Developing Sustainable Data Services in Cyberinfrastructure for Higher Education: Requirements and Lessons Learned

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Abstract: The University of California, San Diego (UC San Diego) Research Cyberinfrastructure (RCI) program provides long-term quality services in centralized storage, colocation, computing, data curation, networking and technical expertise. To help define the data storage needs and set priorities, the RCI data services (RCIDS) team conducted a series of interviews with faculty and senior staff members between September 2012 and February 2013. A total of 50 groups from 29 separate departments and organized research units (ORUs) participated in the interviews, representing more than 600 UC San Diego researchers. From human genomic sequences, marine natural products, to cosmological simulations, their diverse datasets are shared with hundreds of thousands of users worldwide. The top 10 requirements on data services and the top 5 existing challenges and risks as reported by UC San Diego researchers have been identified. Based upon these requirements, the RCIDS team recommends a Network Attached Storage (NAS) data service to be first deployed with a sustainable business model. Additional services will be developed through further discussion with the research community and in view of emerging cloud computing technologies. An extensive discussion is provided on the implementation plan, cloud-based data services, and the lessons learned in building sustainable e-science infrastructure for higher education research.

Keywords: higher education; research cyberinfrastructure; data cloud; sustainable data services; network-attached storage

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1 INTRODUCTION

Cyberinfrastructure [1] is increasingly recognized as essential for the state of the art universities in the 21st century because it enables “faster, better, and different scientific capabilities”[2]. Institutional development of high performance computing environment has been correlated to increases in National Science Foundation (NSF) funding and research competitiveness [3]. The investment in cyberinfrastructure is no longer a question of “why and

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when” but “what and how”. Data is the cornerstone of successful research laboratories and reputable universities in a data-driven knowledge economy. The proliferation of data from sensor networks, large scale mapping and surveys, scientific simulations, and user contributed content in social networks is constantly redefining the perception and understanding of “big data.” Big data is characterized by the volume, variety and velocity of data at an unprecedented scale \[4\]. Building a sustainable infrastructure to support the data life cycle and expedite the retrieval of information and genesis of knowledge is absolutely necessary for any university to lead higher education.

In April 2009, the UC San Diego RCI design team (RCIDT) published a report titled “Blueprint for the Digital University”\[1\]. The campus-wide cyberinfrastructure is designed to be environmentally conscious through the adoption of green technology and economically sound through cost-effective services. The goals are (1) to provide UC San Diego researchers with competitive advantages when they conduct research and apply for grants, (2) to enhance the quality of student education at UC San Diego, (3) to preserve the University’s data and intellectual property, (4) to reduce redundant campus infrastructure, and (5) to conserve the global environment through green technology. The six core elements are centralized storage, colocation, data curation, research computing, research network, and technical expertise. Examples include the deployment of UC-wide computing resources such as the Triton Resource \[2\] and the new Triton Shared Compute Cluster (TSCC)\[3\].

In the area of centralized data storage, the rapid growth of big data sciences has outpaced existing support mechanism to meet the demands. To stay current with the investigators’ research advances and data growth, the RCIDS team has conducted a series of in-person interviews with UC San Diego faculty investigators and information technology (IT) staff members, guided with a questionnaire\[5\] focused on research data services. Ultimately, a long-term sustainable business model is to be developed with the active participation of UC San Diego researchers to build an infrastructure that meets their needs to create, share, and discover.

The rest of this paper will first describe related works in this area, followed by the demographics of the interview participants, and the results including common data flows, usage patterns, requirements, risks, and challenges. Then the implementation plan is presented with respect to the business model, the rationale and recommendation of an initial NAS data service, and an exploratory view on cloud based data storage solutions in the near future. Finally, the conclusion summarizes the key findings that provide insight to the practical implementation of sustainable campus cyberinfrastructure for e-science in higher education.

2 RELATED WORKS

2.1 Data management and sharing requirements

There has been a gradual recognition that tax dollars funded research could be made more valuable by increasing public access, long-term preservation, and re-use. Funding agencies already impose various guidelines on how long the data must be kept and shared through requirements of data management plans (DMP) by the NSF and data sharing plans (DSP) by the National Institutes of Health (NIH). Researchers need to prepare

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\[1\] http://rci.ucsd.edu/_files/Blueprint.pdf.
\[2\] http://tritonresource.sdsc.edu/.
\[3\] http://rci.ucsd.edu/computing/index.html.
\[4\] http://tinyurl.com/omfchcq.
for increasing expectations from funding agencies, as directed by the White House Office of Science and Technology Policy (OSTP) guidance in early 2013\(^\text{①}\).

The Royal Society published a report\(^\text{②}\) titled “Science as an open enterprise” in June 2012 outlining ten recommendations that may enable a fourth paradigm for scientific research. The new data science paradigm focuses on big data capture, curation, and analysis, adding to the classical duo of experiment and theory and the third paradigm of simulation science. The top two recommendations are: (1) Scientists should share data using the best practices that allow open and free access, and (2) “Universities and research institutes should play a major role in supporting an open data culture…”

Darby et al have conducted a series of interviews and workshops to identify drivers, barriers, and enablers to the process and context of data sharing and reuse\(^\text{③}\). In particular, they have identified the need for a persistent and sustainable preservation infrastructure through a combination of journal, learned society, funding agency, and institutional archives. Xuan et al have proposed architectural design principles for infrastructure to support data integration and curation in higher educational institutions\(^\text{④}\).

2.2 Institutional efforts on shared cyberinfrastructure

There have been increasing efforts at different institutions around the world to develop sustainable models for research computing and data management\(^\text{⑤}\) services. Frequently these efforts are characterized by campus-wide activities with the participation of the faculty, staff, information technology experts in research computing, and librarians for data curation. For example, University of Colorado Boulder published a comprehensive report on their recommendations in research data management with detailed analyses on the funding models from peer institutions. Purdue University has established a PURR data repository using the HubZero platform\(^\text{⑥}\) with a very active user community.

