Interoperable Convergence of Storage, Networking and Computation

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Abstract

In every form of digital store-and-forward communication, intermediate forwarding nodes are computers, with attendant memory and processing resources. This has inevitably given rise to efforts to create a wide area infrastructure that goes beyond simple store and forward, a facility that makes more general and varied use of the potential of this collection of increasingly powerful nodes. Historically, efforts in this direction predate the advent of globally routed packet networking. The desire for a converged infrastructure of this kind has only intensified over the last 30 years, as memory, storage and processing resources have both increased in density and speed while simultaneously decreasing in cost. Although there seems to be a general consensus that it should be possible to define and deploy such a dramatically more capable wide area facility, a great deal of investment in research prototypes has yet to produce a credible candidate architecture. Drawing on technical analysis, historical examples, and case studies, we present an argument for the hypothesis that in order to realize a distributed system with the kind of convergent generality and deployment scalability that might qualify as “future-defining,” we must build it up from a small set of simple, generic, and limited abstractions of the low level processing, storage and network resources of its intermediate nodes.

1 Introduction

A variety of technological, economic, and social developments — most notably the general movement toward Smart Cities, the Internet of Things, and other forms of “intelligent infrastructure” [1] — are prompting calls from various quarters for something that the distributed systems community has long aspired to create: A next-generation Internet. For example, the authors of a recent Computing Community Consortium white paper, writing with the US “Smart Cities” initiative [2] in view, express the research challenge as follows:

“What is lacking—and what is necessary to define in the future—is a common, open, underlying ‘platform’, analogous to (but much more complex than) the Internet or Web, allowing applications and services to be developed as modular, extensible, interoperable components. To achieve the level of interoperation and innovation in Smart Cities that we have seen in the Internet will require federal investment in the basic research and development of an analogous open platform for intelligent infrastructure, tested and evaluated openly through the same inclusive, open, consensus-driven approach that created Internet.” [3] [Emphasis in source]

The experiences of the last two decades have made the distributed systems community acutely aware of how elusive the invention of such a future-defining platform is likely to be. After all, achieving this vision has been the explicit or implicit ambition of a succession of well funded and energetically pursued research and development efforts within or around this community, including Active Networking [4], Grid Computing [5], PlanetLab [6], and GENI [7], to name a few. Although these broad efforts have produced both valuable research and useful software results, nothing delivered so far has achieved the kind of deployment scalability necessary initiate the kind of viral growth that everyone expects such an aspirational platform to exhibit. At the same time, chronic problems with network hotspots were an early and persistent sign that the Internet’s stateless, unicast datagram service had scalability limitations with respect to data volume and/or popularity. This fact has led to increasingly sophisticated and increasingly expensive technology “workarounds,” from the FTP mirror sites and hierarchical Web caches of the early years, to the content delivery networks (CDN) and commercial Clouds we see today.

The central idea of this paper is that the appropriate common service on which to base an interoperable platform to support distributed systems is an abstraction of the low layer resources and services of the intermediate node, i.e., a generalization of the Internet stack’s layer 2. Drawing on technical analysis, historical examples, and case studies, in this paper we argue that in order to build distributed systems with the kind of interoperability, generality and deployment scalability that might qualify as “future-defining,” we must implement them using a small set of simple, generic, and limited abstractions of the data transfer, storage and processing services available at this layer. In our model, these abstractions all revolve around the most fundamental common resource, namely, the memory/storage buffer.
2 Background

Given the inclination of computer scientists to add features, the fact that every form of digital store-and-forward communication (including the Internet) has intermediate forwarding nodes that are computers, with attendant memory and processing resources, makes attempts to create a wide area infrastructure with services beyond simple store-and-forward inevitable. Such efforts to make more general use of these increasingly powerful nodes—a generalized converged network, in our terminology—predate the advent of globally routed packet networking (e.g. uux [8]). The exponentially increasing density and speed, and rapidly decreasing cost of memory, storage and processing resources over the past 30 years has only intensified the desire to define and scalably deploy a converged infrastructure of this general description; and yet despite the general consensus that it should be possible to do so, this aspiration has remained unfulfilled.

One problem is that the goal of converged networking runs in the opposite direction of the traditional architectural approach of the traditional Internet design community, which insists that services other than datagram delivery must be kept out of the Network Layer of the communication protocol stack. This community maintains that the ability of the Internet to function properly and to continue growing globally depends on keeping this common service layer “thin”, in the sense that it provides services that are simple, generic and limited [9]. From this point of view, services other than datagram delivery should be implemented in systems connected to the Internet as communication endpoints. Various rationales that support this point of view has been collectively referred to as “End-to-End Arguments”[9].

Since a router that has substantial system storage (i.e. other than network buffers) and generalized computational resources (i.e. other than forwarding) is neither difficult nor expensive to build, there have been numerous efforts to resist this orthodox point of view. The simple fact that storage and computational resources can be provisioned and located throughout the network at reasonable cost stimulates efforts in this direction. Moreover, the apparent opportunity to create such a powerful distributed infrastructure presents a temptation that is inherently difficult for computer scientists and engineers to resist. These facts, however, do not make it a good idea to add extensions to the fundamental service of the global Internet, nor do they ensure that if it is built, service creators and users will adopt it in sufficient numbers to enable economic sustainability beyond the prototype stage. Indeed, while a number of plausible network service architectures have been defined that can provide access to such distributed resources [4,10], the widespread deployment of such extended services on a converged wide area infrastructure has so far not been achieved.

