A Cloud Computing Survey: Developments and Future Trends in Infrastructure as a Service Computing

Jonathan Stuart Ward and Adam Barker
School of Computer Science, University of St Andrews, UK.
{jw497, adam.barker}@st-andrews.ac.uk

Abstract

Cloud computing is a recent paradigm based around the notion of delivery of resources via a service model over the Internet. Despite being a new paradigm of computation, cloud computing owes its origins to a number of previous paradigms. The term cloud computing is well defined and no longer merits rigorous taxonomies to furnish a definition. Instead this survey paper considers the past, present and future of cloud computing. As an evolution of previous paradigms, we consider the predecessors to cloud computing and what significance they still hold to cloud services. Additionally we examine the technologies which comprise cloud computing and how the challenges and future developments of these technologies will influence the field. Finally we examine the challenges that limit the growth, application and development of cloud computing and suggest directions required to overcome these challenges in order to further the success of cloud computing.

1 Introduction

Cloud Computing is the latest term encapsulating the delivery of computing resources as a service. It is the current iteration of utility computing and returns to the model of ‘renting’ resources. The terms cloud computing and cloud are now accepted as part of industry lexicon and despite frequent misuse of these terms in advertising there is a significant body of research which underpins the area. Leveraging cloud computing is today, the de facto means of deploying internet scale systems and much of the internet is tethered to a small number of cloud providers. The advancement of cloud computing is therefore intrinsic to the development of the next generation of internet. This paper considers the technologies underlying cloud computing, their pasts and their futures and the potential implications for the future of the internet. In particular we examine the shortcomings of existing cloud systems and the requirements of future cloud users.

The definition of cloud computing has been well established. Where previous reviews and taxonomies have sought to provide a clear and unambiguous definition of the domain, this is no longer necessary. The objective of this paper is threefold. First, we examine previous analogues to cloud computing and consider past precedent for current issues in cloud computing. Second, we examine the constituent technologies, consider the problems within these areas and suggest the paths for future development in cloud computing. Finally, we examine current issues and challenges for cloud users and providers from both a technical and socio technical perspective through specific examples.

1.1 Scope

“The cloud” and “cloud computing” have been argued by many observers to be ill defined and insubstantial terms. Initially dismissed by prominent organisations including Oracle and the Free Software Foundation, Cloud Computing has since developed into a significant and well defined domain. The most accepted description of the general characteristics of cloud computing comes from the US based National Institution of Standards and Technology (NIST) and other contributers [21][3]. It defines a concise set of properties which define a cloud computing system:
On-demand Self Service: A consumer is able to provision resources as needed without the need for human interaction.

Broad Access: Capabilities of a Cloud are accessed through standardised mechanisms and protocols.

Resource Pooling: The Cloud provider’s resources are pooled into a shared resource which is allocated to consumers on demand.

Rapid Elasticity: Resources can be quickly provisioned and released to allow consumers to scale out and in as required.

Measured Service: Cloud systems automatically measure a consumers use of resources allowing usage to be monitored, controlled and reported.

The NIST standard also defines three layers within the cloud stack: Infrastructure as a Service (IaaS), Platform as a Service (PaaS) and Software as a Service. Software as a service is defined as the delivery of an application, typically a web application, on-demand via the Internet. Platform as a Service is the delivery of a software platform and associated development tools via a service model. Infrastructure as a Service is the provisioning of computer resources including virtual machines (VMs), storage, networking and other resources via a service model. This paper refers primarily to IaaS as it is IaaS which serves as the foundation of the cloud stack and has facilitated the phenomenon of cloud computing. While there will inevitably be significant future development within the domains of PaaS and SaaS this development will be highly dependent upon advances in Infrastructure as a Service. We attempt to consider IaaS computing from both the perspective of the consumer and the often neglected perspective of the provider.

2 The Cousins of Cloud Computing: Similar Computing Paradigms

2.1 Mainframe Computing

In many ways cloud computing has seen the industry come full circle. In the 1960s computers were extremely expensive, this prompted the development of the mainframe computing paradigm. This paradigm saw an expensive, powerful mainframe accessed via inexpensive terminals. The 1980s saw the rise of the PC which largely supplanted the mainframe paradigm. Cloud computing now sees a conceptual return to the mainframe era. In lieu of terminals, cloud computing uses cheap consumer devices to provide cloud services. Android, iOS and especially ChromeOS devices are inexpensive compared with regular PCs and are designed with extensive support for cloud services. There are of course significant differences between mainframe and cloud computing however a number of similarities suggests value in the analogy.

A distinct point of similarity between the mainframe era and cloud computing is vendor lock in. IBM dominated mainframe computing and imposed significant restrictions on the use of their software. This led to accusations of anticompetitive practices but ultimately eliminated competition. Cloud computing has no equivalent of IBM, public cloud services are currently dominated by Amazon, Google, Microsoft and Rackspace. There is however little or no interoperability between these providers’ services. As a user’s dependency upon a provider’s services increases it becomes increasingly difficult for them to migrate to an alternative provider. Unlike mainframe computing, there is no investment in hardware however the cost and difficulty of migration can be similarly prohibitive. Increased interoperability is essential in order to avoid the market shakeout the mainframe industry encountered in the 1970s. This is a significant concern for the future of cloud computing.

A noteworthy point of distinction between mainframe and cloud computing is ownership of data. In the mainframe world, ownership of data was clear. Mainframes were owned and operated by businesses, governments and scientific institutions. Data which resided on the mainframe was owned by the organisation which owned the mainframe. This is not the case with cloud computing. The devices accessing cloud services are owned by the users, the services are owned by the providers. No longer does the institution owning the equipment assert ownership of the data. This necessitates both a legal and technical framework for asserting ownership and restricting access to cloud hosted data. At present, ownership of data is defined only through a providers terms of
service which provides insufficient guarantee of the assumed ownership for a considerable volume of organisations and users.

