

# Tempest: Soft State Replication in the Service Tier\*

Tudor Marian, Mahesh Balakrishnan, Ken Birman, Robbert van Renesse

*Department of Computer Science  
Cornell University, Ithaca, NY 14853*

{tudorm, mahesh, ken, rvr}@cs.cornell.edu

## Abstract

*Soft state in the middle tier is key to enabling scalable and responsive three tier service architectures. While soft-state can be reconstructed upon failure, replicating it across multiple service instances is critical for rapid fail-over and high availability. Current techniques for storing and managing replicated soft state require mapping data structures to different abstractions such as database records, which can be difficult and introduce inefficiencies. Tempest is a system that provides programmers with data structures that look very similar to conventional Java Collections but are automatically replicated. We evaluate Tempest against alternatives such as in-memory databases and we show that Tempest does scale well in real world service architectures.*

## 1 Introduction

Service-Oriented Architectures (SOAs) have emerged as the paradigm of choice for structuring large datacenter-hosted systems. Most contemporary large-scale applications are built as SOAs: online stores, search engines, enterprise software and financial infrastructure are some examples. The canonical design for such systems is a three-tier architecture: a first tier load-balancing proxies sends requests to a second tier of state-less service logic which in turn accesses and updates a third tier of durable databases or filesystems.

Soft state in the service tier is key to building highly responsive and scalable SOAs. Soft state is characterized as data that does not have to be stored durably and can be reconstructed at some cost [39, 24, 17] — examples include short-lived user sessions, stored aggregates and transformations on large datasets, and general purpose write-through

caches for files and database records. Third-tier constructs are extremely fault-tolerant but correspondingly slow and expensive, and soft state is typically used to limit their role in performance-critical data paths. For example, the developer of an online travel service might use the memory of the service instance to store intermediate choices made by a user during the booking process, so that only the final sale transaction — a small fraction of all user activity — hits the third-tier database.

In this paper, we consider the availability of soft state stored in the service tier. When soft state is lost or made unavailable due to service instance crashes and overloads, reconstructing it through user interaction or third-tier re-access can be expensive in time and resources. Replicating soft state provides applications with two critical capabilities: rapid fail-over to other instances during crashes and fine-grained load-balancing across instances to prevent overload [39]. For example, a user request can be transparently redirected during a crash or overload to a different service instance that has up-to-date session context, without requiring her to log in again.

Many options exist for adding high availability to programs that manipulate soft state and these can be broadly classified into three categories: clustered application servers [3], messaging toolkits, and collocated in-memory databases. However, all these options require the developer to write code in “state-aware” ways, mapping data structures to special replication-aware containers, replicated state-machine stores and database-style records, respectively. Such mapping needs to be done carefully to avoid performance issues — for example, storing fine-grained variables in a database could result in severe locking contention [1]. However the natural way for programmers to store and manage soft state in a service is to use conventional in-memory data structures such as hash tables or linked lists.

In this paper, we present Tempest, a Java runtime library designed for easy storage and replication of service-level soft state. Tempest provides developers with *TempestCollections*: custom data structures that look similar to con-

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ventional Java Collections [35]. Data stored in these structures is transparently and *fully* replicated upon multiple machines, providing fail-over and load-balancing for soft (in-memory) state with zero extra effort by the developer. Under the hood, Tempest uses a fast but unreliable IP multicast operation to spread/broadcast invocations to multiple service instances and then uses gossip-based reconciliation to maintain replica consistency in the face of faults and overloads. Additional adaptive mechanisms are used to maintain high responsiveness during failures.

High-performance in-memory databases are used extensively to store soft state in currently deployed systems [6, 30, 13] and we show that Tempest outperforms them in large-scale SOA settings. Real-world SOAs often have many services interacting with each other to perform complex tasks — for example, a first-tier front-end could contact a hundred second-tier services to assemble a webpage [20]. Further, each service is potentially contacted in parallel by a large number of load-balancing first-tier front-ends. Tempest scales in both the number of front-ends querying a single service and the number of services being queried by a single front-end. In contrast, in-memory databases fail to scale in these dimensions due to contention, large latency variations and inefficiencies in cross-process interactions between the service and the database.

Accordingly, the contributions of this paper are as follows:

- We present a Java runtime library that exposes data structures to programmers that are transparently replicated across multiple nodes.
- We describe the gossip-based mechanisms used within the system for rapidly replicating data and speeding-up access to it.
- We evaluate Tempest on two datacenter-style testbeds — the Emulab testbed at Utah [37] and a 252 node cluster at Cornell. We show that Tempest maintains rapid responsiveness under heavy loads and outperforms in-memory and on-disk databases while scaling in two important dimensions — the number of front-ends accessing a single service and the number of services composing a single response.

