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File Timestamps for Digital Cloud Investigations

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***Abstract*: This paper discusses how abstract pieces of information may be extracted from the hypervisor kernel logs running within a Linux Operating system Virtual Machine (VM) environment. We posit that seemingly insignificant evidence sources may exist by using VM system log file timestamps and correlating them as evidence sources within the cloud computing environment. A VM log auditor prototype was developed to help VM investigators determine the course of events as they occurred according to file timestamps.**

The prototype results and criticisms of these results are also presented in this paper. This work in summary allows the digital investigator to start formulating hypotheses about a VM digital investigation, considering the uncertainty value of the time-stamped log evidence presented to him.

***Keywords*: SAN, Virtual Machine, Cloud, Timestamps, Auditor.**

I. Introduction

Digital evidence is not well perceived by the human senses [10]. Crucial pieces of digital evidence may simply be missed due to the fact that examiners do not fully comprehend how seemingly useless pieces of data can be converted to evidence of high value. There is even more cause for concern by the examiners working within the Cloud Computing environment who are challenged in defining the public network domain elements and parameters associated with virtual machine instances. This is particularly useful as it may help to create an incomplete picture of digital crimes under inspection [2]. It is therefore important to examine all evidence, no matter how insignificant it may seem.

We argue that if a VM investigation team can understand an intruder's modus operandi, it may then be possible to determine various attributes describing the intruder, such as skill level, knowledge and location [3]. Security mechanisms such as log files will usually be used to determine the actions of the intruder.

It is however possible that an active security system running on the compromised system may be configured incorrectly or disabled completely [9]. In such circumstances VM investigators will have to turn to alternative sources of digital evidence.

File timestamps may serve as a worthy alternative, as timestamp information may be viewed as a simplistic log of events as they occurred. Although file timestamp information may be considered one-dimensional in a sense that it only records the time of the very last action that was performed on a file, it may still be a valuable source of evidence when very few alternatives remain. Unfortunately the processing of file timestamp information may be complicated by the sheer volume of available timestamps that should be processed.

Arguably the overabundance of digital evidence that need to be processed in small amounts of time could be described as an audit reduction problem [4]. The audit reduction problem describes the situation in which the presence of too much information obscures the focus point of investigations. Audit reduction would therefore be prevalent in digital evidence analysis due to the masses of files that needs to be inspected, spurred on by massive storage capacities of modern storage devices.

Hypervisor kernel log file timestamps analysis is an excellent example of the audit reduction problem: modern hard drives storage capacity may be anywhere in between the gigabyte to exabyte ranges; a very large number of files may be found on these devices, with each file having different timestamp information associated with it. Although most of the file timestamps would be irrelevant to a case, a few may still be the key to its successful resolution. If these timestamps are simply overlooked, an incorrect conclusion could potentially be reached which may have dire consequences in store for the accused as well as the data cloud investigation team.

The paper discusses the use of timestamps as a supplement or alternative to the actual hypervisor kernel log file sources when they are not available. Our work is motivated by earlier work done on formal temporal log models within the Cloud computing environments[13].The information deficiency problem, which describes the situation in which not enough information is available to allow investigators to get a clear picture of forensic significant events is also discussed. This is done to inform the user of possible problems that may be experienced with alternative evidence sources. The concept of synergy applied to digital data is proposed as a solution to the information deficiency problem. The principle should allow VM investigators to use various insignificant evidence sources to generate abstract forms of information that are considered to be of forensic value. The paper is structured as follows.

Section II will discuss the importance of file timestamps as used within a cloud digital investigation environment. Section III will focus on file timestamps related to incident phases within the Cloud Computing domain. Section IV will introduce the information deficiency problem and section V will discuss a possible solution to the problem within the context of ongoing related work supported by authors. Section VI will discuss the development of a virtual machine log auditor prototype, section VII will discuss the results obtained by use of this prototype and section VIII will discuss the prototype flaws. Finally, section IX will describe the future work and section X will discuss the conclusion.

II. File Timestamps as a source of Evidence within a Cloud Computing Environment

Attackers may try to delete or alter hypervisor log files in an attempt to cover their tracks; fortunately pieces of information may still remain due to a lack of skills or access rights [9]. As an example, consider the use of well-known UNIX commands such as cat and grep. The attacker may use these two commands to remove identifying information from a system log file. A clever attacker may even change the log file's modification date after the alteration as not to arouse any suspicion from the VM system administrator. With the system log files compromised, VM investigators will have to find an alternative source of evidence as compromised evidence sources may not be credible in a court of law.

