CMSC818s: Project 3
A Brief Survey of Modern Virtualization Research

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1 Introduction

The idea of virtualization has been around for a long time, reaching back to the 1960s and the introduction of virtual memory in timeshared machines. However, in the last decade or so it's become a very exciting area of research, particularly motivated by a new market for server virtualization. Commerical products like VMWare and open-source platforms like Xen [1] have made it possible for companies to host dozens of instances of their servers on the same hardware. Companies can now spend less on metal, can seamlessly and easily migrate servers from one machine to another, and can even adjust their fleet size on the fly in response to fluctuations in server traffic by spinning up new instances. In addition to the commercial successes that have come as a result of server virtualization, there have been tremendous breakthroughs in the research community as well, ranging from new solutions to problems of isolation and protection to novel algorithms for scheduling and resource allocation.

Despite the recent flurry of activity in this area, there are still many interesting and difficult problems to be solved. Sharing finite resources fairly and safely amongst many competing processes has never been easy, but the popularity of virtualization in the Cloud makes scalability and efficiency bigger concerns than ever before. Furthermore, the commercialization of virtual machines raises questions of how to ensure quality of service in an environment where everyone is in contention for the hardware. In this paper, we will examine some of the recent literature in this area and seek to draw some conclusions about the problem space and the directions of future work.

The rest of the paper is structured as follows: in Section 2 we provide background information on the history of virtualization and the sorts of techniques which are utilized today. Section 3 presents summaries of a foundational virtualization paper from the 5$^{\text{th}}$ USENIX Symposium on Operating Systems Design and Implementation, as well as three recent papers from the virtualization session of the same Symposium in 2010. Section 4 attempts to analyze and classify these papers in terms of how they relate to each other and how they approach the larger problem space. Finally, in Section 5 we conclude by discussing our thoughts and opinions on the problem space as a whole, and postulate about how virtualization may evolve in the future.

2 Background

Virtualization techniques arose more than half a century ago in the early 1960s, when developers of large time-sharing systems sought ways to give each user the illusion that they had sole access to a private, virtual computer, despite the fact that many users were in fact sharing computing resources. Once private physical computers became available, popular, and cheap in the 80s, virtualization took a backseat to other areas of research. However, many of the ideas put forth in these early days lived on in work involving virtual memory and operating system protection paradigms.

Server virtualization arrived on the scene about a decade ago, with VMWare appearing in 1999, Denali in 2002, and Xen in 2003. Since then, research and commercial interest in virtualization has sparked significantly, especially in conjunction with the rise of Cloud computing and Infrastructure-as-a-service.

In a virtualized context, we have many *virtual machines*(VM) sharing the same physical hardware. In a *fully virtualized* system, each VM has the illusion that it alone has sole access to the hardware, although in a *para-virtualized* system VMs may be modified to be aware of the fact that they are virtualized. This sharing of resources is possible because access to the hardware is regulated by a special piece of software, the *virtual machine monitor* or *hypervisor*. In many ways, the hypervisor plays the role of the kernel in a traditional operating system - it contains the privileged software that can directly access the hardware.

The hypervisor (and potentially other administra-

tive software) runs in the *host* domain (in Xen, this is called *dom0*), while other OSes running in VMs are referred to as *guests* (in Xen, all guests run in *domU*). It is crucial that all guests are isolated from one another, so that the actions of one guest cannot adversely affect the performance of any other. This is a difficult property to guarantee in a system where all guests are in contention for limited hardware resources.

In the early days of virtualization, there was little-to-no hardware support, and so the multiplexing of VMs onto the physical hardware was accomplished by *emulating* hardware devices in the software for each VM. This had the unfortunate drawback of being extremely slow and inefficient, because the hardware was emulated by the hypervisor, and so most device accesses by a guest VM resulted in multiple traps into the hypervisor (and therefore multiple crossings of protection boundaries). In the past decade or so, chipsets have become more virtualization-friendly, and most architectures (notably the x86) now offer hardware-level support for virtualization, along with a set of privileged instructions for making use of it. This has allowed hardware virtualization to become fast enough to be viable, so that virtualized systems are now reasonably competitive with their native counterparts.