2.2 Grid Computing

Grid computing is conceptually similar to cloud computing and faces some of the same challenges. While cloud computing arose from industry, grid computing traces its lineage to academia. The objective of grid computing is to link the collective resources of multiple independent parties to create a high performance virtual supercomputer capable of executing computationally intensive jobs. Grid computing is typically linked to eScience: science requiring highly distributed computation. eScience problems typically entail substantial computation and large data sets and as such require significant infrastructure. The bio-informatics, computational physics and earth science communities are increasingly encountering eScience problems and as such make heavy use of grid computing. Grids therefore, are most commonly used by the scientific community for performing simulations, running models, in-silico experimentation and other complex, eScience problems which necessitate significant resources.

The key property of grid computing which, as of yet, is not found in cloud computing is federation. Grid computing allows for the provisioning of a single virtual organisation (VO) from resources distributed between a number of organisations. The VO provides dynamic resource sharing, user authentication and access control with varying scale, structure and duration between a number of related organisations and serves as the basis of grid computing.

Grid computing focuses on providing high performance and high scalability. Cloud computing alternatively focuses on delivering high scalability and low cost. Cloud services therefore aim to provide a far lower performance to price ratio and cannot surpass the performance of individual grid components. This is problematic for message passing workloads which rely heavily on high performance computers and fast interconnects. Embarrassingly Parallel workloads however do not require high speed interconnects and scale extremely easily. The cloud is ideal for this workload. For this reason Hadoop [6] is widely considered as the cloud’s first so called killer application.

Gradually cloud providers are realizing the need for high performance compute applications on the cloud. Amazon has been the first to realize this need and offers an HPC VM instance with 10GB ethernet and substantial performance. The lack of the preferred infiniband interconnect, slightly lowered performance and difficulties relating to moving data to the cloud have limited adoption of HPC clouds. Despite this, it is clear that the cloud is capable of executing traditionally grid based workloads though not without challenge.

A ever present bottleneck within cloud computing is the inability to scale up. This is argued as a strength, rather cloud applications are intended to scale out. There are, however, use cases whereby scaling up is preferable. HPC applications and other applications well suited to grid computation often benefit from high memory and high compute servers. With only a small number of cloud providers offering high memory and high CPU VM instances this remains a crucial limitation. This limitation is even more significant in cloud infrastructure software which predominantly lacks support for technologies such as Non Uniform Memory Access (NUMA) which allows for virtual machines to utilise the resources of several physical machines. With commodity x86 now supporting NUMA and support for NUMA and related technologies available in the Linux kernel since around 2005 [11] it is now a potential area for significant research which could see hpc as a service become the norm, trumping even conventional cluster computing.

The demise of grid computing in favour of cloud computing has long been predicted. The defining properties of grid computing: loose coupling, heterogeneity and geographic dispersion occurred due to the need for inter-organisational cooperation. As such the grid is designed with inter-organisational federation as a key goal. This is a property distinctly lacking from cloud computing. While the challenges of inter-organisational workflow management, security and governance remain unresolved by cloud computing, grid computing will remain a significant platform for high performance computing.

2.3 Cluster Computing

Despite the prevalence of grid and cloud computing it is dedicated in-house clusters which remain the preferred platform for HPC. The principle behind cluster computing is simple: interconnect numerous compute nodes to provide a high performance system. Typically this is achieved by networking large numbers of x86 servers via a high
speed Infiniband interconnect running a message passing system to facilitate job execution. Most clusters deploy some variation of GNU/Linux using the Message Passing Interface (MPI) or other interface. However Solaris, Mac OS X and Windows have all been used in significant cluster deployments. Clusters have a number of advantages over cloud and grid systems. Typically clusters are owned and operated by a single authority. This allows full access to the hardware and removes any need for federation. Full hardware access enables users to specifically modify both the cluster and the application to achieve optimum performance. Furthermore, the resource sharing which is crucial in cloud computing does not take place within a cluster. An application is executed with the full resources of the underlying hardware, not a specifically provisioned slice. Clusters can therefore achieve significantly greater performance than the equivalent grid or cloud solution. The drawbacks of cluster computing are predominantly financial. Clusters require substantial investment and substantial maintenance, these costs are often entirely prohibitive for smaller organisations. There exists a convention of using a dedicated compute cluster whenever resources are available. This convention often has numerous related groups each deploying their own infrastructure. This can result in periods of under utilisation or idling where a small group cannot sufficiently utilise a cluster. The resource sharing and federation of cloud and grid computing respectively would alleviate the problems of under utilisation by allowing for superior inter-institutional resource usage.

3 The Foundations of Cloud Computing

Cloud computing originated as a union of virtualization, distributed storage and service oriented architecture. These three technologies have entirely separate origins however they each encountered a renaissance in the early 2000s which led to a co-evolution. To date, major advancement within cloud computing is attributable to advancement within one of these fields, a trend which is set to continue. We therefore examine the origins and potential futures and challenges of each of these technologies in an attempt to gain insight into the future of cloud computing as a whole.

3.1 Virtualization

Originating from the IBM CP/CMS operating system, virtual machines (VMs) are one of the cornerstones of cloud computing. A VM is a software implementation of a computer system, running in isolation alongside other processes, which behaves as physical system. A single multi-processor server is capable of running several VMs, typically one per core (though cloud providers often oversell their CPUs). This allows for a single server to be effectively used to capacity, reducing any unused CPU cycles and minimising wasted energy. Virtualizing a computer system reduces its management overhead and allows it to be moved between physical hosts and to be quickly instantiated or terminated. These properties create the rapid elasticity and scalability which underpins cloud computing. A VM is executed on top of a hypervisor, which presents a virtual hardware platform to the VMs and manages their execution. Historically virtualization has been a feature of platforms with specific hardware support and remained under the purview of mainframe computing until the late 1990s. The development of Xen in 2003 and later the development of Intel VT-x and AMD-V, in 2005 and 2006 respectively, made high performance x86 server virtualization feasible. This allowed for unprecedented server consolidation and greatly decreased the time required to provision new servers. The large scale in house deployment of virtualization at a number of major companies is the direct catalyst for the development of cloud computing.

