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(54) SYSTEM AND METHOD FOR IDENTIFYING UNAUTHORIZED ACTIVITIES ON A COMPUTER SYSTEM USING A DATA STRUCTURE MODEL

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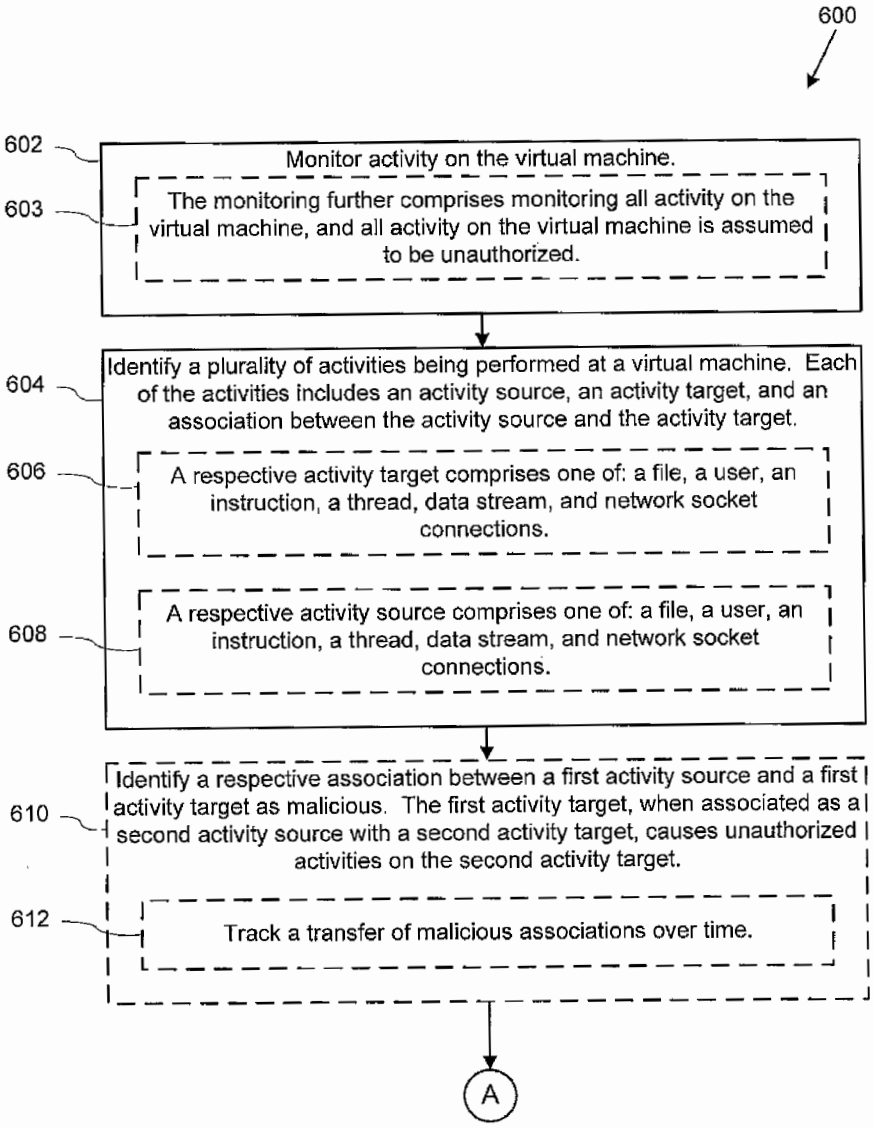
(57) **ABSTRACT**

A computer implemented method includes monitoring activity on the virtual machine. A plurality of activities being performed at the virtual machine is identified. Each of the activities includes an activity source, an activity target, and an association between the activity source and the activity target. The activity sources, activity targets, and associations are stored in the memory. A fingerprint indicative of the activity on the virtual machine is created from the stored activities. The fingerprint is transmitted to prevent future attacks that comprise the same or similar activities as indicated by the fingerprint.



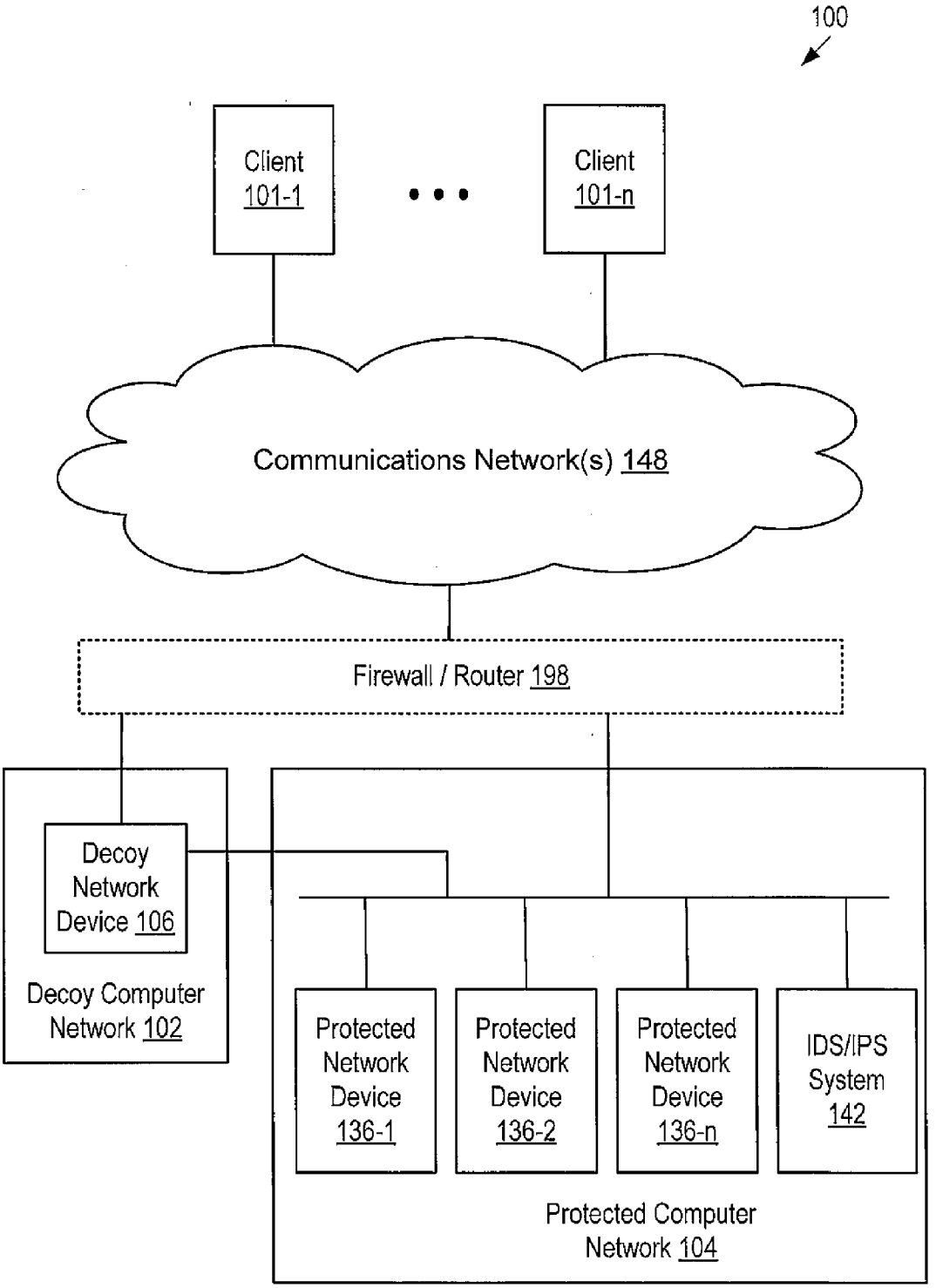

100
Client 101-1
Client 101-n
Communications Network(s) 148
Firewall / Router 198
Decoy Network Device 106
Decoy Computer Network 102
Protected Network Device 136-1
Protected Network Device 136-2
Protected Network Device 136-n
IDS/IPS System 142
Protected Computer Network 104

Figure 1

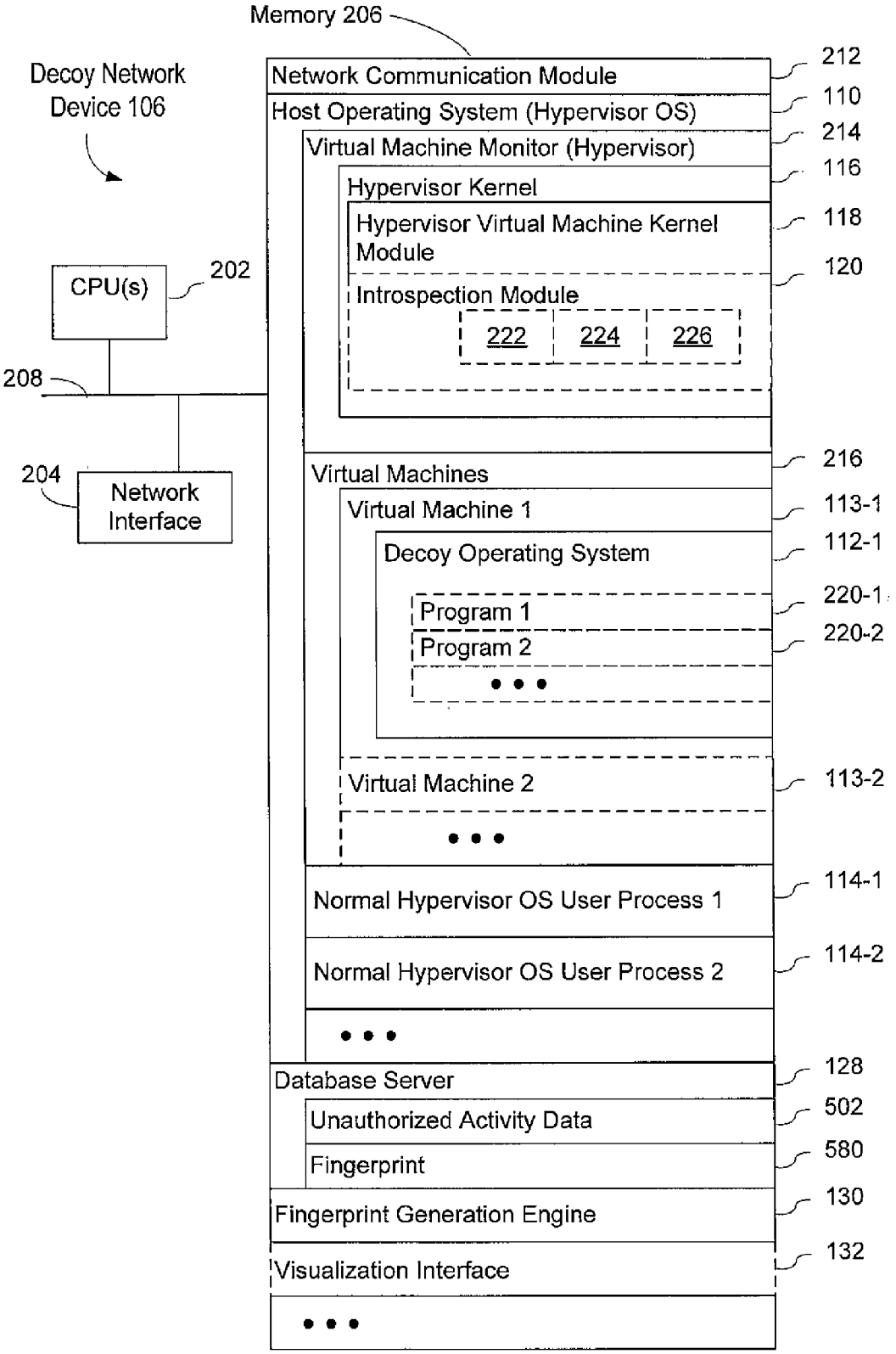

Memory 206
Decoy Network Device 106
Network Communication Module
212
Host Operating System (Hypervisor OS)
110
Virtual Machine Monitor (Hypervisor)
214
Hypervisor Kernel
116
Hypervisor Virtual Machine Kernel Module
118
Introspection Module
120
222
224
226
CPU(s)
202
208
204
Network Interface
Virtual Machines
216
Virtual Machine 1
113-1
Decoy Operating System
112-1
Program 1
220-1
Program 2
220-2
Virtual Machine 2
113-2
Normal Hypervisor OS User Process 1
114-1
Normal Hypervisor OS User Process 2
114-2
Database Server
128
Unauthorized Activity Data
502
Fingerprint
580
Fingerprint Generation Engine
130
Visualization Interface
132

Figure 2

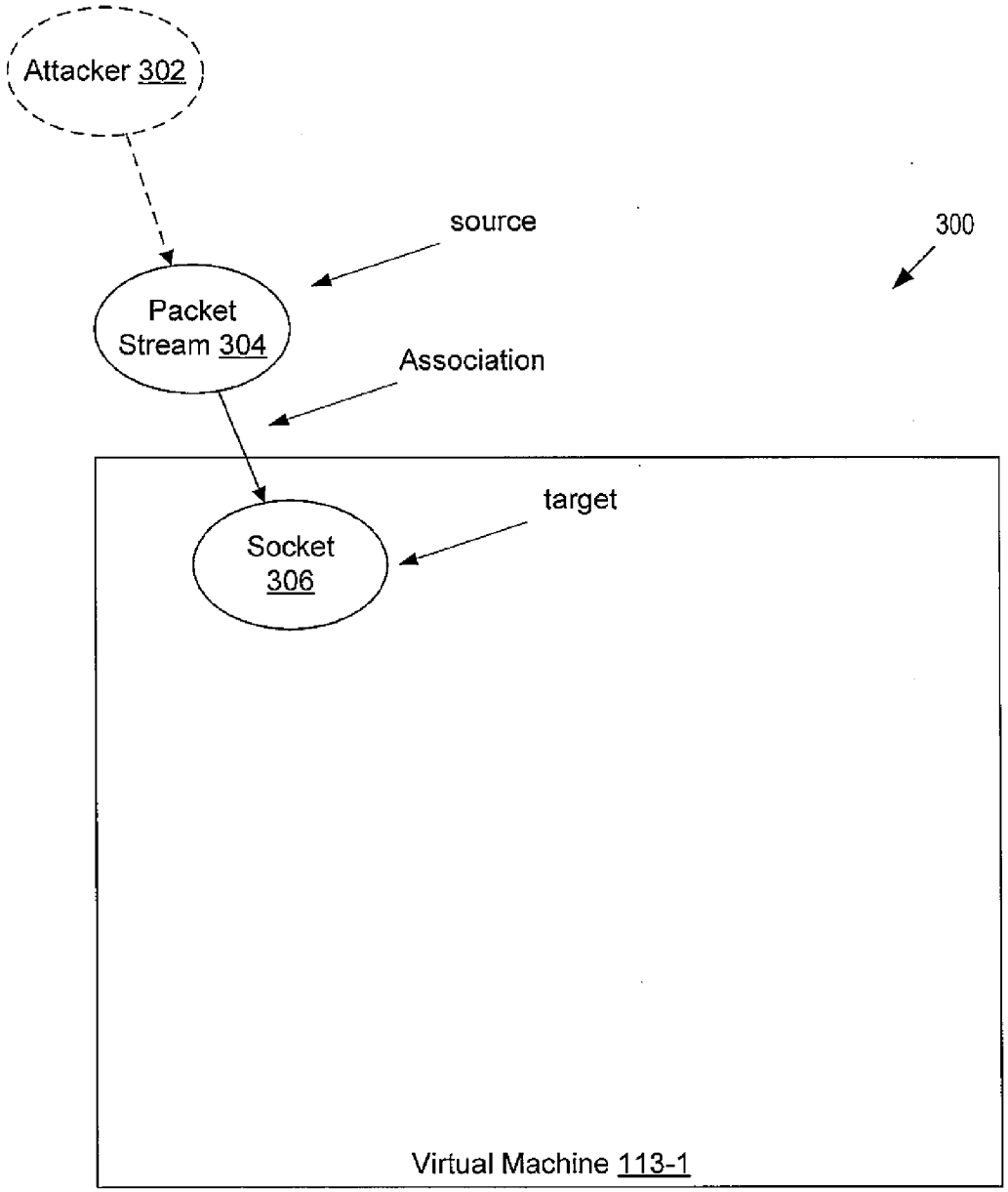

Attacker 302
source
300
Packet
Stream 304
Association
target
Socket
306
Virtual Machine 113-1

