Static Analysis of Executables to Detect Malicious Patterns

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Problem & Motivation…

- Malicious code is … malicious
- Categorize: Propagation Method & Goal
  - Viruses, worms, trojan horses, spyware, etc.
- Detect Malicious Code
  - In executables

The Classical Stuff

- Focus mostly on Viruses
  - Code to replicate itself + Malicious payload
  - Inserted into executables
- Look for *signatures*
- Not always enough
- Obfuscation-Deobfuscation Game

Common Obfuscation Techniques

- Encryption
- Dead Code insertion*
- Code transposition*
- Instruction Substitution*
- Register reassignment*
- Code Integration
- Entry Point Obscuring

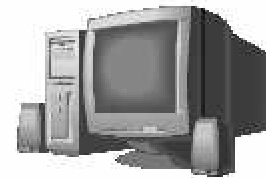
Common Deobfuscation Techniques

- Regular Expressions
- Heuristic Analyses
- Emulation

Mostly Syntactic…

The Game

- Vanilla Virus
- Register Renaming
- Packing/Encryption
- Code Reordering
- Code Integration



- Signatures
- Regex Signatures
- Emulation/Heuristics
- ?
- ?

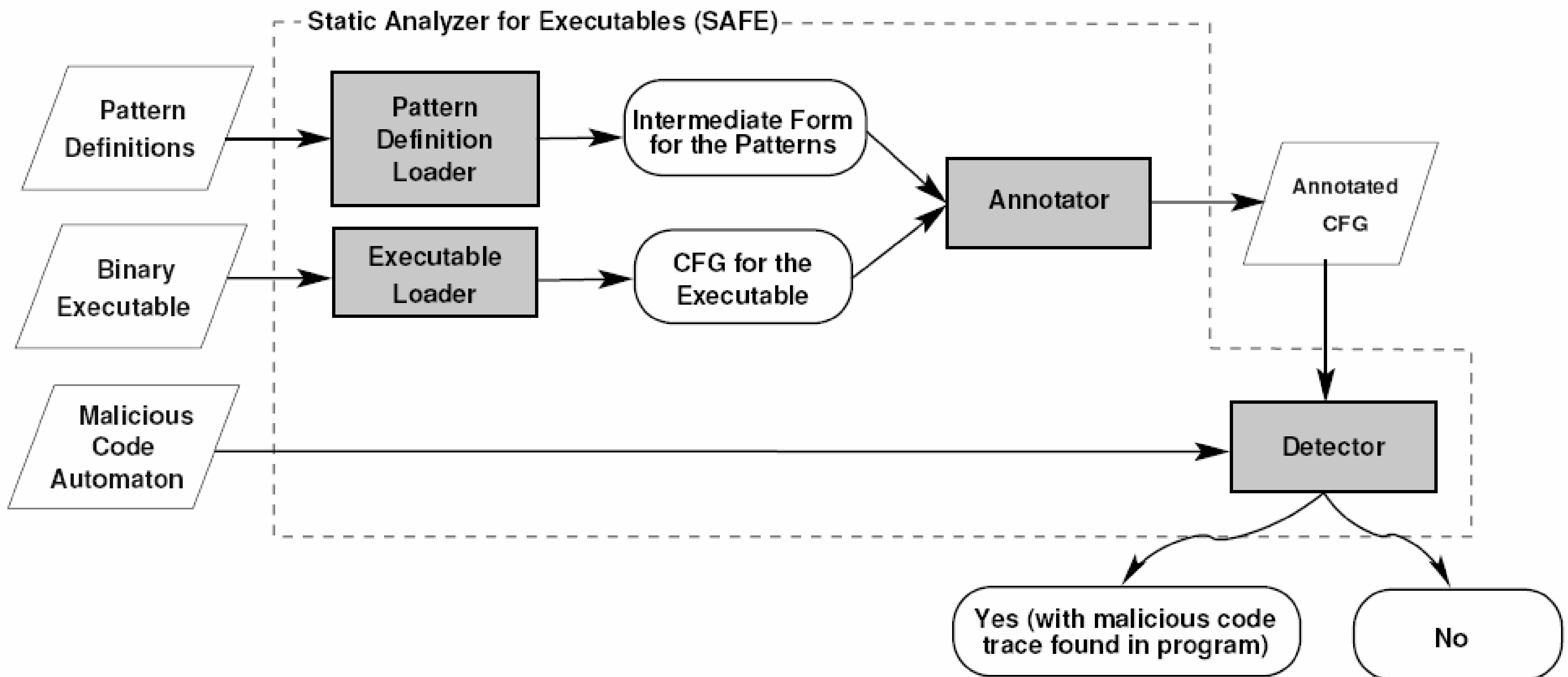
Current Technology

- Antivirus Software
  - Norton, McAfee, Command
- Brittle
  - Cannot detect simple obfuscations
  - nop-insertion, code transposition
- Chernobyl, z0mbie-6.b, f0sf0r0, Hare

