How to Sandbox IIS Automatically without 0 False Positive and Negative

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Big Picture

- Ways to get malicious code/data into victim sites

  (1) Break cryptography

  (2) Exploit design flaws in security protocols

  (3) Leverage applications' convenience features

  (4) Exploit application-level implementation bugs

  (5) Exploit language-level implementation bugs

  (6) Non-technical attacks: insider, social engineering, etc.

- The majority of attacks are based on (3), (4) and (5)

Software Security

- Bugs in programs lead to vulnerabilities that attackers exploit
- Design vs. Implementation bugs
- How to detect security-related bugs
  - Static analysis
  - Dynamic checking
  - Intrusion detection/prevention

Control- Hijacking Attacks

- Network applications whose control gets hijacked because of software bugs: Most worms, including MS Blast, exploit such vulnerabilities
- Three-step recipe:
  - Insert malicious code/data into the victim application

    Sneaking weapons into a plane
  - Trick the attacked application to transfer control to the inserted code or some existing code

    Taking over the victim plane
  - Execute damaging system calls as the owner of the attacked application process

    Hit a target with the hijacked plane

Control-Hijacking Attack

- Three types of overflows:
  - buffer overflow
  - integer overflow
  - input argument list overflow (format string attack)
- Consequences
  - Code Injection
  - Return-to-libc
  - Data attack

Example: Stack Overflow Attack

```
main() {
   input();
}
input() {
    int  i = 0;;
    int userID[5];

    while ((scanf("%d", &(userID[I]))) != EOF)
        i ++;
}
```

STACK LAYOUT

FP → 124 Return address of input() **100**

120 Local variable i

116 userID[4]

112 userID[3]

108 userID[2] **INT 80**

104 userID[1]

SP → 100 userID[0]

Proposed Defenses

Stop the attack at either of the three steps:

- Overflowing some data structures

  Bounds checking compiler, e.g., CASH (world's fastest array bound checking compiler on Linux/X86 platform)

- Triggering control transfer

  Branch target check, e.g., FOOD (Foreign code detection on Windows/X86 platform)

- Issuing damaging system calls

  System call pattern check, e.g., PAID

Program semantics-Aware Intrusion Detection (PAID)

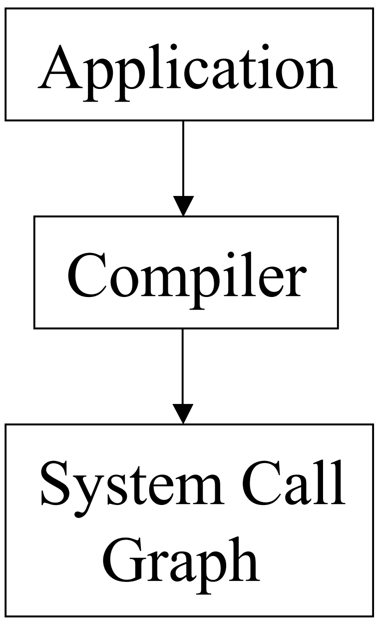
- As a last line of defense, prevent intruders from causing damages even when they successfully take control of a target victim application
- Key observation: Most damages can only be done through system calls, including denial of service attacks
- Idea: Prevent a hijacked application from issuing system calls that deviate from its semantic model

System Call Model Checking

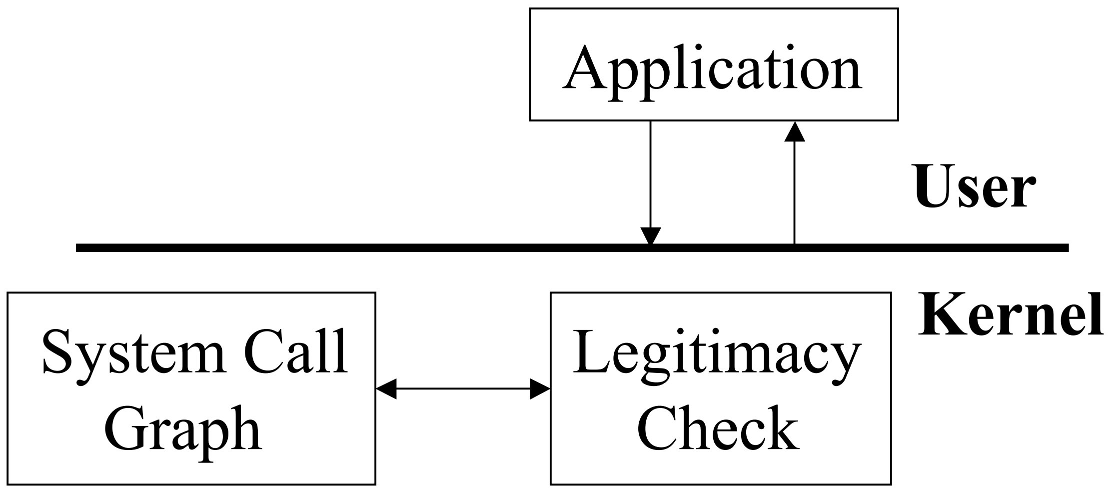
- Achilles Heel: How to derive a system call model for an arbitrary application?
  - Manual specification: error-prone, labor intensive, non-scalable
  - Machine learning: error-prone, training efforts required
- PAID's approach: Use compiler to extract the *sites* and *ordering* of system calls from the source code of any given application automatically
  - Guarantees zero false positives and very-close-to-zero false negatives
  - System call policy is extracted automatically and accurately

PAID Architecture

Compile Time Extraction



Run Time Checking



System Call Flow Graph

- Take a program's control flow graph, and eliminate all nodes that are not related to system calls
- Traverse the SCFG at run time to verify the legitimacy of every incoming system call
- Non-determinism:
  - If-then-else statements
  - Function with multiple call sites

System Call Instance Coordinate

- Each system call instance is uniquely identified by
  - The sequence of return addresses used in the function call chain leading to the corresponding “int 80” instruction
  - The return address of the “int 80” instruction itself
- Example:

  Main→ F1→ F2 → F4 → system_call_1 vs.

