

GAIA: Strengthening the Reliability of Datacenter Computing via Fast Distributed Consensus

Abstract:

To process the rapidly increasing amount of data, more and more software applications run within a datacenter containing massive computing resources. To harness these resources, applications are typically ran by either of two independent infrastructures: schedulers and virtual machines (VM). Unfortunately, as an application runs on more computers, computer errors will occur more likely at runtime and can turn down the entire application, causing disasters such as the 2015 NYSE trading halts and recent Facebook outages. Existing infrastructures lack a high availability support for applications.

This GAIA project takes a holistic methodology to greatly improve application availability via three objectives. First, we will create FALCON, a fast distributed consensus protocol for general applications. Distributed consensus, a strong fault-tolerance theory, runs multiple replications of the same application and makes these replications behave consistently as long as a majority of them work normally. An open challenge is that traditional consensus protocols are slow because their protocol messages go through various software layers (e.g., OS kernels). FALCON will introduce a new consensus algorithm with an ultra-fast OS kernel bypassing technique called Remote Direct Memory Access (RDMA). Preliminary results published in [SOSP '15] show that FALCON supports unmodified real-world applications, and it is 32.3x to 85.8x faster than traditional consensus protocols.

Second, we will construct a first scheduler for application availability by integrating FALCON with popular schedulers. A main challenge is that existing schedulers' resource allocation schemes can be conflicting with replication schemes, because the former schemes abstract away computer identity, but the later schemes must deploy replications on different computers. Our scheduler introduces a replication-aware resource allocation scheme to resolve conflicts efficiently. Preliminary results published in [APSys '16] show that this scheme supports real-world applications with only 3.22% performance overhead.

Third, we will build a new VM for application availability by integrating FALCON with popular VMs. One performance problem in existing VM fault-tolerance techniques is that they need to transfer all memory modified by applications across VM replications. Our new VM integrates FALCON into the hypervisor layer to enforce same application inputs across VM replications, so that VM replications maintain mostly same memory. We also propose a new algorithm to efficiently track minor different memory.

This GAIA project will greatly strengthen the reliability of many real-world applications and will benefit almost all computer users and software vendors, including many HK financial platforms. GAIA will also advance broad reliability techniques (e.g., VM migration) and infrastructures.

Long term impact:

The emergence of big data with its increasing computational demand is pushing software applications to embrace more and more computing resources. Therefore, applications now often run within a datacenter containing numerous computers. Many applications are mission-critical (e.g., financial platforms, social network platforms, and medical services), so they naturally desire both high reliability and performance.

To harness the massive computing resources within a datacenter, applications are typically ran by either of two independent infrastructures: schedulers and VMs. Depending on runtime trade-off such as performance or security isolation, some applications are ran solely by schedulers (e.g., Mesos [NSDI '11] usually uses lightweight containers, not VMs), and some other applications are ran solely by VMs (e.g., Amazon EC2).

Unfortunately, as an application runs on more computers, computer errors will occur more likely at runtime. If a failed computer happens to run an essential application component, the entire application can be turned down. A downtime often causes severe disasters, especially for online or long-running applications. For instance, due to minor computer errors, New York Stock Exchange (NYSE) was down for a whole day in 2015. Moreover, although social network applications tend to be online 24-7, minor computer errors have turned down the Facebook site for several times in recent years.

A key problem causing these disasters is that datacenter infrastructures lack a high availability support for applications. To tackle this problem, this GAIA project takes a holistic methodology: it first builds a fast consensus protocol, it then integrates this protocol into the two typical infrastructures. By doing so, applications ran by either of these infrastructures can enjoy two significant benefits.

First, the availability of mission-critical applications can be greatly strengthened. Distributed consensus is recognized a strong fault-tolerance theory because it maintains multiple consistent replications of the same application to overcome computer failures in minor replications. Although consensus consumes extra computing resources for fault-tolerance, it has been widely adopted in industry, because resource capacity is often not a bottleneck for mission-critical applications.

Second, it is easy to make fault-tolerance itself robust. Distributed consensus is notoriously difficult to understand, build, or test. For instance, although some genius companies (e.g., Microsoft) have built consensus protocols for individual applications, ironically, recent research tools have detected numerous bugs in these protocols. Building one consensus protocol for each application could be a nightmare for application developers. Fortunately, with GAIA, people only need to carefully test our protocol and infrastructures, then applications can enjoy robust fault-tolerance.

We envision significant impacts from this GAIA project in three terms.

In the near term, our fast consensus algorithm and its implementation protocol FALCON (Objective 1) can drastically improve the performance of many applications that use distributed consensus. For instance, Scatter [SOSP '11], a remarkable key-value store application, deploys consensus groups using a traditional consensus protocol. By using FALCON, the latency of Scatter can be one or two orders of magnitude faster.

In the intermediate term, by realizing the new infrastructures in Objective 2 and 3, GAIA will greatly strengthen the reliability of general applications and benefit almost all computer users and software vendors. For instance, HK has many financial applications which naturally demand stringent availability in operational hours, and GAIA can meet this demand.

In the long term, we anticipate that this GAIA project will advance broad datacenter techniques (e.g., VM migration) and attract researchers to build more reliable datacenter infrastructures. As datacenter emerges to be a "giant computer", a fast and reliable datacenter OS for such a novel computer will gradually come up. Therefore, reliable consensus protocols, schedulers, and VMs will become essential datacenter OS techniques, and the outcomes of this project will be adopted in a future datacenter OS.

Overall, due to these prospective impacts, we name our project after gaia, an ancient Greek goddess who takes good care of everything on earth, including software applications.

Objectives:

1.

[To create a fast distributed consensus protocol].

We will develop an RDMA-powered distributed consensus algorithm and its implementation protocol FALCON. This new algorithm aims to be one or two orders of magnitude faster than traditional consensus protocols.

2.

[To construct a first datacenter scheduler for improving application availability].

This scheduler will replicate all or essential application components by integrating FALCON with popular schedulers. We will develop a new scheme to seamlessly manage both resource allocation and replication logic, so that this scheduler can efficiently schedule applications.

3.

[To build a new fault-tolerant VM for improving application availability].