3 Paper Summaries

3.1 Scale and Performance in the Denali Isolation Kernel

Three years after VMWare's appearance, Denali [2] sought to provide a virtualization solution with two goals in mind, scalability and security. Denali's authors envisioned a separation between the management of physical hardware and the management of software services, transforming how internet services could be deployed. Such a system would allow untrusted software to run on third party infrastructure, support the distribution of dynamic content in delivery systems, or provide a foundation for virtual hosting.

In order to meet this vision, the Denali project introduced *para-virtualization* by providing a simplified and pared-down emulation of the hardware for VMs to interface with. Denali also adopted complete isolation of guest VMs, and made VMs extremely lightweight, so that the system could support over 10,000 VMs on commodity machines. Denali diverged from many related projects by sacrificing backwards compatibility for its primary objectives, but its designers argued that this design tradeoff was well worth the benefits.

At the high level, Denali provides an isolation kernel (a small kernel operating system) running on top of x86 hardware. The kernel is designed to host many untrusted applications which are isolated and require little-to-no data sharing. Denali multiplexes between the guest operating systems and isolates them using private virtualized namespaces. Some special privileges, like dowloading a remote VM or loading initial disk images, are handled by a supervisor host VM.

The isolation kernel exports a simpler interface to guest VMs than would be required by a traditional operating system. Since the x86 ISA includes instructions whose behavior differs in user and kernel mode, these are excluded from Denali's instruction set, while two additional virtual instructions are added. First, `idle-with-timeout` lets VMs halt their execution for a bounded amount of physical time, or until an interrupt arrives for the VM, which allows the system to avoid needlessly scheduling sleeping VMs. Second, Denali provides a virtual instruction which a VM can use to self-terminate.

Denali's virtual architecture and implementation adhere to a separation between mechanism and policy so changes can be easily made. CPU virtualization holds a policy split into two elements, a *gatekeeper policy* to choose the subset of active VMs to admit into the system, and a *scheduler policy* to switch between active VMs. For simplicity, the authors use FIFO and round robin in the described implementation, although other scheduling policies could be implemented. The system provides a non-traditional interrupt model, where virtual interrupts for a VM are batched and delivered asynchronously when the VM is next scheduled.

Denali's memory virtualization aims to keep a VM's working set in memory, so physical memory is redistributed from inactive to active VMs, and swap regions for each VM are used to page its memory. The isolation kernel itself is kept pinned in memory at all times.

Denali also provides some limited emulated hardware. In particular, a virtual ethernet NIC is provided for each VM, with queues for incoming and outgoing packets. Incoming packets for each VM are accumulated in the appropriate queues and are later processed once the corresponding VM is given focus by the scheduler. Outgoing packets are processed in a round-robin manner from outgoing queues. Denali's TCP/IP stack runs at the user level, which has its drawbacks, since all packets have to cross the user/kernel boundary. However, the paper contains a packet dispatch evaluation, which suggests that cost of network virtualization is low and that the the driver

itself is responsible for the majority of packet processing costs.

The Denali paper provides a comprehensive evaluation of the isolation kernel running the Ilwaco operating system, with basic metrics like switching times between VMs, swap disk microbenchmarks, and packet dispatch latency, and TCP and HTTP throughput. Some of the most interesting evaluations were conducted to examine the scalability and performance of Denali. The authors found that batched interrupts provided a performance gain of 30% when the number of VMs exceeded 800, and that using idle-with-timeout in Denali lead to higher performance as the number of VMs increased.

However, Denali is certainly not free from bottlenecks, and the authors discuss two major challenges to Denali's performance and scalability. First, Denali tries to reduce the amount of per-VM kernel data that it has to manage by no keeping information for inactive VMs, but it still requires about 81MB of data for 10,000 virtual machines. The authors suggest that with the growing size of memory, this bottleneck might be acceptable. Secondly, the paging behavior of the guest is crucial to overall performance, and while Denali does its best to keep VMs' working sets in memory, a misbehaving guest can severly damage the performance of the system. The authors claim that this problem may be solvable with good memory management and garbage collection techniques, which could increase locality.

3.2 The Turtles Project: Design and Implementation of Nested Virtualization

The Turtles Project [3] aims to tackle the problem of nested virtualization; rather than being able to run multiple guest OSes on a single host machine, the authors want to take things a step farther and be able to run multiple guest hypervisors. This is actually a much harder problem than its single-level counterpart, because while most hardware now supports virtualization, chips are generally designed to only handle a single level. Furthermore, the strawman solution of using software to emulate the virtualization-enabled hardware for the next level is extremely expensive, because any kernel traps generated at the highest level (from memory paging or device I/O) generate traps in the levels below as well, resulting in cascading crossings of protection boundaries and a serious performance penalty.

