Virtual Computing Laboratories Using VMware Lab Manager

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Abstract

Virtual computing laboratories provide remote user access to standardized computing resources and enable many types of complex experiential and project-based learning applicable in the simulation of information warfare exercises, incident response training and digital forensics analysis. As more universities and government agencies consider implementing VLABs, they are faced with choosing an appropriate architecture and infrastructure components. This paper reports on a current VLAB implementation using VMware virtualization products. We describe the system architecture and report on benefits and challenges of the architecture and supporting infrastructure including issues of accessibility, administrative complexity, security, performance, configuration, and integration with other University IT resources and services. Our report is intended to guide faculty and administrators considering a similar implementation with lessons learned from our experience.

1. Introduction

Virtual computing laboratories (VLABs) in higher-education environments have been reported by many researchers [1] [2] [3] [4] [5] spanning a wide range of educational programs and lab architectures. As in many early adoption scenarios, initial implementations were largely based on locally-developed solutions, for example, [3] [4]. As experience has been gained and as the overall market for virtualization technology has grown, off-the-shelf components have emerged that simplify development and administration of VLABs.

This paper reports specifically on a University of New Mexico (UNM) computing lab implemented with VMware Lab Manager and supporting products. This VLAB replaced an earlier custom-developed VLAB and is now in its second year of use. Though we briefly describe how the lab is used from an educational perspective, our primary intent is to describe matters of practical importance to instructors and administrators seeking to implement a similar lab in education, corporate, or governmental environments, with specific emphasis on security-related education and training. Thus, our observations, analysis, and conclusions address issues such as accessibility, administrative complexity, security, performance, configuration, and integration with other IT resources and services.

2. Virtual computing environments

A virtual computing environment (VCE) simulates one or more sets of computing hardware resources, or virtual machines (VMs), within another set of computing hardware resources, the host. The first widely-deployed VCE was OS/VM used on IBM mainframe computers in the 1970s [6]. Virtualization fell out of favor for two decades but reemerged in the late 1990s. Widely available and relatively inexpensive computer hardware, powerful CPUs optimized for virtualization, increasing need for flexible deployment of IT resources, and a significant rise in administration and support costs have all contributed to the resurgence of VCEs [7].

Advantages of VCEs include lower hardware cost due to sharing across multiple uses, increased deployment flexibility, and simplified configuration management through the use of VM templates and cloning. VCEs are applied in a variety of scenarios including:

- Software testing with test machines implemented as separate VMs executing on a single host workstation or server
server consolidation, with smaller servers implemented as VMs within a larger host
• Desktop virtualization, with user desktops implemented as server-hosted VMs
• Complex test environments containing multiple VMs on an isolated virtual network

Combining the latter two use scenarios with remote access provides a powerful mechanism for implementing VLABs in educational environments at universities or in government. Remote access services to virtual desktops enables interaction with a standardized set of general-purpose software resources from a distance. When needed, software and hardware resources can be customized to the needs of the user for specific exercises, simulations or analysis. VMs needed in longer-lived environments (e.g., to support a semester-long system development project or ongoing investigations) can be defined as a template, cloned for each user, and destroyed at the end of the course or project. Multiple-VM test environments can support upper-level courses or advanced simulations with complex project-based and experiential learning in areas such as system & network administration, database administration, and information assurance [8] [9].

Conceptually, a VLAB implemented using a VCE has the components depicted in Figure 1. Users access the VLAB via a portal, typically implemented as a web site. The portal enables users to view the contents of a library of single VMs or configurations consisting of multiple VMs connected by a supporting virtual network. The deployment manager is a back-end software component that manages the library and interacts with a set of computing, storage, and network resources. When a user requests access to a VM or configuration, the deployment manager accesses it from the library and creates a deployed instance by allocating appropriate computing resources. Once initialized, the user interacts with the VM(s) through a Web browser plug-in functioning as a virtual console, remote desktop protocol (RDP) connection, or similar technology. When the user is finished with a VM or configuration, the deployment manager saves the VM state(s) back to the library or a user workspace (if appropriate), deletes the deployed VM(s), and returns their associated resources to the appropriate pools.

Figure 1. VLAB Components
VMware offers a relatively mature set of products that has developed through many workstation- and server-oriented versions. VMware has 80% market share in the server consolidation arena [10] and has actively sought additional markets and application areas including education (VMware 2010). VMware VirtualCenter provides core services for managing VM libraries and deploying them to servers running VMware ESX as an operating system. VMs executing within an ESX host support console interface using a protocol similar to Microsoft's RDP. Users can also log in remotely to the VM's DNS name or IP address using whatever supporting software is installed on the VM. VMware's Lab Manager product is an add-on that provides the VLAB portal component via a Web site hosted on a Microsoft Windows 2003 Server. Lab Manager also supports browser-based VM consoles via browser plug-ins.