We will leverage the VM hypervisor layer to transparently enforce same application inputs across VM replications. Compared to existing VM fault-tolerance techniques (e.g., primary-backup), our VM will greatly reduce the amount of transferred memory across VM replications, saving most time and network bandwidth. We will also develop a new algorithm to efficiently track and transfer minor different memory across replications.

1 Research Background

This section presents the background of consensus (§1.1) and datacenter computing infrastructures (§1.2), motivation of objectives (§1.3), others' related work (§1.4), and PI's related work (§1.5).

1.1 Paxos Consensus

Consensus protocols (typically, PAXOS [45, 46, 48, 61]) play a core role in distributed systems, including ordering services [31, 42, 50], leader election [9, 18], and fault-tolerance [25, 33, 43]. A PAXOS protocol replicates the same application on a group of computers (or *replicas*) and enforces the same order of inputs for this application, as long as a majority of replicas are still alive. Therefore, PAXOS tolerates various faults, including minor replica failures and packet losses.

PAXOS is widely served in many systems. For instance, Scatter [31] runs 8~12 replicas in a PAXOS group to order client requests, and it lets replicas reply requests in parallel. A bigger group size will improve Scatter throughput. Moreover, state machine replication (SMR) systems [25, 33, 43] use PAXOS to improve the availability of server applications (e.g., MySQL [10]).

Unfortunately, the group size of existing PAXOS protocols can hardly go up to a dozen because their consensus messages go through OS kernels and software TCP/IP layers (a ping round-trip takes about 200 μ s in a 10Gbps network), causing the consensus latency to increase almost linearly to group size [9, 25, 31].

To address this PAXOS performance problem, Remote Direct Memory Access (RDMA) (e.g., Infini-band [5]) is a promising solution due to its commonplace in datacenters and its decreasing prices. An RDMA round-trip takes only about 3 μ s [51]. This ultra low latency not only comes from its kernel bypassing feature, but also its dedicated network stack implemented in hardware. Therefore, RDMA is considered the fastest kernel bypassing technique [41, 51, 57]; it is several times faster than software-only kernel bypassing techniques (e.g., DPDK [2] and Arrakis [56]).

1.2 Datacenter Computing Infrastructures

More and more applications are ran in a datacenter by two independent types of infrastructures. The first type is schedulers [11, 17, 36, 37, 39, 62, 63, 71]. Although existing schedulers themselves have been made available via PAXOS (e.g., [36]), their applications are not. Therefore, if failures such as computer hardware errors occur, these schedulers have to re-launch applications, leading to a substantial application downtime and thus a huge lost for mission-critical applications (e.g., financial platforms and social networks).

The second infrastructure type is VM [12, 14, 44, 55, 64]. VM abstracts away the heterogeneous physical computing resources, making computing resources easy to utilize and balance loads (e.g., via live migration [20, 53]). VM is also known for its secure isolation on resources [14, 44, 60]. Although some VM fault-tolerance approaches such as primary-backup [26] exist, they consume much time and network bandwidth as they need to transfer all memory modified by applications across VM replications.

These two infrastructures usually work independently depending on runtime trade-off such as performance or security isolation. Some applications are ran solely by schedulers (e.g., Mesos [36] usually uses lightweight Linux containers, not VMs), and some other applications are ran solely by VMs (e.g., Amazon EC2). Therefore, this GAIA project strengthens the two infrastructures respectively. If people need to run an application with both infrastructures, they can choose either infrastructure developed from GAIA and the other one from outside.

1.3 Motivation of Objectives

The proposed objectives stem from two research problems in datacenter computing. First, despite the core role and wide deployments of PAXOS, it suffers from high consensus latency. Therefore, **Objective 1** addresses this problem by leveraging RDMA to create a fast distributed consensus algorithm and its implementation protocol. Second, although many mission-critical applications demand high availability, existing infrastructures lack such support. To benefit these applications, **Object 2 and 3** take a holistic methodology to integrate our protocol with two major infrastructures, potentially benefiting almost all applications.

1.4 Related Work by Others

Various Consensus Protocols. There are a rich set of PAXOS algorithms [45, 46, 48, 52, 61] and implementations [18, 19, 25, 48]. PAXOS is notoriously difficult to be fast and scalable [31, 42, 50]. Since consensus protocols play a core role in datacenters [1, 36, 70] and worldwide distributed systems [21, 47], various works have been conducted to improve specific aspects of consensus protocols, including commutativity [52], understandability [46, 54], and verifiable rules [32, 68].

To make PAXOS’s throughput scalable (i.e., more replicas, higher throughput), various systems leverage PAXOS as a core building block to develop advanced replication approaches, including partitioning program states [15, 31], splitting consensus leadership [16, 47], and hierarchical replication [31, 42]. These approaches have shown to largely improve throughput. However, the core of these systems, PAXOS, still faces an unscalable consensus latency [31, 42, 50]. By using GAIA as a building block, these prior systems can scale even better.

Fault-tolerance in schedulers. Datacenter schedulers [11, 17, 36, 37, 39, 62, 63, 71] can support diverse applications (e.g., Hadoop [34], Dryad [38], and key-value stores [59]). Existing schedulers mainly focus on ensuring high availability for themselves by replicating their own important components, or focus on recovery instead of availability of applications [71]. To the best of our knowledge, no existing schedulers provide a high availability support to general applications.

Fault-tolerance in VM. Two approaches, primary-backup and live migration, exist for improving application reliability in VM. Primary-backup uses the hypervisor layer to record application execution state changes in a primary VM and frequently propagate the changes to a backup VM on another computer. Live migration is invoked for both computer load balance and handling failures, and it uses a similar hypervisor technique as primary-backup. Despite much clever effort, both these two approaches consume substantial application down time (e.g., 8 seconds in vMotion [53]) and network bandwidth.

RDMA techniques. RDMA has been realized in various types of datacenter networks, including Infini-band [5], RoCE [8], and iWRAP [6]. RDMA has been leveraged in many software systems to improve different performance aspects, including high performance computing [30], key-value stores [28, 40, 41, 51], transactional processing systems [29, 66], and file systems [67]. These systems are complementary to GAIA.