Key contributions of this work include the design and implementation of a truly efficient nested VM for the x86 architecture, including novel techniques for *multidimensional paging* and *multi-level device assignment*. The Turtles hypervisor is able to run unmodified guest hypervisors and OSes with a performance penalty as low as 6-8%. The paper also presents what the authors claim is the first thorough analysis and evaluation of nested hypervisor performance, with an eye to the identification and reduction of performance bottlenecks.

Turtles is designed for the x86 architecture, which subscribes to a single-level hardware support model. This means that there are only two levels of execution privilege. Turtles runs its host hypervisor, which we will call L_0, at the most privileged level of execution. Now, suppose we have a hypervisor running above L_0 at level L_1, and further suppose that hypervisor is running a guest OS at level L_2. Everything running at L_1 and L_2 has to run at the same privilege level, and only L_0 is privileged enough to interact with the hardware. Essentially, levels L_1 through L_n only exist logically; in reality they are all multiplexed to be running directly on top of L_0 (see Figure 1). All traps generated at L_2 go immediately to L_0, which may handle them itself, or forward them back to L_1 for handling if hardware interaction is not required.

There are two difficult problems here that turtles provides a unique solution for. The first involves page tables for the MMU. In a nested model, virtual addresses for L_2 will need to be translated three times (first to physical addresses at L_2, then to L_1 addresses, and finally to L_0 addresses) before they are readable by the hardware. Modern MMUs provide support for virtualization in the form of two distinct translation tables to make this process fast, but this is not sufficient for more than one level of virtualization. Furthermore, providing these translation tables by emulating them in software is slow, particularly on updates, for reasons described previously. The paper's novel solution here is to use *multidimensional page tables*. Essentially, each level keeps its own shadowed page tables in software, but they are read-only. On a page fault in L_2, L_0 catches the trap and forwards it to L_1. If L_1 also faults, L_0 allows it to update its shadow table with the L_2-to-L_1 translation, but then applies its tranlation for L_1 addresses to update the hardware-level table with the correct L_2-to-L_0 translation before returning. In this way, the hardware table at L_0 contains all the shadow tables above it compressed into a single table, so that any MMU accesses can look up the correct translations directly from the hardware without having to go through cascading levels of shadow tables first. Turtles also employs "huge pages" and Virtual Processor ID tags on page table entries to ensure that page tables remain small and fast, and to prevent excessive

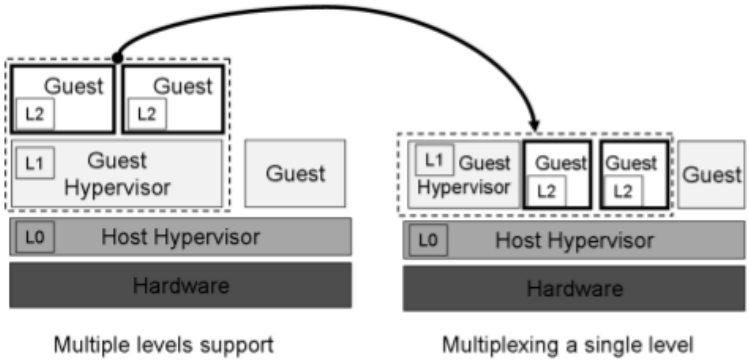


Figure 1: The Turtles hypervisor maintains logical nested virtualization, but in reality multiplexes all levels of nesting into L_1. (Figure courtesy of [3])

TLB flushing on context-switches.

The second difficulty deals with device I/0. Traditional approaches to this problem involve either software emulation (which is slow), installing modified drivers in the guest (which is not preferrable), or assigning devices to guests as they have need of them (which is hard in the nested case). Turtles uses something called *multi-level device assignment*, which is essentially an adaptation of the multidimensional page table idea to the device I/O problem. Modern chipsets include a component called an IOMMU, which resides between the DMA and main memory and performs translations just like the MMU does for the CPU. By shadowing read-only IOMMU translation tables at higher levels, and then compressing them into a single hardware-level table, the DMA can avoid the same cascading translation issue that would affect the MMU, thus making DMA I/O access very efficient. For Memory-Mapped I/O and Network Port I/O, address translation is not an issue, and so here techniques for single-level device assignment are used without any efficiency penalty, although this does raise questions of fairness.