Figure 3A

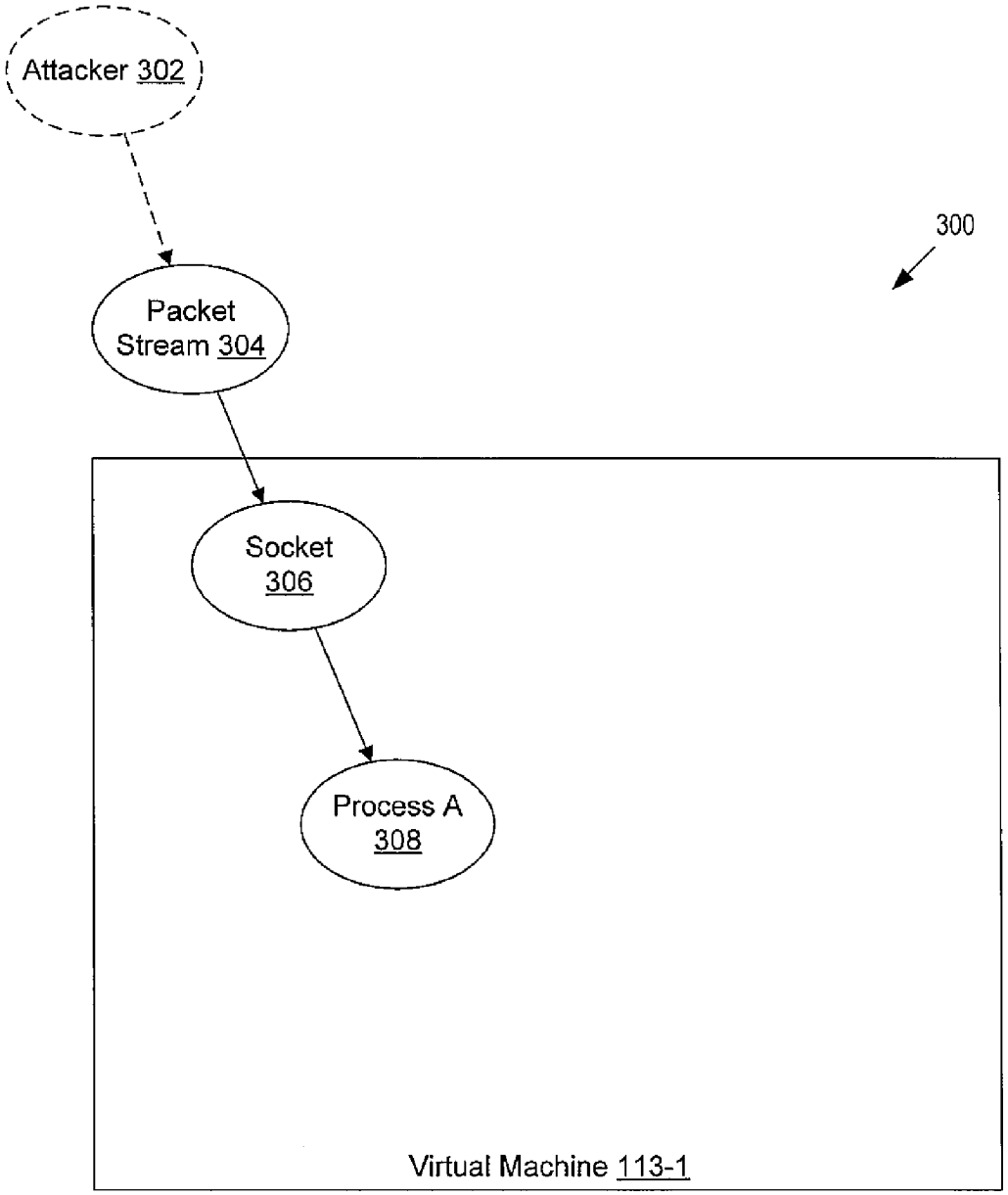

Attacker 302
300
Packet Stream 304
Socket 306
Process A 308
Virtual Machine 113-1

Figure 3B

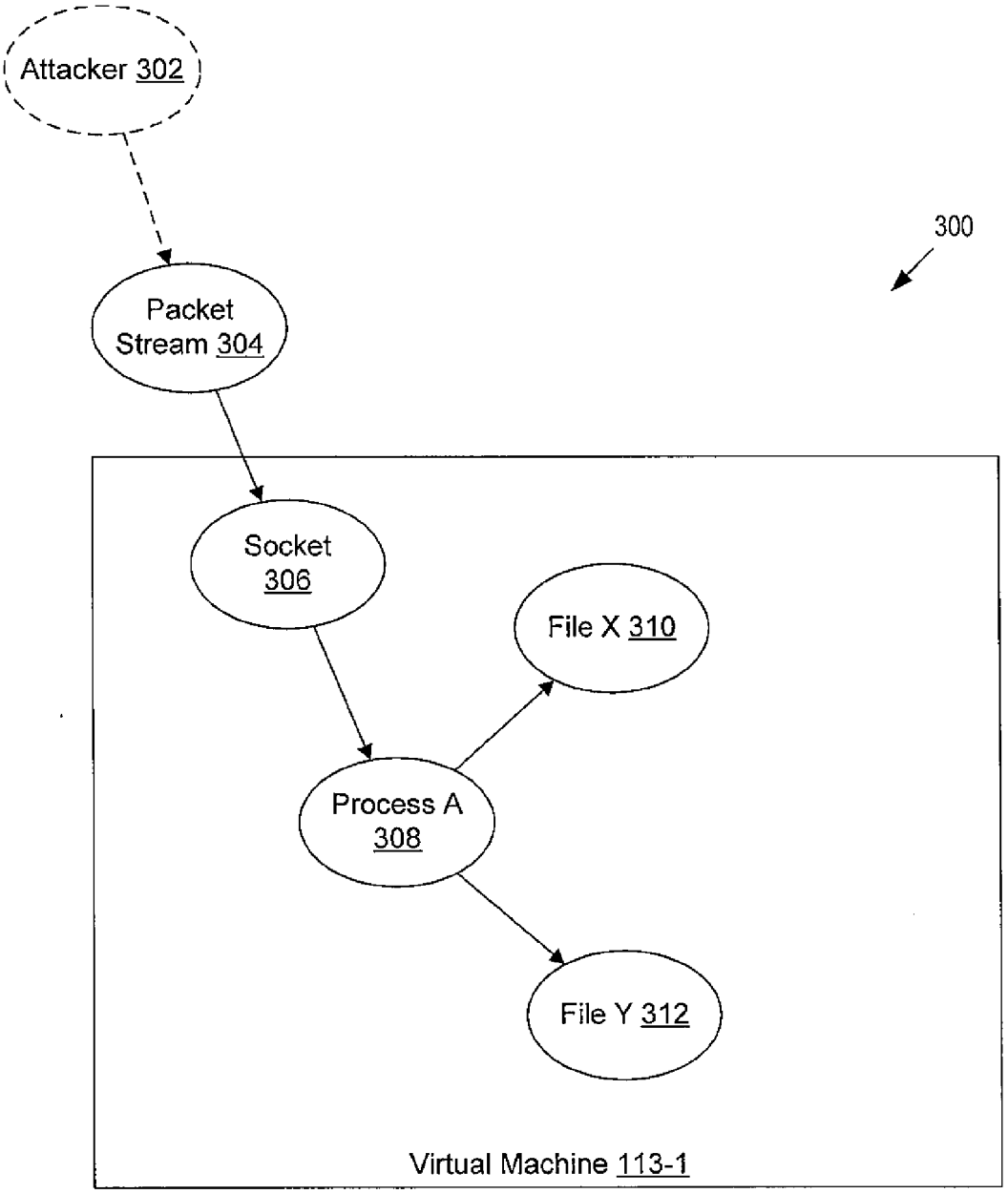

Attacker 302
300
Packet Stream 304
Socket 306
File X 310
Process A 308
File Y 312
Virtual Machine 113-1

Figure 3C

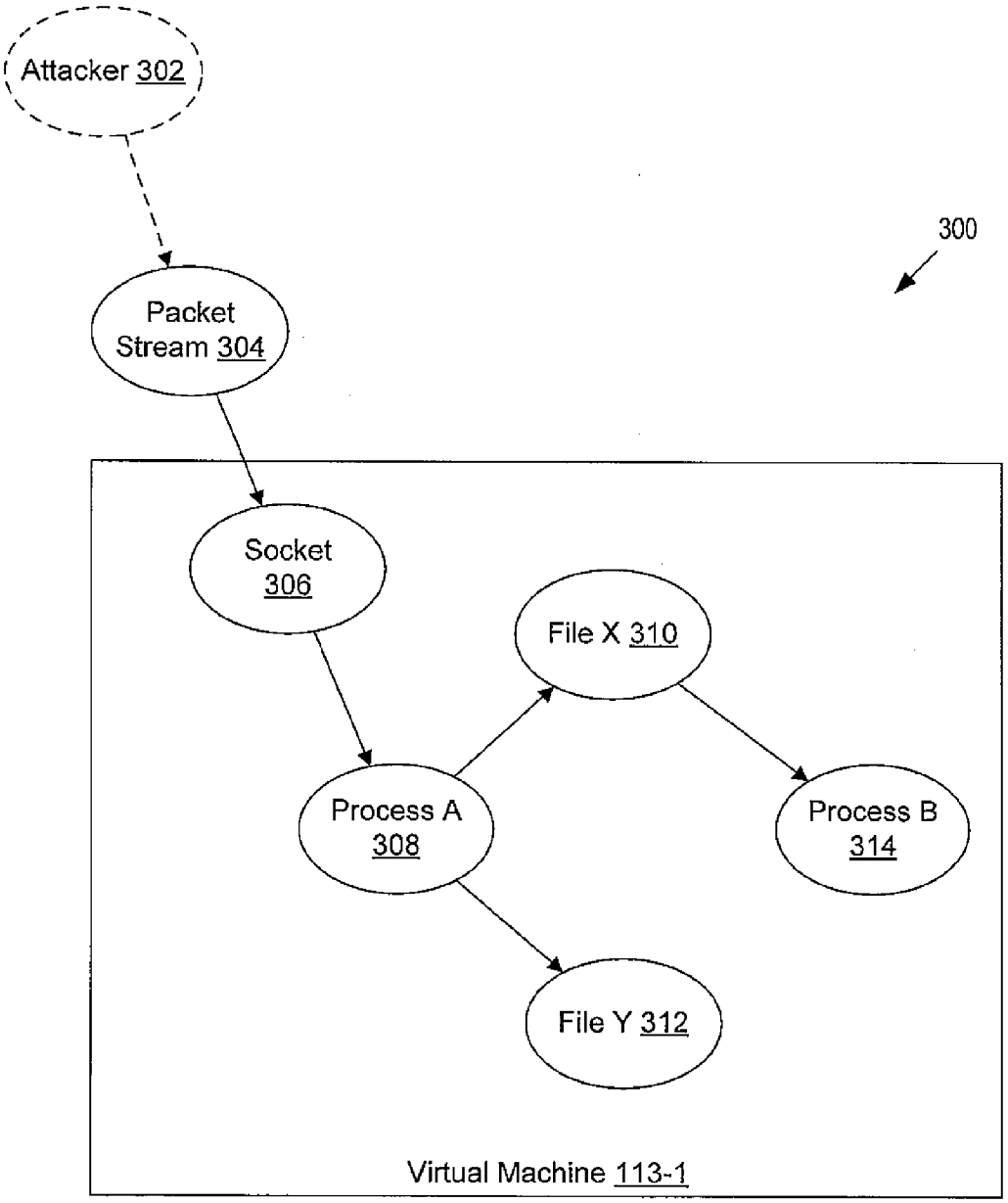

Attacker 302
300
Packet Stream 304
Socket 306
File X 310
Process A 308
Process B 314
File Y 312
Virtual Machine 113-1