Many IT professionals are still concerned that the maturity of Cloud Computing as a well understood service oriented model is still fraught with problems. The arguments for providing economies of scale by making available, on demand system resources, represents a convenient means to provide rentable computing services[16]. The issues of managing the physical data centre does not replace the tradition that the digital evidence is still collected from local databases resident to such data centers. This activity dates from the period of mainframe and grid computing during the late 1960's to late 1970's.

The popularity of the various known cloud deployment models (public, private, hybrid, and community clouds etc) continue to be featured as a part of the growing commercial and scientific communities. The physical evidence collected from the data centers can be stored within any one of these SAN cloud deployments. The hypervisor as a virtual operating system enables the VM user to relate to the physical disk by using the hypervisor to monitor the targeted OS codes within the physical host .

Realistically there exists a less obvious source of digital evidence as a VM digital footprint can be wiped quickly- file timestamps. Consider the example where an attacker uses a combination of well-known tools such as the cat and grep commands to remove identifying information from the system log file. Very few attackers would actually reset the file access timestamps that were created when the shell command was executed. Even if they did manage to modify the file access times, they would have used a tool to do so. This means that although the commands used by the attacker do not have valid timestamps associated with it, a valid timestamp would be left somewhere on the system by the attacker, unless the command was executed from a read-only medium. From the discussion it should be obvious that only extremely skilled attackers would be able to access a system without leaving a single trace; less skilled attackers are bound to leave small pieces of evidence behind that may ultimately be used to identify the responsible parties.

Popular file systems such as FAT, NTFS and EXT store file timestamps to keep record of:

- The file creation time
- Last time the file was accessed
- The last time the file was modified

These timestamps are updated by the underlying operating system when appropriate, but skillfully written applications also have the ability to manipulate timestamps as they require. Applications have different approaches concerning the management of timestamps. As an example, consider two well-known UNIX applications, namely cp and tar. When a file is copied using the cp command, the resulting creation and modification timestamps of the destination file would indicate the time that the cp command was executed. This is not the case with the tar command. When a compressed archive is created, the relevant files, along with their timestamps, are stored in a compressed archive. It should therefore be noted that some applications will posses timestamp modification capabilities which may have a negative effect on the timestamp analysis process. This topic will be discussed further in section 8.

III. Timestamps and Incident Phases

Three digital evidence stages have been identified by Koen and Olivier [6] which classifies evidence according to its temporal relationship with a digital incident. The identified stages are as follows:

- Pre-incident
- Incident
- Post-incident

The pre-incident stage focuses primarily on forensic readiness. Forensic readiness describes the extent to which a system is able to supply forensically sound information to aid the digital investigation process [7]. Special software and hardware can be installed to monitor user actions and minimize the likelihood that the users of these systems can participate in mischievous activities without being noticed through policy management and the enforcement of restrictions. Suspicious activities may be captured and logged as required.

The incident stage is concerned with the capture of digital evidence while a crime is being committed. The incident stage is primarily responsible for the capture and archiving of events as they occur in real time. The last stage is the post-incident stage in which the entire suspect and/or victim system's state is captured and analyzed after the digital crime has been committed.

The phase is characterized by the mass-archiving of the states of the systems involved in the digital crime in an attempt to determine how the systems were used and by whom.

The information supplied by timestamps is very limited in a sense that a timestamp only records the last time a specific activity took place [12].

To simplify this discussion, it will be assumed that a file will only have an atomic timestamp value associated with it.

In reality the time-stamped log file will be affected by various complex and primitive events which will produce multiple timestamp values over time to develop a history of several VM complex events[17]. We hence assume by principle, for the purposes of this paper, that the timestamp value is the same and may remain the same for timestamp-based information.

The most accurate timestamp from an evidence timeline classification point-of-view would be the timestamp recorded in the pre-incident stage as a timestamp with a time earlier than the incident means that the file in question was used before the incident occurred. This means the file may have executed an action on files involved with the incident, but it could only have done so up until the point that it was last loaded in memory. Timestamps captured in the incident stage indicate that the files in question were used during the incident stage, but could also have been used during the pre-incident stage.