  Main→ F3→ F5 → F4 → system_call_1

System Call Flow Graph Traversal

- Is there a path from the previous system call instance (R_1, R_2, R_3, … R_n) to the current system call instance (S_1, S_2, S_3, … S_m)?
- Largely deterministic → low latency

Dynamic Branch Targets

- Not all branch targets are known at compile time: function pointers and indirect jumps
- Insert a notify system call to tell the kernel the target address of these indirect branch instructions
- The kernel moves the current cursor of the system call graph to the designated target accordingly
- Notify system call is itself protected

Asynchronous Control Transfer

- Setjmp/Longjmp
  - At the time of setjmp(), store the current cursor
  - At the time of longjmp(), restore the current cursor
- Signal handler
  - When signal is delivered, store the current cursor
  - After signal handler is done, restore the current cursor
- Dynamically linked library such as dlopen()
  - Load the library's system call graph at run time

Mimicry Attack

- Hijack the control of a victim application by over-writing some control-sensitive data structure, such as return address
- Issue a legitimate sequence of system calls after the hijack point to fool the IDS until reaching a desired system call, e.g., exec()
- None of existing commercial host-based IDS can handle mimicry attacks

Mimicry Attack Example

- Legitimate sequence:

  `open() → read() → receive() → send() → exec()`

- Buffer overflow vulnerability exists between open() and read()
  - Hijack the program's control between open() and read()
  - Execute `read() → receive() → send() → exec()`

Mimicry Attack Details

- To mount a mimicry attack, attacker needs to
  - Issue each intermediate system call without being detected

    Nearly all system calls can be turned into no-ops

    For example `(void) getpid()` or `open(NULL,0)`
  - Grab the control back after each intermediate system call

    Set up the stack so that the injected code can take control after each system call invocation

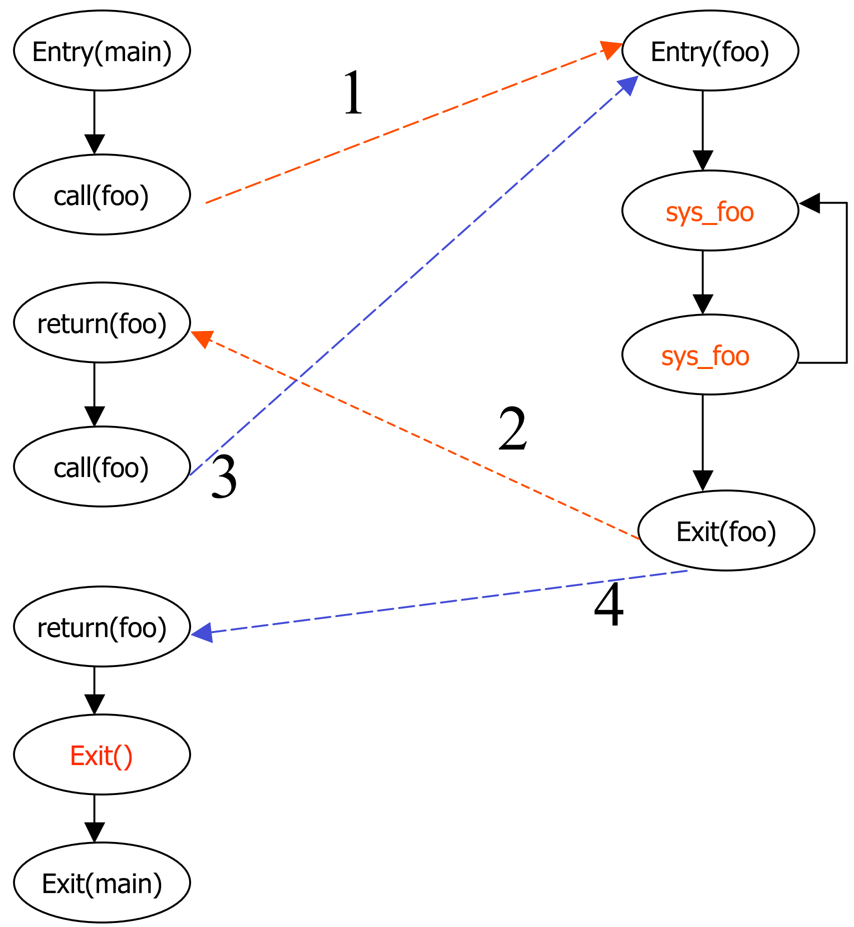
Countermeasures

- Minimize non-determinism in the system call model
  - If (a>1) { open(..)} else {open(..); write(..)}
- Checking system call argument values whenever possible
- Random insertion of null system calls at load time to defeat guessing
  - Different SCFGs for different instances of the same program

Impossible Path Example

```
main()
{
    foo();     % W
    foo();     % X
    exit();    % E
}

foo()
{
    for(….){
        sys_foo(); % Y
        sys_foo(); % Z
    }
}
```



With PAID

- Legitimate Path:
  WY → WZ → XY → XZ → E
- Impossible Path:
  WY → WZ → E ✗

PAID Checks

- Ordering
- Site: return address sequence
- Arguments
- Checking performed in the kernel with SCFG stored in the user space