Perhaps an even more compelling reason for the continued drive to create such a converged infrastructure is that some important distributed applications cannot be efficiently and effectively implemented through decomposition into two components, one implemented by a “thin” datagram delivery service and the other implemented at “fat” endpoints. For example, some applications require an implementation that is sensitive to the location of storage and computation in the network topology. Point-to-multipoint communication was an early and obvious example. Using simple repetition of unicast datagram delivery was viewed as too inefficient by early Internet architects, but an efficient tree could be built only through the use of network topology information. Such low level information was seen as inappropriate for users of the “thin” and stable Network layer to access. Thus, multicast was added to Layer 3, fattening that thin layer with services that seemed to address this issue. However, IP multicast has proved difficult to standardize and has failed to achieve the universal deployment of “simple, generic and limited” unicast IP datagram delivery.

But problems with lack of generality in the intermediate nodes were manifest even in highly successful Internet applications. The early growth of the Internet was fueled by applications that seemed to fit the unicast datagram delivery model well enough: FTP and Telnet. Of these, the one-to-many nature of FTP, albeit asynchronous, created a problem in the distribution of popular and high-volume files. Ignoring the implications of topology led to ineffective use of the network, with hotspots at servers that attracted high volumes of traffic and unnecessary loads placed on expensive and overburdened wide area links. The result was the creation and management of collections of FTP mirror sites [11], and the ubiquitous invitation for users to “choose a mirror site near you”, which meant the use of approximate information about network topology by the end-user, at a level above even the Internet stack’s Application Layer.

The advent of the World Wide Web exacerbated the problem of indiscriminate access to servers with no reference to network topology or even geography. Mirror sites for file download proliferated, and redundancy in the storage of all high-traffic Web content became a necessity. A Network layer ignorant of topology is, after all, an inherently inadequate platform on which to build high traffic globally distributed systems. The need to work around this reality gave rise to automated Web caching [12,13] and server replication [14,15], which were precursors to modern Content Delivery Networks [16,17].

It should be noted that, although both Web caching and server replication are obvious examples of the convergence of networking and storage, they also require computation in the implementation of policy and server-side processing; and so in fact they represent convergence of all three fundamental computational resources. Logistical Networking, discussed in Section 7.1 implements a convergence of networking and storage service that avoids the need for general computation by minimizing policy and other server-side processing [18], but was later extended to include limited server-side operations [19].
3 The Dialectic of Divergence and Convergence
The interplay between technological divergence and convergence is a dialectic with a long history. In the area of computing and communications, there was an early divergence in the conception and implementation of several different information technology resources. Because of the phenomenon of path dependence [20], such divergence has tended to be self-reinforcing, leading to a set of familiar technology silos:

- Radio frequency analog audio and video transmissions are well adapted to unidirectional one-to-many communication, and gave rise to traditional broadcast medium.
- Circuit-based digital and analog audio/video transmissions are well adapted to point-to-point communication, and gave rise to traditional telegraph, telephone and (local area) video networks.
- Tube and transistor amplifiers and switches are well adapted to the implementation of Boolean logic, and gave rise to digital computation circuits and functional units.
- Capacitors and magnetic storage cells are well adapted to implementation of value persistence, and gave rise to digital memory and storage systems.

This early divergence has given rise to conceptual, technological and organizational silos corresponding to correspondingly isolated communities. Formal models and methods of reasoning have been adapted to deal with the complexity and specific issues of each niche. For example:

- Boolean logic is a useful tool for modeling the function of aggregations of transistors (gates) connected to persistent memory cells (variables). This has given rise to the development of Boolean Logic Design as a specialized discipline.
- Circuit-based communication without “hard state” is a useful tool for modeling the function of scaleable, wide area computer-to-computer services. This has given rise to the development of Computer Networking as a specialized discipline.

The development of silos has been an enabling strategy for modeling and optimization of these quickly evolving technological fields. However, they have also led to the creation of service stacks, or silos, with highly specialized services at the top layers (see Figure 1). But because the low level resources that these silos encapsulate can only be accessed through high level services, this inevitably tends to create barriers to the natural and efficient use of constituent low level resources.

The problem with silos as a strategy for dealing with the complexity and specialization of disparate underlying technologies has become more pronounced due to the evolution of low level systems toward general mechanisms that utilize processors or digital logic controlled by software, firmware or by hardware designed using computerized tools. Such generality in low level mechanisms holds out the possibility of the implementation of highly efficient system architectures, with optimizations that span traditionally disparate resources. The challenge is to bridge or eliminate the existing silos, or, in other words, to implement convergence. However, there are two fundamentally different strategies for achieving convergence: overlay convergence which combines silos at a layer above their high level services, and interoperable convergence which unifies their foundations. We discuss these two strategies in turn below.

We use familiar illustrative examples throughout the remainder of this paper to help the reader understand the terms being defined. We then use more detailed case studies to elaborate the implications of applying the concepts we have introduced.