The remainder of this paper is structured as follows: Section 2 describes the interface and semantics provided by TempestCollections to service developers. Section 3 describes the protocols and mechanisms used by Tempest to implement the TempestCollection abstraction, and Section 4 provides an evaluation of Tempest on datacenter testbeds.

## 2 The TempestCollection Abstraction

### 2.1 Service Model

Services are self-contained entities designed to support interoperable machine to machine interaction over a network. Each service exposes an API through which a set of methods can be invoked by clients, and each service offers its own quality of service and availability guarantees. Take for example the interface of a shopping cart service as listed in Figure 1.

```
public interface ShoppingCartIF extends Iterable {
    update int add(String itemSymbol, int count);
    update int remove(String itemSymbol, int count);
    update int update(String itemSymbol, int count);
    read int check(String itemSymbol);
}
```

**Figure 1. ‘Shopping Cart’ service interface.**

Add, remove and update do the obvious things; these are classified as update operations because they change state. Check is a read operation; it retrieves the current number of items in the shopping cart for the symbol of interest. Clients issue add/remove/update and check requests against the service; the service processes each request and in return sends back a reply. This simple example can be trivially extended to services like item browsing history, product availability, product rating, or caching services.

In this work we assume that business logic is collocated with soft state stored in the memory of the service instance; as mentioned before, this is a natural design choice for applications requiring scalability and responsiveness. For example, storing shopping cart information in-memory allows the service to handle a large quantity of browsing traffic that otherwise would have reached the third tier. A developer implementing the shopping cart service in Java could use different data structures to store the state of the cart; a natural way would involve using a hash table to store mappings between item identifiers and corresponding counts.

Service state is modified by updates sent to it through its *interface* — in the conventional three-tier setup, this refers to database state hidden by the service, but in our case it includes soft state maintained by the service. In our shopping cart example, items are added to or subtracted from the cart.

The implementation of a service as a Java application running on a single node is obviously prone to crashes, overloads and slowdowns. Our goal is to transparently replicate a service on multiple nodes while retaining the programming ease and familiarity of Java’s built-in Collection data structures. Accordingly, we provide developers with *TempestCollections* — data structures very similar to vanilla Collections but providing automatic replication of the data stored in them.

## 2.2 TempestCollection: Syntax and Semantics

TempestCollections are syntactically identical to standard Java Collections. For example, a `TempestHashtable` exposes `get` and `put` methods while a `TempestSet` has `add`, `remove` methods. Like most Java Collections, objects stored in a `TempestCollection` cannot be modified in place. For example, to change a field inside an Object stored in a `TempestSet`, the programmer would have to remove the Object, modify it and then re-insert it into the set.

This is a very common programming idiom within the Java Collections framework. For example, Java `TreeSets` provide ordered iteration over their elements, and changing the value of an item in-place can push the `TreeSet` into an inconsistent state by modifying the outcome of compare operations. Programmers are expected to instead change values by removal, modification and re-insertion if they want the `TreeSet` to remain consistent and ordered. In general, many Collections involve comparisons through `equals` and `compareTo` — such as `HashMaps`, `TreeSets` or `HashSets` — and do not allow safe in-place modification of objects stored within them. In this respect, `TempestCollections` offer identical semantics.

To prevent accidental modification of stored items, `TempestCollections` implement *by-value* parameter passing. Deep clones of added Objects are stored within the `TempestCollection` and clones of stored Objects are returned by accessor functions. For example, calling `put(K, A)` on a `TempestHashMap` will result in a clone  $A'$  being stored within the collection, and calling `get(K)` will return  $A''$  to the programmer.

However, the Tempest runtime can alter the contents of `TempestCollections` by adding and / or removing items to keep collections consistent across replicas. `TempestCollections` provide *eventual consistency* — all replicas converge to the same set of objects [12, 10]. An implication of this model is that the programmer is not provided with ACID transactions; however, this is not a major limitation for soft state management [10]. In many soft state applications, data stored within structures is naturally immutable — for instance, a browsing history service that stores a list of item identifiers. For others, updates do not depend on current state — for example, a map from users identifiers to last viewed items. Even if the soft state is manipulated with arbitrary operations, it is expected by definition to not have strong semantics — the user is always asked to verify the contents of a shopping cart or the final itinerary of a travel plan before committing to it.

To summarize, `TempestCollections` are data structures exposing interfaces identical to those in the Java Collections framework and supporting similar semantics by not allowing in-place modifications of stored Objects. The sole devi-

ation from the Java Collections framework — aside the weak consistency implications — is that Tempest enforces Object immutability by passing parameters by-value — a side effect of this is the possibility for services to operate on stale data. By deliberately choosing a weaker consistency model we had more opportunities to provide a massively scalable solution — as a result developers are required to understand and account for unreliable soft state.