Theoretical Limits

- Virus Detection is undecidable
- Some Static Analyses are undecidable
- But, Obfuscation is also hard

The SAFE* Methodology



Procedure

- Key Ideas:
  - Analyze program's semantic structure
  - Use existing static analyses (extensible)
  - Use uninterpreted symbols
- Abstract Representation of Malicious Code
- Abstract Representation of Executable
  - Deobfuscation
- Detect presence of malicious code

The Annotator

- Inputs:
  - CFG of the executable
  - Library of Abstraction Patterns
- Outputs:
  - Annotated CFG

Some groundwork

- Instruction I : $\tau_1 \times \ldots \times \tau_k \rightarrow \tau$
- Program P : $\langle I_1, \ldots, I_N \rangle$
- Program counter/point
  - pc : $\{ I_1, \ldots, I_N \} \rightarrow [1,\ldots,N]$
  - $pc(I_j) = j, \forall\, 1 \leq j \leq N$
- Basic Block, Control Flow Graph*
- Static Analysis Predicates
- Types for data and instructions

Example Predicates

$Dominators(B)$	the set of basic blocks that dominate the basic block B
$PostDominators(B)$	the set of basic blocks that are dominated by the basic block B
$Pred(B)$	the set of basic blocks that immediately precede B
$Succ(B)$	the set of basic blocks that immediately follow B
$First(B)$	the first instruction of the basic block B
$Last(B)$	the last instruction of the basic block B
$Previous(I)$	$\begin{cases} \bigcup_{B' \in Pred(B_I)} Last(B') & \text{if } I = First(B_I) \\ I' & \text{if } B_I = \langle \ldots, I', I, \ldots \rangle \end{cases}$
$Next(I)$	$\begin{cases} \bigcup_{B' \in Succ(B_I)} First(B') & \text{if } I = Last(B_I) \\ I' & \text{if } B_I = \langle \ldots, I, I', \ldots \rangle \end{cases}$
$Kills(p, a)$	*true* if the instruction at program point p kills variable a
$Uses(p, a)$	*true* if the instruction at program point p uses variable a
$Alias(p, x, y)$	*true* if variable x is an alias for y at program point p
$LiveRangeStart(p, a)$	the set of program points that start the a's live range that includes p
$LiveRangeEnd(p, a)$	the set of program points that end the a's live range that includes p
$Delta(p, m, n)$	the difference between integer variables m and n at program point p
$Delta(m, p_1, p_2)$	the change in m's value between program points p_1 and p_2
$PointsTo(p, x, a)$	*true* if variable x points to location of a at program point p

Abstraction Patterns

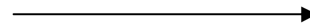
- Abstraction pattern Γ : (V,O,C)
  - $V = \{ x_1 : \tau_1, \ldots, x_k : \tau_k \}$
  - $O = \langle\, I(v_1, \ldots, v_m) \mid I : \tau_1 \times \ldots \times \tau_m \rightarrow \tau \,\rangle$
  - C = boolean expression involving static analysis predicates and logical operators
- Represents a deobfuscation
- Predicate controls pattern application
- *Unify* patterns with sequence of instructions

Example of a pattern

$$
\begin{aligned}
\Gamma(\ X : int(0:1:31)\ ) = \\
&(\quad \{\ X : int(0:1:31)\ \}, \\
&\quad \langle\ p_1 :\ \text{“}pop\ X\text{”}, \\
&\quad\quad p_2 :\ \text{“}add\ X, \texttt{03AFh}\text{”}\ \rangle, \\
&\quad p_1 \in LiveRangeStart(p_2, X)\ \ )
\end{aligned}
$$

