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Towards Discovering and Containing Privacy Violations in Software

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Abstract

Malicious code can wreak havoc on our cyberinfrastructure. Hence, discovering and containing malicious code is an important goal. This paper focuses on privacy-violating malicious code. Examples of privacy violations are leaking private user data to an external entity or downloading data to a user's host without their permission. Spyware, which has recently received considerable attention in the popular literature, is an important example of privacy-violating malicious code. We propose a multi-step approach to discovering and containing privacy violations. We have designed and implemented a dynamic slicing tool to discover dependencies between events in an execution trace. We demonstrate that dynamic slicing can be used to discover privacy violations. Information gathered using dynamic slicing can be used to construct security policies to contain the discovered privacy violations. These security policies are then enforced by a sandbox. We have implemented a sandbox for Windows, and have successfully evaluated our approach on two applications: KaZaa and RealOne Player. For both of these applications we were able to discover privacy violations in them using our dynamic-slicing tool. Moreover, using information gathered through dynamic slicing we were able to design policies to thwart these privacy-violations. Although our preliminary evaluation was performed on spyware, in the future we will evaluate our approach on other privacy-violating malicious code.

1 Introduction

Malicious code can infiltrate hosts using a variety of methods, such as attacks against known software flaws, hidden functionality in regular programs, and social engineering; a taxonomy of malicious code appears in [35]. Disruption of services caused by malicious code can have catastrophic effects, including loss of human life, disruption of essential services, and huge financial losses. The increased reliance of critical services on our cyberinfrastructure and the dire consequences of security breaches have highlighted the importance of detecting and containing malicious code.

This paper addresses privacy-violating malicious code, where a privacy violation is defined as the disclosure of private information or use of a resource without its owner's permission or knowledge. Transmitting sensitive user data to an external server and downloading data to a user's host without their knowledge are two concrete examples of privacy-violations. *Spyware* is an important example of privacy-violating malicious code. Spyware [52, 56] is malicious code that performs useful functionality, but results in disclosure of sensitive information, such as a customer's credit card information. RealNetworks' Real Jukebox [31, 43] was one of the well publicized examples of spyware. In [35] spyware is defined as follows:

> *Spyware* is a useful software package that also transmits private user data to an external entity.

A recent measurement study discovered that 10% of active hosts on a campus of a major public university were infected with spyware [47]. Given the widespread prevalence of spyware and privacy breaches that can result from them, detecting and containing privacy-violations is an important goal. The initial focus of our work is on spyware, but in the future we will evaluate other privacy-violating malicious code. Discovering privacy violations can be viewed as a special case of information-flow analysis [14, 36, 44, 54]. Since we are analyzing programs without access to source code, we will have to perform information-flow analysis on large executables. To our knowledge, information-flow analysis techniques have not be demonstrated to scale to large executables. Dynamic slicing finds dependencies between events in an execution trace. Our methodology uses a combination of dynamic slicing (which can be thought of as information-flow analysis for execution traces) and sandboxing.

There are two major classes of techniques for addressing malicious code: *static* and *dynamic*. Static analysis techniques [6, 7, 11, 12, 24, 33] attempt to detect malicious behavior in programs. Typically, virus scanners search for a pattern of instructions and thus use static analysis (albeit a very simple one). Dynamic techniques confine the behavior of a potentially malicious program using *sandboxing*. A sandbox [15, 19, 23, 29] monitors a program and confines its execution to a security policy. However, these techniques have not been applied to contain privacy violations.

This paper makes the following contributions:

Discovering privacy-violations using dynamic slicing: Malicious code, such as a virus or a worm, leave an observable footprint behind. In contrast, privacy-violating malicious code (e.g., spyware) perform useful functionality, such as downloading or replaying music, but also perform stealthy privacy-violating activities. Therefore, discovering such privacy-violating features is challenging. We have designed and implemented a dynamic-slicing algorithm that enables an analyst to discover privacy-violating features using event traces. Unlike traditional dynamic-slicing algorithms [3, 30] our algorithm works with incomplete information (in our case, a sequence of Win32 API calls made by the application). A description of our dynamic-slicing algorithm and its use in discovering privacy-violations appears in Section 4. Recent work on mimicry and hiding attacks [50, 51, 55] has demonstrated that it is important to incorporate dependency and argument information in security policies used for enforcement. Dynamic slicing can be used to recover dependencies between events and recover argument values, which can be used to construct precise security policies.

Containing privacy-violations using sandboxing: We present the design and implementation of a dynamic-monitoring infrastructure for Windows, called *sandBoX86* . We have designed a language called the *event description language* or *EDL*, to abstract events. EDL provides a decoupling between raw events (Win32 API calls in our case) and abstract events used for monitoring, which makes porting our architecture to other platforms easier. Security policies are defined using a language called the *event sequence language* or *ESL*, which uses the abstract events defined by a EDL specification. These security policies also use the information gathered using dynamic slicing. EDL and ESL specifications for an application are then compiled into a monitor. Details about the architecture can be found in Section 5.

Case studies: In order to evaluate our sandboxing system we considered two applications: KaZaa [25] and RealOne Player [41]. A detailed description of these applications along with privacy-violating features we discovered in them can be found in Section 6. Details about these features were discovered using our dynamic slicing tool. For these two applications, we were able to construct security policies to thwart the discovered privacy-violating features, which lead us to believe that sandboxing can be very effective in containing privacy-violating malicious code, such as spyware. We also measured the memory and execution overheads introduced by our sandbox. Our evaluation demonstrated that the performance and resource costs associated with sandBoX86 are nominal. The macrobenchmarks show a slow down of less than 3.2% for all our applications. The results of these experiments can be found in Section 7.

2 Overview

This section gives an overview of our entire methodology. We describe how dynamic slicing can be used to discover privacy violations and gather information for constructing security policies. We also give two examples of security policies in ESL.

2.1 (Step 1) analyzing execution traces using dynamic slicing

Dependencies between events in an execution trace can be inferred using dynamic slicing. These dependencies can then be used to discover privacy violations and gather information to construct security policies. We will illustrate the use of dynamic slicing using two scenarios.

