End-User Effects of Microreboots in Three-Tiered Internet Systems

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Abstract

Microreboots restart fine-grained components of software systems “with a clean slate,” and only take a fraction of the time needed for full system reboot. Microreboots provide an application-generic recovery technique for Internet services, which can be supported entirely in middleware and requires no changes to the applications or any a priori knowledge of application semantics.

This paper investigates the effect of microreboots on end-users of an eBay-like online auction application; we find that microreboots are nearly as effective as full reboots, but are significantly less disruptive in terms of downtime and lost work. In our experiments, microreboots reduced the number of failed user requests by 65% and the perceived downtime by 78% compared to a server process restart. We also show how to replace user-visible transient failures with transparent call-retry, at the cost of a slight increase in end-user-visible latency during recovery. Due to their low cost, microreboots can be used aggressively, even when their necessity is less than certain, hence adding to the reduced recovery time a reduction in the fault detection time, which further improves availability.

1 Introduction

Transient faults account for a large fraction of failures in today’s Internet systems and production software in general [37,2]; even mainframe-class operating systems are not immune to such transients [41]. Running out of memory or file descriptors, Heisenbug-triggering load spikes, deadlocks, performance degradation due to unexplained interactions between subsystems, etc. are just few examples of what Internet service operators face on a regular basis [30,15].

Reboots have been shown to be an effective way to cure many such transients, even in critical software [1,32]. Full-system reboots, however, can be expensive [22] both in terms of downtime and amount of disruption; to mitigate this, we introduce the concept of a microreboot.

In this paper, we demonstrate that microreboots can be used to improve the availability of applications hosted on a rich middleware platform. A microreboot is a restart of a subset of fine-grained (smaller than a process) software components in a running system. In this paper, the system in question can be any Java 2 Enterprise Edition (J2EE) application running on an open-source J2EE application server that we have augmented with fault injection, instrumentation, and the ability to microreboot individual beans (application components) as well as functional subsystems such as the Web server tier and Java Servlet Pages.

Microrebooting reflects the emphasis on improving availability by lowering mean time to recover (MTTR); availability is commonly thought of as $\frac{MTTF}{MTTF + MTTR}$. With respect to interactive services, lowering MTTR not only improves the user experience of the service and the users’ perception of service availability [46,13], but also serves as a leverage point for applying aggressive statistical-anomaly-based failure detection [31,14]. In our case, we also demonstrate that microreboots can reduce the number of users impacted by a particular transient failure and the amount of work they lose.

Because our approach is based on observation and control at the middleware layer, it is application-generic and requires no a priori knowledge of application structure. This addresses the fact that today’s services are heterogeneous and dynamic, encompassing many vendors’ hardware and software components that evolve rapidly and often turbulently, resulting in a main challenge in maintaining dependability of those services [20].

1.1 Contributions

The main contributions of this paper are to demonstrate the efficacy of microreboots as a technique for improving the availability of distributed interactive applications and to circumscribe the types of failures and applications for which microreboots are effective. Specifically:

- We identify a user-centric availability metric for characterizing the availability of Internet services. This
metric reflects the observation that not all types of user interactions contribute equally to user-perceived system availability.

- We augment an off-the-shelf Java application server with the ability to microreboot individual components in unmodified J2EE applications. We show that microrebooting one or a small number of components is just as effective as restarting the entire application or server (full reboots are currently the most common method in use for recovering from transients [30, 16]), but that microrebooting is faster, leading to lower recovery time.

- We show that, since microreboots are less disruptive, using them for recovery can reduce the number of end users who actually experience the failure and allows some transient failures to be masked by additional request latency. At the same time, the total amount of work lost during recovery is reduced.

- We identify specific cases in which microreboots do not result in satisfactory recovery, explain why this is the case, and propose concrete changes to the middleware (not to the applications themselves) to remedy this.

Microreboots separate the concern of recovery from that of diagnosis and bug finding. When an online system fails, downtime is expensive and the first priority is to restore service by any means necessary. Identifying and fixing the root cause of the transient failure is a separate effort, and we do not claim that microrebooting offers any insight into doing these things, nor that it is more than a “temporary fix” to recovering from the transient. We expect production systems to have thorough logging mechanisms that will allow developers to fix root causes; microreboots improve availability (by lowering MTTR) without changing reliability (reflected in MTTF).

Therefore, in this paper we try to isolate the effects of microrebooting as a recovery procedure as much as possible. In particular, our microbenchmarks trigger recovery actions directly, rather than injecting faults and waiting for fault detection to trigger recovery. We recognize that reducing fault detection time is critical, and we explain how microreboots have the potential to enable the use of promising new approaches to fast and aggressive detection. Similarly, we recognize that understanding what to microreboot when a failure occurs is important; we have addressed that problem elsewhere [6] and we use the results of that technique to drive the experiments in this paper.

In Section 2 we describe the microrebooting approach and motivate its use for three-tier Internet applications. We then describe the changes we made to enable microreboots in JBoss, an open-source J2EE application server (middleware platform). Section 3 describes our experimental setup, sample application, and metrics. Section 4 presents experimental results, using trace playback and induced recovery, to support our claims. We discuss implications of the approach in Section 5 survey related work in Section 6 and then conclude.

