Emerging Paradigms and Areas for Expansion

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IEEE Cloud Computing seeks articles on emerging cloud and adjacent technologies and their impact on the perception and use of the cloud.

Cloud computing was born from the opportunity to open major distributed datacenters to end users to provide on-demand services, ranging from infrastructure as a service (IaaS) to software as a service (SaaS). The new pay-per-use business model is so appealing that we're entering an everything-as-a-service (EaaS) era, extending the approach beyond existing borders—such as hardware-as-a-service (HaaS) and business-process-as-a-service (BPaaS)—to other areas and dimensions (robot-as-a-service, sensor-as-a-service, and so on). The cloud is like the Borg from Star Trek, making all resistance futile and assimilating all existing technologies and services.

Emerging paradigms and technologies will have a major impact on society and industry. We plan to cover these paradigms in the "Cloud and Adjacent Technology Trends" area as well as provide a long-term futuristic vision of how the cloud will look and the new opportunities it will offer.

These paradigms and related technologies can be domain-driven (for example, personalized medicine and social networks) or transversals (such as big data and the Internet of Things). In this introductory article, I'll describe some potential major players. By its nature, the list is nonexhaustive, and I expect even more upcoming breakthroughs to revolutionize how we see things.

Growth in Data

With the development of new technologies in biomedicine, researchers gained access to "-omics"—experimental readouts of high dimensionality and volume, such as genomics, transcriptomics, proteomics, and metabolomics.[1] Consequently, tremendous amounts of data have become available. One reason is the great reduction of "-omics" costs. In the last decade, the price of genetic sequencing (genomics) dropped from millions to thousands of US dollars per sequence, and the costs will eventually drop even more.[2] At the same time, the scope of collected data keeps growing, from sequencing a family a few years ago, to cohorts today, to entire populations in the future.

Although the prices are dropping, the size of the collected genomics data remains the same—roughly 0.3 terabytes per sequence. With the number of sequences reaching hundreds, current networks can't support their prompt transfer. Instead, major

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transport companies (Fedex, UPS, TNT, DHL, and so on) ship disks across the globe. From a broader perspective, these data transfers occur in huge data flows. Newly developed models and techniques will be required to parallelize the information transfer to exploit the many paths connecting one point to another but also multipoint communications.

Another biomedical domain observing a rapid increase in the size and volume of collected data is imaging. Here the challenge isn't only to store or analyze the data,[3] but also to remotely visualize large images.[4]

Big data and data analytics are among the biggest technology trends.[5] IBM divides big data into four dimensions: volume, velocity, veracity, and variety, or the "4 Vs." Each dimension brings new challenges in terms of required models, methods, algorithms, and technologies. The notion of big data is also tightly coupled with the emergence of the cloud. Indeed, Web 2.0 technologies and social networks present a tremendous amount of data that can't be stored locally to be processed for key information, such as societal or marketing studies.

Tying together zetabytes of data with the required processing power and providing this as a service to potential customers involves some major underlying challenges. We'll need new generations of data warehouses, (no-)file systems, and data-processing techniques. *IEEE Cloud Computing* will investigate all of these adjacent technologies and explore how they'll impact and shape the cloud's future.

Hardware Advances

Some of the paradigm shifts, such as sustainable computing and technologies like those developed for mobile computing (for example, low-power CPUs and systems on chip) or advanced networking (such as passive components and network coding) are also expected to revolutionize the cloud's core components. Cyberphysical systems develop quickly, and cloud computing will help further blur the hardware/software border.[6]

Because of the mass market, i.e. billions of units sold per year, the unit prices of the newest generation of hardware components has dropped low enough to allow an HaaS approach, in which hardware sharing needs, such as CPUs using virtualization, are less crucial. Some of the techniques developed by the grid computing community, such as elastic parallel designs, will be re-explored and further developed in this new context.

Hardware advances boosted by research on mobile computing create new opportunities to enrich the cloud. For example, more than 10 billion ARM processors are sold each year. Moreover, chip and board manufacturers continually announce new generations of low-power chipsets and the coupling of such chipsets at the cache level with GPUs and other accelerators, such as field-programmable gate arrays (FPGAs). We intend to investigate new generations of hardware, how well they work in the cloud paradigm, which category of cloud services they can provide, and upcoming trends.

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At the other end of the cloud spectrum, the main reason for the current relatively restrictive use of the cloud for high-performance computing (HPC) resides in the lack of cloud offers featuring high-performance interconnects, such as Infiniband, as well as the lack of efficient cloud driver implementations for such interconnects. Therefore, HPC users typically restrict their use of cloud computing to the bag-of-tasks paradigm—that is, groupings of uncorrelated tasks.

The virtualization and cloud management layers also induce an overhead; however, the pay-per-use paradigm and the cloud's elasticity features are so attractive that users are willing to pay this extra price.

Technology advances in this field that will increase the cloud's appeal for scientific computing in the coming years is another prime area of interest.

Toward a Safer and Trusted Cloud

A key goal is to increase the security level and trust in the cloud. Indeed, the virtualization layer, including the hypervisor and various device drivers, is the source of several newly discovered vulnerabilities. Standard subcontracting approaches involve a service-level agreement (SLA) and trusting the subcontractor. However, trusting the subcontractor's other customers, which is somehow implicit when sharing hardware with them, is rather new and unusual. Dedicated hardware coupled with trusted platform modules will help build chains of trusts and attract more customers to the cloud.

