Intrusion Detection via Static Analysis

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Outline

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- Models
  - Trivial model
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  - Abstract stack model
  - Digraph model
- Implementation
- Evaluation

Introduction

- IPS: Intrusion Prevention System
  - Find buffer overflows and remove them
  - Use firewall to filter out malicious network traffic
- IDS: Intrusion Detection System
  - Is what you do after prevention has failed
  - Detect attack in progress
    - Network traffic patterns, suspicious system calls, etc

Introduction

- Host-based IDS
  - Monitor activity on a single host
  - Advantage: better visibility into behavior of individual applications running on the host
- Network-based IDS
  - Often placed on a router or firewall
  - Monitor traffic, examine packet headers and payloads
  - Advantage: can protect many hosts

Problem

- Prevalent security problems
  - Abnormal behavior: Buffer Overflows
- Current Methodology
  - Define a model of the normal behavior of a program
  - Raise an alarm if the program behaves abnormally
- The Problem
  - False alarm rate is high!!!

Motivation

- System Call Interposition
- Observation: all sensitive system resources are accessed via OS system call interface
  - Files, Network, etc.
- Idea: Monitor all system calls and block those that violate security policy

Model Creation

- Training-based:
  - Use machine learning and data mining techniques
    - Log system activities for a while, then “train” IDS to recognize normal and abnormal patterns
  - Easy but may miss some of the behavior
- Static analysis:
  - Extracted the model from source or binary
  - NO false positives!!!

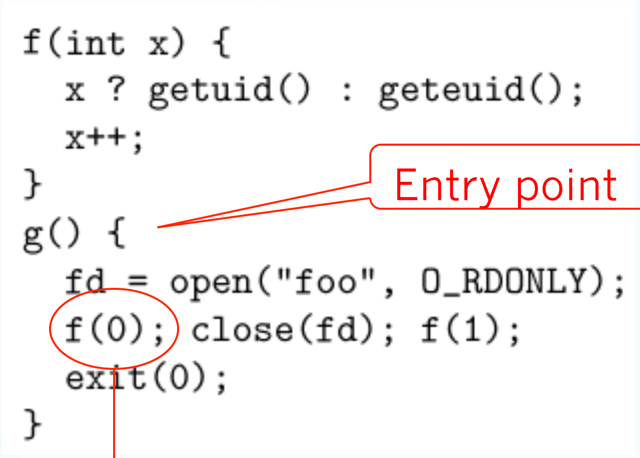
A Trivial Model

- Create a set of system calls that the application can ever make
- If a system call outside the set is executed, terminate the application
- Pros: easy to implement
- Cons: miss many attacks & too coarse-grained

Callgraph Model

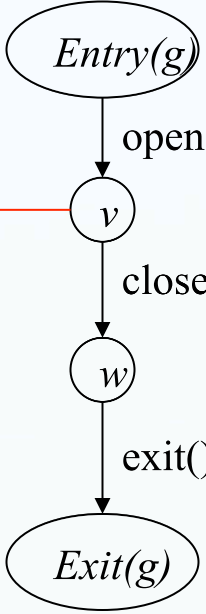
- Build a control flow graph of the program by static analysis of its source or binary code
- Result: non-deterministic finite-state automaton (NDFA) over the set of system calls
  - Each vertex executes at most one system call
  - Edges are system calls or empty transitions
  - Implicit transition to special “Wrong” state for all system calls other than the ones in original code
  - All other states are accepting