2 What Are Microreboots?

In this section we explore the conditions under which reboot-based recovery is feasible and describe the concept of a microreboot. We present the platform chosen for our work, how it satisfies the conditions for reboot-based recovery, and conclude with a description of our implementation of the microreboot mechanism.

2.1 Reboot-based recovery

Chandra and Chen [12] and Lowell and Chen [33] formulated an approach to application-generic recovery (i.e. recovery without application-specific knowledge) based on checkpointing, and demonstrated that relatively few existing applications could be successfully recovered by this approach. They studied both Unix-style monolithic applications such as vi and large open-source Internet service components such as MySQL and Apache.

However, part of the appeal of rebooting as a recovery technique [11] is precisely that it discards corrupted transient state that might itself be the cause of the failure or whose cleanup may be necessary in order for recovery to succeed. Therefore we expect that replacing recovery with rebooting—which is logically equivalent to restarting from a checkpoint that is the start state of the component—is more likely to work, assuming it is safe to try. To ensure that it is safe to try, we must consider three environmental conditions:

1. Boundary: There must be a clear boundary around what is being rebooted, i.e., it should be possible to indicate unambiguously what state will be lost, what resources released, what loci of control returned to their start state, etc. For example, in the case of a process, the boundary is typically the process’s heap and any kernel data structures or resources being maintained on the process’s behalf.

2. Loose coupling: if the entity being rebooted is part of a distributed system, other entities that communicate with it must be able to tolerate the reboot event as normal. For example, in a distributed system, calls to an RPC server that has failed and is in the process of recovering could be stalled or temporarily rerouted to a failover RPC server.
3. Preserving state and consistency: To avoid data loss, we must be sure that all state visible outside the component’s boundary is either soft or discardable state or is committed to a separate persistent state store (which presumably has its own recovery procedures in case of failure). For example, UDP multicast tree information is discardable soft state whose reconstruction is explicitly part of the corresponding routing protocol.

Note that these conditions do not guarantee that rebooting will be a successful recovery method, only that it will not result in a change in application semantics (e.g., loss of data or loss of consistency).

Analogous to rebooting, a microreboot is a logical restart of an application component that may be finer-grained than a process, but the same requirements apply. Architectures that have these properties, such as Microsoft’s .NET and Sun’s Java 2 Enterprise Edition (J2EE), provide an excellent platform for studying microreboots. For the work presented here we used J2EE; in the next section we briefly review the J2EE programming model and why J2EE applications meet our requirements.

2.2 The synergy between μRB and J2EE

Most Internet applications are deployed in a “three tier” arrangement [46][11] that makes state management explicit. The presentation tier consists of stateless Web servers that handle and demultiplex incoming connections. The application logic tier runs the code that constitutes the application. Finally, the persistence tier stores state that is expected to survive across requests, whether per-user or across all users.

J2EE [42] is a model for constructing the application logic tier of such applications and lends itself well to a microreboot-based failure management approach. J2EE applications are constructed from reusable Java modules, called Enterprise Java Beans (EJBs). Beans run in the managed environment of an application server, which provides containers in which the beans are instantiated and run, provides naming/directory/authentication services for inter-bean communication at runtime, etc. (see Figure 1).

To run a J2EE application, one must boot the operating system, start the J2EE application server, start any necessary additional components required by the application (e.g., a database used for persistent state storage and the Web server front-ends), and finally “deploy” the application on the application server, i.e. instantiate each EJB in its container and allow the application to begin accepting requests from the Web servers. Once the application is running, Java threads are mapped to incoming Web requests, and several EJBs may be called during servicing of a given request. Thus EJBs are really akin to event handlers: each EJB does not have a separate locus of control, rather a single thread “shepherds” the user request through multiple EJBs.

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With this description, we can now see how the safe-reboot requirements from Section 2.1 map onto J2EE applications.

Item (1), clear boundaries around microrebootable components, maps onto J2EE in at least two different ways. First, each EJB is a well-circumscribed entity that can be microrebooted by undeploying it and redeploying it. Second, the Web server processes that dispatch incoming HTTP traffic to EJBs are also self-contained and can be restarted. We describe in detail how this is done in Section 2.3.

For item (2), loose coupling, observe that since inter-bean calls are mediated by the application server, we can modify the application server to intercept on those calls. In particular, if an EJB is in the process of being microrebooted, we can stall calls to that EJB rather than allowing them to experience an error as a result of the callee EJB being unavailable.

Item (3), maintenance of persistent state, essentially falls out of the J2EE application model. J2EE applications manipulate two kinds of state that are visible from outside an EJBs boundary. Persistent state, such as user profiles and static content, is stored in a traditional RDBMS and accessed via JDBC connectors. RDBMSs are well known for having robust, if not always fast, recovery procedures that provide strong data integrity guarantees. The second kind of non-transient state is session state, which is tied to the maintenance of a particular user’s session (a set of related interactions with the service). Since HTTP is stateless and most browsers provide only cookie management facilities, any nontrivial session state must be managed by the service. J2EE provides an abstraction called a stateful session bean that preserves session state across invocations, but the precise implementation of this abstraction varies among J2EE application server implementations. As we describe in Section 2.4 a deficient implementation of this feature could cause microreboots to change application semantics; in that same section we propose a solution to this problem that leverages existing research and does not require changing individual
applications.

