various blockchain applications.

Protocol improvements are required. Consensus by proof-of-work, as used in BitCoin, is inefficient by design and has high external (ecological) cost due to heavy resource consumption. Many applications will benefit from a lighter-weight decentralized consensus mechanism.

**Cryptographic methods** already support publicly recording confidential yet verifiable information. Issues of bandwidths, reactivity, and availability will be handled with concepts and tools of distributed systems (causality, concurrency, monotonicity, etc). Domain-specific languages and proof tools (e.g. for the soundness of contracts) should be developed. This will increase the security, performance, and legal weight of blockchains.

In addition, without traditional central security procedures, data protection and sharing mechanisms must be fully reconsidered.

**Neutrality and governance** are tied to blockchain technology and to economic, social and legal domains. For instance, one can build fully distributed on-line identities that rely on no central third party. This decentralization relies on a mix of economic incentives and "ideological commitments" (e.g. by fear of a central authority), and impacts the governance of the platform. In open blockchains (e.g., decentralized cryptocurrencies), understanding and designing effective trust mechanisms and economic rewards to drive adoption and decentralization requires collaborations with the **social sciences**.

France hosts an active and enthusiastic community on these topics. The subject brings hope for new social and business forms and is a concern for a variety of actors in public affairs. Industry is already running in-house experiments, and many start-ups propose ingenious use-cases. Yet, this broader group of stakeholders often lacks scientific background and ethos, and, with some notable exceptions remains unaware of academic research. A natural mission for Inria is to serve as a **“scientific accelerator”** and help this community become more rigorous in their designs and to keep them abreast of new developments.

> “Trust is an overwhelming issue, embodied in the concept of Legal Certainty. There is no such thing for blockchains today because there are many risks concerning their algorithms and their governance.”

Célia Zolynski (Professor of Private Law at UVSQ, member of the French Digital Council, an independent expert group)
To meet the challenge of certifying software-intensive systems and CPS it is essential to improve on the foundations and interconnection of tools and formalisms for interactive and automated program verification such as Coq, Why3, F*, TLA+, as well as various static analyzers, such as Astrée. The automation and the expressivity of these tools must be improved so that they can scale to the verification of larger software systems, and certify both qualitative and quantitative properties.

The challenge of building a safe, efficient and secure CPS requires progress in the areas of semantic formalisms, programming paradigms, and modeling and verification techniques for hybrid and embedded systems. A particular focus should be put on the formalization and verification techniques for hybrid systems’ modeling languages that mix discrete-time and continuous-time dynamics. This part of the challenge will also involve novel certification efforts in areas of mathematics that so far have received less attention. This concerns both hybrid (continuous/discrete) system models for CPS and software for advanced numerical computations.
An essential part of the challenge of building safe and secure CPS concerns the certification of the underlying software infrastructures and operating systems (with recent significant progress on the latter). On the resource-constrained devices found in the internet of things, the challenge is to build on the certified OS platform to certify properties not only of qualitative nature (absence of runtime errors, protection of confidential and private information, resilience against attacks) but also of quantitative nature, pertaining to use of resources such as time and energy. Efficient, certified cryptographic primitives for resource-constrained devices constitute another important part of such an infrastructure.

“Inria has been a precursor in the development of formal methods, showing that theoretical research can lead to practical tools. Coq is a fine example of software that has given a competitive edge to French industry in the software certification sector. At Prove & Run, we develop and employ formal methods for developing critical software such as our formally proven OS kernel, ProvenCore. The proposed challenge in cyber-physical systems is of prime interest to our business development.”

Dominique Bolignano (CEO and founder, Prove & Run)
End-to-end verified cryptographic protocols

Security of online communications is in particular ensured by cryptographic protocols: these protocols are distributed programs that use cryptography to guarantee confidentiality or authenticity of communications. However, their correct design and implementation is extremely tricky, as the overall security relies on the security of the weakest link: errors may occur in the protocol logic (which is complicated due to the distributed nature of these programs), in the underlying cryptography and, last but not least, in their implementation. There have been numerous examples of subtle bugs that may lead to security failures. For example, the Transport Layer Security (TLS) protocol, the most widely used protocol to secure transactions on the web, has been subject to many vulnerabilities: the Heartbleed attack, due to a memory overflow in the popular OpenSSL implementation, allows an attacker to read parts of the server’s memory; the Logjam and FREAK attacks allow a man-in-the-middle attacker to downgrade the cryptography to use weak keys. As a result of the Snowden reports there is now an increasing demand from the public for providing solid security guarantees on cryptographic protocols and from
protocol designers and developers to provide better techniques for developing secure implementations.

Rather than just discovering and fixing bugs one at a time (which is difficult and costly) we propose using computer-aided, formal security proofs, that allow one to avoid entire classes of vulnerabilities. The challenge is to provide proofs that take into account all aspects of the protocol, including implementation details of real-world cryptographic protocols. This will allow us to state precise security theorems based on well-understood cryptographic assumptions directly on implementations. This approach contrasts with most existing ones that only analyze protocol specifications, properties of cryptographic primitives without considering the particular context they are used in, or particular aspects of the implementation. The feasibility of the proposed approach has been demonstrated in the miTLS project, a joint project between Inria and Microsoft Research, that resulted in a completely proven, interoperable reference implementation of the current version 1.2 of TLS.

However, the approach used for miTLS does not carry over to existing implementations, as it requires code to be carefully written and annotated, which is difficult for non-experts in formal verification. Our goal is to provide the means for end-to-end proven reference implementations for many more protocols. The forthcoming TLS 1.3 protocol is a natural target but by no means the only one: protocols such as Signal underlying secure messaging applications, single-sign-on protocols, a fully verified electronic voting protocol as well as protocols deployed for the internet of things constitute other targets. Some of these applications may require developing new cryptographic primitives and their security definitions, e.g. lightweight cryptography for protocols running in constrained environments. Another challenge will be to implement cryptography that provides guarantees against side-channel attacks without an unacceptable performance decrease. At the moment where many new implementations are developed, we aim at widely usable proof techniques: a promising approach is to identify fragments of widely used programming languages and strict programming disciplines that could be adopted by developers and that will simplify proofs. Another direction is to combine existing tools and techniques that are specialized to particular aspects (e.g., the protocol logic or security proofs of cryptographic primitives) in order to form a complete tool chain.