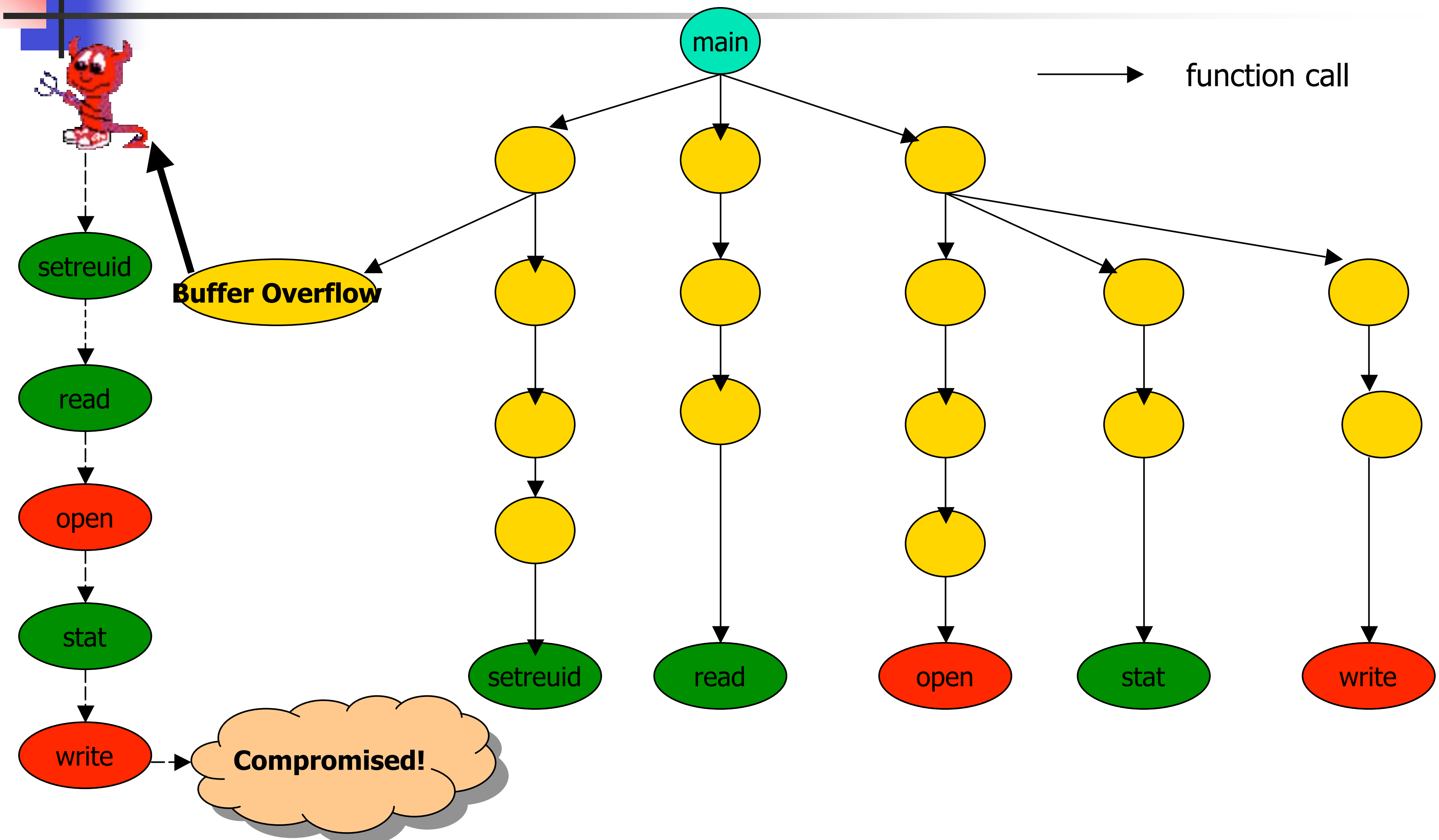
System Call Argument Check

- Start from each “file name” system call argument, e.g., open() and exec(), and compute a backward slice towards the “inputs”
- Perform symbolic constant propagation through the slice, and the result could be
  - A constant: static constant
  - A program segment that depends on initialization-time inputs only: dynamic constant
  - A program segment that depends on run-time inputs: dynamic variables