4 Convergence
We say that a service interface (i.e., an API) is converged if it gives unified access to multiple low-level resources (or services) traditionally available only through isolated service silos.

For example, one of the areas where disparate underlying resources have been brought together in common solid-state implementation technologies and under interoperable digital control is the CPU core, system communication buses and memory subsystems of modern computers, which are not fully siloed.

- A simple example of the convergence of storage and processing is in the auto-increment register.
- Vector processing represents the convergence in the control of registers, processor buses and functional units.
- DMA disk operations can require the coordination of magnetic storage involving complex controller hardware and firmware, system buses with autonomous control logic, processor buses and memory subsystems and synchronization with operating system drivers through interrupts.

A common approach to convergence among non-interoperable resources is to create a high level interface that provides access to a number of traditionally separate service silos. We term this approach overlay convergence because it typically involves the creation of an overlay service that accesses the existing service stacks through their high level client interfaces (see Figure 1).
By contrast, at the other end of the convergence spectrum is what we call **interoperable convergence**, which is discussed at some length in Section 5. Interoperable convergence allows access to the underlying common resources without imposing the overhead and restrictions that are associated with complex and specialized service silos. Some examples that fall along this continuum are give below:

- The BSD kernel created an overlay convergence of Unix process and local file management with local and wide area networking through the addition of the *socket* related system calls. While some file system calls such as *read* and *write* were extended to operate on sockets, the level of integration was a convenience that did not extend deeply into integration of common functions such as buffer management.

- A distributed file system converges storage and data movement in a more interoperable manner. These resources are traditionally available through local file management and networked file transfer tools.

- A database system that allows a filter to be uploaded (perhaps as JVM byte-code) and applied to the contents of a relation in-situ converges storage and computation. This also represents a more interoperable form of convergence.

4.1 Case Study: Broadcast Media, Telephony and Internet

Broadcast media (radio and television) have their technological roots in the propagation properties of radio frequency (RF) waves. A wave emanating from an antenna spreads in all spatial directions, becoming attenuated as the inverse of the squared distance from the source. Governmental agencies such as the Federal Communication Commission use extensive application procedures and public hearings as a means of contending for allocation of RF bandwidth at fixed frequencies. This allows a powerful signal to be received and amplified to a useful level within a reception area, the extent of which depends on a number of factors including intervening geography, structures, meteorological and astronomical conditions and events. Each receiver is independent and has no impact on others.

Telephony has its technological roots in the propagation of electrons along a wire. A voltage placed on one end of a wire will be transmitted throughout the extent of electrical connectivity, so that a signal encoded as a varying voltage level can be seen and amplified by one or more receivers. The broadcast form of simple telephony is used in local area public address systems, but its main application is as a component in the creation of wide area circuits controlled and extended using switches and intermediate amplifiers. The control of these intermediate elements is greatly simplified by the restriction of telephony to point-to-point circuits, which serves the largest application community. In the context of wide area point-to-point telephony, propagation to multiple receivers (conference calling) is implemented using multiple point-to-point circuits connected at a hub.

Packet networking uses either a broadcast or a circuit infrastructure to connect digital switches which communicate data encoded using the underlying analog signaling mechanism. Switches and repeaters can either implement “virtual circuits” or a stateless datagram delivery model. As is the case with telephony, resource allocation and control are greatly simplified through the implementation of point-to-point communication (unicast). Broadcast can be implemented using repeated unicast in a hub topology (as with telephony) or it can be implemented using a more complex but more efficient tree-structured forwarding scheme.

The generality and scalability of the Internet’s datagram delivery model has given rise to the idea of using it to implement the convergence of broadcast, telephony and data services. The emergence of unicast datagram delivery as the only universal Internet service (discussed in Section 2) has meant that the underlying capabilities of analog connectivity mechanisms to implement true broadcast and to provide quality of service guarantees through resource reservation are not accessible to Voice over IP and Streaming Media over IP protocols. In spite of such limitations, the convenience and cost benefits of convergence workarounds continue to dominate the commercial development of these services.

4.1.1 Case Study: Web Caching and CDNs

The absence of a universal point-to-multipoint communication mechanism within the common Network layer of the Internet has generated a whole series of overlay workarounds (see Figure 2). For instance, the distribution of static Web pages (those that
require only minimal rewriting of stored HTML pages) can be viewed as a form of point-to-multipoint application. A browser cache uses moderate storage resources in the network endpoint to capture the delivered Web page and associated metadata and minimal processing to implement the cache policy and mechanism. A proxy cache uses larger scale storage and has a greater processing load, which is supplied by a substantially provisioned network intermediate node. The convergence of resources in Web caches led to an architectural development in which application-specific proxies are uploaded to the a “middlebox” platform which implements both caching and general processing.

An alternative approach is to start from the source, and to replicate the functionality of the Web server on multiple network nodes. Manual procedures for FTP mirroring led to automated mechanisms like Netlib [11], and high traffic Web sites gave rise to sophisticated cluster and geographically distributed server replication schemes [14, 15]. Modern Content Delivery Networks use a combination of server side caching, distributed file and database systems and complex streaming and synchronization protocols implemented on proprietary international networks of application-specific servers.