In summary, the J2EE application model is a good fit for the requirements of microrebooting, with the possible exception of the management of session state, which we will return to in Section 3.4. We now describe the particular J2EE application server implementation that we augmented for the work in this paper.

### 2.3 Microreboots in JBoss

We built upon the popular JBoss J2EE server [27], because it is open source and because its performance and features compare favorably with proprietary closed-source offerings [3]. Its use in production environments is increasing rapidly, having had over 3 million downloads this year. We instrumented JBoss in a number of ways; a description of the early changes we made appeared in [24]. In this paper we focus on how we enabled the application server for microreboots.

Our basic microrebootable component of J2EE applications is the EJB. In the same way an OS kernel does for processes, JBoss maintains for each active EJB a rich set of metadata. Some of the items include the name under which this component is known to other parts of the application, the Java class implementing its functionality, the type of EJB (session, entity, etc.), whether the bean requires transactional support, along with references to other beans that this EJB might call and references to the resources required by the EJB.

JBoss already includes a mechanism for cleanly "shutting down" an EJB; our microreboot mechanism builds upon that. A Java class runnable as an EJB must implement the standard EJB interface. When an EJB is created, its constructor ejbCreate() gets invoked and, when it is destroyed, ejbRemove() allows it to clean up prior to deletion. When the application activates an EJB to process a request, it invokes the ejbActivate() method; when the EJB is disassociated, its ejbPassivate() method is called. When microrebooting an EJB, our version of JBoss discards all metadata associated with the bean and resets the corresponding entries in the server structures that keep track of the bean; if the EJB was involved in any ongoing transactions, those transactions are aborted. To restart the EJB, we simply use the existing deploy mechanism to reinstantiate it.

In the simple call model, whenever an EJB wants to invoke another EJB’s method, it looks up the target EJB by name in the Java Naming Directory (JNDI) and uses the Java class resulting from the lookup to make the invocation (similar to the way RPC stubs work). Since doing a lookup on every call is expensive, JBoss provides the caller with a proxy on the first lookup, which then handles all subsequent calls without interacting with JNDI.

A problem can arise when a recovering EJB is called by another EJB or a servlet; all interactions between EJBs, however, are controlled by the application server. When a bean is microrebooted, other components can see the effect of this in one of two ways: either the bean is not currently registered in JNDI (which would result in a failure when the bean reference is looked up), or it is not available for processing requests. In either case, we arrange for the calling proxy to receive a RetryLater(t) exception, where t is the estimate, in milliseconds, of how much longer it will take for the callee to recover.

EJBs run inside bean containers, and it is these containers that are in charge of making the various calls outside the bean. Our modified JBoss container catches RetryLater(t) exceptions, pauses for approximately t milliseconds, and retries the call in the hope that the target bean has recovered. If the call succeeds after a predetermined number of retries, the original bean code sees a successful call and has no knowledge that the target bean had actually failed and recovered in the meantime. Otherwise, the container throws an exception to the caller. These transparent retries allow us to mask transient failures from callers, as will be shown in Section 4.4. Such masking makes transient failure an acceptable mode of operation.

A major issue when transparently retrying calls is idempotence. In the present case, however, JBoss guarantees invocations to be atomic: if the call can be made to the component, it goes through, otherwise the RetryLater exception is thrown; this preserves JBoss’s regular call semantics. As expected, calls that were in-progress at the time of the microreboot will fail in exactly the same way they would fail if the EJB crashed, had a bug, etc.

### 3 Experimental Setup and Metrics

In this section we describe the testbed for our work; we describe briefly our sample J2EE application, the client emulator used to generate load on the application, and then conclude with a definition of the metric used to quantify the benefits of microreboots.

In our hardware setup we tried to mimic what would be typical of a small Internet service. We use Linux RedHat 9.0; JBoss and the Web tier run on an AMD Athlon XP 2600+ PC with 1.5 GB RAM, and the database (MySQL Max 3.23) on another identical node. We use the Sun HotSpot JVM 1.4.1. and allocate it 1 GB of RAM through command-line arguments. Our client emulator, described below, runs on a dual Pentium III (2×866 MHz) with 1 GB RAM. All machines are interconnected by a 100 Mbps Ethernet switch.

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3.1 eBay-like test application

RUBiS is an open-source web-based auction application, developed at Rice University and modeled on eBay. It offers selling, browsing, and bidding. It distinguishes three kinds of users: visitor, buyer, and seller, with buyer and seller sessions requiring login. A buyer can bid on items and consult a summary of their current bids, rating and comments left by other users. Seller sessions require a fee before a user is allowed to put up an item for sale. The seller can specify a reserve (minimum) price for an item. RUBiS contains 582 Java files and about 26K lines of code; it uses MySQL for the database back end and stores 7 tables. In the default configuration, RUBiS has about 33,000 items for sale, distributed among eBay’s 40 categories and 62 regions. There is an average of 10 bids per item, or 330,000 entries in the bids table. The users table has 1 million entries.

