Program semantics-Aware Intrusion Detection

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Introduction

- Computer attacks that exploit software flaws
  - Buffer overflow: heap/stack/format string
    Most common; building blocks for worm attacks
  - Syntax loopholes: SQL injection, Directory traversal
  - Race conditions: mostly local attacks
- Other attacks
  - Social engineering
  - Password cracking
  - Denial of service

Control- Hijacking Attacks

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

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

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

    Hit a target with the plane

Stack Overflow Attack

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

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

STACK LAYOUT

	128 Return address of input()	100
FP →	124 Previous FP	
	120 Local variable i	
	116 userID[4]	
	112 userID[3]	
	108 userID[2]	INT 80
	104 userID[1]	
SP →	100 userID[0]	

Palladium (since 1999…)

- ***Array bound checking***: Preventing code insertion through buffer overflow
- **Integrity check for control-sensitive data structure**: Preventing unauthorized control transfer through over-writing return address, function pointer, and GOT
- ***System call policy check***: Preventing attackers from issuing damaging system calls
- ***Repairable file service***:Quickly putting a compromised system back to normal order after detecting an intrusion

Array Bound Checking

- Prevent unauthorized modification of sensitive data structures (e.g., return address or bank account) through buffer overflowing → The cleanest solution
- Check each pointer reference with respect to the limit of its associated object
  - Figure out which is the associated object (shadow variable approach)
  - Perform the limit check (major overhead)
- Current software-based array bound checking methods: 3-30 times slowdown

Segmentation Hardware

X86 architecture's virtual memory hardware supports both segmentation and paging

Virtual Address = Segment Selector + Offset

↓ segmentation — base + offset <= limit

Linear Address

↓ paging

Physical Address

Checking Array bound using Segmentation Hardware (CASH)

- Exploiting segment limit check hardware to perform array bound checking for free
- Each array or buffer is treated as a separate segment and referenced accordingly

```
for (i = M; i < N; I++) {
    B[i] = 5;
}
```

```
offset = &(B[M]) – B_Segment_Base;
GS = B_Segment_Selector;
for (i = M; i < N; i++) {
    GS:offset = 5;
    offset += 4;
}
```

Performance Overhead

	CASH	BCC
SVDPACK	1.82%	120.00%
Volume Rendering	3.26%	126.38%
2D FFT	3.95%	72.19%
Gaussian Elimination	1.61%	92.40%
Matrix Multiply	1.47%	143.77%
Edge Detection	2.23%	83.77%

Return Address Defense (RAD)

- To prevent the return address from being modified, keep a redundant copy of the return address when calling a procedure, and make sure that it has not been modified at procedure return
- Include the bookkeeping and checking code in the function prologue and epilogue, respectively

Binary RAD Prototype

- Aims to protect Windows Portable Executable (PE) binaries
- Implementing a fully operational disassembler for X86 architecture
- Inserting RAD code at function prolog and epilog without disturbing existing code
- Transparent initialization of RAR

Performance Overhead

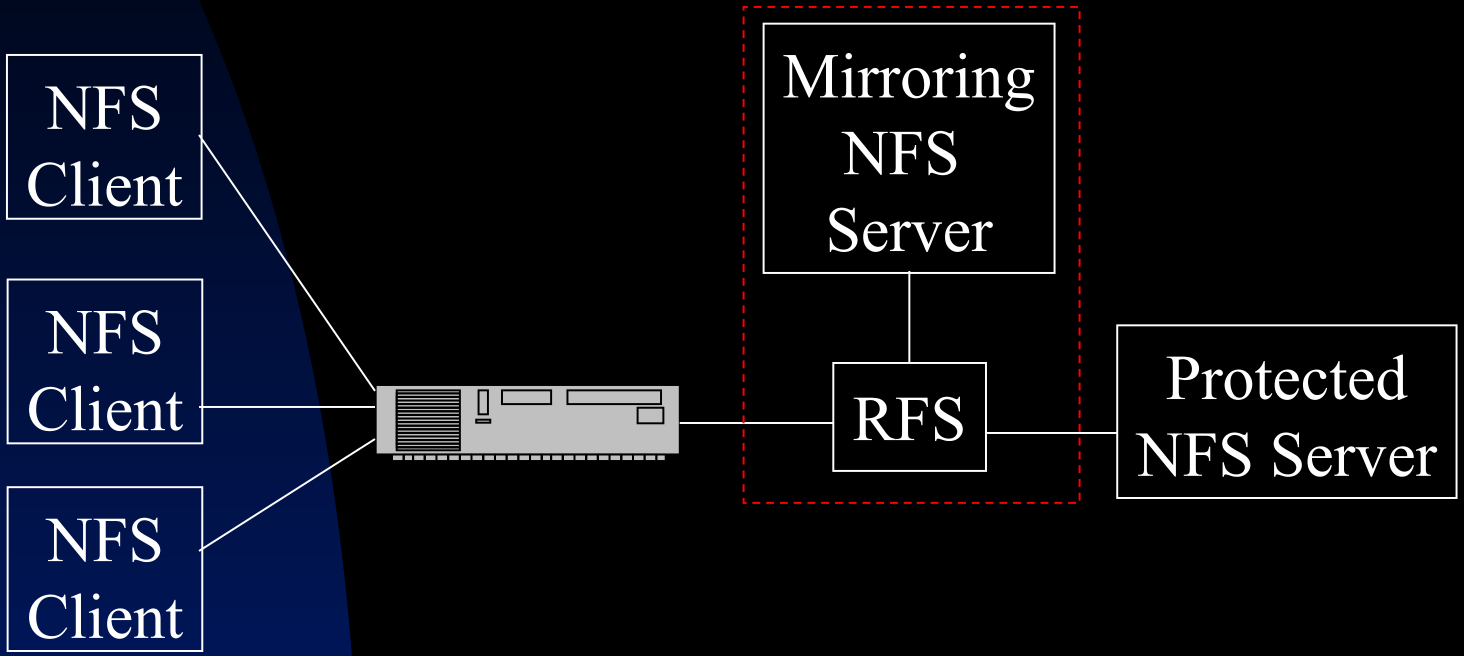
Program	Overhead
BIND	1.05%
DHCP Server	1.23%
PowerPoint	3.44%
Outlook Express	1.29%

