Architecting Dependable Systems Using Virtualization

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Abstract

We propose new methods of leveraging virtualization for addressing system dependability issues. Using combinatorial modeling, we analyze multiple design choices when a single physical server is used to host multiple virtual servers. Our results show that unless certain conditions (e.g., regarding the reliability of the hypervisor and the number of VMs) are met, virtualization could decrease the reliability of a single physical node. In light of the prevailing ad-hoc approach to virtualization and the general inclination to move services out of the operating system into the virtualization layer, our results point out the need for a more cautious and rigorous approach.

1 Introduction

Virtualization allows abstracting away the real hardware configuration of a system. One method of virtualizing the hardware resources of a computer involves using a layer of software, called the Virtual Machine Monitor (VMM), to provide the illusion of real hardware for multiple virtual machines (VMs). Inside each VM, the operating system (often called the *guest* OS) and applications run on the VM's own virtual resources such as virtual CPU, virtual network card, virtual RAM, and virtual disks. A VMM can be hosted directly on the computer hardware (e.g., Xen [4]) or within a host operating system (e.g., VMware).

Introduced in the 1960s, virtualization has lately enjoyed a great surge of interest. The improved efficiency, flexibility, and cost savings that virtualization of storage, networking, and computing resources enables in data centers have been the key drivers of this interest.

We address the issue of using virtualization as a building block for enhancing dependability not just in data centers, but also in more general settings. With few exceptions, current solutions in this space have been largely ad-hoc. There seems to be an increasingly prevalent tendency to think of virtualization as a cure-all. Suggestions to shift almost anything that runs on a real machine to a virtual machine and to move services (such as networking and security) currently provided by the operating system to the virtual machine monitor are becoming commonplace (e.g., [9]).

We make the following contributions. First, we present new ways of using virtualization for addressing system dependability issues. Second, we use combinatorial modeling to analyze multiple design choices when a single physical server is used to host multiple virtual servers and to quantify the reliability impact of virtualization. In light of the prevailing general inclination to shift services out of the guest OS into the virtualization layer, we show that this shift, if not done carefully, could adversely affect system reliability.

2 Related Work

Bressoud and Schneider [5] implemented a primary-backup replication protocol tolerant to benign faults at the VMM level. The protocol resolves non-determinism by logging the results of all non-deterministic actions taken by the primary and then applying the same results at the backups to maintain state consistency.

Double-Take [2] uses hardware-based real-time synchronous replication to replicate application data from multiple VMs to a single physical machine so that the application can automatically fail over to a spare machine, by importing the replicated data, in case of outage. Since the replication is done at the file system level below the VM, the technique is guest-OS-agnostic.

Douceur and Howell [7] describe how VMMs can be used to ensure that VMs satisfy determinism and thereby enable state machine replication at the VM level instead of the application level. Specifically, they describe how a VM's virtual disk and clock can be made deterministic with respect to the VM's execution. The design relieves the burden off the application programmer to structure the application as a deterministic state machine.

Dunlap et al. describe ReVirt [8] for VM logging and replay. ReVirt encapsulates the OS as a VM, logs non-deterministic events that affect the VM's execution, and uses the logged data to replay the VM's execution later.

Joshi et al. [11] combine VM introspection with VM replay to analyze whether an OS vulnerability or application vulnerability was activated in a VM before a patch was applied. The analysis is done based on vulnerability-specific predicates, which are provided by the patch writer. After the patch has been applied, the same predicates can be used during the VM's normal execution to detect and respond to attacks.

Backtracker [12] can be used to identify which application running inside a VM was exploited on a given host. An extension of Backtracker [13] has been used to track attacks from a single host at which infection has been detected to the originator of the attack and to other hosts that were compromised from that host.

3 Virtualization: New Opportunities for Dependability

Commodity operating systems provide a level of dependability that is much lower than what is desired. This trend hasn't seen much change in the last decade or so. Hence, the focus has shifted to designing dependable systems around the OS problems.