In the data storage area, UCLA, University of Iowa, Stanford University, and many other universities offer researchers the options to purchase shared storage space for high performance computing, standard performance data storage and backup, or offline tape backup. University of Michigan (UM) offers a comprehensive set of cyberinfrastructure services with a useful “storage solution summary chart” for the different options\(^\text{⑦}\). UM is among the first to negotiate contracts with Box and Google to offer cloud based storage solutions for university use. These commercial solutions offer friendly user interface and ease of access from mobile devices.

The RCIDS team has collected raw data storage pricing information from about 50 universities that offer shared storage space. The numbers range from $80/terabyte (TB)/year for a single copy of data, or $250/TB/year for replicated data, to about $1800/TB/year. In the data curation area, curated data storage is often offered in the range of $1000–$2000/TB/year with long-term preservation up to 10 years or more. It should be noted that these prices vary greatly depending on the number of copies, the quality of hardware, the value of added services, and the level of university subsidies.

2.3 Condo compute and storage activities

As the price of commodity hardware for computing and storage drops, more and more researchers find themselves mired in the business of managing laboratory needs in computing and storage on a routine basis. In

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\(^\text{①}\) http://www.whitehouse.gov/sites/default/files/microsites/ostp/ostp_public_access_memo_2013.pdf.
\(^\text{③}\) http://hdl.handle.net/10971/1398.
\(^\text{④}\) http://www.itcs.umich.edu/itcsdocs/r1468/.
recent years, the condominium (condo) computing model has gained popularity. Analogous to the condominium in real estate, the principal investigators (PIs) own the “condos”, computing nodes purchased with their grants, that are part of a larger cluster and their universities fund the professional management to various degrees. The PIs also pay a preset “condo association fee” to help cover the maintenance cost of shared infrastructure.

In contrast, the condo storage model has not gained much traction. The complexity of providing condo storage has hampered its implementation and adoption due to the persistent nature of data, the higher cost of hardware platform, and the evolving requirements of funding agencies. Only a handful of universities offer services for PI-purchased storage hardware. For example, Purdue University and Clemson University have programs in which the universities pay the full cost of operating the storage hardware bought by the PIs.

3 METHOD

3.1 Demographics of interviewees

The selection of the participants is based on known knowledge of their data storage needs and representative of similar investigators on campus in their respective areas of research. The participants represent 29 different departments and organized research units (ORUs) on campus, including researchers from the fields of biology, physics, sociology, marine studies, arts and humanities, medicine, and pharmacy. The total number contacted for interviews was 80 with 50 completed interviews at a 63% response rate. This is about 4% of the UC San Diego ladder rank faculty members. According to an estimate based upon the average group size, the total number of personnel covered under these interviews is about 600 including faculty, staff, researchers, and students. Similarly, the estimated number of external users who may benefit from the released research data from these laboratories is about 300,000. The major funding sources for these researchers are NIH, NSF, and private foundations.

3.2 Interviews

The interviews typically last one hour. The questionnaire was provided ahead of time and the responses were entered by the interviewers based upon the replies from the interviewees. This provides the opportunity to clarify any confusion that may exist due to misinterpretations of technical jargons. Detailed notes were taken to capture any issues not mentioned in the questionnaire but deemed important by the PI’s. Any response entries not covered by the multiple choices provided are entered as exceptions in a text field category of “Other.” During the compilation phase, these responses were expanded into new categories or combined with existing categories when appropriate.

4 RESULTS

4.1 Common data flow patterns

Researchers from the interviews often use a subset of the illustrated components in their routine data flows (Fig. 1). Data generated from software applications or instruments such as sequencers are sent to the primary storage nodes, which may be processed and analyzed using cluster compute nodes, or a high performance file system in TSCC or XSEDE. Usually data is replicated to a secondary storage node through snapshots, which also serve as a limited backup mechanism when the data turnover rate is low. With high data turnover rate, the only data retrievable is from a snapshot up to 24 hours earlier with a daily snapshot policy. The primary storage

is considered “hot,” as the data is always accessible from laptops or workstations using the Network File System (NFS) or Common Internet File System (CIFS) protocol. Amazon Glacier is a long-term archival solution for data rarely needed. Cloud storage nodes are often used for sharing data through a private cloud provider such as the San Diego Supercomputer Center (SDSC) Cloud Storage\(^1\) or commercial providers such as Dropbox, Google Drive, or SkyDrive.

The data sources for Fig. 1 are listed in Table 1, and the type of storage devices and services utilized are shown in Table 2. The total percentage may be more than 100% when users chose multiple selections in their responses.

Topping the data sources are sequencers and software applications for simulations in computational chemistry, biology and physics (Table 1). The genomic sequencing effort has been generating data faster than Moore’s law with the cost of sequencing an entire human genome lowering to about $1000. Soon it might be cheaper to resequence a genome than to store the data for the long term.

The majority of researchers (73%) use NAS, 70% use USB drives, and 65% use local hard drives on workstations to store their data (Table 2). Of these, USB drives and local hard drives are considered economical storage options, and both may be taken offline for long-term archival. Up to 43% of the participants use Dropbox (33%) or Google drive (10%) to manage their data sharing needs (up to tens of GB).

### 4.2 Growth of data storage needs and cost

The current, projected, and permanent amount of data storage over the next two years are illustrated in Fig. 2. The researchers are primarily dealing with data in the 1 to 100 TB range (75%), though more users will be dealing with data in the 10 TB to 1 PB range (70%) in the next two years. However, the amount of data to be kept permanently are under 100 TB for most users and under 100 GB for 23% of users.