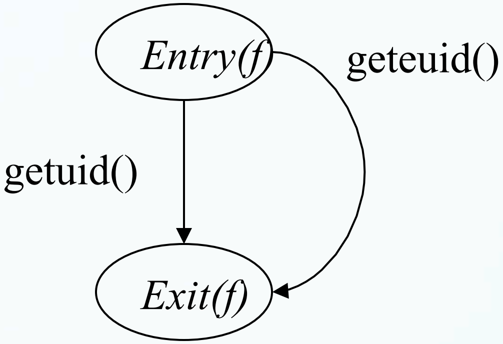
Callgraph Example



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

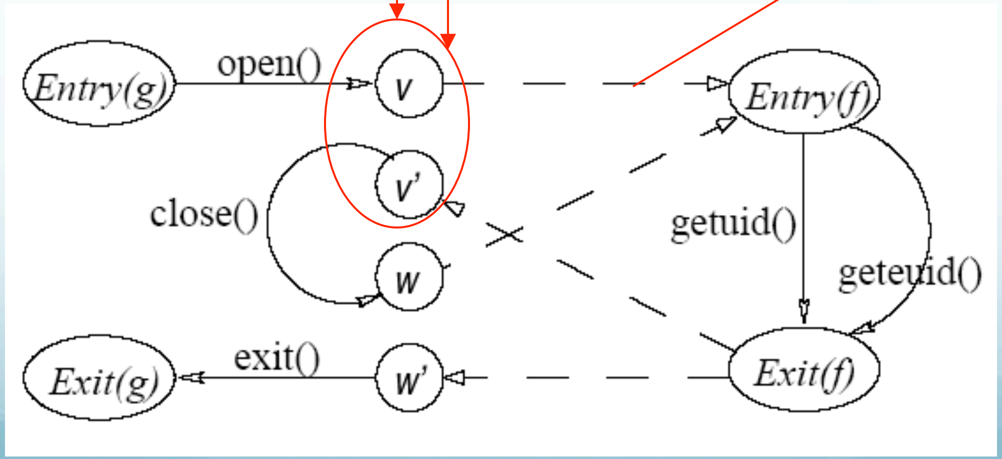
Entry point



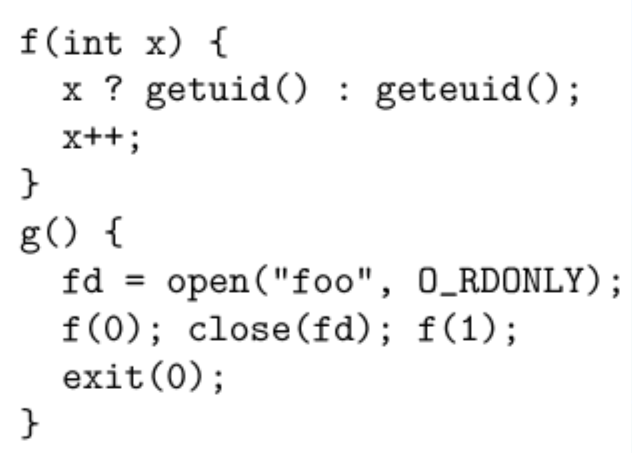


Epsilon edges

Function call site is split into two nodes

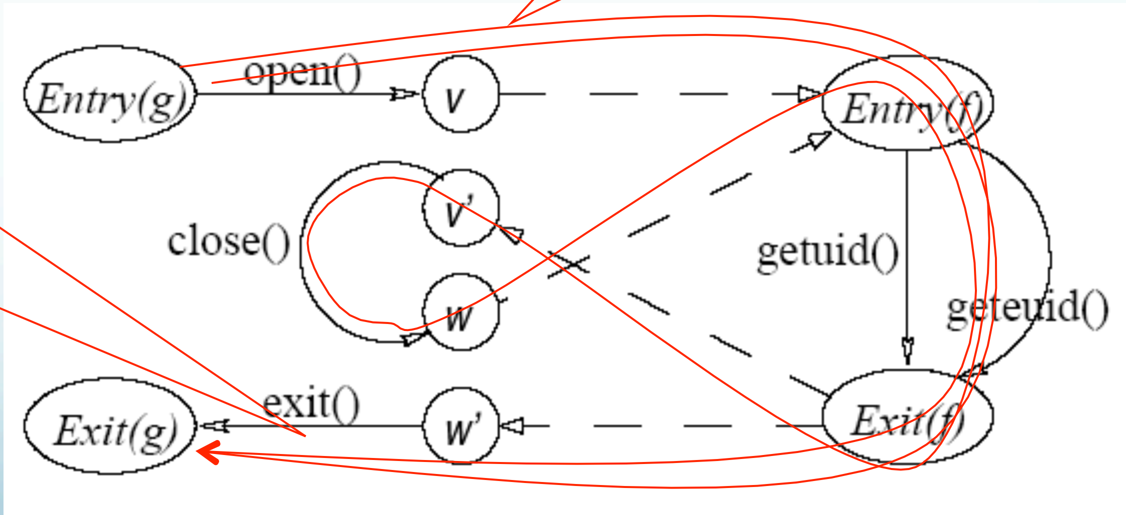


Imprecision in Callgraph



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

The return address in f can be overridden.