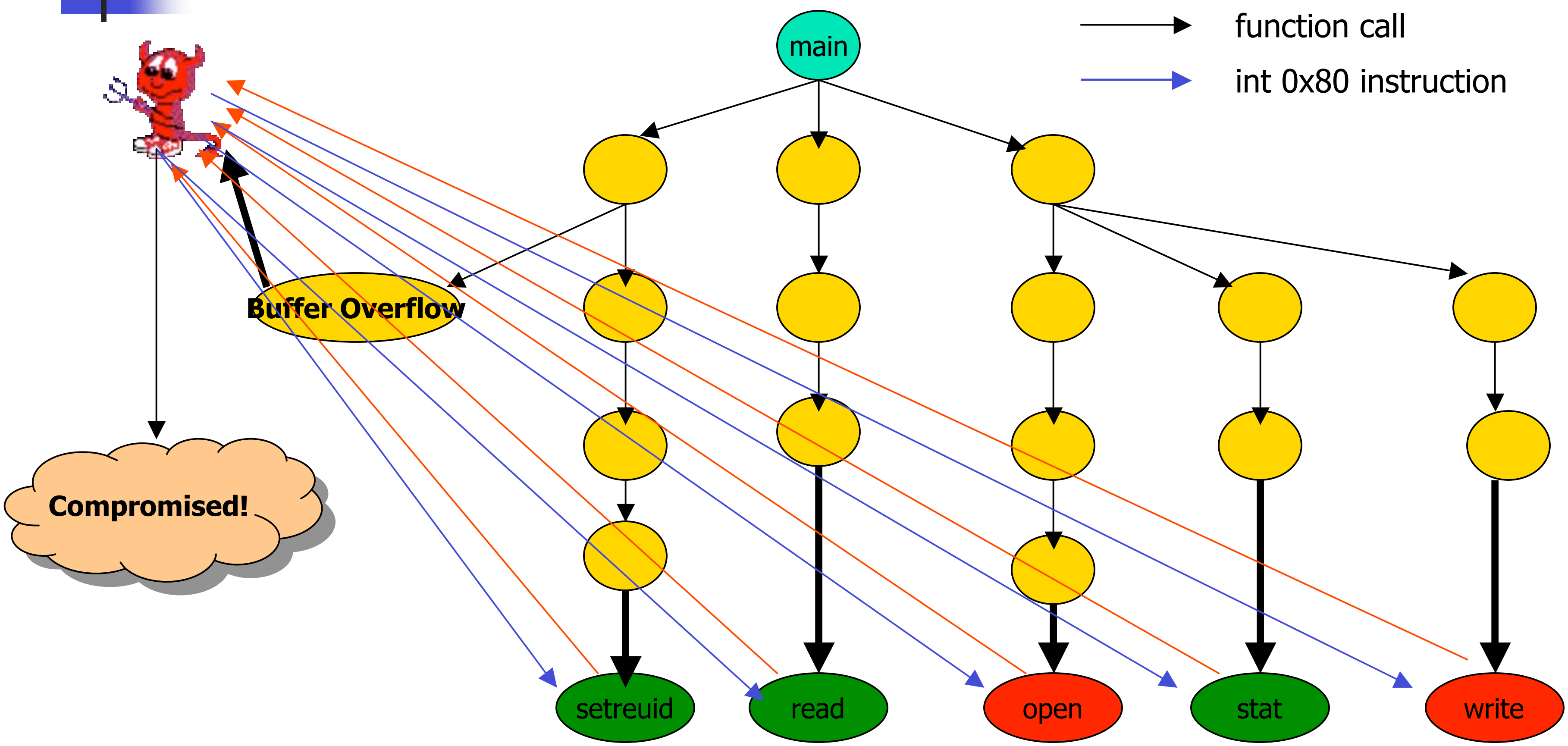
Dynamic Variables

- Derive partial constraints, e.g., prefix or suffix, "/home/httpd/html"
- Enforce the system call argument computation path by inserting null system calls between where dynamic inputs are entered and where the corresponding system call arguments are used