3.2 Challenges in Virtualization

The x86 architecture was not conceived as a platform for virtualization. The mechanisms which allow x86 based virtualization either require a heavily modified guest OS or utilise an additional instruction set provided by modern CPUs which handles the intercepting and redirecting traps and interrupts at the hardware level. Due to these levels of complexity there is definite performance penalty imparted through the use of virtualization. While this penalty has considerably decreased over recent years [22] it still results in a virtual machine delivering a percentage of the performance of an equivalent physical system. While some hypervisors are coming close to delivering near native CPU performance, IO performance is still lacking. IO performance in certain scenario’s suffers an
88% slowdown compared to the equivalent physical machine. VMs effectively trade performance for maximum utilisation of physical resources. This is non ideal for high performance applications and is in part a motivation for the continued popularity of grid computing where non virtualized systems achieve far greater performance.

Significant challenges still exist within virtualization regarding improving resource utilisation. A recent trend has been the scheduling of multiple VMs on a single CPU core. This drastically increases the number of VMs a single host can accommodate but comes at a significant performance penalty. As each CPU core can execute one one VM at a time the hypervisor must switch between VMs. Each VM that is not being executed on the CPU lies idle. This introduces IO latency as the inactive VM cannot respond to IO activity while it is inactive. Alleviating this problem is a significant research issue as this problem significantly limits the performance of IO intensive applications, especially multimedia and real-time applications.

Improving resource utilisation is beneficial for the cloud provider and allows cheaper and greater numbers of VM instances to be made available to the consumer however it is not always without penalty. Smaller and lower cost VM instances are also significantly problematic for many applications. In order to offer greater utilisation and lower costs many cloud providers will schedule multiple VMs per CPU core. In the case of smaller instances there is only one CPU core available to it. In this case the host will context switch the running VM intermittently to allow another VM to run. Context switching a VM is a significant feat and requires the storage of considerable state. The process of context switching imparts a significant performance overhead and has several implications for the VMs [5]. This phenomena can create additional end to end delay as packets queue waiting for the recipient to return to being executed on the CPU [23]. Furthermore it limits the ability of VMs to handle applications with real time or time sensitive applications as the VM is not aware that for a time it is not running on the CPU and cannot account for this. In theses cases, a less powerful non virtualized system is better suited to the task. At present the types of application running on cloud platforms are mostly RESTful delay tolerant applications which do not suffer significant performance or network Quality of Service (QoS) degradation given these issues. The cost and impact of context switching in virtualization is gradually decreasing due to improved hardware support and more efficient hypervisors however the overselling of CPUs makes small cloud VM instance unsuitable for many applications.

3.3 Storage

The field of databases has been dominated by SQL based relational databases for the past thirty years. SQL and relational properties provided an appropriate model for the representation of complex information systems. The rigid structure of the relational model does not fit all problems however. Over the past decade it has become clear that the fixed structures of tables, rows and columns are limitations when dealing with information which is far more varied than that of traditional information systems. This had led to the development of schema-less data storage systems which lack the conventional fixed data model. These types of systems are highly varied and typically designed for a specific use case. Despite the vast differences, they are all united under the common identity of NoSQL databases. NoSQL, was initially not an acronym and was used to refer to database systems which do not employ an dialect of SQL as a query language. NoSQL has now been rechristened as "Not Only SQL" and refers to a wide array of systems [17]. It is NoSQL which has been a driving force behind cloud computing. The unstructured and highly scalable properties of many common NoSQL databases allows for large volumes of users to make use of single database installation to store many different types of information. This is the principle behind Amazon S3 [25], Google Storage, Rackspace Files and Azure Storage [8].

ACID (atomicity, consistency, isolation, durability) properties are the principles which govern relational database systems and have been central to the field since its inception. Contrary to this notion is BASE (Basic Availability, Soft state, Eventual consistency) [30]. BASE is a notion diametrically opposed to ACID. A BASE system is one in which requests cannot be guaranteed to be responded to, does not store data indefinitely and is not immediately consistent. ACID properties specify properties which ensure that database transactions are processed reliably. BASE properties meanwhile specify the properties which allow for superior performance and superior scalability. No system fully adheres to all BASE properties but rather expresses a mixture of ACID and BASE properties. Each NoSQL system compromises at least one ACID property and therefore expresses at least one BASE property. The exact combination of ACID and BASE properties depends entirely upon the NoSQL solution and it’s design goals.
The CAP theorem, postulated by Brewer [7] and later formally proven by Gilbert et al [15] specifies a distinct limitation for databases. The CAP theorem states that it is impossible for a distributed system to provide the following three guarantees:

- **Consistency**: Upon a value being committed to the database the same value will always be returned unless explicitly modified.
- **Availability**: The database will successfully respond to all requests, regardless of failure.
- **Partition Tolerance**: The ability of the database to continue operating correctly in case of becoming disjointed due to network failure.