VMware is not without competition to provide core components for VLABs. Competing commercial and open source products include:

- **Apache Virtual Computing Lab (AVCL)** - an open source software kit for deploying a VLAB. It arose out of a VLAB development project at North Carolina State that was donated to the Apache Software Foundation in 2008 [1]. AVCL provides a VLAB portal, VM/configuration library, deployment manager, and VM console interface. The deployment manager can interact with back-end servers running the Linux operating system or can be interfaced with a commercial VCE such as VMware ESX.

- **Microsoft HyperV (MHV)** - released with Windows Server 2008. Like VMware Virtual Center and ESX, MHV provides the back-end components needed manage VM deployments and back-end resources. Microsoft does not currently offer a product similar to VMware Lab Manager though the Microsoft Internet Information Services (web and application server) bundled with Windows Server provides a platform for developing a VLAB portal.

- **Xen** - released by Citrix under the GNU public license. Xen provides similar capabilities to MHV but is primarily oriented to Linux and UNIX with limited Windows support. Xen doesn't include a product similar to VMware Lab Manager but a portal can be custom-developed using supporting software such as the Apache web server.

- **VMLogix LabManager** - a commercial product similar to VMware Lab Manager that supports VCEs from multiple vendors.

The combination of VMware Lab Manager, VirtualCenter, and ESX appears to be the closest to being an "out-of-the-box" VLAB solution. That said, a VLAB based on any collection of components will require significant customization to implement, with the nature and scope of the effort varying substantially across products and user organizations.

Our purpose in this paper is not to recommend a "best" platform for VLAB implementation. Our use of VMware products was driven by previous experience implementing a VLAB using VMware Workstation and by contributed resources to redevelop that VLAB using Dell hardware and VMware server-oriented products. Our purpose is to report and analyze the results of that experience, not to make direct comparisons between VMware products and other possible solutions.

3. UNM VLAB implementation and use

The UNM VLAB is implemented with VMWare Lab Manager version 3.0, VirtualCenter version 2.5, and ESX version 3.5. Lab Manager is hosted on a Dell rack-mount server running Windows Server 2003. VirtualCenter and ESX are installed on a cluster of four rack-mount Dell 2900 series servers with a combined pool of 32 CPUs (2.3 GHz) and 128 GB of memory. ESX also controls a Dell iSCSI array with 4 TB of storage. Replacement value of the current hardware is approximately $50,000 and annual software licensing costs are $5,000. All VLAB-related hardware currently occupies a single rack connected via multiple Gigabit Ethernet connections to the campus network. Though demand fluctuates throughout the semester, typical simultaneous VM deployments range from several dozen up to a peak of approximately 120.

The UNM VLAB provides general-purpose computing lab support for students as well as course-specific support for approximately one dozen courses. Many students use a standard Windows VM that includes Microsoft Office, software development and database management tools, SPSS, AMOS, and Endnote. Supported courses encompass general and specialized management disciplines including accounting, finance, information systems, marketing, operations management, and organizational behavior. Standard VMs are cloned from a template each time a student accesses the VLAB and are deleted as soon as the student logs off the VLAB.

Additional VM templates and multiple-VM configurations support classes in accounting, information assurance, information systems, and marketing. Many of the VMs and configurations used in the courses are long-lived with deployments ranging...
from a few days to an entire semester. For example, students in a system & network administration course are each assigned a configuration with multiple server and client VMs connected by a private virtual network. Students configure the servers and clients over the course of the semester through a series of projects that mimic real-world system administration tasks. Similarly, accounting students interact with a single VM over the course of 2 months to configure an accounting information system, populate it with transaction data, and generate year-end reports.

4. UNM VLAB benefits

The UNM VLAB provides a number of benefits to students, instructors, and lab administrators in educational institutions and corporate and governmental training scenarios. Though most benefits would be realized regardless of the underlying VLAB implementation, we briefly summarize them here to provide a more complete picture of the VLAB's impact.

4.1. Accessibility and availability

As compared to physical computing labs, the primary benefit of the UNM VLAB to students is increased accessibility of computing resources. Many students do not have access to software used in specialized classes and others lack sufficiently powerful hardware or the administrative sophistication to install or run needed applications. The VLAB provides a set of preconfigured software resources, customized to specific educational activities, and available to any student with a Web browser and Internet connection. VLAB access is especially valuable to students enrolled in distance education classes who live far from campus.