Virtualization enables such a design in at least two ways. One way is to encapsulate the OS and applications in a VM and introduce dependability enhancements at the VMM-level, which are transparent to the guest OS and applications. Such a design allows the VM to be treated as a black box. For example, checkpointing and recovery can be done at the granularity of VMs instead of processes. Another way is to instrument applications, middleware, and/or the guest OS with explicit knowledge of their running on a virtual as opposed to physical machine. For example, in programming languages supporting VMs (such as Java and OCAML), checkpointing the application state at the VM-level or byte-code-level (as opposed to native code) can allow restarting the saved state on a hardware platform different from the one in which checkpointing was done [3].

Virtual machines offer a degree of flexibility that is not possible to obtain on physical machines. That is mainly because VM state, much like files, can be read, copied, modified, saved, migrated, and restored. In this section, we propose various new methods based on virtualization for improving dependability.

Coping with Load-Induced Failures: Deploying services on VMs instead of physical machines enables higher and more flexible resilience to load-induced failures without requiring additional hardware. Under load conditions, the VMs can be seamlessly migrated (using live migration technology [6]) to a lightly loaded or a more powerful physical machine. VM creation is simple and cheap, much like copying a file. In response to high load conditions, it is much easier to dynamically provision additional VMs on under-utilized physical machines than to provision additional physical machines.

Patch Application for High Availability Services: Typically, patch application involves system restart, and thus negatively affects service availability. Consider a service running inside a VM. Virtualization provides a way to remove faults and vulnerabilities at run-time without affecting system availability. For this purpose, a copy of the VM is instantiated, and the patch (be it OS-level or service-level) is applied on the copy rather than on the original VM. Then, the copy is restarted for the patch to take effect after which the original VM is gracefully shut down and future service requests are directed to the copy VM. The patch is applied at the copy VM and the copy VM is restarted while the original VM still continues regular operation, thereby maintaining service availability. To ensure that there are no undesirable side effects due to the patch application, the copy VM may be placed in *quarantine* for a sufficiently long time while observing its post-patch behavior before shutting down the original VM. If the service running inside the VM is stateful, then additional techniques based on a combination of VM checkpointing and VM live migration [6] may be used to retain network connections of the original VM and to bring the copy up-to-date with the last correct checkpoint.

Enforcing Fail-Safe Behavior: The average time between when a vulnerability is made public and when a patch is available is still measured in months. In 2005, Microsoft took an average time of 134.5 days for issuing critical patches for Windows security problems reported to the company [1]. Developing patches for a software component is a time-consuming process because of the need to ensure that the patch does not introduce new flaws or affect the dependencies between that component and other components in the system. In many cases, a service administrator simply does not have the luxury of suspending a service immediately after a critical flaw (in the OS running the service or the service itself) becomes publicized until the patch becomes available.

Virtualization can be used to prolong the availability of the service as much as possible while at the same time ensuring that the service is fail-safe. We leverage the observation that publicizing a flaw is usually accompanied by details of possible attacks exploiting the flaw and/or symptoms of an exploited flaw. Developing an external monitor for identifying attack signatures or symptoms of an exploited flaw may be done independently of the patch development. The monitor may also be developed much faster than the patch itself, because the monitor may not be subject to the same stringent testing and validation requirements.

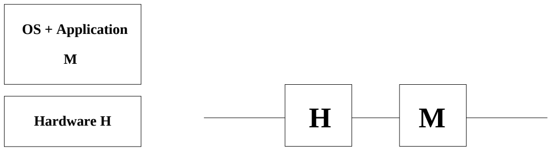
Consider a service run inside a VM instead of directly on a physical machine. Then, a VM-external monitor, running parallel to the VM, can be used detect the symptoms of the exploited flaw and to signal the VMM to crash the VM. Alternatively, if the attack signature is known, the monitor can be used to identify an ongoing attack and terminate interaction with the attack source. The monitor could be implemented at the VMM level or in a privileged VM (such as Dom0 in Xen [4]). If it is important to revert the service to its last correct state when a patch does become available, then the above technique can be augmented with a checkpointing mechanism, which periodically checkpoints the state of the service with respect to the VM (e.g., [3]).