## 3 Tempest Architecture

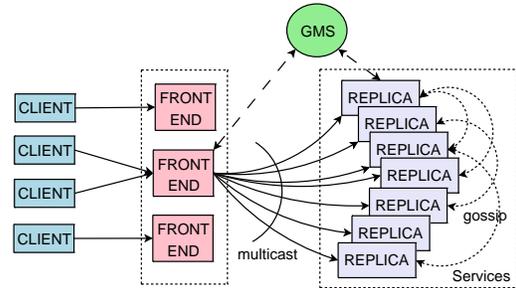


Figure 2. Tempest architecture.

In this section we describe the mechanisms used to implement replicated `TempestCollections`. Tempest services reside on second-tier *servers*; a single server represents the platform configuration on a single computer and might run several services. A service instance stores data in one or more `TempestCollections`. Multiple instances of a service execute across different servers, and invocations to a service are sent by first-tier front-ends to all the service instances. Figure 2 depicts a front end initiating a multicast to the servers containing replicas of the same service instance.

The life-cycle of a Tempest invocation begins when a client sends a request to the datacenter, which gets load balanced to a web-facing front-end node. The front-end is then responsible for contacting a set of services and aggregating individual service responses into a composite result that it returns to the client. Front-ends use IP multicast (there is a distinct IP multicast group for each replicated Tempest service) to perform web-service invocations on service instances, allowing very rapid communication in the general case. When multicast packets are dropped, gossip-based point-to-point (typically UDP) reconciliation is used to repair gaps and errors in the `TempestCollections` maintained by the different service instances of the same service.

### 3.1 Client Invocations

When a client request enters the datacenter at a front-end, it's tagged with a web service invocation identifier (wsiid) consisting of a tuple containing the front-end node identifier

and sequence number. Front-end node identifiers are obtained by applying the SHA1 consistent hash function over the front-end’s IP address and port pair. Each Tempest request is thus uniquely identified by its wsiid.

As mentioned previously, Tempest differentiates between updates and queries or reads. For updates, Tempest uses IP multicast to send the operation directly to the full set of Tempest servers that hold replicas of the service for which the requests were intended. A hashing mechanism is employed to determine which server instance is responsible for replying. In the absence of message loss, the common case, IP multicast within datacenters is reliable and ordered.

For read requests, front-ends use an adaptive querying mechanism. Each front-end periodically multicasts a beacon to each service and waits for unicast responses from each instance. It selects the  $k$  instances that respond first — where  $k$  is the *redundant querying* parameter — and subsequently directs service read invocations to these instances.

### 3.2 The Tempest Gossip Mechanism

Tempest is designed under the assumption that the multicast protocol used might not be fully reliable or might recover lost packets at high latencies. If some replicas miss an update, they can become inconsistent. Tempest uses a gossip protocol to repair these kinds of inconsistencies rapidly. Servers use a custom tailored gossip protocol to reconcile differences between the TempestCollection replicas.

Tempest keeps track of all the operations performed at the data structure boundary — this is possible due to our *by-value* semantics of altering the collections. When an object is added to a collection, it is annotated with the web service invocation identifier of the corresponding invocation; when an object is removed from a collection, a death certificate for it is created and annotated with the wsiid. A death certificate is simply a means of retaining the information necessary to identify which objects were removed from a collection. In particular each TempestCollection keeps a history of the removed objects in an internal private data structure not exposed via the standard interface.

The anti-entropy mechanism works by having each server “gossip about” the sets of web service invocation identifiers (wsiids) that annotated objects in TempestCollections. Suppose for example that during one gossip round we have two service replicas  $r_1$  and  $r_2$  respectively engaged in an exchange; let their *sets* of wsiids be denoted by  $w(r_1)$  and  $w(r_2)$ . If  $w(r_1) = w(r_2)$  no action is taken, otherwise some invocations were missed by one (or both) and a “reconciliation” phase is triggered:

- If  $w(r_1) \subset w(r_2)$  then  $r_1$  missed invocations and holds a stale version of the state – as a result  $r_1$  retrieves from  $r_2$  the objects and death certificates annotated with the wsiids from the set  $w(r_2) \setminus w(r_1)$ .

Objects referred by the death certificates are removed, newly received objects are added; also  $r_1$ ’s set of wsiids is updated accordingly:  $w(r_1) \leftarrow w(r_2)$ .