Brewer theorised that these properties are intrinsically linked and cannot be simultaneously provided. Two years later it was proven that at best a distributed system can provide two of these three guarantees. The third property must be provided in a lesser form. This therefore entails the following taxonomy:

- **Consistent and Partition Tolerant (CP)**: Provides consistent data and continue to correctly operate while partitioned. This is achieved at a loss of the guarantee of availability. Within such systems there exists the possibility that a request may fail due to a node failure or other form of failure. BigTable [9], HBase, MongoDB [10] and Redis are all CP systems.
- **Available and Partition Tolerant (AP)**: Continues to service requests in the event of failure and partitioning, this is done at the cost of consistency. Usually this is achieved through some form of replication scheme which entails out of date replicas. These replicas are rendered consistent after a given period of time of inactivity. This is generally referred to as eventual consistency. Cassandra [16], Amazon Dynamo [36], Voldemort [34] and CouchDB [2] all follow this model.
- **Consistent and Available Systems (CA)**: Provides consistency and will correctly service requests if there exists no partitioning. Most RDBMS systems fall into this category, including MySQL and Postgres.

Relational Database Management Systems (RDBMS) have long been the standard means of managing large volumes of structured data. The ACID and relational properties associated with RDBMS systems are a limiting factors for many use cases. Occupying the CA portion of the Brewer taxonomy RDBMS systems are unable to provide the same scalability as CP and AP systems. Owing to these characteristics, RDBMs suffer from limitations in scale, performance and fault tolerance which present a bottleneck in cloud systems [1] [19] [37]. In order to achieve vast horizontal scalability and superior performance, the recent trend of NoSQL databases violate these conventions [28]. As a result, NoSQL databases almost entirely lack a conventional relational model and most notably lack the ability to perform joins. In return for this sacrifice NoSQL databases achieve unrivaled scalability. Unlike traditional RDBMS which were initially conceived to operate on a single powerful server and are not easily distributed, NoSQL databases are designed from the ground up to operate over large numbers of servers. This allows NoSQL databases to scale through the addition of further servers. Therefore, NoSQL databases are well suited to storing massive volumes of non-relational, complex data which makes it well suited as a basis for cloud systems. The loss of relational and ACID properties however renders NoSQL unfit for many use cases.

### 3.4 Challenges in Storage

When properly designed and nominalized, RDBMS map well to physical storage mediums and can achieve noteworthy performance. While this performance is eclipsed by that of NoSQL, that performance is gained at the expense of the relational model. Many types of data inherently lend themselves to being represented relationally, especially data regarding people such as customer data or social network data. When these types of data are represented non relationally, as in the case of using NoSQL, relations are often reconstructed out with the purview of the databases. While this regains some of the lost functionality it does not fully counter for the loss of relations within the database. Furthermore as the underlying storage systems of cloud computing rely heavily upon BASE properties there is little support for applications heavily reliant upon strong ACID compliance within the cloud. At present, the Amazon Relational Database Service (RDS) is the predominant means of accessing a ACID compliant
database in a cloud setting. Amazon RDS exposes a web service to deploy and configure SQL databases running in a VM instance. The underlying database is otherwise typical. This does not mitigate the problems of traditional SQL databases and will still suffer from scalability and performance issues when dealing with “big data”. For applications which are heavily dependant upon SQL databases the only way to achieve scalability remains scaling vertically. Hence, an active problem with the area of cloud data storage is the provisioning of relational databases. Most cloud database research has all but forgotten relational databases and moved on to investigating NoSQL and the problems of big data. While big data does pose significant challenges the demands of users tied to relational databases are largely unresolved. What is required is a new relational database developed specifically for the cloud able to scale horizontally and offer some a greater degree of ACID properties than current NoSQL solutions.

3.5 Service Oriented Architecture and Web Services

Service Oriented Architecture (SOA) is in many ways an intermediate step between older concepts in distributed system and the current generation of cloud computing systems. SOA is the practice of developing and providing software as a series of interoperable services. Services as designed as loosely coupled units with minimum interaction between them, with each services providing a single piece of functionality. Individual services are then coordinated through the process of orchestration to build an application that utilises the services.

The ideal of SOA is the clean partitioning and constant representation of distributed resources [12]. This ideal is achieved by abstracting over previous technical and design differences to present a universally accepted standard for the representation of services and information. It is for this reason that cloud computing is highly dependant upon the concept of services. SOA allows cloud computing to abstract over the specifics of the resources being requested allowing for a standard representation of cloud resources.

SOA can be implemented using a number of standards including: DCOM, DDS, CORBA, Java RMI and WCF. It is Web services however which have become a crucial part of cloud computing. Web services are exposed over either using SOAP messages and XML encoding over HTTP or as a RESTful service over HTTP. The combination of these technologies allows for a very simple and open standard for service orientated communication.

Web service encountered an extraordinary growth in popularity in the early 2000s, largely supplanting many earlier technologies. During this time many companies began exposing their services to developers as web services. Simultaneous developments in storage and virtualization led to the marriage of these technologies resulting in cloud computing. Though in many cases they are hidden behind user interfaces, it is web services which expose cloud services.

Web services are a mature and well developed technology and as such have few significant challenges to overcome. Web services are likely to retain their position as the predominant means for accessing cloud services and will likely retain their current form until the next iteration of the web.

4 Issues for Future Cloud Computing

4.1 Bandwidth and Data Movement Costs

Cloud services which are chiefly concerned with storing or operating over data are limited by the bandwidth available to the end user. Despite Internet bandwidth in certain areas of the world achieving gigabit speeds, broadband bandwidths in other regions can be as low as 500kbps. Mobile Internet bandwidth also has the potential to be significant limited and depend on service availability in a given area. Bandwidth limitations pose a significant bottleneck for cloud computing. Not all cloud services are bandwidth intensive, however those which are require substantial bandwidth to achieve timely functionality. The initial upload is often the most significant. A user wishing to make use of a cloud storage service to store a relatively conservative 100 GB could have to wait around 200 hours on a 2 megabit connection for the upload to complete. This problem is even greater in the domain of mobile devices where phones, tablets and other devices attempt to access cloud services through high latency 3G networks where delays even more evident. Substantial delay is obviously probative and will deter users from adopting cloud services where local bandwidth constraints act as a bottleneck. These issues are beyond the purview of cloud providers but are distinct and substantial limitations to the accessibility of their services.
For cloud services to be considered viable alternatives to local data storage it is essential for ubiquitous and fast broadband connections to be available.