Scenario 1 (discovering privacy violations): A security analyst wants to discover whether a network event (e.g. sending a message to a remote host) depends on a sensitive event (e.g. reading from a specific file). This dependency indicates that the application is sending data obtained from a sensitive operation to a remote host.

Analysis: A forward slice from a sensitive event shows all the events that depend on it. If a network event is in the forward slice, it represents a potential privacy violation.

Scenario 2 (information gathering): Suppose a security analyst wants to discover all the remote hosts that an application connects to. This information will be useful in recognizing servers that are used by certain applications to download pop-up advertisements or to send information about user activity.

Analysis: Figure 1 demonstrates information gathering using dynamic slicing. The left side of the figure lists a portion of a program's running trace. The right side shows the results of dynamic slicing. In this example, we want to find all the hosts which a program has sent data to using the `send` call. First, we isolate the send events. In this case there are two: *170* and *284*. Next, backward slicing is performed from each one of the two send events. The result from the backward slicing consists of two trees, one from each of the two send events. From the two slices, we extract only the *gethostbyname* calls, which give us the set of hosts the

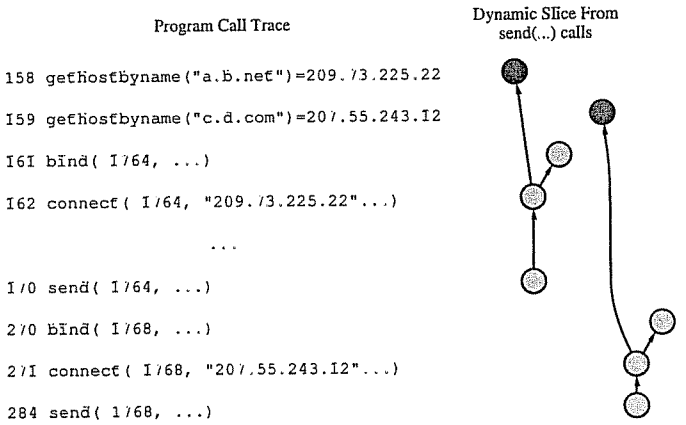


Figure 1: Information Gathering using Dynamic Slicing.

program has sent data to. Appendix B.2 shows a screen shot of our GUI interface to the dynamic slicer. The GUI interface provides a mechanism for a security analyst to visualize and browse the slices.

2.2 (Step 2) constructing security policies

In this step a security analyst designs ESL security policies to thwart privacy violations. Next we show two example policies which are related to scenarios 1 and 2 described before.

Example 1 Assume that using dynamic slicing an analyst was able to discover a privacy violation. Dependencies between events exposed during dynamic slicing helps an analyst construct a policy to thwart the discovered policy violation. Hence dynamic slicing can expose some of the context missing from traditional kernel-level enforcement mechanisms by detecting and tracking dependencies between operating system interface calls (e.g., API calls in windows, syscalls in UNIX). We demonstrate the power of this approach by describing the implementation of a canonical privacy policy: *preventing the transmission of sensitive files across a network.*

Consider a user who wishes to protect the files in her web browser cache from being exported by a malicious program. Pragmatically, she wants to prevent any process from reading items in her cache and then subsequently transmitting them over the network. This requires the system to infer dependencies between two very separate operations; the reading of data from the sensitive (cache) directory, and the use of network interfaces.

Figure 2 shows an ESL policy that protects the browser cache. Line 1 indicates that this ESL security policy uses the EDL specification given in file `generic.edl`. Lines 4, 5, and 6 define how the reading of sensitive material is detected. Line 4 defines a protection domain by identifying the sensitive cache directories for both Internet Explorer and Netscape, and lines 5 and 6 indicate how access to the protection domain should be monitored. The policy tracks the `open` and subsequent `read` of sensitive files by saving state between API calls. Specifically, the `addHash` operator allows `open` and `read` operations to be correlated with the file handle results of `open` calls (which are stored in the *handles* hash table).[1] Using

[1]Note that such mappings can be trivially circumvented by file descriptor aliasing operators such as `dup`. Note that these require OS API or system calls, and as such can be governed by policies in a similar manner as the `open` call. For brevity, we omit further discussion of these interfaces.

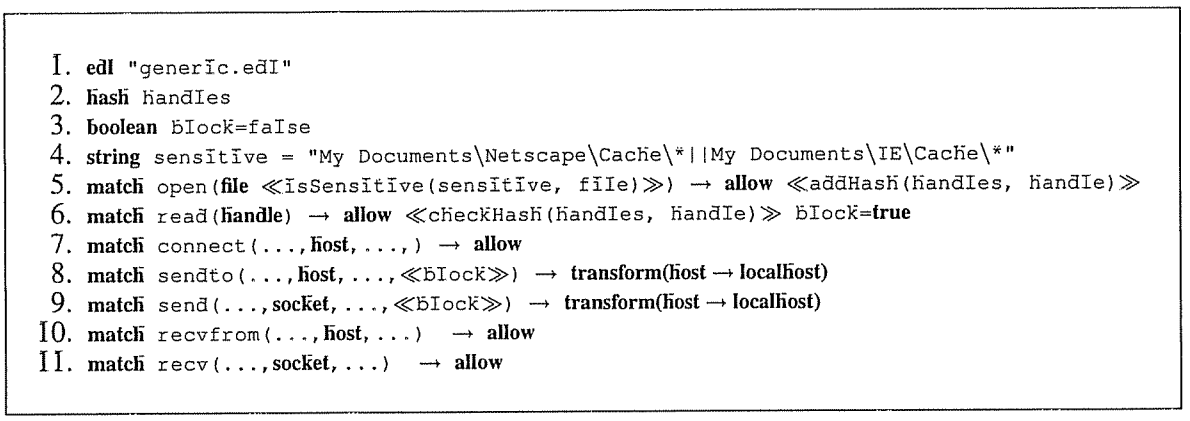


Figure 2: Preventing an application from leaking sensitive information.

the file descriptor mapping in the hash table, line 6 annotates (with a `block` flag) the process as having consumed sensitive data when it reads from a sensitive file. Note that prior to this annotation, the process can freely send and receive data over the network. Lines 7-11 state how the policy is enforced. If the *block* flag is true, then the argument corresponding to the host in the send call is changed to the localhost (lines 8-9). All other operations are permitted independent of annotation, e.g., `connect`, `recv`, `recvfrom`, etc.