- If  $w(r_1) \not\subset w(r_2)$  and  $|w(r_1)| \neq |w(r_2)|$  (the sets have different cardinality) both replicas have missed at least one update each, therefore to make progress it is safe for any of the replicas to assume the other replica’s state – without violating the “eventual consistency” guarantees offered by the system. Choose the replica that has the smaller  $w$  set – let it be  $r_1$  without loss of generality;  $r_1$  performs the following steps:
  - For every identifier  $i$  in the set  $w(r_1) \setminus w(r_2)$ , if  $i$  annotates an object then the object is discarded, otherwise if  $i$  annotates a death certificate the object referred by the death certificate is “resurrected” (added back to the collection).
  - Fetch from  $r_2$  all objects and death certificates annotated with identifiers from the set  $w(r_2) \setminus w(r_1)$ . Remove objects referred by the death certificates, add the new objects, and update  $w(r_1) \leftarrow w(r_2)$ . Here we used the heuristic of discarding the state of the replica that received less invocations, however one can imagine other criteria.
- If  $w(r_1) \not\subset w(r_2)$  and  $|w(r_1)| = |w(r_2)|$  then the initiator of the gossip round between  $r_1$  and  $r_2$  “plays the role” of the replica with the smaller  $w$  and performs the same operations as in the previous case.

An upcall is provided such that the service developer using TempestCollections is notified when a gossip reconciliation was triggered.

If no new invocations are issued against the system, and if no permanent network partition that splits the servers into two or more disjoint communication parties occurs the TempestCollection replicas will eventually contain identical elements with probability 1 [11].

During a gossip round, there can never be more than 3 messages issued per process (by protocol design). Currently the sets of web service identifiers are monotonically increasing as new invocations are issued, therefore gossip messages size increases with time. We are working on a method for garbage collecting the stale wsiids by appending an epoch number at wsiid generation time — tempest servers will discard wsiids that are more than  $\delta$  epochs old for some choice of parameter  $\delta$ . Another option is to use efficient set reconciliation methods like the ones in [27, 5].

The strength of gossip protocols lies in their simplicity, the fact that they are robust (there are exponentially many paths information can travel in between two endpoints), and the ease with which they can be tuned to trade speed of

delivery against resource consumption. The Tempest epidemic protocols evolved out of our previous work on simple primitive mechanisms that enable scalable services architectures in the context of large-scale data-centers [26].

### 3.2.1 TempestCollections Update Order Sensitivity

The gossip protocol described above requires that operations against TempestCollections be commutative, or order insensitive – which is the expected common case for most soft state applications [10]. The framework cannot support data structures that inherently depend on the order of operations – e.g. lists, stacks or queues.

Since this is a limitation developers may find hard to accept, we provided Tempest with a variant of the gossip protocol that uses for each TempestCollection *ordered lists* instead of sets of web service invocation identifiers. The protocol description is roughly identical with the one presented above with a few minor differences. Set inclusion tests are replaced with list prefix matching, and reconciliation between replicas is more elaborate – however due to space limitations we omit a more in depth description.

### 3.3 Membership and Failure Detection

Membership in Tempest is handled by the Group Membership Service (GMS), which maintains the mapping between servers and service replicas. In addition, it also acts as a UDDI (Universal Description Discovery and Integration) registry providing appropriate WSDL (Web Services Description Language) descriptions for the services deployed on Tempest servers — consequently it provides the appropriate mapping between a service identifier and the corresponding IP multicast group. The GMS also fills the administrator role for Tempest servers, monitoring the overall stress and spawning new servers to match the load imposed on the system. Finally, it monitors components to detect failures and adapt the configuration.

Tempest assumes that processes fail by crashing and can be reliably detected as faulty by timeout. Accordingly, Tempest processes monitor the peers with which they interact using a secondary gossip-based heartbeat mechanism. Processes that are thought to be deceased are reported to the GMS, which waits for  $f$  distinct suspicions before actually declaring it *deceased*. It then updates and disseminates group membership information to all interested parties. While in our experiments the GMS is hosted on a single high-end node, in a datacenter it could potentially be replicated and partitioned across multiple machines for scalability and fault-tolerance.

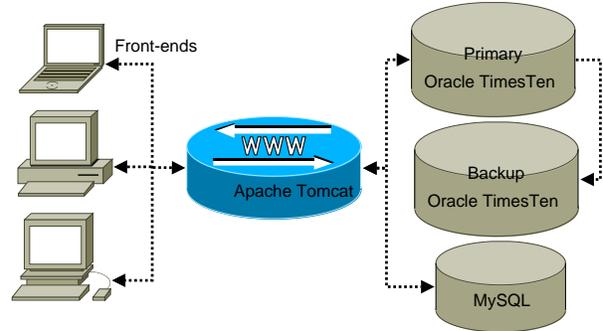


Figure 3. Baseline configurations.

### 3.4 Node Recovery and Checkpointing

TempestCollections are automatically checkpointed. Periodically, each Tempest server batches the items in each TempestCollection and writes them atomically to disk using a copy-on-write technique. When a node crashes and reboots, upon starting the Tempest server, the services are brought up to date with the state that was last written to disk before the crash.

When a server is newly spawned, or when a server that has been unavailable for a period of time missed many updates, Tempest employs a bulk transfer mechanism to bring the server up to date. In such cases, a source server is selected and the contents of the relevant TempestCollections are transmitted over a TCP connection. When multiple services are collocated in a single server, the transfers are batched and sent over a single shared TCP stream.

