0x1A Great Papers in Computer Security

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http://www.cs.utexas.edu/~shmat/courses/cs380s/

After All Else Fails

- Intrusion prevention
  - Find buffer overflows and remove them
  - Use firewall to filter out malicious network traffic
- Intrusion detection is what you do after prevention has failed
  - Detect attack in progress
  - Discover telltale system modifications

What Should Be Detected?

- Attempted and successful break-ins
- Attacks by legitimate users
  - Illegitimate use of root privileges, unauthorized access to resources and data …
- Malware
  - Trojan horses, rootkits, viruses, worms …
- Denial of service attacks

Intrusion Detection Systems (IDS)

- Host-based
  - Monitor activity on a single host
  - Advantage: better visibility into behavior of OS and individual applications running on the host
- Network-based (NIDS)
  - Often placed on a router, firewall, or network gateway
  - Monitor traffic, examine packet headers and payloads
  - Advantage: single NIDS can protect many hosts and look for global patterns

Intrusion Detection Techniques

- Misuse detection
  - Use attack “signatures” (need a model of the attack)
    - Sequences of system calls, patterns of network traffic, etc.
  - Must know in advance what attacker will do (how?)
  - Can only detect known attacks
- Anomaly detection
  - Using a model of normal system behavior, try to detect deviations and abnormalities
  - Can potentially detect unknown (zero-day) attacks
- Which is harder to do?

Misuse Detection (Signature-Based)

- Set of rules defining a behavioral signature likely to be associated with attack of a certain type
  - Example: buffer overflow
    - A setuid program spawns a shell with certain arguments
    - A network packet has lots of NOPs in it
    - Very long argument to a string function
  - Example: denial of service via SYN flooding
    - Large number of SYN packets without ACKs coming back

      …or is this simply a poor network connection?
- Attack signatures are usually very specific and may miss variants of known attacks
  - Why not make signatures more general?

Extracting Misuse Signatures

- Use invariant characteristics of known attacks
  - Bodies of known viruses and worms, RET addresses of memory exploits, port numbers of applications with known vulnerabilities
  - Hard to handle mutations
    - Polymorphic viruses: each copy has a different body
- Big research challenge: fast, automatic extraction of signatures of new attacks

Anomaly Detection

- Define a profile describing "normal" behavior
  - Works best for "small", well-defined systems (single program rather than huge multi-user OS)
- Profile may be statistical
  - Build it manually (this is hard)
  - Use machine learning and data mining techniques
    - Log system activities for a while, then "train" IDS to recognize normal and abnormal patterns
  - Risk: attacker trains IDS to accept his activity as normal
    - Daily low-volume port scan may train IDS to accept port scans
- IDS flags deviations from the "normal" profile

Statistical Anomaly Detection

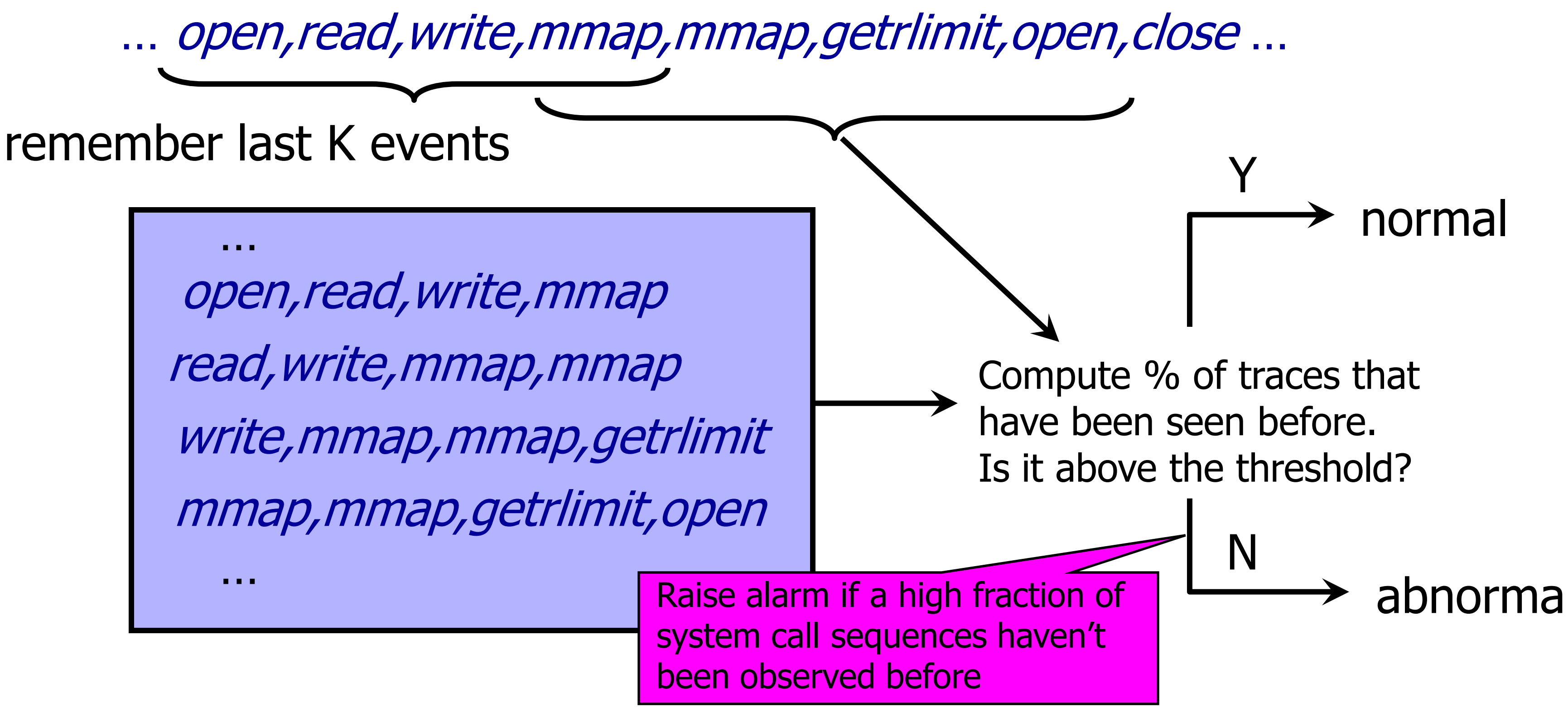
- Compute statistics of certain system activities
- Report an alert if statistics outside range
- Example: IDES (Denning, mid-1980s)
  - For each user, store daily count of certain activities
    - For example, fraction of hours spent reading email
  - Maintain list of counts for several days
  - Report anomaly if count is outside weighted norm