4.2 Security and Trust

Cloud computing introduces the possibility for the near universal outsourcing of all computation and data storage requirements. The unprecedented delivery of everything as a service brings with it a number of new security challenges. Trust is an essential element of delivering everything as a service. Confidentiality, integrity and availability of cloud hosted resources is given only as a trust relationship between the client and the cloud provider. Trust management is an approach to symbolically quantify decisions related to trust by combining security policy, access control, cryptography, behavioral analysis and artificial intelligence. The difficulties of trust management is a significant obstacle limiting the growth of cloud computing. The most significant issue of trust management is the acquisition of data from which to derive decisions. The lower the volume of data, the less effective the resulting decision. Part of the difficulty with cloud based systems is that only a portion of the system is visible to the end user. The rest of the system, which is operated by the cloud provider is inaccessible to the end user and as such cannot be factored into trust management. This means that any trust management decision is based on a partial view of the system and as a result is more likely to be incorrect. This is another problem whereby the interests of the user, in this case their interest in security is at odds with the cloud providers desire to obfuscate their infrastructure.

4.3 Mitigating Privilege Based Attacks

The cloud provider has total control over all operations within it’s infrastructure, therefore the integrity of user’s data and software rests entirely on their trust in the provider. There are very few technical provisions to ensure that this trust is not violated. A rouge system administrator with root privileges on the VM hosts can undermine all security mechanisms and obtain access to users’ applications and data. This can be easily achieved by using libVMI or attaching gdb to the VM to access the memory of a user’s VM. This can allow the rouge system administrator access to private keys, plaintext representations of data and the ability to modify any VM state. Furthermore with physical access to the VM host, the rouge administrator can perform a number of side channel attacks and even tamper with the hardware. In order to mitigate the risk of attack it is necessary to provision a of closed box execution environment [23] [22] that ensures confidential VM execution. It is equally necessary to provide a means to securely and accurately attest to the confidentially of the execution environment. At present, without such mechanisms it is impossible for a user to fully trust that their VM instances are not subject to a privileged attack. To date, no such scheme has seen been fully implemented. Despite being in the best interests of users and encouraging greater enterprise cloud adoption the deployment of a trusted hyper vicars is arguably not in the greatest interests of a cloud provider. The deployment of a trusted hypervisor would require the cloud provider to expose access to each host’s trusted hypervisor and restrict their access to their own infrastructure. The development of a trusted cloud computing environment is therefore a trade-off between the confidentiality and security of the users and the amount of control cloud providers exert over their infrastructure.

4.4 Virtual Machine Interoperability

Cloud services are extensively based on VM formats which are specific to a given virtualization technology results in minimal interoperability. For IaaS clouds it is virtual machine image formats and storage formats which are the primary point of incompatibility. Format incompatibility is further compounded by incompatibilities in authentication, billing and resource allocation methods. Lastly, the APIs themselves, despite being based on open standards vary highly between cloud providers and each use alternative structures and semantics. This incompatibility makes migration of VM, storage and other resources between cloud providers difficult and often in the case of large migrations, entirely unfeasible. Significant effort has been made in attempting to standardise aspects of IaaS cloud computing. The Open Virtualization Format (OVF) introduced in 2007 provides a standard format for representing VMs and is the most likely candidate for allowing VM interoperability between IaaS providers. In addition to OVF there are standard efforts underway by the Distributed Management Task Force
Which, if any, of these standards will gain acceptance is uncertain. Each of these standards offer a universal set of APIs and data formats for common IaaS tasks, namely the provisioning of VMs and storage. Unfortunately few cloud providers offer these standardised formats. Each cloud provider offers a number of unique features which are expressed via their own formats and protocols and cannot be easily marshalled into a standard format. This suggests that open standards such as OVF may never be the default formats of IaaS clouds but rather a serialisation format to allow migration from one service provider to another at the loss of features which cannot be represented by the format.

4.5 API Interoperability

The largest and most influential cloud providers utilise predominantly proprietary and closed software. With limited collaboration and communication between providers the earliest iterations of cloud technologies utilised entirely different protocols and access mechanisms and were therefore largely non-interoperable [27]. There has been considerable effort invested in the development of open standards and protocol to facilitate API level interoperation between clouds. Amongst the initial high profile efforts towards clouds interoperability was the Eucalyptus project [24] which provides an open source framework for developing private clouds which are API compatible with Amazon web services. Eucalyptus, however, provides compatibility only with a subset of AWS features and therefore falls short of complete interoperability. The degree of interoperability between Eucalyptus and AWS is also noteworthy as it is now supported by an agreement between the respective companies.

A number of other ad hoc agreements between organizations offer some degree of API compatibility between various, predominantly proprietary software. In each case there is less than complete API compatibility, with obscure, legacy or new features being excluded. In addition to these ad hoc agreements there are a number of standards bodies which have published sets of interoperability standards for cloud computing. These formalised standards have varying degrees of adoption. Organizations including the Cloud Management Unitive, the IEEE, the Cloud Industry Forum and the Cloud Standards Council and OASIS [26] have either proposed or advocated the adoption of a set of cloud standards. Unfortunately, as is typical in the early stages of standards development there is a wide and often incompatible set of cloud computing standards. There are at least a dozen additional organisations either specifically dedicated to cloud standardisation or otherwise involved in cloud standardisation which have each released a number of draft standards [35]. Few of these standards have however achieved significant adoption beyond niche areas.