While context mapping allows semantically deep policy enforcement, it is still limited to the information present in the interface calls themselves. In the normal case, this may lead to false-positives. For example, this example is sufficient to prevent arbitrary malicious software from performing these operations, but a normally behaving browser would frequently violate this policy and be prevented from using the network. During normal operation a browser frequently reads cache files and sends data. However, the cache data is not sent by the browser. The problem is that the policy does not have sufficient context to determine if the data being sent is derived from sensitive data. In general, determining data dependence requires information flow analysis, which is well known to be enormously difficult. For example, the cascade problem involves aggregation of authorized information flows to produce an unauthorized flow, which arises in networks of systems. The problem of removing such cascades is NP-complete [21]. While this work does not solve the most general problem (information flow), we argue that the semantically rich policies made possible using this approach represent a significant step forward in tracking and controlling the behavior of untrusted software.

Example 2 Our second example is related to scenario 2. KaZaa downloads and displays advertisements during its use. Furthermore, KaZaa users cannot prevent KaZaa from displaying the advertisements unless they choose to uninstall it. Our goal, therefore, is to be able to disable KaZaa's advertisement feature without having to uninstall KaZaa. We now give a policy that can detect and prevent KaZaa from connecting, sending or receiving any data from a list of blocked servers. At the same time, the policy allows other activities such as searching and downloading files from peer hosts. The policy is shown in Figure 3. Line 3 specifies the list of remote servers we want to block KaZaa from accessing. This list is constructed using dynamic slicing as was discussed earlier. In Line 4, we hash each IP address KaZaa has obtained through the *gethostbyname* call. Line 5 of the policy prevents KaZaa from establishing TCP connections to any of the remote servers that is on the *blocked* list. Lines 6 and 7 deal with the cases where KaZaa attempts to send or receive data from the blocked servers using UDP sockets.

This policy achieves the goal of stopping KaZaa from downloading advertisements from a list of remote

```
1. edl "kazaa.edl"
2. hash iptable
3. string blocked = "cydoor|doubleclick|adserver|fastclick.com|..."
4. match gethostbyname(blocked) → allow ≪addHash(iptable, ret, name)≫
5. match connect(...,host,...,≪checkHash(iptable, host)≫) → return success
6. match sendto(...,host,...,≪checkHash(iptable, host)≫) → return success
7. match recvfrom(...,host,...,≪checkHash(iptable, host)≫) → return success
```

Figure 3: Stopping an application from sending or receiving data from remote servers.

servers, which, consequently, prevents KaZaa from displaying the advertisements. The policy has one additional property: it also stops KaZaa from *sending* any information to these servers, which potentially could be more damaging since KaZaa can send private or sensitive data back to these servers. Line 6 stops this potential spying activity by intercepting any attempt to send data to the blocked servers. When KaZaa tries to send data to any one of the remote servers, we do not execute the *send* call but instead return *success* as if the call went through.

Above we give an example policy that stops KaZaa from receiving unwanted data from remote servers. We want to emphasis that this is just one example demonstrating the expressiveness of our policy language. In general, one can use ESL policies to block any sequence of events where the policy may seem to fit.

2.3 (Step 3) enforcing security policies

ESL security policies are enforced by our sandbox. We briefly describe the the process by which the security policies are enforced. Details can be found in Section 5. The ESL security policies described before are compiled into two dynamically loadable libraries (DLLs): *event-interceptor* and *policy-enforcer* DLL. A raw event (in our case of Win32 API call) is transformed into an abstract event by the event-interceptor DLL. The abstract event is passed onto the policy-enforcer DLL, which decides on the action to be taken for that event.

3 Related Work

This section considers how past works have detected and contained undesirable software behavior (e.g., bugs, spyware, malicious code).

Dynamic slicing algorithms typically reconstruct dependencies between statements in an execution trace [3, 4, 30, 53, 57]. Since slicing tracks the flow of values between statements, it can be cast in an information-flow framework [9, 14, 20, 44]. Agrawal *et al.* showed how dynamic slicing can be used to narrow the search for software errors, and hence reduce debugging costs [3]. Their dynamic slicing tool works backward from a known erroneous output toward the possible sources of the error. All code upon which the error state is dependent (as indicated by trace and symbolic information) is included in the program *slice*. Because all causality is captured in the slice, no other code need be searched for the source of the error. Smith and Korel recognized the difficultly and cost of obtaining and analyzing potentially large execution traces [49]. Also used for debugging, they define an algorithm that detects dependencies between logged resource usage events, rather than complete execution traces. Event slices are constructed from computed event dependencies and used to identify the cause of an error.

Slicing has also been shown to be a valuable tool for detecting malicious behavior. For example, King and Chen show how to reconstruct adversarial behavior from traces of operating system events on compromised hosts [27]. Their BackTracker system uses timed filesystem and process system call traces to reconstruct possible compromising events. BackTracker reconstructs a graph of relevant operations working from some known compromised behavior. This graph highlights the possible sources of compromise, and hence is a succinct and intuitive forensic representation of the attack. We note that such solutions may face similar issues as debugging slicer applications. For example, the cost of keeping complete execution or event traces may be prohibitive. We posit that sampling techniques, such as those proposed Liblit *et. al.* [32], may help mitigate these costs.