Confidentiality and privacy are also of primary concern to many cloud customers. Many applications transport much more information than required because they process data centrally, leading to potential data leakage. Decentralized approaches should let applications call remote services, keep the data where it's produced, and return just the requested result—no more, no less. New cryptographic data processing will allow applications to process data without uncovering unnecessary information.[7]

Among other issues, the abundance of information and the opportunity to cross compare it enable us to rebuild original, missing information. For example, recent stories have reported successful attempts to trace the names of "anonymous" genetic sequences simply by looking at publicly available information, such as the study location and local phone books. An enhanced legal framework and recommendations are required to bring customers peace of mind. Such frameworks have started to appear,[8] but the technologies needed to enforce such rules require further development.

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Cloud management techniques must also be improved. Many recent publications have highlighted the problem's multiobjective nature, minimizing cost and energy while maximizing resilience. These aspects are currently handled at various levels—from hardware to middleware to application. Decisions at the various levels could be contradictory, or they might unnecessarily reinforce some requirements, for example, duplicating resources used for fault tolerance. This certainly calls for cross-layer approaches, such as hardware-software codesign, and for the various research communities to join forces.

The Last Mile

Ubiquity of services, anywhere, anytime, will be reflected in the cloud's expansion to mobile devices required to meet the challenges of the "last mile."[9] At the other end, the cloud is expected to provide the necessary backbone to the Internet of Things. Sensors are now everywhere, enabling new trends of continuous monitoring of individuals provided by fancy hardware such as smart watches, clothes, and glasses. The cloud should let us mine our quantified selves.

Service roaming will let users move from one cloud to another, regardless of the service provider. This trend, initiated by the need for multitenant clouds, will also favor cloud brokering, which aims to find the best match between customers and providers. Cloud brokering will also help create higher-value services by combining services from various providers.

But the client side also becomes more demanding with the appearance of 4K TV, Qualcomm's NexCave, and other emerging high-resolution 3D screens such as the University of California, San Diego (UCSD) SCOPE (Scalable Omnipresent Environment) project, smart surface, and smartboards. Thus, the cloud's "last mile" also requires broad connections to support these technical challenges. To put the cherry on the cake, the new generation of applications will require not only large bandwidth, but also low latency (for gaming, HPC, remote control of robots, and so on).

Other Areas of Development

There is certainly still room in the cloud computing paradigm for theoretical development. The cloud is driving new needs. The many underlying sets of ontologies describing the data form complex networks that can be described using hypergraphs, which are known to turn simple problems into NP-hard ones.[10] We need new algorithms and heuristics to meet these new challenges. Also, with millions of devices interconnected through the cloud, some of which will certainly fail, there is a critical need for stochastic and fault-tolerant approaches.

On the economic side, the paradigm change brought by the cloud induces new business models, empowering small- and medium-sized companies, as well as individuals, to operate worldwide businesses. These new business models coupled with the opportunities of microcredit and community funding, allow anyone to have a major impact. Now anyone can potentially accomplish what only corporations could do in the past.

Finally, because major findings will likely come from multidisciplinary research, major world changes will likely emerge from a mix of technology, law, and economics. This is illustrated in recent actions to fight global warming and in the grid computing community's attempts to provide a sound business model. For example, the government of Luxembourg passed a project of law guaranteeing the conservation of data in the event of a local provider's bankruptcy.

Because clouds are distributed across many countries, international laws and regulations also play a key role. Classical ways of dealing regionally with copyright for technologies, such as zoning, don't hold in distributed cloud services. Watching the emergence of new international laws and regulations facilitating the use of the cloud will also be of a prime importance.

IEEE Cloud Computing calls for the academic and research communities to provide exciting articles on emerging paradigms on cloud and adjacent technology trends and their impact on how we perceive and use the cloud in the short, medium, and long term.

References

1. J. Lederberg and A. McCray, "'Ome Sweet 'Omics—A Genealogical Treasury of Words," *The Scientist*, vol. 15, no. 7, 2001, p. 8.
2. J.C. Roach et al., "Analysis of Genetic Inheritance in a Family Quartet by Whole-Genome Sequencing," *Science*, vol. 328, no. 5978, 2010, pp. 636–639; www.ncbi.nlm.nih.gov/pubmed/20220176.
3. B. Neumann et al., "Phenotypic Profiling of the Human Genome by Time-Lapse Microscopy Reveals Cell Division Genes," *Nature*, vol. 464, no. 7289, 2010, pp. 721–727; www.ncbi.nlm.nih.gov/pubmed/20360735.
4. S. Samsi, A.K. Krishnamurthy, and M.N. Gurcan, "An Efficient Computational Framework for the Analysis of Whole Slide Images: Application to Follicular Lymphoma Immunohistochemistry," *J Computer Science*, vol. 3, no. 5, 2012, pp. 269–279; www.ncbi.nlm.nih.gov/pubmed/22962572.
5. V. Mayer-Schonberger and K. Cukier, *Big Data: A Revolution That Will Transform How We Live, Work, and Think*, Eamon Dolan/Houghton Mifflin Harcourt, 2013.
6. E. Lee, *Cyber Physical Systems: Design Challenges*, Univ. of California, Berkeley, tech. report UCB/EECS-2008-8, 23 Jan. 2008.
7. M.D. Ryan, "Cloud Computing Security: The Scientific Challenge, and a Survey of Solutions," *J. Systems and Software*, vol. 86, no. 9, 2013, pp. 2263–2268.
8. Committee on Strategies for Responsible Sharing of Clinical Trial Data; Board on Health Sciences Policy; Institute of Medicine. *Discussion Framework for Clinical Trial Data Sharing: Guiding Principles, Elements, and Activities*, Nat'l Academies Press, 2014.
9. S. Fowler, "Survey on Mobile Cloud Computing—Challenges Ahead," *IEEE CommSoft E-Letters*, vol. 2, no. 1, May 2013.
10. C. Berge, *Hypergraphs, Combinatorics of Finite Sets*, North Holland Mathematical Library/Elsevier, 1989.

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