We obtained a description of the failure dependencies between RUBiS’s components using automated fault-propagation inference (AFPI). As can be seen in Figure 2, the majority of such dependencies in RUBiS are between the stateless servlets and EJBs; the only beans that can propagate faults to other beans are IDManagerEJB, ItemEJB, CategoryEJB, and UserEJB. AFPI information is collected during a completely automated fault-injection campaign that requires no a priori knowledge of the applications’ structure or semantics. In this paper, however, we focus on μRB-ing as a technique, not on how we might use μRBs in a production system or what policies we might devise based on AFPI-generated graphs.

For RUBiS, a simple recovery policy could be based on the fact that there is a known mapping from the URL being accessed to the action being taken (and hence the EJBs being touched). For instance, if a failure is seen on http://ejb_rubi­s_web/servlet/BrowseCategories, then we know that something in the path starting at the BrowseCategories servlet has gone wrong, and the system should therefore automatically μRB the corresponding components.

3.2 Client emulator

Our client emulator is a modified version of the load generator that ships with RUBiS.

We describe the workload of the simulated clients using a state transition table $T$ that has the client’s possible states as rows and columns; these states correspond naturally to the various operations possible in RUBiS, such as Register, SearchItemsInCategory, PutBid, etc. (27 in total). In addition to the application-specific states, we also have two states corresponding to the user hitting the back button (Back) and spontaneously deciding to end his/her session (End). $T(S_a, S_b)$ represents the probability of a client transitioning from $S_a$ to $S_b$. For example, $T(ViewItem, BuyNow)$ describes the probability we associate with the user clicking on the “Buy Now” button while viewing an item’s description.

The client emulator uses this table to automatically navigate the web site; when in a given state $s$, it will randomly choose the next state based on $T(s)$ with the requested probability; it then constructs the URL for this state and “clicks” on it. The table $T$ also has a column for how long a user waits in-between clicking from a certain state to the next; in our experiments however we set this wait time to zero. Unlike a real user, our emulator will therefore initiate the next HTTP request as soon as the current request completes (whether successfully or not). The emulator uses one thread per simulated client.

We classify responses from the server as correct or incorrect. Correct responses are used to compute the server’s goodput (throughput of correct responses per second); we will describe our other metrics in more detail later. A response will be classified as incorrect if it results in a network-level error (cannot connect to server, etc.), an HTTP 4xx or 5xx error code, or an HTML page containing particular keywords that we know to be indicative of application errors. Clearly this is not fully application generic; we have successfully detected all error pages in RUBiS and other J2EE applications with no false positives by searching for “error”, “failed”, and “exception” in the reply HTML, but this assumes none of the users is selling an item that would match these searches.

3.3 Metrics

A typical interaction of a client with the web site proceeds as follows: client goes to the homepage, browses around for a while performing different site actions (search-
Figure 3. Goodput anomaly: We induced a failure (unrecovered) in QueryEJB at $t = 30$, thus causing certain queries against the database to fail. On the left we show a request profile (both good and failed requests); on the left we show a profile of the sessions (both the ones that completed and those that failed). Witness the goodput anomaly: in the face of failure, the raw goodput increases simultaneously with the rate of unsatisfied requests. The session profile, however, shows that the number of aborted sessions goes from zero to an average of 14 aborted sessions/second. Users start a new session after the previous one has failed, so the increased number of aborted sessions brings about an increase in the session initiations—in real services, this could constitute an unwelcomed load spike for certain types of services, such as user login and authentication.
Figure 4. **Session-weighted goodput**: On the left we see a run with no failures; on the right, we inject a permanent/unrecovered fault in QueryEJB at $t = 100$ sec. Notice how this causes unsatisfied requests to show up even “before” $t = 100$ sec, because operations done as part of sessions that started at $t < 100$ and failed at $t \geq 100$ are marked as failed by the $G_{wop}$ metric. Even though these individual requests were satisfied, the usefulness of satisfying them is lost because of the session failure. We also notice that the throughput of satisfied requests starts dropping prior to $t = 100$, for similar reasons: some sessions starting in that interval end up failing.

Figure 5. **Sweetspot**: On the left we show the session-weighted goodput for a 1000-client load; on the right we show the same for a 20-client load. We empirically determined that the experimental results are most consistent for 20 concurrent fast clients. For higher numbers than that, our single-node application server starts thrashing and throughput becomes erratic and slightly lower on average, as seen in the left graph. Moreover, inspecting traces of 20 clients for correctness is considerably easier than 100 or 1000 clients.

### 4 Results

In order to experimentally isolate the $\mu$RB recovery mechanism from fault detection, we initiated various forms of rebooting in the application without actually injecting faults. The aspect of detecting such faults was the focus of [9]. We are, therefore, assuming in all our experiments that the application server has instantaneously detected the fault and initiated reboot-based recovery. Note that the problem of failure detection is orthogonal to the recovery method used, though in section 5 we argue that $\mu$RBs make it potentially much easier to apply certain kinds of fast failure detection algorithms.

Reboot-based recovery is typical for many failures noticed in deployed Internet systems, where resource leaks, deadlocks, etc. occur on a regular basis [30]. In fact, the original version of RUBiS/JBoss had a bug that caused it to deadlock when the number of concurrent users exceeded 10, and we have shown in [9] that a modified JBoss could automatically recover from this deadlock. The version of
RUBiS used in our experiments incorporates a number of fixes to enable it to run with many concurrent users.