Valid Path

Impossible Path.
Yet the model will not be able to detect it since all transitions are valid.

NDFA: Model Tradeoffs

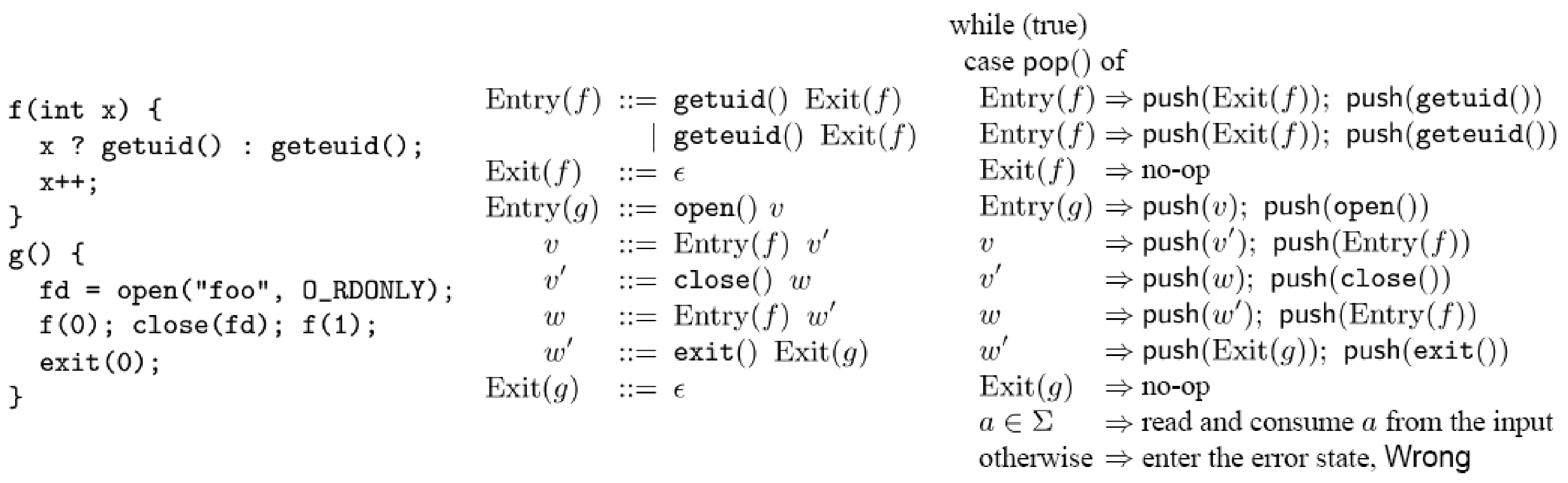
- A good model should be…
  - **Accurate:** closely models expected execution
    - Need context sensitivity!
  - **Fast:** runtime verification is cheap