Repairable File Service (RFS)

- There is no such thing as unbreakable computer systems, e.g., insider job and social engineering
- A significant percentage of financial loss of computer security breaches is productivity loss due to unavailability of information and personnel
- Instead of aiming at 100% penetration proof, shift the battleground to fast recovery from intrusion: reliability vs. availability → MTTF/(MTTF+MTTR)
- Key problem: Accurately identify the damaged file blocks and restore them quickly

RFS Architecture

Transparent to protected network file server



Fundamental Issues

- Keeping the before image of all updates so that every update is undoable: transparent file server update logging
- Tracking inter-process dependencies for selective undo
- Contamination analysis based on inter-process dependencies and ID of the first detected intruder process, P
  - All updates made by P and its children
  - All updates by processes that read in contaminated blocks after P's birth time

RFS Prototype

- Implemented on Red Hat 7.1
- Works for both NFSv2 and NFSv3
- A client-side system call logger whose resulting log is tamper proof
- A wire-speed NFS request/response interceptor that deals with network/protocol errors
- A repair engine that performs contamination analysis and selective undo
- Undo operations are themselves undoable

Performance Results

- Client-side logging overhead is 5.4%
- Additional latency introduced by interceptor is between 0.2 to 1.5 msec
- When the write ratio is below 30%, there is no throughput difference between NFS and NFS/RFS
- Logging storage requirement: 709MBytes/day for a 250-user NFS server in a CS department → a 100-Gbyte disk can support a detection window of 8 weeks

Program semantics-Aware Intrusion Detection (PAID)

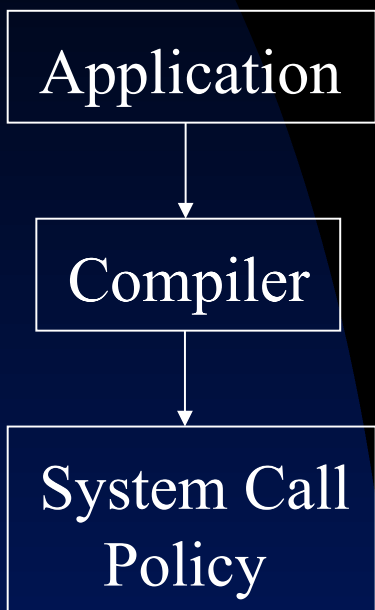
- As a last line of defense, prevent intruders from causing damages even when they successfully take control of a target victim application
- Key observation: Most damages can only be done through system calls, including denial of service attacks
- Idea: prohibit hijacked applications from making arbitrary system calls

System Call Policy/Model

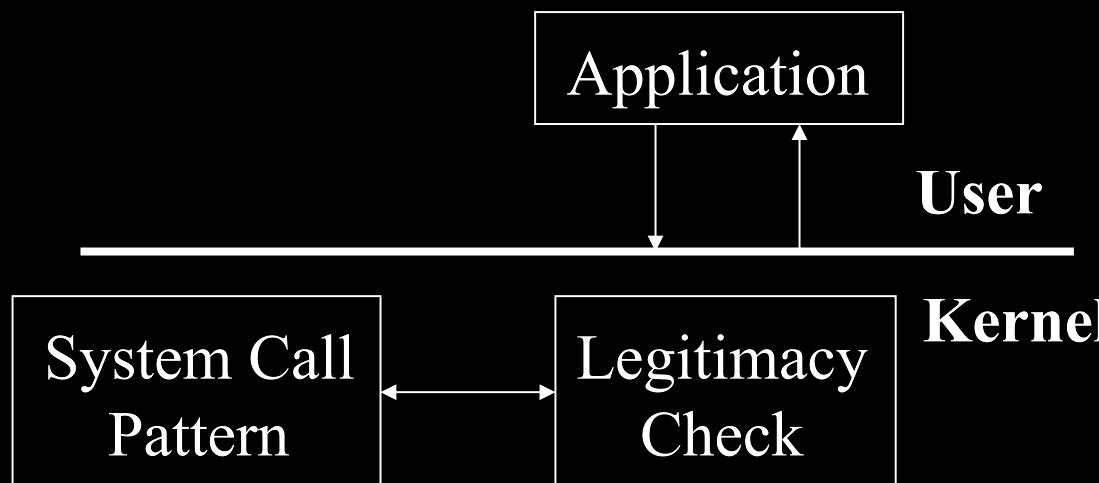
- Manual specification: error-prone, labor intensive, non-scalable
- Machine learning: error-prone, training efforts required
- Our approach: Use compiler to extract the *sites* and *ordering* of system calls from the source code of any given application automatically
- Only host-based intrusion detection systems that 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