Capital expenditure shows that the majority of PI’s spend less than $25K per year on inventorial storage equipment (Fig. 3). Inventorial storage equipment include only those that cost more than $5000, and usually represents a NAS storage device (Table 2). This indicates that most researchers are dealing with data in the 10–40 TB range, using an estimated raw storage hardware cost of about $500/TB with replication, or $250/TB for a single copy. Those who spent money in the past 18

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\(^1\) [http://cloud.sdsc.edu](http://cloud.sdsc.edu).

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### Table 1 Data sources and relative distribution

<table>
<thead>
<tr>
<th>Data Source</th>
<th>%</th>
<th>Representative Fields</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sequencers</td>
<td>28</td>
<td>Biology</td>
</tr>
<tr>
<td>Software applications</td>
<td>28</td>
<td>Biology, Physics</td>
</tr>
<tr>
<td>Field sensors/instruments</td>
<td>20</td>
<td>Marine Biology, Astronomy</td>
</tr>
<tr>
<td>Audio visual equipments</td>
<td>10</td>
<td>Arts</td>
</tr>
<tr>
<td>Mass spectrometers</td>
<td>8</td>
<td>Biology</td>
</tr>
<tr>
<td>Tomographic instruments</td>
<td>8</td>
<td>Biology, Medicine</td>
</tr>
<tr>
<td>External data repositories</td>
<td>8</td>
<td>Biology</td>
</tr>
<tr>
<td>LHC particle detectors</td>
<td>3</td>
<td>Physics</td>
</tr>
<tr>
<td>Archelogical studies</td>
<td>3</td>
<td>Humanities</td>
</tr>
<tr>
<td>Curation</td>
<td>3</td>
<td>Sociology</td>
</tr>
</tbody>
</table>

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Fig. 1 Simplified mashup of common data flow patterns. Researchers use a subset of these components usually depending on actual requirements.
months also tend to spend less in the next 18 months because of the storage hardware tend to last 3 to 5 years on average. This translates into about $50/TB/year for a single copy of data at “bare metal cost” over a period of five years, which is the likely upper bound of the hardware lifetime.

Keenly aware that having only a single copy of data is risky, researchers mitigate that risk by using an identical NAS configuration for disaster recovery (DR) or lower cost devices such as USB drives, local workstation hard drives, tape, or even CD/DVD disks. Thus, the minimal “bare metal cost” for replicated storage ranges from $50/TB/year to $100/TB/year. This price continues to drop from year to year as the hard drive capacity continues to increase.

4.3 Data life cycle characteristics

When asked about how long they intend to keep their data, the researchers (63%) mostly only intend to keep the data for the duration of projects (Fig. 4). 30% of the research groups have data that are kept permanently. The rest of the data may be kept up to 5 years. Some data (3%) has very complicated management policies.

Frequently researchers would like to keep the data as long as possible. Currently there is no standard way to sustain this activity. What happens to the data when the original funding is ended or when there is a funding gap? Some data may be lost irrevocably without some way to bridge the gap between funding periods. Most grants do not allow the investigators to pay forward for services in the future. The data management costs are not considered as “publication” costs by most funding agencies yet.

About half of the researchers will release the data immediately when published, and about 30% will release the data as soon as it is produced (data not shown). Some data is restricted to collaborators only until published. The data release policy is typically designed to be in compliance with funding agency requirements (38%) and/or protection of intellectual property rights (33%).

The RCIDS team inquired about the desire for investigators to use curation tools to add metadata to their data collection (Fig. 5). Metadata is the data about other data, which may facilitate the reuse and discovery of the other data 9. The majority recognize the need for metadata annotation and data curation:

<table>
<thead>
<tr>
<th>Type</th>
<th>%</th>
<th>Primary purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network attached storage (NAS) devices</td>
<td>73</td>
<td>Standard performance network filesystem</td>
</tr>
<tr>
<td>USB Drives</td>
<td>70</td>
<td>Storage and backup</td>
</tr>
<tr>
<td>Local server hard disk drives</td>
<td>65</td>
<td>Storage and backup</td>
</tr>
<tr>
<td>Dropbox</td>
<td>33</td>
<td>Data sharing</td>
</tr>
<tr>
<td>SDSC Project Storage</td>
<td>13</td>
<td>Standard performance network filesystem</td>
</tr>
<tr>
<td>XSEDE Lustre Filesystem</td>
<td>10</td>
<td>Parallel filesystem</td>
</tr>
<tr>
<td>Google Drive</td>
<td>10</td>
<td>Storage and sharing</td>
</tr>
<tr>
<td>Amazon S3</td>
<td>8</td>
<td>Storage and sharing</td>
</tr>
<tr>
<td>SDS Cloud Storage</td>
<td>8</td>
<td>Storage and sharing</td>
</tr>
<tr>
<td>Tape library</td>
<td>5</td>
<td>Storage and backup</td>
</tr>
<tr>
<td>Small Area Network Storage Array</td>
<td>3</td>
<td>Databases</td>
</tr>
<tr>
<td>CD/DVD</td>
<td>3</td>
<td>Storage and backup</td>
</tr>
<tr>
<td>Hadoop Filesystem</td>
<td>3</td>
<td>Replication and Map Reduce</td>
</tr>
<tr>
<td>iRODS</td>
<td>3</td>
<td>Metadata driven storage and sharing</td>
</tr>
</tbody>
</table>

The distribution may change as funding agencies develop more detailed requirements and funding models for data curation, archiving, and preservation\(^1\).

\(^1\) [http://www.whitehouse.gov/sites/default/files/microsites/ostp/ostp_public_access_memo_2013.pdf](http://www.whitehouse.gov/sites/default/files/microsites/ostp/ostp_public_access_memo_2013.pdf)
Data Storage and Growth in the Present and Next 2 Years

Fig. 2 Growth of data storage needs in the present and the next two years.

Estimated Annual Budget on Equipment and Storage over 36 Months

Fig. 3 Annual spending on inventorial equipment which are over $5000 in value over the past and future 18 months. Red columns are for storage equipment only in the past 18 months.