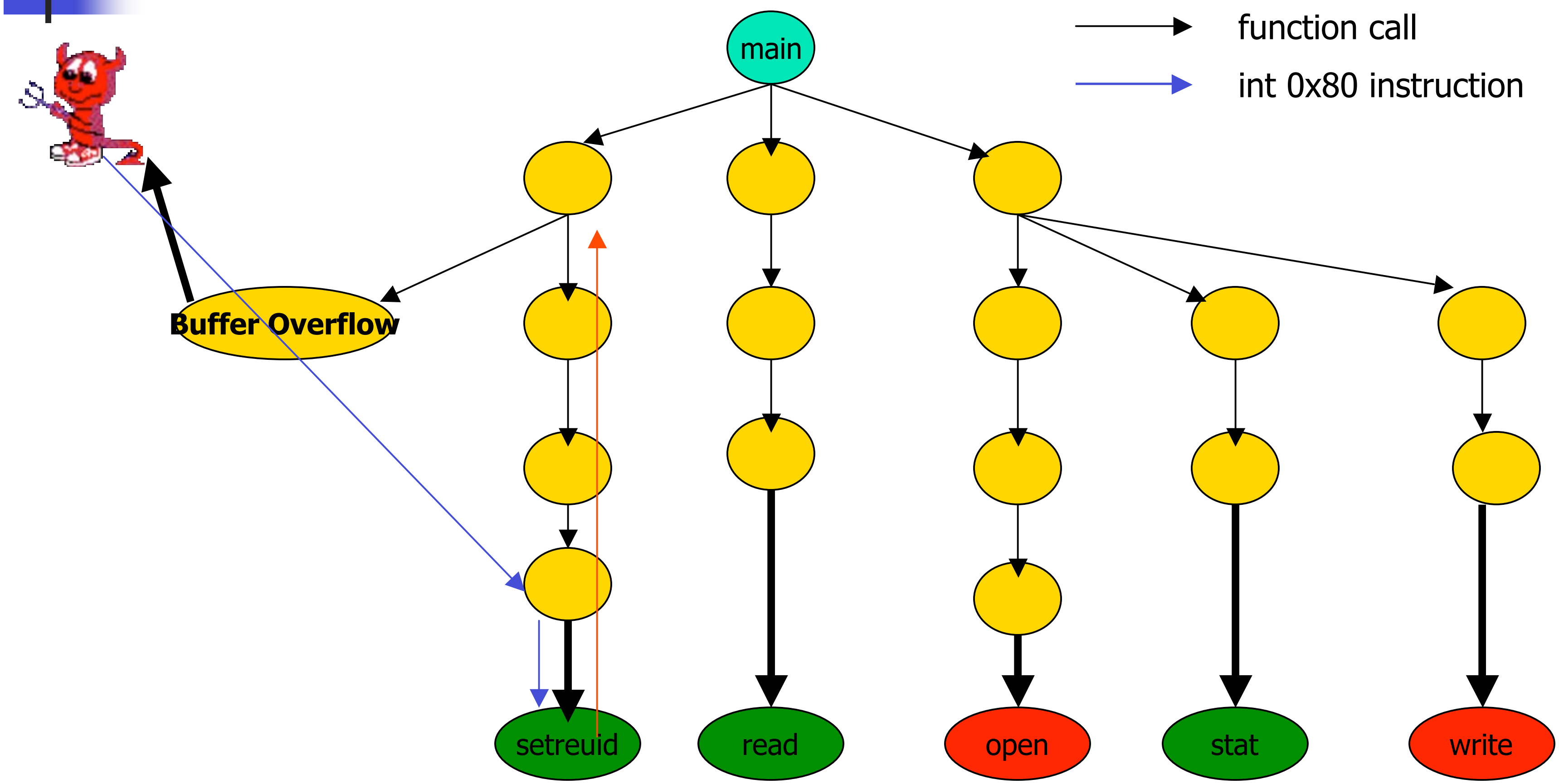
Ordering Check Only



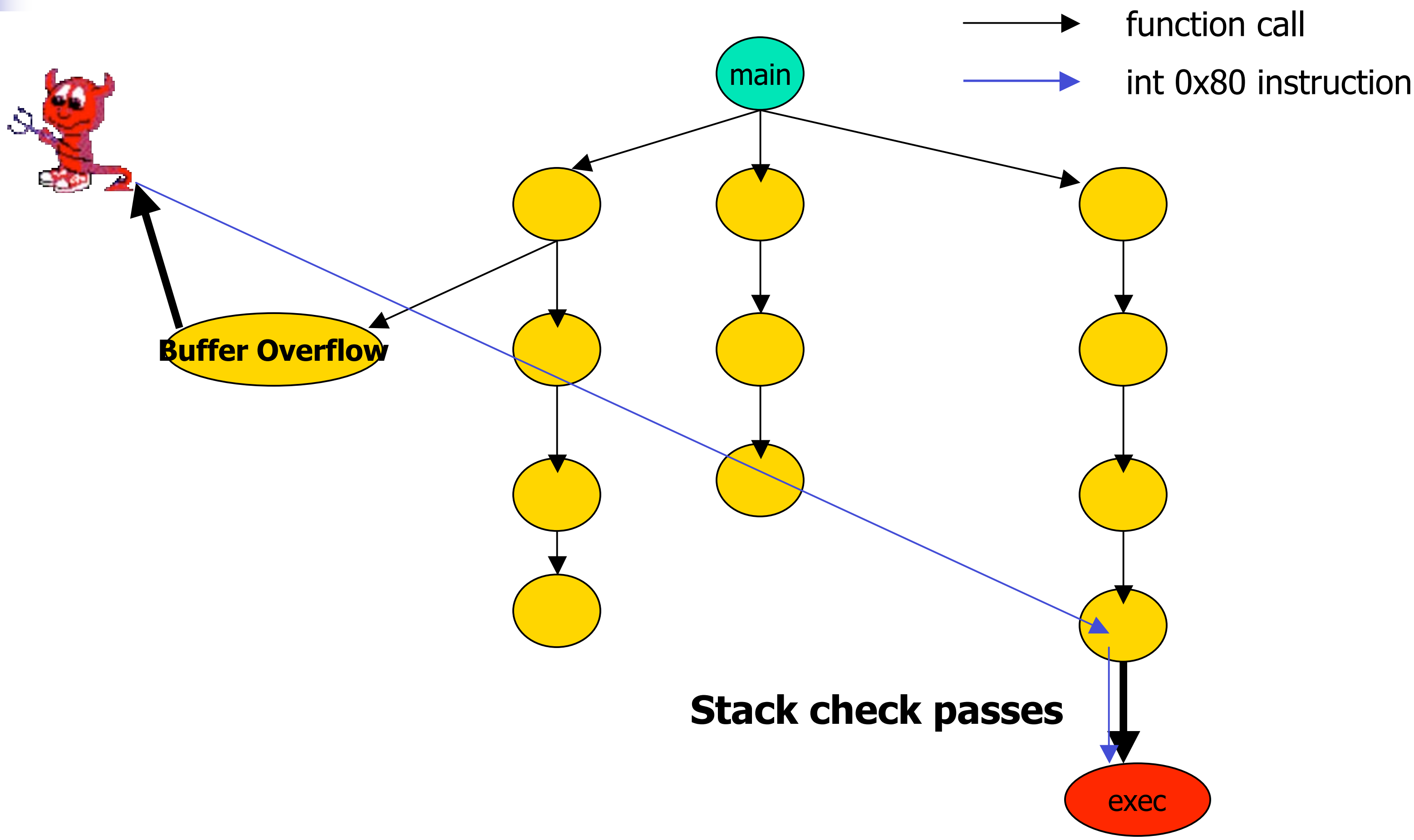
Ordering and Site Check



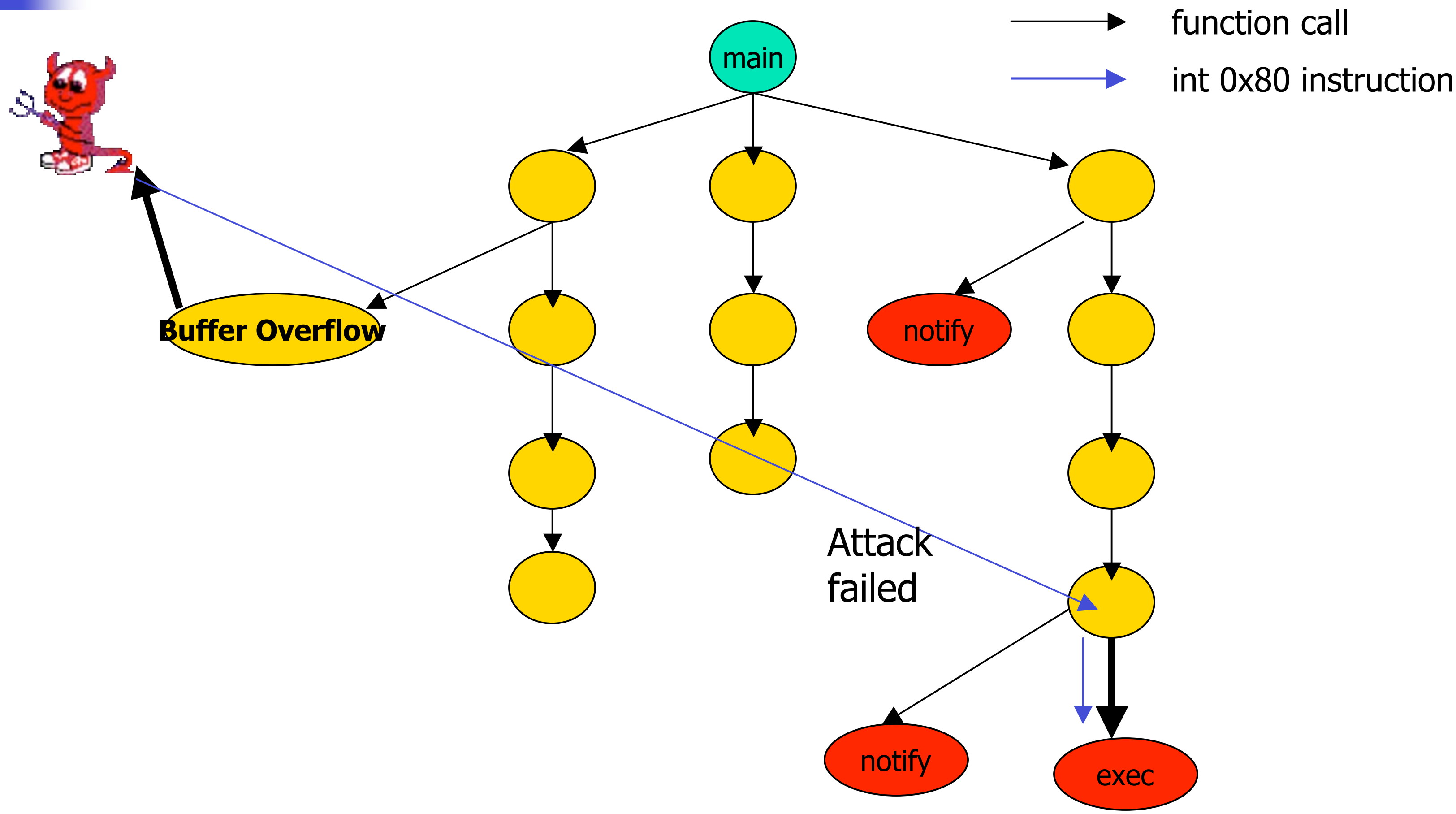
Ordering, Site and Stack Check (1)