Sandboxing is an increasingly important tool for secure systems deployment [15, 17, 18, 19, 23]. Sandboxing tools prevent malicious behavior by monitoring and regulating security relevant operations according to some *policy*. For example, Provos regulates process operation by intercepting and enforcing policy over system calls [39]. These policies reduce the range of possible behaviors of a governed process, and hence the power of the compromising adversary. Garfinkel provides a thorough treatment of complex issues faced by designers of these *system call interposition* solutions [16]. Other systems are based on similar ideas, but built upon formal policy models [8, 45, 46]. Based on the Flask architecture, the SELinux platform uses a number of similar enforcement mechanisms to enforce role based access control, type safety, and multi-level security policy [34].

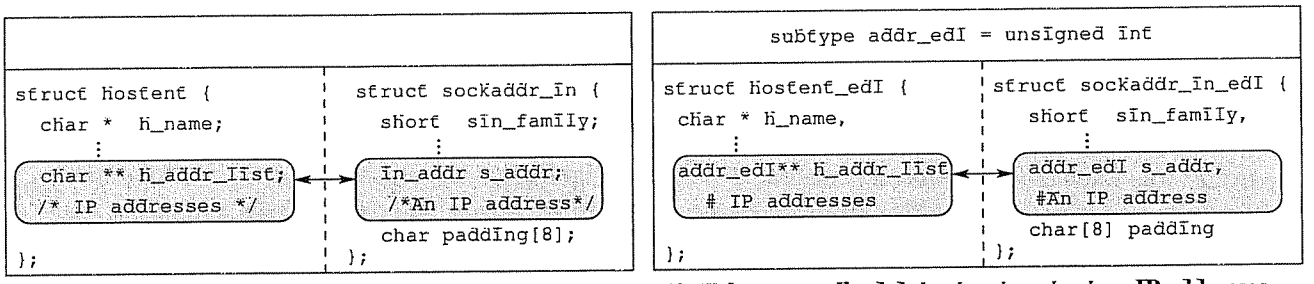
Policy enforcing solutions need not require privileged or kernel level access. Jain and Sekar introduce the notion of user level interposition of system calls as a vehicle for intrusion detection and malicious behavior mitigation [23]. Other solutions attempt to control program flow [28] or monitor for and prevent specific behaviors (e.g., buffer overflows) [13] through code instrumentation or process introspection.

Several commercial products have recently been launched in response to heightened public concern about spyware. In addition to a range of other security related features, *Zone Alarm* [58, 59] restricts local network connections based on a local policy. Zone Alarm further allows policy to be learned through user input, e.g., by appealing to the user when network operations with unspecified policy occur. Other commercial products treat spyware as viral behavior. Products such as *Ad-aware* [1, 2] develop signatures for spyware. Local drives, memory, and attachments are checked for the presence of spyware. Where found, the offending sources are quarantined.

While we build on many of these works, but the goals and execution of sandBoX86 make it unique. The novelty of our solution lies not only in the technology, but in the domain of policy; we focus on services that ensure *user privacy*. We use dynamic slicing to analyze behavior and guide policy construction, rather than as a forensic tool. Moreover, our dynamic slicing tool processes execution traces that do not have complete information (e.g., only system calls are visible but all the internal computation is hidden). The idea of interposing a library to intercept Win32 APIs has been suggested [22, 42] and UNIX system call interposition is well understood. However, we are the first to integrate comprehensive tools for policy creation and their subsequent enforcement. The following sections detail how we bring these elements together to form a complete and novel solution to combat privacy violations.

4 Dynamic Slicing

Dynamic slicing attempts to discover dependencies between events in an execution trace. In this section we present our dynamic-slicing algorithm. One of the main challenges we faced in dynamic slicing was incomplete information. For example, we only log events that correspond to Win32 API calls, and therefore all the information about the internal computation of the application is absent from the trace. We present a



(a) Two different ways to store IP addresses **(b) Using normalized data structure to store IP addresses**

Figure 4: Using type normalization to improve slicing precision.

dynamic-slicing algorithm which constructs slices using such event traces.

4.1 Dynamic Slicing

This subsection provides the description of our dynamic-slicing algorithm. First, we formally define events and traces. Different events (such as `gethostbyname` and `bind`) use different types to represent the same information. For example, `gethostbyname` and `bind` use different types to represent IP addresses (see Figure 4 (a)). In order to determine dependencies between events, types of arguments and return values have to be normalized, e.g., all elements representing IP addresses should have the same type. We describe such a type-normalization procedure. Using types of arguments and return values to events, we define dependencies between events. Finally, dependencies between events are used to define forward and backward slices.

Events and traces. An *event* is a triple $e = \langle pc, \textit{event-name}, \textit{arg-list} \rangle$, consisting of the program counter *pc*, name of the event *event-name*, and a list of typed arguments $\textit{arg-list} = (v_1 : \tau_1, \cdots, v_k : \tau_k)$ (where value v_i has type τ_i). An event represents a Win32 API call made at a specific location by the application. By convention, the last value in the argument list is the value returned by the event. A *trace* T is simply a sequence $\langle e_1, \cdots, e_n \rangle$ of events.

Type normalization. The type mismatch problem is a result of the fact that equivalent data types can have different representations in C. For example, types `char*` and `char[]` are equivalent. Instead of using sophisticated type equivalence algorithms [10, 37] we normalize the types using the EDL specification. For example, the Windows' socket API defines two structures that refer to hosts, shown in Figure 4 (a). The structure `hostent` uses a `char**` to represent a list of possible IP addresses. On the other hand, the structure `sockaddr_in` stores a single IP address for a host using the type `struct in_addr` (which is a union of 4 bytes). Some calls like `gethostbyname`, and `gethostbyaddr` use `hostent` to return the address information for a given host. On the other hand, calls such as `connect` and `bind` use `sockaddr_in` to pass IP address information. Our slicing algorithm needs to deduce equivalence between types in order to determine dependency information.

Using the EDL specification we normalize all equivalent types and replace them by an unique type. This unique type is used in every place where one of the equivalent types is used in the API. Continuing with the example, we choose to use `addr_edI` as the unique type to represent IP addresses. We first create a unique type to represent the normalized type, and then update all corresponding data structures inside EDL to use this new data type. The corresponding EDL data structures (all the type names end with the suffix `edI`) are shown in Figure 4 (b). Here the new unique type `addr_edI` is used to represent IP addresses in the two data structures `sockaddr_in_edI` and `hostent_edI`. This solution works as long as the types

are compatible, and the fact that both structures now use the same subtype allows the slicing algorithm to infer data dependency.