Defeating Garbage Insertion

<instruction A>
<instruction B>



<instruction A>
add ebx, 1
sub ebx, 1
nop
<instruction B>

Pattern:

instr 1
…
instr N
Where
Delta(state pre 1, state post N) = 0

Defeating Code-reordering

Pattern:

jmp TARGET
where
Count (CFGPredecessors(TARGET)) = 1

The Annotator

- Given set of patterns $\Sigma = \{ \Gamma_1, \ldots, \Gamma_m \}$
- Given a node n for program point p
- Matches each pattern in Σ with
  $\langle \ldots, \mathit{Previous}^2(I_p), \mathit{Previous}(I_p), I_p \rangle$
- Associates all patterns that match with n
- Also stores the bindings from unification

The Detector

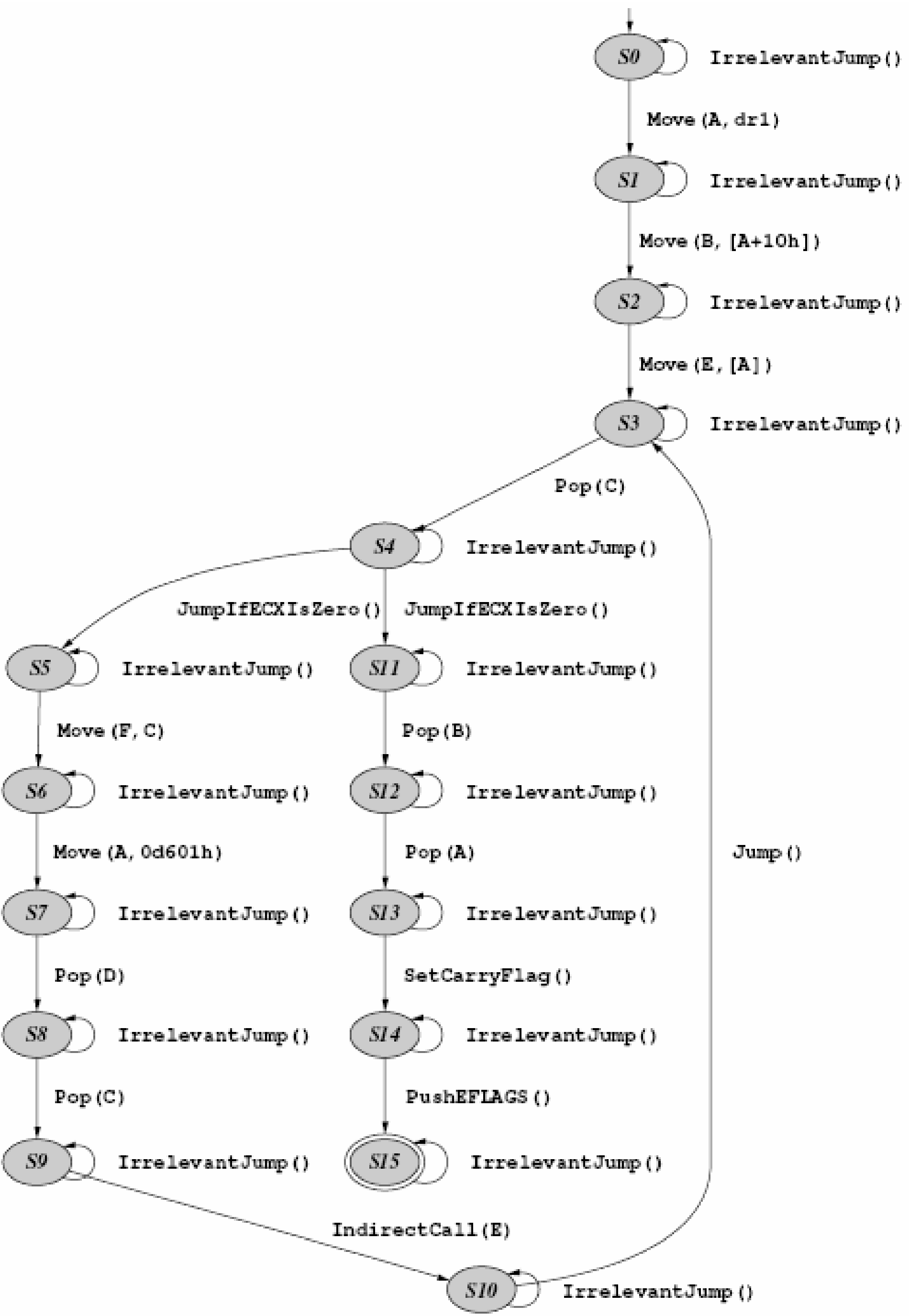
- Inputs:
  - Annotated CFG for a procedure
  - Malicious code *representation*
- Output:
  - Sequence of instructions exhibiting the malicious pattern