The situation gets worse in the post-incident stage: files with timestamp in this stage may have had actions performed on them during any one of the phases. An information deficiency problem therefore exists with regards to timestamps and the incident stage and especially the post-incident stage.

For analysis purposes it will have to be assumed that evidence had actions performed on it in every stage prior to its current incident stage. A solution to the information deficiency problem may be to introduce additional evidence sources in an attempt to build a timelines that indicate upper and lower bound incident stages in which actions were performed on the object in question.

IV. Applications and File Timestamp Relationships

In order for a VM file timestamp to change an action is needed. The action will have to be triggered by an application or device driver resident in memory at the time of change. For this discussion it is assumed that three types of timestamps exist, namely the creation, modification and access timestamp and that the operating system alone can modify file timestamp values. The value of the timestamp is not important in this example as its meaning is largely dependent on the application that triggered the event.

What should be considered important is the fact that an executable code that triggered the event to be executed should have been active in physical memory prior to triggering the event. This means that the file in question should have been loaded into memory, thus modifying its file access timestamp. An executable that accesses or modifies a file should therefore have a file access timestamp which is smaller than the file in question’s timestamp (create, read or modify depending on the action performed). The following macro can be defined to determine if an application’s create, access or modify time has been edited as adopted from [12]:

touched(f) = ceil (create(f), access(f), modify(f))

Using the defined macro, the following condition should therefore hold:

access (executable) <= touched(file)

Due to the information deficiency problem identified , a piece of executable code may be loaded again in the future which means that the stated condition will not hold anymore as the access time of the executable code changed. The following situation may therefore exist:

access (executable) <= touched(file) or access (executable) >= touched(file)

This basically means that it would not be possible to pinpoint the application responsible for the modification of a file as not enough information exists. If the VM hypervisor kernel log file timestamp found an executable piece of code, that shows that the executable was last accessed before a file timestamp was last modified, it however does not necessarily rule out the executable as the accessory or modifier of the file in question as some sections of code may stay resident in memory for a period of time before it actually accessed the file.

It can therefore be concluded that application/file timestamp relationships is of very little forensic significance on its own; some additional form of information is needed to help to rule out executables that could not have modified the file in question. The executable access hypervisor kernel log timestamp cannot be used to help rule out the application associated with it as the application may have been resident in memory for some time before it triggered the modification of a file’s timestamps. If it were possible to prove that the application in question was removed from memory some time after its file access timestamp indicated, it may be enough to rule out the application as the trigger source.

As an example, consider the diagram illustrating the executable access timestamps in the different incident stages (see figure 1). Various evidence artifacts have been organized according to file creation timestamp dates.

As discussed previously, application/file timestamp relationships are not of forensic significance on their own; executable 1, 2 and 3 could therefore individually have created files A, B, C, D and E. It is therefore not possible to rule out any executables from the equation.

Imagine the intruder managed to VM reboot the system in question during the incident phase. Knowledge of this event may help to place an upper-bound on the last possible time that executable 1 could have had an effect on the file timestamps of the listed artifacts. File access information informs us that executable 1 was last executed during the pre-incident phase; a VM system log file (collaborating evidence) shows us that the system went offline during the incident phase. Executable 1 was not loaded again after the system went back online after the reboot. It can therefore be concluded that executable 1 did not have an effect on the timestamps of the listed artifacts after the VM system reboot. With enough collaborative evidence at hand it may be possible to narrow the list of possible executables down substantially which may have been responsible for triggering an event that modified timestamp information.

This example relied on the knowledge that a VM host system rebooted. Normally such information will be gathered from a system log file, but in the absence of credible log files, VM investigators may once again need to turn to file access timestamps as an indicator of VM system events. When a VM system boots, various executables are loaded as services.

These executables are usually only loaded once and stay loaded until a system halts or reboots. By looking at the access timestamps of these services it may actually be possible to determine when the system booted. This method will be discussed further in section VI.

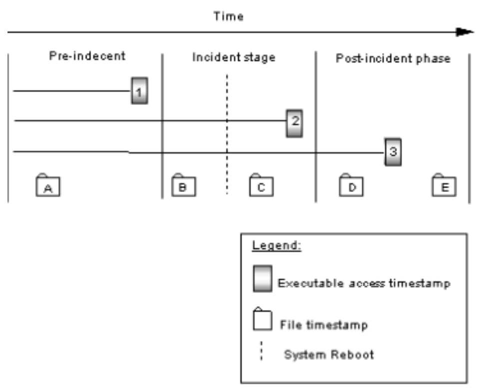

Figure 1. Files organized according to VM system Log timestamp information

V. Solution to the Information Deficiency Problem

Synergy describes the situation in which the whole is greater than the sum of the parts [11]. Although the discussed events may be seen as insignificant on their own, their importance may increase when their collective importance is realized in the virtual machine log forensics environment.