“Securing Internet communications is a vast subject, spanning from specification validation all the way down to secure implementations, while taking the ecosystem into account. A lot of work has already been done about SSL/TLS by Inria: cryptographic and protocol attacks, verified implementation, participation to the IETF working group concerning TLS 1.3. For the following steps, the comprehensive approach proposed in this challenge is required to get lasting results. This challenge will improve the cryptographic protocols we use every day, and serve as a building block towards robust network stacks and towards a more secure Internet.”

Olivier Levillain (Head of cybersecurity training center at ANSSI)
Towards a trustworthy Internet of Everything

Today’s Internet — data, services, and people — paves the way to tomorrow’s internet of things (IoT), also known as the internet of everything (IoE). “Things” in this context include both high-end smart objects (e.g. a smart phone, a RaspberryPi processor) and low-end IoT devices (e.g. microcontrollers with sensors, actuators). “Things” are interconnected using various wired and wireless communication technologies. Leveraging Internet-scale ubiquitous instrumentation and interconnection, IoT is expected to reshape not only user-machine interaction but also machine-to-machine communication. Challenges ahead regarding IoT access networks include: developing secure, energy- and resource-efficient, certified, reconfigurable & maintainable IoT software and protocols; operating systems and architectures; managing heterogeneity spanning all IoT layers for technologies and semantics; understanding of people’s behavior that appears as a power-player to the future of IoE.

IoT’s societal impact stems from the capacity of IoT applications to inform, automate, and transform. On the one hand, IoT will improve operational efficiency in a very broad sense: enhanced situational awareness, sensor-driven decision analytics, optimized resource consumption, and control loops in complex autonomous systems. But all of these benefits come with new risks. IoT will also exacerbate challenges concerning security, safety and privacy. Neither industry nor end-users are going to trust IoT unless significant progress is made to guarantee more standard, usable, sustainable, maintainable, safe and secure IoT software and network (meshed, cellular or hybrid). To favor transparency, IoT should enable an open horizontal integration of technologies, applications and data for the stakeholders, instead of the current vertical/silo-ed/vendor lock-in solutions which are the norm today.

Some breakthroughs are linked to IoT network architecture complexity at the edge of Internet. Improving energy and resource efficiency while maintaining quality of service and latency remains a hot topic since it requires managing the following three properties: context-aware sensing coverage and data quality, energy efficiency, and the latency of data dissemination.

A key breakthrough lies in enabling heterogeneous IoT devices to work together: efforts underway aim to create...
Scientific Challenges

open standards and guarantee interoperability at large scale. Another critical issue concerns IoT software security and maintenance. Before massively connecting heterogeneous operational systems to IoT, guarantees on re-programmability and security are needed from the IoT network and software. This requires combining remote, secure software updates with low-end IoT operating system versatility. Other breakthroughs are related to the applications of the IoT, and concern novel solutions (protocols, algorithms, models) better predicting and leveraging human behavior. Finally, IoT applications should be proven/certified at large scales: IoT devices typically feed data to the system through a (local or remote) API. Programming, maintaining and proving the sustainability of an entire networked system for an extended period of time remains a challenge.

This complex challenge will benefit from Inria’s investment in software and hardware platforms (the operating system RIOT, the reference protocol stack implementation OpenWSN, the large-scale experimental platform FIT IoT-LAB). This research effort should contribute to major standardization bodies.

“IoT aims to digitize our surrounding. Catching up every signal from a net rolled out around the earth, will drive to huge amount of data to predict the future. Algorithms will benefit from volume and data diversity, to deliver messages to human in an augmented reality way. Animals feel vibrations of tsunami, we will receive an instant message before it happens!”

Ludovic Le Moan (CEO of Sigfox)
Bridging time and space scales

In many scientific areas, models have been primarily developed in order to understand phenomena at given fixed time and space scales. Nowadays, with the increasing processing power of computers on the one hand, and the development of new mathematical techniques on the other hand, more and more models aim at simulating phenomena at large scales starting from descriptions at small scales. Models at small scales are typically high dimensional and often involve probabilistic features (to model uncertainty or fluctuations of the microscopic state). On the mathematical side, this calls for homogenization, averaging, ergodic limits, boundary layers, invariant manifolds for dynamical systems, mean field models, propagation of chaos, etc. On the modeling side, multiscale techniques have been used in materials science, fluid mechanics, geophysics, life sciences, climate models, agent-based models for traffic, economy or social sciences, etc. As an example, the 2013 Nobel prize in chemistry was awarded jointly to M. Karplus, M. Levitt and A. Warshel “for the development of multiscale models of complex chemical systems.” Bridging the gap between small and large scales requires dedicated new mathematical and numerical tools. The challenge is to design efficient and certified algorithms to handle space and time multiscale
models, based on the rigorous mathematical understanding of change of space and time scales. This is particularly difficult when the slow or coarse variables are not known a priori.

The strong temptation when simulating multiscale models is to rely on increasing computing facilities. Better numerical approaches for such models based on a deeper understanding of their multiscale features would significantly reduce the computational cost and yield reliable error estimates.

Major breakthroughs are needed to extend the state of the art. On the mathematical side, more robust techniques to handle changes of time and space scales are needed, especially for nonlinear, dynamical or stochastic models. In terms of numerical analysis, handling efficiently these models requires to develop seamless model reduction techniques and coupling paradigms: nonlinear approximation methods for high dimensional functions, predictor-corrector schemes, adaptive strategy to couple fine and coarse descriptions. On the algorithmic side, these new models are a great opportunity to develop highly scalable numerical methods well adapted to the new computer architectures. In many cases, efficient massively parallel (in time and space) numerical methods can be devised, leveraging the fact that small units evolve independently on certain (small) time or space scales.