Research Data Life Time

Fig. 4 Research data life time as reported.
4.4 Risks and Challenges

The storage density continues to double approximately every 13 months, according to the Kryder’s Law \[8\], faster than the 18 months cycle for transistor density in the Moore’s Law. The continuing decrease in unit storage (terabyte or TB) per dollar has enabled some users to manage their own growing storage requirements (Fig. 6). In addition, plug’n play NAS devices such as Drobo drives or Synology NAS servers have seen increased adoption as a local low cost NAS option for small research groups that do not have strong performance requirements.

With a sustained yearly investment to take advantage of the doubling of storage density, one could store substantial amount of data seemingly “free” of additional cost. However, the hidden costs of “doing it yourself (DIY)” are often overlooked. As shown in Fig. 6, only 35% of the research groups have their own system administrators. The majority of the rest rely on departmental shared support or self-support. Many groups have seen their departmental support reduced over the years and self-support is becoming their only option.

At least 30% of the groups rely on postdoc and graduate students, developers, research scientists, and even the PI themselves for support of their research infrastructure. The effort spent by developers, scientists, and PI’s to support their own infrastructure will certainly negatively affect their productivity in research and development. The DIY researchers tend to ignore the hidden cost of their own labor when they compare and shop for services, let alone network and colocation costs. They usually assume that they can purchase and use two storage nodes for five years if they manage the nodes by themselves. In contrast, when they look for other service providers, such as SDSC or Amazon, they could only obtain two years of service from SDSC with the approved recharge rates that reflect the real cost of hardware cost recovery, labor, network, and colocation expenses.

Many researchers are aware of their precarious situation in data management when asked about existing risks and challenges in their present strategies. The top five risks and challenges facing the researchers are shown in Table 3. The number one risk is the sustainability of the campus research cyberinfrastructure program. The termination of the RCI program poses a serious problem if they have already invested time and grant money into the research cyberinfrastructure themselves. This concern outranks the constant increasing demand of data storage needs (65%) and lack of back plans and dedicated support.
staff to keep data safe (50%). In a way, even though the PIs are concerned about the safety of their data, they unknowingly jeopardize their data by choosing low cost alternatives and jeopardize their long term success in the process. Another top concern is that the cost may be higher down the line in a “bait and switch” style (53%). To address these concerns, the university and the faculty have to develop mutually beneficial and sustainable. In short, these risks and challenges stress the need to develop a long-term strategic plan for campus research cyberinfrastructure.

4.5 Requirements

The top 10 requirements from the interviews are shown in Table 4. Of these, the top categories are cost, sharing, ease of use, backup and recovery, and network bandwidth. These requirements are in agreement with the proposed minimal criteria for cloud based data services. However, there is one important distinction. The majority of research groups are using NAS as the principal platform for data storage, as illustrated in Fig. 1. Cloud based storage solutions such as SDSC Cloud and Amazon S3 only received adoption by a small percentage of users. On the other hand, the dropbox- or Google Drive-like services are preferred by up to 43% of researchers. Users will choose different platforms depending on actual requirements and usage scenarios. While it is tempting to develop a single solution for all scenarios, it may be more practical and economical to have a number of options to choose from.

(1) Better cyberinfrastructure with minimal direct cost (91%). More than 90% of the PIs want sustainable and better research cyberinfrastructure without a significant burden on their grants. At the same time, the top risk (85%, Table 3) shared by the researchers is that UC San Diego may not have the long-term budgetary commitment necessary to make the cyberenvironment better for its faculty members. An associated risk is the “bait and switch practice” that will increase the cost for the PIs down the line (53%). While the RCIDT document outlined a long-term strategy, a “Blueprint for the Digital University,” the faculty and staff members are concerned over the future of RCI and their hope for better cyberinfrastructure.

The UC San Diego Cyberinfrastructure Planning and Operation Committee (CIPOC) report in 2010 outlined a guiding principle in the development of a business model for RCI Centralized Storage. The PIs pay “79% of the start-up costs, 59% of the annual costs for the initial years, and 68% of the steady-state annual costs” and UC San Diego provides the rest of the cost through energy savings and indirect cost recovery. This is a long-term mutual commitment as far as the planning and operation are concerned. Many researchers have expressed that the lack of commitment at the university level may continue to prevent them from adopting RCI services. There would be a shortage of funds to manage the data critical to their research if the RCI program were discontinued. The RCIOC may have a greater role to play to solidify the mutual commitment and ensure that RCI services continue to meet the requirements of UC San Diego faculty and researchers.

(2) Network Attached Storage (NAS, 73%) and replicated backup (66%). Having a primary storage node accessible anywhere on campus with a replicated backup is a recurring requirement (Fig. 1). The storage nodes are primarily accessed via NFS mount for Linux

<table>
<thead>
<tr>
<th>Risks and Challenges</th>
<th>%</th>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Campus may cease funding for RCI</td>
<td>85</td>
<td>Adoption barrier</td>
</tr>
<tr>
<td>Constantly increasing storage demands</td>
<td>65</td>
<td>Distraction from research</td>
</tr>
<tr>
<td>Bait and switch with increased cost later</td>
<td>53</td>
<td>Poor business practice</td>
</tr>
<tr>
<td>Poor backup plan</td>
<td>50</td>
<td>Lack of expertise</td>
</tr>
<tr>
<td>No dedicated support staff</td>
<td>50</td>
<td>Distraction from research</td>
</tr>
</tbody>
</table>
machines or CIFS mount for Windows/Mac based hosts. They may be configured to use the AD authentication system for ease of access by researchers and their collaborators on campus. External collaborators may benefit from federated identity management services, e.g., the InCommon.org⁷, to access data located at UC San Diego. This usage pattern is consistent with our survey of more than 20 other universities. The POSIX (portal operating system interface) style file systems that provide mountable workspace have the strongest demand at most universities.