The 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 or research host-based IDS can handle mimicry attacks

Mimicry Attack Details

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

    Nearly all syscalls can be turned into no-ops

    For example `(void) getpid()` or `open(NULL,0)`
  - Grab the control back during the emulation process

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

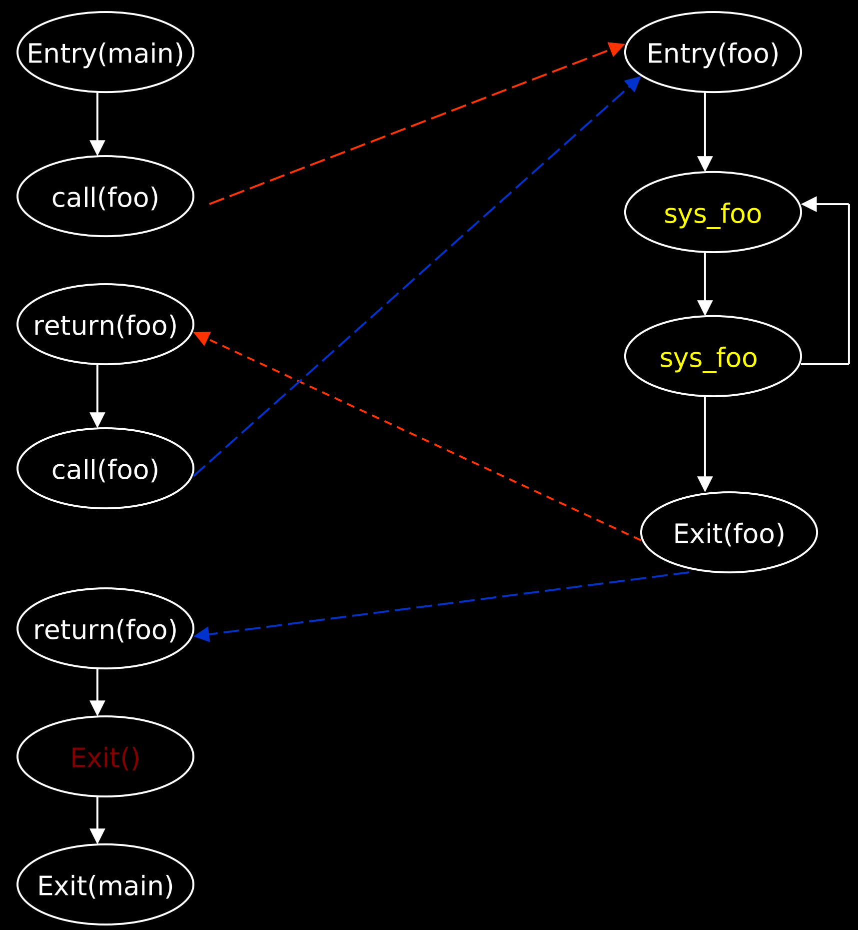
Countermeasures

- Checking system call argument values whenever possible
- Checking the return address chain on the stack to verify the call chain
- Minimize ambiguities in the system call model
  - If (a>1) { open(..)} else {open(..); write(..)}
  - Multiple calls to a function that contains a system call

Example

```
main()
{
    foo();
    foo();
    exit();
}

foo()
{
    for(....){
            sys_foo();
            sys_foo();
    }
}
```



System Call Policy Extraction

- From a given program, build a system call graph from its function call graph (FCG) and per-function reduced control flow graph (RCFG)
- For each system call, extract its memory location, and derive the following system call set
- Each system call site is in-lined with the actual code sequence of entering the kernel (e.g., INT 80), and thus can be uniquely identified

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
- Notification 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
  - Load the library's system call graph at run time

From NFA to DFA

- Use graph in-lining to disambiguate the return address for a function with multiple call sites
  - Every recursive call chain is in-lined and turned into self-recursive call
- Use system call stub in-lining to disambiguate two system calls that are identical and that are at two arms of a conditional branch
  - Does not completely solve the problem: F1→ system_call()
  - Difficult to implement because some glibc functions are written in assembly
- Adding extra notify() for further disambiguation