This vast array of potential standards has inhibited the universal adoption of a single standard. A likely candidate for providing a future basis for interoperability is the OpenStack project. Openstack [31] provides a open source cloud computing platform and is backed by over 20 significant industry bodies. In addition to providing a set of interoperability guidelines, Openstack also implements those guidelines providing a reference implementation for other developers. The availability of a working implementation of their own standards has placed OpenStack in a superior position to competing standards which have yet to have significant implementations. The availability of an open, standardised cloud platform has seen numerous cloud providers including Red Hat, VMWare, HP and Citrix adopt all or part of the Openstack standards within their own technologies. While the public cloud market is still held firmly by the likes of Amazon EC2, Windows Azure and Rackspace Cloud, OpenStack is proving to be a dominant force in the private cloud market. OpenStack has been extensively deployed by industry, government and academia. Organisations including NASA, The US Department of Energy and HP all operate significant private cloud deployments based on OpenStack and adhering to open standards [32]. It is therefore the case that while other efforts continue to develop standardised APIs the best accepted standards are those of OpenStack due to the availability of a working implementation of those standards. The viability of other standards is thus dependant upon the implementation of these standards in real world software. Failure to provide implementations of cloud standards will inevitably see the demise of many of the current range of standards attempts.

4.6 Cloud Compliance

Certification has long been a well accepted means to enforce compliance with a standard. Typical standards enforce security mechanisms, performance levels and the use of specific technologies. Certification in order to
ensure compliance to a given standard is a process common to many fields. Payment processing, the storage of confidential data and the providing services as an affiliate of a third party organisation all frequently require some form of compliance process in order to obtain the necessary authorisation. Such standards are vast, complex and well established and many were written without cloud computing in mind.

As such, cloud computing is incompatible with many significant standards [20]. Many security security standards require physical access to hardware to be controlled, network communication to be isolated and all third parties barred from accessing data. In the context of cloud computing there is no ability to manage physical access, resources are shared between a large pool of users and the cloud provider conceptually has access to users' data. Standards which enforce performance requirements fare better with cloud computing but still have some limitations. In clouds where VMs are not given exclusive access to a processor there is periodic context switching. This alone prohibits compliance to standards pertaining to real time applications. Furthermore the inability to guarantee exact levels of bandwidth, latency and other metrics is prohibitive against standards requiring network guarantees.

In an initial attempt to placate users which require certain standards to be guaranteed cloud providers provided Service Level Agreements which made moderate claims as to security, uptime, network properties and performance. Due to some degree of ambiguity and range of interpretations with PCI and ISO standards some organisations which require the likes of PCI-DSS compliance have taken SLA guarantees as adequate to maintain compliance [29]. Therefore major cloud providers have strived to achieve compliance for a number of basic standards. Amazon Web Services, Rackspace Cloud, Azure and others have achieved certified compliance with the PCI-DSS Level 1 and ISO 27001 security standards [33]. Compliance with these standards is to perform credit card processing and the handling of other financial data. Cloud providers’ adherence to these standards allows users who deal with such use cases to provision part of their architecture in the cloud. These new standards will allow ‘business as usual’ in the cloud but do so by removing the need for physical access, dedicated infrastructure and other concepts which are fundamentally incompatible with cloud computing.

There are however other, more strict standards which cloud providers have yet to achieve which prohibit other use cases from being performed in the cloud. Data protection standards, confidentiality standards and more stringent financial services standards have yet to be adopted by any major cloud provider. Instead standards bodies have begun to develop a series of standards intended specifically for cloud computing. Organisations including the PCI, ISO, the BSI and others have begun developing and releasing new standards which avoid inherent incompatibilities with cloud computing.

Whether cloud specific standards gain acceptance by cloud providers and whether or not relevant industries accept these new standards as being equal to current standards will determine the success of cloud specific standards compliance.

4.7 Government Regulation

In 2010 following the release of a series of diplomatic cables, controversial website Wikileaks encountered a substantial multi gigabit Distributed Denial of Service attack. In order to mitigate the effects of this attack Wikileaks migrated their operations to Amazon Web Services [4]. AWS effectively resisted the attack and allowed Wikileaks to continue operating for several hours until Amazon was compelled by the US government to terminate all Wikileaks operations on AWS. This was not the first case where a government or government agency has compelled a cloud provider to withdraw their services, it is however the largest and most high profile incident. The Wikileaks event sets an uneasy precedent. Despite Wikileaks making use of Amazon European data center they were sanctioned under US law. One of the often touted properties of the cloud is that data is seldom hosted in a known location. With some services, data can at best be localised to the data center. These creates a complex jurisdictional issue. What groups can assert control over data and services hosted in the cloud. Case can be made for the cloud provider, the cloud provider’s government and the government of the country which hosts the data. Without a comprehensive legal framework in place it is impossible to conclusively argue what parties cannot access or otherwise interfere with cloud based operations. This issue is problematic for organisations such as Wikileaks which are not well received by world governments. Unfavorable organisations can be effectively barred from operating on the cloud by any organisations able to exert influence against the provider. Worse still is the possibility that governments can compel cloud providers to provide access to client’s services or data. This
is a major problem for cloud computing and if this issue remains unanswered could potentially see cloud providers relinquishing user and company data to world governments based on a legal mandate.

5 Summary Of Issues and Conclusion

The decreasing costs and increasing performance, flexibility and scalability of cloud computing systems offers cloud providers, industry, developers and users both a comprehensive set of advantages and a significant set of challenges:

For cloud providers: to continue delivering a cloud service requires significant investment in meeting the increasing demand for resources. The initial investment and total cost of ownership of cloud infrastructure represents a significant and increasing cost. In order to reduce these overheads and elicit future development new methods are required to improve resource utilisation, detect and reduce wastage and to reduce management complexity.

For Industry: the lack of government and industry certification for cloud systems is a substantial barrier to industry cloud adoption. Outsourcing mission critical operations to a cloud provider is an uncomfortable paradigm for many corporations. The development of robust certification and compliance testing for cloud providers will alleviate some of these concerns however, further development is required to reduce the costs and complexity of managing large scale cloud systems.