Consider the example in figure 1 again: each of the VM events that caused changes in timestamp information associated with the files is of very little forensic value when considered on their own. Even the timestamp that indicated that the system in question performed a boot operation would seem relatively useless on its own as it does not convey any useful information other than a system boot took place. The real value in the timestamp information lies in the fact it represents events that took place. On a higher level these events may be related with one another to create an abstract view of the events as they occurred. The example in the previous section illustrates that it may be possible to extract useful information from seemingly useless data when viewed on its own. A file's access timestamp may have very little importance on its own; its importance is directly related to the importance of the event that it represents. A principle based on synergy that focuses on the creation of abstract evidence information from insignificant pieces of data may therefore be formulated as follows:

Event data is generated when a significant digital event occurs. Although the generated event data is of little value when viewed independently, collectively event data can produce information that can help investigators to deduce relationships between events to produce abstract views of the evidence at hand.

Investigators usually have lots of complex questions to answer in a short period of time [3]; the possibility therefore exists that evidence may be over-looked as investigators focus their attention to evidence that seems more important in an attempt to save valuable time. Identifying the relationships that may exist between seemingly unimportant pieces of digital evidence may be an extremely tedious task to perform. As Adelstein [1] points out, it is not feasible for investigators to manually analyze storage devices with storage capacities in access of gigabytes as there is just too much data to process. This concept similarly applies when we consider the merits of analyzing VM storage device elements which has a source physical storage of Exabyte amounts.

Without some form of automated processing the benefit obtained as a result of time invested by investigators would be minimal due to the sheer volumes of data that needs to be processed.

VI. Virtual Machine Log Auditor Prototyping

A VM log audit prototype has been created based on application/timestamp relationships discussed previously in an attempt to illustrate the defined principle in action. The log auditor makes a SAN disk image by copying hypervisor kernel logs resident on the SAN LUN physical disk to a third party target evidence server [14,15]. The prototype was originally developed to extract information from VMWare essx3i and Citrix Xen virtual operating systems under the Windows 7 OS. In our current work we explore the prototype's scalability to run Xen Citrix on Linux to extract information from the Linux-Mandriva kernel based EXT2/3 file system storing ordinary files, applications and system logs. The prototype was built under the assumption that the VM file timestamps have not been tampered with. It has also been assumed that the executable access time indicated the last time the application was loaded by the operating system. File creation timestamps were ignored as it is assumed that file access and modification times will always be larger than a file's creation time.

Casey [2] proposed a certainty scale that may be used to determine the level of trust that can be placed in the information deduced by the investigators by examining the forensic evidence at hand. Evidence that appears highly questionable will have a low certainty level associated with it while evidence that can be correlated with other captured evidence sources will receive a higher certainty rating. Casey's certainty scale can be used in addition to the defined principle to increase the level of trust experienced with extracted information; evidence which can be correlated with other sources of information may experience a higher degree of certainty.

Relating Casey's work and the defined principle to timestamp information it can be assumed that timestamp information that is correlated with timestamp information from the same SAN disk image will have a lesser degree of certainty than timestamp information that may be related to some other form of evidence, such as VM system logs. The prototype was built with the purpose of identifying the last possible time that an application could have been loaded in memory, known as the last possible execution time. This was done in an attempt to determine which files could have been modified by the application in question. The last possible execution time is determined in one of two ways: by correlating an application's access timestamp with system log entries or by correlating an application's access timestamp with the access timestamps of system applications and/or files that are accessed on VM system boot or shutdown events.