A NAS data service could address the top risks and challenges identified: constantly increasing storage demands (65%), lack of or incomplete data backup and management plan (53%), and no dedicated support staff (50%). The NAS data service may also be used for data replication, enterprise level backup of servers, virtual hosts, and databases, and user level backup of desktops and workstations with the appropriate software solutions.

<table>
<thead>
<tr>
<th>Type</th>
<th>%</th>
<th>Comments</th>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Better CI with minimal direct cost</td>
<td>91</td>
<td>Least burden on research budget</td>
<td>Cost</td>
</tr>
<tr>
<td>Network Attached Storage</td>
<td>73</td>
<td>Shared POSIX compliant filesystem</td>
<td>Sharing</td>
</tr>
<tr>
<td>Data replication as backup</td>
<td>66</td>
<td>Keep a second copy somewhere safe</td>
<td>Recovery</td>
</tr>
<tr>
<td>Dropbox- or Google Drive-like service</td>
<td>43</td>
<td>Ease of access and worry free backup</td>
<td>Ease of use</td>
</tr>
<tr>
<td>10G network connection</td>
<td>38</td>
<td>High speed network bandwidth</td>
<td>Network bandwidth</td>
</tr>
<tr>
<td>Minimal cost beyond hardware cost</td>
<td>24</td>
<td>Little operating cost</td>
<td>Cost</td>
</tr>
<tr>
<td>Shared technical expertise</td>
<td>20</td>
<td>Infrastructure, software and application consulting</td>
<td>Expertise</td>
</tr>
<tr>
<td>Distributed multisite replication</td>
<td>18</td>
<td>Geographical safety</td>
<td>Recovery</td>
</tr>
<tr>
<td>Desktop backup</td>
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<td>Routine research data safety</td>
<td>Backup</td>
</tr>
<tr>
<td>Compliant and secure storage for sensitive data</td>
<td>16</td>
<td>Personal and clinical data safety</td>
<td>Security</td>
</tr>
<tr>
<td>Tiered storage plans</td>
<td>16</td>
<td>Data retention and automatic removal</td>
<td>Cost</td>
</tr>
</tbody>
</table>

Table 4  Top 10 requirements for campus cyberinfrastructure

Dropbox may be sufficient for small data sharing and backup, they become more expensive when the amount of data increases beyond the low TB range based upon our survey (data not shown). An university may use its collective bargaining power to negotiate favorable licensing and privacy terms to contract these services to commercial companies. For example, UM is currently offering both Box and Google Drive services for general campus use. However, these commercial services may suffer from degraded synchronization performance over wireless network for data sizes beyond tens of MBs. They also have limitations on maximum file size support.

(4) Connection to the 10G network (38%). The 10G network covers most buildings at UC San Diego currently. There is a strong demand to get 10G connections into the labs in these buildings. The high-speed network will provide increased bandwidth and improve the quality of RCI data services. Yet, only a handful of labs are on the 10G network because the “last 100 feet,” the connection into a lab, still requires expensive hardware and installation costs. It may take a dramatic price drop on the consumer components or a form of subsidy from UC San Diego to fully realize the benefits of the 10G network.

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⁷ http://www.incommon.org/
(5) Minimal operation cost beyond the hardware (24%). Some researchers have much tighter research budgets than before. Any RCI data services offered would be competing with the seemingly “free” labor: graduate students, postdocs, and staff researchers who divert their research time into system administration. The PIs pay fixed stipends for their time, and the “volunteer” system administration effort is often considered a good experience to have. These PIs may not adopt any RCI data services priced above hardware cost even though they are putting their own data at risk. Many universities offer free operation of PI-purchased hardware through indirect cost. Some PIs may fear that they are less competitive in grant applications if they write in additional cost for hardware operation.

(6) Shared technical expertise (20%). The requirements in this area are quite diverse and project specific at times. They are grouped collectively under shared technical expertise because few groups can afford it individually. Many researchers require professional support in ① infrastructure design and support; ② software engineering; and ③ research application development in specific areas of statistical and bioinformatics analysis.

Under infrastructure design and support, some researchers have requested help with provisioning services from the Amazon cloud, or testing new file systems such as the Gluster file system. Having these cutting edge technologies tested by individual labs is not very efficient and requires a lot of redundant effort. RCI may be able to facilitate this type of exchange by providing the appropriate forum for discussion, i.e., mass sourcing the necessary support required.

Joint funding applications may be developed with the PIs to support these shared expertise and expand the role of RCI elements in campus research activities. For example, suggestions have been made that would encourage the adoption of electronic laboratory notebooks at UC San Diego to enhance the students’ educational experience and facilitate information management from the moment data is created. Other suggestions include the development of “live” publications that may have data stored at RCI and accessible through the web or linked into other forms of electronic publications. The development of these ideas into funding proposals requires a long-term commitment from UC San Diego to provide the necessary infrastructure for these innovations.

(7) Dual site replication on campus (16%), with SDSC as a second site for backup (18%). Data durability may only be guaranteed when the data is redundantly stored in distinct geographical locations. For example, Amazon S3 provides a standard redundancy service that guarantees data durability with the loss of data at two different facilities and a reduced redundancy service that guarantees data durability with the loss of data at a single facility. Currently, researchers may enhance the data durability by requesting that their data be stored at two separate locations on campus or utilize a RCI NAS data service for their backup. The caveat here is that a RCI NAS data service does not offer single copy storage without replication. This means users who want a second copy at SDSC actually receive an automatically replicated copy at their own cost.