Malicious Code Automaton

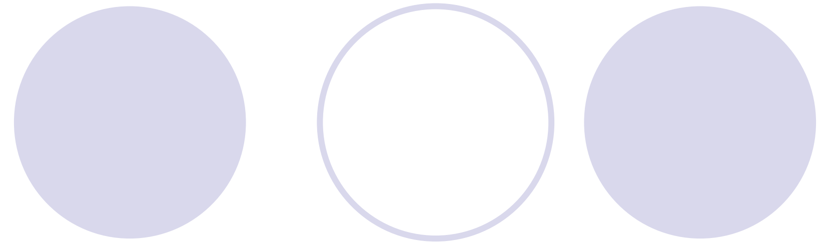
- Abstraction of the vanilla virus
- 6-tuple $(V,\Sigma,S,\delta,S_0,F)$
  - $V = \{ v_1{:}\tau_1, \ldots, v_k{:}\tau_k \}$
  - $\Sigma = \{ \Gamma_1, \ldots, \Gamma_n \}$
  - S = finite set of states
  - $\delta : S \times \Sigma \to 2^S$ is a transition function
  - $S_0 \subseteq S$ is a non-empty set of *initial* states
  - $F \subseteq S$ is a non-empty set of *final* states

Malicious Code

```
   WVCTF:
              mov     eax, dr1
              mov     ebx, [eax+10h]
              mov     edi, [eax]
 LOWVCTF:
              pop     ecx
              jecxz   SFMM
              mov     esi, ecx
              mov     eax, 0d601h
              pop     edx
              pop     ecx
              call    edi
              jmp     LOWVCTF
    SFMM:
              pop     ebx
              pop     eax
              stc
              pushf
```


S0
IrrelevantJump()
Move(A, dr1)
S1
IrrelevantJump()
Move(B, [A+10h])
S2
IrrelevantJump()
Move(E, [A])
S3
IrrelevantJump()
Pop(C)
S4
IrrelevantJump()
JumpIfECXIsZero()
JumpIfECXIsZero()
S5
IrrelevantJump()
S11
IrrelevantJump()
Move(F, C)
Pop(B)
S6
IrrelevantJump()
S12
IrrelevantJump()
Move(A, 0d601h)
Pop(A)
Jump()
S7
IrrelevantJump()
S13
IrrelevantJump()
Pop(D)
SetCarryFlag()
S8
IrrelevantJump()
S14
IrrelevantJump()
Pop(C)
PushEFLAGS()
S9
IrrelevantJump()
S15
IrrelevantJump()
IndirectCall(E)
S10
IrrelevantJump()

Detector Operation



- Inputs:
  - CFG P_Σ
  - $\mathcal{A} = (V,\Sigma,S,\delta,S_0,F)$
- Determines whether the same (malicious) pattern occurs both in $\mathcal{A}$ and Σ
- More formally, tests the emptiness of

$$L(P_\Sigma) \cap (\cup_{\mathcal{B} \in \mathcal{B}_{All}} L(\mathcal{B}(\mathcal{A})))$$

Detector Algorithm

- Dataflow-like Algorithm
- Maintain a *pre* and *post* list at each node of the CFG P_{Σ}
- List is of [s,$\mathcal{B}_s$], s is a state in $\mathcal{A}$
- Join operation is union

Detector Algorithm

- Transfer Function:

$$\begin{array}{l} \textbf{foreach } [s, \mathcal{B}_s] \in L_n^{pre} \\ \quad \textbf{foreach } [\Gamma, \mathcal{B}] \in Annotation(n) \\ \quad\quad\quad \wedge\, Compatible(\mathcal{B}_s, \mathcal{B}) \\ \quad\quad \textbf{add } [\, \delta(s, \Gamma),\ \mathcal{B}_s \cup \mathcal{B}\,] \textbf{ to } NewL_n^{post} \end{array}$$

- Return:

$$\exists\, n \in N \,.\, \exists\, [s, \mathcal{B}_s] \in L_n^{post} \,.\, s \in F$$