Proactive Software Rejuvenation: Rebooting a machine is an easy way of rejuvenating software. The downside of machine reboot is that the service is unavailable during the reboot process. The VMM is a convenient layer for introducing hooks to proactively rejuvenate the guest OS and services running inside a VM in a performance- and availability-preserving way. Periodically, the VMM can be made to instantiate a *reincarnation VM* from a clean VM image. The booting of the reincarnation VM is done while the original VM still continues regular operation, thereby maintaining service availability. As mentioned above in the context of patch application, techniques based on VM checkpointing and live migration may be used to seamlessly transfer network connections and service state of the original VM to the reincarnation VM. It is possible to adjust the performance impact of the rejuvenation procedure on the original VMs performance. To lower the impact, the VMM can restrict the amount of resources devoted to the booting of reincarnation VM and compensate for the restriction in resources by allowing more time for the rebooting to complete.

One can view the above type of rejuvenation as a *memory scrubbing* technique, for reclaiming leaked memory and recovering from memory errors of the original VM. Perhaps, more importantly, such periodic rejuvenation offers a way to proactively recover from errors without requiring failure detection mechanisms (which are often unreliable) to trigger the recovery.

Replica Diversity: In fault-tolerant replication, diversity of replicas is important to ensure that all replicas do not fail because of the same disruptive event. By deploying replicas on a combination of virtual and physical machines rather than on physical machines alone, replica diversity can be enhanced. Also, deploying replicas on virtual machines instead of physical machines opens another layer in which diversity can be introduced: the VMM software. VMM diversity and OS diversity can complement each other to enhance replica diversity without additional hardware costs. On the flip side, using the same VMM for all replica VMs will actually lower replica diversity even if the replicas were deployed on different operating systems. That is because, a fault in the VMM could lead to failure of all replicas.

Containment: Fault containment is an important aspect of dependability. Containment among VMs running on the same VMM is much stronger than containment among processes running on the same OS. To better isolate the fault effects of two services running on the same OS and physical server, one can carve the physical server into two VMs each running one service. On the other hand, fault containment between two VMs is not as strong as the fault containment between two physical machines (e.g., due to covert channels). Hence, when cost is not a restriction (e.g., in highly-critical space and military applications), running software components on distinct hardware would be better for fault containment than running the components in different VMs on the same hardware.



(a) Architecture (b) Combinatorial Model

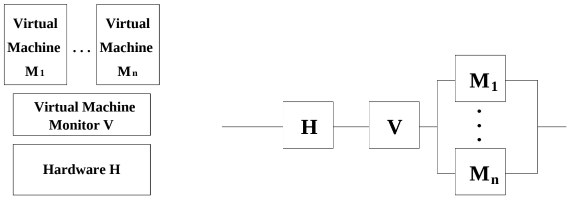
Figure 1. Non-Virtualized Node

4 Quantifying the Impact of Virtualization on Node Reliability

In this section, we use combinatorial modeling to perform reliability analysis of redundant fault-tolerant designs involving virtualization on a single physical node and compare them with the non-virtualized case. We consider a model in which multiple VMs run concurrently on the same node and offer identical service. We derive lower bounds on the VMM reliability and the number of VMs required for the virtualized node to have better reliability than the non-virtualized case. We also analyze the reliability impact of moving a functionality common to all VMs out of the VMs and into the VMM. Additionally, we analyze the reliability of a redundant execution scheme that can tolerate the corruption of one out of three VMs running on the same physical host, and compare it with the non-virtualized case. Our results point to the need for careful modeling and analysis before a design based on virtualization is used.

Combinatorial modeling and Markov modeling are the two main methods used for reliability assessment of fault-tolerant designs [10]. We chose combinatorial modeling because its simplicity enables easy elimination of "hopeless" choices in the early stage of the design process. In combinatorial modeling, a system consists of series and parallel combinations of modules. The assumption is that module failures are independent. In a real-world setting where module failures may not be independent, the reliability values obtained using combinatorial modeling yield upper bounds.