Newly spawned services and services that rebooted after a crash will consequently “catch up” gracefully with the rest of the service replicas by means of the epidemic protocols.

## 4 Experimental Evaluation

Tempest was implemented in Java, adding new transport protocols to the Apache Axis Soap [36] web services stack, i.e. SOAP over TempestTransport instead of SOAP over HTTP. The deep cloning capability was implemented using the Java Reflection API. The system components are built with Java’s non-blocking I/O primitives.

The evaluation is structured as follows: in subsection 4.1 we show that a single replicated Tempest service can provide rapid response to large numbers of concurrent front-end requests. In subsection 4.2 we show that this is true even when services are heavily loaded. Finally, in subsection 4.3, we show that the two knobs provided by Tempest — number of replicas per service and number of redundant queries — enable rapid predictable response for “service-clouds” composed of many collaborating services with differing timing characteristics.

## 4.1 Micro benchmarks

First we ran a set of micro benchmarks to compare Tempest against four multi-tier baseline scenarios. The experiments were run on the Cornell cluster – a pool of 252 machines, each a 1.33GHz Intel single CPU blade-server with 512MB of RAM and 100Mbps ethernet interfaces and 3 higher end servers each a single 2.8GHz CPU with 1GB of RAM and 3 1Gbps ethernet interfaces. Nodes are connected through a mesh of 100Mbps/1Gbps switches (HP ProCurve J4121A 4000m and J4902A 6108). In all configurations we had the same set of front-ends interacting with the `ShoppingCart` web service deployed on the *high end* servers. We deployed the service on top of the Apache Tomcat server. The service stores the data using various relational database repositories as shown in Figure 3. In one configuration we stored the data using the Oracle TimesTen in memory database co-located with the Tomcat server. In the second configuration TimesTen resided on a remote third-tier machine and lastly deployed in a primary-backup configuration with the primary co-located with the Tomcat container and the backup on the third-tier machine.

In all configurations TimesTen worked in “high performance cache-mode” for in-memory operations only, thereby offering ACI guarantees instead of full ACID – without committing durably to disk. The primary-backup scheme provided by TimesTen that we used is called *return receipt*, and it ensures that upon submitting a request to the master the client application is blocked until the replication scheme on the master received an acknowledgment that the update has been received by the backup server.

We also use an ubiquitous on-disk database engine, and for that purpose we relied on MySQL 5.0 with the InnoDB storage engine configured for ACID compliance — flushing the log after every transaction commit, and the underlying operating system (Linux 2.6.15) with the file system mounted in synchronous mode and with barriers enabled. Similarly, we have deployed the `ShoppingCart` service on 3 replicated Tempest servers gossiping at a rate of once every 100 milliseconds — we did not replicate Tomcat for load balancing since Tempest replicas were configured to receive *all* updates. The Tempest `ShoppingCart` service stores the data inside a *TempestMap*.

The workload applied consists of multiple clients issuing small 1024-byte requests against the `ShoppingCart` service in a closed loop — clients submit a job, receive the response and then “think” for some amount of time (20ms) before submitting the next job [33]. Every experiment had a startup phase in which we populated the data repository with 1024 distinct objects identified by object identifiers. Client requests were drawn from a Zipf distribution (with  $s=1$ ) over the space of object identifiers – reads and writes equally distributed. In all experiments clients are the front-

ends from Figure 2. We measure the Web Service Interaction Time, i.e. the request latency as observed by 1, 2, 4, 16, 32, 64, 128, 256, 512, 800 and 1024 concurrent clients – multiple virtual clients ran on the same 64 physical machines. During each run, all clients are initially instructed by a coordinator to start the experiment without taking any measurements – this warm up period of roughly 20 seconds is required for various reasons for example it is well known that to-date JVM’s notoriously underperform until the just in time compiler is fired up. At this point the coordinator instructs all clients to start taking measurements – this lasts 20 seconds as well, at which point the coordinator instructs nodes to cool down for 20 seconds and then stop.