The first method would obviously be the better choice for the correlation of evidence as it contains a rich source of system-related history information. To determine the last possible time an application could have been in memory is simple: use the application in question's access timestamp and search for the earliest system halt or reboot event that occurred after the access time in the log file. The time specified in the log for the halt or reboot event would therefore serve as the last possible execution time as the executable was never accessed again after that specific point in time. The second method may serve as an alternative to log files in situations when it has become evident that the system log files have been tampered with or in environments where no log files exist. When the operating system boots or halts, it will load various system applications and access stored settings, changing their accessed timestamps. In the case of the hypervisor as a virtual machine OS, it uses raw device mapping (RDM) mechanisms to correlate the SAN physical disk OS booting and rebooting processes as previously mentioned. We'll discuss the RDM capabilities in a separate paper. The VM system log timestamps viewed on their own are insignificant, but when used to determine when a system was turned on or off, it may be of great value to forensic investigators. As an example, consider the sequence of events that occurs when a standard Linux system boots. The first process created by the kernel executes the /sbin/init application. When the /sbin/init application starts, it reads the /etc/inittab file for further instructions. By simply checking the accessed timestamps of either one of the two files it would be possible to determine the last time that a system VM booted. It can be argued that the information is also obtainable from alternative sources (such as the /proc/uptime file), but in situations where the alternative is damaged or simply does not exist, timestamps will have to suffice. Calculating the last possible execution time for the second technique is similar to the method used to determine the last possible execution time for the first method: determine an application's accessed timestamp information and determine the last time a system booted or halted by looking at the applications and files associated with the system boot or halt operations.

The prototype reads disk images to produce excel comma delimited files (.csv) containing time-stamp information. These excel .csv log files are then converted to line graphs to corroborate the way timestamp information is presented. The prototype adopts on two freely available libraries, namely the Reco Platform [5] and JFreeChart [8]. The design is illustrated in Figure 2.0

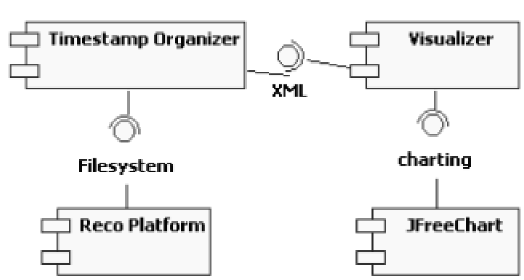

Figure 2: The Log Auditor prototype design

The Reco Platform supplies low-level EXT2/3 support to the system while the JFreechart library supplies the graphing functionality required by the Log auditor application. The prototype source code has been released under the GNU GPL license and is available on Sourceforge [5]. The next section will discuss the results that were obtained using the developed prototype in more detail.

VII. Results

The prototype was tested using the Linux Mandriva 10 environment. A SAN disk image was made and last possible execution times were computed for each VM system log application using both methods described previously to produce separate excel space delimited log (.csv) files. These .csv files are also visually accessible through our XML browser. The SAN disk image records two types of system log events-: (i) VM disk events (ii) Sysmpi (system microprocessor instruction) events. The VM disk events record both the Linux mounted device name and number. This is a complex VM event. The sysmpi records the collective register events that took place on the VM hosted SAN disk. Ideally an atomic register event is a VM primitive event which is hard to isolate for the purposes of an investigation. However collective register events are VM complex event sequences that can be patterned to determine anomalies from the VM SAN host kernel disk.

A Microsoft Excel scatter graph chart was constructed using each detected VM file's log event creation times as coordinate values. A selected application's last possible execution time was plotted as horizontal and vertical lines to indicate the reach of the application in question. Figure 3,4 and 5 represents log event data compiled over two days at a time within an intermittent six month period. The produced line chart as well as the horizontal and vertical lines indicates the maximum reach of the application in question. For the VM disk events two day snapshot recorded in Figure 3 , we noticed that between the times 4:36 p.m. on the 09/11/2010, 9:50 a.m. on the 10/11/2010, and 9:51 a.m. on the 10/11/2010, the number of loaded disk event start up event occurrence count steadily climbed from 26, 34 to 36 events respectively on our test disk. Similarly in Figure 4 for the VM snapshot sysmpi events we took a random sample log of the VM event occurrences on the 10/11/2010 at 9:50 a.m. and 10/11/2010 at 9:51 a.m. The sysmpi event occurrences rose from 34 to 36 events respectively within this time period.