Problem: the most unpredictable user is the most important

"Self-Immunology" Approach

[Forrest]

- Normal profile: short sequences of system calls
  - Use strace on UNIX



Level of Monitoring

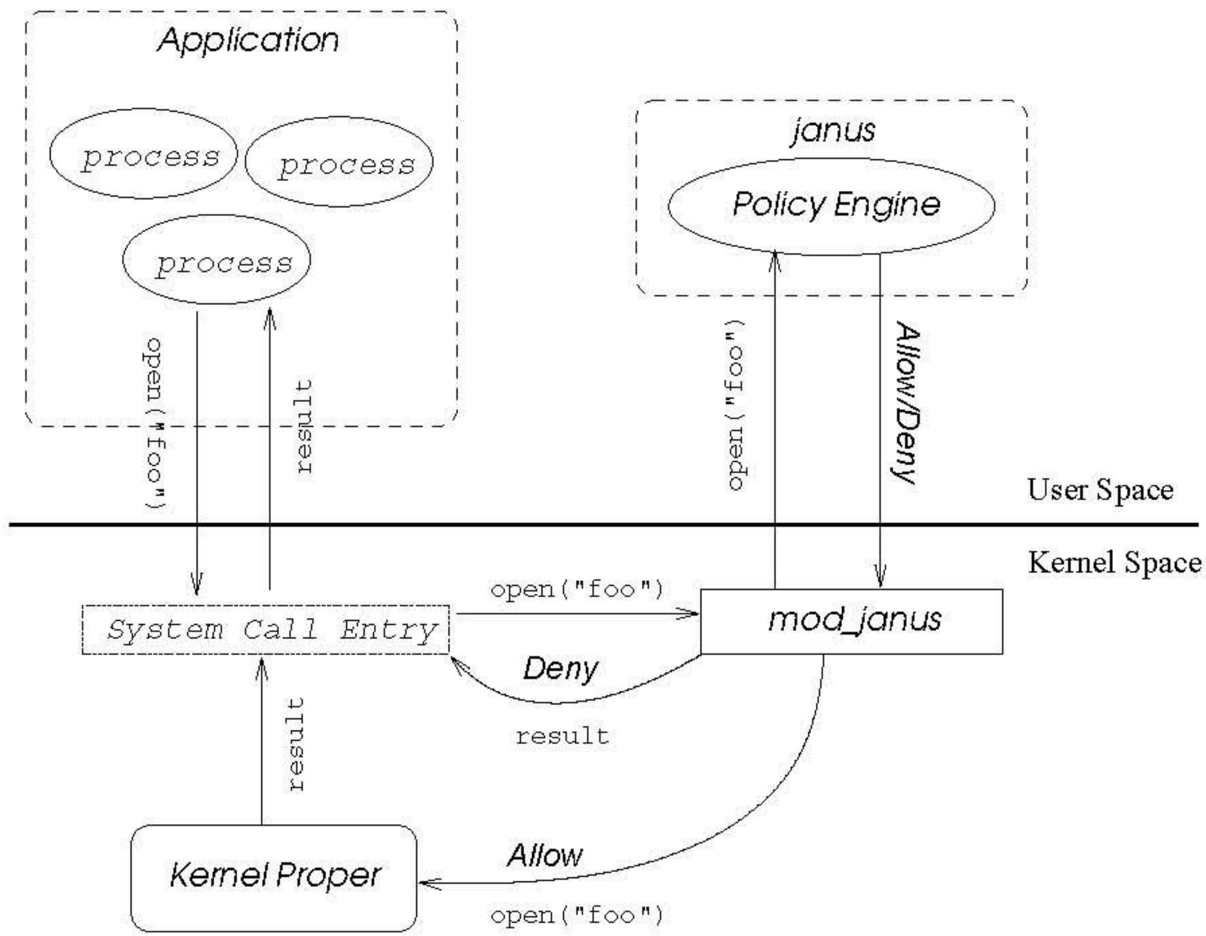
- Which types of events to monitor?
  - OS system calls
  - Command line
  - Network data (e.g., from routers and firewalls)
  - Keystrokes
  - File and device accesses
  - Memory accesses
- Auditing / monitoring should be scalable

System Call Interposition

- Observation: all sensitive system resources are accessed via OS system call interface
  - Files, sockets, etc.
- Idea: monitor all system calls and block those that violate security policy
  - Inline reference monitors
  - Language-level: Java runtime environment inspects stack of the function attempting to access a sensitive resource to check whether it is permitted to do so
  - Common OS-level approach: system call wrapper
    - Want to do this without modifying OS kernel (why?)