As Figure 2 suggests, the Content Delivery Network industry is based on workarounds. Commercial CDNs even make use of lower layer Internet mechanisms through now-commonplace layering violations (such as topology-sensitive DNS resolution). CDNs are thus a kind of Chimera, patched together from proprietary components and standard, low level components of the Internet.

5 Interoperable Convergence

We say that a converged platform is interoperable if it minimizes the imposition of unnecessary high-level structure or performance costs when applying different low-level services.

5.1 Examples

- The POSIX kernel interface supports both networking and file storage. However, in order to move data stored in a file to a TCP stream, it was originally necessary to move it into a process’ address space using the read() system call and then inject it into the TCP stream using send(). A more interoperable approach is a combined sendfile() system call was added to Linux that allows data to be transferred from storage into a kernel memory buffer and from there directly to the network without moving it to process memory or using a dedicated network data buffer.

- A database system can store a set of tuples without order, but traditional data movement tools operate on files. Thus, it is necessary to serialize a set of tuples as a file in order to send it to a remote database system. The file is transferred serially, using TCP with retransmission to keep the serialized data in order. A somewhat interoperable approach would
generate the serialized stream representing the tuple set on demand, rather than creating and storing it as a complete file. A more interoperable approach would be to implement a specialized protocol that takes advantage of the lack of natural sequentiality in the tuple set to perform retransmission out-of-order. This might require additional work to ensure that the new protocol was “TCP-friendly” when used in public shared networks.

- A data analysis system (such as MapReduce [21]) traditionally consists of a deep data store and a dedicated compute resource such as a cluster or a shared-memory parallel computer. Visualization requires data to be moved from the data store to the compute resource which produces its results to the data store. User access then requires that the visualization output be moved to and interpreted by a human interaction system. A more interoperable approach would allow computations to be applied to the data in the data store (in-situ), and for the user to interact with the results of that computation directly as it occurs.

5.2 Case Study: Web Caching and CDNs

Web caching played a pivotal role in the expansion of the Web as a global data distribution service during the period when intercontinental data links were too expensive to allow unfettered access by academics. A hierarchical system of large scale caches was developed and deployed in US Research and Education Networks [12, 13] and use of national caches to access Web data across intercontinental links was made mandatory in many countries including the UK [22].

In spite of its effectiveness in reducing the traffic loads due to delivery of static Web pages, the popularity of intermediate caches has waned dramatically in the past decade. There are several reasons for this trend including:

- The correctness of Web caching relies on lifetime metadata being provided by origin servers which is often missing or inaccurate.
- The growth of dynamic Web applications means that many Web objects are not cachable.
- The lack of an accurate and universal mechanisms for reporting views interferes with the dominant business model of Web advertisers.
- Reliance on a complex cache infrastructure decreases the control of the implementer of a Web service over the Quality of Service experienced by customers.

Many of these factors stem from the implementation of Web caching on top of the HTTP application protocol, albeit with some modifications having been made to increase control over intermediate and browser caches by origin Web servers. Cache networks are an overlay which accesses Web services from the top of the protocol stack and thus does not allow the degree of fine-grained control that is required for seamless convergence.

Content Delivery Networks have approached the problem in a different way, using HTTP and streaming protocols for client access almost unchanged. This is analogous to the way that online services (e.g. Compuserve and AOL) and ISPs used telephone services. CDNs have instead focused their innovation on the underpinnings of the Internet in order to improve the effectiveness and their control over server replication.

Content Delivery Network Web and DNS servers appear to be implemented at the application level, but they use knowledge of network topology and other low level information that is intended to be encapsulated within the Network Layer of the Internet architecture. Modern extensions to the Network Layer may allow this to be implemented without violation of layering, at the expense of creating a “fatter” and less generic Network layer (see Section [6]).

One way of looking at the growth of CDNs is that they are creating a proprietary, specialized network with their own services as the spanning layer, using the Internet as tools in their implementation and as a means of reaching end users. This view is
supported by the trend toward using private or non-scalable mechanisms to implement internal communication among centralized and distributed CDN nodes.

5.3 Case Study: Edge Content Delivery

An extreme form of content delivery moves storage and processing resources to a server located within the edge network, either having a dedicated connection or being topologically very near to the end user interface. This approach has been long been pursued in consumer entertainment, with strategies have ranging from storage-intensive (eg TiVo, PVRs and Boxee) to near-stateless streaming (eg Roku, Smart TV) with high end offerings incorporating both (eg Apple TV, Multimedia PCs).

Efforts to use intermittently or marginally connected servers to overcome backbone connectivity challenges in rural and other isolated areas date back over twenty years [23][24] and continue as approaches to reaching schools and communities in the developing world, including nonprofit projects OuterNet, Kolibri, Critical Links (C3), and Libraries without Borders (Koombox) and companies such as BRCK.