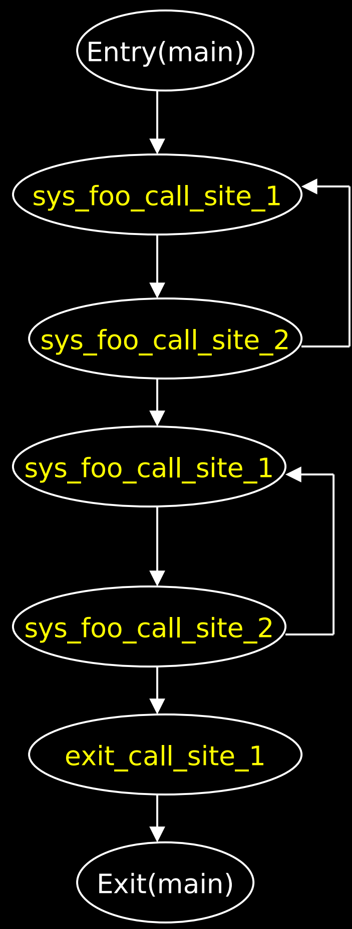
PAID Example

```
main()
{
    foo();
    foo();
    exit();
}

foo()
{
    for(….){

    sys_foo();

    sys_foo();
    }
}
```



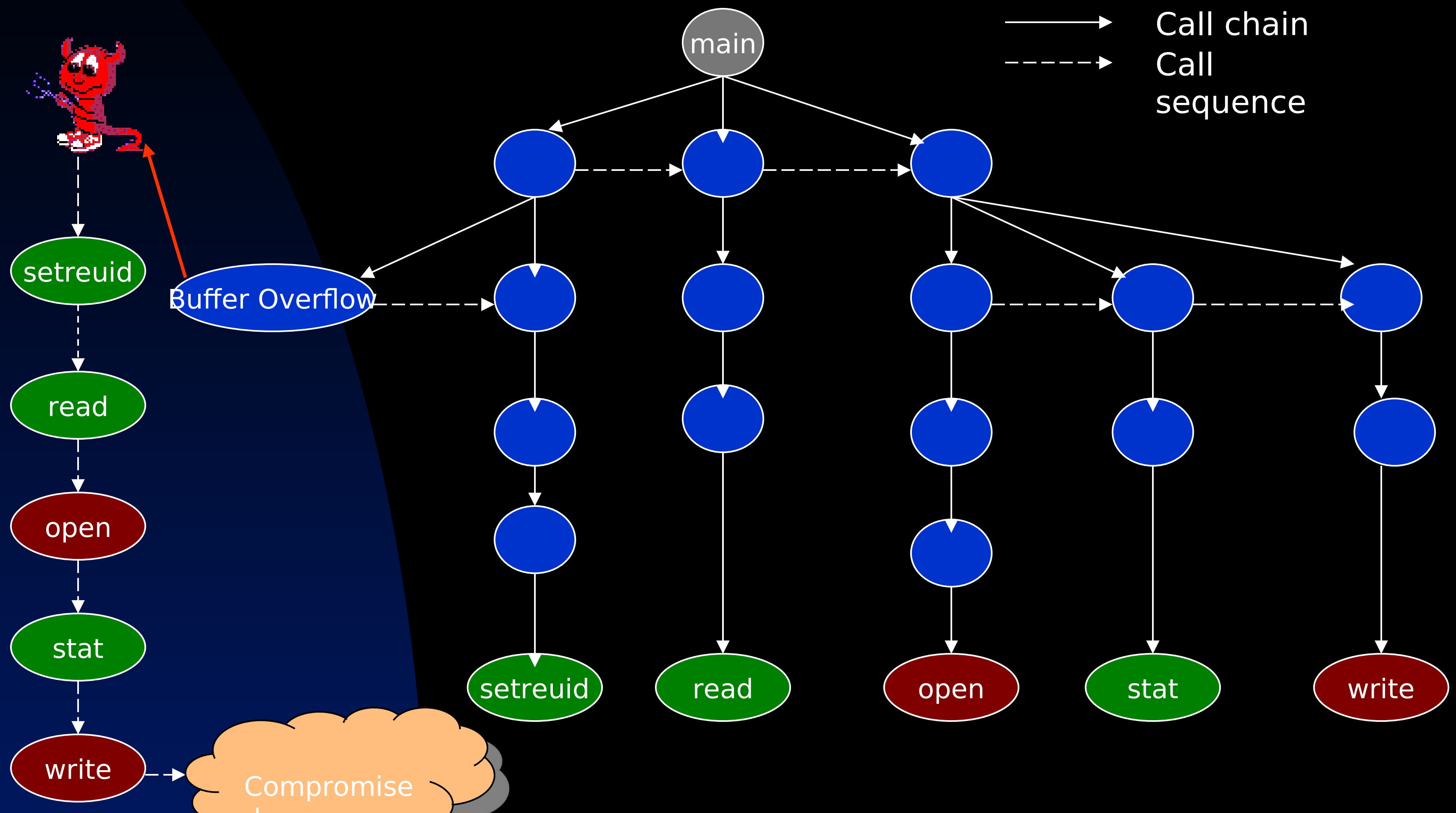

```
foo()
{    for(….){
        { int ret;
          __asm__ ("movl sys_foo_n, %eax\
n"
                   "int $0x80\n"
                   "sys_foo_call_site_1:\n"
                   "movl %eax, ret\n"
                     ….);
        }
        { int ret;
          __asm__ ("movl sys_foo_n, %eax\
n"
                   "int $0x80\n"
                   "sys_foo_call_site_2:\n"
                   "movl %eax, ret\n"
                     ….);
        }
     }
}
```