Janus

[Berkeley project, 1996]



Policy Design

- Designing a good system call policy is not easy
- When should a system call be permitted and when should it be denied?
- Example: ghostscript
  - Needs to open X windows
  - Needs to make X windows calls
  - But what if ghostscript reads characters you type in another X window?

Problems and Pitfalls

[Garfinkel]

- Incorrectly mirroring OS state
- Overlooking indirect paths to resources
  - Inter-process sockets, core dumps
- Race conditions (TOCTTOU)
  - Symbolic links, relative paths, shared thread meta-data
- Unintended consequences of denying OS calls
  - Process dropped privileges using setuid but didn't check value returned by setuid… and monitor denied the call
- Bugs in reference monitors and safety checks
  - What if runtime environment has a buffer overflow?

Incorrectly Mirroring OS State

[Garfinkel]

Policy: “process can bind TCP sockets on port 80, but cannot bind UDP sockets”

6 = socket(UDP, …)	Monitor: “6 is UDP socket”
7 = socket(TCP, …)	Monitor: “7 is TCP socket”
close(7)	
dup2(6,7)	Monitor’s state now inconsistent with OS
bind(7, …)	Monitor: “7 is TCP socket, Ok to bind”
	Oops!

TOCTTOU in Syscall Interposition

- User-level program makes a system call
  - Direct arguments in stack variables or registers
  - Indirect arguments are passed as pointers
- Wrapper enforces some security condition
  - Arguments are copied into kernel memory and analyzed and/or substituted by the syscall wrapper
- What if arguments change right here?
- If permitted by the wrapper, the call proceeds
  - Arguments are copied into kernel memory
  - Kernel executes the call

R. Watson

Exploiting Concurrency Vulnerabilities in System Call Wrappers

(WOOT 2007)