University of Michigan and UCLA do offer single copy data storage. However, the past experience has indicated that users often ignore the “Single Copy No Backup” warning and put data there when it is the only copy. As RCI is in the business of providing reputable data storage services, the RCIDS team does not recommend that the single copy option be offered to general users. Special requests may be considered on a case-by-case basis. The RCI colocation service does offer several potential sites for location of equipment. However, there may be added cost for dual site replication due to the time and effort required to maintain at least one remote site.
(8) Desktop and workstation backup service (18%). This is an area a university to negotiate enterprise level pricing of backup software and providers such as CrashPlan, BackBlaze, and even Amazon Web Services. The situation is similar to Dropbox and Google Drive services, where the quality of service by commercial providers is reliable and scalable. Enterprise level contract and price negotiations may lead to service agreements that meet the privacy requirement of UC San Diego researchers. While the replicated data is a simple form of backup, its primary purpose is disaster recovery. More sophisticated backup plans may be necessary for users who desire to retrieve data with version histories dating back weeks, months, or years (4%). SDSC offers the CommVault backup service\(^1\) on campus. Different campus backup services may be built on top of the RCI NAS data service with minimal overhead.

(9) Compliant and secure storage of sensitive data (16%). While RCI may provide information security features to support research data with personally identifiable information (PII) or protected health information (PHI), these requirements are still evolving and often case dependent. For example, the Health Insurance Portability and Accountability Act (HIPAA) requirements are vague in separating the liability of service providers and users. The UC San Diego network security teams are actively monitoring the related guidelines. Researchers may also need database management support to ensure compliance with research project policies. Currently, RCI can provide NAS data service to users who can encrypt their own data. Highly sensitive data may require customized solutions and users are encouraged to contact RCI for further information. This is an area that requires more investment to meet the challenge of more personalized medicine in the near future.

(10) Tiered storage plans (16%). This is the area of information lifecycle management (ILM), where cost-effective solutions are tightly coupled with information from its creation to disposition upon the expiration of an assigned retention period. The domination of NAS (73%), USB drives (70%) and local server disks (65%) reflects a tiered storage plan independently developed by the researchers, since they are representative of the on-, near- and offline storage media types. NAS storage is the predominant option for “hot” data storage. The commercial Drobo Drives and Synology Drives may provide a self-serviceable solution for nearline data until a better solution emerges. For offline storage of rarely accessed data, commercial providers can operate at very large scales and are extremely competitive in pricing. For example, Amazon Glacier is priced at $132/TB/year and is extremely reliable, with data access guaranteed within a 6-hour window. There is a cost of $120/TB to move data out of Amazon beyond a small monthly allowance.

Automatic data tiering or movement of data based upon access rate and performance requirements is central to ILM solutions. There are hierarchical management solutions such as Storage Archive Manager-Quick File System (SAM-QFS) that automates the movement of data from disk cache to tape drives. The RCIDS team is actively monitoring open source ILM solutions, e.g., iRODS, that may provide economical and reliable services, as well as commercial offerings that may provide educational discounts.

5 IMPLEMENTATION PLAN

Most PI’s are interested in using grant funding to purchase hardware storage and have them professionally managed to keep their data safe. Thus, a sustainable business model is needed for condominium style shared

\(^1\) http://www.sdsc.edu/services/StorageBackup.html.
storage solutions where the PI’s purchase full or partial condo storage based upon their needs.

The UC San Diego Cyberinfrastructure Planning and Operation Committee (CIPOC) report in 2010 outlined a guiding principle in the development of a business model for RCI Centralized Storage. The PIs pay “79% of the start-up costs, 59% of the annual costs for the initial years, and 68% of the steady-state annual costs” and UC San Diego provides the rest of the cost through energy savings and indirect cost recovery. The PIs pay approximately $100/TB/year on hardware only for a replicated data storage service without including the costs for networking, colocation, and labor. As a rule of thumb, doubling the cost of the hardware provides a rough estimate of the total cost of ownership (TCO) for replicated data storage over the useful lifetime of the equipment. Thus, a ballpark figure is $200/TB/year minimum cost if the required economy of scale is achieved. Universities that pay the full cost of operating the hardware provide roughly a 50% subsidy to the TCO.

5.1 Business model considerations

The current business model under development builds upon a fixed investment that covers the startup, optimization, and operation of the core business processes. The economy of scale allows all participating PIs to share the incremental cost and lowers the average cost of operating individual storage nodes. The PIs will enjoy professional management of their critical research data at the most economical price and collectively bear the incrementally growing labor requirements. The viability of this business model may be influenced by the following factors:

(1) Cost-effectiveness. Most users would perform cost comparisons before they make purchase decisions. The storage pricing has to be low without affecting the quality of service to provide the most cost-effective solution. It is noteworthy that the published rates by universities are often for data curation, designed for high quality data in small amounts to be kept permanently. Therefore, a service description and the advertised cost should be examined together.

(2) The subsidy from a university reduces the cost for the PIs and the number of participating PIs builds up the economy of scale. Commitments from both sides are required to generate a recharge rate that is cost-effective to the PIs and sustainable to the university. Of the services following the condo storage model, Notre Dame University offers $250/TB/year without backup; University of Michigan offers the same rate with backup; UCLA offers volume discounted prices starting from $236/TB/year with backup and single copy is available for half of the costs.

(3) Service longevity. The PIs need assurance that the service will be there at the approved recharge rate. It may take up to a year for researchers to get grants funded using the published recharge rates. Researchers should not have to fear increased costs when they get their grant awards or lose access to their data when they have funding gaps. The budgetary threat must be removed in the strategic planning process for a university to ensure the economy of scale necessary for long-term viability of research cyberinfrastructure programs.

(4) Market demand. The interview participants are selected because they likely have major data management requirements. The actual market size for a university as a whole may not be extrapolated directly from the interview data. The biggest users may have application-specific requirements and smaller users may be happy with USB or local NAS drives. Therefore, the main target users may be those dealing with tens to hundreds of TB of data (Fig. 2). A total amount on the order of 3~5 petabytes (PB) may be required to achieve the economy of scale necessary and maximize cost-effectiveness.