The Turtles paper provides an extensive evaluation section, with thorough experimentation comparing performance of applications running on the native OS, a single-level VM, and the Turtles two-level nested VM. The authors measure and discuss performance on microbenchmarks, I/O intensive workloads, and workloads that are designed to fault to the kernel constantly. The paper also analyzes the success of multidimensional paging and multi-level device assignment by testing these techniques against more traditional ways of handling these problems. In general, the Turtles hypervisor far outperforms any other approach to nested virtualization considered, and is able to minimize the overhead of a second level of virtualization to as low as 6-8%, which is rather impressive. No experiments were conducted involving more than two nested levels of virtualization, although analysis seemed to indicate that most of the additional overhead incurred by adding a second level comes from cache pollution and the overuse of privileged instructions where it was not necessary.

3.3 mClock: Handling Throughput Variability for Hypervisor IO Scheduling

The mClock paper [4] is not targeted at nested virtualization, but further explores the issue of fair I/O device assignment raised in the Turtles paper. This turns out to be a very difficult problem even in the single-level case, particularly when applied to virtualization in the Cloud, where networked devices are often shared not just between VMs running on one host, but between many hosts across the network. In the interest of fairness, a good hypervisor will try to share device throughput equally across its guests, but in the networked case, the total amount of capacity to share may fluctuate due to traffic from other networked clients. Furthermore, many OSes run their own device access algorithms above the hypervisor level to improve performance; for example, physical disk accesses may be reordered by the kernel to take advantage of spatial locality when moving the disk head. These sorts of optimizations can make it difficult for the hypervisor to multiplex and schedule I/O requests efficiently.

The mClock algorithm seeks to fairly schedule the device I/O requests of multiple guests, while maintaining each guest's limit (maximum throughput cap), reservation (minimum requirement), and weight

(proportional share of capacity relative to other guests). The algorithm uses a "novel, lightweight" tagging scheme to achieve this despite fluctuation in total capacity. Previous attempts to solve this problem were not able to achieve both of these goals simultaneously.

```
Max_QueueDepth = 32;

RequestArrival (request r, time t, vm v_i)
begin
    if v_i was idle then
        /* Tag Adjustment */
        minPtag = minimum of all P tags;
        foreach active VM v_j do
            P_j^r -= minPtag - t;
    /* Tag Assignment */
    R_i^r = max{R_i^{r-1} + 1/r_i, t} /* Reservation tag */
    L_i^r = max{L_i^{r-1} + 1/l_i, t} /* Limit tag */
    P_i^r = max{P_i^{r-1} + 1/w_i, t} /* Shares tag */
    ScheduleRequest();
end

ScheduleRequest ()
begin
    if Active_IOs >= Max_QueueDepth then
        return;
    Let E be the set of requests with R tag <= t
    if E not empty then
        /* constraint-based scheduling */
        select IO request with minimum R tag from
        E
    else
        /* weight-based scheduling */
        Let E' be the set of requests with L tag <= t
        if E' not empty OR Active_IOs == 0 then
            select IO request with minimum P tag
            from E'
            /* Assuming request belong to VM v_k */
            Subtract 1/r_k from R tags of VM v_k
    if IO request selected != NULL then
        Active_IOs++;
end

RequestCompletion (request r, vm v_i)
  Active_IOs --;
  ScheduleRequest();
```

Figure 2: The mClock algorithm works by tagging requests with a tag for reservations, weights, and reservations, and then executing requests in order of their tags. (Figure courtest of [4])

The mClock algorithm (see Figure 2) works by assigning numerical tags to each queued request. Essentially, tags for VM i with proportional weight w_i will be spaced by $1/w_i$. Requests will be executed in the order of their assigned tags, which ensures that VM i receieves his proportional share. This approach requires a global clock for tag assignment, so that idle clients remain synced with active ones and do not amass "idle credit", thus gaining preferential treatment. The tag for VM i and request j is set as follows:

$$Tag(i,j) = max(curr\ time, Tag(i,j-1) + 1/w_i)$$

After the tagging, the request with the lowest tag will be scheduled.