PAID Checks

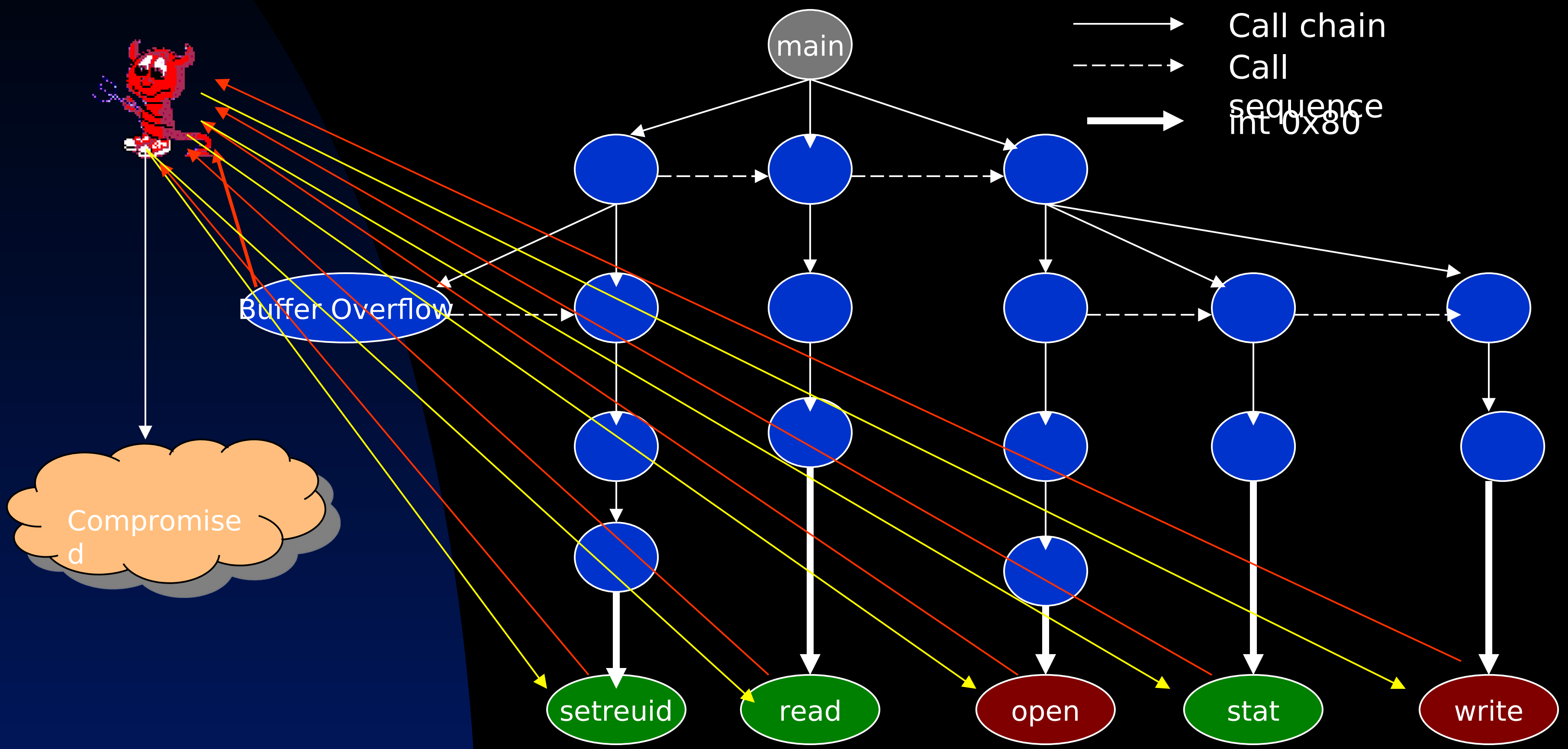
- Ordering
- Site
- Insertion of random notify() at load time
  - Different for different instance
- Stack return address check
  - Ensure they are in the text area
- Checking performed in the kernel