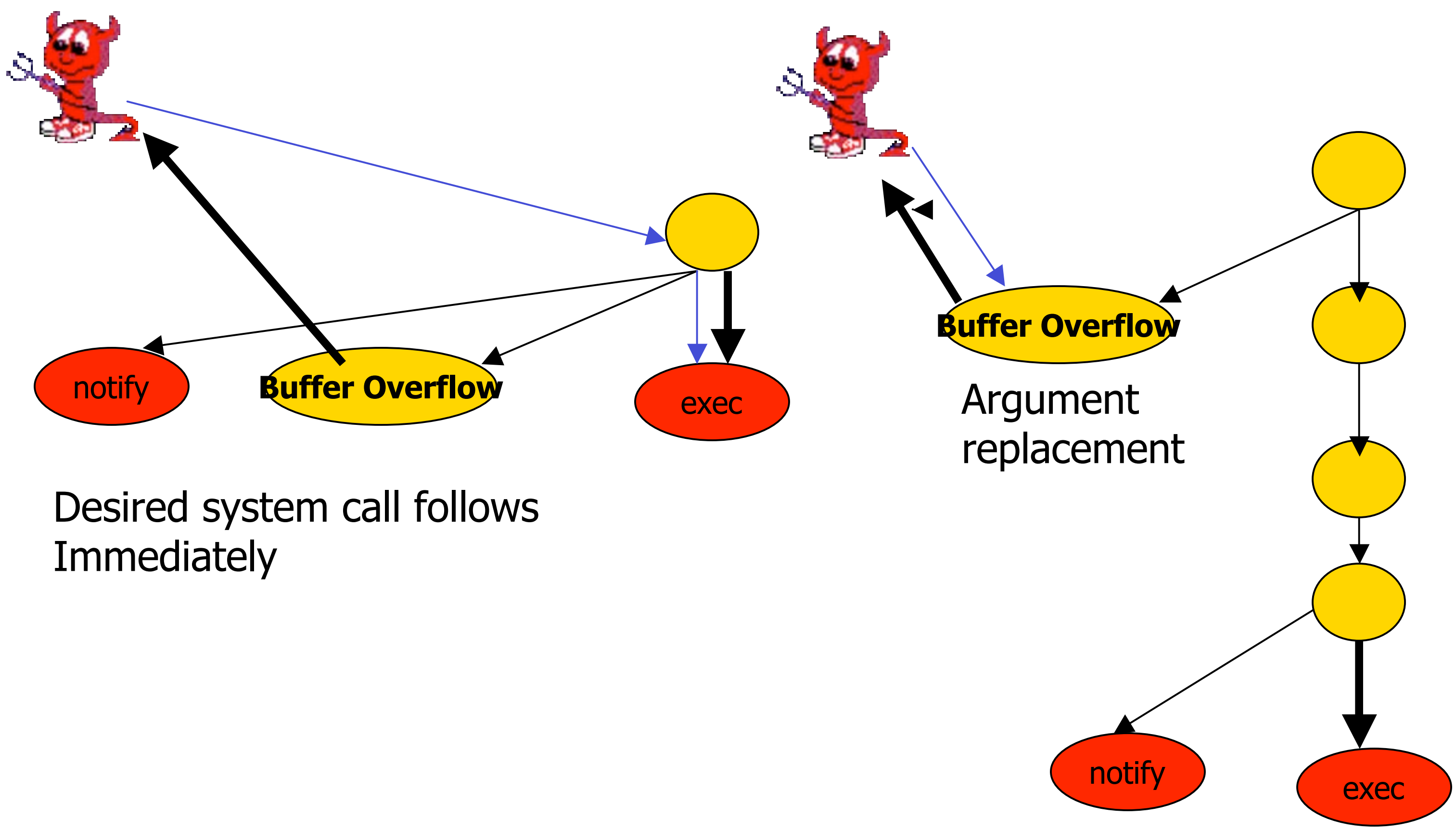
Ordering, Site and Stack Check (2)



Random Insertion of Notify Calls



Window of Vulnerabilities



Prototype Implementation

- GCC 3.1 and Gnu ld 2.11.94, Red Hat Linux 7.2
- Compiles GLIBC successfully
- Compiles several production-mode network server applications successfully, including Apache-1.3.20, Qpopper-4.0, Sendmail-8.11.3, Wuftpd-2.6.0, etc.