For developers: cloud computing will allow the deployment of applications at significant scale. While at present it is possible to leverage cloud computing to deploy scalable applications, this is generally achieved by adapting conventional software to operate in a cloud context. Continued cloud development will require the abandonment of many existing programming paradigms in favour of developing applications specifically designed to operate at scale in the cloud. This will also require the reevaluation of software engineering practice to provide a formally quantifiable approach to the design, implementation and maintenance of cloud applications.

For users: limited network access and limited bandwidth are significant barriers to the availability of cloud services and data. In order to ensure that cloud services are continually available substantial improvement to network infrastructure is required. Furthermore the lack of common standards and robust security mechanisms creates the risk of vendor lock in, loss and theft of data.

The late 2000s saw three separate fields co-evolve to develop cloud computing, which has in turn become a critical and highly influential technology. Amazon EC2 alone has grown from an alternative use of Amazon’s unused capacity to becoming the largest web host in the world [18]. At present, cloud services are used in combination with conventional services and software. The future will see the provisioning of resources as a service become ubiquitous. To achieve this future a number of challenges must be answered.

The compute resources being made available on the cloud are now becoming suitable for high performance scientific computation. However it is clear that at present the cloud lacks the necessary federation mechanisms and sufficient middleware platforms as to allow for the effective execution of eScience workloads. While the middleware of grid computing can be ported to the cloud it lacks sufficient integration with the platform and fails to offer the degree of automation provided by the grid. The economy of cloud computing suggests that IaaS services may be significantly cheaper than cluster or grid use for certain workloads making cloud services a desirable option for eScience. This necessitates the development of frameworks to provide a managed execution environment for eScience workloads on an IaaS cloud.

Security and confidentiality issues remain a significant challenge to enterprise and government cloud adoption. Despite significant cloud security research, we still lack a convincing model of trust in IaaS clouds. There is a clear challenge remaining in developing mechanisms to provide a clear and transparent model of security and trust for IaaS cloud services in simple and intelligible manner.

Cloud computing entails universal outsourcing of data. Users and businesses have never before faced the problems of having their data stored by a third party at such a scale. With increasing consumer and business
services leveraging the cloud model it is becoming clear that it is essential for a comprehensive legal framework to provide an unambiguous definition as to what rights cloud providers have to users' data.

Conceptually cloud services afford a user superior adaptability and flexibility compared to conventional services. Unfortunately the lack of universal interoperability standards limits the ability of users to migrate from one cloud service to another. There exists the significant danger of vendor lock in when a user has committed significant resources to a cloud provider as the costs and technical difficulties of migration may be prohibitive. To avoid the single vendor market that existed during the mainframe era it is necessary for cloud interoperability to be further developed and to be accepted both by users and by cloud providers.

Once these challenges and others have been overcome it will become feasible for the provisioning of virtually all services and resources via a cloud computing model. Cloud computing will eventually become the dominant platform for Internet based hosting, storage, computation and communication and will be one of the foundations of the next generation Internet.

References

[1] Rakesh Agrawal, Anastasia Ailamaki, Philip A. Bernstein, Eric A. Brewer, Michael J. Carey, Surajit Chaudhuri, AnHai Doan, Daniela Florescu, Michael J. Franklin, Hector García-Molina, Johannes Gehrke, Le Gruenwald, Laura M. Haas, Alon Y. HalevY, Joseph M. Hellerstein, Yannis E. Ioannidis, Hank F. Korth, Donald Kossmann, Samuel Madden, Roger Magoulas, Beng Chin Ooi, Tim O'Reilly, Raghu Ramakrishnan, Sunita Sarawagi, Michael Stonebraker, Alexander S. Szalay, and Gerhard Weikum. The claremont report on database research. SIGMOD Rec, 37(3):9–19, September 2008.

[2] Chris Anderson, Jan Lehnardt, and Noah Slater. CouchDB: The Definitive Guide: The Definitive Guide. O'Reilly Media, 2010.

[3] Michael Armbrust, Armando Fox, Rean Griffith, Anthony D. Joseph, Randy Katz, Andy Konwinski, Gunho Lee, David Patterson, Ariel Rabkin, Ion Stoica, and Matei Zaharia. A view of cloud computing. Commun. ACM, 53(4):50–58, April 2010.

[4] Charles Arthur. Wikileaks evades hackers with shift to amazon, 2010.

[5] Paul Barham, Boris Dragovic, Keir Fraser, Steven Hand, Tim Harris, Alex Ho, Rolf Neugebauer, Ian Pratt, and Andrew Warfield. Xen and the art of virtualization. In Proceedings of the nineteenth ACM symposium on Operating systems principles, SOSP '03, pages 164–177, New York, NY, USA, 2003. ACM.

[6] Dhruba Borthakur. The hadoop distributed file system: Architecture and design. 2007.

[7] Eric A. Brewer. Towards robust distributed systems (abstract). In Proceedings of the nineteenth annual ACM symposium on Principles of distributed computing, PODC '00, pages 7–, New York, NY, USA, 2000. ACM.

[8] Brad Calder, Ju Wang, Aaron Ogus, Niranjan Nilakantan, Arild Skjølsvold, Sam McKelvie, Yikang Xu, Shashwat Srivastav, Jiesheng Wu, Huseyn Simitci, Jaidev Haridas, Chakravarthi Uddaraju, Hemal Khatri, Andrew Edwards, Vaman Bedekar, Shane Mainali, Rafay Abbasi, Arpit Agarwal, Mian Fahim ul Haq, Muhammad Ikram ul Haq, Deepali Bhardwaj, Sowmya Dayanand, Anitha Adusumilli, Marvin McNett, Sriram Sankaran, Kavitha Manivannan, and Leonidas Rigas. Windows azure storage: a highly available cloud storage service with strong consistency. In Proceedings of the Twenty-Third ACM Symposium on Operating Systems Principles, SOSP '11, pages 143–157, New York, NY, USA, 2011. ACM.