In actuality, things are a little bit more complicated. mClock maintains 3 types of tags and 3 global clocks, one each for reservations, weights, and limits. Each iteration of the algorithm is deemed to be either a "constraint-based phase", in which some VM has not received capacity above its reservation, or a "weight-based phase", in which the next VM to be scheduled will be chosen by proportional share. This is easily determined after the tagging: if any VM i has request j such that the reservation tag $R(i,j)$ is less than the current time, then VM i is currently receiving less capacity than its reservation, and so the current phase is constraint based. Otherwise, the phase is weight-based, and so the algorithm just picks a request with minimum weight tag $P(i,j)$ whose limit tag $L(i,j)$ is also less than the current time (otherwise, VM i is receiving more capacity than its limit, and so it should not be scheduled).

The paper describes some further tweaks to the algorithm, such as allowing a limited amount of idle credit to be saved up by idle VMs, or breaking "large" requests into a series of smaller requests to account for request latency in the scheduler. There's also a modifed dmClock algorithm for use with a distributed storage system, which multiplexes VM requests fairly across multiple storage servers. Finally, there's a heuristic for setting reservations for all VMs by default, so that no VM will be starved.

The authors include a lengthy evaluation of the performance of their algorithm. They discuss many experiments involving different workloads and different combinations of weights, limits, and reservations, and even test multiple types of devices being assigned to analyze the effects of device latency and varying throughput. Overall, mClock is extremely effective at meeting its guarantees for weights, limits, and reservations when there is enough capacity to satisfy all requests, and the algorithm degrades gracefully by sharing capacity proportionally when the total capacity is insufficient.

The algorithm is successful at delivering on its guarantees despite contention, which is important for ensuring VM isolation, and also has implications in the Cloud, where the ability to meet quality-of-service guarantees has a high impact on financial success.

3.4 Virtualize Everything but Time

The "Virtualize Everything but Time" paper [5] notes that accurate timekeeping has become very important in today's computing systems, with applications to everything from systems measurement and distributed database consistency to high-speed trading and billing for Cloud services. However, timekeeping in a VM context is very difficult. Historically, timekeeping is accomplished using software clocks based on hardware oscillators, which are kept synchronized to an online reference clock. However, the synchronization algorithms used rely on computing delays between timestamped packets, and the delay computation turns out to be extremely unstable in a virtualized context, due mostly to added latency during packet processing.

This paper does not really introduce a novel idea, but rather applies an existing alternative solution for timekeeping to the virtualized context, and then performs some rigorous experimentation to show that this solution is better-suited.

In the hardware, there are a few oscillators that may be used as sources for timekeeping. Most systems today make use of the *Time Stamp Counter* (TSC), a high-resolution counter based on CPU cycles, and the *High Precision Event Timer* (HPET), which (ironically enough) has a lower resolution than the TSC, and is slower to access as well. The authors mention hardware counters only because the technique currently used for timekeeping in virtualized systems, Xen's Clocksource algorithm, relies on these two counters, using the HPET for low-resolution "ticks", but interpolating between them using the TSC. However, this TSC data must be carefully adjusted before use, because it is subject to drift based on a variety of other variables.

The focus of the paper is more on timekeeping synchronization algorithms. The most popular contender in this arena is the *Network Time Protocol* (NTP). NTP is a feedback algorithm, which works by collecting and timestamping a series of packets from a networked reference clock, computing clock error using the reference timestamp-local timestamp pairings as data points, and updating the system clock accordingly. Xen Clocksource makes use of NTP, although it must be adapted to fit the virtualized context. There are two possibilities for this:

- in Dependent Clocksource, *dom0* runs an NTP clock, and all guests running in *domU* sync periodically to this NTP clock and use Clocksource to interpolate between syncs.
- under the Independent Clocksource paradigm, each *domU* guest runs their own NTP clock and send their own reference packets.

The paper conducts evaluation of both paradigms, and argues that neither is well-suited to the virtualized context. Dependent Clocksource exhibits cyclical sawtoothed drift because the Clocksource algorithm in *domU* does not have direct access to the TSC, and so cannot adjust the NTP clock data intelligently. Independent Clocksource is extremely inefficient, but even worse, additional latencies incurred by contention for network I/O tend to push the Clocksource feedback algorithm into instability, so that large error can accumulate even across NTP synchronizations.