4.2. Administrative overhead

In the years before any VLAB was implemented, UNM spent considerable resources equipping and supporting physical computing laboratories. The first VLAB implementation migrated many of the existing workstations into a VLAB workstation farm. Hardware- and space-related cost savings were approximately $100,000. There were some savings in desktop administration but they were largely offset by costs of building and maintaining a customized VLAB portal and the many manual steps required to administer and deploy VM templates and configurations. In the current UNM VLAB, administrative costs have been reduced significantly in multiple categories including the portal management, VM development and deployment, and management of computing resources. Because Lab Manager includes an adequate portal, portal development costs incurred with the previous VLAB are significantly reduced. The primary administrative tasks associated with the portal are content customization and user management, which are further discussed later.

Costs associated with back-end resource management are considerably lower than in the previous VLAB version due to the use of integrated rack-mount hardware. There are only a handful of physical computing resources (servers, storage array, and network switches) which operate for weeks at a time with no administrative intervention. The primary administrative tasks are occasional checks of error logs and application of software patches. More significant administrative effort is required to develop and test standard VM configurations for general-purpose use. But this effort is no greater than in the previous VLAB.

4.3. Support for complex student exercises

The VMware ESX environment supports a variety of virtualized hardware, operating systems, and network configurations. A VM’s CPU power, memory, disk storage, and access to network I/O devices can be customized. Supported operating systems include a full range of Windows and Linux/UNIX versions in 32- and 64-bit versions. Customized network configuration support includes virtual routing, private networks, and built-in core networking services.

VMware VirtualCenter and ESX make it possible to simulate complex real-world environments that students and instructors can manipulate via the VLAB. That capability enables a rich variety of educational activities in classes covering system & network administration, database administration, computer forensics, and advanced computer security. Simply put, the variety and complexity of currently-supported educational activities could not be cost-effectively supported without a robust VCE.

5. UNM VLAB challenges

Though the benefits of a VMware-based VLAB are considerable, they are accompanied by a series of challenges—some specific to VMware and some that apply to most or all VLAB support technologies. Before detailing challenges, we'll define VMware-specific terms used in the subsequent discussions.

- **Template** - A fully-configured VM with a defined maximum for allocated CPU, memory, and network resources (stored in a configuration file)
and a virtual disk whose contents are stored in a single virtual disk file.

- **Configuration** - One or more fully-configured VMs, connected by a virtual network, with optional core networking services and an optional connection to a physical network and/or the public Internet.

- **Workspace** - A user-specific storage area into which configurations are cloned and from which configurations are deployed.

- **Deployment** - The act of allocating physical computing and network resources to a configuration, starting the embedded VM(s), and opening console connection(s) to the VM(s).

- **Organization** - A portal and resource subunit containing library configurations and users. Organizations partition the portal and underlying VirtualCenter resources among groups of administrators, instructors, and students.

The typical workflow is for an instructor or administrator to create templates, create a configuration to support a specific educational activity (for example, a homework project) containing one or more templates and a virtual network, and store the configuration in a library. A student clones a configuration from the instructor's library to their own private workspace and then deploys the configuration to start the embedded VMs.

### 5.1. User interface

Despite its name, VMware Lab Manager was not originally designed as a computer lab management tool in the higher-education sense of that phrase. Rather, it was originally designed to support production and test environments for server consolidation. Its origin is apparent in the design of its user interface, which is tractable to an IT professional with some training but rather foreign to typical end-users. Figure 2 shows a portion of the user interface through which users interact with library VMs and configurations. The interface has typical web application features including fixed menu options in the left frame, pop-up menu options, and tabular and graphical representations of objects that users can manipulate. As with most web-based applications, clicking on a menu option or object activates a hyperlink that updates the current page or opens a new browser window with additional content.

![Figure 2. Partial screen capture of the VLAB portal.](image-url)

Many menus, icons, and tabular objects are labeled with VMware-specific terms such as those defined earlier that are ambiguous to ordinary users. Tasks that an end-user would consider atomic, such as starting a VM, require multistep processes that navigate through a series of screens and menus. For example, running a
single VM requires cloning a library configuration to a user workspace, deploying the VM from that workspace (see Figure 2), and opening a console. VLAB staff and instructors have developed online documentation and tutorials to help students navigate this interface. Despite these resources, many students fail to correctly navigate the process unless trained step-by-step in a computer classroom setting.