For most of the results reported here we used 20 concurrent clients with no think time inbetween successive requests. Given that a human user typically spends in excess of 2 seconds between clicks, we believe the load placed by one of our simulated clients is equivalent to that of 100 or more real clients. We did not want to introduce artificial think time (the way it is done, for instance, in the TPC-W benchmark) because having think time would add one more variable to the experiment and would not offer any useful insight for µRB experiments. The reason we settled for 20 concurrent rapid clients is that it appeared to be the threshold beyond which thrashing and other side effects would reduce throughput; see Figure 5 for a comparison of throughput for 20 vs. 1000 clients.

An important characteristic of our chosen workload is that it covers all possible RUBiS operations; experimentally we have determined that, in runs lasting 1 minute or longer with 20 clients, we routinely exercised all components. While this might be surprising for a set of 20 human users, our no-wait-time clients navigate through the site very rapidly. The workload we used for the experiments reported here had an approximate mix of 85% read operations and 15% DB write operations.

In the remainder of this section we will show that µRB-ing is faster and less disruptive than other forms of reboot, discuss correctness in the presence of µRB-ing, and conclude with a technique that, in conjunction with microreboots, can mask transient failures from end users.

4.1 Microreboots are fast

Our first goal was to determine whether the microreboot mechanism we built into JBoss can indeed reduce recovery time. We performed four sets of experiments, comparing full reboot of the JBoss application server, full reboot of the RUBiS application, microreboot of one EJB (QueryEJB), and microreboot of multiple dependent EJBs (UserEJB, ItemEJB, and BidEJB), respectively. This would be a normal response to a variety of reboot-curable failures, such as a bean running out of memory (quite frequent in Java sys-
tems) or being hung in a deadlocked transaction. We can think of these experiments as attempting to recover a failure in one of the application components; Figure 6 shows the results.

In the four graphs we show profiles both of successfully served requests and failed requests. We are particularly interested in reducing the total number of failed requests (area under the bold curves in the graphs), as this reflects exposure of the failure to end users. We also want to reduce the amount of time during which the service appears down to any user. In the case of single-component microreboots, we reduced the number of failed requests by a factor of 2.84 over server process restart and by a factor of 2.45 over an application restart. The duration of time during which the site was perceived down by some users was reduced by a factor of 4.5 over server process restart and by a factor of 3.92 over application restart.

In graph (d) we show the effect of microrebooting a group of EJBs. This can be required either because multiple components have failed, or because there are dependencies between components. In this case, we may be reacting to a failure in UserEJB; as can be seen in Figure 5, the transitive closure of UserEJB over the fault propagation graph is the group of beans UserEJB, ItemEJB, and BidEJB. Based on this information, we microreboot the three beans together. By microrebooting the EJBs instead of restarting the application, we reduce the number of failed requests by a factor of 1.78 and the downtime by a factor of 3.24. Table 1 summarizes the results of these experiments.

| Recovery Technique | Failed Requests | Downtime [sec] | Improve over JBoss restart Requests | Improve over JBoss restart Downtime |
|--------------------|-----------------|----------------|-------------------------------------|------------------------------------|
| JBoss restart      | 713             | 108            | –                                   | –                                  |
| RUBiS restart      | 615             | 94             | 14%                                 | 13%                                |
| 1-EJB µRB          | 251             | 24             | 65%                                 | 78%                                |
| 3-EJB µRB          | 345             | 29             | 52%                                 | 73%                                |

Table 1. Improvement relative to process restart: Comparison of application restart, one-EJB microboot, and three-EJB microboot in terms of failed requests and perceived downtime.

4.2 Microreboots are less disruptive

If a recovery method is effective, then users of the recovered system should be able to resume their work immediately following the recovery of the system under load. As evidenced by the lack of failed requests after recovery completes (Figure 5), the system sustains all four methods of recovery equally well, and users can continue their work after microreboots just as in the case of regular reboots. In fact, the implementation of whole-application reboot is in effect a collection of microreboots, because “rebooting” the application consists of undeploying and then redeploying the individual application components.

As can be seen in Figure 6, microreboots have the potential to be considerably less disruptive than either server or application restarts. For example, in graphs (a) and (b) goodput drops down all the way to zero, while the rate of failed requests does not increase dramatically. In both cases, the application loses all its network connections to the clients; when clients try to establish new connections, they are refused flat out, since no process is listening on the corresponding port. The result is that all users of the service experience downtime, hence the zero goodput.

When using a µRB to recover a component, however, we are effectively partitioning the user population into two groups: those whose requests require the services of that component and those whose requests do not. As seen in graphs (c) and (d), goodput does not drop to zero even instantaneously, because non-affected (non-recovering) components can continue to deliver service while faulty ones are microrebooted. Users whose sessions do not require the recovering component can continue working as if nothing had failed. Thus, in addition to recovering faster, microreboots also offer the opportunity to reduce the impact of failures on users who are active at the time of failure.

4.3 Microreboots and correctness

“Correct behavior” in the face of microreboots is difficult to define, because by assumption microreboots are useful only because there are transient bugs in the application or server. With or without µRBs, such bugs clearly might cause incorrect behavior. However, we can argue that the effect of a µRBs no different than the effect of a full reboot.