1.5 Related Work by the PI

The PI is an expert on reliable datacenter software systems [25, 65] and reliable, secure multithreading runtime systems [22–24, 69]. The PI’s works are published in premier conferences on systems software (OSDI 2010, SOSP 2011, SOSP 2013, and SOSP 2015) and programming languages (PLDI 2012 and ASPLOS 2013). As preliminary results for this GAIA proposal, the PI has developed a general consensus protocol [25] (part of **Objective 1**) and a fault-tolerant datacenter scheduler [65] (part of **Objective 2**).

2 Research Plan and Methodology

GAIA strengthens the reliability of datacenter computing with a holistic methodology. This section first proposes FALCON (§2.1), a fast consensus protocol, it then leverages FALCON to build a scheduler (§2.2) and a VM replication infrastructure (§2.3) to improve the availability of applications ran by these infrastructures. Finally, this section describes research plan (§2.4).

2.1 Objective 1: Building Fast Distributed Consensus via RDMA

This section describes a performance problem (§2.1.1) in existing PAXOS protocols and presents FALCON (§2.1.2), a fast PAXOS protocol by leveraging RDMA.

2.1.1 Problem: consensus latency of existing PAXOS protocols are slow and unscalable

Despite the wide deployments of PAXOS (§1.1), its high consensus latency makes many software applications suffer. For efficiency, PAXOS typically assigns one replica as the leader to propose consensus requests, and the other replicas as backups to agree on requests. To agree on an input, at least one message round-trip

is required between the leader and a backup. A round-trip causes big latency (hundreds of μ s) as it goes through various software layers (e.g., OS kernels).

As replica group size increases, PAXOS consensus latency scales poorly: it increases drastically [31] due to the linearly increasing number of consensus messages. One common approach to improve PAXOS scalability is leveraging parallel techniques such as multithreading [9, 16] or asynchronous IO [25, 58]. However, the high TCP/IP round-trip latency still exists, and synchronizations in these techniques frequently invoke expensive OS events such as context switches.

Our preliminary study (Figure 3) ran four PAXOS-like protocols [9, 16, 25, 58] on 40Gbps network with only one client sending consensus requests. When changing the replica group size from 3 to 9, the consensus latency of three protocols increased by 30.3% to 156.8%, and 36.5% to 63.7% of this increase was in OS kernel. The only exception is SPaxos [16] because it batches requests from backups and invokes consensus when the batch is full. More replicas causes shorter time to form a batch, but batching causes its consensus latency the highest with less replicas.

RDMA appears a promising approach (§1.1) to speed up PAXOS. However, fully exploiting RDMA speed in software systems is widely considered challenging by the community [29, 41, 51, 57]. For instance, DARE [57] presents a two-round, RDMA-based PAXOS protocol in a sole-leader manner: leader does all RDMA workloads and backups do nothing. Although DARE was fast with 3~5 replicas, our study (Figure 3) shows that DARE’s sole-leader nature incurred a scalability bottleneck and thus a linearly increasing consensus latency.

2.1.2 Falcon: a fast, scalable RDMA-based PAXOS protocol

Our key observation is that we should carefully separate RDMA workloads among the leader and backups, especially in a scalability-sensitive context. Intuitively, we can let both leader and backups do RDMA writes directly on destination replicas’ memory, and let all replicas poll their local memory to receive messages.

Although doing so will consume more CPU resources than a sole-leader protocol [57], it has two major benefits. First, both leader and backups participate in consensus, making it possible to reach consensus with only one round [48]. Second, all replicas can just receive consensus messages on their bare, local memory. An analogy is threads receiving other threads’ data via bare memory, a fast and scalable computation pattern.

We propose FALCON,¹ a new RDMA-based PAXOS protocol and its runtime system. In GAIA, all replicas directly write to destination replicas’ memory and poll messages from local memory to receive messages, and our runtime system handles other technical challenges such as checking message delivery and recovering replica failures.

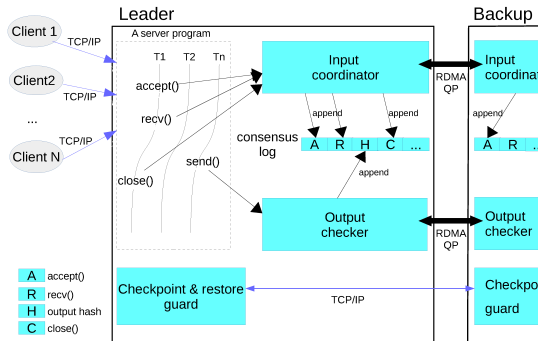


Figure 1: The FALCON protocol architecture. Protocol components are shaded (and in blue color).

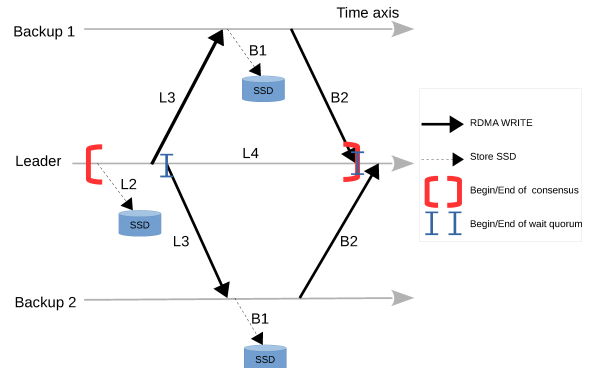


Figure 2: RDMA-powered consensus algorithm.

FALCON supports unmodified applications. FALCON automatically deploys the same application on

¹We name our protocol after falcon, one of the fastest birds.

multiple replicas, intercepts the application’s network inputs from its inbound socket calls (e.g., `recv`) with a Linux technique called `LD_PRELOAD`, and invokes its RDMA-based consensus protocol to enforce same network inputs across replicas. Figure 1 shows FALCON’s architecture on the leader replica with three key components: an input consensus coordinator, an in-memory consensus log, and a guard that checkpoints and recovers application execution states.