Throughput Overhead

	PAID	PAID/stack	PAID/random	PAID/stack random
Apache	4.89%	5.39%	6.48%	7.09%
Qpopper	5.38%	5.52%	6.03%	6.22%
Sendmail	6.81%	7.73%	9.36%	10.44%
Wuftpd	2.23%	2.69%	3.60%	4.38%

However

- PAID assumes source code availability, but most users do not have access to the source code of their applications, especially on the Windows platform
- What is the SCFG for Microsoft's IIS?
- Enters the BIRD (Binary Interpretation using Run-time Disassembly) project
- Binary PAID = BIRD + PAID

Motivation

- Many state-of-the-art solutions to software security problem are based on program transformation techniques
- Achilles Heel: cannot be applied to existing executable binaries, especially for Windows PE32 binaries
- From source code to binary code:
  - Static disassembly does not always work
  - Binary instrumentation is non-trivial

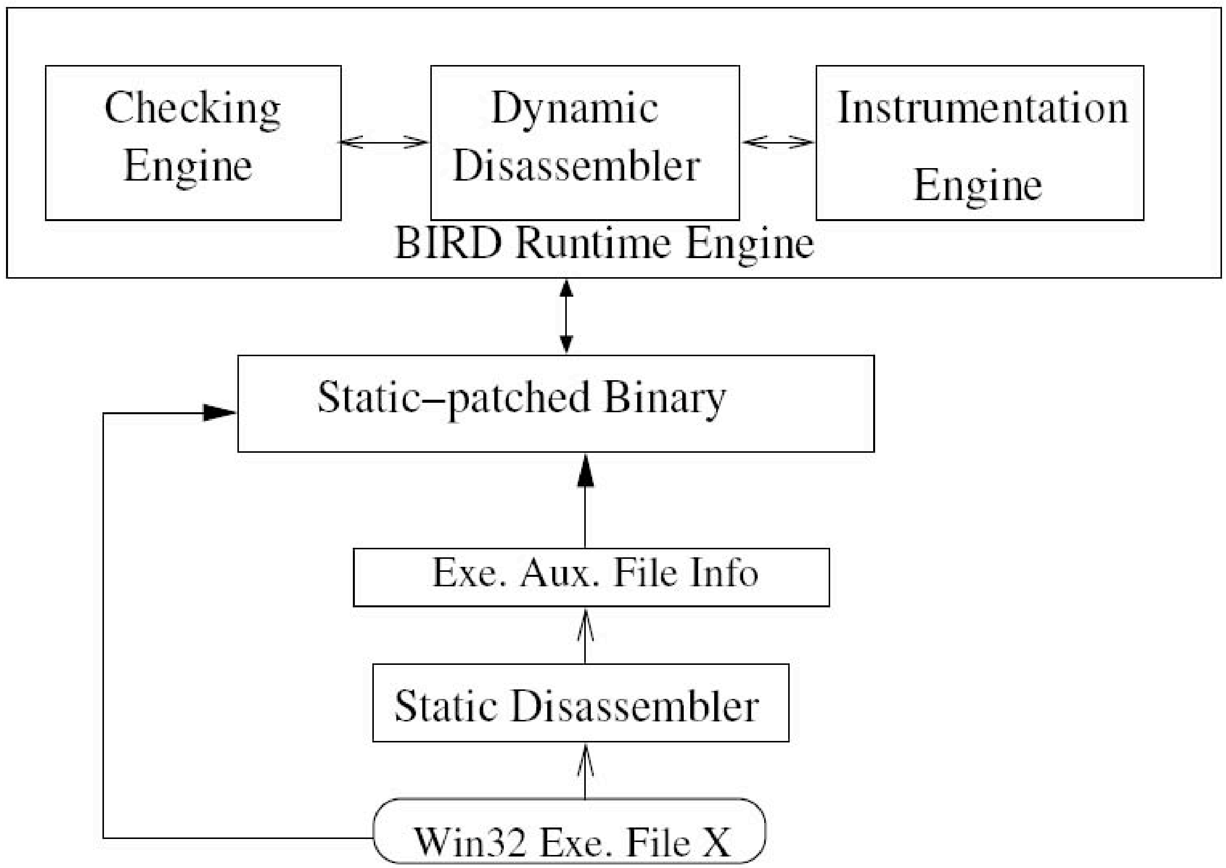
Static Disassembly

- No guarantee for 100% recovery: no way to know for sure
- Distinguishing between instruction and data is fundamentally undecidable
- Linear sweeping: data (e.g., jump table) could be embedded code section
- Recursive traversal: some functions do not any explicit call sites in the binary
- Windows DLLs are full of hand-crafted code sequences designed to defeat reverse engineering tools
- Bottom line: about 90% coverage with absolute confidence

BIRD

- A binary analysis and instrumentation infrastructure on the Windows platform
  - Do as much static disassembly as possible
  - Uncover "statically unknown" instructions through dynamic invocation of disassembler
  - Provide an API for developers to add application-specific analysis and/or instrumentation routines
  - Guarantee 100% disassembly accuracy and coverage

Architecture



Dynamic Disassembly

- Statically redirect all indirect jumps/calls to a check() routine
- Redirect delivery of exception handlers to the check() routine also
- In the check() routine
  - Check if the target address is known or not
  - If known, jump to the target; else invoke the dynamic disassembler to disassembly the target area and jump
  - Update the unknown-area list and modify indirect jumps/calls in dynamically disassembled instructions