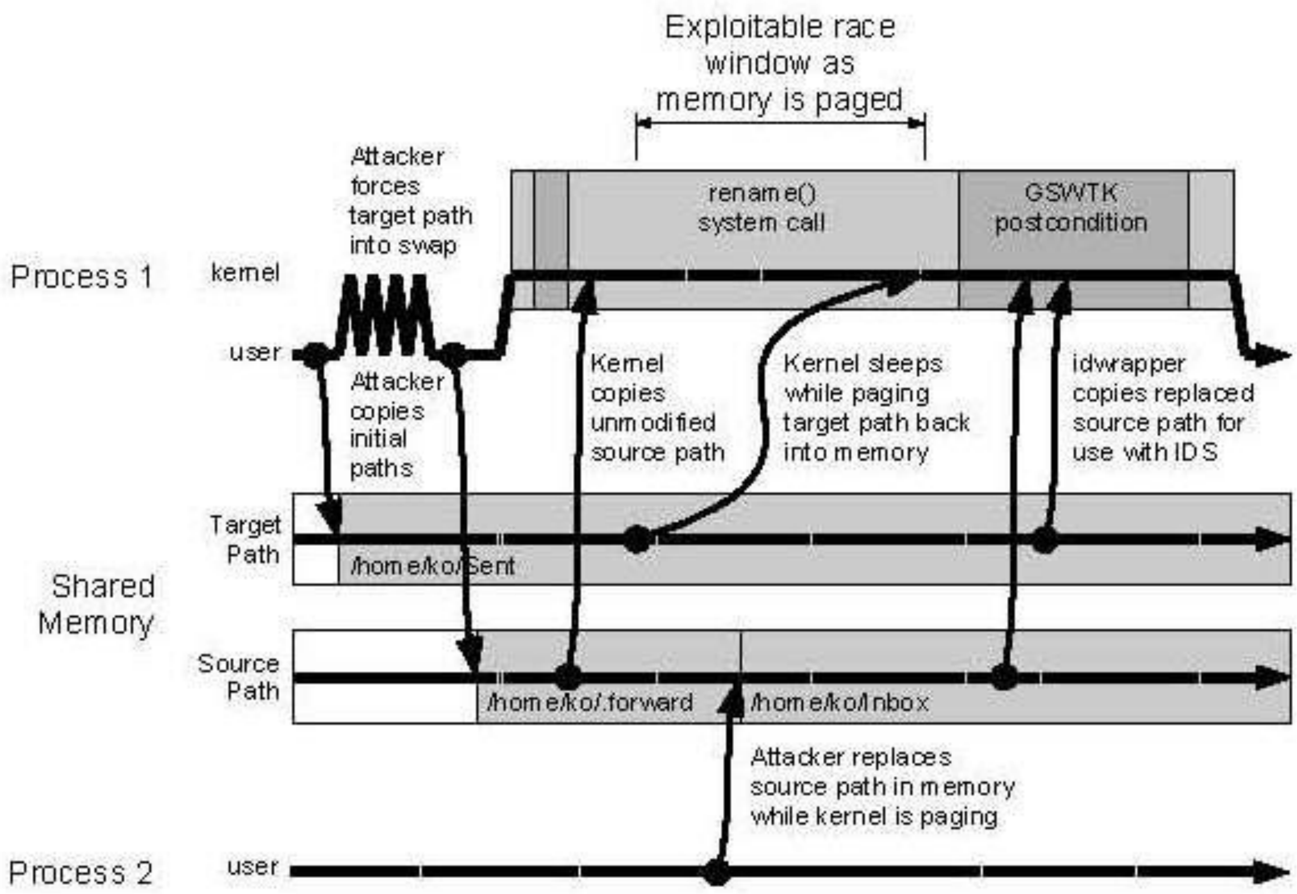
Exploiting TOCTTOU Conditions

[Watson]

- Forced wait on disk I/O
  - Example: rename()
    - Page out the target path of rename() to disk
    - Kernel copies in the source path, then waits for target path
    - Concurrent attack process replaces the source path
    - Postcondition checker sees the replaced source path
- Voluntary thread sleeps
  - Example: TCP connect()
    - Kernel copies in the arguments
    - Thread calling connect() waits for a TCP ACK
    - Concurrent attack process replaces the arguments

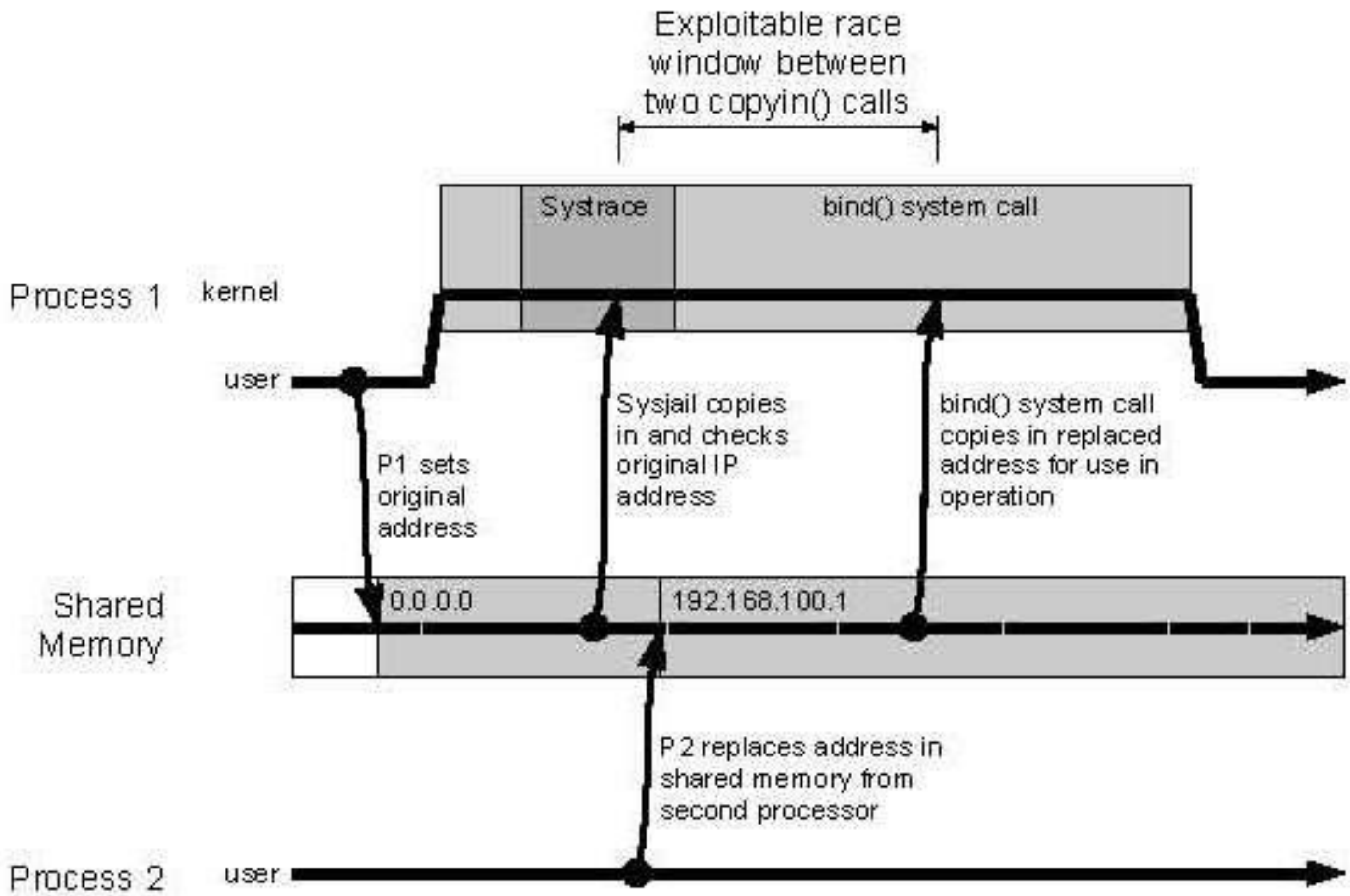
TOCTTOU via a Page Fault

[Watson]



TOCTTOU on Sysjail

[Watson]



Mitigating TOCTTOU

- Make pages with syscall arguments read-only
  - Tricky implementation issues
  - Prevents concurrent access to data on the same page
- Avoid shared memory between user process, syscall wrapper and the kernel
  - Argument caches used by both wrapper and kernel
  - Message passing instead of argument copying
    - Why does this help?
- Atomicity using system transactions
- Integrate security checks into the kernel?