Figure 2 shows FALCON’s consensus algorithm in normal case. The leader first executes the actual inbound socket call to get and store the actual inputs, it then invokes consensus across replicas. All solid arrows (**L3** and **B2**) are direct RDMA writes to remote replicas’ memory. All replicas poll from their own bare memory to receive consensus messages. To handle replica failures, all replicas persistently log inputs to local SSD storage (**L2** and **B1**). For these writes, the sending replicas only need to copy the data to local RDMA NIC and then the writes finish, FALCON is scalable when more backup replicas are added.

Preliminary results. We implemented a FALCON prototype with two steps. First, to support unmodified applications, we implemented its socket-intercepting protocol, published in SOSP 2015 [25]. FALCON was able to support five widely used server applications (e.g., MySQL) without modifying them. Second, we implemented its RDMA-powered consensus algorithm on a 40bps RDMA network. Figure 3 shows FALCON performance with 5 existing consensus protocols. To analyze the scalability of our algorithm, we ran FALCON and DARE on up to 105 replicas. FALCON’s consensus latency outperforms 4 popular PAXOS protocols by 32.3x to 85.8x on 3 to 9 replicas. FALCON is faster than DARE by up to 3.3x.

Future work. Since FALCON is the keystone of our objectives, this proposal plans to further improve its practicality in two directions: (1) evaluate its performance and generality on more latency-critical applications, and (2) study its protocol robustness on failure scenarios, including leader election and adding/removing replicas.

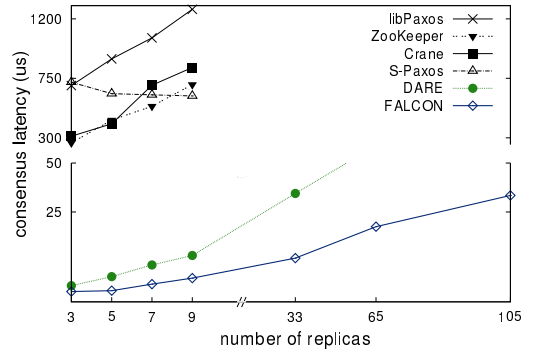


Figure 3: Consensus latency of six PAXOS protocols. Both X and Y axes are broken to fit in all these protocols. FALCON achieves the smallest consensus latency.

2.2 Objective 2: building a fault-tolerant scheduler to improve application availability

Many existing schedulers have adopted PAXOS to improve availability for themselves. Typically, they use PAXOS to replicate their essential components such as a controller, which handles scheduling computation jobs to run on resources. In normal case, only one leading controller does the real work, and the others standby to cope with the leader’s failure. Unfortunately, most applications running by these schedulers have not been made highly-available (although minor applications implement a replication approach [13, 27]).

A naive approach to achieve high application availability could be implementing a PAXOS within each application. However, this approach has two major issues. First, PAXOS is notoriously difficult to understand [45, 54], implement [19, 48], or test [32, 68], thus developing a PAXOS protocol for each application is widely considered a nightmare [19, 32, 68] for application developers.

The second issue is, the scheduler may defeat PAXOS due to unawareness of the application’s PAXOS replication logic. For instance, if an application submits multiple copies of the same computation job to the scheduler, the scheduler may incorrectly schedule several copies on the same computer (it should schedule each copy on different computers to achieve PAXOS fault-tolerance).

2.2.1 TRIPOD: a first fault-tolerant scheduler architecture

This section proposes the design of TRIPOD, a scheduler infrastructure that automatically provides high-availability to general applications. TRIPOD is integrated with a widely used scheduler MESOS [36] and FALCON (**Objective 1**). To avoid the two aforementioned issues (§2.2), TRIPOD chooses to integrate PAXOS

in a scheduler, not in applications. To achieve high application availability, unlike existing schedulers which let only one controller schedule jobs, TRIPOD runs replicas of the same job using replicas of controllers: after controllers agree on a new job with FALCON, TRIPOD lets each controller independently schedule a copy of this job.

Figure 4 depicts TRIPOD’s architecture, and its key components are shaded (and in blue). To illustrate how TRIPOD works in an application perspective, this figure shows two applications, Hadoop and MPI. Each application has a *replica strength* (R) to denote the level of fault-tolerance it demands. This value is either 1 or equals the number of replicas of controllers in TRIPOD.

By default, each application has $R=1$, which means that this application does not need replication. For such a default setting, TRIPOD runs the job as is without replication, like a typical cluster management system (e.g., Mesos).

In this figure, Hadoop’s R is 3, which means that it wants to replicate each of its job with three copies for high-availability. Suppose Hadoop submits two jobs to the leader controller, each has different shapes (triangle or hexagon). The leader controller then invokes a consensus on each job across controllers. Once a consensus is reached, each controller assigns the same job on different slave machines. The leader controller directly returns its computation result to the Hadoop scheduler. Standby controllers ignore the results unless the same mechanism is triggered.

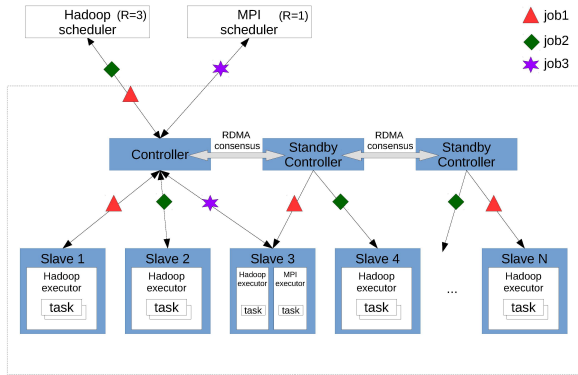


Figure 4: The TRIPOD fault-tolerant scheduler.

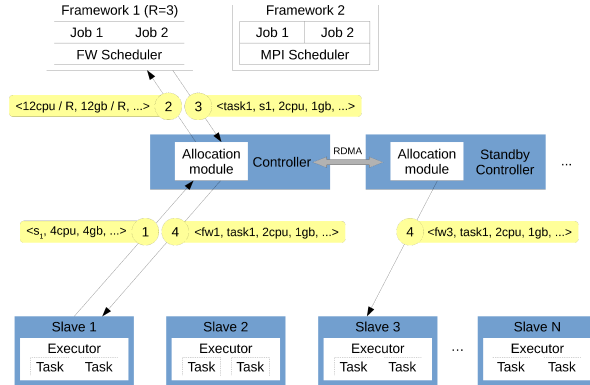


Figure 5: The replication-aware resource allocation scheme.