5.4 Case Study: In-locus Data Analysis

Data Analytics (DA) has emerged as a new paradigm of understanding unreliably varying environments. It goes beyond logging, reporting, and thresholding to perform meaningful analysis of large scale data sources that are networked through dynamic and distributed infrastructure. DA is capable of extracting latent knowledge and providing insight from field sensors, computational units, and large mobile networks. At the same time, the number of these data sources and the resulting ingest rate are growing dramatically with increased end-point hardware integration and hybridization. This requires new algorithmic approaches across the network, I/O, and computational software stacks that are low-overhead and provide non-trivial data metrics. The emerging field of approximate and/or randomized algorithms position themselves perfectly in this role as they combine new methods for matrix approximation via random sampling that have recently been developed by the Applied Mathematics and Machine Learning communities.

Due to the recent interest [25][26] in randomized and approximate algorithms, such methods have become a much better fit in an inherently unstable and constantly changing distributed environments by attaching a probabilistic measure to the result. In fact, there are many statistical techniques in the Randomized Linear Algebra class of algorithms that lend themselves perfectly to accommodate the convergence principles of in-locus computing (as manifest in IBP’s best effort Network Function Unit operations as discussed in Section 7) and respond algorithmically to assimilate the inherent failures that naturally occur in a widely distributed system at the scale that we target. The iterative nature of most approximate methods allows us to incorporate erroneous response from a sensor or a network transmission and gradually remove the malformed data from the multidimensional subspace that is being worked on. Similarly, an intermittent lack of response from a sensor or a network element may naturally be incorporated as a sampling and selection operator that is triggered by a system-reported event as opposed to the classical method that uses a pseudo random number generator (PRNG). Also, the probabilistic nature of the approximate algorithms allows us to weigh the data sources based on their history of reliable responses and the quality of the data they delivered (if a measure of quality can be obtained, from, for example, a duplicate sensor). High quality sensors and network connections will, over time, gain large weights and thus render them highly probable to be approximately correct as envisioned by the Probably Approximately Correct (PAC) learning framework [27].

6 Deployment Scalability

We define deployment scalability as widespread acceptance, implementation and use of a service specification. All the warworkours we have described are building overlay converged network but they are not interoperable and cannot achieve deployment scalability.

In [28], Beck makes an argument for a fundamental design principle underlying systems that exhibit deployment scalability:

**The Deployment Scalability Tradeoff** There is an inherent tradeoff between the deployment scalability of a specification and the degree to which that specification is weak, simple, general and resource limited.

The terms “simple, generic and resource limited” are derived from the classic paper “End-to-End Arguments in System Design” by Saltzer, Reed and Clark which discusses them in the context of Internet architecture. The term “weak” refers to logical weakness of the service specification as a theory of program logic, and is due to Beck’s partial formalization of the arguments in that paper. Stating this principle as a tradeoff is a further refinement by Beck of the usual (and perhaps more accurate) interpretation of the original paper as an absolute rule requiring or prohibiting particular design choices [29].

6.1 Case Study: Fault Detection in TCP/IP

The classic example of the application of the End-to-End Principle, from which its name is derived, is the location of the detection of data corruption or packet loss or reordering in the TCP/IP stack [9].

The scalability argument for end-to-end detection of faults is that removing such functions from the spanning layer makes it weaker, and therefore potentially admits more possible implementations. Because fault detection can be implemented above the spanning layer, the set of applications supported is not reduced.
6.2 Case Study: Process Creation in Unix

In early operating systems it was common for the creation of a new process to be a privileged operation that could be invoked only from code running with supervisory privileges. There were multiple reasons for such caution, but one was that the power to allocate operating system resources that comprise a new process was seen as too great to be delegated to the application level. Another reason was that the power of process creation (for example changing the identity under which the newly created process would run) was seen as too dangerous. This led to a situation in which command line interpretation was a near-immutable function of the operating system that could only be changed by the installation of new supervisory code modules, often a privilege open only to the vendor or system administrator.

In Unix, process creation was reduced to the `fork()` operation, a logically much weaker operation that did not allow any of the attributes of the child process to be determined by the parent, but instead required that the child inherit such attributes from the parent [30]. Operations that changed sensitive properties of a process were factored out into orthogonal calls such as `chown()` and `nice()`, which were fully or partially restricted to operating in supervisory mode; and `exec()` which was not so restricted but which was later extended with properties such as the `setuid` bit that were implemented as authenticated or protected features of the file system. The decision was made to allow the allocation of kernel resources by applications, leaving open the possibility of dynamic management of such allocation by the kernel at runtime, and creating the possibility of “Denial of Service” type attacks that persists to this day.

The result of this design was not only the ability to implement a variety of different command line interpreters as non-privileged user processes, leading to innovations and the introduction of powerful new language features, but also the flexible use of `fork()` as a tool in the design of multitasking applications. This design approach has led to the adaptation of Unix-like kernels to highly varied user interfaces (such as mobile devices) that were not within the original Unix design space.

7 Exposed Buffer Processing

The core resource that is used by all forms of storage, networking and computing is the persistent memory or storage buffer.

- In storage, storage blocks or objects are used in the implementation of higher level file and database systems, along with RAM memory buffers that are used to improve performance, enable application/OS parallelism and allow for flexible exchange of data with other operating system data structures.

- In networking, buffers are used at the endpoints for much the same reasons as storage, and are used at intermediate nodes to allow for asynchrony in the operation of store-and-forward packet networking.