Figure 3D

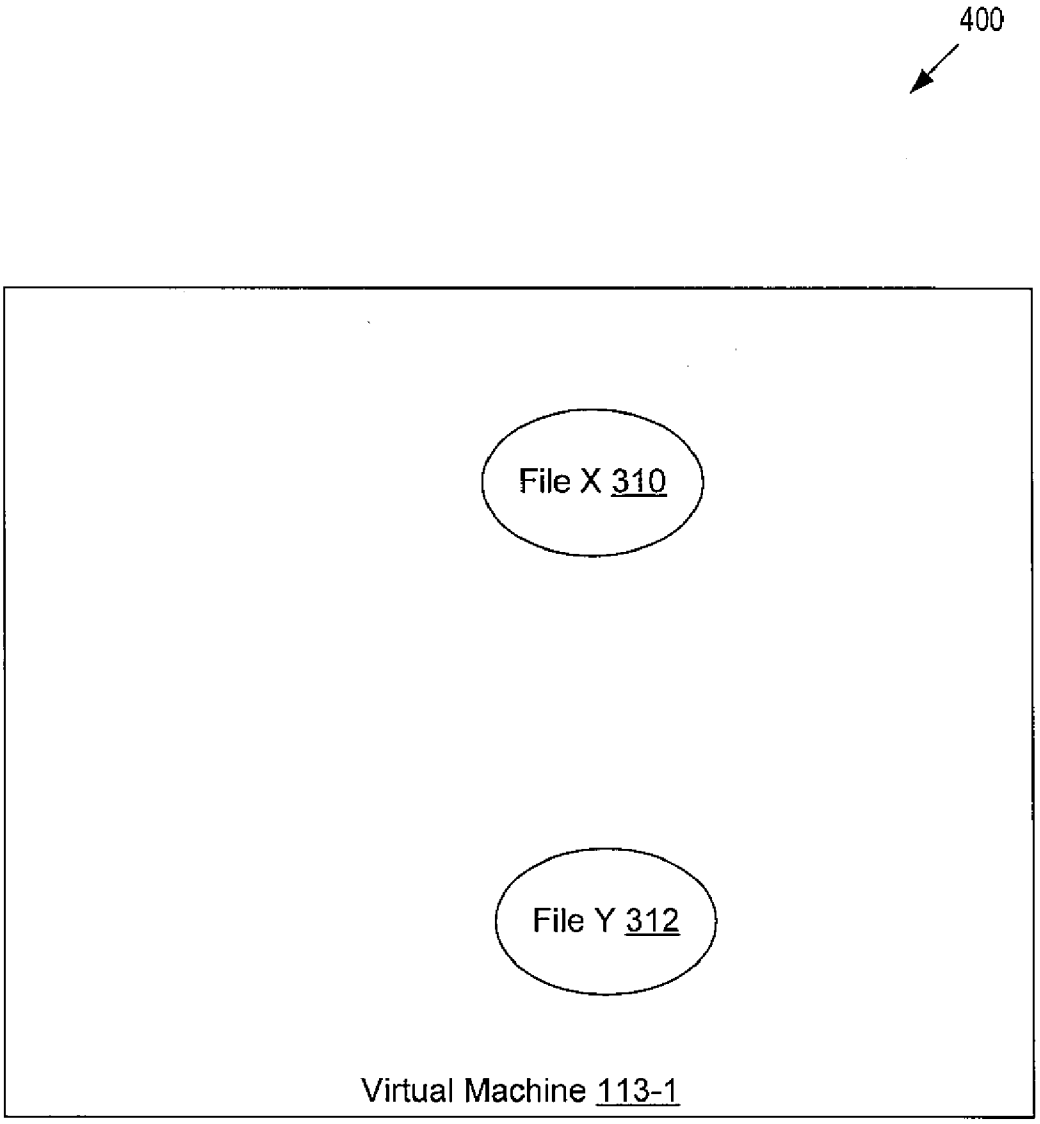


Figure 4A

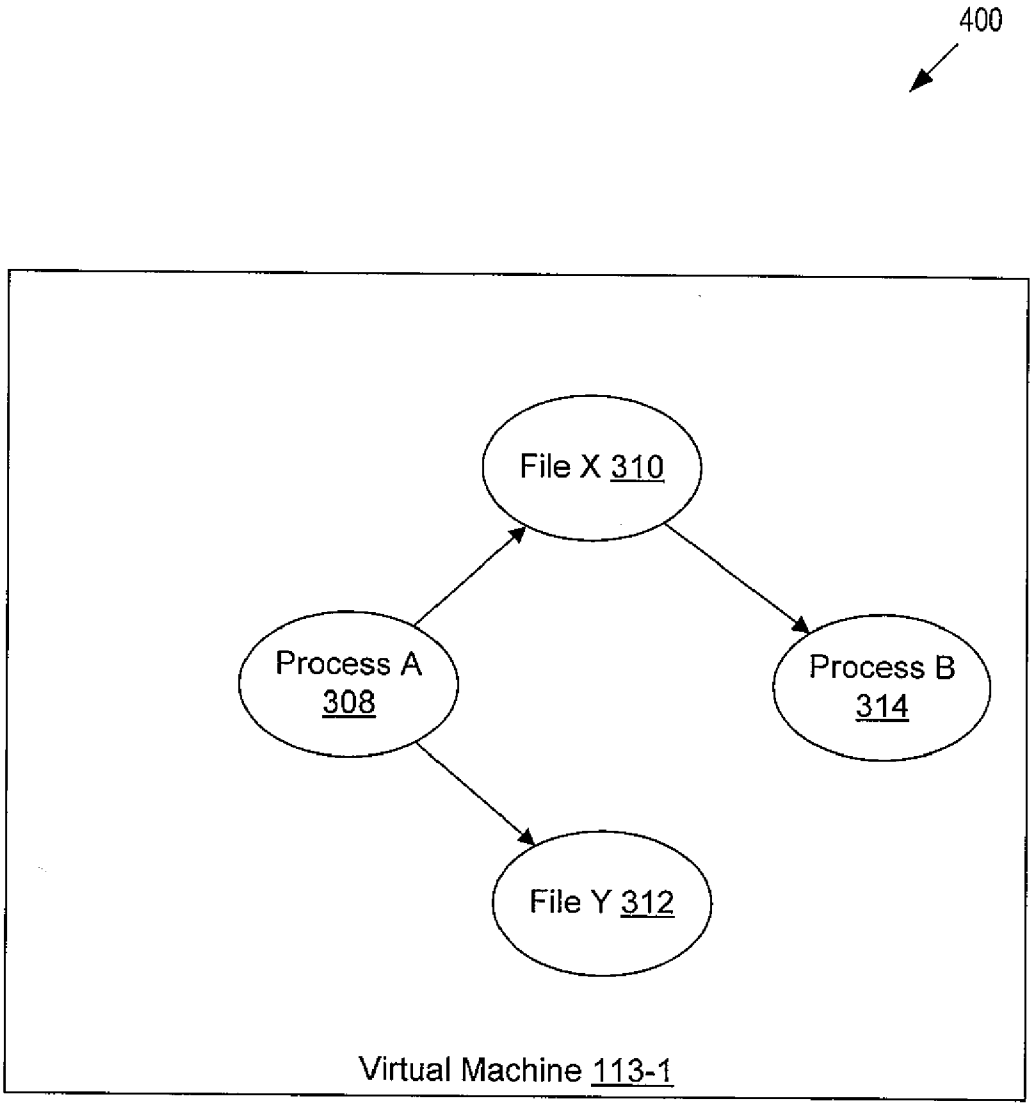

400
File X 310
Process A
308
Process B
314
File Y 312
Virtual Machine 113-1

Figure 4B

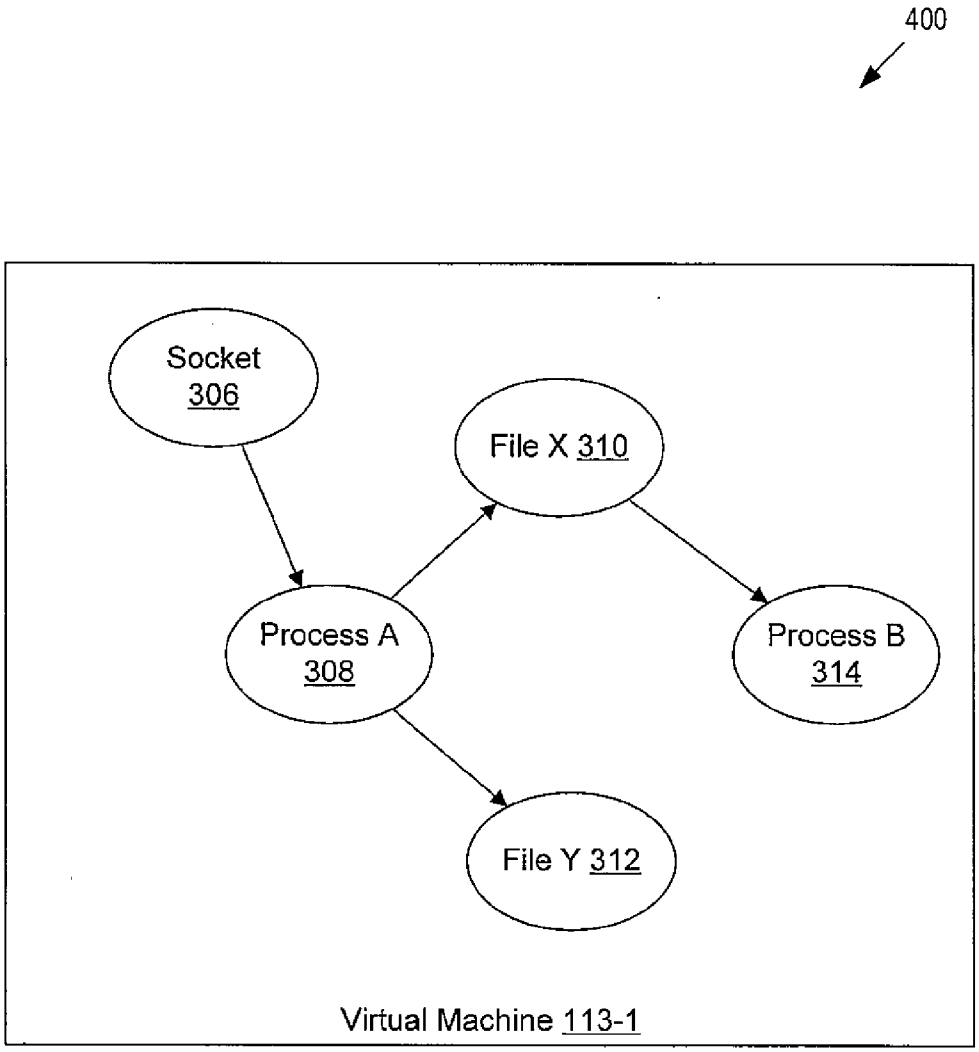

400
Socket
306
File X 310
Process A
308
Process B
314
File Y 312
Virtual Machine 113-1

Figure 4C

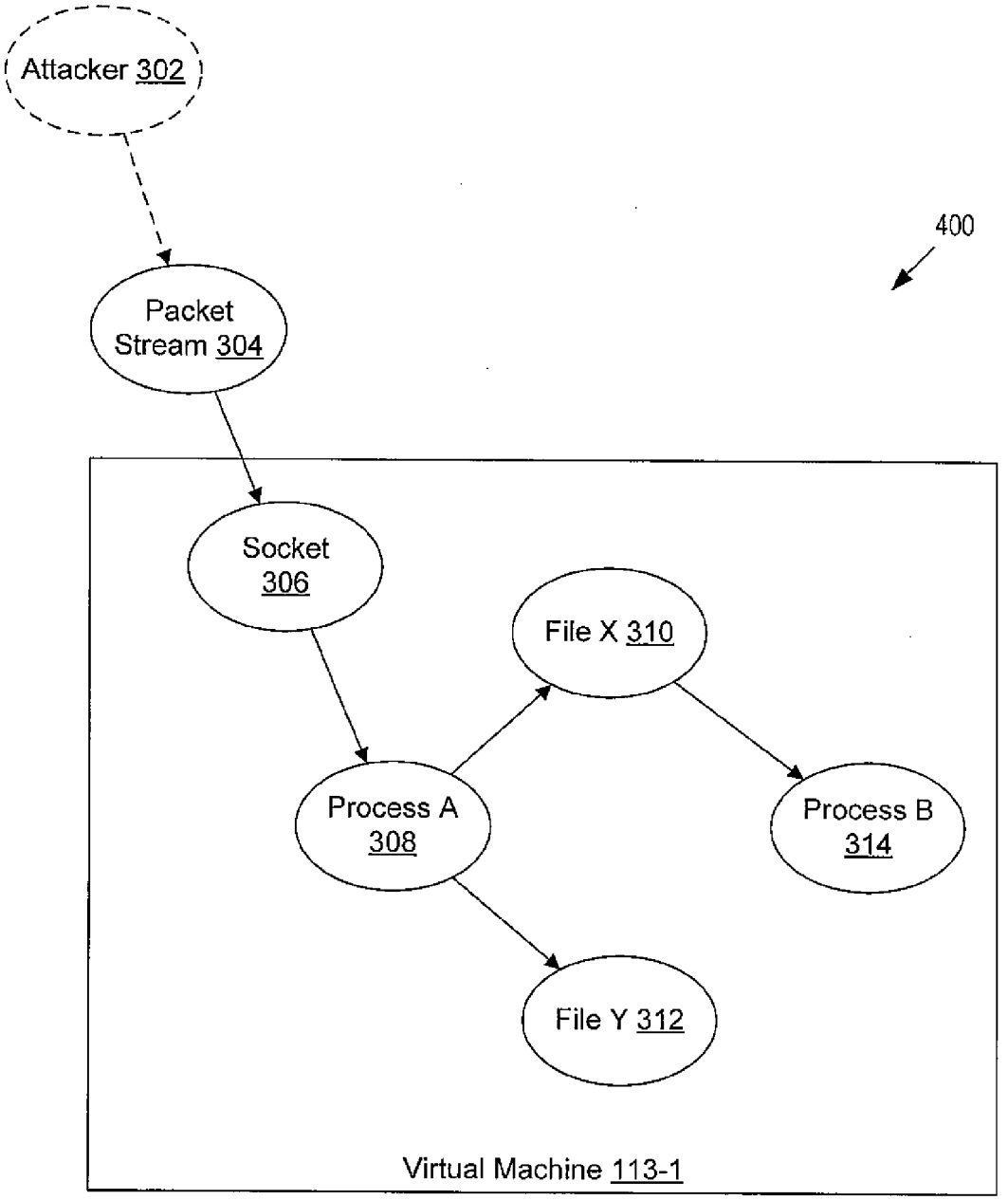

Attacker 302
400
Packet Stream 304
Socket 306
File X 310
Process A 308
Process B 314
File Y 312
Virtual Machine 113-1