Non-Virtualized (NV) Node: For our reliability assessment, we consider a non-virtualized single physical node as the base case. We model the node using two modules: hardware (H) and the software machine (M) consisting of the operating system, middleware, and applications (Figure 1(a)) . Thus, the node is a simple serial system consisting of H and M whose reliability is given by $R_{sys}^{NV} = R_H R_M$, where R_X denotes the reliability of module X (Figure 1(b)).



(a) Architecture (b) Combinatorial Model

Figure 2. Node with n VMs

Virtualized Node with n Independent, Identical VMs: Figure 2(a) shows a physical node consisting of H, a type-1 VMM (V) that runs directly on the hardware (such a VMM is referred to as a *hypervisor*), and one or more virtual machines ($\{M_i\}, i \geq 1$). Each VM has the same functionality as the software machine M shown in the non-virtualized case. The VMs provide identical service concurrently and independently (i.e., without the need for strong synchronization). For example, each VM could be a virtual server answering client requests for static web content. Thus, the node is a series-parallel system (Figure 2(b)) whose overall reliability is given by $R^n_{sys} = R_H R_V[1 - \prod_{i=0}^{n}(1 - R_{M_i})]$. Then, $R^n_{sys} > R^{NV}_{sys}$ gives the condition for n-replicated service to be more reliable than the non-virtualized service. i.e., $R_H R_V[1 - \prod_{i=0}^{n}(1 - R_{M_i})] > R_H R_M$
For simplicity, let $R_{M_i} = R_M$ for all $1 \leq i \leq n$. Then, the above condition becomes

$$R_V[1 - (1 - R_M)^n] > R_M \qquad (1)$$

Inequality (1) immediately yields two conclusions. First, if $n = 1$, then again the above condition does not hold (since $R_V < 1$). What this means is that it is necessary to have some additional coordination mechanism or protocol built into the system to compensate for the reliability lost by the introduction of the hypervisor. In the absence of such a mechanism/protocol, simply adding a hypervisor layer to a node will only decrease the node reliability. Second, if $R_V = R_M$, then it is obvious that above condition does not hold.

It is clear that the *hypervisor has to be more reliable than the individual VM*. The interesting question is, how much more reliable. Figure 3 shows that for a fixed R_M value, the hypervisor has to be more reliable when deploying fewer VMs. The graph also shows that, for fixed values of R_M and R_V, there exits a lower bound on the n value below which the virtualized node reliability will definitely be lower than that of a non-virtualized node. For example, when R_M = 0.1 and R_V = 0.3, deploying fewer than 4 VMs would only lower the node reliability. This is a useful result, since in many practical settings, R_M and R_V values may be fixed, e.g., when the hypervisor, guest OS, and application are commercial-off-the-shelf (COTS) components with no source code access.

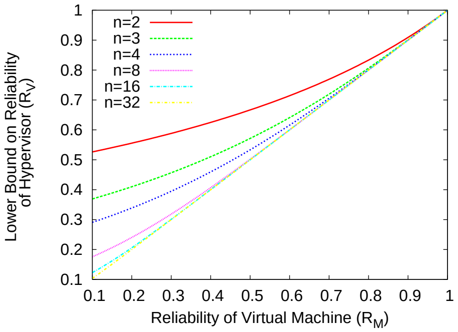


Figure 3. Lower Bound on the Hypervisor Reliability for a Physical Node with n Independent and Concurrently Operating VMs Providing Identical Service.

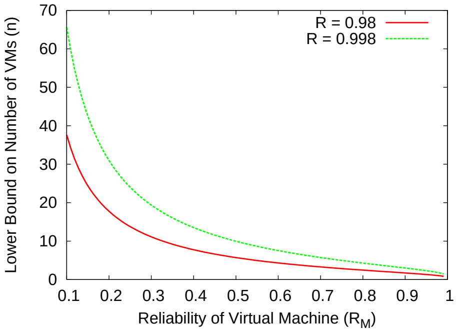


Figure 4. Lower Bound on the Number of VMs to Achieve Desired Reliability R for a Physical Node with n Independent and Concurrently Operating VMs Providing Identical Service when $R_V = 0.999$.