First, observe that the result of a particular user request depends only on the EJB’s it calls and on any persistent state that would affect the way the bean handles the request (whether or not that state is directly visible outside the bean boundary). Instances of stateless beans are by definition indistinguishable from each other, and in fact application servers simply select an available instance from a pool of such beans when the bean is needed for processing an incoming request. Bean-independent state stored in a transactional database (e.g., a list of all bids placed by a given user) is not affected any differently by full reboots vs. microreboots of the application server: as long as the database provides transactional semantics, either event is “serialized” between two transactions. The remaining possibility is that the bean is a stateful session bean, which expects to preserve its state across invocations. In this case we need to know where the state is kept, and whether it would survive a µRB of the bean.

As we stated earlier, management of session state varies
across implementations of J2EE application servers. JBoss offers two options: (a) individual EJB’s can manage their own session state by explicitly updating the transactional database; (b) JBoss can transparently manage session state, which it does by keeping it in RAM with no replication or backup. RUBiS happens to use (a), which means all beans’ session state would survive microreboots of the beans themselves. However, an application that used (b) would not have its session state preserved across a µRB. In fact, we encountered this problem in PetStore, a J2EE application that models a simple e-commerce site; after a µRB, all subsequent requests from the affected (simulated) user systematically failed, until the (simulated) user abandoned the session and logged back in (thereby recreating a new valid session state object), after which subsequent requests succeeded. In other words, µRBs are not transparent to applications relying on JBoss’s implementation of session state. (Note, however, that such applications won’t survive full reboots either: in that case, all currently connected users would lose their sessions, not just the user whose session beans were µRB’d.)

We propose that the correct solution to this problem is to manage session state externally to the EJB’s using a mechanism that is much lighter-weight than a database (for performance and scalability) but provides strong guarantees of bounded persistence. In fact, [31] reports on a lightweight, RAM-only, replication-based session state storage mechanism whose contents survive microreboots and whose use does not compromise overall application throughput. Note that integrating this system into our prototype would not require changes to the applications themselves, only to the application server’s implementation of server-managed session state. We plan to explore the integration of this subsystem into our prototype in future work.

4.4 Low-level retries mask transient failure

When a caller tries to reach a recovering component, that call will typically fail. However, we can build in mechanisms for retrying such calls after the target component has recovered; such retries can be done in a manner completely transparent to the J2EE application, which means J2EE programmers do not need to incorporate retry logic in their applications. Microreboots coupled with transparent low-level retry would allow us to transform many transient failures into additional latency instead of externally visible failure. The effect of a failure on users would then simply be a performance hiccup, rather than the error they would have seen without retry mechanisms. As discussed in Section 4.3.2, calls to recovering EJBs we provide the same semantics as vanilla JBoss, with the addition of a RetryLater(t) exception.

Such retries can be automated and performed transparently at multiple levels. The highest level is provided by HTTP 1.1, which has a Retry-After response header, allowing the web server (or our application server) to instruct the client’s browser to retry after a certain number of seconds. At the lowest level, calls between EJBs can be retried if a particular EJB is microrebooting.

Previous studies [23, 36] have found that, when a user is waiting for an interactive service to respond, a delay of 8–10 seconds is the threshold after which the user comes to believe that the request has failed and clicks the Reload or Stop button (or worse, clicks over to another site). This suggests that if a site can recover from a transient failure and retry the failed in-flight request(s) within 8 seconds, affected users will have the illusion of continuous uptime—they will see a short delay rather than a failure. Microrebooting an EJB takes less than 1 second, which permits us to use call retries to mask EJB failures from most end users.

![Session-Weighted Response Profile (microreboot w/ call retry)](image)

**Figure 7.** Microreboots with call retry: QueryEJB is µRB-ed at $t = 100$; in-flight requests are retried with a timeout of 100 msec. Goodput dips around $t = 100$ but none of the requests fail. In the case of multi-EJB microreboot, the dip would be deeper and wider, but still no requests would be perceived as failed by end users (unless recovery time exceeds 8 seconds).

We built into JBoss the ability to retry inter-EJB calls if the callee is microrebooting; as described in Section 2.3, a call to a recovering EJB results in a RetryLater(t) exception. Using this facility with a hardcoded value of $t = 100$ msec, we ran an experiment in which we microrebooted QueryEJB and observed the effect on end users. We do not compare these results to application-level reboot, because restart time exceed the above-mentioned threshold (restarting all of RUBiS takes on the order of 10-11 seconds with no load, and 20 or more seconds under normal load).

In Figure 4 we show the session-weighted response profile for microrebooting QueryEJB with call-level retry. Notice that the goodput dips slightly around the time when the
Microreboot is made, because the system is now busy retrying in-flight request and can accept fewer new requests than under normal circumstances. However, the goodput only drops slightly and, most importantly, no request fails and hence all sessions can continue unaffected. Since incoming requests sit in the TCP connection queues, it is conceivable that if load was much higher and microreboot time longer, the TCP queues would fill up and connections would be refused (and the site perceived as down by end users).

5 Discussion

5.1 Cheap recovery allows occasional mistakes

Microreboots enable an approach to self-management in which recovery is so fast and inexpensive that false positives during failure detection become less important. The fact that microreboots are fast and safe potentially allows us to apply much more sophisticated failure detection policies, which is important because total recovery time is often dominated by fault-detection time [13].