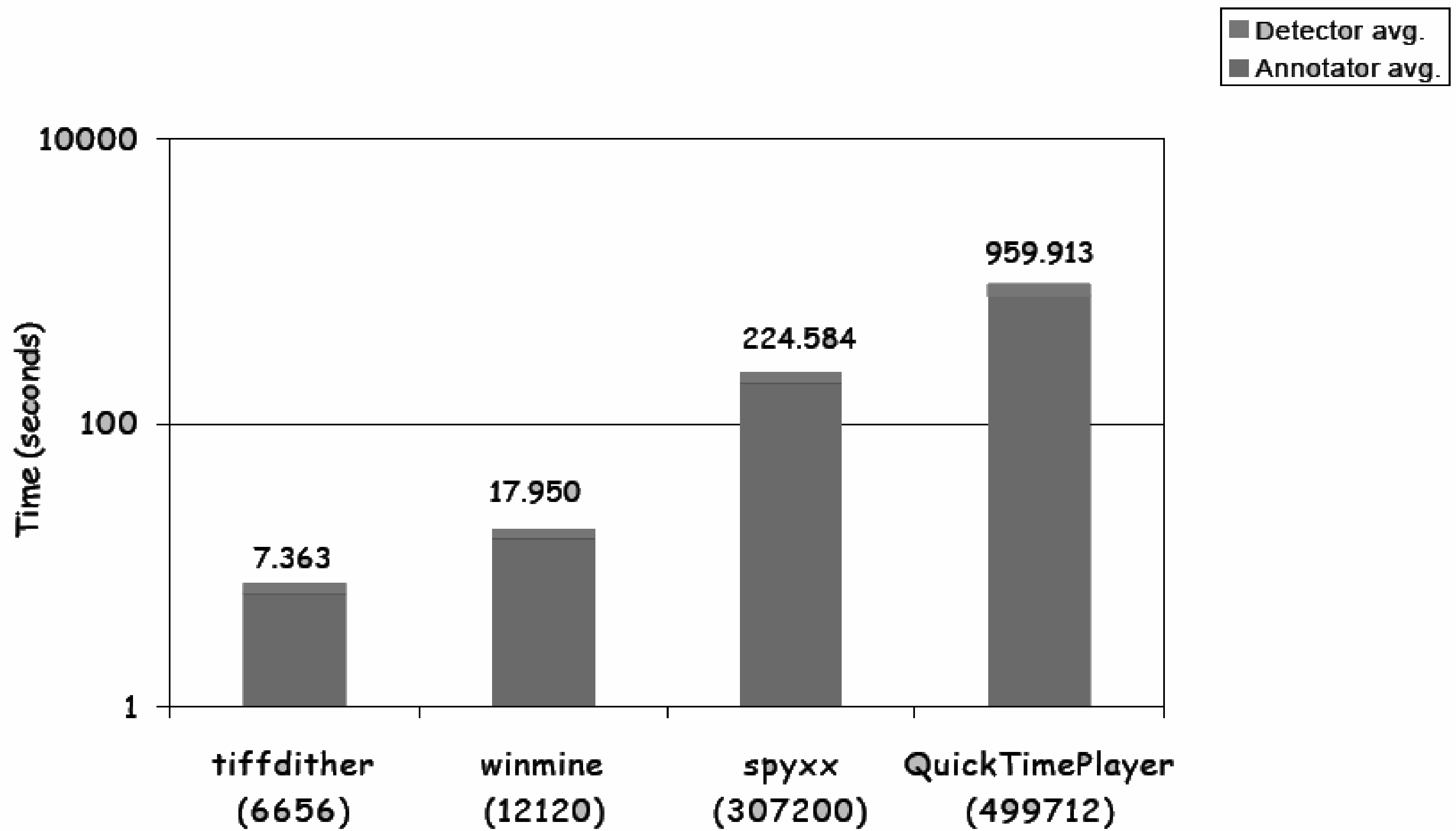
Defenses Against…

- Code Re-ordering
- Register Renaming
- Insertion of irrelevant code
  - nops*, code that modifies dead registers
  - Needs live-range and pointer analyses

Experimental Results

- False Positive Rate : 0
- False Negative Rate : 0
  - not all obfuscations are detected

Performance



Future Directions

- New languages
  - Scripts – VB, JavaScript, ASP
  - Multi-language malicious code
- Attack Diversity
  - worms, trojans too
- Irrelevant sequence detection
  - Theorem provers
- Use TAL/external type annotations

Pitfalls/Criticisms?

- Focus on viruses instead of worms
- Still fairly Ad-hoc
- Treatment of obfuscation is not formal enough
- Intractable techniques
  - Use of theorem provers to find irrelevant code
- Slow
- No downloadable code
- Not enough experimental evaluation