The equation for R^n_{sys} also suggests that by increasing the number of VMs, the node reliability can be made as close to the hypervisor reliability as desired. Suppose we desire the node reliability to be R, where $R < R_V$. Then, $R = R_H R_V[1 - (1 - R_M)^n]$. Assume that the hardware is highly reliable, i.e., $R_H \simeq 1$. Then, the above equation becomes the inequality,

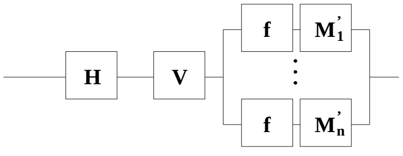
$$R < R_V[1 - (1 - R_M)^n]$$
$$\Longrightarrow (1 - R_M)^n < 1 - \frac{R}{R_V}$$
$$\Longrightarrow n.log(1 - R_M) < log(1 - \frac{R}{R_V})$$

Dividing by $log(1 - R_M)$, a negative number, we get,

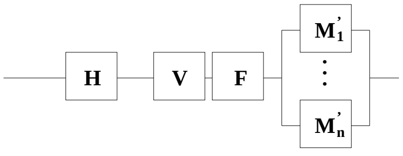
$$n > \frac{log(1 - \frac{R}{R_V})}{log(1 - R_M)} \qquad (2)$$

Inequality (2) gives a lower bound on the number of VMs required for a virtualized physical node to meet a given reliability requirement. In practice, the number of VMs that can be hosted on a physical node is ultimately limited by the resources available on that node. Comparing the lower bound with the number of VMs that can be possibly co-hosted provides an easy way to eliminate certain choices early on in the design process.

Figure 4 shows the lower bound for n for two different R values (0.98 and 0.998) as the VM reliability (R_M) is increased from roughly 0.1 to 1.0 with the hy-



(a) Configuration C_1: Functionality f implemented within each VM



(b) Configuration C_2: Functionality F implemented as part of Hypervisor

Figure 5. Moving Functionality out of the VMs into the Hypervisor

pervisor reliability fixed at 0.999. The figure shows that for fixed R_V and R_M values, higher system reliability (up to R_V) can be obtained by increasing the number of VMs hosted. However, when n is large, one is faced with the practical difficulty of obtaining sufficient diversity to ensure that VM failures are independent.

Moving Functionality out of the VMs into the Hypervisor: We now analyze the reliability impact of moving a functionality out of the VMs into the hypervisor. As before, our system model is one in which a physical node has $n \ge 1$ independent and concurrently operating VMs providing identical service. Consider a functionality f implemented inside each VM. Then, each VM M_i can be divided into two components, f and $M_i^{'}$, the latter representing the rest of M_i. Figure 5(a) shows the reliability model for a node containing n such VMs. Let us call this node configuration C_1. Further, suppose that the functionality f is moved out of the VMs and substituted by component F implemented as part of the hypervisor. Now, the new hypervisor consists of two components F and the old hypervisor V. Figure 5(b) shows the reliability model for a node with the modified hypervisor. Let us call this node configuration C_2.

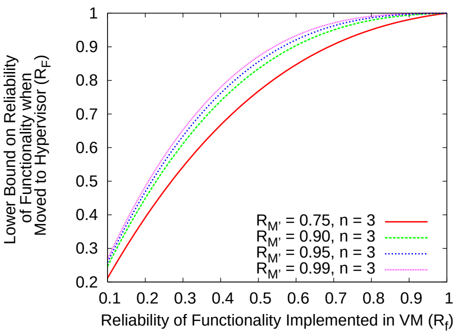
We now derive the condition for C_2 to be at least as reliable as C_1. For simplicity, let us assume that $R_{M_i'} = R_{M'}$ for all $1 \le i \le n$. Then, the desired condition is

$$R_{sys}^{C_2} \ge R_{sys}^{C_1}$$

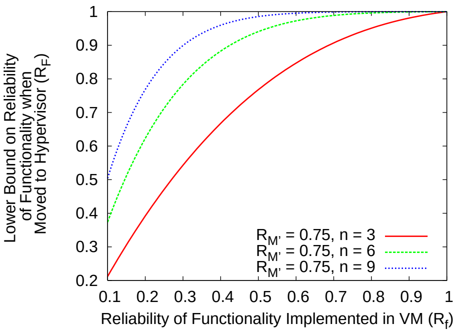
$$\implies R_H R_V R_F[1-(1-R_{M'})^n] \ge R_H R_V[1-(1-R_f R_{M'})^n]$$