Killed and used sets. Consider an event $e = \langle pc, \textit{event-name}, \textit{arg-list}\rangle$, where $\textit{arg-list} = (v_1 : \tau_1, \cdots, v_k : \tau_k)$. We associate two sets of values, called the *killed set* and *used set* (denoted by *killed(e)* and *used(e)*), with an event e. The killed and used set are defined as follows:

$$\begin{aligned} \textit{killed(e)} &= \{v_i \mid v_i \text{ is a pointer and is modified by the event}\} \\ \textit{used(e)} &= \{v_i \mid v_i \text{ is used by the event } e\} \end{aligned}$$

Notice that the killed set only contains pointers. Whether an argument is modified or used by an event is inferred from the documentation of the Win32 API call corresponding to the event. Note that the value corresponding to the return value of an event is always in the killed set.

Computing Dependencies. In order to define data dependence formally, we need to precisely define whether a value v depends on another value v'. In traditional dynamic-slicing algorithms [4, 30, 53, 57], one records all the loads and stores at all memory addresses. Therefore, dependency information is easy to infer from memory addresses. Since our logs have incomplete information, deciding whether a value is dependent on another is tricky. We define a predicate $\textit{depends}(v : \tau, v' : \tau')$, which returns 1 if v is dependent on v' and returns 0 otherwise. Our definition of $\textit{depends}(v : \tau, v' : \tau')$ uses type information associated with values.

In our type system, certain primitive types (such as `addr_edI`) are designated as *types with equality*. Intuitively, primitive types with equality represent an operating-system resource or an entity (such as a host), e.g., a value of type `addr_edI` abstractly represents the host with the specified IP address. Two values of primitive types can only be compared if the types are designated as types with equality. In other words, given two values $v : \tau$ and $v' : \tau$, we say that $v = v'$ is true iff $v = v'$ and τ is a primitive type with equality.

A record type that has k fields of type $\tau_1, \cdots, \tau_k$ is denoted by $\textit{record}(\tau_1, \cdots, \tau_k)$. A pointer to an object of type τ has type $\textit{ref}\,\tau$. Suppose that we have two values v and v' of type $\tau = \textit{record}(\tau_1, \cdots, \tau_k)$ and $\textit{ref}\,\tau$, respectively, where for $1 \leq i \leq k$, τ_i are primitive types (v is a record and v' is a pointer to a record). Let the i-th field of the record v be v_i and the i-th field of the record pointed to by v' be $(\star v')_i$. In this case, we say that v depends on v' if there exists i such that $v_i = (\star v')_i$ and τ_i is a primitive type with equality. Intuitively, the records represented by v and pointed to be v' share an operating system resource or entity corresponding to the primitive type τ_i. This intuitive idea is formalized and extended to the complete type system shown in appendix A.1.

Consider a trace $T = (e_1, \cdots, e_n)$. A value v in an event e is denoted by (v, e). We say that there is a *data dependence* of value (v_i, e_a) on a value (v_j, e_b) if following three conditions are satisfied:

- $v_i \in \textit{used}(e_a)$,
- for all k such that $b < k < a$ we have that $v_j \notin \textit{killed}(e_k)$, and
- value v_i depends on v_j or $\textit{depends}(v_i, v_j) = 1$.

Notice that in traditional program analysis literature this is called a def-clear path from (v_j, e_b) to (v_i, e_a) [5].

Forward and backward slices. Consider a trace $T = \langle e_1, \cdots, e_n\rangle$. The *data-dependency graph* or *DDG* of T is defined as a directed graph $G = (V, E)$, where V and E are defined as follows:

- Consider an event $e = (pc, \textit{event\_name}, (v_1 : \tau_1, \cdots, v_k : \tau_k))$. The set of vertices $V(e)$ associated with e is $\{(v_1, e), \cdots, (v_k, e)\}$. The set of vertices V of the DDG is $\bigcup_{i=1}^{n} V(e_i)$, where $\{e_1, \cdots, e_n\}$ is the set of events occurring in T.
- There is an edge from (v, e_i) to (v', e_k) (denoted as $(v, e_i) \rightarrow (v', e_k)$) iff (v', e_j) depends on (v, e_i).

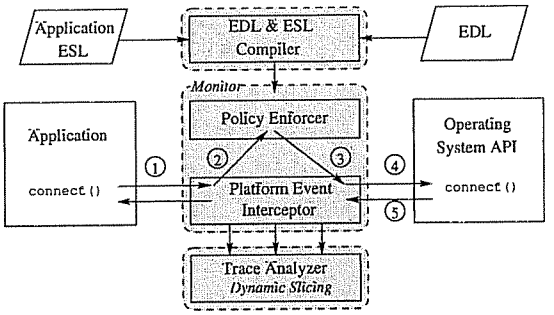


Figure 5: Architecture Diagram

```
1. typedef sockaddr_edl = union string | int
2. typedef socket_edl = int
3. event connect(socket_edl sock, sockaddr_edl addr) = int
4. event gethostbyname(string name) = sockaddr_edl
```

Figure 6: EDL example.

A *forward slice* from a value (v_j, e_i) in the trace T (denoted by $fslice((v_j, e_i), T)$) is the sub-graph of G_T that contains all vertices that correspond to events which are reachable from (v_j, e_i). A *backward slice* from a value (v_j, e_i) in the trace T (denoted by $bslice((v_j, e_i), T)$) is the sub-graph of G_T that contains all vertices that can reach (v_j, e_i).

Implementation details and GUI. Our dynamic-slicing tool is about 9000 lines of Java code. Description of the GUI and additional implementation details can be found in appendix B.2.