Figure 4D

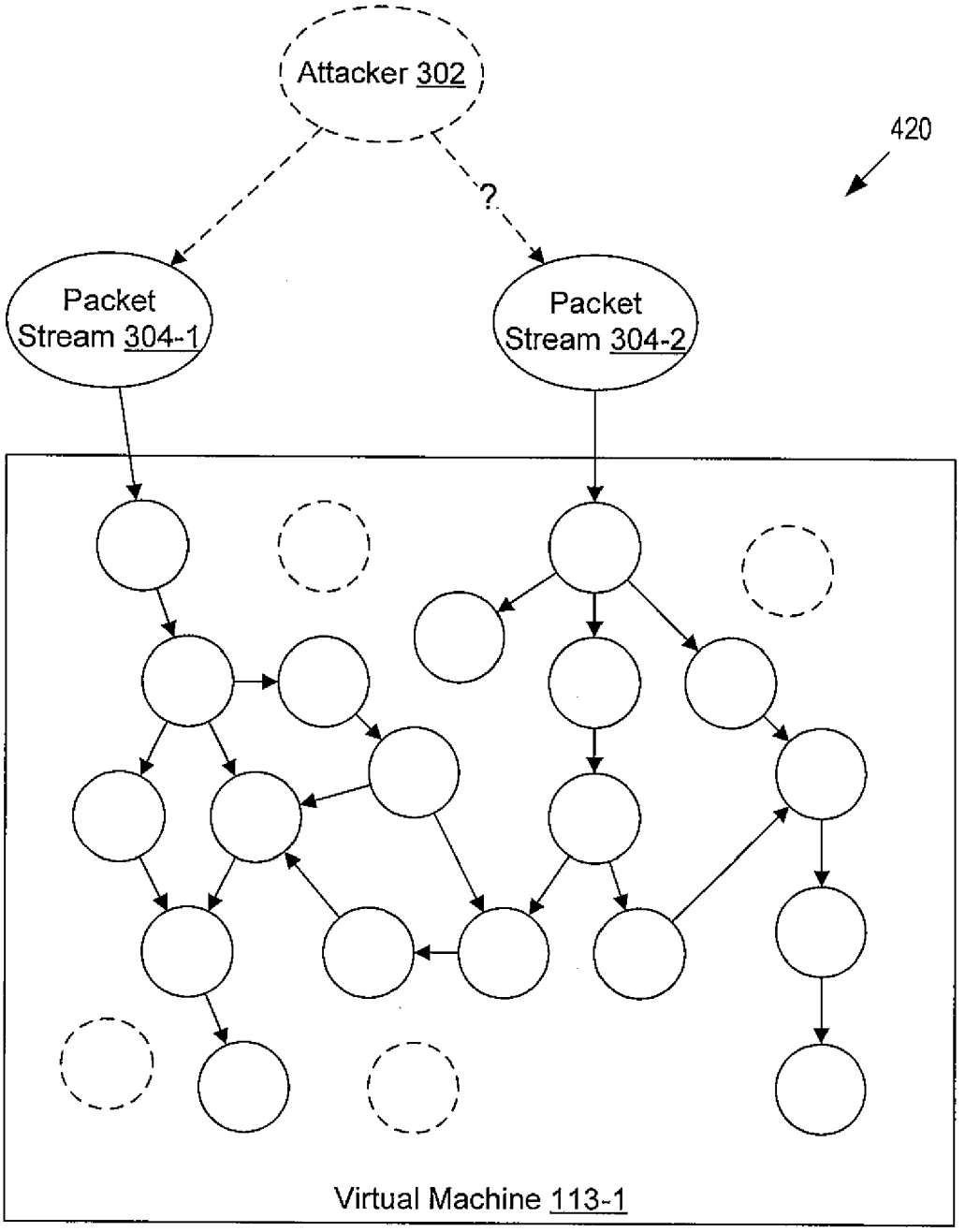

Attacker 302
420
?
Packet Stream 304-1
Packet Stream 304-2
Virtual Machine 113-1

Figure 4E

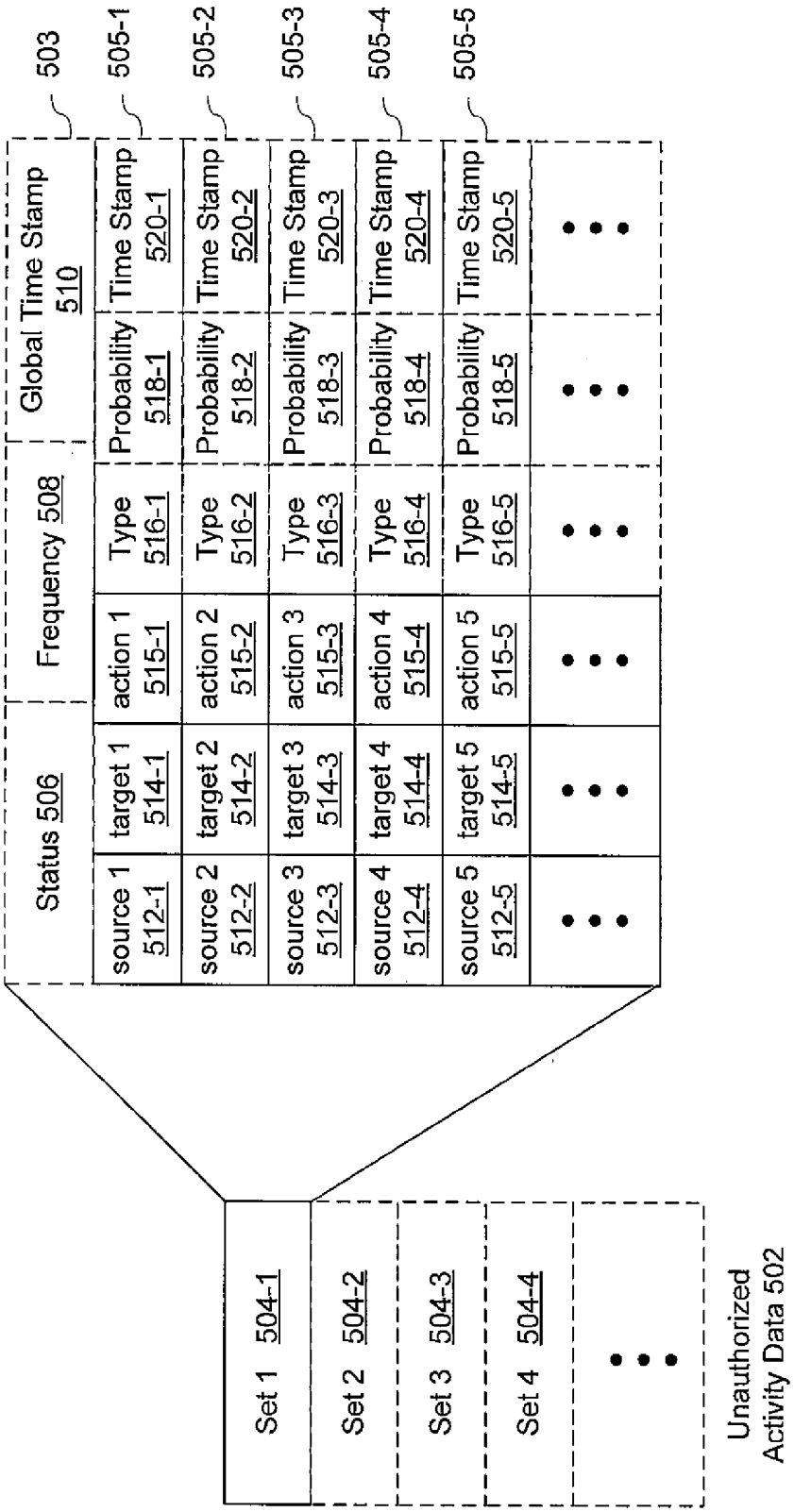

Set 1 504-1
Set 2 504-2
Set 3 504-3
Set 4 504-4
Unauthorized Activity Data 502
Status 506
Frequency 508
Global Time Stamp 510
503
source 1 512-1
target 1 514-1
action 1 515-1
Type 516-1
Probability 518-1
Time Stamp 520-1
505-1
source 2 512-2
target 2 514-2
action 2 515-2
Type 516-2
Probability 518-2
Time Stamp 520-2
505-2
source 3 512-3
target 3 514-3
action 3 515-3
Type 516-3
Probability 518-3
Time Stamp 520-3
505-3
source 4 512-4
target 4 514-4
action 4 515-4
Type 516-4
Probability 518-4
Time Stamp 520-4
505-4
source 5 512-5
target 5 514-5
action 5 515-5
Type 516-5
Probability 518-5
Time Stamp 520-5
505-5

Figure 5A

580-1

Status 506

source 1 512-1	target 1 514-1	Type 516-1	Time Stamp 520-1	505-1
source 2 512-2	target 2 514-2	Type 516-2	Time Stamp 520-2	505-2
source 3 512-3	target 3 514-3	Type 516-3	Time Stamp 520-3	505-3
source 4 512-4	target 4 514-4	Type 516-4	Time Stamp 520-4	505-4
source 5 512-5	target 5 514-5	Type 516-5	Time Stamp 520-5	505-5
⋮	⋮	⋮	⋮	

Figure 5B

580-2

source 1 512-1	Value 1 522-1	Method 1 524-1
source 2 512-2	Value 2 522-2	Method 2 524-2
source 3 512-3	Value 3 522-3	Method 3 524-3
source 4 512-4	Value 4 522-4	Method 4 524-4
source 5 512-5	Value 5 522-5	Method 5 524-5
⋮	⋮	⋮

Figure 5C

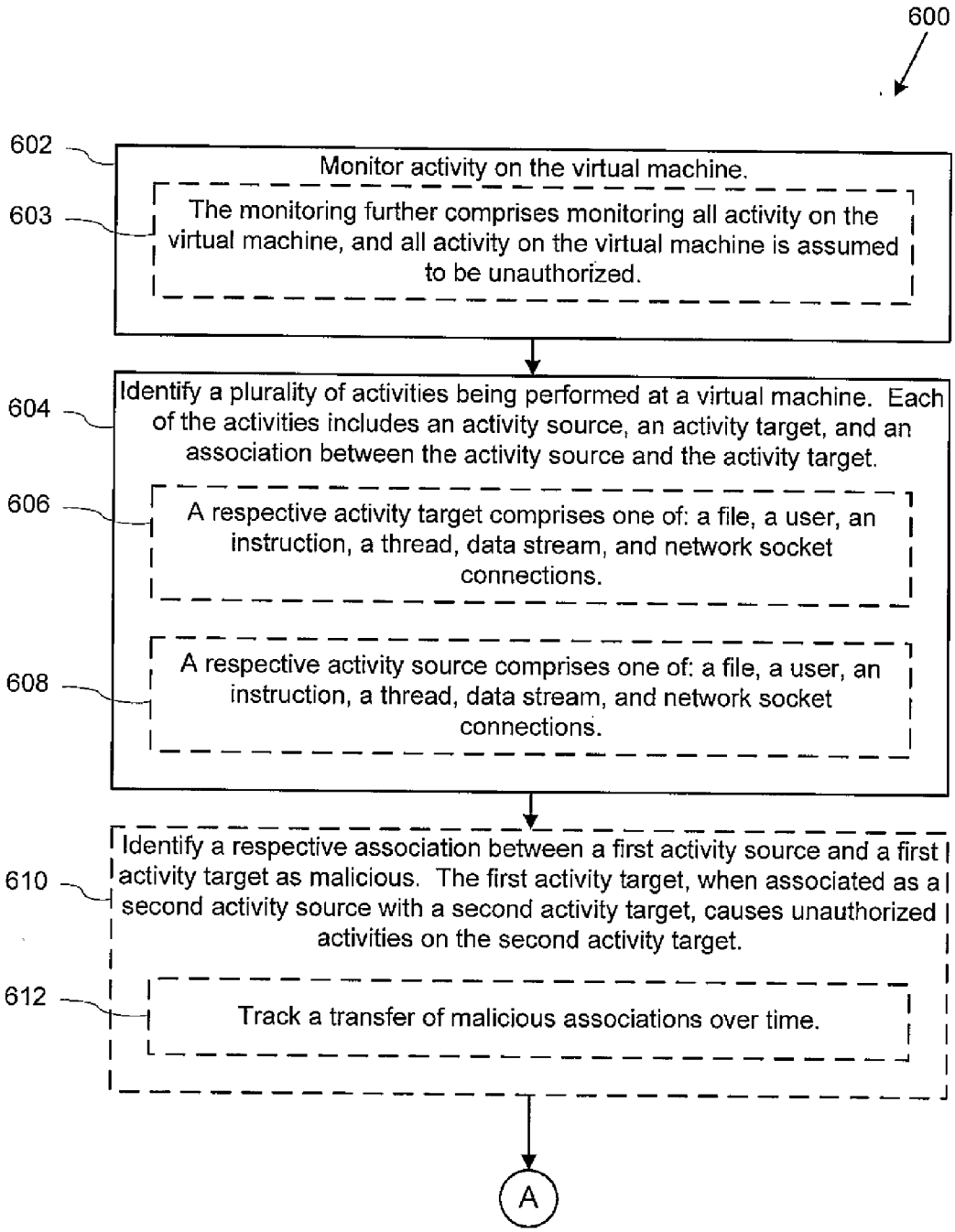

600
602
Monitor activity on the virtual machine.
603
The monitoring further comprises monitoring all activity on the virtual machine, and all activity on the virtual machine is assumed to be unauthorized.
604
Identify a plurality of activities being performed at a virtual machine. Each of the activities includes an activity source, an activity target, and an association between the activity source and the activity target.
606
A respective activity target comprises one of: a file, a user, an instruction, a thread, data stream, and network socket connections.
608
A respective activity source comprises one of: a file, a user, an instruction, a thread, data stream, and network socket connections.
610
Identify a respective association between a first activity source and a first activity target as malicious. The first activity target, when associated as a second activity source with a second activity target, causes unauthorized activities on the second activity target.
612
Track a transfer of malicious associations over time.
A

Figure 6A

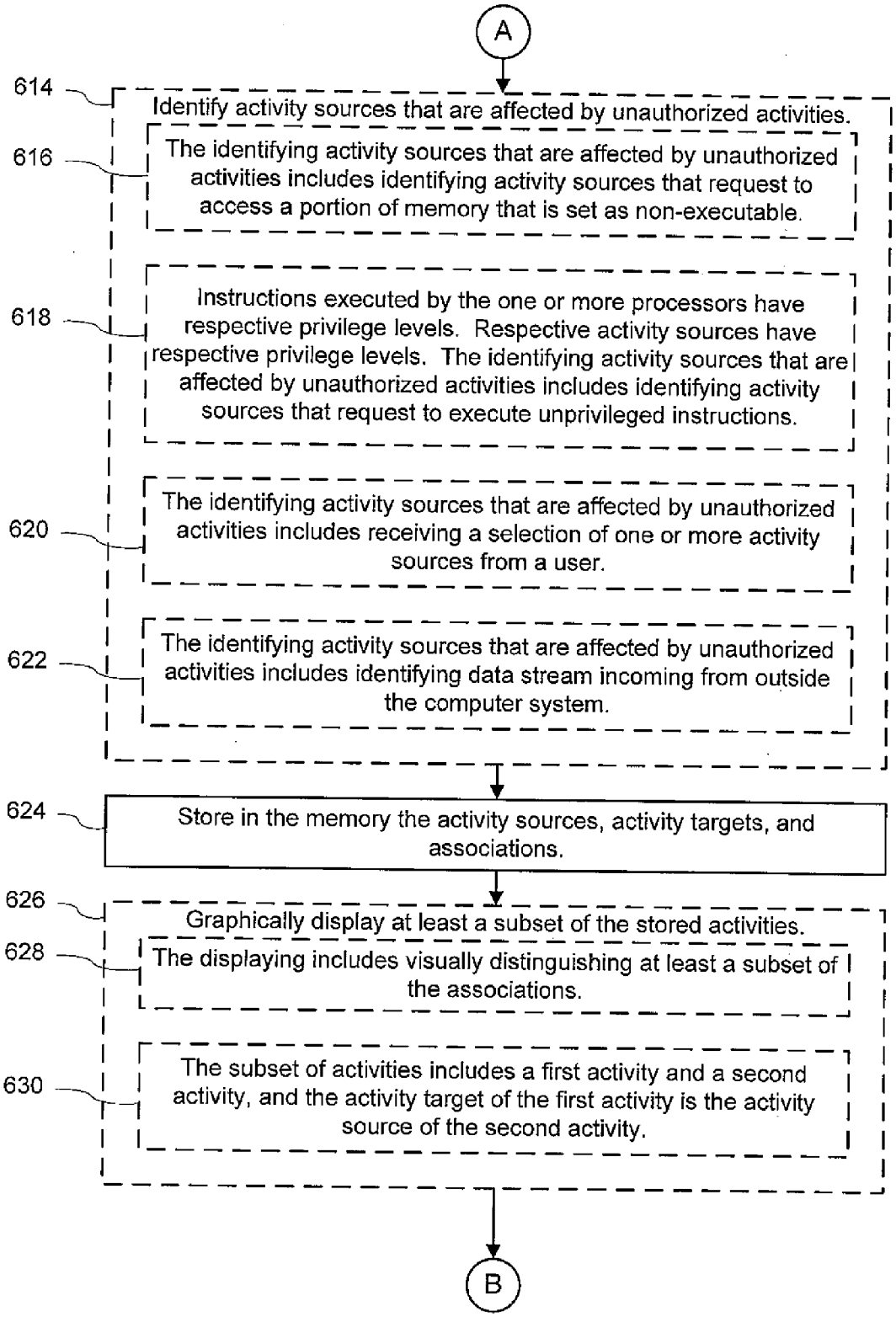

A
614
Identify activity sources that are affected by unauthorized activities.
616
The identifying activity sources that are affected by unauthorized activities includes identifying activity sources that request to access a portion of memory that is set as non-executable.
618
Instructions executed by the one or more processors have respective privilege levels. Respective activity sources have respective privilege levels. The identifying activity sources that are affected by unauthorized activities includes identifying activity sources that request to execute unprivileged instructions.
620
The identifying activity sources that are affected by unauthorized activities includes receiving a selection of one or more activity sources from a user.
622
The identifying activity sources that are affected by unauthorized activities includes identifying data stream incoming from outside the computer system.
624
Store in the memory the activity sources, activity targets, and associations.
626
Graphically display at least a subset of the stored activities.
628
The displaying includes visually distinguishing at least a subset of the associations.
630
The subset of activities includes a first activity and a second activity, and the activity target of the first activity is the activity source of the second activity.
B