Contributing to the development of functional materials and meta-materials, understanding the biological mechanisms in muscle fibers, developing computational methods for in silico drug design, modeling anomalous transport in biological cells, simulating plasmas submitted to strong magnetic fields, handling the numerous physical phenomena involved in climate modeling: these are a few examples of topics where multiscale and stochastic features have to be properly understood and simulated.

“Space or time scale separations are among the most determining features of natural phenomena around us, and at the basis of uncountable reasonings of mathematical physics. Implementing them robustly and accurately in computational schemes would bear enormous promise.”

Cédric Villani (Director of the Henri Poincaré Institute, Fields Medal 2010)
Predictive systems biology

Many fundamental questions and applications in medicine and biotechnology critically rely on our capacity to understand and manipulate complex cell populations. Prominent application examples include microbiota control, engineered microbial consortia bio-production, heterogeneous tumor treatments, or stem-cell-based tissue developments. Subpopulations involve different species, cell types, or predispositions (genetic, epigenetic, or phenotypic heterogeneity) and share complex relationships among themselves and with their environment. Therefore, one needs effectively to understand living systems made of interrelated cell populations and their environment. However, most knowledge on the functioning of cells at the molecular and cellular levels has been acquired so far on homogeneous cell populations and under tightly regulated growing conditions. Rational approaches and predictive models are then needed to bridge scales: the molecular scale (process of interest), the cellular scale (cell physiology) and the cell population and environment scales (ecosystem). The challenge is therefore to propose mathematical methods and computational tools supporting the development of predictive multiscale models, their parameterization, their analysis, and their use for solving optimization and control problems in realistic biological applications.

Several roadblocks stand in the way of this goal: first, the behavior of the system emerges from the core properties of its individual components (molecules, cells). However, computations are efficient only at population levels (molecular concentrations, cell densities) and abstractions are therefore needed. Since describing and abstracting all the molecular processes happening in a cell is intractable, one might resort to using coarse-grained representations of the cell physiology focusing on capturing essential tradeoffs on cellular resources that are then coupled to more detailed representations of the specific process of interest. These methods should retain essential information, notably the stochastic nature of molecular reactions together with the diversity and inter-relations of cell populations in the consortium. They should also preserve connections across levels. Indeed, one should for example be able to predict the global effect of a specific genetic modification, or conversely, the specific effects of global control actions on each individual cell. Secondly, these models need to be calibrated, analyzed and then used for optimization and control. Unfortunately, existing molecular biology tools provide
limited observation and actuation capabilities on live cells. One should therefore design and build sets of systems that together provide the needed information on the systems dynamics. Theoretical developments, modeling and experimental design should then be tightly connected.

The synchronous development of experimental approaches, models and methods is needed to guarantee the effective integration of theoretical and experimental works. Software development is a key element for the effective dissemination of the proposed methods, since a wide adoption of the methods and tools developed for the design, optimization and control of natural or artificial cellular ecosystems will be an important marker of long-term impact. Finally, ethical and societal questions are particularly important in this research.

“It is difficult to overemphasize the importance of predictive multiscale models of microbial ecosystems. Such models will not only advance our scientific understanding of microbial populations, they will also lead to novel applications in industrial and medical biotechnology”.

Mustafa Khammash (Professor of Control Theory and Systems Biology in the Department of Biosystems Science and Engineering at ETH-Zurich)
Digitizing energy

As worldwide energy consumption keeps growing year after year, it becomes urgent to improve its sustainability and to reduce its impact on the planet. The digitization of the energy sector calls digital sciences to the rescue for optimizing the energy production, distribution, and consumption while increasing the utilization of renewables and designing new energy sources. Meanwhile, the energy consumption of information and communication technologies (ICT) themselves is far from optimal and the vast digitization of most economic sectors weighs heavily in this increasing energy consumption. Thus, although digital sciences offer scientific tools to empower the energy actors to optimize their systems, the use of ICT has a non-negligible energy cost in terms of devices’ production, power supply of the infrastructures (clouds, telecommunication networks, etc.) and software execution.

On the ICT consumption side, the challenge consists in designing metrics and models for stakeholders and end-users, to assess the energy-consumption, efficiency and awareness of infrastructures and applications. Such tools can help in raising the users’ awareness about their energy consumption and could also significantly limit the rebound effects due to the adoption of energy-efficient techniques. Combined with innovative energy-aware approaches, these efforts towards a higher frugality of devices and applications should curb current ICT’s appetite for energy.

On the energy production side, optimizing the processes and predicting their efficiency will favorably impact the global energy management. The role of numerical simulation in the search for new energy sources and the optimization of the energy flows is crucial for an improved sustainability. We also aim at increasing renewable energy integration into the electrical grid, incorporating self-producers, and optimizing systems through adequate distributed and autonomic management algorithms, and suitable pricing systems.

These building blocks will enable the development of analyzer tools for production devices and optimization systems able to evaluate the resources saved through the use of digital sciences and the impacts induced by these smart digital systems. The challenging conception of end-to-end energy cost models, from software components to Internet-scale computing infrastructures, is required for these tools to be profitable to companies and public authorities aiming at the design of smart systems (e.g. smart grids, cities, or buildings).
Achieving these goals requires controlling the energy consumption, from processors to internet-of-things, and to enforce a sustainable digital development. Concretely, it means *fostering the energy efficiency* of our digital consumption patterns and contributing to the design of effective strategies for the energy transition to renewable sources.

“The smart digitization of the energy sector is one of the major challenges of the next decade. Advancing the integration of sustainable energy sources, reducing peak consumption and the carbon footprint through optimization and control, limiting the impacts of ICT applications, devices and infrastructures are some of the research areas where Inria could definitely be a world leader.”

Prof. Catherine Rosenberg (University of Waterloo, Canada)
Modeling and simulating the environment

In the last decade, awareness of the nonlinear increase of global warming and its irreversibility have made environmental changes a crucial societal issue. More than ever, scientists are expected to provide academic, educational, industrial or political stakeholders with the tools needed for learning, forecasting and decision-making so as to preserve the environment. Currently, a truly creative exploration is under way but the challenges faced by scientists are still daunting.
Models and simulation challenges
The scales coming into play in the biosphere evolution extend from milliseconds to millions of years, and from millimeters to tens of thousands of kilometers. Models are highly chaotic and exhibit violent, intermittent, and abrupt events. The strong sensitivity to the initial condition (butterfly effect) requires generating sets of simulations capable of integrating very fine scales. This requires building advanced numerical methods able to scale on high performance computers but also requires the design of new methodological frameworks for the modeling and the analysis of multiscale multi-physics phenomena. Quantifying and modeling uncertainties are also key issues to make reliable predictions, pushing the field towards the paradigm shift of building models from stochastic representations.