$$R_F \ge \frac{[1-(1-R_f R_{M'})^n]}{[1-(1-R_{M'})^n]} \qquad (3)$$

It is easy to see from Figure 5 that when there is only a single VM, it does not matter whether the functionality is implemented in the hypervisor or in the VM. We can also confirm this observation by substituting $n = 1$ in Inequality (3).



(a) Fixed n, Varying $R_{M'}$



(b) Fixed $R_{M'}$, Varying n

Figure 6. Plot of $R_F \ge \dfrac{[1-(1-R_f R_{M'})^n]}{[1-(1-R_{M'})^n]}$

Figures 6(a) and (b) illustrate how R_F varies as R_f is increased from 0.1 to 1. The graphs show that F has to be more reliable than f for the configuration C_2 to be more reliable than C_1. Figure 6(a) shows that as $R_{M'}$ increases, the degree by which F should be more reliable than f also increases. Figure 6(b) shows that the degree is also considerably higher when more VMs are co-hosted on the same physical host. For example, even with modest $R_{M'}$ and R_f values of 0.75, F has to be ultra-reliable: R_F has to be more than .9932 and .9994 when $n = 6$ and $n = 9$ respectively. Thus, when more than a handful of VMs are co-hosted on the same physical node, better system reliability is likely to be obtained by retaining a poorly reliable functionality in the VM than by moving the functionality into the hypervisor.

Virtualized Node with VMM-level Voting: Consider a fault-tolerant 2-out-of-3 replication scheme in which three VMs providing identical service are co-hosted on a single physical node. The VMM layer receives client requests and forward them to all three VMs in the same order. Assume that the service is a deterministic state machine; thus, the VM replicas yield the same result for the same request. The VMM receives the results from the VM replicas. Once the VMM has obtained replies from two replicas with identical result values for a given client request, it forwards the result value to the corresponding client. Such a scheme can

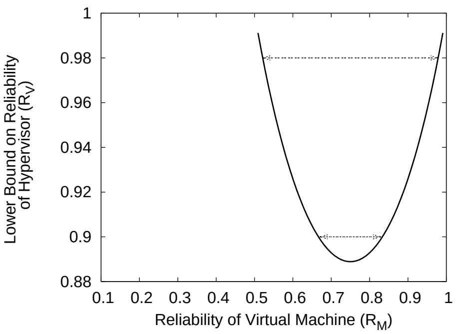


Figure 7. Plot of $(3R_M - 2R_M^2)^{-1} < R_V < 1$

tolerate the arbitrary failure of one VM replica, and is similar to the one suggested in the RESH architecture for fault-tolerant replication using virtualization [14]. Then, assuming that the VMs fail independently, the system reliability is given by

$$R_{sys}^{2-\mathrm{of}-3} = R_H R_V [R_M^3 + \binom{3}{2} R_M^2 (1 - R_M)]$$

Then, $R_{sys}^{2-\mathrm{of}-3} > R_{sys}^{NV}$ gives the condition for the 2-out-of-3 replication scheme to be more reliable than the non-virtualized service. Thus, we obtain

$$R_H R_V [R_M^3 + \binom{3}{2} R_M^2 (1 - R_M)] > R_H R_M$$

$$R_V > \frac{1}{3R_M - 2R_M^2} \qquad (4)$$

Inequality (4) gives a lower bound on the hypervisor reliability for the 2-out-of-3 replication scheme to have better reliability than the non-virtualized case. Figure 7 shows a plot of $\frac{1}{3R_M - 2R_M^2} < R_V < 1$. It is clear from the graph that there exists no R_V value that satisfies Inequality (4) and is less than 1, when $R_M \leq 0.5$. In other words, if the VM reliability (i.e., the OS and service reliability) is poor to begin with, then the 2-out-of-3 replication scheme will only make the node reliability worse even if the hypervisor is ultra-reliable. The graph also shows that the higher the hypervisor reliability, the larger the range of VM reliability values for which the 2-out-of-3 replication scheme has better reliability than the non-virtualized case. For example, when $R_V = 0.98$, the range of VM reliability values that can be accommodated is greater than the range when $R_V = 0.9$.