Figure 6B

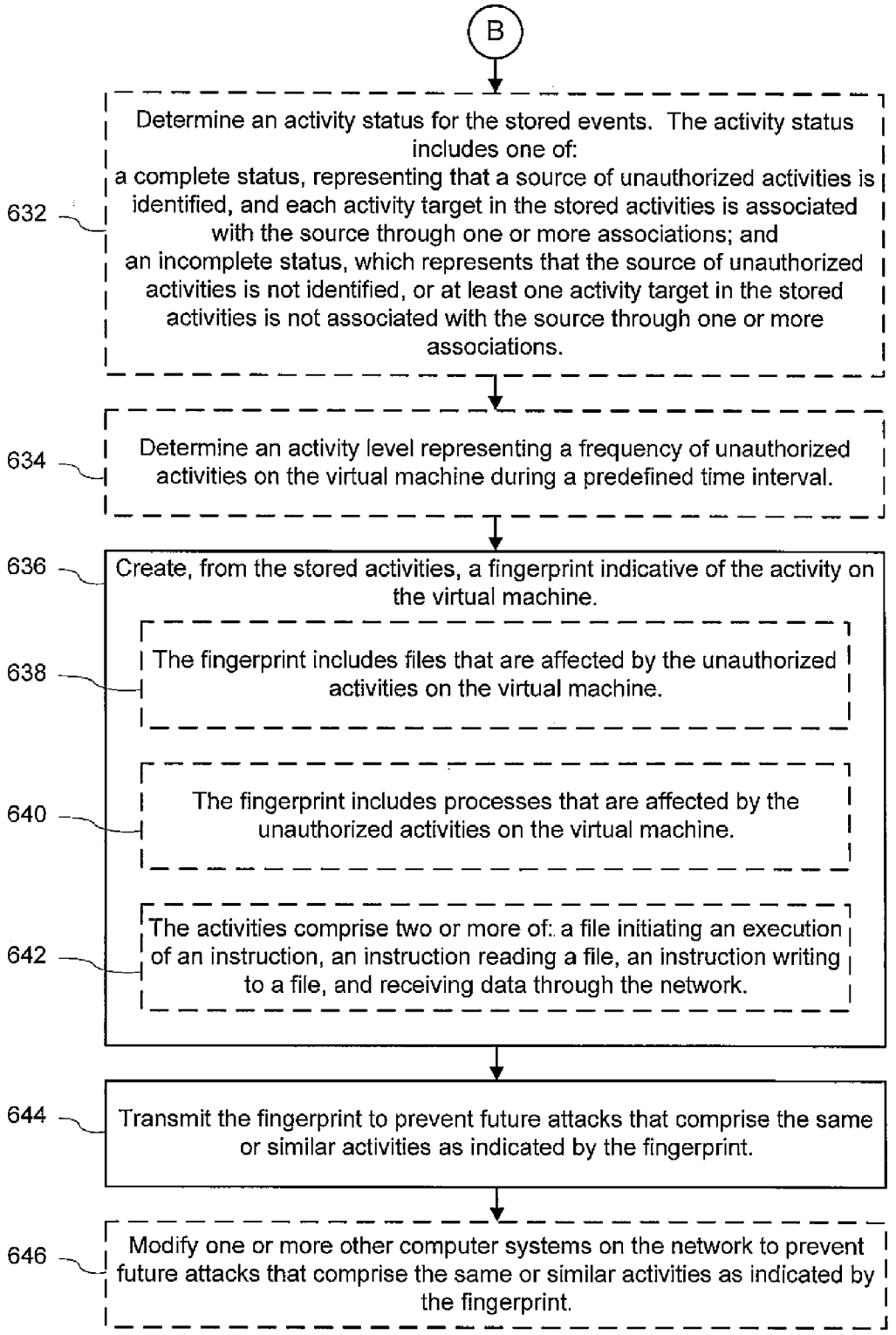

B
632
Determine an activity status for the stored events. The activity status includes one of:
a complete status, representing that a source of unauthorized activities is identified, and each activity target in the stored activities is associated with the source through one or more associations; and
an incomplete status, which represents that the source of unauthorized activities is not identified, or at least one activity target in the stored activities is not associated with the source through one or more associations.
634
Determine an activity level representing a frequency of unauthorized activities on the virtual machine during a predefined time interval.
636
Create, from the stored activities, a fingerprint indicative of the activity on the virtual machine.
638
The fingerprint includes files that are affected by the unauthorized activities on the virtual machine.
640
The fingerprint includes processes that are affected by the unauthorized activities on the virtual machine.
642
The activities comprise two or more of: a file initiating an execution of an instruction, an instruction reading a file, an instruction writing to a file, and receiving data through the network.
644
Transmit the fingerprint to prevent future attacks that comprise the same or similar activities as indicated by the fingerprint.
646
Modify one or more other computer systems on the network to prevent future attacks that comprise the same or similar activities as indicated by the fingerprint.

Figure 6C

SYSTEM AND METHOD FOR IDENTIFYING UNAUTHORIZED ACTIVITIES ON A COMPUTER SYSTEM USING A DATA STRUCTURE MODEL

RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Application Ser. No. 61/358,367, entitled "System and Method for Identifying Unauthorized Activities on a Computer System Using a Data Structure Model" filed on Jun. 24, 2010, which is incorporated by reference herein.

[0002] This relates to U.S. patent application Ser. No. _____, entitled "System and Method for Sampling Forensic Data of Unauthorized Activities Using Executability States" filed concurrently herewith, which claims priority to U.S. Provisional Application Ser. No. 61/358,363 filed on Jun. 24, 2010, entitled "System and Method for Sampling Forensic Data of Unauthorized Activities Using Executability States," both of which are incorporated by reference herein.

[0003] This application relates to U.S. patent application Ser. No. 11/788,795, entitled "System and Method for Analyzing Unauthorized Intrusion into a Computer Network," filed on Apr. 20, 2007, which is a continuation-in-part of U.S. patent application Ser. No. 11/488,743, entitled "Decoy Network Technology With Automatic Signature Generation for Intrusion Detection and Intrusion Prevention Systems," filed on Jul. 17, 2006, both of which are incorporated herein by reference in their entireties.

TECHNICAL FIELD

[0004] This invention relates generally to systems and methods for protecting computer networks, including but not limited to systems and methods for analyzing malicious activities on a computer system in order to better protect the computer system from future malicious activity.

BACKGROUND

[0005] An increasing number of computers are connected to computer networks (e.g., the Internet). Networked computers provide a significant benefit of accessing and sharing data over the networks. However, these networked computers are also vulnerable to attacks, unwanted intrusions, and unauthorized access.

[0006] Certain existing network security systems have been developed to protect computers from attacks, unwanted intrusions, unauthorized access, and other malicious activities. Such network security systems typically include a firewall to prevent unauthorized access to the network or its computers. Exemplary network security systems also include intrusion detection systems (IDS) and intrusion prevention systems (IPS) that typically contain a library of malware fingerprints (e.g., fingerprints of malware payloads and other unauthorized activities). By using the malware fingerprints, the IDS or the IPS can detect attempts to access computer systems without authorization. When a connection is attempted to a network port, the IDS or IPS examines the low-level IP data packets and compares them to its library of fingerprints for a match. When a match is identified, the IDS or IPS provides notification of the match and/or prevents further access. Therefore, the malware fingerprints play a critical role in network security.

[0007] A critical threat to computer networks is the so-called zero-day attack that exploits security vulnerabilities previously unknown to software developers or system operators. Because the security vulnerabilities are unknown to the software developers or system operators, often the fingerprints of such zero-day attacks are unavailable for comparison. Until the fingerprints are identified, attacks exploiting the same security vulnerabilities continue without detection by the network security systems. However, identifying the fingerprints of malicious activities in the middle of numerous other non-malicious processes is not a trivial task.

[0008] Because network security systems depend on the malware fingerprints, there is a great need for efficient methods of identifying fingerprint data for previously unknown types of malicious and/or unauthorized activities.

SUMMARY

[0009] A number of embodiments that address the limitations and disadvantages described above are presented in more detail below. These embodiments provide computer-implemented methods and systems for generating fingerprint data for zero-day unauthorized activities.

[0010] As described in more detail below, some embodiments involve a computer-implemented method performed at a computer system having one or more processors and memory storing one or more programs for execution by the one or more processors. The method includes monitoring activity on the virtual machine. A plurality of activities performed at a virtual machine is identified. Each of the activities includes an activity source, an activity target, and an association between the activity source and the activity target. The activity sources, activity targets, and associations are stored in the memory. A fingerprint indicative of the activity on the virtual machine is created from the stored activities. The fingerprint is transmitted to one or more other computer systems on the network to prevent future attacks that comprise the same or similar activities as indicated by the fingerprint. In some embodiments, the fingerprint is transmitted to identify the attack on other affected systems.

[0011] In accordance with some embodiments, the system includes one or more processors, and memory. The memory stores a virtual machine, a virtual machine monitor supervising the virtual machine, and one or more programs. The virtual machine, the virtual machine monitor, and the one or more programs are configured for execution by the one or more processors. The one or more programs include instructions for monitoring activity on the virtual machine, and instructions for identifying a plurality of activities being performed at the virtual machine. Each of the activities includes an activity source, an activity target, and an association between the activity source and the activity target. The one or more programs furthermore include instructions for storing the activity sources, activity targets, and associations in the memory. The one or more programs also include instructions for creating a fingerprint indicative of the activity on the virtual machine from the stored activities. Finally, the one or more programs include instructions for transmitting the fingerprint to one or more other computer systems on the network to prevent future attacks that comprise the same or similar activities as indicated by the fingerprint. In some embodiments, the one or more programs include instructions for displaying at least a subset of the activities (e.g., action sources, action targets, and actions).

[0012] In accordance with some embodiments, a computer readable storage medium stores one or more programs configured for execution by one or more processors of a com-

puter. The one or more programs include instructions for performing the method described above.

[0013] These embodiments identify unauthorized activities by monitoring and identifying associations between activity sources and activity targets without using pre-determined fingerprints. The data collected by these embodiments can be used to generate fingerprint data in response to the zero-day attacks.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] For a better understanding of the aforementioned aspects of the invention as well as additional aspects and embodiments thereof, reference should be made to the Description of Embodiments below, in conjunction with the following drawings in which like reference numerals refer to corresponding parts throughout the figures.

[0015] FIG. **1** is a high-level block diagram illustrating an exemplary distributed computer system in accordance with some embodiments.

[0016] FIG. **2** is a block diagram illustrating a decoy network device, in accordance with some embodiments.

[0017] FIGS. **3**A-**3**D are exemplary network diagrams illustrating unauthorized activities on a network socket, in accordance with some embodiments.

[0018] FIGS. **4**A-**4**D are exemplary network diagrams illustrating unauthorized activities on files in a computer system, in accordance with some embodiments.

[0019] FIG. **4**E is an exemplary network diagram illustrating unauthorized activities on a computer system, in accordance with some embodiments.

[0020] FIG. **5**A illustrates an exemplary data structure of unauthorized activity data, in accordance with some embodiments.

[0021] FIG. **5**B illustrates an exemplary data structure of fingerprint, in accordance with some embodiments.

[0022] FIG. **5**C illustrates another exemplary data structure of fingerprint, in accordance with some embodiments.

[0023] FIGS. **6**A-**6**C are flowcharts representing a method of identifying unauthorized activities on a computer system, in accordance with some embodiments.

DESCRIPTION OF EMBODIMENTS

[0024] Embodiments of various systems and methods for identifying unauthorized activities are described below. Reference will be made to certain embodiments of the invention, examples of which are illustrated in the accompanying drawings. While the invention will be described in conjunction with the embodiments, it should be understood that these particular embodiments are not intended to limit the invention. Instead, the invention is intended to cover alternatives, modifications and equivalents that are within the spirit and scope of the invention as defined by the appended claims. Moreover, in the following description, numerous specific details are set forth to provide a thorough understanding of the present invention. However, it will be apparent to one of ordinary skill in the art that the invention may be practiced without these particular details. In other instances, methods, procedures, components, and networks that are well-known to those of ordinary skill in the art are not described in detail to avoid obscuring aspects of the present invention.

[0025] FIG. **1** illustrates an exemplary distributed computer system **100**, according to some embodiments. The system **100** includes a decoy computer network **102**, a communications network **148**, and protected computer network **104**. Various embodiments of the decoy computer network **102** and protected computer network **104** implement the unauthorized activity identifying methods described in this document.

[0026] In some embodiments, the systems on the decoy computer network **102** and the protected computer network **104** can be accessed by client computers **101**. The client computers **101** can be any of a number of computing devices (e.g., Internet kiosk, personal digital assistant, cell phone, gaming device, desktop computer, laptop computer, handheld computer, or combinations thereof) used to enable the activities described below. The client computer(s) **101** is also referred to herein as client(s). The clients **101** are connected to the decoy network device **106** and the protected network device **136** (e.g., **136-1**, **136-2**, and **136-*n***) via the communications network **148**.

[0027] The protected network devices **136-1** through **136-*n*** are accessible from the network **148** by one or more authorized users using the clients **101** (e.g., the protected network devices can be servers providing services for webpages, emails, file downloading and sharing, web applications, etc.). Typically, the protected computer network **104** includes a firewall/router **198** to protect the protected network devices **136** and route network traffic to and from the protected network devices **136**. Alternatively, the firewall/router **198** can protect both the decoy computer network **102** and the protected computer network **104**, as illustrated in FIG. **1**.

[0028] In some embodiments, the protected computer network **104** also includes an IDS/IPS system **142** (intrusion detection and prevention system). The IDS/IPS system **142** includes, or has access to, a fingerprint library. The fingerprint library includes fingerprints of unauthorized activities. The IDS/IPS system **142** identifies unauthorized activities based on the fingerprints stored in the fingerprint library, and provides notification to a user or a system administrator, and/or prevents unauthorized activities matching the stored fingerprints by modifying the protected network devices **136** and/or the firewall/router **198**. Suitable IDS/IPS systems **142** include Cisco Systems' IPS 4200 Series, Juniper's IDP 200, and Enterasys' Dragon IDS Network Sensor.

[0029] As explained above, in some embodiments, the IDS/IPS system **142** is coupled to the firewall/router **198** such that the IDS/IPS system can reconfigure the firewall/router **198** to protect the protected network devices **136** in the protected computer network **104** from future attacks. In some embodiments, the IDS/IPS and the firewall are located in a single combined device.