2.2.2 Replication-aware resource allocation scheme

Figure 5 shows TRIPOD’s scheme on scheduling jobs with four steps. This scheme is similar to that in Mesos except the second and fourth steps. These two steps TRIPOD abstract away the replication logic in its resource offers and allocations from the application. An application runs as if GAIA does not replicate any of its jobs, and TRIPOD transparently handles all the replication logic.

In the first step, slave machines periodically report their available computing resources (e.g., CPU cores and memory) to the leader controller. In the second step, instead of offering the available resources aggregated from slave machines, TRIPOD divides the amount of resources by each application’s R value and then sends a resource offer to the application. The goal is to reserve enough resources for TRIPOD to replicate a job with R copies.

In the third step, an application scheduler submits jobs to the leader controller. The leader controller then invokes a consensus on this job by carrying the resource offer made to the application.

Once a majority of controllers agrees on executing this job, each controller does the fourth step. It schedules this job on an available slave machine according to the resource offer. To prevent controllers putting the same job on the same slave machine, the leader controller first makes an assignment on which controller should run this job on which slave machine, it then carries this assignment in its consensus request. Once a consensus on this job is reached, each controller follows this assignment.

Availability v.s. resource consumption. TRIPOD is designed to make a mission-critical application highly available by leveraging R times of resources than the application’s native, unreplicated execution. We deemed this extra resource consumption reasonable, because a major trend is that an application runs on more and more computers, thus minor computer failures tend to happen more likely. Such failures may turn down the entire application and cause if the failure computer runs a critical computation. For instance, Both NYSE and Nasdaq have experienced outage of their whole site [7] or specific IPO events [3] due to minor machine errors. In addition, social-networking applications like Facebook has strong fault-tolerance requirements, because minor machine failures have turned down the whole Facebook site for several times in the last few years [4], costing huge money lost.

Preliminary results. We built and published a TRIPOD prototype in [65]. To evaluate a typical social-networking application, we ran TRIPOD with Memcached [49], a popular key-value store used by Twitter and financial platforms [35]. Compared to Memcached’s unreplicated execution, TRIPOD incurred merely a 3.22% overhead in throughput and 3.31% in response time.

Future work. Our TRIPOD development will go along two directions. First, currently our replication and resource allocation scheme is tied with MESOS. We will study other popular schedulers and summarize their resource allocation scheme patterns, and we will develop a general, scheduler-agnostic scheme. Second, we will study new differential replication schemes, so that we can flexibly assign different R values to different components of an application, getting both satisfiable availability and optimal resource consumption.

2.3 Objective 3: Building a fault-tolerant VM to improve application availability

Virtual machines (VM) infrastructures (e.g., Amazon EC2 [12] and OpenStack [55]) are widely deployed in datacenters and clouds because they can provide a virtualized abstraction of computing resources to different applications and enforce strong utilization isolation and security.

As mentioned in related work (§1.4), two approaches, primary-backup and live migration, exist for improving VM fault-tolerance, resource utilization, and energy saving. Both these approaches face problems on substantial application down time (e.g., 8 seconds in a live migration system vMotion [53]) and network bandwidth. The downtime hurts application availability even if there is no replica failure. The bandwidth consumption often aggravates resource burdens because these approaches are often invoked when resources are tight.

A main reason that causes these two problems is that these approaches have only one actual execution of an application. Therefore, once execution states is required to transferred to a remote computer, the local execution has to be disturbed.

2.3.1 Integrating FALCON with VM

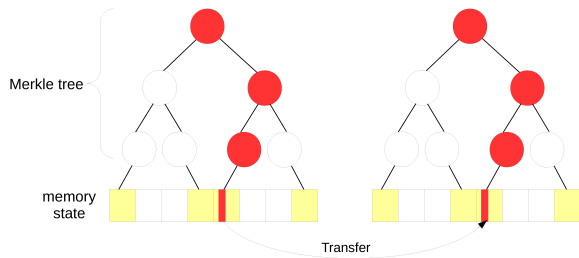


Figure 6: Data structures on tracking different memory pages across VMs. Diverged pages and their parent nodes are marked red by **Algorithm 1**.

Algorithm 1: Tracking different memory pages

Input : The root of merkle tree on leader, $root$
Output: Different memory pages between leader and replica, $pages$
Track($bitmap, root$)
 $diverged \leftarrow$ empty sequence
 $pages \leftarrow$ empty sequence
 $diverged \leftarrow \text{FALCON}(root, root.left(), root.right())$
for $i \leftarrow diverged.push_front()$ **do**
 if i is $leaf()$ **then**
 $pages.append(i)$
 else
 $diverged.append(\text{FALCON}(i, i.left(), i.right()))$
return $pages$

Fortunately, PAXOS-based replication can construct multiple, equivalent executions for the same application, thanking to its robustness and consistency. To ensure high application availability, we can just run

PAXOS to make replicas of VMs see the same sequence of inputs, and doing so is feasible because many VM architectures have input interception layers by default.

We make FALCON and VM form a mutual-beneficial eco-system. In this eco-system, VM provides a hypervisor layer to automatically capture incoming inputs and application execution state changes for FALCON, and FALCON benefits a VM by: (1) improving availability of applications running in this VM, and (2) greatly improving application downtime and bandwidth consumption for the VM's live migration.

Figure ?? shows the architecture of the eco-system. To provide the same fault-tolerance guarantee with primary-backup, a typical replication factor of this eco-system is $R=3$. This eco-system chooses KVM [44] due to two main reasons. First, KVM is an open source hypervisor carried in Linux. Second, it provides `tap_send()`, an input capturing API at its QEMU component running at user space. Compared to other types of hypervisors, this API enables FALCON to coordinate inputs with RDMA, because currently RDMA only supports user space.