Although the system study compiled these results over six months, the snapshots very limited skew of the data, supports only those useful result occurrence sets that corroborated post-mortem log evidence analysis of cited incidences of SAN disk failures over the time. In other words only data that we could tie to an actual incident on the SAN did we deem as useful potential evidence. As the work is still ongoing our intention is to let the user be allowed to select an application of interest in a dropdown control populated with a list of applications. The application's last possible execution time is computed and plotted on the VM log disk line scatter charts upon selection. It is expected that the last possible execution time, access time and modification times are represented by an integer value; the integer value is a timestamp that describes the amount of seconds that have elapsed. At present we don't account for the access or modification times. This unfortunately means that the values could easily be manipulated using a function such as ctime when the event in question occurred or should occur. From Figure 5,the last possible execution time for the application /etc/X11/xdm/chooser was calculated. Translated to human-understandable terms, the last possible execution time(seconds) for the application in question is the 10/11/10 at 9:51 a.m in this sample. The application cannot be responsible for any file access or modification operations performed after the last possible execution time, represented by the horizontal and vertical lines on the graph. Any files outside of the horizontal and vertical lines have been accessed or modified by other applications.

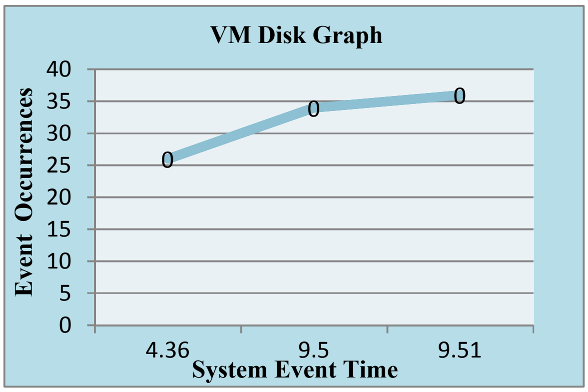

Figure 3: Scatter diagram of the VM Disk log

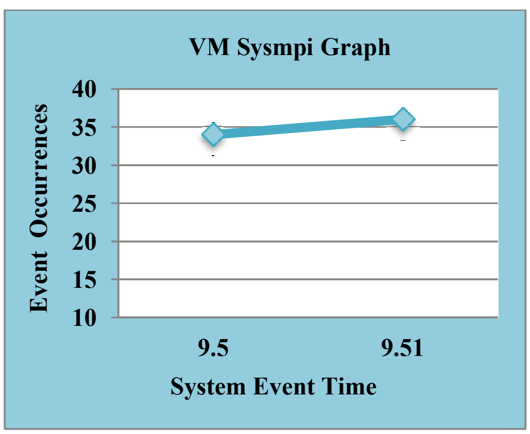

Figure 4: Scatter diagram of the VM Sysmpi log

By simply looking at the generated chart it is not possible to visually detect if any of the files could have been modified by the application in question. Due to the sheer magnitude of the amount of files that are stored on our University SAN disk drives, as extrapolated in Figure 5, the file filter functionality has been suggested to the prototype to search for VM log files with timestamps conforming to specific criteria. Determining the names of the files that could have been modified by the application in question is as simple as submitting a filter VM log event query that contained the VM's last possible execution time of the application in question.

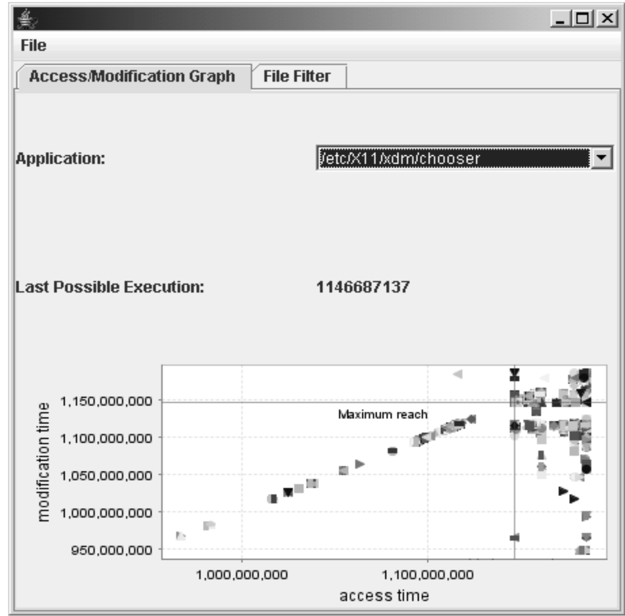

Figure 5: A screenshot of the Log Auditor prototype.

A comparison between the two techniques used to determine an application's last possible execution time yielded the results that were expected-: since VM hypervisor system log files contain detailed history information, more accurate last possible execution times can be calculated leading to more accurate results.