5 SandBoX86

The architecture of our infrastructure is shown in Figure 5. We first describe the life-cycle of an event through our architecture. Since our architecture monitors Windows applications, the events of interest are Win32 API calls. The number of the item given below corresponds to the arrows in Figure 5.

1. The application generates an event which is captured by the *event-interceptor DLL*.
2. The event generated by the application is transformed into an *abstract event* by the *event-interceptor DLL* and is passed to the *policy-enforcer DLL*.
3. The *policy-enforcer DLL* processes the abstract event and decides on an appropriate action.
4. If the abstract event is allowed, then the *policy-enforcer DLL* passes the concrete event to the operating system.
5. Results from the operating system are received and passed back to the application and the state of the monitor is updated. If the abstract event is denied, a failure code is returned to the application.

Event Description Language (EDL). The *event description language* or *EDL* is a platform-independent language for specifying parameterized events. It has a rich type system (described in appendix A) , which allows for detailed specification of events and their associated arguments and return values. Intuitively, EDL describes *abstract events* which are used by the security policy. The intent of the EDL is that it can be used to create an abstract model for a given platform. For example, a model describing the Win32 and socket APIs would be an expected use of the EDL. We have implemented a compiler for EDL, which takes as its input a file with an EDL specification and produces header files which are used in generating the policy-enforcer DLL. We will describe various features of EDL using an example.

Example 3 Consider the EDL example shown in Figure 6. The example defines the following data-types and events:

- **typedef** `sockaddr_edl...` defines a type representing an IP address. It is a union because an IP address may be stored as either a string or an integer value.
- **typedef** `socket_edl...` defines a type representing a socket descriptor, stored as an integer.
- **event** `connect(...)= int` defines an event representing a connect system call. It takes two parameters, a socket, and an address. The event returns an integer error code.
- **event** `gethostbyname(...) =sockaddr_edl` defines an event representing a DNS nameservice lookup. It takes a hostname and returns an IP address.

Event Sequence Language (ESL). Our security policy is expressed in a language called the *event sequence language* or *ESL*. Examples of two ESL policies were given in Section 2. Therefore, due to space limitations we will keep the discussion of ESL brief. An ESL specification defines patterns on *abstract events* specified by the EDL. Once a pattern is matched, rules can be applied to determine whether or not the abstract event should be allowed or denied. Formally, ESL is a framework to describe a security automaton [48] whose alphabet is the set of abstract events defined using EDL. We have built a compiler for ESL which takes files containing EDL and ESL specifications and creates the policy-enforcer DLL. We describe various components of ESL.

Abstract events. In Figure 3 of Section 2, [**edl** `"kazaa.edl"`] refers to the EDL file named `"kazaa.edl"`. All rules defined in this ESL specification use the abstract events defined in the EDL file `kazaa.edl`.

State. The state in the security policy is defined using auxiliary variables. Any valid type in the `C` programming language is an allowable type for an auxiliary variable.

Actions. We define three types of actions in our security policy: `allow`, `deny`, and `transform`. The `allow` action specifies that an event should be allowed and passed on to the operating system. The `deny` action indicates that an abstract event should be disallowed and a failure code should be returned to the application. The `transform` action indicates how certain arguments of an event should be transformed before the event is passed to the operating system (OS). The `transform` action was added because certain applications will shut themselves down if system calls they issue fail. We are investigating OS-virtualization techniques to handle this issue.

Rules. Each rule in the security policy is of the following form:
match *event [precondition]* $\rightarrow$ *action [postcondition]*
An event *e* *matches* the above rule if the state of the security policy satisfies the precondition of the rule and *e* matches the event specified by the rule. If event *e* matches a rule, the action specified in the rule is taken and the state is updated according to the postcondition. If there are multiple rules, then the first rule that matches an event is applied (this is similar to processing of firewall rules). Events that do not match any rule are allowed by default.

Implementation details. The ESL and EDL compiler are about 2700 lines of Java code. For efficiency reasons, the monitor was implemented in C. Our implementation for the monitor is approximately 3000 lines of C code. Additional details can be found in appendix B.1.

5.1 Threats

A thorough discussion of traps and pitfalls of sandboxing systems which rely on system call interposition is given by Garfinkel [16]. The three major threats specific to our sandboxing system are:
DLL bypassing. A hostile application could try to thwart the interposed monitor DLL by not making calls through the standard Win32 API. We have implemented a kernel hook to address this attack. Our kernel hook is described in detail in Appendix C. Eventually, in order to eliminate the DLL bypassing attack we

want to move to a hybrid-sandboxing architecture [2], which is a difficult task given the arcane nature of the Windows kernel API.
Direct attack. This attack can take two forms: modifying the monitor on disk or in memory with the goal of bypassing the security policy.
Mimicry attack. The idea behind this attack is to analyze the specific ESL policies in use, and transform the attack such that it is allowed by the security policy [55].
Countermeasures to direct and mimicry attacks are discussed in the appendix C.

6 Case Studies

To evaluate our infrastructure, we considered two applications: KaZaa [25] and RealOne Player [41]. We chose these two applications because they have two properties in common: *both are very popular* and more importantly, *both are often classified as spyware*. As defined earlier, spyware is a useful software that also transmits private user data to an external entity. As both KaZaa and RealOne Player are used by millions of users, the prospect that they may contain malicious spying activities often causes great concerns. This section gives a brief overview of the two applications.

6.1 KaZaa

KaZaa [25] is a distributed peer-to-peer (P2P) file-sharing application which allows millions of users to share files over the Internet. As of May 2004 [26], an estimated 348 million copies of KaZaa had been downloaded. Although KaZaa itself may not have any spyware features, it often distributes third-party software with every release, and some, if not all, of these third-party software are spyware-laden. We divide these bundled spyware into three categories.