A key benefit of such a PAXOS-based VM replication over primary-backup is that its leadership is strongly consistent (through a majority agreement, which primary-backup lacks), and it saves the bandwidth consumption for transferring application execution states in primary-backup.

2.3.2 Tracking Minor Memory Difference Across VM Replicas

To repair divergence efficiently, we propose a lightweight state synchronization approach. It synchronizes state between replicas by transferring only pages that are different. To do this, each replica maintains a Merkle tree kept updating from the dirty pages. By "dirty", we mean the memory page has been modified since last synchronization. One problem here is that each VM may have dirtied different pages. This leads to different structures of Merkle trees and they are not comparable. GAIA addresses this problem using a fast method as follows:

Our method is efficient for two reasons. First, it only transfers the different pages between replicas. Because we have made consensus on inputs and we can turn off *Address Space Layout Randomization* to trade for correctness, the difference rate will be really small. Second, the use of Merkle tree optimizes the time complexity of comparison between memory states to $O(\log n)$.

Future work. We plan to fully implement the eco-system, including both the replication architecture (§2.3.1) and the novel live migration approach (§??). We will compare the performance overhead of our replication approach with existing open-source VM infrastructure (e.g., OpenStack). We will also compare the performance of our migration approach with existing live migration approaches (e.g., vMotion).

2.4 Research Plan

This project will require two PhD students S1 and S2 to work for three years. In the first year, S1 will design and fully implement the FALCON protocol (part of **Objective 1**), and S2 will evaluate its performance and robustness on various real-world storage applications (part of **Objective 2**). In the second year, S1 will integrate FALCON to a scheduler MESOS (part of **Objective 2**), and S2 will make FALCON and KVM form an eco-system (part of **Objective 3**). In the third year, S1 and S2 will respectively study the efficacy of their systems built Object 2 and Object 3 with real-world applications, including big data applications.

References

- [1] Why the data center needs an operating system. <http://radar.oreilly.com/2014/12/why-the-data-center-needs-an-operating-system.html>.
- [2] Data Plane Development Kit (DPDK). <http://dpdk.org/>.
- [3] Facebook ipo: What went wrong? <http://money.cnn.com/2012/05/23/technology/facebook-ipo-what-went-wrong/>, .
- [4] Is facebook down? a history of outages. <https://www.theguardian.com/technology/2015/jan/27/is-facebook-down-outages>, .
- [5] An Introduction to the InfiniBand Architecture. <http://buyya.com/superstorage/chap42.pdf>.
- [6] RDMA iWARP. <http://www.chelsio.com/nic/rdma-iwarp/>.
- [7] This is why the nyse shut down today. <http://fortune.com/2015/07/08/nyse-halt/>.
- [8] Mellanox Products: RDMA over Converged Ethernet (RoCE). http://www.mellanox.com/page/products_dyn?product_family=79.
- [9] ZooKeeper. <https://zookeeper.apache.org/>.
- [10] MySQL Database. <http://www.mysql.com/>, 2014.
- [11] Tupperware. https://www.youtube.com/watch?v=C_WuUgTqg0c, 2014.
- [12] Amazon Virtual Private Cloud (VPC). <https://aws.amazon.com/vpc/>.
- [13] G. Ananthanarayanan, A. Ghodsi, S. Shenker, and I. Stoica. Effective straggler mitigation: Attack of the clones. In *NSDI'13*, 2013.
- [14] P. Barham, B. Dragovic, K. Fraser, S. Hand, T. Harris, A. Ho, R. Neugebauer, I. Pratt, and A. Warfield. Xen and the art of virtualization. In *SOSP '03: Proceedings of the nineteenth ACM symposium on Operating systems principles*, pages 164–177, 2003.
- [15] C. E. Bezerra, F. Pedone, and R. V. Renesse. Scalable state-machine replication. In *Proceedings of the 2014 44th Annual IEEE/IFIP International Conference on Dependable Systems and Networks, DSN '14*, 2014.
- [16] M. Biely, Z. Milosevic, N. Santos, and A. Schiper. S-paxos: Offloading the leader for high throughput state machine replication. In *Proceedings of the 2012 IEEE 31st Symposium on Reliable Distributed Systems, SRDS '12*, 2012.
- [17] E. Boutin, J. Ekanayake, W. Lin, B. Shi, J. Zhou, Z. Qian, M. Wu, and L. Zhou. Apollo: Scalable and coordinated scheduling for cloud-scale computing. In *Proceedings of the 11th USENIX Conference on Operating Systems Design and Implementation, OSDI'14*, pages 285–300, Berkeley, CA, USA, 2014. USENIX Association. ISBN 978-1-931971-16-4. URL <http://dl.acm.org/citation.cfm?id=2685048.2685071>.
- [18] M. Burrows. The chubby lock service for loosely-coupled distributed systems. In *Proceedings of the Seventh Symposium on Operating Systems Design and Implementation (OSDI '06)*, pages 335–350, 2006.
- [19] T. D. Chandra, R. Griesemer, and J. Redstone. Paxos made live: An engineering perspective. In *Proceedings of the Twenty-sixth Annual ACM Symposium on Principles of Distributed Computing (PODC '07)*, Aug. 2007.
- [20] C. Clark, K. Fraser, S. Hand, J. G. Hansen, E. Jul, C. Limpach, I. Pratt, and A. Warfield. Live migration of virtual machines. In *Proceedings of the 2Nd Conference on Symposium on Networked Systems Design & Implementation - Volume 2, NSDI'05*, 2005.
- [21] J. C. Corbett, J. Dean, M. Epstein, A. Fikes, C. Frost, J. J. Furman, S. Ghemawat, A. Gubarev, C. Heiser, P. Hochschild, W. Hsieh, S. Kanthak, E. Kogan, H. Li, A. Lloyd, S. Melnik, D. Mwaura, D. Nagle, S. Quinlan, R. Rao, L. Rolig, Y. Saito, M. Szymaniak, C. Taylor, R. Wang, and D. Woodford. Spanner: Google's globally-distributed database. In *Proceedings of the 12th Symposium on Operating Systems Design and Implementation (OSDI '16)*, Oct. 2012.
- [22] H. Cui, J. Wu, C.-C. Tsai, and J. Yang. Stable deterministic multithreading through schedule memoization. In *Proceedings of the Ninth Symposium on Operating Systems Design and Implementation (OSDI '10)*, Oct. 2010.
- [23] H. Cui, J. Wu, J. Gallagher, H. Guo, and J. Yang. Efficient deterministic multithreading through schedule relaxation. In *Proceedings of the 23rd ACM Symposium on Operating Systems Principles (SOSP '11)*, pages 337–351, Oct. 2011.
- [24] H. Cui, J. Simsa, Y.-H. Lin, H. Li, B. Blum, X. Xu, J. Yang, G. A. Gibson, and R. E. Bryant. Parrot: a practical runtime for deterministic, stable, and reliable threads. In *Proceedings of the 24th ACM Symposium on Operating Systems Principles (SOSP '13)*, Nov. 2013.
- [25] H. Cui, R. Gu, C. Liu, and J. Yang. Paxos made transparent. In *Proceedings of the 25th ACM Symposium on Operating Systems Principles (SOSP '15)*, Oct. 2015.
- [26] B. Cully, G. Lefebvre, D. Meyer, M. Feeley, N. Hutchinson, and A. Warfield. Remus: High availability via asynchronous virtual machine replication. In *Proceedings of the 5th USENIX Symposium on Networked Systems Design and Implementation*, pages 161–174. San Francisco, 2008.
- [27] J. Dean and S. Ghemawat. Mapreduce: simplified data processing on large clusters. In *OSDI'04: Proceedings of the 6th conference on Symposium on Operating Systems Design & Implementation*, pages 10–10, 2004.
- [28] A. Dragojević, D. Narayanan, O. Hodson, and M. Castro. Farm: Fast remote memory. In *Proceedings of the 11th USENIX Conference on Networked Systems Design and Implementation, NSDI'14*, 2014.