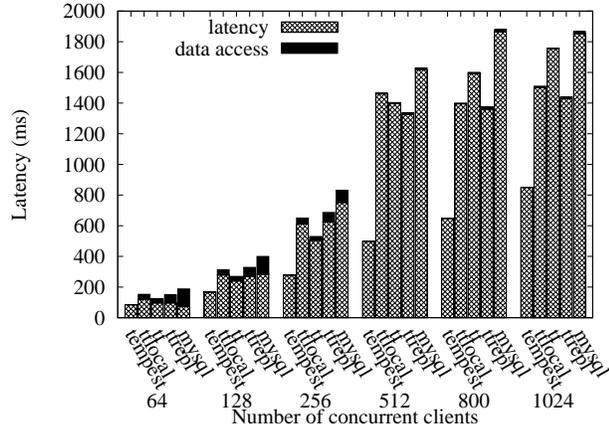
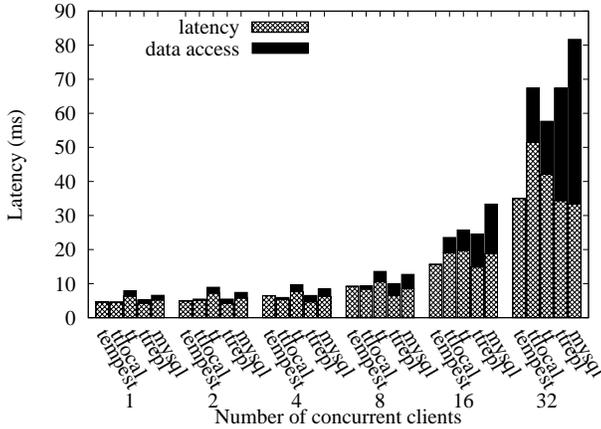
Figure 4 shows that Tempest latency is significantly less than any of the baselines, thus confirming that fault-tolerant services with performance-critical properties can be built on top of the Tempest platform. The graphs also indicate that Tempest scales well with the number of concurrent requests.

As can be seen from the breakdown of the latency, the baselines distribution of overhead is bimodal. For up to 64 concurrent clients the database interaction time (data access) increases roughly linearly. For more than 64 clients the data access time remains the same while the total latency continues to increase with the number of concurrent requests. This indicates that the databases and / or the Tomcat application server have some sort of queueing admission control that takes effect under severe load.

Looking carefully at the breakdown of the latency in Figure 4 (the 1-to-32 concurrent clients spectrum) one can notice that the time spent by a Tempest service manipulating the data (i.e. performing object deep cloning, data structure lock contention, web service invocation identifier tagging and index maintenance) is an order of magnitude smaller compared to the database interaction — as a matter of fact it is around 1 millisecond no matter what the number of concurrent clients is — thus showing that fine grained data structures allow for better performance under contention.

## 4.2 Graceful Recovery under Heavy Load

Next, we ran a set of experiments to report on Tempest’s behavior in the face of failures. Node crashes turned out not to be especially interesting since the gossip failure detection protocols quickly detects failed nodes, expels them from the group and shifts work to other nodes. More details on the timeliness of a variant of the gossip based failure detector we used can be found in our previous work [26]. We did however identify a class of overload scenarios that have a more visible impact on the Tempest replicated services. These scenarios degrade some service components without crashing them. The services become lossy and inconsistent, and queries return results based on stale data. Two questions are of interest here: behavior during the overload, and



**Figure 4. Request latency.** Each group of bars represent Tempest (*tempest*), TimesTen on the local machine with tomcat (*ttlocal*), TimesTen on a remote machine (*tt*), TimesTen in primary-backup mode with the primary on the same machine as tomcat and the backup on a remote machine (*ttrepl*), and MySQL on a remote machine (*mysql*).

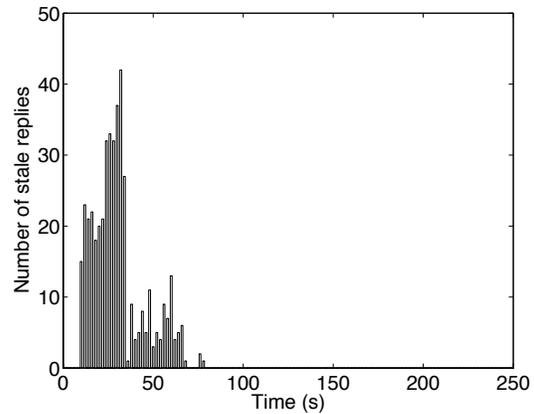
the time required to recover after it ends.

We replicated the `ShoppingCart` service on 6 Tempest low-end servers on the Cornell cluster. A client injects a single source stream of updates at a particular rate of one update every 20 milliseconds. This client also concurrently performs query requests on 8 concurrent threads — the query rate is therefore roughly 8 times higher than the update rate. Under these circumstances Tempest nodes are not overloaded — the overload unfolds as follows:

- At time  $t$ , from the start of the experiment 128 “rogue” clients bombard 3 of the Tempest servers with requests. We call the Tempest services *victims*.
- At time  $t + \Delta$ , the rogue clients terminate. At roughly the same time, the stream of updates also ceases.

In the experiment we report on  $t$  is 10, and  $\Delta$  is 30 seconds. The rogue clients bombard the victims with multiple streams of continuous IP multicast requests in the attempt to saturate their processing capacity and have their kernel / NIC queues drop packets. We found that this was not enough to perturb the normal behavior of the servers, hence at the same time we superimposed additional background load on the victim servers. These attacks do not cause the servers to crash, but they do cause them to become overloaded, drop packets and therefore return stale results.