- In computing, memory pages make up process address spaces, are also used to enable asynchrony in interprocess communication, and hold all other operating system data structures used in the implementation of functions on behalf of processes.

While operating system interfaces such as POSIX provide access to storage, networking and computing services, they do so in ways that conform to these traditional silos.

- File system calls do not have explicit access to general networking or computation resources.

- The sockets interface does not provide access to general storage and or computation resources.

- The POSIX process management functions do have only the minimal necessary overlap with storage and network functions (notably specifying an executable file image in the `exec()` system call).

Convergence of storage, networking and computation is possible through conventional operating system interfaces using the generality of the user process as a gateway between these silos. However, a more interoperable approach is to expose a common abstraction of the underlying resource that all of these high level silos operate on, namely persistent storage blocks or memory buffers, an approach to convergence that we call Exposed Buffer Processing.

7.1 Logistical Networking as EBP in Overlay

Over the past 15 years the Logistical Networking project [31, 18, 19] has worked to define an approach to Exposed Buffer Processing that is implemented as an overlay on the Internet. An examination of the key elements of that implementation provides an EBP proof of concept.

7.1.1 Components of Logistical Networking

The Internet Backplane Protocol (IBP) IBP is a generalized Internet-based storage service that is encapsulated as remote procedure call over TCP. IBP was designed to be simple, generic and limited following the example of the Internet Protocol (IP) [9]. It is a best effort service, its byte array allocations are named only by long random keys (capabilities) and represent leases whose duration and size are limited by the individual intermediate node (in analogy to the IP MTU).
The intermediate node that implements IBP is called a depot, and it is intended as a storage analog to IP routers. In many ways IBP is closer to a network implementation of malloc() than a conventional Internet storage service like FTP, and in addition every IBP allocation is a lease of storage resources which can be limited in duration.

The exNode Because IBP is such a limited service, the abstraction of an allocation that it supports does not have the expressiveness of the file abstraction that users typically expect of a high level data management system. The exNode is an abstract data structure that holds the structural metadata required to compose IBP allocations into a file of very large extent, with replication across IBP depots, identified by their DNS name or IP address [32]. The exNode can be thought of as an analog to the inode used in early Unix file system implementations. The exNode has a standard XML sequentialization.

The Logistical Runtime System (LoRS) The exNode can be used as a file descriptor to implement standard file operations such as read and write. The Logistical Runtime System (LoRS) uses the exNode to implement efficient, robust and high performing data transfer operations. Some of the techniques used in the implementation of LoRS are comparable to those used in parallel and peer-to-peer protocols [33].

The Logistical Distribution Network (LoDN) While the exNode implements topological composition of IBP allocations to implement large distributed and replicated files, it does not deal with the temporal dimension introduced by IBP’s use of storage leases. LoDN is an active service which holds exNodes and applies storage allocation, lease renewal and data movement operations as required to maintain policy objectives set by end users through a declarative language and manageable by an intuitive human interface.

The Network Functional Unit (NFU) The NFU was introduced as a means to allow simple, generic and limited in-situ operations by a depot to data stored in its IBP allocations. The NFU has been used in numerous experimental deployments, and has been shown to enable robust fault tolerance and high performance is a wide variety of applications [34, 35, 36]. However, the middleware stack that supported such experimentation has never been fully integrated with the deployed versions of LoRS and LoDN or the Data Logistics Toolkit (discussed below), and so the NFU has never been used in a persistent large scale deployment.

7.2 “Packetization” of Networking, Storage and Processing

The argument for the definition of a common spanning layer based on simple, generic and limited abstractions has never been intuitive to designers who have historically relied on the more complex, specialized and virtually unbounded service models.

7.2.1 Networking

Size: Circuit-based networks allow an unbounded amount of data to pass over a persistent circuit, in analogy to an electrically connected circuit, and masking the underlying digital implementation in terms of MTU-limited packets. The Internet exposed the MTU and required endpoints to explicitly concatenate packets into streams.

Failure: Circuit-based networks provide Quality-of-Service (QoS) guarantees sufficient to enable application developers to either ignore occasional communication faults or to fail catastrophically when they are detected. The Internet exposed the possibility of failure by dropping faulty packets and by exporting a best effort service, requiring endpoints to explicitly detect and respond to failures.

Locality Independence: Circuit-based networks can allocate resources and maintain state along a specific path from sender to receiver, helping to ensure fast forwarding and providing a stable platform for implementation of auxiliary services. The Internet allows every packet in a connected flow to be forwarded along a different path, putting the burden for maintaining stability on the packet routing scheme and ruling out connected services that require the maintenance of state, but enabling great resilience in the face of failures and changes in topology.

7.2.2 Storage

Size: File-based models of storage allow a very large amount of data (assumed by many applications to be virtually unbounded) to be stored as a single linear data extent. Logistical Networking exposes a maximum storage allocation size imposed by the storage resource (analogous to the Internet Protocol’s MTU) requiring endpoints to explicitly concatenate allocations into files.