Mathematical challenges
Environmental models involving nested and coupled (biological, chemical, and multiphase) processes, including in many cases an anthropogenic forcing, raise strong mathematical questions: existence and uniqueness of solutions, bounds of minimal errors for simplified dynamical systems, system instabilities, ergodicity and existence of stationary distributions, etc. Most of these mathematical challenges are long-term endeavors. A well-known related example concerns the well-posedness of the Navier-Stokes equations (dating back to the middle of the 19th century), which is still crucially missing. More recently, optimal control theory has taken more than 20 years to bring significant improvements to routine weather forecast through the recent concept of data assimilation. Clearly, these fundamental questions strongly impact numerical simulations or data-driven estimation issues and must be forcibly studied.

Data challenges
For several years, the very fast progress of technology has allowed scientists to get access to a huge amount of data depicting fine-scale details of the involved phenomena. These data sequences with a resolution that goes beyond the highest resolution of numerical models advocate the development of data-model coupling strategies (data assimilation) and learning frameworks providing data-driven monitoring systems of extreme events. However, the huge dimension of the data restrains their direct use either in classical inverse problems or for their coupling with dynamical models. Dimensional reduction and multiscale strategies to analyze, visualize and handle those heterogeneous and incomplete data are crucially needed.

“As a member of the parliament, concerned with environmental preservation, I need Inria research to model various scenarios to help environmental decision-making. Running simulations based on the size of a town or a county is crucial for the development of territories on the very long term. In my view, it is by being able to act locally, as close as possible to users, that we will become free citizens!”

Isabelle Attard (PhD in environmental archaeology, former member of French parliament)
Lifelong adaptive interaction with humans

Interactive digital and robotic systems have a great potential to assist people in everyday tasks and environments, with many important societal applications: cobots collaborating with humans in factories; vehicles acquiring large degrees of autonomy; robots and virtual reality systems helping in education... In all these applications, interactive digital and robotic systems are tools that interface the real world (where humans experience physical and social interactions) with the digital space (algorithms, information repositories and virtual worlds). These systems are also sometimes an interface among humans, for example when they constitute mediation tools between learners and teachers in schools, or between groups of people collaborating and interacting on a task. Their physical and tangible dimension is often essential both for the targeted function (which implies physical action) and for their adequate perception and understanding by users.

Several major challenges need to be addressed to enable real-life applications that serve the needs and goals of human users. A key target is to enable lifelong multimodal interactions that adapt to each particular user, and that the user can control and modify skillfully. This involves efficient and reliable perception and understanding of human intentions, cognitive states, emotions and social situations. This requires the development of fast, cheap and reliable sensors, signal processing methods, and artificial intelligence algorithms for the perception and interpretation of human behavior, ranging from low-level non-verbal signals to language. This also involves designing personalized models and simulations of the user and context, to predict their behavior and the effects of the interface on their body and mind. The behavior of these systems should enable users to clearly understand their goals and to learn how to control and use them.

In the long term, users change in capabilities and preferences, while contexts and tasks are modified: For example, robots that assist children or the elderly have to be able to adapt to the physical and cognitive changes of individuals over time. Here, machine learning approaches are needed to adapt models of human behaviors, preferences and tasks: a central technical challenge is to develop techniques for incremental autonomous learning which need minimal
Scientific Challenges

Another approach is to enable end-user modification of interactive systems, with techniques ranging from intuitive visual programming to modular hardware based on 3D printing and Do-It-Yourself methods.

Safety is naturally an important issue, but even more so when physical interaction is involved. A formal approach to define and enforce safety at mechanical, control and software levels is mandatory, and can be particularly intricate in real-life scenarios. Traceability and explainability are key aspects in this regard, which will be required for establishing certification frameworks, to allow these technologies to be deployed and adopted by society. A related challenge is to understand how to design interactive systems compliant with human ethical values, for example in relation to when and how personal data can be accessed.

“Digital interactive assistants are going to play an ever-growing role in our daily life. They will help us, serve us, teach us, but also act as key ambassadors to brands and products in the business realm. The key challenge is to go beyond scripted rigid scenarios, towards grounded and dynamic meaningful interactions that truly understand the user and its cultural background. We have to move beyond traditional machine learning to explore embodiment, emotions and autonomous learning, and there is still an important body of research to conduct on this road”

Jean-Christophe Baillie (CEO, Novaquark)
Educational and learning practices evolve, with the blurring of lines between formal graduate initial education and autonomous lifelong education and training, and the digital transformation of education. A major challenge lies in providing models, paradigms, algorithms, tools, and environments to support the emergence of innovative approaches to learning and teaching. The upcoming new educational designs will, for instance, ensure a fine-tuned adaptation of the learning environment to the users’ cognitive, emotional, behavioral and social profile and the learning context, allow to implement disruptive pedagogy (e.g., using gamification or resources co-construction), enhance the appetite for learning via multi-media contents, and also deploy economical models that preserve the objective of an education for all, even with restrained public budgets.

By improving education modalities, and changing learning paradigms themselves, advances in digital science and technologies should provide effective means against failure at school, thereby democratizing education, renewing higher education, and supporting continued training to access new professions and lifelong training of citizens.