File access timestamps contain only the last time the file was accessed and can therefore be compared to a VM log file containing entries which date back to the last time a system in question was booted. This implies that the method could work with the same efficiency as the first method in a scenario where a system rarely goes offline. However, this method would be a very inaccurate for a system that goes offline frequently.

VIII. Criticisms

As discussed in section II, some VM system log applications like many other system applications have the ability to modify timestamps. The work in this paper assumed that the timestamps are modified by the physical operating system only, and hence the VM hypervisor kernel logs represent only an instance of the physical OS execution processes and as such did not take into account that applications may manipulate the proposed analysis method by changing file timestamps to render the method invalid. In reality, the interpreted meaning of a timestamp is therefore largely dependent on the way in which the application responsible for the creation or modification of a file manages the VM hypervisor kernel log timestamp information.

It has also been assumed that applications will be stored on a writable physical medium as the VM storage device still has to dereference the physical disk addresses from paged memory ; an hence an application's timestamp information will therefore be updated each time the application is loaded into paged memory. This may not necessarily be the case as it is possible in the UNIX environment to mount file systems in read-only mode. This means that an application's file access time will not change hence challenging the method described in this paper.

Another concern is that an application may have accessed or modified a suspicious file prior to its last possible time of execution; if the suspicious file was accessed or modified again sometime later in the future (presumably after the application in question's last possible time of execution), the timestamp may be labeled as being out of reach of the application in question.

Technically this is true as the file was last modified by another application, but this situation may not always be desirable. A way to overcome this problem is to divide application hypervisor kernel log timestamps into the various incident stages discussed in section 3. Only applications with access timestamps falling in the incident and post-incident phase will have to be considered for inspection as it can be assumed that applications with last possible execution times falling in the pre-incident stage were not involved with the incident in question.

IX. Future Work

The log events extracted from the hypervisor kernel are complex events that describe the behavior of the SAN disk hosting these VM instances. A greater effort is still needed to correlate event patterns in the behavior of the disk as a basis for compiling forensic digital evidence . One such consideration includes the size of the logs used in the study. We only use two day cycles of data at a time , given that we do not maintain long term backups for the existing VM test environments. Data compiled over several months and even years may filter better correlation patterns and certainty values supporting the history of the potential timestamp evidence.

Ideally a complex VM application would typically touch various files while it is executing. A typical scenario would be where the VM application in question first accesses its configuration files and then data files. By describing a VM application's actions formally, it may be possible to create a profile that accurately describes an application's file access characteristics.

Another topic that requires attention is the inspection of the VM file access of an operating system's boot process. When an operating system performs the VM system boot process via its hypervisor, various files will be accessed. Different operating systems would access different files which create the possibility that the file access operations performed by an operating system could potentially be used as a fingerprint to help operating system identification in circumstances in which conventional methods are not deemed appropriate. The described process could potentially be improved by adding the concept of a termination signature. The termination signature describes the characteristics of an application when it terminates, in other words what actions it takes just before it terminates. If such a VM log signature can be incorporated into the concepts described in this paper, more accurate results may be obtained.

X. Conclusion

This paper addressed how abstract pieces of information were extracted from the hypervisor kernel logs running within the Linux Mandriva Operating system environment. We posit that seemingly insignificant evidence sources may exist by using VM system log file timestamps as a source of correlating evidence.

A VM log auditor prototype was developed to help VM investigators determine the course of an event as they occurred according to file timestamps. The prototype results and the criticisms leveled against these results were also addressed. The VM log auditor prototype calculated various applications' last possible execution times and visually depicted the information in a manner that can easily be understood by the VM observer. The prototype helped to visualize abstract virtual machine digital data.

Unfortunately the method used by the VM log auditor prototype is not absolute in that it cannot successfully be applied to all environments under all conditions. It has become evident that a great need exists for ways in which VM digital log evidence can be visualized for the ubiquitous cloud computing environments. More research will have to be conducted to find ways to visualize digital information to allow investigators to easily understand digital evidence at hand as collected from a private versus public SAN cloud.

This work ably allows the digital investigator to start formulating hypotheses about a VM digital investigation in the face of uncertainty in the VM log timestamp results presented.

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Author Biographies

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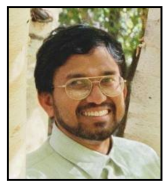

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