D. Wagner, D. Dean

Intrusion Detection via Static Analysis

(Oakland 2001)

Interposition + Static Analysis

<u>Assumption</u>: attack requires making system calls

1. Analyze the program to determine its expected behavior
2. Monitor actual behavior
3. Flag an intrusion if there is a deviation from the expected behavior
   - System call trace of the application is constrained to be consistent with the source or binary code
   - Main advantage: a conservative model of expected behavior will have zero false positives

Trivial "Bag-O'Calls" Model

- Determine the set S of all system calls that an application can potentially make
  - Lose all information about relative call order
- At runtime, check for each call whether it belongs to this set
- Problem: large number of false negatives
  - Attacker can use any system call from S
- Problem: |S| very big for large applications

Callgraph Model

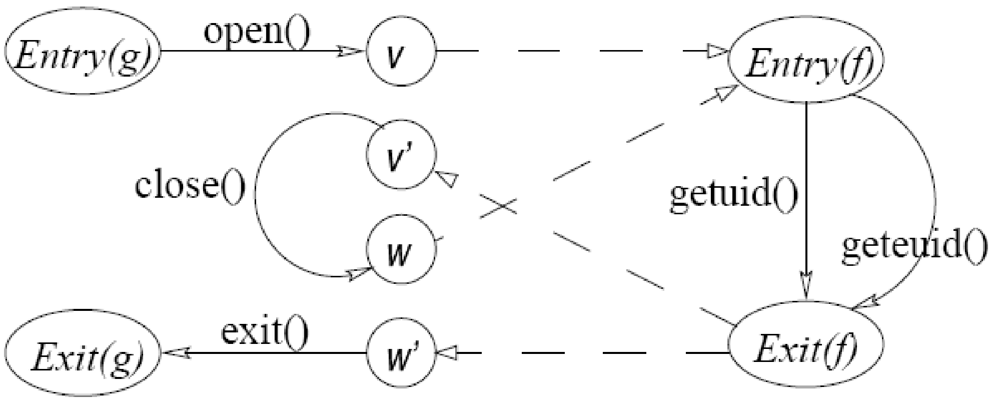
[Wagner and Dean]

- Build a control-flow graph of the application by static analysis of its source or binary code
- Result: non-deterministic finite-state automaton (NFA) over the set of system calls
  - Each vertex executes at most one system call
  - Edges are system calls or empty transitions
  - Implicit transition to special “Wrong” state for all system calls other than the ones in original code; all other states are accepting
- System call automaton is conservative
  - No false positives!

NFA Example

[Wagner and Dean]

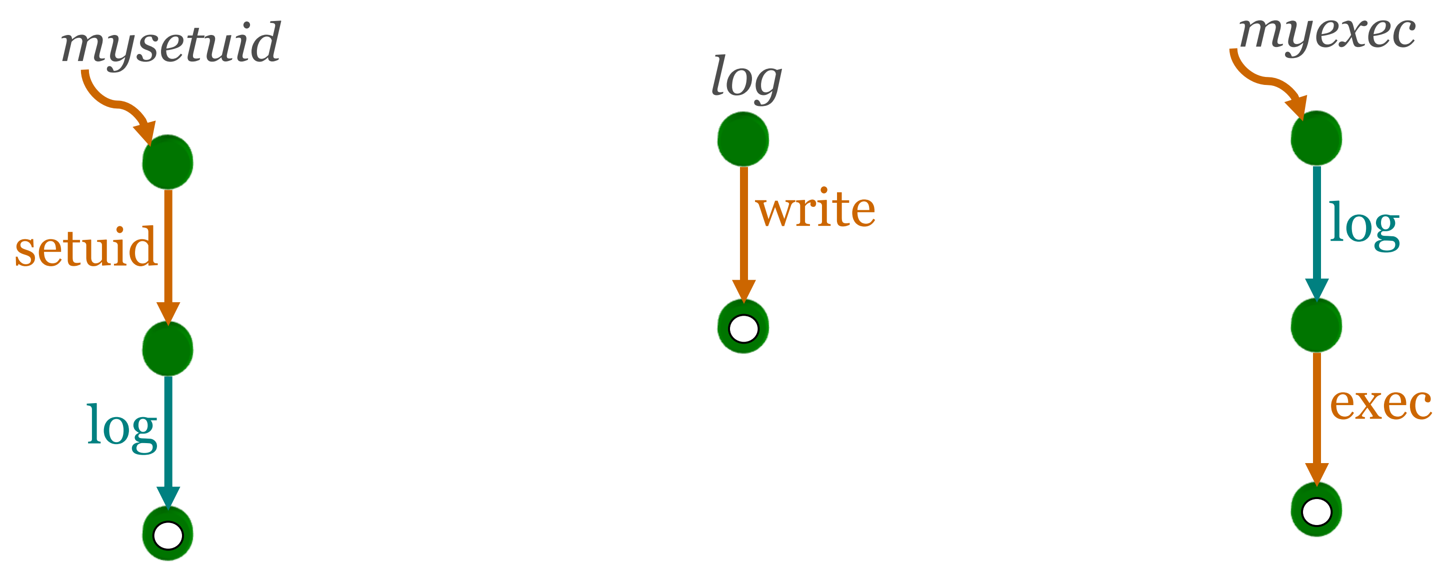
```
f(int x) {
  x ? getuid() : geteuid();
  x++;
}
g() {
  fd = open("foo", O_RDONLY);
  f(0); close(fd); f(1);
  exit(0);
}
```