5 Conclusion

We described new ways of leveraging virtualization for improving system dependability. Using combinatorial modeling, we provided more detailed analysis than was previously available on how virtualization can affect system dependability. Our results show that unless certain conditions (e.g., regarding the reliability of the hypervisor and the number of VMs) are met, introducing virtualization could decrease the reliability of a physical node. In light of the general inclination to move services out of the guest OS into the virtualization layer, our results point out the need for a more cautious approach. Notwithstanding the simplicity of the modeling technique and its associated strong assumptions (regarding independent module failures), our exercise points to the need for more thorough and rigorous modeling and assessment in the context of virtualization.

References

[1] A Time to Patch. `http://blog.washingtonpost.com/securityfix/2006/01/a_time_to_patch.html`.

[2] VMWare Double-Take. `http://www.vmware.com/pdf/vmware_doubletake.pdf`.

[3] A. Agbaria and R. Friedman. Virtual Machine Based Heterogeneous Checkpointing. *Software: Practice and Experience*, 32(1):1–19, 2002.

[4] P. T. Barham, B. Dragovic, K. Fraser, S. Hand, T. L. Harris, A. Ho, R. Neugebauer, I. Pratt, and A. Warfield. Xen and the Art of Virtualization. In *Proc. 19th ACM Symposium on Operating Systems Principles (SOSP-2003)*, pages 164–177, October 2003.

[5] T. C. Bressoud and F. B. Schneider. Hypervisor-Based Fault Tolerance. *ACM Trans. Comput. Syst.*, 14(1), 1996.

[6] C. Clark, K. Fraser, S. Hand, J. G. Hansen, E. Jul, C. Limpach, I. Pratt, and A. Warfield. Live Migration of Virtual Machines. In *Proc. 2nd Symposium on Networked Systems Design and Implementation (NSDI-2005)*, May 2005.

[7] J. R. Douceur and J. Howell. Replicated Virtual Machines. Technical Report MSR TR-2005-119, Microsoft Research, Sep 2005.

[8] G. W. Dunlap, S. T. King, S. Cinar, M. A. Basrai, and P. M. Chen. ReVirt: Enabling Intrusion Analysis through Virtual-Machine Logging and Replay. *SIGOPS Operating System Review*, 36(SI):211–224, 2002.

[9] T. Garfinkel and M. Rosenblum. When Virtual is Harder than Real: Security Challenges in Virtual Machine Based Computing Environments. In *Proc. 10th Workshop on Hot Topics in Operating Systems (HotOS-X)*, May 2005.

[10] B. W. Johnson. *Design and Analysis of Fault-Tolerant Digital Systems*. Addison-Wesley, 1989.

[11] A. Joshi, S. T. King, G. W. Dunlap, and P. M. Chen. Detecting Past and Present Intrusions through Vulnerability-Specific Predicates. In *Proc. 20th ACM Symposium on Operating Systems Principles (SOSP-2005)*, pages 91–104, 2005.

[12] S. T. King and P. M. Chen. Backtracking Intrusions. In *Proc. 19th ACM Symposium on Operating Systems Principles (SOSP-2003)*, pages 223–236, 2003.

[13] S. T. King, Z. M. Mao, D. G. Lucchetti, and P. M. Chen. Enriching Intrusion Alerts Through Multi-Host Causality. In *Proc. Network and Distributed System Security Symposium (NDSS-2005)*, 2005.

[14] H. P. Reiser, F. J. Hauck, R. Kapitza, and W. Schröder-Preikschat. Hypervisor-Based Redundant Execution on a Single Physical Host. In *Proc. 6th European Dependable Computing Conference (EDCC-2006)*, page S.2, 2006.