Binary Instrumentation

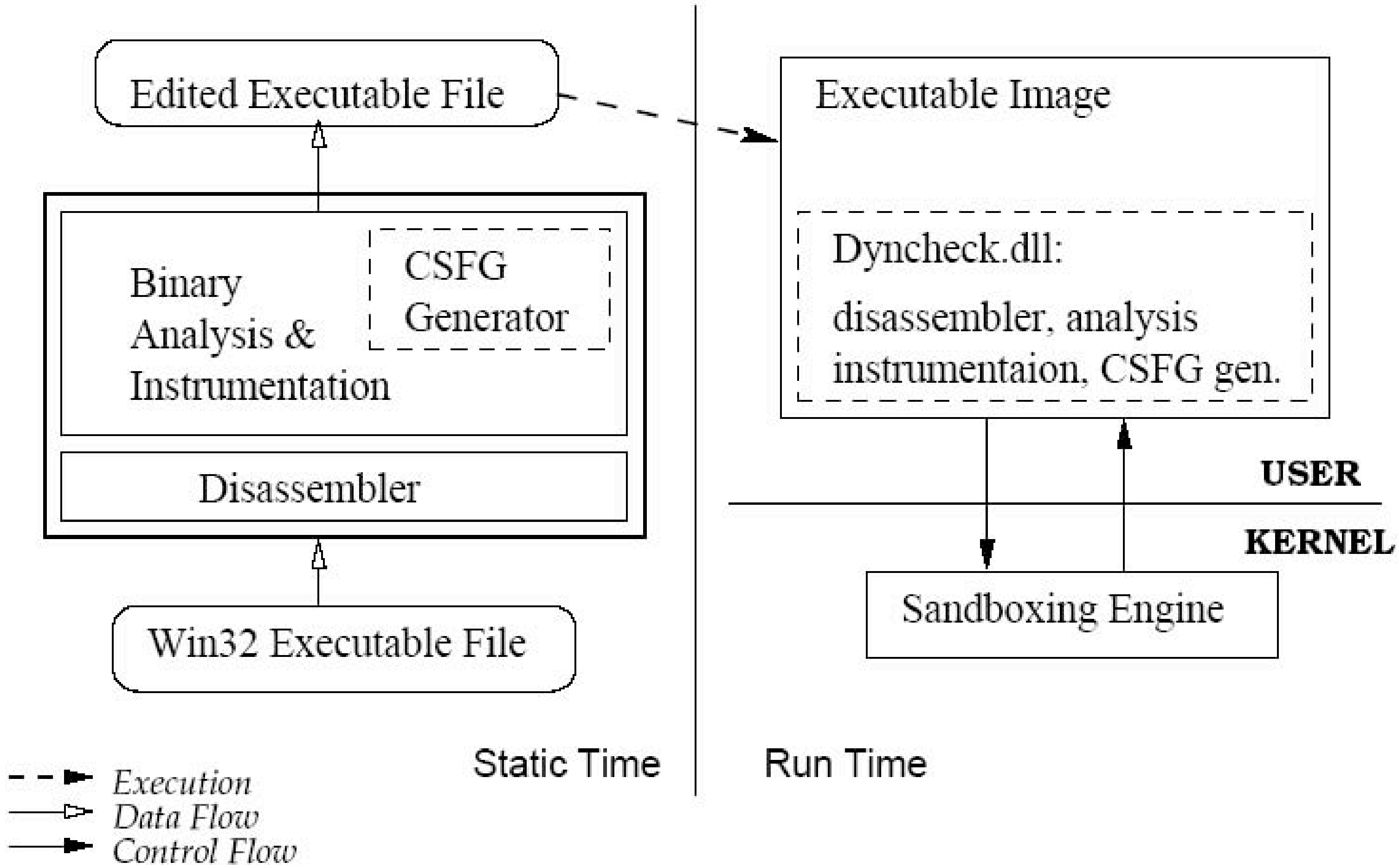
- Need to find enough bytes in a given instrumentation point to put in a 5-byte jump instruction
- Can use neighboring instructions only if they are not targets of other direct jump instructions in the same function
- Use INT 3 as a fall-back mechanism, which goes through an exception handler to invoke check()

Performance Penalty

- Works for all programs in MS Office suite and IE
- Latency overhead

Program	Description	Original	Modified
gzip	Encrypt a 10MB file	3.4%	0.18%
comp	Compare two similar5MB files	10.0%	0.15%
strings	List all strings in a binary file	6.4%	2.4%
find	Find a string in a 500KB file	19.0%	16.7%
objdump	Show object headers in an EXE file	3.5%	0.8%

Binary PAID


Edited Executable File
Binary
Analysis &
Instrumentation
CSFG
Generator
Disassembler
Win32 Executable File
Executable Image
Dyncheck.dll:
disassembler, analysis
instrumentaion, CSFG gen.
USER
KERNEL
Sandboxing Engine
Static Time
Run Time
Execution
Data Flow
Control Flow

Throughput Overhead

Application	BIRD		BIRD+ BASS		BIRD+BASS +Random	
Apache	99.9%	0.9%	94.2%	5.5%	94.0%	5.6%
BIND	97.8%	3.1%	92.3%	7.7%	91.9%	7.9%
IIS W3 Service	99.1%	1.1%	93.9%	6.3%	93.5%	6.8%
MTSEmail	99.7%	1.4%	97.3%	3.2%	97.3%	3.2%
Cerberus Ftpd	99.2%	1.2%	93.0%	7.6%	93.0%	8.2%
GuildFTPd	79.9%	25.3%	73.3%	32.7%	71.3%	33.2%
BFTelnetd	99.9%	1.5%	97.4%	3.4%	96.9%	3.5%

Other Application: FOOD

- Goal: Ensure no dynamically injected code can run by monitoring target addresses of all indirect branches
- Assumption: no self modifying code, thus read-only text segment
- Approach: check the legitimacy of each instruction based on its location rather than its content
- Intercept at all indirect jumps/calls, return instructions and invocation of exception handlers
- Overhead: 10-25%

Conclusion

- PAID is the most efficient, comprehensive and accurate host-based intrusion prevention (HIPS) system on both Linux and Windows platform
- Automatically generates per-application system call policy
- Guarantee 0 false positive and almost 0 false negative
- Effective countermeasures against mimicry attacks,
  - Extensive system call argument checks
  - Load-time insertion of random null system calls
  - Return address sequence check
- Can handle function pointers, asynchronous control transfer, threads, exceptions, and DLL

Future Work

- Further reduce the latency/throughput overhead of Binary PAID
- Reduce the percentage of "dynamic variable" category of system call arguments
- Apply it to generate security policy for SELinux automatically
- Create a counterpart of PAID for NIDS

For more information

Project Page: *http://www.ecsl.cs.sunysb.edu/PAID*

Thank You!