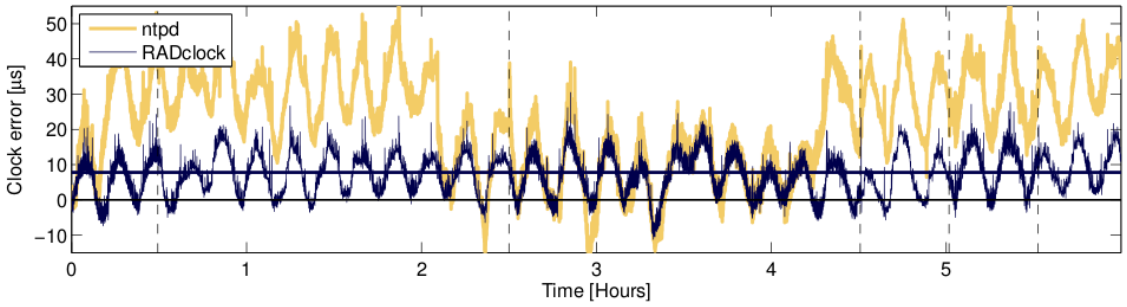
The authors instead endorse an alternative sync algorithm, *RADClock* (Robust Absolute and Difference Clock). RADClock is a stateless, feed-forward algorithm. Like NTP, RADClock timestamps reference packets, but does so using a "raw" clock based on hardware counters. The raw clock's error is estimated as before, but rather than using this data to update the clock (which would make RADClock a feedback algorithm), the error is instead stored in memory, along with some other clock parameters for the period of the counter and an offset for the timescale being used. When the clock is read, the time is adjusted as

$$C(t) = Raw(t) * (ctr\ period) + (offset) - error(t)$$

RADClock adjusts equally well to either the dependent or equally dependent paradigm, since no interpolation is needed to maintain the clock between syncs, as long as all dependent clocks can look up accurate and up-to-date parameters.

The paper proceeds to rigorously evaluate the performance of Xen Clocksource using NTP against RADClock, both in dependent and independent modes of operation, and in a variety of different system conditions. The conclusion seems to be that RADClock is generally unaffected by the errors and drift that plague clocksource (see Figure 3). This is especially clear in a series of experiments conducted involving VM migrations, where "migration shock" pushes the Independent Clocksource clock into a state of instability that takes nearly 20 minutes to correct, while dependent RADClock converges instantly. Furthermore, the RADClock algorithm works equally well regardless of the choice of underlying hardware counter, and is much less affected by high contention for the network and system resources, making it a better solution for the problem of timekeeping in the context of virtualization.

Figure 3: The RADClock algorithm consistently outperforms ntpd clocksource; here, the drift in clocksource is simply due to feedback from increased latency in the network. (Figure courtesy of [5])



4 Paper Relationships

As we surveyed this series of papers, we noticed that the literature in this area seems to neatly classify itself by *motivation*. Many papers on virtualization come from the realm of academia, and these are mostly characterized by a focus on clean abstractions and solutions with good theoretical properties, such as fairness and strong isolation. Many more papers, however, originate from corporate research at places like Microsoft and HP Labs. These papers seem much more interested in providing fast, scalable solutions using commodity hardware and software. In our papers, we found a series of tensions which seemed to be expressing this fundamental question of motivation. We will now turn our attention to these tensions, keeping in mind that the Turtles and mClock papers share corporate authorship, while the Denali, Xen, and "Virtualize Everything but Time" papers originate in the realm of academia.

4.1 Performance and Fairness

The most obvious tension which surfaced in the literature was a question of priority between performance and fairness. Generally speaking, there is a trend in corporate papers to be heavily concerned with speed and efficiency, while academically-minded papers seem more focused on strong properties of isolation and guarantees of fairness between VMs. This should not be particularly surprising, given the authorship; more efficient virtualization seems a logical step toward maximizing profit, which has a certain appeal in the corporate sphere. It is worth noting, however, that in the more recent literature corporate papers seem to be taking note of the importance of fairness; we will discuss this further in Section 4.4.

