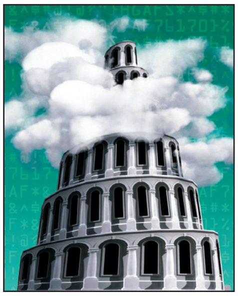
Editor: George Pallis • gpallis@cs.ucy.ac.cy



The Client and the Cloud

Democratizing Research Computing

Roger Barga, Dennis Gannon, and Daniel Reed • *Microsoft Research*

Extending the capabilities of desktop and mobile applications through on-demand cloud, data-driven services will significantly broaden the research community's capabilities, accelerating the pace of engineering and scientific discovery. The net effect will be the democratization of research capabilities that are now available only to the most elite scientists.

Cloud computing has attracted much attention in the popular press and technical literature, most of which has focused on virtualization's advantages, private clouds versus public clouds, rapid scale-out of services, reliability, security, and privacy. Although these topics are all important, the cloud revolution is really about how cloud services extend and amplify the power of our client devices such as desktops, laptops, phones, and pads. Whether we realize it or not, nearly all of us as consumers experience client-plus-cloud technology in our daily lives — when we share photos, shop online, download and use applications for mobile phones, or use a search engine. This seemingly invisible technology has changed how we live and work, empowering us with new kinds of information and services, new ways of communicating and collaborating, and unparalleled convenience.

The next phase of this client-plus-cloud revolution is under way and will transform how we conduct basic scientific and scholarly research. Until now, the only researchers who had access to large-scale computing were those with access to supercomputers or large computing clusters. With the power of the cloud, the easy-to-use tools that scientists and engineers work with every day can become infinitely more powerful — accessing and manipulating more data and applying more complex calculations — but in familiar ways. This ability to provide easy access to data and computation at an arbitrary scale has the power to democratize research by making computing power available for the vast majority of researchers using desktop computers. In the same way that the cloud has created online social networks, scientists can share data and analysis tools to build collaborative research communities.

To make this vision a reality, the computer systems research community must develop new approaches to building application platforms to support a new type of science. However, many technical challenges exist.

The Changing Nature of Research

Virtually all research has become data-centric. Over the years, researchers in all disciplines have benefited from improved computer performance, but now low-cost sensors and instruments are amassing petabytes of data from computer-assisted experiments, simulations, and other sources. In 2010, 1,200 zetabytes (1.2×10^{21} bytes) of data will have been generated.[1] Scientists and engineers are capturing data at an unimaginable scale; this necessitates a sea change in how they extract insight from all that data.

As a result of this explosive data growth, research is at an inflection point. The practice of scientific discovery is constantly evolving. The first paradigm of science was experimentation. This was quickly followed by theory, which formalized what we learned from our experiments. In the 20th century, we realized that computational simulation was a new paradigm that let us test theories in areas where experimentation was

 1089-7801/11/$26.00 © 2011 IEEE

either extremely expensive or impossible. The data deluge we've created has driven us to a fourth paradigm of science,[2] in which we ask fundamentally different questions than in the past. Rather than use data to verify a theory, we can use massive amounts of data to create theory. This data takes the form of very accurate models that we couldn't build from small data collections.

An excellent example of this is the recent progress in natural-language translation. Researchers spent many years looking at language structure's fundamentals to solve the automatic-translation problem. Today we've made remarkably accurate automatic-translation systems based on models built from deep Bayesian statistical analysis of vast collections of translated text. Researchers have also developed similar statistical methods that let us discover the phylogenic tree representing the rapid evolution of viruses such as HIV.[3]

These changes in how we go about scientific discovery are amplified by the growing trend toward interdisciplinary research. Scientists and academics often must access and share large datasets and collaborate with other researchers in many disparate locations. For example, accurately understanding and predicting the long-term effects of a major environmental disaster such as an oil spill requires detailed analysis of ocean chemistry, biology, and ecology, and the simulation of complex oceanographic and atmospheric models.

However, experts in each of these areas often work in silos and only have access to information relevant to their specific areas. To truly address increasingly complex global issues such as climate change, genetic diversity, and personalized medicine, researchers will be expected to develop ever more complex simulations and models. To do so, they'll need to mine, search, and analyze huge sets of data in nearly real time and collaborate across disciplines like never before. Their ability to extract insight based on deep analysis of data and to collaborate will drive a transformative change in research.

The Systems Research Challenges for Cloud Computing

To address the massive challenge of extracting knowledge from vast data collections, researchers have turned to parallel computing in the cloud. As a concept, the cloud is an abstraction for remote, infinitely scalable computation and storage. In reality, it's built from massive datacenters comprising thousands of servers and disk drives. These datacenters were created to hold copies of the Web for search engines, vast media collections, message systems, email, e-commerce, and social networks.

To make it possible to store and quickly access such large collections, the data had to be distributed and replicated over thousands of servers. The first challenge was to build indexes for the data. The standard solution was based on MapReduce, an old parallel-programming paradigm that maps a function onto each distributed partition of the data and reduces each computation's results to a single output by another reduction function. MapReduce has proven extremely popular, and Yahoo's Hadoop[4] implementation is widely used.