(5) Actual adoption rate. The adoption rate is influenced by all the other three factors above, and is the...
indicator of a successful business model. Advertising at different levels may help increase the community awareness of research data services to encourage adoption.

(6) Service scalability. The number of users and complex support requests from an individual group will increase the cost of user support. A missing campus-wide UID/GID system at a university should be resolved with a long-term solution with consideration of federated identities with other universities. The business processes must be streamlined with greater automation to reduce the operating cost of adding and supporting individual users and groups. Short-term users increase the operating cost and reduce the service scalability unless the business process is highly automated. Complex support requests may be resolved through limited support of shared technical expertise and a recharge mechanism.

(7) Integrated services. Due to the diversity of requirements by the researchers (Table 4), there may be budgetary constraints on the number of services provided. Further discussion on the specific requirements is necessary to determine whether they can be met with existing campus-based recharge services, as opposed to developing new services. Moreover, the most cost-effective solutions are often developed with the complete data life cycle\(^1\) in mind, i.e., from data collection, processing, distribution, discovery, analysis, to repurposing, and archiving. Coordinated efforts using different technologies are required to develop integrated solutions from the moment of data creation to archival. A cautionary note here is that long-term archival is closely tied in with the Data Curation element of RCI. The data archived should be searchable and in a readable format by future generations to avoid the possibility of a data graveyard.

5.2 Recommendation

The NAS data service is central to the research data workflow of many laboratories (Fig. 1) and utilized by 73% of the interview participants (Table 2). Even though the 50 groups of researchers represent less than 5% of the UC San Diego faculty members, they generated more than two PBs of data over the past year, and expect to add new data at that rate over the next two years.

A NAS data service from RCI addresses the following risks and challenges:

- Constantly increasing storage demand (65%)
- Lack of or incomplete data management and backup plan (53%)
- No dedicated support staff (50%)

SDSC has offered a NAS data service called Project Storage\(^2\) over the past 18 months. It currently comprises 8 nodes, each with 88TB usable space and fully replicated. More than 20 research groups have taken advantage of the service. The adoption of Project Storage is gradually increasing with good performance and stability from the underlying architecture (Fig. 7).

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\(^1\) http://www.ddialliance.org/what.
\(^2\) http://project.sdsc.edu.
enjoys a hotel model as well, which allows users to pay a higher rate without having to purchase any hardware. The existing Project Storage customers are converted into the RCI NAS data service to enjoy a reduced rate when the service goes into production.

The RCI NAS data service enables the flexible provisioning of professionally managed storage space on demand with full replication as the backup option and support of disaster recovery. The service also guarantees campus-wide accessibility for data storage and sharing. The NAS data service is priced favorably to encourage sufficient adoption to achieve the economy of scale. There is minimal operating cost over hardware and the bait and switch practice is avoided.

However, a potential drawback of the proposed NAS data service is the scalability at the enterprise level and the cost of administration and user support. Therefore, the NAS data service may be viewed as an interim solution that meet existing demands while a more scalable solution is developed.

5.3 Cloud computing

In the era of big data, the demand for a high integrity, centralized, and durable storage solution is getting stronger and stronger. According to the Gartner, Inc., "big data is forecast to drive $34 billion of IT spending" in 2013\(^1\). From the perspective of data availability and protection, storage is the most critical component of an IT infrastructure. Managing the design, deployment, growth, consolidation, backup, recovery, and archival solutions and making informed and strategic purchasing decisions are constant challenges facing both educational and industrial institutions.

The RCI NAS data service is a storage solution that provides reliability and standard performance at a modest cost. It is widely used by small- to medium-sized research labs in the university environment. This platform complements the high performance parallel file systems such as Lustre, GPFS (global parallel file system), and PVFS (parallel virtual file system), which may scale to thousands of nodes and tens of thousands of cores. However, these high performance solutions are much more expensive and are usually associated with high performance computing (HPC) systems. As illustrated in Fig. 1, researchers need to pick the best data storage platform based upon their application and performance requirements.

Cloud computing, as originally described in the 2009 RCIDT report, combines storage and computing resources into “a set of managed infrastructure operated by third-party providers”, with emerging technology that enables on-demand provisioning of machines (IaaS, infrastructure as a service), execution environments (PaaS, platform as a service), applications (SaaS, software as a Service), and network resources (NaaS, network as a service). "More than 30% of organizations will move at least one enterprise data center workload to the cloud in 2013. Cloud services will be deployed even more broadly for private storage, including disaster recovery, backup, and archiving," according to Jay Kidd from NetApp\(^2\). Amazon EC2 (elastic computing cloud), Amazon S3, and Google Cloud Platform are leading cloud computing providers. Many popular services such as Dropbox and Google Drive leverage the cloud computing platforms to provide SaaS.

There is strong competition between cloud storage providers such as Amazon or Rackspace and high capacity storage solution providers such as Dell, Data Direct Networks (DDN), or EMC Corporation. Cloud based storage provides a reasonable cost of entry but lacks the performance, ease of access, and cost effectiveness desirable in the university research environment currently. On-site enterprise solutions such as Dell Compellent and Oracle SAM-QFS provide robust,
high performance, and tiered storage but have high purchase prices and maintenance fees. Many of these providers such as Rackspace and Dell also offer private cloud solutions to organizations that want full control of their cloud environment behind their own firewalls. While they are expensive to implement at universities, commercial vendors often offer academic discounts to increase adoption. For example, Cornell University has partnered with DDN to offer storage solutions that include endpoints for Globus Online.

5.4 Data cloud services

SDSC Cloud Storage was unveiled with more than 2 PB of storage capacity in 2011 as the largest academic private cloud storage environment to date. The recharge rates of SDSC Cloud Storage have been lower than SDSC Project Storage because of the OpenStack Swift object-based storage platform. However, most researchers require POSIX file systems such as the NAS data service that support traditional applications. While it is currently possible to use additional hardware enabled configurations to access SDSC Cloud Storage, the price-performance ratio has not reached a level required by the mass market.