One promising direction involves using statistical anomaly detection to infer failures. Such techniques have been shown to reduce time-to-detection at the cost of some false positives [14], and a simplified version of this approach appears to have been successfully demonstrated in a state-management layer designed specifically to make reboots fast and safe [51].

In general we believe this is an important design trend for robust systems: fast, cheap recovery mechanisms will blur the line between “normal operation” and recovery. When recovery becomes an order of magnitude cheaper, it allows one to think differently about how and when to apply it. Since microreboots result in only a minor cost in goodput if applied by mistake, they provide the level of recovery performance needed to pursue a rationally-aggressive approach of initiating recovery at the slightest hint of failure.

5.2 $\mu$RB-ing in Internet services

We believe the $\mu$RB technique is best suited for large scale Internet services. The workloads faced by such services consist of short-lived, mostly-independent requests coming from a large population of distinct users. The work that Internet services must do is generally partitioned into disjoint sets of discrete operations, and RUBiS reflects this. The consequence is that, even if a few requests fail, it is possible for most users to be unaffected. $\mu$RBs take advantage of the application’s structure to realize this potential.

Additionally, the underlying protocol (HTTP) and most of the application logic is stateless and, except for marked, non-idempotent requests, end-users can safely retry failed requests until they succeed. This lets us reboot components in the system, knowing that any users affected will face only a minor inconvenience. In fact, this property makes it useful to recover even from purely deterministic bugs such as a pathologically malformed request: if recovery is fast enough, other users issuing non-pathological requests may still be able to use the service.

Many Internet services today use huge in-memory caches in order to avoid the central database bottleneck (e.g., the servers at a large Internet portal use 64 GB of RAM just for caching database queries [59]). Unfortunately, a machine reboot flushes this cache, and re-warming it can take a long time (transferring 64 GB from a 40 MB/sec wide-SCSI disk takes at least half an hour), which is why whole-system reboots are generally avoided.

5.3 When reboot-based recovery fails

Rebooting is a correctness-preserving form of restart only to the extent that no “critical” state is lost and no inconsistency created. We identified three requirements for allowing safe reboots: a well-defined reboot boundary, loose coupling between the rebooting component and its peers, and preservation or state (or preservation of consistency of state) visible outside the reboot boundary. We chose to target three-tiered Internet applications based on thick middleware because the programming model largely enforces these properties already. Monolithic applications, in contrast, typically lack these properties, and we would not expect microreboots to work without extensive changes to the applications themselves.

Also, since microrebooting still introduces nonzero recovery latency, it may be inappropriate for systems with tight real-time constraints; hot standby with fast failover may be the only acceptable option in those cases, since even failover to a cold spare may take too long. Of course, substantially all Internet services exploit some form of standby at multiple levels to mask transient failures [34], but standby capacity is expensive so standbys are rarely kept idle during normal operation. As a result, when failover does occur, the standby is serving more than its steady-state share of workload; presumably, the faster the primary is returned to its online condition, the higher total throughput can be realized. In fact, the CNN.com meltdown on 9/11/01 [29] demonstrated that slow node-level recovery time can lead to service collapse even when fast failover is in place. Ideally, if more transient failures could be masked as slight delays to the user, fast failover would not have to be used as often. Microreboots are thus orthogonal to failover as a technique, but they may result in failover being required much less often.
5.4 Application-generic recovery

In applying microreboots to the application server rather than by modifying individual applications, we have attempted to address the question: What level of effective fast recovery can we do exploiting just the middleware, and without application-specific efforts? We found that microreboots can recover just as effectively from failures that today are usually cured by whole-system restart or whole-application restart, but they do so more rapidly. Moreover, the shorter downtime during recovery can sometimes be masked by a delay well within an established “distraction threshold” for most users, allowing the failure to be hidden from them; this is not practical for the longer recovery times required for whole-application restart.

In our experience we have found few failures from which whole-system restart recovers but microreboots do not. Nevertheless, such failures exist; for example, we observed that under high load, the JVM running the application server would sometimes run out of file descriptors, or served that under high load, the JVM running the application

cannot. Nevertheless, such failures exist; for example, we observed that under high load, the JVM running the application server would sometimes run out of file descriptors, or encounter an internal error, requiring a process restart of the JVM. We have also encountered a resource leak involving serialized objects sent over a socket: the object does not get garbage collected even when our references to it are gone, and eventually the leaks require a JVM restart. Finally, on our version of Linux, we also encountered on occasion a kernel bug in the swapping code which would trigger under high memory utilization conditions; in such cases, any memory allocation (specifically, any call to the brk system call) hangs, and a full system restart is necessary.

Although none of these problems would have been cured by microreboots, we still expect microreboots to recover from a significant subset of those faults that a full reboot would cure. The strategy we proposed in [7] suggests that restarts be attempted at the finest granularity, and then progressively encompass more components if the failure is not cured. In this sense, microreboots as presented here are an optimization over full reboots, albeit one that results in qualitatively less disruptive recovery than full reboots.