- [29] A. Dragojević, D. Narayanan, E. B. Nightingale, M. Renzelmann, A. Shamis, A. Badam, and M. Castro. No compromises: Distributed transactions with consistency, availability, and performance. In *Proceedings of the 25th ACM Symposium on Operating Systems Principles (SOSP '15)*, Oct. 2015.
- [30] M. P. I. Forum. Open mpi: Open source high performance computing, Sept. 2009.
- [31] L. Glendenning, I. Beschastnikh, A. Krishnamurthy, and T. Anderson. Scalable consistency in scatter. In *Proceedings of the 23rd ACM Symposium on Operating Systems Principles (SOSP '11)*, Oct. 2011.
- [32] H. Guo, M. Wu, L. Zhou, G. Hu, J. Yang, and L. Zhang. Practical software model checking via dynamic interface reduction. In *Proceedings of the 23rd ACM Symposium on Operating Systems Principles (SOSP '11)*, pages 265–278, Oct. 2011.
- [33] Z. Guo, C. Hong, M. Yang, D. Zhou, L. Zhou, and L. Zhuang. Rex: Replication at the speed of multi-core. In *Proceedings of the 2014 ACM European Conference on Computer Systems (EUROSYS '14)*, page 11. ACM, 2014.
- [34] Hadoop. Hadoop. <http://hadoop.apache.org/core/>.
- [35] R. Hecht and S. Jablonski. Nosql evaluation: A use case oriented survey. *2012 International Conference on Cloud and Service Computing*, 0:336–341, 2011. doi: <http://doi.ieeecomputersociety.org/10.1109/CSC.2011.6138544>.
- [36] B. Hindman, A. Konwinski, M. Zaharia, A. Ghodsi, A. D. Joseph, R. Katz, S. Shenker, and I. Stoica. Mesos: A platform for fine-grained resource sharing in the data center. In *Proceedings of the 8th USENIX conference on Networked Systems Design and Implementation*, NSDI'11, Berkeley, CA, USA, 2011. USENIX Association.
- [37] M. Isard. Autopilot: Automatic data center management. *SIGOPS Oper. Syst. Rev.*, 41(2):60–67, Apr. 2007. ISSN 0163-5980. doi: 10.1145/1243418.1243426. URL <http://doi.acm.org/10.1145/1243418.1243426>.
- [38] M. Isard, M. Budiu, Y. Yu, A. Birrell, and D. Fetterly. Dryad: distributed data-parallel programs from sequential building blocks. In *EuroSys '07: Proceedings of the Second ACM SIGOPS/EuroSys European Conference on Computer Systems 2007*, pages 59–72, 2007.
- [39] M. Isard, V. Prabhakaran, J. Currey, U. Wieder, K. Talwar, and A. Goldberg. Quincy: Fair scheduling for distributed computing clusters. In *Proceedings of the ACM SIGOPS 22Nd Symposium on Operating Systems Principles*, SOSP '09, pages 261–276, New York, NY, USA, 2009. ACM. ISBN 978-1-60558-752-3. doi: 10.1145/1629575.1629601. URL <http://doi.acm.org/10.1145/1629575.1629601>.
- [40] J. Jose, H. Subramoni, K. Kandalla, M. Wasi-ur Rahman, H. Wang, S. Narravula, and D. K. Panda. Scalable memcached design for infiniband clusters using hybrid transports. In *Proceedings of the 2012 12th IEEE/ACM International Symposium on Cluster, Cloud and Grid Computing (Ccgriid 2012)*, CCGRID '12, 2012.
- [41] A. Kalia, M. Kaminsky, and D. G. Andersen. Using rdma efficiently for key-value services. Aug. 2014.
- [42] M. Kapritsos and F. P. Junqueira. Scalable agreement: Toward ordering as a service. In *Proceedings of the Sixth International Conference on Hot Topics in System Dependability*, HotDep'10, 2010.
- [43] M. Kapritsos, Y. Wang, V. Quema, A. Clement, L. Alvisi, M. Dahlin, et al. All about eve: Execute-verify replication for multi-core servers. In *Proceedings of the Tenth Symposium on Operating Systems Design and Implementation (OSDI '12)*, volume 12, pages 237–250, 2012.
- [44] Kernel Virtual Machine (KVM). <http://www.linux-kvm.org/>.
- [45] L. Lamport. Paxos made simple. <http://research.microsoft.com/en-us/um/people/lamport/pubs/paxos-simple.pdf>.
- [46] L. Lamport. The part-time parliament. *ACM Trans. Comput. Syst.*, 16(2):133–169, 1998.
- [47] Y. Mao, F. P. Junqueira, and K. Marzullo. Mencius: building efficient replicated state machines for wans. In *Proceedings of the 8th USENIX conference on Operating systems design and implementation*, volume 8, pages 369–384, 2008.
- [48] D. Mazieres. Paxos made practical. Technical report, Technical report, 2007. <http://www.scs.stanford.edu/dm/home/papers,2007>.
- [49] Memcached. <https://memcached.org/>.
- [50] E. Michael. *Scaling Leader-Based Protocols for State Machine Replication*. PhD thesis, University of Texas at Austin, 2015.
- [51] C. Mitchell, Y. Geng, and J. Li. Using one-sided rdma reads to build a fast, cpu-efficient key-value store. In *Proceedings of the USENIX Annual Technical Conference (USENIX '14)*, June 2013.
- [52] I. Moraru, D. G. Andersen, and M. Kaminsky. There is more consensus in egalitarian parliaments. In *Proceedings of the 13th ACM Symposium on Operating Systems Principles (SOSP '91)*, Nov. 2013.
- [53] M. Nelson, B.-H. Lim, and G. Hutchins. Fast transparent migration for virtual machines. In *Proceedings of the Annual Conference on USENIX Annual Technical Conference*, ATEC '05, 2005.
- [54] D. Ongaro and J. Ousterhout. In search of an understandable consensus algorithm. In *Proceedings of the USENIX Annual Technical Conference (USENIX '14)*, June 2014.
- [55] OpenStack: Open Source Cloud Computing Software. <https://www.openstack.org/>.
- [56] S. Peter, J. Li, I. Zhang, D. R. K. Ports, D. Woos, A. Krishnamurthy, T. Anderson, and T. Roscoe. Arrakis: The operating system is the control plane. In *Proceedings of the Eleventh Symposium on Operating Systems Design and Implementation (OSDI '14)*, Oct. 2014.