    In most cases, only two comparisons are needed

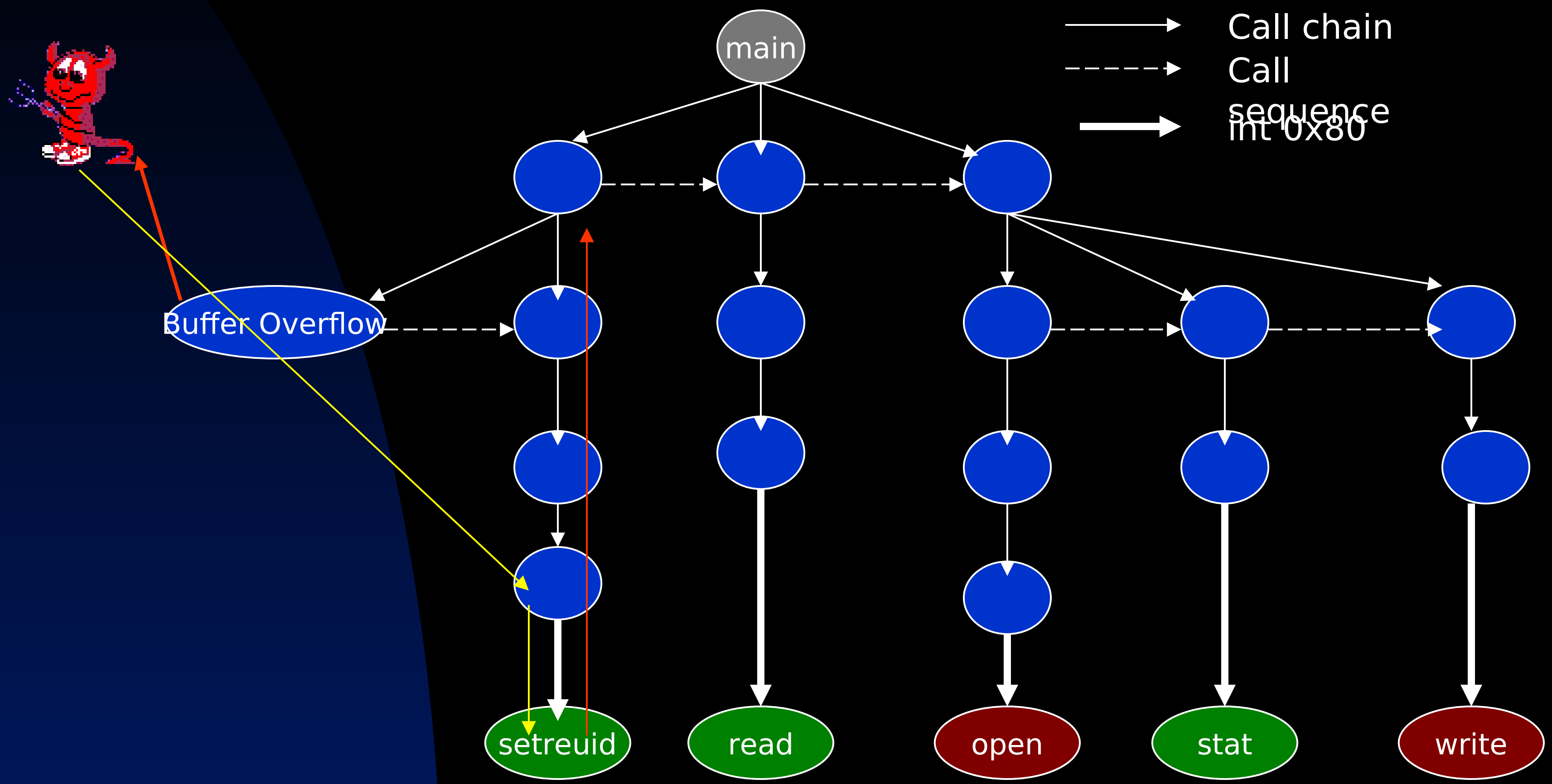
Ordering Check Only



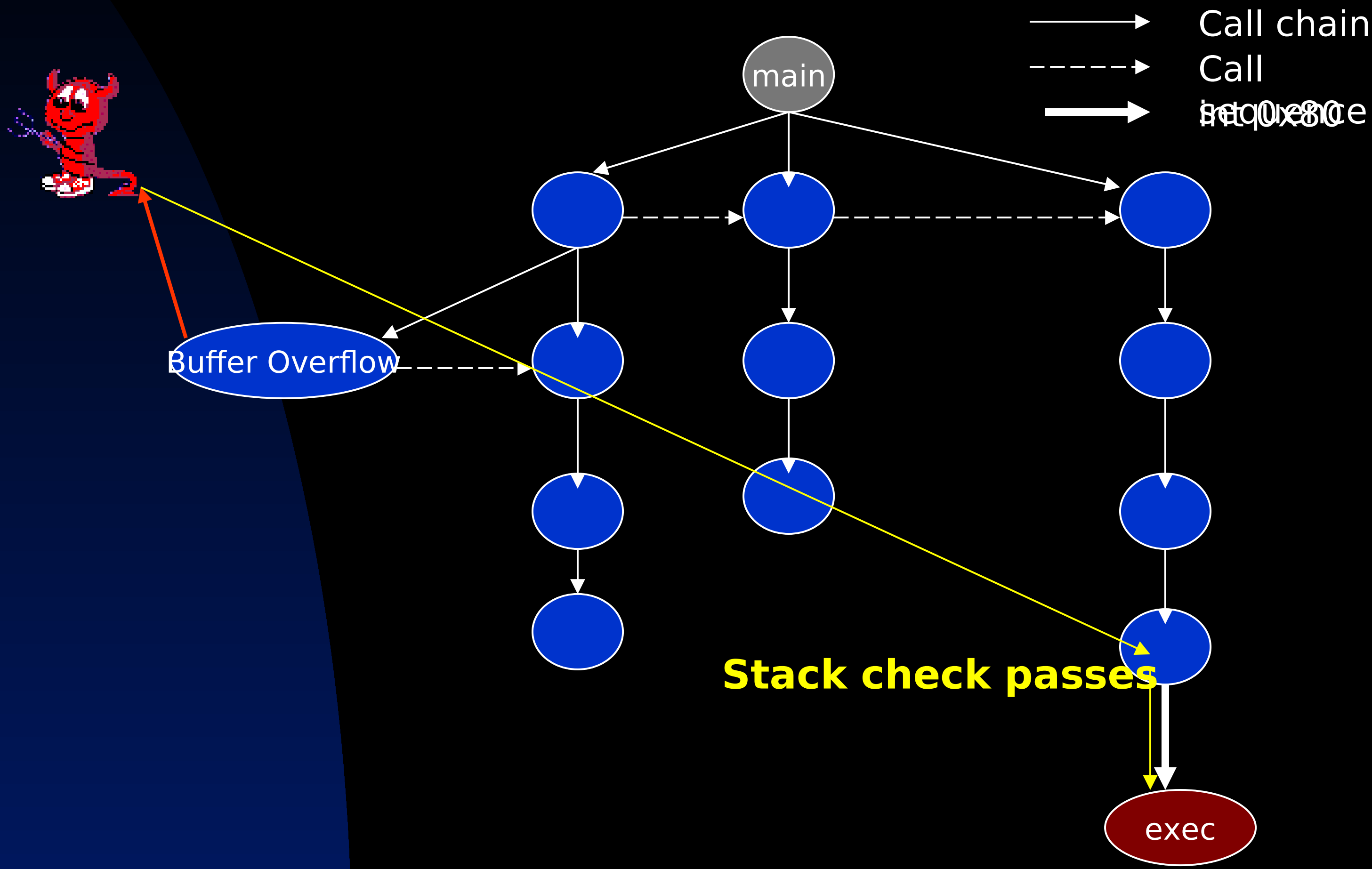
Ordering and Site Check



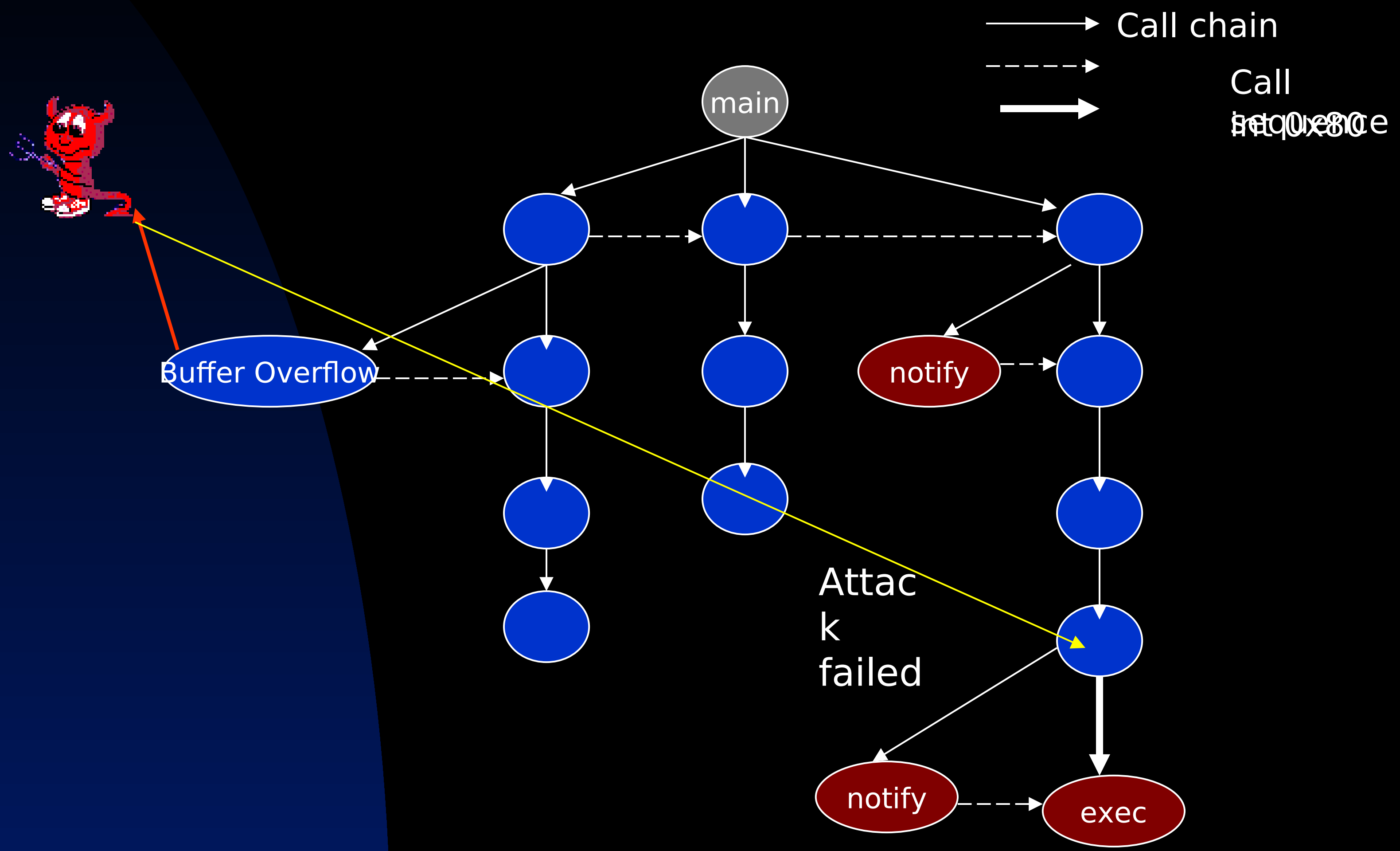
Ordering, Site and Stack Check (1)



Ordering, Site and Stack Check (2)



Random Insertion of Notify Calls



Alternative Approach

- Check the return address chain on the stack every time a system call is made
  - Every system call instance can be uniquely identified by a function call chain and the return address for the INT 80 instruction
  - Main→ F1→ F2 → F4 → system_call_1 vs.