[0030] The decoy computer network **102** includes one or more decoy network device(s) **106**. The decoy network device **106** is a decoy system that is monitored to collect fingerprint data of unauthorized activities. In some embodiments, the decoy network device **106** is intentionally kept vulnerable to unauthorized or malicious activities (e.g., known security weaknesses may be intentionally left unfixed or other security components (e.g., firewalls) are intentionally not installed). In other embodiments, the decoy network device **106** includes security devices and software applications like other protected network devices (e.g., the decoy network device **106** may be protected by the firewall/router **198** and any other security measures included in the protected network devices **136**). The purpose of the decoy network device **106** is to allow attackers to attack the decoy network device **106**, so that the pattern of the attack can be monitored

and analyzed to generate a fingerprint. This fingerprint of the attack can be used to prevent similar attacks on the decoy network device **106** and/or other computers (e.g., protected network devices **136**).

[0031] Attackers can initiate attacker activities over the communications network(s) **148** on both the decoy computer network **102** and the protected computer network **104**. Ideally, the firewall/router **198** or security software on the protected network devices **136** will protect the protected network devices **136** from at least some of the attacker activity(s), whereas the decoy network device **106** is typically exposed to the attacker activity(s) in order to attract the attacks.

[0032] Although FIG. **1** illustrates the decoy computer network **102** and the protected computer network **104** as separate networks, in some embodiments, they are part of a same network. For example, in some embodiments, the protected computer network **104** includes the decoy computer network **102**. In other embodiments, the decoy computer network **102** and the protected computer network **104** are the same network. Although the methods described herein are described with respect to monitoring the decoy network device **106**, persons having ordinary skill in the art would recognize that similar methods may be used for monitoring one or more non-decoy systems, such as the protected network device **136**.

[0033] FIG. **2** is a block diagram illustrating the decoy network device **106** in accordance with some embodiments. The decoy network device **106** typically includes one or more processing units (CPUs) **202**, one or more network or other communications interfaces **204**, memory **206**, and one or more communication buses **208** for interconnecting these components. In some embodiments, the communication buses **208** include circuitry (sometimes called a chipset) that interconnects and controls communications between system components. In some other embodiments, the decoy network device **106** includes a user interface (not shown) (e.g., a user interface having a display device, a keyboard, and a mouse or other pointing device), but when implemented as a server, the decoy network device **106** is more typically controlled from and accessed by various client systems (e.g., the client **101** in FIG. **1**; and more typically, a client connected through a secure private network).

[0034] The memory **206** of the decoy network device **106** includes high-speed random access memory, such as DRAM, SRAM, DDR RAM or other random access solid state memory devices; and may include non-volatile memory, such as one or more magnetic disk storage devices, optical disk storage devices, flash memory devices, or other non-volatile solid state storage devices. The memory **206** may optionally include one or more storage devices remotely located from the CPU(s) **202**. The memory **206**, or alternately the non-volatile memory device(s) within the memory **206**, comprises a computer readable storage medium. The memory **206** or the computer readable storage medium of the memory **206** stores one or more of the following programs:

[0035] the network communication module (or instructions) **212** that is used for connecting the decoy network device **106** to computer networks (e.g., communication network(s) **148**, decoy computer network **102**, and protected computer network **104**), and/or other computers (e.g., the client **101**) via the one or more communications interfaces **204** and one or more communications networks **148**, such as the Internet, a wireless network (e.g., Wi-Fi, WiMAX, 3G, 4G, etc.), any local area network (LAN), wide area network (WAN), metropolitan area network, or a combination of such networks;

[0036] the host operating system **110** (also called Hypervisor OS) that includes procedures for handling various basic system services and for performing hardware dependent tasks;

[0037] database server **128**, which stores data (e.g., unauthorized activity data **502** and/or fingerprint **580**);

[0038] fingerprint generation engine **130**, which generates the fingerprint data **580** from the unauthorized activity data **502**); and

[0039] visualization interface **132**, which prepares data (e.g., the fingerprint or unauthorized activities on the computer system) for display (e.g., on a GUI of a client **101**).

[0040] The fingerprint **580**, as described below with reference to FIGS. **5**B and **5**C, include data indicative of unauthorized activities on the decoy network device **106**. Such fingerprint **580** can be used (e.g., by the IDS/IPS system **142**) to detect and prevent unauthorized activities on protected network devices **136**.

[0041] In some embodiments, the host operating system (e.g., the host OS **110**) includes one or more of the following:

[0042] a virtual machine monitor **214** (also called a hypervisor);

[0043] virtual machines **216**, including virtual machine **1** (**113-1**) and (optional) virtual machine **2** (**113-2**); and

[0044] normal hypervisor OS user processes (e.g., **114-1** and **114-2**), such as administrative utilities, network tools (e.g., netcat and ifconfig), shell processes (e.g., ssh and bash), package management utilities (e.g., dpg and apt), drivers, filesystem utilities, and programming environments (e.g., python and lua).

[0045] The virtual machine monitor **214** includes a hypervisor kernel **116** that resides in physical memory and provides the basic services to the virtual machine monitor **214**. In some embodiments, the hypervisor kernel **116** is a part of the hypervisor operating system **110** (e.g., a kernel of the hypervisor operating system **110**). In such embodiments, the hypervisor kernel **116** is a part of the operating system that activates the hardware directly or interfaces with another software layer that, in turn, drives the hardware.

[0046] The hypervisor kernel **116** includes a hypervisor virtual machine kernel module **118** that supports virtualization of a "guest" decoy operating system **112**. The hypervisor kernel **116** also includes an introspection module **120** interposed between the virtual machine monitor **214** and decoy operating system(s) **112**. The introspection module **120** performs introspection (e.g., monitoring) into the physical memory segments assigned to each of the virtualized decoy operating system **112**.

[0047] Because no software is installed in the virtualized decoy operating system **112**, it is more difficult for the virtualized decoy operating system **112** (or an attacker who has gained access to the virtualized decoy operating system **112**) to detect that its memory is being monitored.

[0048] The introspection module is configured to examine the memory assigned to virtualized decoy operating systems **112** in order to acquire low-level data about the interaction between the decoy operating systems **112** and attack activity. The introspection module examines the memory of virtualized decoy operating systems **112** by means of three functional components: a code region selector **222**, a trace instrumentor **224**, and a trace analyzer **226**. Regular expressions

(also known as 'regex') are used throughout the process to identify, describe, and profile the contents of the memory segments of the virtualized decoy operating systems **112**. The code selector **222** identifies regions of code in memory that are of interest for further introspection. Regions of interest may include, but are not limited to, system calls, the arguments of system calls, the returns of system calls, device and memory input-output, driver information, library calls, branching information, instruction pointer jumps, and raw network information. The instrumentor **224** copies the memory traces of interest identified by the code selector and then profiles them. The trace analyzer **226** takes the profiled traces and uses them to build a simulation of the states in the virtualized decoy operating system **112** over time. In this manner, the introspection module examines the contents of the memory segments of the virtualized decoy operating systems **112** in an instrumented context that generates and retrieves forensic data (or fingerprint). In some embodiments, the trace analyzer **226** is located outside the introspection module **120** (e.g., in the fingerprint generation engine **130**).

[0049] In some embodiments, the trace instrumentor **224** is configured to perform operations in accordance with one or more user-defined conditions. The one or more user-defined conditions may specify when one or more memory traces should be generated. Respective user-defined conditions may be rule-based or pattern-based, and may be based on system states or independent of system states. In some embodiments, the trace analyzer **226** is configured to perform operations in accordance with one or more user-defined conditions. The one or more user-defined conditions may specify what portions of the profiled traces to analyze. This allows the user to easily find traces of interest, without having to go through the entire set of traces.

[0050] In some embodiments, the introspection module **120** is configured to pause the execution of the virtualized decoy operating system **112**, copy the content of memory at prescribed locations, and return execution control to the virtualized decoy operating system **112**. In some embodiments, the introspection module **120** pauses the execution of the virtualized decoy operating system **112** for preventing malicious or undesired execution from occurring in the virtualized decoy operating system **112**.

[0051] An attacker may be able to detect that the decoy operating system **112** is a virtualized operating system, based on the time it takes to perform standardized tasks. However, since the introspection module **120** runs completely outside the virtualized decoy operating system **112**, it is difficult for an attacker accessing the decoy operating system **112** to determine whether the decoy operating system **112** is being monitored. In other words, the attacker may suspect that the virtual machine monitor **214** exists, but the attacker may not determine whether the virtual machine monitor **214** includes the introspection module **120**. As explained above, the introspection module **120** monitors and introspects into the memory segments of the virtualized decoy operating systems **112**. The introspection module **120** introspects and gathers information on any virtualized operating system supported by the hypervisor operating system **110**.

[0052] The virtual machines **216** are one or more software applications emulating one or more physical machines (e.g., computer systems). In some embodiments, at least one virtual machine (e.g., the virtual machine **1** (**113-1**)) includes a decoy operating system **112-1**, which in turn optionally includes one or more programs (e.g., **220-1** and **220-2**). The virtualized decoy operating systems **112** access the physical memory assigned to them by the virtual machine monitor **214** (or the hypervisor kernel **116**).

[0053] These virtualized operating systems **112** act as decoy operating systems to attract attacker activity. For example, the decoy operating system **112** can be one of WINDOWS, SUN MICROSYSTEMS, SOLARIS, or any version of LINUX known to persons skilled in the art, as well as any combination of the aforementioned. The decoy network device **106** may include any number of virtualized decoy operating systems **112** or any number of virtual machines **113**.

[0054] Each of the above identified modules, components, and applications in FIG. **2** corresponds to a set of instructions for performing one or more functions described herein. These modules (i.e., sets of instructions) need not be implemented as separate software programs, procedures or modules, and thus various subsets of these modules may be combined or otherwise re-arranged in various embodiments. In some embodiments, the memory **206** may store a subset of the modules and data structures identified above. Furthermore, the memory **206** may store additional modules and data structures not described above.

[0055] Notwithstanding the discrete blocks in FIGS. **1** and **2**, these figures are intended to be a functional description of some embodiments rather than a structural description of functional elements in the embodiments. One of ordinary skill in the art will recognize that an actual implementation might have the functional elements grouped or split among various components. In practice, and as recognized by those of ordinary skill in the art, items shown separately could be combined and some items could be separated. For example, in some embodiments, the fingerprint generation engine **130** and the virtualized decoy OS **112** are part of or stored within the decoy network device **106**. In other embodiments, the fingerprint generation engine **130** and the virtualized decoy OS **112** are implemented using separate computer systems. In some embodiments, the fingerprint generation engine **130** includes the database server **128**. In some embodiments, the database server **128** is a remote database server located outside the decoy network device **106**.

[0056] The actual number of servers used to implement the decoy network device **106** and how features are allocated among them will vary from one implementation to another, and may depend in part on the amount of data traffic that the system must handle during peak usage periods as well as during average usage periods, and may also depend on the amount of data processed by the decoy network device **106**. Moreover, one or more of the blocks in FIGS. **1** and **2** may be implemented on one or more servers designed to provide the described functionality. For example, the decoy network device **106** may be implemented on two distinct computing devices: a monitor device and an analyzer device. The monitor device includes the virtual machine monitor **214**, the virtual machines **216**, and processes and modules therein. The analyzer device includes the database server **128**, the fingerprint generation engine **130**, and optionally the visualization interface **132**. In such configuration, the monitor device collects unauthorized activity data, and the analyzer device analyzes the unauthorized activity data to generate fingerprints.

[0057] When in use, attackers typically search for vulnerable computers connected to the shared communication net-

work(s), and attempt to perform unauthorized activities on such vulnerable computers through the shared communication network(s).

[0058] Attacker activity may be directed at the decoy computer network **102** through one or more ports of each of the virtualized decoy operating system **112** that are left open as a gateway for the attacker activity. For example, the decoy network **102** can be configured to respond to connection attempts made at network addresses that do not exist on the protected network **104** (e.g., through a connection from the firewall/router **198** to the decoy network device **106** as illustrated in FIG. **1**). Connections to these non-existent network addresses are assumed to be unauthorized and routed to one of the decoy operating systems **112**, since no production hardware (e.g., protected network device **136**) exists on the protected network **104** at these addresses. In particular, the decoy operating systems **112** are not configured to provide any user service, and therefore, no ordinary (i.e., authorized and/or non-malicious) user would attempt to access to the virtual machine.

[0059] The decoy operating systems **112** (in the form of a virtualized operating system) may be configured to respond to any such non-existent network address. In a typical attack, the attacker activity scans for an open port, ostensibly in an attempt to make a network connection and then access one or more computing devices on the protected computer network **104**. When the attacker activity scans for open ports at non-existent network addresses, however, the attacker is presented with a virtualized decoy operating system **112** instead.

[0060] When the attacker connects to a virtualized decoy operating system **112** through an open port, the attacker sees a fully-functional standard operating system fingerprint. Since the decoy network device **106** can be configured to present any operating system as a fully-functional virtualized decoy operating system **112**, responses to connection requests from attacker activity are guaranteed to be authentic for the operating system running on that decoy. For example, an FTP port access request for WINDOWS may return a specific character sequence that differs from an FTP response for LINUX. Similarly, an FTP access request to a WINDOWS port may return a response ">ftp: connect: Connection refused." This character sequence may be slightly different from that generated by LINUX. Further, different versions of WINDOWS may respond with slightly different, version-specific character sequences. Since attackers often use these sequences to identify what type of operating system is at a particular network address and the version (or range of possible versions) for that operating system, the fact that virtualized decoy operating systems **112** generate authentic responses makes them realistic decoys and encourages intruders to attempt unauthorized access to them. The instigator of the attack is thus lured into accessing the decoy **112**, which is overseen by the hypervisor operating system **110** running on the hardware-based, decoy network device **106**. Attacker activity may then initiate previously unknown attacks for the observed operating system. When the attacker activity proceeds to interact with the decoy operating system **112**, the attacker provides the decoy operating system **112** with the data used to obtain control of the decoy operating system **112**. These data are recorded and analyzed by the introspection module without the knowledge of the attacker.

[0061] All scans by the attacker activity receive real-world operating system and service information, leading the instigator of the attack activity to believe that there is a potentially vulnerable system responding. The attacker is thus lured into communicating with the decoy network device **106** and its virtualized decoy operating systems **112** and services. Since the decoy network device **106** includes real hardware, the attacker is essentially attacking an actual physical system and, therefore, cannot tell that the system is actually an instrumented honeypot that monitors the attacker activity from the introspection module. When an attacker connects to a network port and begins interacting with a virtualized decoy operating system **112**, the introspection module monitors and captures information from the connection, including port numbers, data streams, file uploads, keystrokes, ASCII or binary files, malicious payloads, memory manipulation attempts, and any other data transfers or malicious attempts.

[0062] In some embodiments, the introspection module monitors all activity (e.g., system calls, library calls, kernel calls, etc.) on virtualized decoy operating systems **112**. In other embodiments, the introspection module, instead of monitoring all activity on virtualized decoy operating systems **112**, monitors activity on virtualized decoy operating system **112** based on a monitoring priority (e.g., key system calls and kernel calls). The monitoring priority may be set based on the type of unauthorized activities. For example, in some embodiments, incoming network packets are given high priorities, and therefore, the incoming network packets are thoroughly monitored and analyzed. In some other embodiments, system calls are given high priorities. In yet other embodiments, a virtualized decoy operating system (e.g., **112-1**) on a virtual machine **1** (e.g., **113-1**) is given a high priority than other virtualized decoy operating system, when the virtual machine **1** is experiencing a high frequency of unauthorized activities. Also a combination of the factors stated above can be used to determine the monitoring priority. In some embodiments, the monitoring priority is user-configurable.