The following issues have to be addressed in order to arrive at a real impact in education:

- the intensive exploitation/reuse of data available on the Web to create learning material. This involves indexing and annotating heterogeneous multimedia resources to integrate them, retrieve them, combine them and reason on them;
- the learners’ ability to reflect and monitor their own learning. This involves learning analytics and data visualizations and also includes modeling and improvement of new evaluation paradigms (e.g. peer-to-peer evaluation);
- the adaptation of learning material and learning paths to user needs. This involves analyzing learner’s behavior and interaction traces and modeling learner profile and context, by developing machine learning approaches, while preserving privacy;
- human computer interactions within the learning environment adapted to the learning objects as well as to the user’s profile: as the case may be, tangible interactions, virtual reality, 3D interaction, brain-computer interaction.
To meet the challenge, real-world use cases, pedagogical resources and learning traces are needed. This requires collaborations with universities, schools, and companies specialized in e-Education. Additionally, close collaborations with researchers in Education Sciences, teachers, and pedagogical engineers will be required from the early stage of development to evaluate the proposed models, techniques and "proofs-of-concept" and to analyze their impact in terms of learning improvement.

Inria has a longstanding involvement in the domains of knowledge representation and reasoning, machine learning, multimedia, natural language processing, human-computer interaction, virtual reality and robotics, and also in science outreach, and has recently established a "learning lab". The production of online courses by Inria yields a real acquired expertise in the field, while making pedagogical resources and learning traces are available for research purposes. Several researchers are involved in actions aiming at sharing computer science principles with teachers or citizens, in relation with science outreach.

“Digital Science is only a means, of course, but it is a means that can change everything. Education, in particular, must change in France, the OECD country in which schools struggle most poorly against social inequalities.”

Jérôme Saltet (cofounder of the Play Bac company)
Improving rehabilitation and autonomy

Digital sciences offer the prospect of a more inclusive society, by proposing innovative solutions dedicated to prognosis, diagnosis, evaluation, assistance and training of people with motor, sensory or cognitive deficiencies, fragilities or disabilities in order to improve their rehabilitation and autonomy.

Research in this field should allow developing and deploying new tools to facilitate the observation and analysis of behaviors in ecological (clinics/home) and mobility situations considering individual specificities. This relies on the ability to propose personalized models, realistic identification protocols and uncertainties integration to manage measurement and modeling errors or individual erratic behavior. It requires wearable devices embedding connected networks of sensors, actuators and software.

Monitoring and assistive technology (software and hardware) should be accessible to the final user via dedicated interfaces or digital worlds providing synthetic indicators and supporting collaborative decisions and assistance with certified solutions ensuring the safety and protection of the individual person as well as its associated data.

Clinical partners are in strong demand for diagnostic and prognostic tools such as neuromarkers, physiological and biomechanical parameters defining patient profiles, identifying future responders to a given rehabilitation strategy and predicting functional recovery.

The challenge lies in the constant integration of recent advances in neuroscience (clinical, cognitive, sensory, motor control), biomechanics, kinesiology and physiology, with informatics, signal processing, automatic control, mathematical modeling, simulation, electrophysiology, biomechanics, virtual reality, physics, human-machine interaction. New pathways should be explored and combined including soft robotics/orthoses, neuroprosthetics, immersive environments, serious games, everyday objects adaptation, internet of things, new communication channels.

Inria also intends to promote intensively these scientific advances, as well as improving the accessibility of its own websites, software and interfaces...therefore making assistive technologies a leverage of social progress through the improvement of users’ autonomy, self-esteem and quality of life.
"The World Health Organization defines disability as a complex phenomenon that reflects the interactions between the physical and mental characteristics of a person and the society in which this person lives. By way of consequence, correcting a disability is also a complex process. It requires treating a physical or mental defect as well as possible, adapting the environment to make it as accessible to the disabled person as it is to all other persons, and implementing societal policies in which disabled people are accepted as integral parts of the society in which they live and function. In the domain of respiratory insufficiency, the correction of the physical defect is a major challenge. Indeed, mechanical ventilation, namely the very treatment that corrects the respiratory physical defect, is in itself a source of disability as it imposes major constraints on the patients and their families. In other words, correcting the respiratory defect with mechanical ventilation does little to improve the disability in its global meaning. The involvement of Inria in advanced research in the field of assistive technologies clearly appears invaluable in the fight against difficult kinds of handicap to make patients less dependent on others and helping them find their place into society."

Prof. Thomas Similowski
(Pneumology and intensive care unit director, Pitie-Salpetriere Hospital)
Modern medicine is turning to highly personalized approaches, and a major challenge is to design and develop a new generation of techniques to assist prevention, diagnosis, prognosis and therapy in medicine and surgery. A major difficulty for mid- and long-term research is the integration and exploitation of heterogeneous data acquired on the patient and on populations. These data include multimodal medical images and signals acquired at varying spatial and temporal scales, biological and genomic measurements (blood tests, -omics data, etc.), clinical and behavioral data coming for various sensors (smart phones, smart clothes, cameras, etc.) as well as detailed information on the environment and lifestyle of the patient during a period which may cover their entire existence (Cf. UK-Biobank including up to 500 000 participants in the UK, Constances data-bank including up to 250 000 adults in France, data from the “France Médecine Génomique” program, etc.).

To develop the new tools of integrated computational medicine, a personalized model of the digital patient must be created. This model has to be versatile enough to integrate multiscale heterogeneous data and to extract clinically useful information. This is possible only through the development of algorithmic, mathematical, biological, physical, chemical and semantic models of the anatomy and physiology of the patient at all available temporal and spatial scales, as well as statistical models at the patient or population scales. One needs to design personalization algorithms taking into account uncertainties and missing data. One also needs to design interaction models of the personalized digital patient with drugs. Finally, one needs to develop analysis and simulation algorithms of the personalized digital patient to assist the physician and the surgeon concretely for the diagnosis, prognosis, planning, simulation and delivery of the therapeutic action.

Flagship applications are cardiovascular and neurodegenerative diseases, cancer, and functional rehabilitation of disabled people. Inria will also participate in the prescription of standards for the construction and indexation of large multi-centric databases in France and in the world, as well as providing software platforms for the exploitation of these data to assist precision medicine of the future. Obviously, ethical, confidentiality and security questions are particularly acute in this context.
“Neurodegenerative and cardiovascular diseases, cancer and the metabolic syndrome (diabetes, NASH, …), are chronic conditions that demand comprehensive, quantitative, and persistent computational models, which Inria, with Inserm and CNRS, has the unique capacity to deliver.”