- Monitoring is O(|V|) per system call
- Problem: attacker can exploit impossible paths
  - The model has no information about stack state!

Another NFA Example

[Giffin]

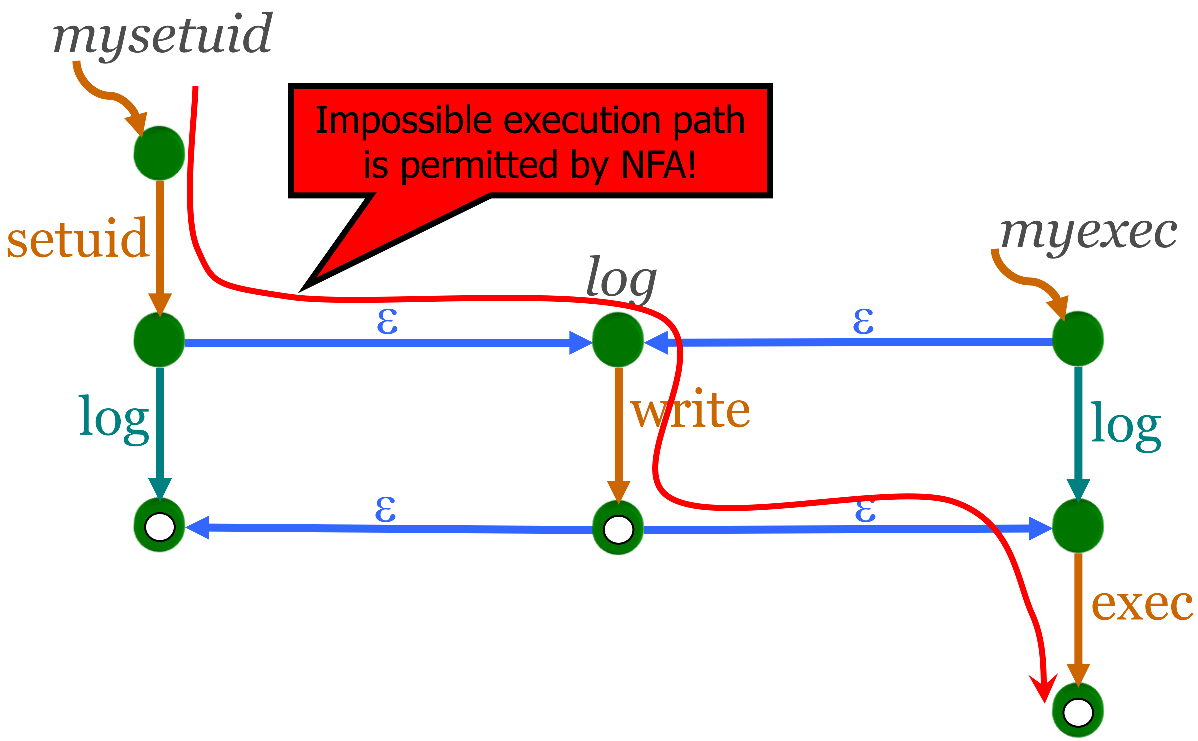



```
void
mysetuid (uid_t uid)
{
  setuid(uid);
  log("Set UID", 7);
}
```

```
void
log (char *msg,
     int len)
{
  write(fd, msg, len);
}
```

```
void
myexec (char *src)
{
  log("Execing", 7);
  exec("/bin/ls");
}
```

NFA Permits Impossible Paths



NFA: Modeling Tradeoffs

- A good model should be…
  - Accurate: closely models expected execution
  - Fast: runtime verification is cheap