	Inaccurate	*Accurate*
Slow		
Fast	NDFA	

Abstract Stack Model

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

NDPDA Example



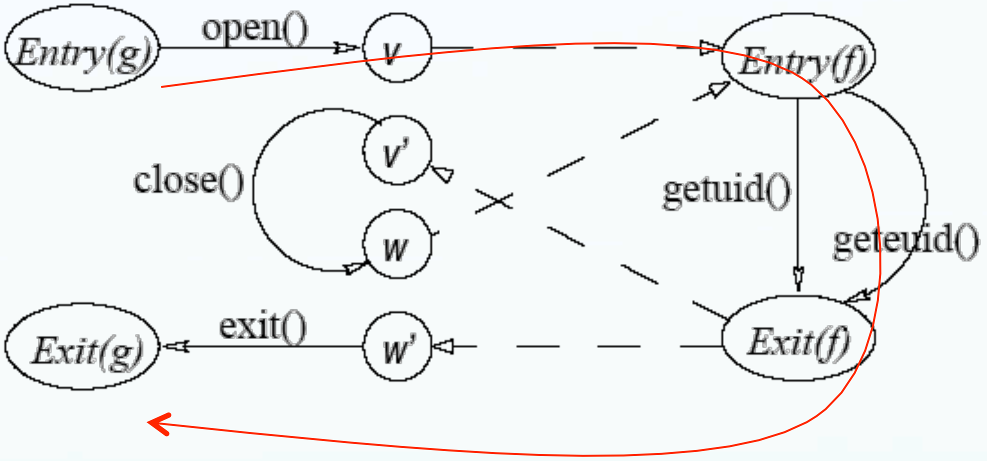
```
f(int x) {
  x ? getuid() : geteuid();
  x++;
}
g() {
  fd = open("foo", O_RDONLY);
  f(0); close(fd); f(1);
  exit(0);
}
```

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

```
while (true)
  case pop() of
    $\text{Entry}(f) \Rightarrow \text{push}(\text{Exit}(f));\ \text{push}(\texttt{getuid}())$
    $\text{Entry}(f) \Rightarrow \text{push}(\text{Exit}(f));\ \text{push}(\texttt{geteuid}())$
    $\text{Exit}(f) \Rightarrow$ no-op
    $\text{Entry}(g) \Rightarrow \text{push}(v);\ \text{push}(\texttt{open}())$
    $v \Rightarrow \text{push}(v');\ \text{push}(\text{Entry}(f))$
    $v' \Rightarrow \text{push}(w);\ \text{push}(\texttt{close}())$
    $w \Rightarrow \text{push}(w');\ \text{push}(\text{Entry}(f))$
    $w' \Rightarrow \text{push}(\text{Exit}(g));\ \text{push}(\texttt{exit}())$
    $\text{Exit}(g) \Rightarrow$ no-op
    $a \in \Sigma \Rightarrow$ read and consume $a$ from the input
    otherwise $\Rightarrow$ enter the error state, Wrong
```

Solve Impossible Path

- Consider the previous example of an impossible path.



- The Abstract Stack model will detect the attack since it stores stack information. When returning from state *Exit(f)*, the stack will have the return address *v'*.
- State *v'* does not have a transition on system call *exit()* hence the attack will be detected.

NDPDA: Model Tradeoffs

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

	Inaccurate	*Accurate*
Slow		NDPDA
Fast	NDNFA	

Digraph Model

- Combines some of the advantages of the callgraph model in a simpler formulation
- Model consists of a list of possible k-sequences of consecutive system calls (k=2 for simplicity)
- Monitor the application by checking the executed system calls vs. a precomputed list of the allowed k-sequences
- +: much more efficient than NDFA & NDPDA
- -: less precise than NDFA & NDPDA