Server overloads will not influence the performance of Tempest at non-attacked services, hence *we report only on the impact of the disruption at the victim replicas*. Figure 5 shows the number of “stale” query results on the y-axis against the time in seconds on the x-axis, binned in 2-second intervals. The Tempest gossip rate is set at once



**Figure 5. Number of stale results.**

every 40 milliseconds. Throughout this period, the victim nodes are overloaded and drop packets, while the Tempest repair protocols labor to repair the resulting inconsistencies. Meanwhile, queries that manage to reach the overloaded nodes could glimpse stale data (not reflecting recent issued updates since the updates were lost).

Note that once the attack ends, Tempest is able to recover gracefully. The number of stale replies observed follow a tri-modal distribution corresponding to normal operational regime, response under heavy load (between 30 and 40 seconds in the experiment) and a transient recovery period during which the gossip protocol brings the state up to date (between 40 and 65 seconds in the experiment) – as mentioned before the update stream ceases at the same time as the attack does therefore new updates are not responsible

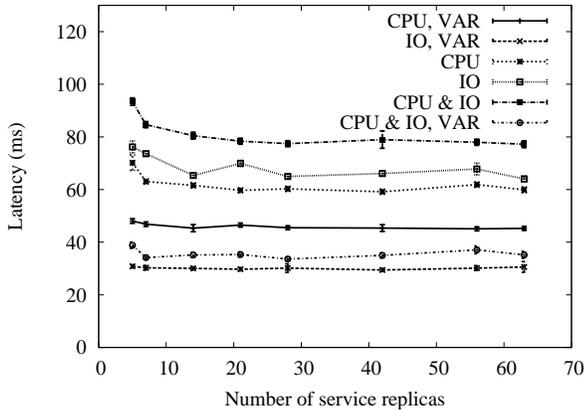


Figure 6. PetStore services characteristics.

for “clearing up” the stale state.

### 4.3 Scalability in the Number of Services

To estimate how Tempest scales in different dimensions — in particular, the size of the collaborating services, number of front-ends and number of replicas — we built a synthetic PetStore on top of Tempest and evaluated it on the Emulab testbed. The application consists of a battery of front ends issuing requests to a “cloud” of services.

The services in the cloud have different response time characteristics: some are IO intensive – for example an indexing service may access disk much more often than the average service, others are CPU intensive – for example a recommendation service may require considerably more CPU cycles than the average service, while other services are both IO and CPU bound. We also consider the response time variances for these types of services, in particular the PetStore services have both small and large response time variance. We observed that services performing multiple IO operations are likely to suffer from scheduling delays. Lock contention within Tempest may be another cause for large response time variance. All PetStore services store soft state using some form of a TempestMap or TempestSet.

Initially we ran a set of baseline experiments to measure the behavior of each type of service individually, under normal load. The experiment consisted of two front ends issuing request streams (half updates half reads) of one query every 40 milliseconds in closed loop to a single replicated service. Services have the gossip rate set for once every 100 milliseconds. We repeated the experiment for various number of replicas and for each of the types of services mentioned above. Figure 6 shows the query latency for all services; the error bars represent standard error. Note that even for services that we instrumented to have small response time variance, if they are IO bound they do exhibit large

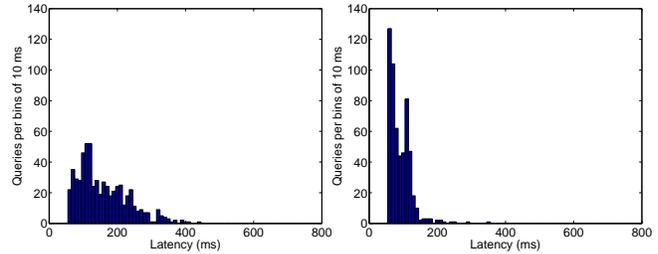


Figure 7. Pet-store response time histograms, left: no replicas, right: 8 replicas.

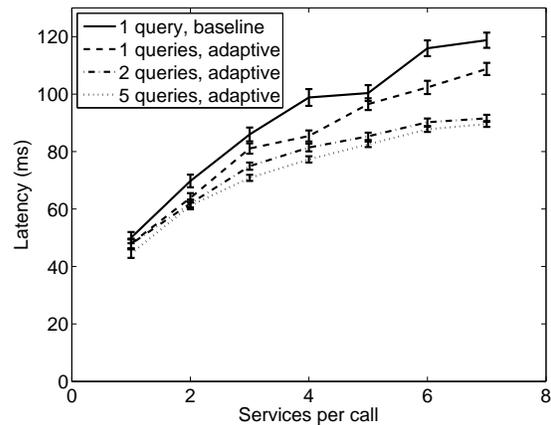


Figure 8. Pet-store latency, 5 replicas each.

variance — in particular note the CPU & IO bound service for 42 replicas and the IO bound service for 56 replicas. For this client request load, the service instances become overloaded if we drop below 3 replicas, and hence we don’t report those values (response times are meaningless when the service is unable to keep up with the request rate).