However, MapReduce is only one parallel-programming pattern that you can apply to extract information from a distributed data collection. Often, computations require an iteration in which a MapReduce operation is only one step. For example, clustering is an important data analysis technique that often requires an algorithm that repeats a distributed computation until an answer converges. A major challenge for algorithm and cloud system designers involves designing distributed computations that optimize for memory and local disk use but are also fault tolerant at an extremely large scale. Achieving both efficient use of locality and fault tolerance requires using replication in both data storage and computation.

Another important challenge for data analytics in the cloud involves streaming data and large data collections that must be continuously updated. Google recently described Percolator, a system that has replaced traditional MapReduce to deal with the constant incremental changes in Google's data collections.[5] Microsoft's StreamInsight lets users express continuous queries over streaming data.

Regarding system research, there are three additional ongoing challenges. One is to improve the datacenter's power efficiency. Current datacenter designs have a power usage effectiveness near 1.0, but to reduce overall power usage, we must consider more aggressive ways to optimize the computation per watt. This can involve predicting loads and putting servers into low power states when loads are light.

The second challenge is improving datacenter networks' design. These networks are optimized for Internet access by thousands of simultaneous users, whereas supercomputer networks are optimized to provide high bandwidth and low latency between the servers. But as more data analysis and machine learning tasks move to the cloud, there are advantages to applying architectural ideas from supercomputing networks to datacenter networks.

The third challenge is to create programming models that better support client-plus-cloud applications. The state of the art is to separately build scalable services and the client tools to access these services. Perhaps it's possible to create a programming model that lets developers codesign clients and the associated cloud services to allow more adaptive management of the resources.

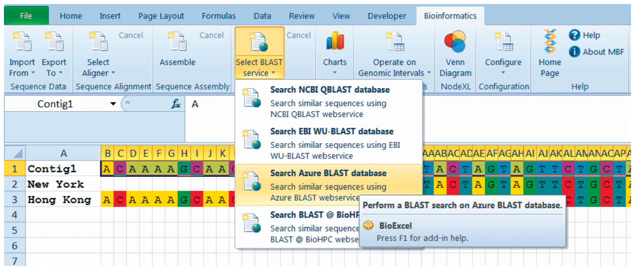


Figure 1. We extended Excel to make it a client interface to remote cloud computations.

Controlling Cloud Data Analytics from the Client

MapReduce, clustering, and streaming data analysis are only a small fraction of the analysis tools that are important to science. Other common algorithms include locally weighted linear regression, *k*-means clustering, logistic regression, naive Bayes classifiers, support-vector-machine classifiers, principal component analysis, Gaussian discriminant analysis, and other, more advanced machine learning tools.

Large corporations tend to use cloud-based data analysis as part of a standard workflow. For example, a system to manage user preferences and recommendations must continuously update a large corpus of data representing sales and then cluster related purchases and topics. Such a system might run continuously and be monitored by the analysis staff.

In contrast, researchers tend to explore. They're interested in what the data tells them. They want to interactively apply a variety of tests and models to the data, and they want great ways to visualize the results. Besides generic data analysis algorithms, each scientific discipline has its own specialized tools.

Consider the following example of the client-plus-cloud model. A research bioinformatician wants to explore 5,000 DNA sequences as part of a biofuel project. A basic requirement is a sequence comparison against known sequence data. The US National Center for Biotechnology Information (NCBI) provides the Basic Local Alignment Search Tool (Blast) for this. NCBI also provides access to the public known sequence data. Researchers can use Blast to pose research questions such as, "Where does a certain sequence of DNA originate?" or "What other genes encode proteins that exhibit structures or motifs such as ones that have just been determined?" NCBI also has a cluster that researchers can use for small studies, but not for 5,000 sequences.

However, if the researcher can afford a few hundred dollars of cloud computing time, various cloud providers can help him or her out. Microsoft recently released NCBI Blast for Windows Azure as a free software package (http://research.microsoft.com/azure). Microsoft also hosts a copy of the NCBI reference databases in Azure. A scientist simply creates a Windows Azure cloud account and installs this package to create an "instant" Blast Web portal that our researcher and his or her colleagues can use to run very large Blast jobs. The collaborators can also use the Web portal to share access to the results data, which is automatically stored in the cloud.

Although a Web portal is useful, it still doesn't illustrate the concept of integrating client applications with the cloud. The most frequently used data analysis tool is the humble spreadsheet. Its beauty is how it lets us interact with data, to organize it in different ways and visualize it easily. Spreadsheets operate on tabular data. What if the spreadsheet isn't just a local table of data but a window on a massive table in the cloud? To illustrate this concept's power, we extended the Excel spreadsheet to invoke remote cloud-based analysis services on cloud-based data. Figure 1 illustrates a prototype Excel extension connected to NCBI Blast running on Windows Azure. Users can input DNA sequences directly into the spreadsheet and pull down a menu to run the remote computation. The results are stored in the cloud and can be pulled back to the spreadsheet.