Prof. Sir Michael Brady (Oxford University)
“Forecasting future technological transformations, imagining their potential impact, and building the relevant expertise and infrastructure early on are essential parts of my roles at Facebook and at NYU. I have been at the center of two recent technological shifts: the emergence of Data Science as a new discipline – the tools and methods to derive knowledge from data –, and the AI renaissance brought about by deep learning. Having spent half my career in industry (mostly at AT&T), the other half in Academia (at NYU), and now straddling the ever-shrinking fence between the two worlds, I have been working to redefine the relationship between them, bringing down the barriers to collaborations often caused by overly-restrictive IP policies.

I have read with great interest Inria’s scientific strategy plan. I view the exercise of strategic planning as particularly relevant for research, as long as it avoids two pitfalls. First, the pretentious belief that it can predict the future! Second, the over-simplified vision that the plan translates directly into operational implementation. Any planning exercise will miss some of the unexpected breakthroughs that are bound to occur during the period. What is expected from a plan is that some, certainly not all, major trends are taken into account and planned for ahead of time. Inria’s plan manages to provide an up-to-date vision of the issues facing digital sciences and to propose a choice of scientific challenges for the next five years.
I am pleased to observe that several key research problems, as seen from my perspectives, are addressed by Inria. For instance, I strongly believe in the necessity to connect people (perhaps because of my position at Facebook), I thus applaud the challenges related to a “reliable connected world”. The general field of data management and artificial intelligence is also central, but is clearly a transverse domain with implications in mathematics, statistics, algorithmics, high-performance data analytics... Several of Inria’s scientific challenges correctly address the combination of expertise from a number of disciplines. Some of those challenges contain key enablers for emerging transformations in manufacturing (robotics), transportation and personalized medicine.

Beyond the listed challenges and applications, I believe that long-term fundamental research is the seed from which future revolution and innovations will spawn. For example, a major scientific challenge is devising machine learning paradigms that would have similar capabilities and performance as animal and human learning: learning common sense by observing the world, and automatically constructing hierarchical representations and high-level abstractions suitable for perception, reasoning, planning, and action. This is one of the most important scientific questions of our time (how does the human mind come about and can we reproduce its function in machines?) and a long-term research program, rather than a technology development project. While its resolution may be decades away, one can now foresee a number of promising avenues which, if successful, will enable a new leap in machine intelligence.

Other implications of research in digital sciences are identified in Inria’s scientific strategy plan, and resonate with the current and future needs of society and business. The questions around reproducible research, or digital education, call for an active role of all parties including digital companies. Important themes are emerging surrounding best practices for the deployment of machine learning and AI technology: testing for reliability, ensuring that bias is minimized, designing objectives for autonomous intelligent systems that are aligned with human values, and promoting technological development that have a positive impact of society as a whole.

Because of the acceleration of the research process, and the accelerated pace at which technology transfer seems to happen these days, a new relationship between academia, public research, and industry needs to be defined. Increasingly frequently, North-American academics in AI have part-time appointments in industry research labs and contribute tremendously to the dissemination of AI technology in industry and society. Economists say that AI is a “GPT”, a General Purpose Technology, that will disseminate in every corners of the economy (and society) over the next 10 to 20 years, and will cause an increase in productivity. What limits the speed at which AI will disseminate in society is how fast the workforce will re-train and acquire the new skills and knowledge. Inria has a tremendously important role to play in creating and disseminating the knowledge on which the future economy will be built.”
Inria’s research centers
The Inria Bordeaux - Sud-Ouest Research Centre was created in 2008 and is located in Talence and Pau. In 2016, 342 people worked at the centre (including 283 scientists), 201 people being paid by Inria (including 147 scientists), and 17 project-teams were run there. The centre’s academic partners are the CNRS, Université de Bordeaux, Bordeaux INP, Université de Pau et Pays de l’Adour, Inserm, ENSTA ParisTech and Institut d’Optique Graduate School. The centre is involved in the E2S Isite, the Université de Bordeaux Idex and the Liryc IHU. It works in close collaboration with CEA CESTA, Institut Bergonié and CHU - Hôpitaux de Bordeaux. It is involved in the Aerospace Valley, Avenia and Alpha-RLH competitiveness clusters. Its industry partners include Total, Thales, Airbus Group, Ariane Group, Naval Group, EDF, Evollis, Valeol, Immersion, Ertus Group and I2S.

**Main research domains**
- Modeling, high-performance computing and parallel architectures
- Uncertainty management and optimization
- Modeling and simulation for health and biology
- Human and computing: interaction and visualization

**Main involvement in Inria’s scientific challenges**
- Extreme-scale computing for data intensive science
- Bridging time and space scales
- Predictive systems biology
- Lifelong adaptive interaction with humans
- Integrative computational medicine

**Particular topics in relation with the centre’s partners**
The centre researches methods to simulate the effects of environmental changes (e.g. coastal risk due to extreme events) and decision strategies to reduce human impact (e.g. phytosanitary treatments in viticulture). It collaborates with cognitive scientists and neuroscientists to better model the cognitive and physiological basis of human learning, leading to new machine learning approaches, and with education specialists on the design of methods and tools to improve learning and teaching.
Established in 1992, the INRIA Grenoble-Rhône-Alpes research center gathers 650 persons (240 researchers and faculty, 240 PhD students and postdocs, 170 engineers, technicians and administrative staff) and is a founding member of the Communautés d’universités et d’établissements (COMUE) Université Grenoble-Alpes and Université de Lyon. With its 35 research teams, common with major local academic partners in Grenoble and Lyon (Université Grenoble-Alpes, Grenoble INP, Ecole Normale Supérieure de Lyon, Université Claude Bernard Lyon 1, INSA Lyon), and 25 startups created since 1999, the center is a reference for research in computational sciences and a key actor in the thriving Grenoble and Lyon research and innovation eco-systems.