We evaluated the PetStore as a “cloud” of seven services — the six with the characteristics presented in the previous experiments, along with another baseline “null” service that shows the overhead caused solely by Tempest. Four clients perform multi-service requests (half queries half updates) against the PetStore in a closed loop, each at a rate of once every 50 milliseconds — we chose the rate so as to not completely overload the platform and observe queueing effects instead. A multi-service request is a set of  $n$  parallel requests sent to  $n$  distinct PetStore services — this is how the PetStore’s front end web page aggregates content.

Figure 7 shows response time distributions for multi-service requests sent to *all* services — every request issued by a front-end is sent in parallel to each of the seven services, the front end returning when all replies are received. Requests have the redundant querying parameter  $k=2$ . Each histogram shows the number of requests per bins 10 mil-

liseconds wide. We show two scenarios: the one in which none of the services is replicated, and the one in which services have 8 replicas each – for a yield of 7 distinct multicast groups of 8 servers each. The graphs show that replication provides more opportunities for queries to be absorbed by load balancing — fewer queries reach each replica.

Figure 8 shows response times for multi-service requests (with standard error denoting the error bars). Every multi-request issued by a front-end chooses at random  $n$  distinct services, where  $n$  is the number of services per query, presented on the  $x$ -axis. We used the adaptive query algorithm with the  $k$  parameter set to 1, 2 and 5. For baseline we used a simple query discovery algorithm by which the first query for a service is multicast, and all subsequent queries are sent to the one replica that replied the fastest to the multicast. We conclude that adaptive redundant querying does indeed improve performance when replicas are not overloaded, with the largest payoff for  $k = 2$ .

## 5 Related Work

Amazon’s Dynamo [10] provides a highly available key-value persistent storage system. Dynamo also sacrifices consistency for availability and uses object versioning and application-assisted techniques for conflict resolution. Unlike Tempest, where data structures are fully replicated, Dynamo works like a zero-hop distributed hash table (DHT) with data replicated over the  $N$  predecessor nodes.

Like Tempest, Sinfonia [1] introduces a set of abstractions that support building scalable distributed systems. However Sinfonia replaces the message passing model by providing a distributed shared memory abstraction. Developers would simply design and manipulate data structures on top of a flat, unstructured fine-grained shared address space. At its core, Sinfonia uses a lightweight minitransaction primitive that applications use to atomically access and conditionally modify data across distributed memory nodes.

Soft state mechanisms have been used extensively in network protocols [38, 15], as well as in large cluster-based services like Porcupine [32] and others [17, 7, 34]. Proposals exist for extending the standard web-service model to include soft state — a prominent example is the Grid Computing standard [16]. Recovery-oriented computing [8] is an alternative approach to providing fast failover and availability in the face of failures — however, it does not replace replication as a mechanism for balancing heavy load across multiple machines. Distributed data structures have been proposed before [21, 25] as building blocks for clustered services. They follow a strictly defined consistency model: all operations on its elements are atomic, in that any operation completes entirely, or not at all — however transactions across multiple elements are not supported. The work in [39] is very similar in spirit to Tempest, but examines

the orthogonal question of providing customizable durability levels through a single storage abstraction; one of these levels is meant for soft state that needs to be replicated for high availability. SSM [24] is a system for managing and storing a particular category of soft state — user session.

Clustered application servers like BEA WebLogic [3], IBM WebSphere [22], JBoss [23], to mention a few, allow storage of state in special containers that are typically stored within persistent databases. Most often than not, these middleware solutions handle soft state using distributed cache infrastructures, at times relying on third party products like Oracle Coherence [29] or GemFire Enterprise [18] for example. There has been a large amount of work in the field of fault-tolerant middleware, especially around CORBA [2, 28, 14], but most of this work does not consider interaction with a database third tier. DBFarm [31] is an architecture for scaling a core of multiple clustered databases through the use of less reliable replicas.

Google’s Bigtable [9] is a distributed storage system for managing petabytes of structured data across thousands of commodity nodes in a datacenter. It relies on the Google File System [19] to store log and data files and the Chubby lock service [4] to store metadata. These systems address problems orthogonal to Tempest, such as enabling high volume computations over massive amounts of data.

## 6 Conclusion

Modern three-tier architectures achieve scalability and responsiveness through the extensive use of soft state techniques in the service tier. Availability and rapid fail-over requires data replication, and Tempest provides programmers with data structure abstractions for storing and managing replicated soft state. Tempest scales well in key dimensions — the number of front-ends contacting a service and the number of services contacted by a front-end — and outperforms in-memory databases in realistic settings. As a result, Tempest simplifies the construction of highly responsive systems that seamlessly mask load fluctuations and faults from end-users.

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