Failure: File and database systems provide QoS guarantees sufficient to enable application developers to either ignore occasional storage faults or to fail catastrophically when they are detected. Logistical Networking exposes a simple failure model (faulty operations terminate with unknown state for write-accessible storage) and by exporting a best effort service, requiring endpoints to explicitly detect and respond to failures.
**Locality Independence**: File-based models of storage can allocate resources and maintain state on a well-connected “site” to manage fault tolerance and replication in terms of where “copies” reside. Logistical Networking allows every allocation comprising a file to be managed independently, potentially spreading them across topologically separated nodes, moving and storing data on a fine-grained basis as called for by applications (e.g., data streaming).

### 7.2.3 Computation

**Size**: Process-based computation allows an unbounded amount of processing to be performed one or a set of closely-coupled threads. The Network Functional Unit exposes a unit of processing that can be limited in many resource dimensions, including elapsed clock time, CPU cycles consumed, RAM allocated during execution and I/O activity performed, requiring a runtime system to concatenate limited resources to create an unbounded virtual execution environment.

**Failure**: Process-based computation provides QoS guarantees sufficient to enable application developers to either ignore occasional processing faults or to fail catastrophically when they are detected. The Network Functional Unit exposes a simple failure model (faulty operations terminate with unknown state for write-accessible storage) and exports a best effort service, requiring endpoints to explicitly detect and respond to failures.

**Locality Independence**: Process-based computation can allocate resources and maintain state on a set of well-connected processors, enabling successive time slices to execute sequentially in a manner that leverages continuity of operating system and application data state. The Network Functional Unit allows every allocation comprising a file to be managed independently, potentially moving them and the memory/storage allocations that comprise the state of supervisory and application data state as required (e.g., fault tolerance and load balancing).

### 7.2.4 Deployments, SW Distribution and Apps

The National Logistical Networking Testbed (NLNT) and the Research and Education Data Depot Network (REDDnet) were two NSF-funded infrastructures that deployed IBP at roughly a dozen sites nationwide (including Hawaii) and in Europe. The NLNT (2002-2007) was a terascale project based at the University of Tennessee’s LoCI Lab, while REDDnet (est. 2007) was a petascale project based at Vanderbilt’s ACCRE. In addition to these dedicated deployments, IBP was persistently deployed on the nodes of the shared PlanetLab infrastructure and has also been deployed on GENI [7] through the efforts of the Data Logistics Toolkit project.

Leveraging the work of the NLNT and REDDnet projects, the L-Store project [37], based at Vanderbilt University’s Academic Computing Center for Research and Education, has constructed an alternate stack upon the common IBP service that is more adapted to supporting large scale enterprise storage. It has been in use for over a decade and currently supports multi-petabyte collections and high-performance local and wide-area data access through a variety of standard file access protocols.

The Data Logistics Toolkit (DLT) is an NSF-funded effort based at the Indiana University’s Center for Research in Extreme Scale Technologies to collect, package and harden the components of the Logistical Networking Stack, L-Store and related tools including perfSonar and Periscope, installable via Linux package manager. The exNode repository and active management function of LoDN has been reimplemented using IU’s Unified Network Information Service (UNIS) [38].

Numerous experimental and preproduction applications of Logistical Networking have been extensively documented over the past 20 years [39, 40, 41, 42, 43, 44, 36, 35]. These applications include functions such as large email attachments, large file storage and delivery, reliable multicast, large scale data management and access and edge processing for volume reduction (e.g., filtering) or conditioning (e.g., sorting). Many of these functions were implemented using Logistical Networking infrastructure with no or minimal help from application-specific servers or persistent managers long before the advent of commercial cloud services that address the same requirements. Some have implemented advanced functionality not yet replicated in any conventional paradigm of distributed wide area infrastructure [45].

### 7.3 EBP Below the Network Layer

The question of where in any stack of services convergence between disparate underlying resources should be located is one that has gone on for decades. The effects of path dependence, the entrenchment of silos and the pressures against disruption of low-level standards and practices in highly developed engineering niches are very strong. These factors can lead to a belief that current silos cannot be disrupted, and that trying to do so is foolhardy or wrong. Anecdotal accounts abound of resistance to the dominance of the Internet in the late 20th Century.

On the other hand, the argument for creating a converged layer to support the Internet and other global distributed services is compelling. The need for distributed systems to have access to and control over low layer network characteristics including topology and performance is clear in the steps that have been taken to work around the stricture that forbids such direct access in the Internet architecture. The situation is similar in other resources which do not have such restrictive rules, leading to lopsided designs in which high layers of the Internet stack are combined with low layers of other services (e.g., transportation).

The use of a standard spanning layer to enable interoperability carries with it the issues associated with path dependence. Once a standard has been set, it becomes difficult and costly to change (witness the decades-long delays in replacement of IPv4...
Anderson, Peterson, Shenker and Turner discuss the barriers to innovation (network ossification in their parlance) that have resulted from the standardization on IP at the network layer [46].

For these reasons, innovation increases when the spanning layer is placed lower in the network stack. A common spanning layer which is the equivalent of a generalized Layer 2 in the current Internet stack would enable heterogeneity at Layer 3, allowing services such as Content Delivery Networks and Distributed Files Systems to be supported by appropriate globally routed services incorporating storage and processing as well as data transfer. Attempts to enforce overlay convergence as a standard above the network layer within the application community has the result of isolating the community of users of that converged interface while acceding to the ossification due to the IP standard at layer 3, as in Grid Computing [5]. This presents the challenge of defining a converged spanning layer below layer 3 (a generalization of the Link Layer of the Internet stack to include storage and processing) that is simple, generic and limited to achieve deployment scalability.