GlusterFS and cephFS are two open source cluster filesystems that provide easy scale-out up to the PB range using commodity hardware. Both are POSIX compliant and offer a single namespace and native support for S3 and Swift APIs. They are excellent choices as processing workspace in genomics applications. However, they are still maturing and extensive testing and customization may be required for production use currently. Commercial support is provided by RedHat and Inktank respectively.

Many UC San Diego departments have built smaller IaaS private cloud services to provision virtual servers and virtual storage to minimize the TCO. UCLA is rolling out cloud storage solutions that utilize IaaS using virtual frontends to enable automatic data replication as soon as data is written to one node. This provides the benefit of load balancing and “hot replication,” with little downtime for disaster recovery.

Through a recent NSF award, researchers at SDSC and Calit2 have begun to build a new “big data freeway,” a state of the art research network named PRISM@UCSD, which will provide 10G and 40G connections between participating research laboratories. CENIC is contributing to establishing 100G connections to UC San Diego that will provide even bigger pipes for data sharing. This may enable commercial cloud access from the campus using virtual private cloud. Together, campus-based solutions will continue to offer the best performance in the “big data freeway”. The emergence of software defined network (SDN) will make NaaS a reality and change how secure and compliant storage is implemented.

In short, advances in cloud computing and network technology will change how data services are implemented in the near future, when software defined data center pushes the technology for data center virtualization.

6 DISCUSSION

Many researchers use the free data storage provided by Dropbox, Google Drive, or other commercial...
services despite privacy concerns. While Dropbox and Google Drive may be sufficient for small data sharing and backup, they become more expensive when the amount of data increases beyond the low TB range. UM has provided a leading example in using its collective bargaining power to negotiate favorable licensing and privacy terms to contract these services to commercial companies. However, these commercial services may suffer from degraded synchronization performance over wireless network for data sizes beyond tens of MBs. They also have limitations on maximum file size support.

A campus based Dropbox-like solution may offer better network performance for data transfer and synchronization. For example, researchers may use the NAS data service coupled with commercial software such as GoodSync or CrashPlan for data synchronization and backup. SDSC Cloud Storage also provides several interfaces such as a web interface, a CyberDuck GUI application, and a command line client for data storage. All the data stored in SDSC Cloud Storage may be shared easily through its web interface. Globus Online has been a successful example for transferring big data. There are also ongoing research efforts to build biomedical research data cloud services using the Duckling\(^1\) Collaboration Library and Opal\(^2\) services (Dong et al, unpublished data). Researchers may choose the most economical option depending on data sizes, sharing needs, production readiness, and performance requirements.

Like Dropbox or Google Drive, researchers also expect research data services to be accessible, affordable, reliable, and sustainable. For example, Google Drive content is searchable for easy data retrieval. Metadata and provenance tools may be provided to enable research intelligence and data mining. These types of tools are under exploration in the RCI data curation element\(^3\). DuraSpace\(^4\) hosts several open source projects in for digital data management that may offer turn-key solutions, e.g., DSpace or flexible and customizable solutions, e.g., Fedora Commons. DSpace has more than one thousand active instances in various universities worldwide.

In a recent talk on “Big Process for Big Data\(^5\)”, I. Foster suggested the scenario of “Dropbox for science” where research cyberinfrastructure is delivered in a “frictionless, affordable and sustainable” fashion and eventually provide a new model for cloud computing, aka, “science as a service.” The enthusiasm for Dropbox- and Google Drive-like services from the interviews is reflective of the desire for cyberinfrastructure that can transform the way scientific research is conducted in the digital age.

7 CONCLUSION

The RCI NAS data service addresses the major current requirements for the interview participants and may be integrated into customized solutions for different schools, departments and ORUs. However, cloud computing and storage technologies are offering many evolving solutions that may change how research data services are delivered. The strong global initiatives to conduct scientific endeavors as open enterprises will lead to new paradigms for science. Future efforts in data services need to address the data life cycle integratively. Strong institutional commitment to support research cyberinfrastructure is a key requirement in the sustainability of the cyberinfrastructure for higher education.

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\(^1\) http://duckling.sourceforge.net.
\(^2\) http://sourceforge.net/projects/opaltoolkit/.
\(^3\) http://libraries.ucsd.edu/about/digital-library/index.html.
\(^4\) http://www.duraspace.org.
\(^5\) http://www.slideshare.net/ianfoster/pnml-may-2013.
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为高等教育信息化基础设施发展可持续的数据服务：要求和可吸取的经验

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摘 要: 美国加州大学圣迭戈分校(UCSD)的科研信息化基础设施(RCI)项目的目标是在集中存储、主机托管、计算、数据管理、联网和技术服务等方面为师生员工提供长期优质的服务。在2012年9月到2013年2月之间，为了确定数据存储的要求以及工作优先排序，RCI数据服务团队(RCIDS)与多名教师和高级职员进行了一系列访谈。这些采访涉及了圣迭戈分校的29个独立的部门和科研单位，有50个不同的小组参加，共代表了600多名研究人员。这些研究小组的各样数据，从人类基因组序列，海洋天然产物，到宇宙模拟实验，是与全球成千上万用户分享的。根据这些访谈的结果，我们总结了圣迭戈分校研究人员对数据服务的10个要求以及5个现有的挑战与风险。RCIDS提出在一个可持续的商业模式下，首先部署网络附加存储(NAS)数据库；然后，再通过进一步的讨论以及考虑新兴的云计算技术来确定更长远的服务计划；最后，我们对于建立可持续性的高等教育 e-科学基础设施的实施方策，基于云计算的数据服务，以及可吸取的经验教训提供了广泛的讨论。

关键词: 高等教育; 科研信息化基础设施; 云数据; 可持续的数据服务; 网络附加存储

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