Our papers are clearly divided by this metric: Turtles is all about efficiency and performance, often at the cost of fairness. The problem seems especially hard here when phrased in the nested context. It seems perfectly logical that a guest OS running in L_2 should only receive a fraction α of the resources allocated to its host in L_1, which in turn should only receive a percentage β of the machine's total resources, then these two fractions should compound and our guest should end up with $\alpha\beta$ of the total capacity available. However, in reality Turtles multiplexes all guests at all levels onto L_0, so in many ways the guest OS and its hypervisor will be treated equally, rather than as parent and child. Multi-level device assignment for Port I/O and Memory-mapped I/O is particularly agnostic to fairness concerns, because it works exactly the same way as single-level device assignment, and so doesn't care whether a guest runs at L_1 or L_{100} - all guests get equal treatment. Furthermore, no experimentation at all is done to analyze the effects of this model on fairness; the authors even make the statement that this is a secondary concern, and so they are content with a sort of best-effort.

On the other hand, Denali and mClock are all about prioritizing fairness. The foundational goal of the Denali isolation kernel is to ensure strong isolation between clients, so that the behavior of any particular VM cannot in any way affect another. And the whole point of the mClock scheduling algorithm is to ensure that limits, reservations, and weights are met fairly between VMs contending for a resource. It should be noted that neither of these papers particularly eschew performance as a worthy goal; rather, the view here seems more to be that fast performance for a particular VM doesn't really matter much if a malicious (or even just selfish) neighbor can somehow choke that VM out and make it impossible to make progress.

The Time paper is somewhat agnostic to concerns of performance and fairness anyway, since it deals

more with the abstractions presented to client applications. We will turn to this next.

4.2 Para-virtualization and Full Virtualization

The second tension seems to arise between the paradigms of *para-virtualization* and *full virtualization*, which were introduced in Section 2. Corporately-funded literature seems to have an eye more toward using as much commodity software as possible here, for the sake of lower adoption costs, while academic papers seem more willing to consider modifying client software in appropriate situations.

The split here is pretty clear as well: Denali, Xen, and Time all consider para-virtualization to be beneficial and even necessary in the right situations. In Denali, the isolation kernel presents a modified and simplified hardware abstraction to its clients, which cleverly allows for some big wins in efficiency and performance as a side effect. Xen claims that para-virtualization is necessary to ensure fairness and prevent starvation in process and I/O scheduling; one could argue, however, that this is no longer a concern due to the advent of newer virtualization-aware hardware (see Section 4.3). The Time paper goes a step further and claims that even with the new hardware, making the guest OS aware of the virtualized context it runs in is necessary to ensure the correctness of certain time-dependent applications, such as systems measurement, high-speed trading, and even video gaming.

In contrast, the Turtles project argues for full virtualization and unmodified guest OSes and hypervisors. In the paper, the argument for this goes back to the motivating goal of performance, though it was unclear to us why para-virtualization would have any negative impact here. But it seems also that for any sort of large-scale commercial deployment of server virtualization technology, the ability to use commodity guests would be crucial in order to make adoption easy, and we consider this to also be a likely factor influencing the design choice.

The mClock paper doesn't really fit into these two classifications, since it mostly deals with the interactions between the hypervisor and its devices, rather than the hypervisor and its guests. However, the paper does mention that one of the reasons this disk scheduling problem is so difficult is because guest OSes have their own algorithms for efficient disk scheduling, which generally don't play nice with each other. If it were possible to modify the guest OS to disable these algorithms, so that the hypervisor could handle all disk scheduling decision, the difficulty of this problem could likely be reduced. This seems to be an argument in favor of para-virtualization.

4.3 Hardware Support and Software Emulation

The "tension" between hardware support for virtualization and the use of software emulation is perhaps better described as a paradigm shift. It seems that over the last decade virtualization-friendly hardware has become commonplace and inexpensive. When the Xen and Denali papers were written, there was no real alternative, and so everything had to be done through slow, inefficient software emulation. But when hardware manufacturers began to produce virtualization-enabled chipsets like the x86, this problem essentially disappeared overnight, and it has largely remained out-of-scope for most of the intervening decade.