We propose the creation of a platform based on a common service similar to IBP but which models the networking capabilities of the Link Layer. We use the term Exposed Buffer Processing for this as-yet-unrealized service. The central idea of this paper is that the appropriate platform for the creation of distributed systems is some form of EBP. We emphasize that EBP need not follow the design of IBP, as long as it takes appropriate account of the Deployment Scalability Tradeoff. However we offer experience with IBP as an overlay form of EBP for the consideration of the community.

8 Applications of EBP

In Section 5 we discussed a simple, well-known example occurs when data that resides in a file is to be sent on a connected TCP stream. An operation that allows the direct movement of data between the file system and network buffers, or even better one that would allow network transfers directly buffers that are also used for file system operations can eliminate some or all of this unnecessary copying.

8.1 Case Study: Scientific Content Delivery

Dissemination of data is one of the fundamental challenges of modern experimental and observational science. There is a general move toward the open sharing of raw data sets, enabling replication of analyses, cross-cutting studies, innovative reexamination of previously collected data and historical examination of collection and analysis techniques [47, 48]. In many case the data collected is large and observation is continuous, as in remote data from satellites and other sensors [49], experiments such as the Large Hadron Collider [50], or broad harvesting of multimedia content [51]. The resources required to make such data streams instantaneously and persistently available can exceed the centralized capabilities of institutions or government agencies.

Commercial CDN or Cloud solutions may be too expensive, and may not adequately serve the entire global user community (see discussion of the Digital Divide below) and may not adequately support the publication by users of secondary data products resulting from their processing of raw data. However, the ICT resources required to address such problems may be affordable, and the community of user institutions may be capable of hosting them in a distributed manner. Using shared EBP infrastructure, we can build a distributed, federated content management system using the resources of the content provider and user communities.

8.2 Case Study: Digital Divide and Disaster Recovery

Modern network services take full advantage of the strong assumptions that can be made about the implementation of the Internet in the industrial world. It is common for services to rely on continual low-latency datagram delivery, always-connected servers, stable and uninterrupted datagram routing paths and high bandwidth connectivity to take just a few examples. Services implemented at Cloud Computing centers are among those that place the greatest demands on the Internet backbone and “last mile” connectivity to edge networks.

Many services can be decomposed into synchronous and asynchronous components, and different “Data Logistics” strategies
applied to each part. Techniques used in Content Delivery Networks, including caching and prestaging can be applied on a fine-grained and even per-client basis. It is sometimes the case that the entire service can be implemented using edge resources. In other cases there is a component that can only be implemented using synchronous end-to-end datagram delivery across the backbone, but it requires only low bandwidth so that scarce high-quality network resources can be used. In some cases, a careful analysis of the application combined with reconsideration of the truly necessary characteristics of the service delivered to the end-user can reduce the need for high quality synchronous connectivity to the vanishing point. In a sense, strong network assumptions are a crutch that allows wasteful application design and ease of development.

Today, some environments cannot support strong network assumptions, even when local IT resources are available. Examples are communities isolated through geography, economic (poverty, discrimination) or political circumstances (famine, war), or social factors. Disasters create environments where infrastructure is disrupted even in the most advanced societies (e.g. Hurricane Katrina). The recent response of modern network technologists has been to bring fixed or mobile wireless technology (satellite, 4G) into remote locations and to the scene of disasters or to create complex wireless infrastructures based on continuous aviation drones such as Google’s balloon-based project Loon [52] and Facebook’s drone-based project Aquila [53]. Some aggressively optimistic projects have already been abandoned, such as Google’s drone-based Project Titan [54]. The alternative of using a mix of interoperable heterogeneous synchronous and asynchronous data transport integrated into a flexible platform to support a variety of distributed applications can, by contrast, be cheap, robust and easily deployed.

8.3 Case Study: Big Data and Edge Processing

One of the inexorable trends in the collection of data is the emergence of large scale online sensors and instrument that produce data that must be subjected to volume-reducing processing before it can be passed over the network. Growing trends in sensor networks, the Internet of Things, and Smart Cities will severely exacerbate this problem, to say the least [55]. The historical approach of sending all such data to computation centers that are either self-contained or connected to their peers through heroic networking that may be private or even proprietary in nature is no longer sufficient to address the total size, globally distributed generation, and need for immediate use by applications that we see today [56].

An alternative possible using EBP is to apply limited edge processing on the collection device or in the edge network using a converged infrastructure that can also store and transport data.

9 Conclusions

In this paper, we have argued that interoperable convergence of storage, networking and processing is necessary in building a platform to support distributed systems which exhibits deployment scalability, and that the most effective implementation is a form of Exposed Buffer Processing at a layer below that which implements the Internet. Our argument rests on practical historical examples of the problems caused by the Internet’s lack of expressiveness and an argument based on a partially formalized design methodology that the spanning layer of any converged infrastructure must be simple, generic and limited.

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