- [57] M. Poke and T. Hoefer. Dare: High-performance state machine replication on rdma networks. In *Proceedings of the 24th International Symposium on High-Performance Parallel and Distributed Computing*, HPDC '15, 2015.
- [58] M. Primi. LibPaxos. <http://libpaxos.sourceforge.net/>.
- [59] Redis. <http://redis.io/>.
- [60] J. Sugerman. Private communication, Dec. 2005.
- [61] R. Van Renesse and D. Altinbuken. Paxos made moderately complex. *ACM Computing Surveys (CSUR)*, 47(3):42:1–42:36, 2015.
- [62] V. K. Vavilapalli, A. C. Murthy, C. Douglas, S. Agarwal, M. Konar, R. Evans, T. Graves, J. Lowe, H. Shah, S. Seth, B. Saha, C. Curino, O. O'Malley, S. Radia, B. Reed, and E. Baldeschwieler. Apache hadoop yarn: Yet another resource negotiator. In *Proceedings of the 4th Annual Symposium on Cloud Computing*, SOCC '13, pages 5:1–5:16, New York, NY, USA, 2013. ACM. ISBN 978-1-4503-2428-1. doi: 10.1145/2523616.2523633. URL <http://doi.acm.org/10.1145/2523616.2523633>.
- [63] A. Verma, L. Pedrosa, M. Korupolu, D. Oppenheimer, E. Tune, and J. Wilkes. Large-scale cluster management at google with borg. In *Proceedings of the Tenth European Conference on Computer Systems*, EuroSys '15, pages 18:1–18:17, New York, NY, USA, 2015. ACM. ISBN 978-1-4503-3238-5. doi: 10.1145/2741948.2741964. URL <http://doi.acm.org/10.1145/2741948.2741964>.
- [64] C. A. Waldspurger. Memory resource management in VMware ESX server. In *Proceedings of the Fifth Symposium on Operating Systems Design and Implementation (OSDI '02)*, 2002.
- [65] C. Wang, J. Yang, N. Yi, and H. Cui. Tripod: An efficient, highly-available cluster management system. In *Proceedings of the 7th ACM SIGOPS Asia-Pacific Workshop on Systems*, APSys '16, 2016.
- [66] X. Wei, J. Shi, Y. Chen, R. Chen, and H. Chen. Fast in-memory transaction processing using rdma and htm. In *Proceedings of the 25th ACM Symposium on Operating Systems Principles (SOSP '15)*, SOSP '15, Oct. 2015.
- [67] G. G. Wittawat Tantisiriroj. Network file system (nfs) in high performance networks. Technical Report CMU-PDLSVD08-02, Carnegie Mellon University, Jan. 2008.
- [68] J. Yang, T. Chen, M. Wu, Z. Xu, X. Liu, H. Lin, M. Yang, F. Long, L. Zhang, and L. Zhou. MODIST: Transparent model checking of unmodified distributed systems. In *Proceedings of the Sixth Symposium on Networked Systems Design and Implementation (NSDI '09)*, pages 213–228, Apr. 2009.
- [69] J. Yang, H. Cui, J. Wu, Y. Tang, and G. Hu. Determinism is not enough: Making parallel programs reliable with stable multithreading. *Communications of the ACM*, 2014.
- [70] M. Zaharia, B. Hindman, A. Konwinski, A. Ghodsi, A. D. Joesph, R. Katz, S. Shenker, and I. Stoica. The datacenter needs an operating system. In *Proceedings of the 3rd USENIX Conference on Hot Topics in Cloud Computing*, 2011.
- [71] Z. Zhang, C. Li, Y. Tao, R. Yang, H. Tang, and J. Xu. Fuxi: A fault-tolerant resource management and job scheduling system at internet scale. *Proc. VLDB Endow.*, 7(13):1393–1404, Aug. 2014. ISSN 2150-8097. doi: 10.14778/2733004.2733012. URL <http://dx.doi.org/10.14778/2733004.2733012>.