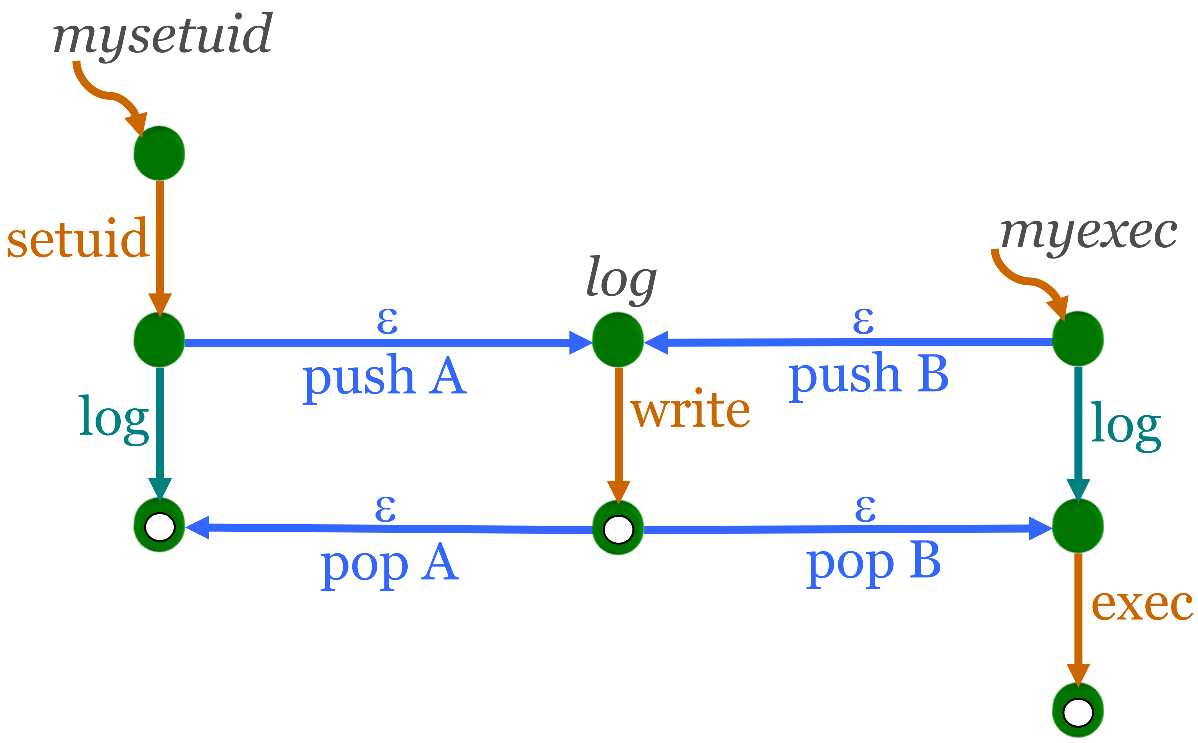
	Inaccurate	*Accurate*
Slow		
Fast	NFA	

Abstract Stack Model

- NFA is not precise, loses stack information
- Alternative: model application as a context-free language over the set of system calls
  - Build a non-deterministic pushdown automaton (PDA)
  - Each symbol on the PDA stack corresponds to single stack frame in the actual call stack
  - All valid call sequences accepted by PDA; enter "Wrong" state when an impossible call is made

PDA Example

[Giffin]



Another PDA Example

[Wagner and Dean]

```
f(int x) {
  x ? getuid() : geteuid();
  x++;
}
g() {
  fd = open("foo", O_RDONLY);
  f(0); close(fd); f(1);
  exit(0);
}
```

$$
\begin{array}{lcl}
\text{Entry}(f) & ::= & \texttt{getuid}()\ \ \text{Exit}(f) \\
 & | & \texttt{geteuid}()\ \ \text{Exit}(f) \\
\text{Exit}(f) & ::= & \epsilon \\
\text{Entry}(g) & ::= & \texttt{open}()\ \ v \\
v & ::= & \text{Entry}(f)\ \ v' \\
v' & ::= & \texttt{close}()\ \ w \\
w & ::= & \text{Entry}(f)\ \ w' \\
w' & ::= & \texttt{exit}()\ \ \text{Exit}(g) \\
\text{Exit}(g) & ::= & \epsilon
\end{array}
$$

while (true)
  case pop() of

$$
\begin{array}{ll}
\text{Entry}(f) & \Rightarrow \text{push}(\text{Exit}(f));\ \ \text{push}(\texttt{getuid}()) \\
\text{Entry}(f) & \Rightarrow \text{push}(\text{Exit}(f));\ \ \text{push}(\texttt{geteuid}()) \\
\text{Exit}(f) & \Rightarrow \text{no-op} \\
\text{Entry}(g) & \Rightarrow \text{push}(v);\ \ \text{push}(\texttt{open}()) \\
v & \Rightarrow \text{push}(v');\ \ \text{push}(\text{Entry}(f)) \\
v' & \Rightarrow \text{push}(w);\ \ \text{push}(\texttt{close}()) \\
w & \Rightarrow \text{push}(w');\ \ \text{push}(\text{Entry}(f)) \\
w' & \Rightarrow \text{push}(\text{Exit}(g));\ \ \text{push}(\texttt{exit}()) \\
\text{Exit}(g) & \Rightarrow \text{no-op} \\
a \in \Sigma & \Rightarrow \text{read and consume } a \text{ from the input} \\
\text{otherwise} & \Rightarrow \text{enter the error state, Wrong}
\end{array}
$$

PDA: Modeling Tradeoffs

- Non-deterministic PDA has high cost
  - Forward reachability algorithm is cubic in automaton size
  - Unusable for online checking