[9] Fay Chang, Jeffrey Dean, Sanjay Ghemawat, Wilson C Hsieh, Deborah A Wallach, Mike Burrows, Tushar Chandra, Andrew Fikes, and Robert E Gruber. Bigtable: A distributed storage system for structured data. ACM Transactions on Computer Systems (TOCS), 26(2):4, 2008.

[10] Kristina Chodorow and Michael Dirolf. MongoDB: the definitive guide. O'Reilly Media, 2010.
[11] The Linux Scalability Effort. Linux support for numa hardware. http://lse.sourceforge.net/numa/.

[12] Thomas Erl. Service Orientated Architecture, Concepts, Technology and Design. 2005.

[13] Distributed Management Task Force. Cloud management initiative. http://dmtf.org/standards/cloud.

[14] The Open Grid Foundation. The open cloud computing interface. http://occi-wg.org/.

[15] Seth Gilbert and Nancy Lynch. Brewer’s conjecture and the feasibility of consistent, available, partition-tolerant web services. SIGACT News, 33(2):51–59, June 2002.

[16] Avinash Lakshman and Prashant Malik. Cassandra: a decentralized structured storage system. ACM SIGOPS Operating Systems Review, 44(2):35–40, 2010.

[17] Neal Leavitt. Will nosql databases live up to their promise? Computer, 43(2):12–14, 2010.

[18] Netcraft Ltd. Amazon web services’ growth unrelenting. http://news.netcraft.com/archives/2013/05/20/amazon-web-services-growth-unrelenting.html.

[19] Simon Malkowski, Deepal Jayasinghe, Markus Hedwig, Junhee Park, Yasuhiro Kanemasa, and Calton Pu. Empirical analysis of database server scalability using an n-tier benchmark with read-intensive workload. In Proceedings of the 2010 ACM Symposium on Applied Computing, SAC ’10, pages 1680–1687, New York, NY, USA, 2010. ACM.

[20] Tim Mather, Subra Kumaraswamy, and Shahed Latif. Cloud security and privacy: an enterprise perspective on risks and compliance. O’Reilly Media, 2009.

[21] Peter Mell and Tim Grance. The nist definition of cloud computing. National Institute of Standards and Technology, 53(6):50, 2009.

[22] Aravind Menon, Jose Renato Santos, Yoshio Turner, G. (John) Janakiraman, and Willy Zwaenepoel. Diagnosing performance overheads in the xen virtual machine environment. In Proceedings of the 1st ACM/USENIX international conference on Virtual execution environments, VEE ’05, pages 13–23, New York, NY, USA, 2005. ACM.

[23] Aravind Menon, Jose Renato Santos, Yoshio Turner, G. (John) Janakiraman, and Willy Zwaenepoel. Diagnosing performance overheads in the xen virtual machine environment. In Proceedings of the 1st ACM/USENIX international conference on Virtual execution environments, VEE ’05, pages 13–23, New York, NY, USA, 2005. ACM.

[24] Daniel Nurmi, Rich Wolski, Chris Grzegorczyk, Graziano Obertelli, Sunil Soman, Lamia Youseff, and Dmitrii Zagorodnov. The eucalyptus open-source cloud-computing system. In Cluster Computing and the Grid, 2009. CCGRID’09. 9th IEEE/ACM International Symposium on, pages 124–131. IEEE, 2009.

[25] Mayur R. Palankar, Adriana Iamnitchi, Matei Ripeanu, and Simson Garfinkel. Amazon s3 for science grids: a viable solution? In Proceedings of the 2008 international workshop on Data-aware distributed computing, DADC ’08, pages 55–64, New York, NY, USA, 2008. ACM.

[26] AV Parameswaran and Asheesh Chaddha. Cloud interoperability and standardization. SETLabs Briefings, 7(7):19–26, 2009.

[27] Dana Petcu, Ciprian Craciun, and Massimiliano Rak. Towards a cross platform cloud api. Components for Cloud Federation, Procs. CLOSER, pages 166–169, 2011.

[28] Jaroslav Pokorny. Nosql databases: a step to database scalability in web environment. In Proceedings of the 13th International Conference on Information Integration and Web-based Applications and Services, iiWAS ’11, pages 278–283, New York, NY, USA, 2011. ACM.
[29] Kresimir Popovic and Zeljko Hocenski. Cloud computing security issues and challenges. In *MIPRO, 2010 proceedings of the 33rd international convention*, pages 344–349. IEEE, 2010.

[30] Dan Pritchett. Base: An acid alternative. *Queue*, 6(3):48–55, May 2008.

[31] Rackspace. Openstack open source cloud computing software. http://www.openstack.org/.

[32] Rackspace. Openstack uses stories. http://www.openstack.org/user-stories/.

[33] S Subashini and V Kavitha. A survey on security issues in service delivery models of cloud computing. *Journal of Network and Computer Applications*, 34(1):1–11, 2011.

[34] Roshan Sumbaly, Jay Kreps, Lei Gao, Alex Feinberg, Chinmay Soman, and Sam Shah. Serving large-scale batch computed data with project voldemort. In *Proceedings of the 10th USENIX conference on File and Storage Technologies*, pages 18–18. USENIX Association, 2012.

[35] various authors. The cloud standards wiki. http://cloud-standards.org/wiki/index.php.

[36] Werner Vogels. Eventually consistent. *Communications of the ACM*, 52(1):40–44, 2009.

[37] Hiroshi Wada, Alan Fekete, Liang Zhao, Kevin Lee, and Anna Liu. Data Consistency Properties and the Trade-offs in Commercial Cloud Storages : the Consumers Perspective. pages 134–143, 2011.