However, the question of software emulation may need to be re-examined as virtualization research moves foward. While hardware-enabled approaches are clearly much faster than any attempt to do all the work in software, it seems that it just may not be possible to do everything at the hardware level. The Turtles project is a perfect example of this - there is no hardware support for nested levels of virtualization, and so a lot of cleverness is required to be able to compensate in the software without an unacceptable performance penalty. In some ways, this problem has essentially sent us back to where single-level virtualization solutions were a decade ago. Some of the future work mentioned in the Turtles paper involved examining ways to provide architectural support for nested virtualization, but we are somewhat skeptical that this will prove fruitful. Attempting to provide support for an unbounded number of levels of nesting with finite hardware does not seem like it would be particularly successful. It will be interesting to see what direction this sort of work takes in the future, and whether hardware designers will rise to the challenges of nested virtualization.

4.4 Scalability and the Cloud

The final tension we wish to consider is the question of scalability and designing for the Cloud. We have observed that there is a commercial interest in developing super-scalable server virtualization, largely because it has found such a unique niche with the market growth of Cloud computing and Infrastructure-as-a-service (IaaS). While academic research is not uninterested in the question of scale or the Cloud use case, we do not feel that they are as much of a driving factor in this realm.

We see this trend in the papers we have been discussing as well. The Turtles paper presents the motivation for nested virtualization using the argument of its suitability for Infrastructure-as-a-service, as the two are essentially made for each other. The mClock paper, although it does not particularly market itself for scalability, is motivated by the Cloud-enabled scenario of many virtualized clients needing to schedule the use of a shared network disk. Furthermore, the guarantees mClock makes about fairness, reservations, and proportional share are especially important in this scenario, as they allow IaaS providers to keep service-level agreements with their clients. We find this particularly interesting, as it seems to indicate that in the Cloud, fairness and performance may find themselves on equal footing in terms of importance, despite what we have observed in Section 4.1.

Interestingly, the Denali paper also has a particular eye to scalability, and a large portion of the evaluation section is devoted to demonstrating that the isolation kernel performs well even when supporting over 10,000 VMs. However, even in Denali, scalability is just one goal amongst many, and the paper does not really consider applications to Cloud computing, being written several years before the Cloud really became prominent.

The Time paper does not really consider the question of scalability at all, being somwhat orthogonal to the problem of accurate timekeeping on a single VM. The paper does point out that there are scalability benefits to the dependent RADClock algorithm, as each VM no longer needs to send out synchronization packets on the network, but can depend on the hypervisor to do this once for all VMs that it hosts. However, this is in many ways just an added bonus, and is not really a motivational argument for the paper.

5 Conclusion

Having examined the recent literature along these four axes of tension, it is our belief that a clear trend has emerged in virtualization research. We believe that as Cloud computing and IaaS continue to take off, research in this area will continue to trend toward what is both popular and financially successful. We expect that the majority of virtualization research will continue in the direction of full virtualization over para-virtualization, and that the Cloud-computing/IaaS scenario will become the driving use case. However, we think that as a result, fairness and performance will no longer be competing ends, but will in fact become equal goals in virtualized system design. This will be necessary in order for Cloud providers to meet their SLAs to their consumers, and we believe fair-scheduling and resource-isolation research will move from the shadows to the forefront of both corporate and academic research.

As to the question of hardware support versus software emulation, we believe that as new directions like nested virtualization are explored, some sort of hybrid approach will continue to be needed. However, we do not expect the status quo of fast hardware-enabled virtualization to be shaken up in the general case; it seems that performance is too critical in the driving Cloud-based use cases, and we would be surprised to see nested virtualization (or any other software-hybrid approach) gaining much momentum here anytime soon.

Cynical though it may be, we feel that a lot of the interesting problems in virtualization have already been solved, at least from an academic perspective. So much of the recent literature seems to be in the direction of just making things more efficient and more reliable for the sake of the commercialized Cloud. We have stopped asking the question, "can we do crazy thing x?", and now are only asking "how much faster can we make x work?" and "how can we make x work with fewer resources?" This is certainly an important part of the research process for any area, but it is ostensibly less exciting than the ground-breaking work that was going on earlier in the decade.

Of course, we cannot say with any certainty that there is not some new, groundbreaking discovery just waiting to be made and lurking around the corner. Such a discovery could revitalize the field and take virtualization off into all sorts of new and exciting directions. But we do feel that the way the problem has been framed makes it unlikely that such a new discovery could shift the focus away from Cloud-based server virtualization. With so much focus on making the problem fit into the market niche, such a new discovery would have to be truly monumental indeed - monumental enough that no one could possibly predict it.

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