[0063] In use, the introspection module captures (through the introspection) raw attack information. The raw attack information is then communicated to and stored on the database server **128** as forensic data **236** for later analysis. The fingerprint generation engine **130** or the trace analyzer **226** then uses this raw forensic information **236** to generate a signature of the attack. In some embodiments, the fingerprint generation engine **130** or the trace analyzer **226** uses the raw attack information to generate a signature of the attack without storing the raw attack information (i.e., unauthorized activity data) in a database server (e.g., database server **128**) first. In some embodiments, the fingerprint generation engine **130** or the trace analyzer **226** uses the raw attack information to generate a signature of the attack without storing the raw attack information in persistent data storage (e.g., database server **128**) at all. It should be appreciated that although the signature of the attack may be used to generate an attack signature suitable for use in security applications (e.g., IPS, AV, etc.), the signature of the attack is distinct from the attack signature. The signature (also called a fingerprint) may be used for providing detailed forensic analysis of the character and nature of the attack and its impact on the target operating system, which can be used as the basis for generating triggers. Such triggers may be used to deny malicious system or library calls on the decoy operating system **112**.

[0064] In some embodiments, the entire process from attack detection through fingerprint generation occurs automatically, i.e., without any human intervention, at a timescale

ranging from nearly immediate to several minutes. The IDS/IPS system **142** uses the attack signature to identify and prevent subsequent attacks.

[0065] In one or more embodiments, the signature may be sent from the fingerprint generation engine **130** to the intrusion detection and/or prevention (IDS/IPS) signature library **134** through a second network connection **140**, which is used by the fingerprint generation engine **130** to directly interact with the IDS/IPS system **142**.

[0066] After collecting unauthorized activity data, the introspection module **120** may easily clean the virtualized decoy operating system **112** at any time by removing the running system image of the compromised virtualized decoy operating system and replacing it with a pre-attack system image. Thus the introspection module **120** can cleanse or reset the virtualized decoy operating system **112** of any malicious software or payload, removing the possibility that attacker(s) can use that virtualized decoy operating system **112** for further attacks on other networks. In this manner, the attack can be thwarted, and the operating system does not become a tool of the attacker(s). This procedure may also be automated, i.e., may occur without further human intervention.

[0067] FIGS. **3**A-**3**D and **4**A-**4**E illustrate exemplary network diagrams representing unauthorized activity on a computer system (e.g., the virtual machine **113-1**), in accordance with various embodiments. Although FIGS. **3**A-**3**D and **4**A-**4**E illustrate unauthorized activities on the virtual machine **113-1**, analogous methods can be used to represent and analyze unauthorized activities on non-virtualized computer systems.

[0068] FIG. **3**A-**3**D illustrate exemplary network diagrams **300** representing unauthorized activities on a network socket (e.g., the virtual machine **113-1**), in accordance with some embodiments. In FIG. **3**A, a data packet stream **304** at a socket **306** of the virtual machine **113-1** is detected by the virtual machine **113-1** and monitored by the virtual machine monitor **214**. When the virtual machine **113-1** is a decoy system, the virtual machine **113-1** typically does not actively send and receive packet streams over the network (because the purpose of the decoy system is to wait for a potential attack from an attacker), and any incoming packet stream **304** of data is treated as an unauthorized activity (e.g., an attempt by a hacker to probe a security system of the virtual machine **113-1**). In some embodiments, any request to access a computer that does not exist on the protected computer network is treated as an unauthorized activity, and such request is routed to one of the decoy systems (e.g., a virtual machine **113-1** on the decoy network device **106**), which is monitored for additional unauthorized activities. In some embodiments, an attacker **302** who sends the packet stream **304** to the socket **306** is identified (e.g., by the Internet Protocol (IP) address).

[0069] Once the packet stream **304** and the socket **306** are identified as affected by unauthorized activities, related unauthorized activities are identified. FIG. **3**B shows that the packet stream **304** received by the socket **306** is directed to a process A **308**, and the process A **308** is treated as affected by unauthorized activities. In turn, in FIG. **3**C, the process A **308** accesses a file X **310** and a file Y **312**, and both the file X **310** and the file Y **312** are treated as affected by unauthorized activities. Thereafter, the file X **310** initiates a process B **314**, and the process B is treated as affected by unauthorized activities.

[0070] By analyzing these activities, the fingerprint of the unauthorized activities can be identified (e.g., the unauthorized activities start with the packet stream **304**; the unauthorized activities send the packet stream **304** into the computer system **398** through the socket **306**; the packet stream **304** is directed to the process A **308**; etc.). By using this information, the security of the protected network devices **136** can be improved (e.g., the socket **306** can be closed; the process A **308** can be modified to not respond to data similar to the packet stream **304**; etc.).

[0071] FIGS. **4**A-**4**D illustrate exemplary network diagrams **400** representing unauthorized activities on files in a computer system (e.g., the virtual machine **113-1**), in accordance with some embodiments. In FIG. **4**A, unauthorized activities on the file X **310** and the file Y **312** in the virtual machine **113-1** are detected. For example, the unauthorized activity may be detected by using checksum values of the file X **310** and the file Y **312** (e.g., a different checksum value can indicate that a corresponding file has been modified by an unauthorized process). Alternatively, the unauthorized activity may be detected by monitoring data execution prevention (DEP) exceptions associated with the file X **310** and the file Y **312**, generated by the one or more processors (e.g., **202** in FIG. **2**); or by a manual selection from a system administrator (e.g., based on a file corruption or an erratic behavior).

[0072] FIG. **4**B shows that the process A **308** accesses both the file X **310** and the file Y **312**, and the process A **308** is treated as affected by unauthorized activities. Also in FIG. **4**B, the file X **310** initiates the process B **314**, and the process B is treated as affected by unauthorized activities.

[0073] In FIG. **4**C, data from the socket **306** is directed to the process A **308**, and the socket **306** is treated as affected by unauthorized activities. FIG. **4**D shows that the socket **306** receives the packet stream **304**, and the packet stream **304** is treated as affected by unauthorized activities. In some embodiments, the attacker **302** who sends the packet stream **304** to the socket **306** is identified (e.g., by the IP address).

[0074] FIG. **4**E illustrates an exemplary network diagram **420** representing unauthorized activities on a computer system (e.g., the virtual machine **113-1**), in accordance with some embodiments. In FIG. **4**E, multiple packets of data streams (e.g., **304-1** and **304-2**) are detected, and all activity on the computer system **498** are monitored and recorded. When the type of associations is identified (e.g., malignant, benign, etc., as described in more detail below with reference to a type **516** in FIG. **5**A), at least a subset of the associations can be visually distinguished (e.g., a respective bold arrow representing a malignant association; a regular arrow representing a benign association; alternatively, any other graphical scheme can be used to visually distinguish the subset of the associations, such as color, font, shape, icons, etc.). It is also noted that certain objects drawn with dashed lines (e.g., files, processes, etc.) may have been identified as affected by unauthorized activities, but their associations with other objects may not have been identified.

[0075] FIG. **5**A is a block diagram illustrating exemplary data structures of unauthorized activity data **502** and unauthorized activity entries **505** in the unauthorized activity data **502**, in accordance with some embodiments. Unauthorized activity data **502** includes unauthorized activity entries **505**. In some embodiments, the unauthorized activity entries are grouped into one or more sets (e.g., **504**) based on time (e.g., time when the entries are recorded or time window of recorded activity), association types (e.g., malicious associa-

tions v. benign associations), source types, target types, and other characteristics of the unauthorized activities.

[0076] The unauthorized activity data **502** shown in FIG. **5**A is grouped based on time (e.g., when the entries are recorded). Each set optionally includes one or more of the following set variables **503**:

[0077] status **506**, which indicates whether the unauthorized activity data **502** is complete or incomplete; the set (e.g., **504-1**) is determined to be complete if associations for all objects (e.g., activity sources and activity targets) affected by unauthorized activities are identified; the set (e.g., **504-1**) is determined to be incomplete if an association for any object affected by unauthorized activities is not identified;

[0078] frequency **508**, which indicates a number of unauthorized activities on the computer system (e.g., virtual machine **113**) during a predefined time interval (e.g., one second, five seconds, one minute, five minutes, one hour, five hours, one day, two days, etc.); in some embodiments, the frequency **508** is a relative frequency measured by a number of computer processes affected by unauthorized activities and a total number of computer processes running on the computer system; for example, if the computer system (e.g., virtual machine **113**) runs fifty total processes including ten processes affected by unauthorized activities, the frequency **508** is 20% (=10/50); and

[0079] a global time stamp **510**, which represents the time when the data in the set (e.g., **504-1**) was collected.

[0080] Each set **504** in the unauthorized activity data **502** in FIG. **5**A also includes one or more unauthorized activity entries **505** (e.g., **505-1**, **505-2**, **505-3**, **505-4**, and **505-5**). Each unauthorized activity entry **505** includes one or more of the following:

[0081] an activity source **512**, which calls, accesses, or executes the activity target **514**; the activity source **512** may be one of the following: access to a particular file, access from a particular user, an Internet Protocol address, an instruction, a message, data stream, a hardware component, and a network port; for example, when an instruction A accesses a file X, the instruction A is the activity source, and the file X is the activity target **514**;

[0082] an activity target **514**, which is called, accessed, or executed by the activity source **512**. The activity target **514** may be one of the following: a file, an Internet Protocol address, an instruction, a message, data stream, a hardware component, and a network port; and

[0083] an action **515**, which represents an event or operation occurring between the activity source **512** and the activity target **514**. The action **515** is typically one of: calling, executing, modifying, or accessing operation, such as system calls and library calls.

[0084] An (optional) association, type **516**, which when identified, represents the type of association between the activity source **512** and the activity target **514**; the association type may be one of the following:

[0085] malignant, which represents that the activity source **512** has modified the activity target **514** to perform unauthorized activities;

[0086] benign, which represents that the activity source **512** has interacted with the activity target **514** but has not modified the activity target **514** to perform unauthorized activities (e.g., the instruction A reads the file X, but does not modify the file X); and

[0087] remission, which represents that the activity source **512** is determined to be no longer active in propagating unauthorized activity; for example, the activity source **514** may be modified to remove malicious data and/or to stop unauthorized activities (e.g., by the IDS/IPS system **142**);

[0088] (optional) probability **518**, which when identified, represents a probability that the corresponding association is malignant; and

[0089] (optional) time stamp **520**, which when identified, represents the time when the activity source **512** associates with the activity target **514** (e.g., when the activity source **512** calls, accesses, or executes the activity target **514**).

[0090] FIG. **5**B illustrates an exemplary data structure of fingerprint **580**, in accordance with some embodiments. In FIG. **5**B, the fingerprint **580-1** includes one or more of the following: an (optional) status **506**, an activity source **512**, an activity target **514**, an (optional) association type **516**, and an (optional) time stamp **520**, all of which are described above.

[0091] The fingerprint **580-1** can be used to prevent future attacks on the computer system or other computer systems, by modifying the activity targets **514** (e.g., increasing privileges, changing the file/instruction name, changing the file/instruction structure, moving the file/instruction to a different location, blocking a particular port, encrypting the file, etc.) to protect the activity targets **514** or blocking the same or similar (e.g., at least partially matching) pattern or sequence of activities (e.g., if the fingerprint of the unauthorized activities starts with sending packets A, B, and C in order, blocking the receipt of the packet C after receiving the packets A and B).

[0092] In some embodiments, the fingerprint **580** consists of respective pairs of activity sources and activity targets, when the association type for a respective pair is malignant. This reduces the size of the fingerprint **580**.

[0093] FIG. **5**C illustrates another exemplary data structure of fingerprint **580**, in accordance with some embodiments. In FIG. **5**C, the fingerprint **580-2** includes the following, or a subset or superset thereof:

[0094] (one or more) activity sources **512**, as described above;

[0095] a reference value **522**, which is used to identify a particular activity source **512**; for example, the reference value **522** can be a file size, a checksum value, one or more portions of the file, instruction, or data packet;

[0096] an (optional) method **524**, which is used to indicate how the reference value **522** is used to identify a corresponding activity source **512**, or how the activity source is processed to obtain a measured value which can be compared with the reference value **522** to identify the activity source **512**. For example, the method can be "checksum," which requires determining a checksum value of the activity source **512**, or "match," which requires matching the reference value with the activity source **512**. The method **524** is typically omitted when a default method is used to identify the source **512**.

[0097] The fingerprint **580-2** can be used to prevent future attacks on the computer system or other computer systems, by blocking activity sources that match a pattern of unauthorized activities (e.g., the reference value **522**). For example, if the fingerprint of the activity source includes a data stream with a repeated character of a predefined length (e.g., a 2 KB long string of a repeated character), the IDS/IPS can block such data stream by using the reference value **522**.

[0098] In some embodiments, the fingerprint **580-2** includes activity targets **514** in lieu of or in addition to, the activity sources **512**.

[0099] In some embodiments, the fingerprint **580** includes one or more of system calls, arguments of system calls, returns of system calls, device and memory input-output, driver information, library calls, branching information, instruction pointer jumps, and raw network information collected from a respective virtual machine **113** or a respective decoy operating system **112** (not shown).

[0100] FIGS. **6**A-**6**C are flowcharts representing a method **600** of identifying unauthorized activities on a computer system (e.g., the virtual machine **113-1**) attached to a computer network, in accordance with some embodiments. The computer-implemented method **600** is performed at a decoy network device (e.g., **106** in FIG. **1**B) having one or more processors and memory storing a virtual machine and a virtual machine monitor supervising the virtual machine. The memory also stores one or more programs for execution by the one or more processors to perform the method. Typically, the one or more programs executed by the one or more processors to perform the method are executed at the virtual machine monitor.

[0101] The decoy network device monitors (**602**) activity on the virtual machine. In some embodiments, the decoy network device monitors a predefined set of activity on the virtual machine. In some embodiments, the decoy network device monitors all activity related to incoming data stream on the virtual machine, based on an assumption that all incoming data stream on the virtual machine is unauthorized (e.g., FIGS. **3**A-**3**D). In some embodiments, the decoy network device monitors activity based on the monitoring priority.

[0102] In some embodiments, the monitoring further includes monitoring all activity on the virtual machine, and all activity on the virtual machine is assumed (**603**) to be unauthorized, because the virtual machine is not configured to provide user services (e.g., email, web, or file services, etc.) and no authorized user would need to access the virtual machine. In some embodiments, all incoming data packet on the virtual machine is assumed to be unauthorized.

[0103] The decoy network device identifies (**604**) a plurality of activities being performed at the virtual machine. Each of the activities includes an activity source, an activity target, and an association between the activity source and the activity target. For example, the activity between the file X **310** and the process B **314** in FIG. **3**D includes the file X **310** as an activity source, the process B **314** as an activity target, and the association represented by the arrow from the file X **310** to the process B **314**.

[0104] In some embodiments, a respective activity target comprises (**606**) one of: a file, a user, an instruction (such as computer processes or system calls), a thread (e.g., a thread of processes), data stream (e.g., network packets), and network socket connections (or sockets). In some embodiments, the respective activity target is an Internet Protocol address.

[0105] In some embodiments, a respective activity source comprises (**608**) one of: a file, a user, an instruction (such as computer processes or system calls), a thread (e.g., a thread of processes), data stream (e.g., network packets), and network socket connections (or sockets). In some embodiments, the respective activity source is an Internet Protocol address.