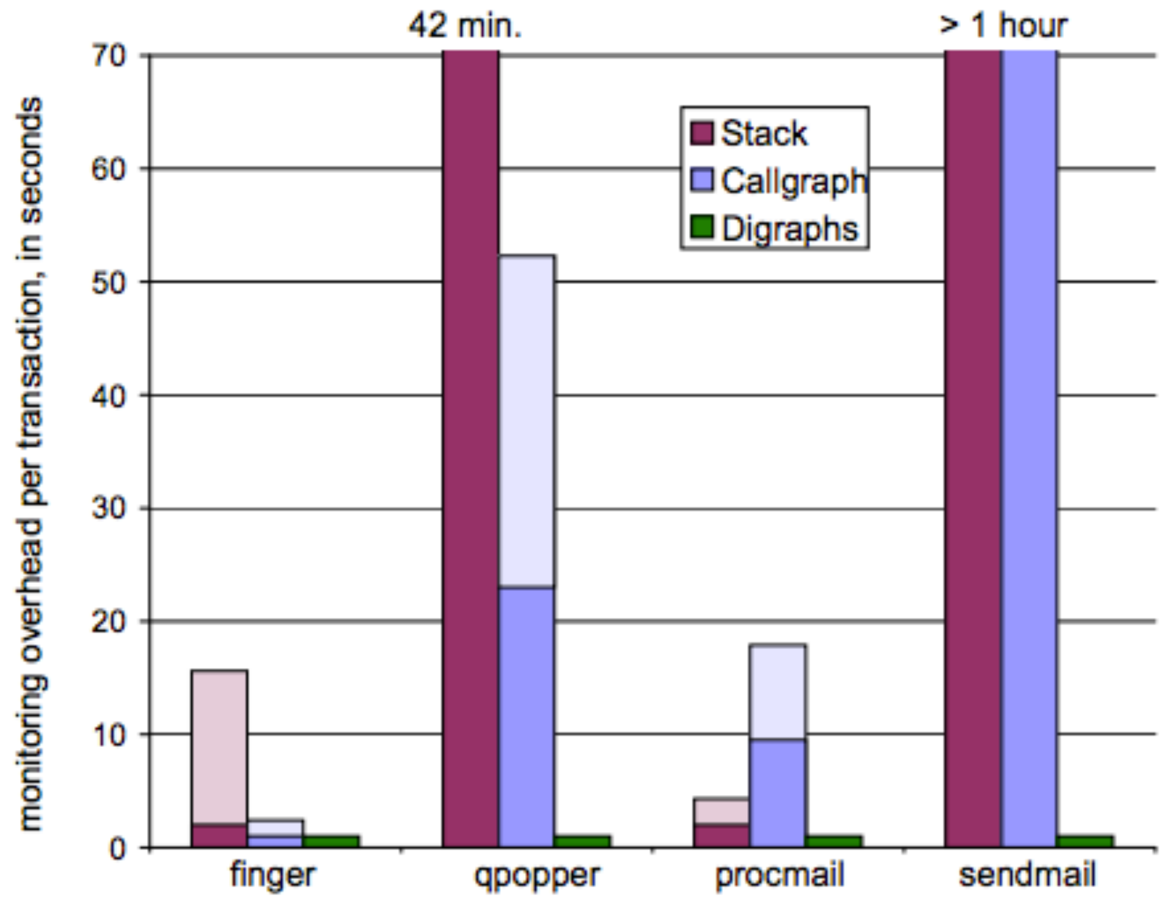
Implementation Issues

- Non-standard control
  - Function pointers
  - Signals
    - Add extra edge to each handler + pre-/post-guard
  - Setjmp()
    - Modify stack, not suitable for NDPDA
    - Extend runtime monitor to handle
- Other modeling challenges
  - Libraries
  - Dynamic linking
  - Threads