	Inaccurate	*Accurate*
Slow		PDA
Fast	NFA	

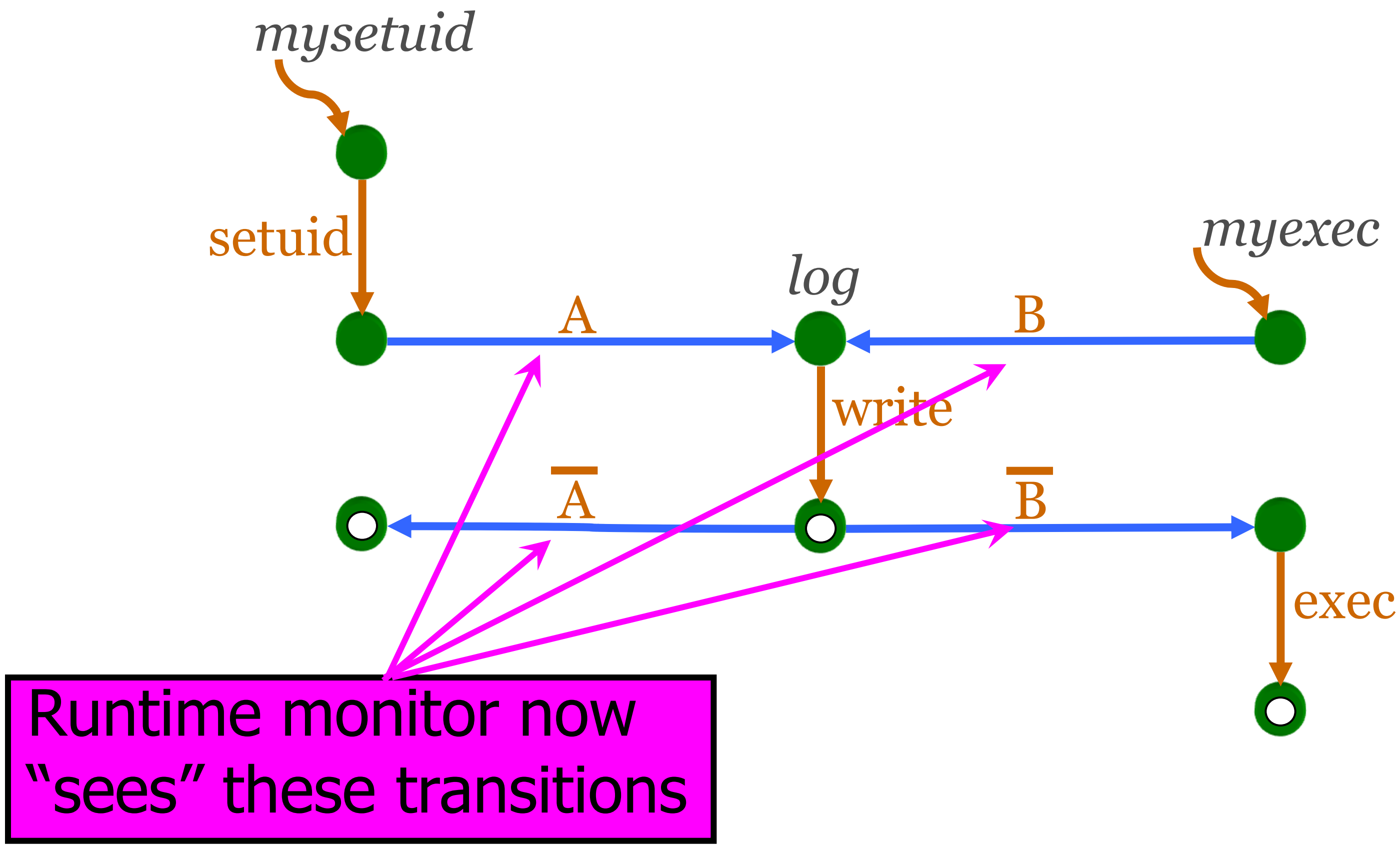
Dyck Model

[Giffin et al.]

- Idea: make stack updates (i.e., function calls and returns) explicit symbols in the alphabet
  - Result: stack-deterministic PDA
- At each moment, the monitor knows where the monitored application is in its call stack
  - Only one valid stack configuration at any given time
- How does the monitor learn about function calls?
  - Use binary rewriting to instrument the code to issue special “null” system calls to notify the monitor
    - – Potential high cost of introducing many new system calls
  - Can’t rely on instrumentation if application is corrupted

Example of Dyck Model

[Giffin]



CFG Extraction Issues

[Giffin]

- Function pointers
  - Every pointer could refer to any function whose address is taken
- Signals
  - Pre- and post-guard extra paths due to signal handlers
- setjmp() and longjmp()
  - At runtime, maintain list of all call stacks possible at a setjmp()
  - At longjmp() append this list to current state

System Call Processing Complexity

[Giffin]

Model	*Time & Space Complexity*
NFA	$O(n)$
PDA	$O(nm^2)$
Dyck	$O(n)$

n is state count

m is transition count

Dyck: Runtime Overheads

[Giffin]

Execution times in seconds

Program	Unverified execution	Verified against Dyck	Increase
procmail	0.5	0.8	56%
gzip	4.4	4.4	1%
eject	5.1	5.2	2%
fdformat	112.4	112.4	0%
cat	18.4	19.9	8%

- Many tricks to improve performance
  - Use static analysis to eliminate unnecessary null system calls
  - Dynamic "squelching" of null calls

Persistent Interposition Attacks

[Parampalli et al.]

- Observation: malicious behavior need not involve system call anomalies
- Hide malicious code inside a <u>server</u>
  - Inject via a memory corruption attack
  - Hook into a normal execution path (how?)
- Malicious code communicates with its master by “piggybacking” on normal network I/O
  - No anomalous system calls
  - No anomalous arguments to any calls except those that read and write