Source code for the Lab Manager portal pages can be modified to implement changes or extensions to the user interface. Our IS staff made significant changes including modifying the look and feel of the pages to match UNM standards, adding additional links for lab documentation, and providing a hyperlink for one-step deployment of the standard student VM.

5.2. Searching the VM/configuration library

The standard Lab Manager portal stores little descriptive information about VMs and configurations and provides no related search capability. Each library configuration is identified by a name (see Figure 2) but no additional details are available to describe the content or purpose of the configuration. Only a handful of configurations can be displayed on each Web page. Thus, users searching through a large library may have to access many pages via "Next" and "Previous" links. For small VLAB implementations with a handful of configurations, using descriptive names is sufficient to enable users to find, clone, and deploy a desired configuration.

Students in computer forensics and systems security classes typically interact with a new configuration every week and additional configurations for presentations, exams, and special projects. As a result, the number of configurations in our VLAB has grown to over one hundred. Though views of available configurations can be restricted to users within specific organizations, the problem of finding an appropriate configuration for a particular project or exercise is still significant. To address this limitation, IS support staff expanded the portal interface for some organizations to include an additional link that describes available configurations in detail and provides direct links to their library images (See Figure 3).

![Partial screen capture showing a customized extension to the Lab Manager portal.](image)

5.3. Browser support

Browser support for our VLAB is limited to Internet Explorer (IE) versions 7 and 8 and FireFox versions 2 and 3 due to limited availability of supported Active-X browser plug-ins to implement the VM console interface. The console is installed on first use though the browser must be configured to accept and install downloaded ActiveX controls. With many browser configurations, the user must explicitly enable downloaded files and must click OK in one or more dialogs to install the control. Additional issues arise for browser security settings and firewall settings at remote locations since the Lab Manager console interface uses some non-standard ports. Users running IE under Windows Vista and 7 must add the VLAB URL to their trusted sites list and must disable protected mode for all trusted sites.

Complex configuration for supported browsers and incompatibility with other browsers such as...
Chrome and Safari is a continuing source of frustration to both students and instructors. UNM has a support staff to assist students, though problem diagnosis and corrective actions sometimes require multiple attempts and some accessibility issues simply can't be solved without significant changes to user computers. In particular, accessing the VLAB from a Macintosh computer requires the user to install a later Windows version within VMware Fusion or a similar product.

5.4. Server resources

ESX is an efficient allocator of hardware resources [11]. But there are specifics of the VM configuration and deployment process that must be tightly managed to ensure that available resources can support a large number of simultaneous users. We describe three of these processes including controlling VM resource usage, managing related VMs and configurations, and managing server storage.

When a VM is deployed it is allocated one or two virtual CPUs and a specific amount of memory. ESX implements multitasking and virtual memory management so the sum of CPUs and memory for all deployed VMs can exceed available physical resources. VMs used in our VLAB tend to use bursts of CPU time separated by significant periods of idle time. Since ESX effectively scavenges unused and underused CPU resources, we have encountered little trouble providing sufficient CPU capacity to support VLAB VMs.

Providing sufficient memory has been more problematic. ESX is reluctant to page large amounts of VM memory to disk—for good reason since doing so would significantly tax both available disk space and disk-related I/O bandwidth. But leaving the majority of deployed VM memory in physical RAM quickly consumes available server memory. To conserve memory, we have optimized widely-used configurations to minimize their memory footprint by various methods including using older operating system versions and disabling operating system features that would increase memory footprint. The standard VM used by many students is a tightly configured Windows XP machine with only 512 MBytes of RAM.

A VMware template is stored as a relatively small file describing "settings" such as number of CPUs, allocated memory, and network connections, and a larger file (or files) that stores the contents of the VM's disk(s). New templates can be defined based on existing (base) templates. When one template is defined from another, VMware doesn't duplicate the entire virtual disk file(s). Instead, VMware creates an additional file or file(s) to store the content differences between the base and derived templates (sometimes called a delta file). A similar process occurs when a configuration is cloned to a workspace and deployed. The cloning process duplicates the "settings" file(s) of the corresponding template(s) but all disk references refer to the template's disk file. When a configuration is deployed, VMware creates a delta file to store only the differences between the disk content of the workspace VM(s) and the template(s) from which they're derived.

Using delta files to store changes from a base disk image minimizes the amount of required disk space for derived templates and deployed configurations. However, it also creates a dependency chain between the disk file(s) of the original template, the delta files holding content changes for deployed VMs, and any intermediate delta files such as those for derived templates. When executing, a deployed VM accesses all of those files and VMware must keep track of which disk input and output operations read from or write to which file(s). As the length of the dependency chain and the number of files increases, disk read and write operations become more resource intensive.