6 Related Work

Chandra and Chen [12] classified software faults into three categories. Environment-independent (EI) or “Bohr bugs” are deterministic and do not depend on the operating environment; environment-dependent-transient (EDT) or “Heisenbugs” are due to timing or other transient conditions and may disappear if the operation is retried; environment-dependent-nontransient (EDN) bugs are related to the operating environment in such a way that immediate retry is not likely to work, because the environmental condition(s) responsible for the bug will not have changed enough (for example, a failure due to a memory leak will persist until more heap space is made available). There is disagreement regarding whether most bugs remaining in production-quality software are EDT [16] or EI/EDN [12], but reboot-based recovery techniques address all three categories.

Other projects attempting checkpoint-based recovery have fared similarly to Lowell and Chen [33]. ARMOR [28] provide a micro-checkpointing facility for application recovery, but applications must be (re)written to use it; limited protection is provided for legacy applications without their own checkpointing code. ARMOR’s own fault detection and recovery middleware does use the microcheckpointing facility, but in the cases where middleware recovery failed [44], it was because of a corrupted checkpoint caused by an injected fault. Libft [24] provides a C library for checkpointing and the internal state of an application process periodically on a backup node, but like ARMOR, it requires applications to be written specifically to use this feature.

Process pairs [41] were an early mechanism that combined resource redundancy and state mirroring to allow failover to a hot standby, but because they were difficult for programmers to use, they have had limited impact outside of specialized high-end systems. Transactions [19] have enjoyed much wider impact, and remain a key element of today’s Internet applications, because they are easy for programmers to use and export a clean abstraction for dealing with recovery; however, when combined with relational semantics, providing transactional guarantees requires substantial engineering in order to get both good steady-state performance and complete crash-safety and recovery. Indeed, high-volume, high-performance database systems cost hundreds of thousands of dollars to deploy and maintain. Separating applications into stateless logic plus transactions simplifies recovery; we exploit this property by attempting application-generic recovery for the logic, and intend to push it further by specializing the state stores used for other kinds of Internet service state, including session state and persistent non-relational state such as user profiles.

The authors of [38] define a performability [35] metric for interactive Internet services that captures the decrease in throughput as they operate under fault conditions. Their work is an important step in applying performability to this domain, although as presented, it does not capture the effect of faulty operation on a typical end-user—how likely is it that a typical user request will fail or be delayed, and by how much?

An important part of managing partial failures is isolation. Indeed, a significant use of VMware’s software is fault isolation, and there is a new research focus on using lightweight virtual machines primarily for isolation. Recent efforts include Denali [45], which provides an Intel x86 isolation kernel that omits support for some instructions in exchange for orders-of-magnitude lighterweight opera-
tion; JanosVM, which allows a single logical Java virtual machine to be split among multiple OS processes; and Luna and the Sun MVM, which improve isolation among “tasks” running in a single Java VM.

BASE and BFT try to detect and correct what would otherwise be silently-wrong answers, e.g., due to data corruption or a malicious adversary. Their work is complementary to ours and composes with it, though we note that session state corruption errors such as we encountered would be difficult for these approaches to find as well.

7 Future Work

We intend to study the feasibility of using microreboots for software rejuvenation, the preemptive reboot of applications to stave off failure caused by software aging (e.g., due to resource leaks). By microrejuvenating one component at a time in a rolling fashion, we may be able to rejuvenate the entire applications without any downtime or failed requests. Combined with recursive restarts, a technique that selectively restarts system components either reactively or proactively, we hope microreboots can preserve the benefits of reboots while eliminating some of their drawbacks.

Other research has focused on developing microreboot-safe storage systems for session state and non-relational persistent state such as user profiles and catalog data. We intend to integrate these subsystems with our prototype to realize a complete three-tier Internet application in which every subsystem is microrebootable. We hope to then use microreboots to enforce simple, predictable fault models, by coercing any component failure into a fast-recovering crash failure. Using microreboots aggressively in this fashion has the potential to help with containment of faults and to improve predictability of component behavior in the face of failures.

Finally, although in this paper we tried to identify the limitations of µRBing on unmodified J2EE Internet applications, our longer-term goal is the development of design rules, tools, and building blocks for writing componentized applications for which recovery is dramatically simplified because they are completely µRB-safe—that is, crash-only applications.

8 Conclusions

We described some problems faced by Internet sites for which rebooting in response to failure may be appealing but too expensive, and proposed microreboots as a way to alleviate the problem. Microreboot-based recovery works well for componentized applications when the components have well-defined boundaries, when externally-visible (to the component) state is either discardable or persisted elsewhere, and when normal control flow mechanisms are designed to handle the case of a component being temporarily unavailable because it is recovering. These constraints are largely met by existing component architectures; we used a J2EE three-tier application to show that microreboots can improve recovery time and simplify recovery from transient faults, with no application-specific a priori knowledge.

Because microreboots are predictable and lightweight, it becomes acceptable to make occasional mistakes regarding recovery, which in turn enables the future use of sensitive fault detection techniques for aggressive triggering of recovery. This approach blurs the line between normal operation and recovery and leads toward the design of systems that are always “recovering” as one way of adapting to changing conditions. We hope that this will result in one concrete path to “self.*” systems.

The current release of our software is available for download at http://crash.stanford.edu/download; future versions will be posted there as well.

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