**Main research domains**
- Distributed systems and mobile networks, including research on high performance and cloud computing systems, wireless and ad-hoc networking, network science.
- Reliable software and embedded systems for ambient computing, including research on formal methods and model checking for embedded and distributed systems, compilation and run-time for multi-core and multiprocessor architectures.
- Modelling and simulation of multi-scale and multi-component phenomena, including research on numerical schemes and control for non-linear and stochastic dynamical systems, statistics, computational biology and medicine, ocean and atmospheric models.
- Perception and interaction with the real and virtual worlds, including research on computer graphics, image recognition, autonomous vehicles and robots in human environments.

**Main involvement in Inria’s scientific challenges**
- Extreme scale computing for data intensive science
- Formal Methods for Cyber-Physical systems
- Towards a trustworthy Internet of Everything
- Bridging Time and Space Scales
- Predictive systems biology
- Modeling and simulating the environment

**Particular topics in relation with the centre’s partners**
- In addition, the center should make important contributions to the scientific challenge of connected autonomous vehicles, and should play a key role in addressing a number of societal and transverse issues identified in this plan, notably with respect to personal data and privacy, the challenge of reproducible research and that of governing a complex digital society.
- In connection with the developments in the Grenoble eco-system, which has put in place a comprehensive research programme on quantum engineering that leverages the considerable resources available in the Grenoble COMUE in physics and nano and micro systems engineering, a key question to address by the INRIA Grenoble-Rhône-Alpes research center is how to accompany this effort with research on quantum computing and algorithmics.
The Inria Lille – Nord Europe research center was created in 2008 and gathers researchers both in Lille and Brussels, in 16 project-teams and teams. In 2017, 360 were working there, including 300 scientists. Academic partners of the research center are Université de Lille, CNRS, Ecole Centrale Lille and ULB. The center is strongly active for the strategy of the region Hauts-de-France and contributes to the three areas of the State-Region Contract CPER Data, which are internet of things, knowledge and data intelligence, and HPC. The center is involved in the I-SITE ULNE, the excellence sites EuraTechnologies and Eurasanté, and maintains close collaborations with competitiveness clusters Picom (trade) and Matikem (materials). InriaTech, the first technology transfer platform of Inria, was initiated by the center and has already clocked up numerous successes serving regional businesses. It contributed to collaborating with companies ranging from PMEs to major industry groups.

**Main research domains**
- Data science
- Everrunning software
- Humans, physical and digital worlds: models and interactions

**Main involvement in Inria’s scientific challenges**
- Lifelong interactive interaction with humans
- Bridging time and space scales
- Ever-running software
- Data science for everyone
- Towards a trustworthy Internet of Everything

**Particular topics in relation with the centre’s partners**
The center is strongly involved in research on data, ranging from IoT to artificial intelligence, with major contributions to HPC, software and databases for data sciences. Beyond fundamental research, the center focuses on applications such as e-commerce, health, e-learning, or in a global way on the city of tomorrow and on the digital world. This is conducted within the I-SITE ULNE (« Human-Friendly Digital World » axis) and in the context of the third industrial revolution initiative REV3.
The Inria Nancy – Grand Est research centre was created in 1986 and is located in Nancy, Strasbourg, and Saarbrücken. In 2017, 430 people worked at the centre (including 380 scientists), 200 people were paid by Inria (including 160 scientists) and 21 project-teams were run there. The centre’s academic partners are Université de Lorraine, Université de Strasbourg, CNRS and Max-Planck-Institut für Informatik. Inria is a core member of the I-Site Lorraine Université d’Excellence (LUE) initiative. This Inria research centre also enjoys a tight relationship with IHU-Strasbourg of which Inria is a founding member. It works in close collaboration with the competitiveness clusters Alsace Biovalley, Materia (in the Grand Est region) and Cap Digital, System@TIC (outside the Grand Est region). Its main industry partners are Alcatel-Lucent, Altran, EDF, GE, Orange, Thales (large companies), Groupe Open, Intrinsèque, Pharmagest (mid-sized companies), Ateliers CINI, BonitaSoft, Data Publica, Docapost, Invoxia, ip-label, NetLooks, SBS Studio, Studio MAIA, TVPaint (SMEs).

**Main research domains**
- Modeling and simulation of complex systems for engineering and life sciences
- Security, reliability and safety of computer-based systems
- Understanding and emulating the mechanisms of human cognition and perception

**Main involvement in Inria’s scientific challenges**
- Extreme-scale computing for data intensive science
- Towards a trustworthy Internet of Everything
- Bridging time and space scales
- Integrative computational medicine
- Lifelong interactive interaction with humans

**Particular topics in relation with the centre’s partners**
In Nancy, our teams will in particular address research questions on “IT-security and digital trust” in the context of one of the six socio-economic challenges of the LUE initiative. In Strasbourg, the Inria centre will work to increase its presence on the NextMed campus on topics such as medical simulation and health technologies, in connection with its implication in the IHU. Overall the Inria centre will strengthen its research on several aspects of the Factory of the Future (additive manufacturing, robotics, meshes, etc.) of which the Grand Est region ambitions to become one of the European leaders.
The Inria Paris Research Centre was created in 1967 in Rocquencourt and is now located in downtown Paris. In 2017, 600 people worked at the Centre in 36 project-teams (including 530 scientists), of whom 330 people were paid by Inria (including 260 scientists). The Centre’s academic partners are the ENPC, the ENS, UPMC, Paris Diderot, UMLV, CEREMA, CNRS, ICM, INSERM. The Centre works in close collaboration with the competitiveness clusters Cap Digital and Systematic, and with the incubator Agoranov. Each project-team has collaborations with industrial partners. The Centre’s main industry partners are Microsoft and Nokia Bell (in common Labs), as well as Facebook, Safran, Orange, Linux Foundation, Thales, Dassault System, Huawei, Google, Waterloo Maple Inc, Airbus, Renault, Valeo, AKKA Technologies, Tatamotors, Technicolors SA, Transdev, ObjectVideo Inc, Air Liquide and Instem. There are also many relationships with SMEs and start-ups, as well as software consortia, e.g. the one for Caml with 15 participants.

**Main research domains**
- Reliable software and security;
- Mathematical models and simulation;
- Artificial intelligence and machine learning;
- Networks and communication systems.