Managing the disk space consumed by "families" of related templates and deployed VMs is a balancing act between storage resources and efficient VM execution. VMware template chains can be consolidated, a time-consuming process that creates a new disk image file and improves the performance of related VMs. Based on testing and live experience, we've determined that overall VLAB performance degrades substantially when deployed VMs are based on templates more than one generation removed from a base template. Living within this limitation sometimes requires using fewer less-customized templates to support a wider variety of users than might otherwise be desired.

Another concern in managing template and configuration families is the effect of damage to or destruction of a template or a delta. We encountered one instance in which a base template became corrupted. As a result, all dependent templates and configurations were also corrupted and the entire family had to be reconstructed.

Other storage management tasks in a VMware-based VLAB include determining which pools of storage resources will be available to which groups of users, how many deployed VMs can be stored in a student or instructor workspace, and the lifetime of a deployed VM. VirtualCenter enables the VLAB administrator to assign available computing resources including storage into mutually exclusive pools.
which are then allocated to organizations. VMware makes it difficult to share resource pools across organizations so care must be exercised in matching allocated resources to anticipated demand.

Templates, library configurations, and deployed VMs are each assigned a deployment lease which specifies the maximum time that they can be deployed and a storage lease that specified the maximum time that they can be stored while not deployed. Whenever possible, VLAB configurations are defined using "throw-away" VMs that are deployed for a maximum of 4 hours and then disposed of immediately. Such VMs have minimal impact on available storage resources due to their short life, but provide no capability for a user to save customizations or data embedded within the VM.

Longer-lived VMs save the contents of their virtual disks when deployment ceases and resume in their former state when redeployed. Although their storage requirements only consist delta file contents, these files grow over the life of the VM(s). Storage requirements can be very high for classes that require long-lived VMs, have a large number students, use complex configurations, require long configuration life, or require multiple configurations. The VLAB administrator sets relatively stringent defaults for all of these variables that are raised only when absolutely necessary.

5.5. Access control and security

Lab Manager supports two options for managing users and groups accounts. The first one is a local account management database running in Microsoft SQL Server which is accessed through the web interface. The second one is through direct access to an LDAP server as Lab Manager supports Active Directory and OpenLDAP. While the first option is easy to install, configure and use, the LDAP solution provides greater scalability and avoids the need of a duplicate account management system within the organization. There are different options available in terms of communication with the LDAP server and LDAPS (LDAP over Secure Sockets Layer) on port 636 is recommended when traffic must be kept confidential. At the same time the LDAP connection does increase the complexity of the deployment as information such as distinguished names, authentication methods and connectors must be configured properly.

Within the web based front end, Lab Manager provides the ability to configure roles which can be assigned to users or groups. A role will determine what type of privileges are available for a specific account. As an example some roles may be able to only clone and deploy a library configuration, while other roles can create templates, increase resources requirements and more. Each workspace is accessible by the owner, the administrator and any other user that it has been shared with. The sharing option can provide simple viewing permissions (read-only) or complete access where addition, changes or deletions can be executed.

Additionally each workspace has a corresponding network configuration where all traffic can be isolated, routed through a NAT virtual router or directly bridged over to the physical network. When isolated or routed through a NAT virtual router, systems in the workspace can be “fenced” so that they cannot route traffic back and forth to another workspace. It is possible to isolate multiple workspaces from outside physical traffic while allowing systems in those environments to connect to each other through an “un-fenced" configuration.

6. Conclusion

We've successfully operated our VMware-based VLAB for over a year and have used it to support courses in a variety of disciplines including systems & network administration, information assurance, and computer forensics. Our success evidences the sufficiency of the VMware product suite to provide appropriate virtualization and portal infrastructure. The challenges in building and managing the VLAB have been significant but all important obstacles were overcome. By far the most significant challenges have been ensuring accessibility for a large and diverse student population, training student and instructor users, and managing the underlying computing resources, especially disk space.

With respect to Web browser compatibility, we are primarily limited by the availability of VM console plug-ins. This is an area of continuing product development by VMware. Training is an ongoing effort and is best addressed with a combination of development of training materials and modifications to the portal to simplify student interaction. Finally, managing disk space and other computing resources is also an ongoing effort that isn't significantly different from that of any computer center. Instructors and VLAB administrators must work together continuously to find the best match between educational needs, VLAB performance, and available resources.
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8. References