[0106] In some embodiments, the decoy network device identifies (**610**) a respective association between a first activity source and a first activity target as unauthorized. The first activity target, when associated as a second activity source with a second activity target, causes unauthorized activities on the second activity target. For example, we turn to illustrations in FIGS. **3**B-**3**C. Data from the socket **306** modifies the process A **308** so that the process A **308** performs unauthorized activities (FIG. **3**B). Therefore, the socket **306** is an activity source in relation to the process A **308**, which is an activity target in relation to the socket **306**. Then, as shown in FIG. **3**C, the process A **308** modifies the file X **310**, performing unauthorized activities (e.g., corrupting data or writing a malicious code). The process A **308**, as an activity source to the file X **310**, causes unauthorized activities on the file X **310**. By identifying that the process A **308** performed unauthorized activities, the process A **308** is determined to be affected by the unauthorized activities, and the association between the socket **306** and the process A **308** is determined to be malicious (i.e., unauthorized).

[0107] In some embodiments, the decoy network device tracks (**612**) a transfer of malicious associations over time. For example, as shown in FIG. **5**A, the decoy network device stores propagation of unauthorized activities (or malicious associations) as a function of time. This allows time-based analysis of the unauthorized activities, and preventing unauthorized activities based on time or sequence-based filters.

[0108] In some embodiments, the decoy network device identifies (**614**) activity sources that are affected by unauthorized activities. In some embodiments, the identifying activity sources that are affected by unauthorized activities includes (**616**) identifying activity sources that request to access a portion of memory that is set as non-executable. This can be achieved by data execution prevention (DEP) mechanisms. For example, microprocessors manufactured by Intel Corporation (Santa Clara, Calif.) allow setting one or more portions of the memory as non-executable (e.g., using a non-executable bit in respective page table entries), and generate an exception when there is an attempt to execute an instruction that is set as non-executable. Similarly, operating systems sold by Microsoft Corporation (Redmond, Wash.) has an analogous function implemented in the operating system (e.g., Windows XP, Windows 7, etc.).

[0109] In some embodiments, instructions executed by the one or more processors have (**618**) respective privilege levels. Respective activity sources have respective privilege levels, and the identifying activity sources that are affected by unauthorized activities includes identifying activity sources that request to execute unprivileged instructions. For example, low level processes (or fundamental OS processes) typically require a fundamental privilege level (e.g., privilege levels 0, 1, and 2 in a microprocessor architecture provided by Intel Corporation), and most applications run at a different privilege level (e.g., privilege level 3 in Intel Architecture). An application running at the privilege level 3 is unprivileged to run a privilege level 0 process. When the privilege level 3 application attempts to run a privilege level 0 process, such activity is identified as an unauthorized activity.

[0110] In some embodiments, the identifying activity sources that are affected by unauthorized activities includes (**620**) receiving a selection of one or more activity sources from a system administrator. For example, a system administrator may suspect that a certain file or process is affected by unauthorized activities, and select the file or process as affected. The decoy network device monitors activity sources

and activity targets associated with the selected file or process, thereby identifying additional unauthorized activities.

[0111] In some embodiments, the identifying activity sources that are affected by unauthorized activities includes (**622**) identifying a data stream incoming from outside the computer system. As discussed above, all incoming data stream on a decoy system is assumed to be affected by unauthorized activities.

[0112] The decoy network device stores (**624**) the activity sources, activity targets, and associations in the memory. For example, the decoy network device **106** stores unauthorized activity data **502** (e.g., as illustrated in FIG. **5**A) in memory **206** (as shown in FIG. **2**) or in the database server **128** (as shown in FIG. **2**).

[0113] In some embodiments, the decoy network device graphically displays (**626**) at least a subset of the stored activities. For example, the graphical representation can be an activity diagram as shown in FIGS. **3**A-**3**D and **4**A-**4**E.

[0114] In some embodiments, the displaying includes (**628**) visually distinguishing at least a subset of the associations (e.g., in FIG. **4**E, certain associations are visually distinguished with bold lines. Alternatively, certain associations are visually distinguished with any other visual indications, such as color, shape, icons, etc.). In some embodiments, the visually distinguishing includes visually distinguishing at least a subset of the associations based on the associated probability.

[0115] In some embodiments, the subset of activities includes (**630**) a first activity and a second activity, and the activity target of the first activity is the activity source of the second activity. For example, FIG. **3**C illustrates the first activity between the socket **306** and the process A **308** and the second activity between the process A **308** and the file X **310**. The process A **308** is the activity target of the first activity and the activity source of the second activity. In other words, the first activity and the second activity are connected through the process A **308**. In FIG. **3**C, both the first activity and the second activity are graphically illustrated.

[0116] In some embodiments, the decoy network device determines (**632**) an activity status for the stored events. The activity status includes one of: a complete status and an incomplete status. The complete status represents that a source of unauthorized activities is identified, and each activity target in the stored activities is associated with the source through one or more associations (e.g., in FIG. **4**D, each activity is associated with the source, packet stream **304** through one or more associations). The incomplete status represents that the source of unauthorized activities is not identified, or at least one activity target in the stored activities is not associated with the source through one or more associations (e.g., in FIG. **4**A, the source is not identified, and activities are not associated with the source).

[0117] In some embodiments, the decoy network device determines (**634**) an activity level representing a frequency of unauthorized activities on the virtual machine during a predefined time interval (e.g., frequency **508** in FIG. **5**A).

[0118] In some embodiments, the decoy network device determines a probability of a respective association (or a probability/confidence of an unauthorized association). The probability represents likelihood that the association is malignant (or benign). For example, if the process A **308** reads the file Y **312** (in FIG. **4**B), the file Y **312** is not modified, and the association is not malignant. The probability for the association between the process A **308** and the file Y **312** is 0%. However, if the process A **308** writes to (or modifies) the file X **310** (in FIG. **4**B), the association can be malignant. If we know that the process A **308** is affected by the unauthorized activities, the probability for the association between the process A **308** and the file X **310** is 100%. If we do not know that the process A **308** is affected by the unauthorized activities, the probability for the association between the process A **308** and the file X **310** is a predefined number (e.g., 50%). If the file X **310**, in turn, calls the process B **314**, the association between the file X **310** and the process B **314** can be assigned a probability based on a predefined rule (e.g., 25%=50% of the probability associated with the file X **310**, which is 50%).

[0119] In some embodiments, the probability is used to adjust monitoring priority for the introspection module. For example, if the association between the process A **308** and the file Y **312** has 0% probability, the association between the process A **308** and the file X **310** has 50% probability, and the association between the file X **310** and the process B **314** has 25% probability, the monitoring priority would be placed in the order of the process A **308** (which can be 100% affected by unauthorized activities), the file X **310** with a 50% probability association, the process B **314** with a 25% probability association, and the file Y **312** with a 0% probability association.

[0120] The decoy network device creates (**636**) a fingerprint indicative of the activity on the virtual machine from the stored activities. For example, the fingerprint can be fingerprint **580-1** in FIG. **5**B, fingerprint **580-2** in FIG. **5**C, or any other fingerprint described herein. The fingerprint **580-1** can be created directly from the stored activities (e.g., unauthorized activity data **502**). The fingerprint **580-2** can be created by analyzing unauthorized activity data **502** (in particular the activity sources **512**) or collecting additional data associated with the activity sources **512** (e.g., calculating a checksum value of an activity source **512**, etc.).

[0121] In some embodiments, the fingerprint includes (**638**) files that are affected by unauthorized activities on the virtual machine. For example, the activity source **512** in the fingerprint **580-1** can be a file or file information (e.g., file name, location, size, checksum value, etc.).

[0122] In some embodiments, the fingerprint includes (**640**) processes that are affected by the unauthorized activities on the virtual machine. For example, the activity source **512** in the fingerprint **580-1** can be a process or process information (e.g., process name, size, privilege level, related processes, etc.).

[0123] In some embodiments, the fingerprint includes one or more of: system calls' arguments and returns, device and memory input-output, driver calls' arguments and returns, library calls' arguments and returns, branching information, instruction pointer jumps, and raw network information collected from a respective virtual machine **113** or a respective decoy operating system **112**.

[0124] In some embodiments, the fingerprint includes one or more of port numbers, data streams, file uploads, file downloads, keystrokes, ASCII or binary files, malicious payloads, operating system configuration changes (e.g., new or updated registry keys in windows) and memory manipulation attempts.

[0125] In some embodiments, the activities comprise (**642**) two or more of: a file initiating an execution of an instruction, an instruction reading a file, an instruction writing to a file, and receiving data through the network.

[0126] The decoy network device transmits (**644**) the fingerprint to one or more protected network devices **136** to prevent future attacks that comprise the same or similar activities as indicated by the fingerprint. In some embodiments, the decoy network device transmits the fingerprint to the IDS/IPS system **142** to prevent future attacks that comprise the same or similar activities on one or more protected network devices **136**.

[0127] In some embodiments, one or more other computer systems (e.g., protected network devices **136**) on the network are modified (**646**) to prevent future attacks that comprise the same or similar activities as indicated by the fingerprint (e.g., in FIG. **1**A, the IDS/IPS system modifies at least one of the protected network device(s) **136** to prevent future attacks that comprise the same or similar activities).

[0128] The foregoing description, for purpose of explanation, has been described with reference to specific embodiments. However, the illustrative discussions above are not intended to be exhaustive or to limit the invention to the precise forms disclosed. Many modifications and variations are possible in view of the above teachings. The embodiments were chosen and described in order to best explain the principles of the invention and its practical applications, to thereby enable others skilled in the art to best utilize the invention and various embodiments with various modifications as are suited to the particular use contemplated.

[0129] For example, although the activity source **512** and the activity target **514** are described with respect to processes, threads, files, addresses, instructions, messages, hardware components, etc., persons skilled in the art would recognize that similar methods can be used with respect to other types of activity sources and activity targets. In some embodiments, the analysis engine is configured to maintain several layers of network diagrams, where each layer uses the layer beneath it as input and providing more generalized representations of the unauthorized activity as output. For example, a low-level layer might consist of a process reading from a file and subsequently writing many new files. In some cases, the analysis engine might identify this low level pattern as a representation of a file archive being unpacked, and generate a higher-level layer that includes an unpacking process. This exemplary generalization allows the system to identify common elements of attacks, identify classes of attack that have not been seen before (e.g., zero-day attacks), and generate higher-quality signatures. A layer including the level of detail appropriate to the context may be selected for analysis.

[0130] Moreover, the methods described herein need not be restricted to analysis of a single virtualized operating system but, rather, are able to follow a chain of unauthorized activity across multiple virtualized operating systems. This is important in identifying and thwarting advanced threats that involve multiple attackers spread across multiple systems and that evolve over long periods of time.

[0131] Furthermore, although the methods are described with respect to security application, it should be appreciated that similar methods can be used generally for monitoring behavior of a computer system that follows a source event. For example, similar methods can be used for tracking a user behavior on a system, and/or profiling application behavior for performance improvement or debugging purposes.

What is claimed is:

1. A computer implemented method of identifying unauthorized activities on a decoy computer system attached to a computer network, wherein the decoy system comprises:
- one or more processors; and
- memory storing:
  - a virtual machine; and
  - a virtual machine monitor supervising the virtual machine, the method comprising, at the virtual machine monitor:
- monitoring activity on the virtual machine;
- identifying a plurality of activities being performed at the virtual machine, wherein each of the activities includes an activity source, an activity target, and an association between the activity source and the activity target;
- storing in the memory the activity sources, activity targets, and associations;
- creating, from the stored activities, a fingerprint indicative of the activity on the virtual machine; and
- transmitting the fingerprint to prevent future attacks that comprise the same or similar activities as indicated by the fingerprint.

2. The method of claim **1**, wherein the monitoring further comprises monitoring all activity on the virtual machine, and all activity on the virtual machine is assumed to be unauthorized.

3. The method of claim **1**, wherein the fingerprint includes files that are affected by the unauthorized activities on the virtual machine.

4. The method of claim **1**, wherein the fingerprint includes processes that are affected by the unauthorized activities on the virtual machine.

5. The method of claim **1**, wherein the activities comprise two or more of: a file initiating an execution of an instruction, an instruction reading a file, an instruction writing to a file, and receiving data through the network.

6. The method of claim **1**, wherein a respective activity target comprises one of: a file, a user, an instruction, a thread, data stream, and network socket connections.

7. The method of claim **1**, wherein a respective activity source comprises one of: a file, a user, an instruction, a thread, data stream, and network socket connections.

8. The method of claim **1**, further comprising graphically displaying at least a subset of the stored activities.

9. The method of claim **8**, wherein the displaying includes visually distinguishing at least a subset of the associations.

10. The method of claim **8**, wherein the subset of activities includes a first activity and a second activity, and the activity target of the first activity is the activity source of the second activity.

11. The method of claim **1**, further comprising identifying a respective association between a first activity source and a first activity target as unauthorized, wherein the first activity target, when associated as a second activity source with a second activity target, causes unauthorized activities on the second activity target.

12. The method of claim **11**, further comprising tracking a transfer of malicious associations over time.

13. The method of claim **1**, further comprising identifying activity sources that are affected by unauthorized activities.

14. The method of claim **13**, wherein the identifying activity sources that are affected by unauthorized activities includes identifying activity sources that request to access a portion of memory that is set as non-executable.

15. The method of claim **13**, wherein:

instructions executed by the one or more processors have respective privilege levels;

respective activity sources have respective privilege levels; and

the identifying activity sources that are affected by unauthorized activities includes identifying activity sources that request to execute underprivileged instructions.

16. The method of claim **13**, wherein the identifying activity sources that are affected by unauthorized activities includes identifying data stream incoming from outside the computer system.

17. The method of claim **1**, further comprising determining an activity status for the stored events, the activity status comprising one of:

a complete status, representing that a source of unauthorized activities is identified, and each activity target in the stored activities is associated with the source through one or more associations; and

an incomplete status, which represents that the source of unauthorized activities is not identified, or at least one activity target in the stored activities is not associated with the source through one or more associations.

18. The method of claim **1**, further comprising determining an activity level representing a frequency of unauthorized activities on the virtual machine during a predefined time interval.

19. A system, comprising:

one or more processors; and

memory storing:

a virtual machine;

a virtual machine monitor supervising the virtual machine; and

one or more programs, the one or more programs including instructions for:

monitoring activity on the virtual machine;

identifying a plurality of activities being performed at the virtual machine, where each of the activities includes an activity source, an activity target, and an association between the activity source and the activity target;

storing in the memory the activity sources, activity targets, and associations;

creating, from the stored activities, a fingerprint indicative of the activity on the virtual machine; and

transmitting the fingerprint to prevent future attacks that comprise the same or similar activities as indicated by the fingerprint.

20. A computer readable storage medium, including one or more programs for execution by one or more processors of a computer system, the one or more programs including instructions for:

monitoring activity on the virtual machine;

identifying a plurality of activities being performed at the virtual machine, where each of the activities includes an activity source, an activity target, and an association between the activity source and the activity target;

storing in the memory the activity sources, activity targets, and associations;

creating, from the stored activities, a fingerprint indicative of the activity on the virtual machine; and

transmitting the fingerprint to prevent future attacks that comprise the same or similar activities as indicated by the fingerprint.

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