- **Advertising.** Most of the spyware distributed with KaZaa is related to advertising (and hence is called *AdWare*) and their main objective is to display advertisements to KaZaa users. Since KaZaa receives fees from third-party software vendors, there is an incentive for KaZaa to make sure that the users cannot bypass the AdWare. For example, *Cydoor*, a frequently cited spyware bundled with Kazaa, is in fact embedded within KaZaa so that a forceful removal of *Cydoor* will cause KaZaa to malfunction. The latest version of KaZaa that we have investigated (version 2.5.2) has the capability of thwarting users from using simple techniques to block its third party software. If KaZaa is unable to detect or undo the changes made by users, then it will crash when the built-in spyware attempts to connect to the home servers.
- **Spying.** Although KaZaa claims that it no longer bundles any spyware, older versions of software bundled with KaZaa had features such as tracking and reporting user activities back to the vendors and downloading and installing binary programs.
- **Hidden features.** When first revealed to the public in 2002, *Altnet*, a software bundled with KaZaa, caused an uproar amongst users. Altnet, once enabled, could allow Altnet's distributor, Brilliant Digital, to tap into the vast computer resources of the KaZaa users. For instance, Brilliant Digital could use millions of KaZaa users' computers to store and retrieve files, or to perform computation tasks. Altnet software is currently still bundled with KaZaa, even though Brilliant Digital has not activated it.

[2] In a hybrid sandbox, the trapped event is first passed to a kernel module which consults a user module (which contains the security policy) to decide on the appropriate action for the event.

6.2 RealOne Player

RealOne Player [41] is a part of the widely used software suite developed by Real Networks. RealOne Player can manage and play back many types of media files, such as *real, mpeg* and *MP3*. In addition, as a feature, RealOne Player can retrieve detailed information about the media file being played. For example, when a user is playing a music CD, RealOne Player can display the title of the CD as well as details about each track. Real Networks' software has a well known history of sending user-related information back to Real's server, which is clearly stated in their End-User License Agreement (EULA). Although Real Networks does not reveal the details about what kind of information their software is collecting, it was widely reported that Real Jukebox from Real Networks used to send its user's music preferences back to Real Networks' home servers. For instance, when a user is listening to a CD, Real Jukebox could send information about the CD and the user's unique identifier to Real Networks.

6.3 Thwarting Privacy Violations

Using a process very similar to the one described earlier (see scenario 2 in section 2) we were able to discover privacy violations in KaZaa and RealOne Player and gather detailed information about them. Using this information we were able to design security policies (which are very similar to the policy shown in Figure 3 of Section 2) to thwart these privacy violations. Details about this process are omitted due to space limitations.

7 Evaluation

This section describes an empirical study of the performance of sandBoX86. We evaluate cost over three sets of experiments. We measure low-level costs by collecting per-API call *microbenchmarks*, and profile application sandboxing using *macrobenchmarks* collected from user programs. Finally, we study the resource usage of our tool by analyzing memory consumption. These tests reveal that the performance and resource costs associated with sandBoX86 are nominal. Moreover, they further illustrate that these costs are less than those incurred by the majority of extant sandboxing tools, and did not demonstrably change the user experience in interactive applications (e.g., the sandboxing did not visibly change application response time). For example, the macrobenchmarks show a slow down of less than 3.2% for all three test applications.

We conducted all experiments on a 2.8GHz Intel Pentium-4 based machine with 1GB of memory, running Windows 2000 Professional. We use the *high-performance timer* (with the precision of 0.28μ-sec/cycle) to obtain the experiment data. The *SSH Secure Shell* (version 3.2.0), *KaZaa* (version 2.5.2) and *RealPlay* (version 2.0) were profiled in our experiments. The *SSH Secure Shell* application was tested by connecting to a random host selected from a host pool. This test further simulates a SSH workload by connecting to the remote host, executing a fixed series of UNIX commands (e.g., `cd`, `tar`, `gzip` and `grep`), and disconnecting. The KaZaa application searched and downloaded the KaZaa installation binary (about 7MB), after which it exited. Finally, the *RealPlay* played a music file (about 3 minutes long) and terminated. Each experiment was conducted three times and results were averaged.

7.1 Microbenchmarks

Microbenchmarks measure the per-API call overhead. Our base metrics are obtained by measuring the time of each API call as uninstrumented (*original* in Table 1) and sandboxed. The difference between the two metrics is the measured *total overhead* of our sandbox infrastructure. We note that it is necessary to

Table 1: Microbenchmarks (partial)[a]

API Name	Application	Original (μs)	Overhead (μs)			
			Monitor	Enforcement	Logging	Total
bind	RealPlay	78.78	5.87	1.68	16.34	23.89
	KaZaa	66.99	5.92	1.57	16.17	23.66
closesocket	SSH	69.84	6.15	2.23	6.70	15.08
	RealPlay	64.81	6.29	1.54	8.66	16.49
	KaZaa	57.93	6.31	1.47	7.93	15.71
connect	SSH	77.24	6.15	3.49	31.71	41.35
	RealPlay	126.41	6.29	4.75	20.11	31.15
	KaZaa	81.76	6.12	3.10	22.70	31.92
gethostbyname	SSH	31669.40	8.38	82.41	39.39	130.17
	RealPlay	7314.34	8.38	84.65	22.07	115.10
	KaZaa	34144.00	8.66	117.85	29.10	155.61
select	RealPlay	4736480.00[b]	4.90	0[c]	0[c]	4.90
	KaZaa	107134.30[b]	4.20	0[c]	0[c]	4.20
send	SSH	29.49	6.99	1.79	60.38	69.16
	RealPlay	13.13	6.70	1.68	100.85	109.23
	KaZaa	38.13	5.95	1.56	45.25	52.76
socket	SSH	620.75	6.98	3.91	9.50	20.39
	RealPlay	286.53	7.26	4.84	9.08	21.18
	KaZaa	78.05	6.04	1.66	8.72	16.42
WSAAsyncSelect	SSH	8.89	5.81	1.44	8.52	15.77
WSARecv	SSH	10.48	5.88	1.46	12.67	20.01
	KaZaa	40014.94	5.90	1.52	14.25	21.67
WSARecvFrom	KaZaa	11.56	5.94	1.50	23.94	31.38

[a]Due to space limitation, we only show a subset of the data. Trivial API calls such as `ntohl`, `htonl`, etc are omitted here.
[b]The cost here includes the time spent waiting for I/O to complete, therefore is not an accurate reflection of the CPU overhead.
[c]In this case, the policy does not enforce or log the *select* call. Therefore there is no overhead.

construct finer-grained metrics to capture the impact of application specific behavior. For example, policy enforcement is naturally application dependent. Additionally, because logging records the arguments of each API call, its cost could differ greatly from application to application (and in some cases, within the same application). For these reasons, we broke down the total overhead into three cost categories: *monitor overhead*, *enforcement overhead* and *logging overhead*. The results are shown in Table 1.