At Microsoft Research, we're developing a suite of client tools and cloud services to aid scientific research. Besides the Excel extension we just described, we're building a suite of cloud data analytics and machine learning services that users can invoke from the Excel client and run over cloud-stored or streaming data collections. The project aims to enable the ad hoc data analysis that reflects how scientists understand data.

In addition to using Excel as a remote control panel for analysis in the cloud, we're exploring ways to visualize data analysis results. The great challenge of visualizing massive collections of data lies in creating images that expose structure without losing important details. For example, we've used Microsoft Silverlight PivotViewer (www.microsoft.com/silverlight/pivotviewer) to let users see different views of multidimensional data sorted along different dimensions. Because PivotViewer leverages Deep Zoom technology, it can display full, high-resolution content without long load times, with natural transitions that provide context and prevent users from feeling overwhelmed by large quantities of information.

Finally, one of the most needed capabilities is to use the cloud to perform a simple task that must execute thousands of times, such as running a simple command-line application on a very large number of data inputs. We built a simple-to-use application that does this for native Windows applications, without requiring any special programming or understanding of how to deploy applications in the cloud.

As we've just described, cloud computing can provide software applications and computing power to users as a service over the Internet via familiar tools. The offsite cloud is constantly managed and upgraded, providing the ability to deliver computational resources on demand — a "pay as you go" strategy with access to virtually unlimited computational capacity. The cost to use 10,000 processors for an hour is the same as using 10 processors for 1,000 hours but will deliver radically faster analysis to researchers.

Organizations can buy just-in-time services to process and exploit data, rather than a perpetual refresh of infrastructure that increases not only the capital costs associated with the computing but also the energy management and security issues — an increasingly important constraint. Money can be invested in the research and the acquisition of cloud services rather than in the distributed maintenance of infrastructure, letting researchers focus on unsolved questions and discovery.

With cloud computing, virtually any researcher will be able to use simple tools to get answers to complex data-intensive questions. For example, a scientist might use a spreadsheet to tap into a genomic-analysis service running on 600 servers or use a simple script to do data mining across 10,000 functional-magnetic-resonance-imaging images in minutes. He or she can then immediately share the results with colleagues on the other side of the world. A researcher could access data from remote instruments such as sensors in the rain forest and pull it down to his or her desktop for visualization and analysis.

Extending the capabilities of powerful, easy-to-use PC, Web, and mobile applications through on-demand cloud services will significantly broaden the entire research community's capabilities, accelerating the pace of engineering and scientific discovery. The net effect will be the democratization of research capabilities that are now available only to the most elite scientists.

References

1. J.F. Gantz et al., "The Diverse and Exploding Digital Universe," white paper, IDC, Mar. 2008; www.emc.com/collateral/analyst-reports/diverse-exploding-digital-universe.pdf.
2. T. Hey, S. Tansley, and K. Tolle, eds., *The Fourth Paradigm: Data-Intensive Scientific Discovery*, Microsoft Research, 2009; http://research.microsoft.com/en-us/collaboration/fourthparadigm.
3. J. Carlson et al., "Phylogenetic Dependency Networks: Inferring Patterns of CTL Escape and Codon Covariation in HIV-1 Gag," *Public Library of Science Computational Biology*, vol. 4, no. 11, 2008, e1000225.
4. C. Lam, *Hadoop in Action*, Manning, 2010; www.manning.com/lam.
5. D. Peng and F. Dabek, "Large-Scale Incremental Processing Using Distributed Transactions and Notifications," *Proc. 9th Usenix Symp. Operating Systems Design and Implementation* (OSDI 10), Usenix Assoc., 2010, pp. 251–265.

Roger Barga is the principal architect for the Cloud Research Engagement Project in Microsoft Research's eXtreme Computing Group. Contact him at barga@microsoft.com.

Dennis Gannon is the director of the Cloud Research Engagement Project in Microsoft Research's eXtreme Computing Group. Contact him at dennis.gannon@microsoft.com.

Daniel Reed is the Corporate Vice President for Strategy and Policy at Microsoft Research and the leader of Microsoft Research's eXtreme Computing Group. Contact him at reed@microsoft.com.

Selected CS articles and columns are also available for free at http://ComputingNow.computer.org.

"All writers are vain, selfish and lazy."

—George Orwell, "Why I Write" (1947)

(except ours!)

The world-renowned IEEE Computer Society Press is currently seeking authors. The CS Press publishes, promotes, and distributes a wide variety of authoritative computer science and engineering texts. It offers authors the prestige of the IEEE Computer Society imprint, combined with the worldwide sales and marketing power of our partner, the scientific and technical publisher Wiley & Sons.

For more information contact Kate Guillemette, Product Development Editor, at kguillemette@computer.org.

IEEE CSPress

www.computer.org/cspress