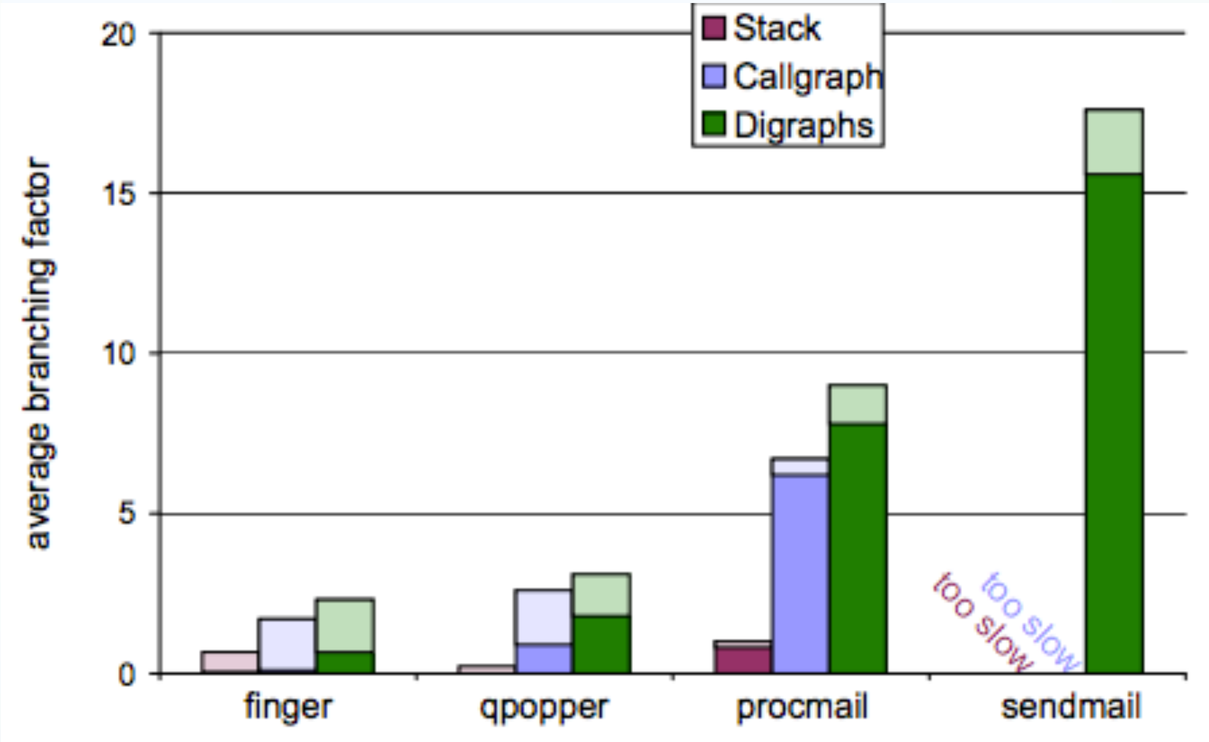
Optimizations

- Irrelevant systems calls
  - Not monitoring harmless but frequently executed system calls such as brk()
- System call arguments
  - Monitoring the arguments at runtime improves both precision and performance

Evaluation: Performance



Evaluation: Precision



Precision of each of the models, as characterized by the average branching factor. Small numbers represent better precision.

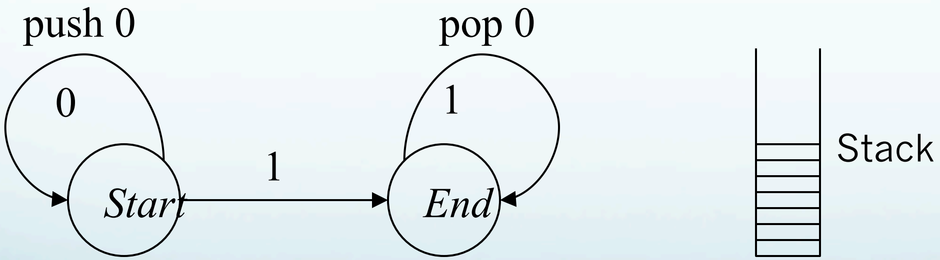
Unsolved Issues

- Mimicry Attack
  - Require high precision model to detect (poor performance)
- Runtime Overhead
  - Use more advanced static analysis to get more precise models
  - Later work such as VtPath, Dyck and VPStatic try to solve this problem

Backup

Push-down automata

- As in FSA, PDA have a set of states and a transition function.
- They differ from FSA by also having a stack. They accept context-free languages.
- At every transition, a symbol can be pushed or popped from the stack.
- They can accept either by state or by stack (if stack is empty), which are equivalent in terms of computational power.
- PDA is stronger than FSA. It can accept regular languages and also *some* irregular ones such as 0^n1^n.



Once you see a 1, switch to the *End* state.
The stack contains as many 0 as seen in the input.
If the stack is empty at the end of the input, accept.

Dyck Model

[Giffin et al.]

- Idea: make stack updates (i.e., function calls) explicit symbols in the automaton 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 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

System Call Processing Complexity

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

n is state count

m is transition count

Reference

- cseweb.ucsd.edu/classes/sp02/cse231/eugene.ppt
- www.cs.utexas.edu/~shmat/courses/cs380s_fall09/08hostids.ppt
- Moss.csc.ncsu.edu/~mueller/seminar/spring05/sezer.ppt