7.2 Memory Usage

Note that in all tests, the `select` call appears to be abnormally expensive. This is because the measured `select` calls are blocking, and much of the measured time was actually spent waiting for the I/O to be ready, i.e., the program had yielded the processor. The actual CPU time for a `select` call should be a tiny fraction of the cost shown in the table. The measured cost of the `WSARecv` calls in the KaZaa application is also high for the same reason. Similarly, `gethostbyname` shows high execution cost in all three test cases also due to the blocking nature of the call.

The monitoring costs are small and nearly identical in all tests. This is not surprising because monitor-

Figure 7: Macrobenchmarks

Application	Orig. (ms)	Overhead (ms)			
		Monitor	Enforcement	Log	Total(%)
SSH Client	838	12.17	2.65	12.72	27.54(3.20%)
RealPlay	2146	0.43	0.14	0.43	1.00(0.05%)
KaZaa	4124	22.19	1.70	9.09	32.98(0.80%)

Figure 8: Memory Overhead

Application	Original (KB)		Overhead (KB)		
	Text	Data	Text	Data	Total
SSH Client	2126	991	94	42	136
RealPlay	37	164	94	42	136
KaZaa	1143	1126	94	45	139

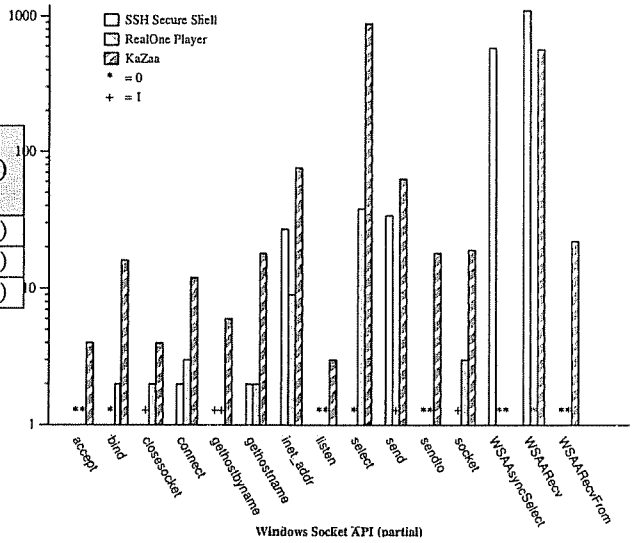


Figure 9: API Call Patterns For Each Application.

ing is implemented by a largely fixed matching operation. The measured enforcement overhead is highly dependent on the policy and hence exhibits variation between tests. Note that `gethostbyname` calls have relatively high enforcement cost. This is because the regulating policy requires expensive book-keeping. In particular, enforcement requires the hashing of multiple IP addresses [38]. Logging overhead also differs among applications since each application may use the same API slightly differently. However our results show that this variance is largely insignificant. In one exception, the logging overhead for `send` calls on KaZaa is smaller that those of other applications. This is because of the variable costs associated with storing the varying "send buffer" sizes, i.e., cost grows linearly with the size of the recorded buffer.

Not every application uses every API call and certainly not in the same way. Figure 9 illustrates the high level of diversity in API use. For example, only KaZaa used the `accept` and `listen` calls. Both *RealPlay* and *KaZaa* made a large number of *blocking* `select` calls. While at the same time *SSH Secure Shell* frequently utilized the non-blocking select call `WSAAsyncSelect`. As we shall see in following section, such call distributions provide insight into the total overhead incurred by an application.

7.3 Macrobenchmarks

While microbenchmarks gives a clear picture on the per-API overhead, it is the performance of the applications which end users care most about. For this reason, we measure the total overhead incurred by each application using *macrobenchmarks*. Shown in Table 7, these metrics reflect the aggregate cost by measuring the applications' total run time. Out of the three applications tested, SSH incurred the highest overhead. For monitoring only, SSH took an additional *12.17* milliseconds of overhead; the total overhead for SSH is *27.54* milliseconds, or about *3.2%* comparing to the original cost. In comparison, both RealOne Player and KaZaa only incurred a small amount of overhead (about *0.05%* and *0.80%*, respectively). In summary, the experiments indicate that interactive or computation bound applications will see little performance impact. Network bound applications may see some performance degradation, but even those costs are within reasonable limits (e.g., 3.2%).

7.4 Memory Usage

In addition to the run-time overhead, we also measured the memory overhead, shown in Table 8. Since we use the same code-base for all three test cases, the text-memory overhead is the same for all applications. The data-memory overhead varies slightly among applications because of the various data structures we maintain are policy specific. Some data structures are shared among applications for efficiency reasons. For example, we maintain a cache of all function pointers to the libraries we are intercepting. This cache is shared among all monitored applications.

8 Conclusion

We presented the design and implementation of a sandboxing infrastructure for Windows. We also described a dynamic-slicing algorithm for analyzing data dependencies in event traces. Our dynamic-slicing algorithm can be used to discover privacy violations. Finally, we performed an evaluation of our techniques on two applications: KaZaa and RealOne Player.

There are several directions for future work. A sandboxing system is only as good as the security policy it enforces. We want to investigate techniques, such as model checking, for analyzing security policies. We also want to develop a more powerful query interface to our dynamic-slicing tool. We believe that this will improve the task of discovering privacy violations. We also plan to undertake a thorough study of weaknesses and vulnerabilities of sandboxing systems for Windows.

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