**Main involvement in Inria’s scientific challenges**
- Quantum technologies and algorithms,
- Data science for everyone,
- End-to-end verified cryptographic protocols,
- Modelling and simulating the environment,
- Integrative computational medicine,
- Connected autonomous vehicles.

**Particular topics in relation with the centre’s partners**
Inria Paris targets specific challenges in close collaboration with the Paris ecosystem:
- Launch of an initiative on artificial intelligence and its applications,
- Simulation for life and environmental sciences, based on multi-physics and multi-scale models, including interactions with data.
Another specificity of the centre is its wide spectrum of the topics involved in:
- Quantum computing from engineering to the impact on computation,
- Software reliability and cybersecurity from specifications to implementations.
Rennes, Nantes and Lannion. In 2017, 725 people worked at the centre (including 632 scientists), 320 people were paid by Inria (including 260 scientists) and 30 project-teams were run there.

- The centre’s academic partners are Université Rennes 1, Université Rennes 2, Université de Nantes, CNRS, ENS Rennes, INSA de Rennes, l’IMT Atlantique, l’IRSTEA, the French National Institute for Health and Medical Research (INSERM), CentraleSupélec, l’Institut Curie and l’IFSTTAR.

- The centre works in close collaboration with the competitiveness clusters Images et Réseaux and ID4CAR.

- Its main industry partners are Alcatel-Lucent, Cisco, EDF, Intel, Google, Huawei, Nokia, Microsoft, Safran, Samsung, SMABTP, Technicolor, Thalès, Total, Toyota, Envivio, Mediego, SenseYou, Secure-IC, and numerous other SMEs and start-ups.

### Main research domains
- Computational sciences for life and environment
- Virtual worlds, Interactions and Robotics
- Performant and Secure Hardware and Software Systems
- Signal, Images and data: Storage, Analysis and Interpretation

### Main involvement in Inria’s scientific challenges
- Lifelong interactive interaction with humans
- Data science for everyone
- Formal methods for cyber-physical systems
- Bridging time and space scales
- Post Moore’s law computer
- Towards a trustworthy Internet of Everything

### Particular topics in relation with the centre’s partners

#### Digital security

In Rennes, Nantes and Lannion, a dozen teams concentrate on computer security and privacy, as a main research objective or as an essential property to bring to their own research objects, ranging from processors to distributed systems. These teams will pursue their efforts to integrate in their systems the 3 aspects of security (prevention, supervision, and reaction) following a privacy or security-by-design philosophy. A special strain will focus on threat and malware analysis.

#### Mixed reality

Virtual/Augmented Reality becomes a key solution in many application fields (e.g., medicine, education, entertainment, sport) raising strong research challenges related to 3D human-computer interactions, such as simulating and controlling self-avatars more effectively or taking into account multi-sensory perception and physiological state of the user.
The Inria Saclay-Île-de-France Research Centre was created in 2008; its headquarters are in Palaiseau on the campus of Ecole Polytechnique, in the recently inaugurated Alan Turing building. Many research teams joint with academic partners are located on the partners’ premises, with 10 different sites in the Saclay area.

In 2017, 510 people work in the centre (including 410 scientists), 300 people are directly paid by Inria (including 200 scientists) in 29 project teams.

The centre’s main academic partners are Ecole Polytechnique, CNRS, ENS Paris-Saclay, Université Paris Sud, CentraleSupélec, CEA, ENSTA and Institut Pasteur. Inria Saclay-Île-de-France is a full member of Université Paris Saclay and of the Paris-Saclay Idex, as well as other excellence initiatives such as the Digicosme and LMH Labex. The centre hosts and leads scientifically the DATAIA Interdisciplinary Institute for Data Science, AI and Society.

The centre hosts three research platforms: the WILDER large visualization display; the FIT IoT-Lab for experiments on the Internet of Things; the GULLIVER high performance computing cluster.

The centre works in close collaboration with the SystemX Technology Research Institute and with local competitiveness clusters such as Systematic. Its main industry partners are, in terms of large groups, Microsoft, EDF, Nokia Bell Labs, Fujitsu, Airbus and Renault, and in terms of innovative SMEs, Artelys, SafetyLine and TKM.

Main domains
- Safety, security and reliability for architectures, software and data.
- From data to knowledge: modelling, querying, analysis and visualisation of distributed massive data.
- Modelling, control and optimisation of complex systems.

Main involvement in Inria's scientific challenges
- Bridging time and space scales
- Integrative computational medicine
- Trusted co-adaptation of humans and AI-based systems
- Data science for everyone
- Formal methods for cyber-physical systems
- End-to-end verified cryptographic protocols

Particular topics in relation with the centre’s partners
The centre will also contribute to the challenges on predictive systems biology and on extreme scale computing.
Sophia Antipolis – Méditerranée

Inaugurated in 1983, the Centre develops its activities with 35 research teams, 8 departments and about 600 people, including 530 scientific and 400 Inria employees. It works in strong partnership with academic actors (Université Côte d’Azur, UNS, UM, CNRS, INRA, etc.) and innovation actors (companies (Airbus, GE, Google, Microsoft, Qwant, ...), competitiveness clusters (SCS, IRT St Exupéry, ...), incubator (IPE), associations (EducAzur, etc.) and is very active in scientific mediation. It has an active European policy (univ. of Bologna, univ. of Athens, EIT Digital) and specific actions around the Mediterranean.

Main research domains
The Centre will continue its policy around its 3 main axes:
1. Communication, Data and Ubiquitous computing,
2. Computational Medicine and Biology
3. Modeling, simulation and interaction with the real world.

Main involvement in Inria’s scientific challenges
- Bridging time and space scales
- Connected autonomous vehicles
- Digitizing energy
- Data science for everyone
- Lifelong interactive interaction with humans
- Formal methods for cyber-physical systems

Particular topics in relation with the centre’s partners
The Inria Sophia Antipolis research center will renew its research activities on networking and distributed computing by focusing on security on privacy, in collaboration with UCAJEDI. The center will also contribute to its sites policies by participating in multidisciplinary researches on environment and digital health, and more specifically, computational neurosciences in Nice, and agro-environment in Montpellier.