    Main→ F3→ F5 → F4 → system_call_1
- Need to check the legitimacy of transitioning from one system call to another
- No graph or function in-lining is necessary

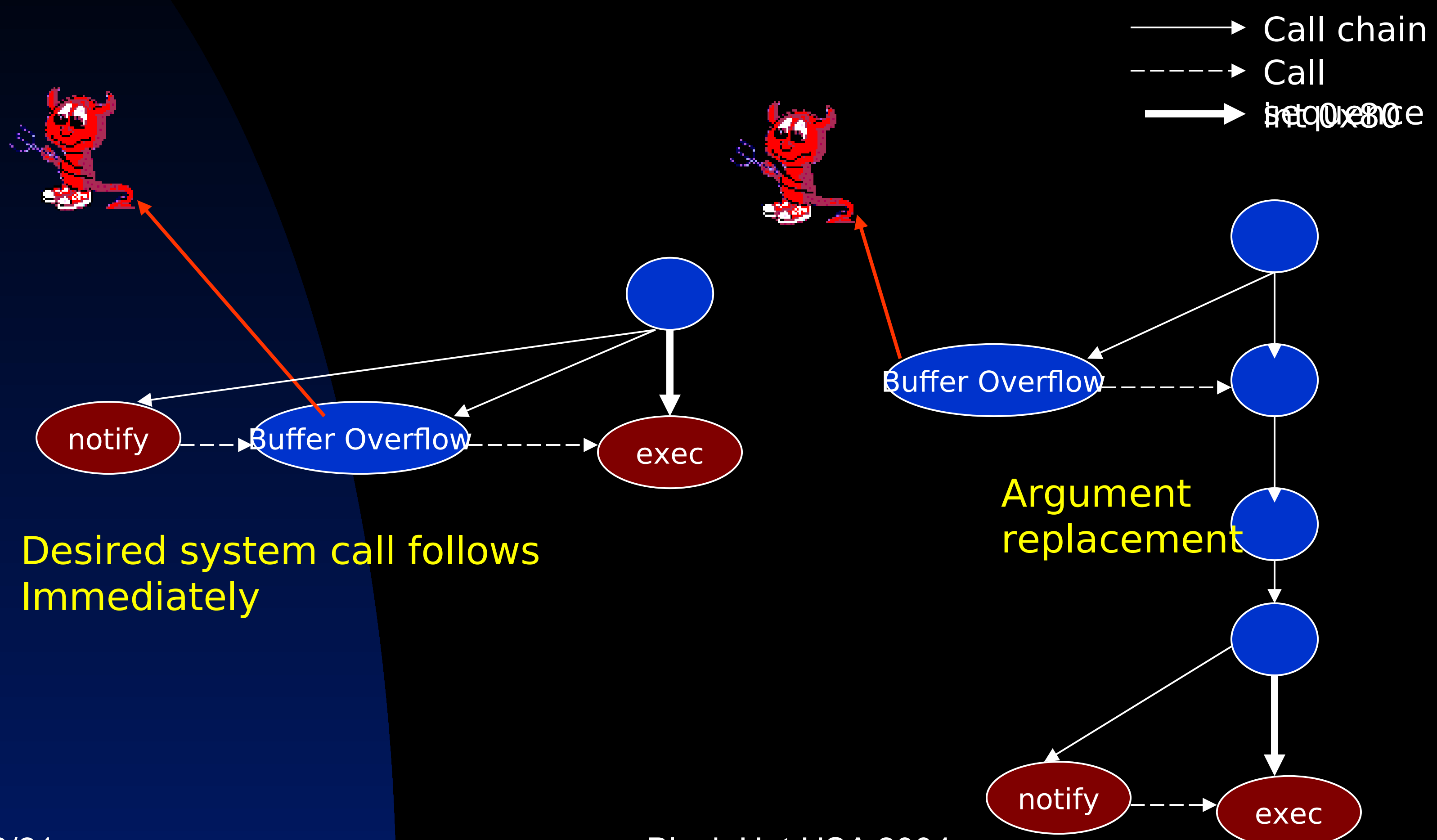
System Call Argument Check

- Start from each "file name" system call argument, e.g., open() and exec(), and compute a backward slice,
- 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

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%

Conclusion

- Paid is the most efficient, comprehensive and accurate host-based intrusion prevention (HIPS) system on Linux
  - Automatically generates per-application system call policy
  - System call policy is in the form of deterministic finite automata to eliminate ambiguities
  - Extensive system call argument checks
  - Can handle function pointers and asynchronous control transfers
  - Guarantee no false positives
  - Very small false negatives
  - Can block most mimicry attacks

Future Work

- Support for threads
- Integrate it with SELinux
- Derive a binary PAID version for Windows platform
- Further reduce the latency/throughput overhead
- Reduce the percentage of “dynamic variable” category of system call arguments

For more information

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

Thank You!