Software Integrity Protection Using Timed Executable Agents

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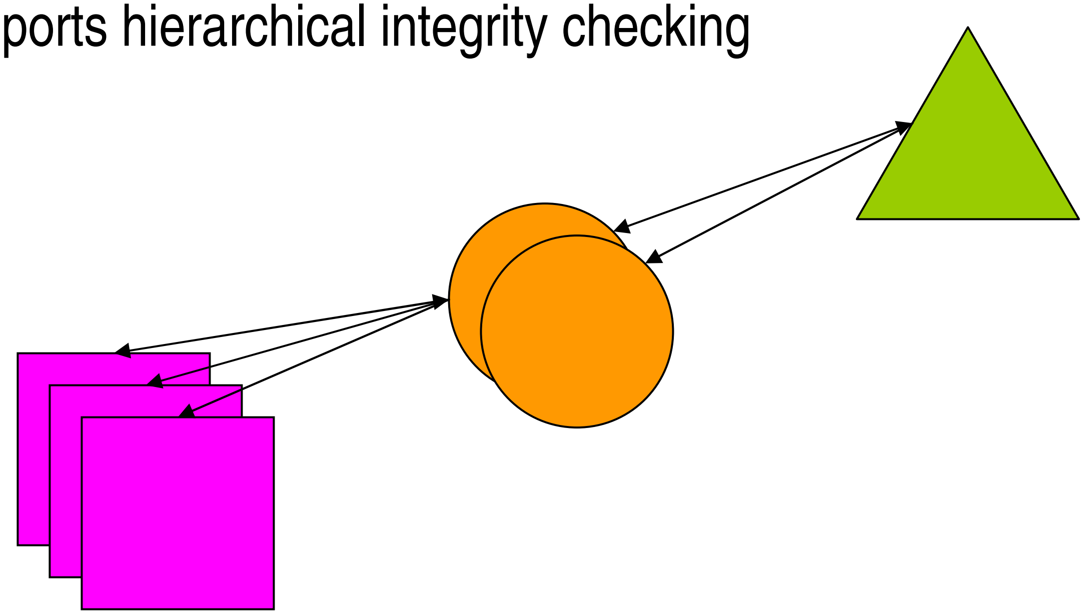
Motivation

- Malware is ubiquitous and on the rise
  - Spam
  - Viruses
  - Trojans
  - Improper reconfiguration
  - Keyboard loggers
  - **...**
- Pressing need to safeguard a system's integrity
- Many deployed systems contain little or no hardware protections
- **Our goal:** Develop off-the-shelf software protections
  - Perhaps not 100% secure, but
  - raise the bar substantially

Software-only Integrity Protection

- Software protection mechanisms
  - Can often detect if malware is present on a system
  - Can make it difficult for present malware to function
  - Requires no special hardware support
  - Ideal for legacy systems that have become vulnerable
  - Supports hierarchical integrity checking

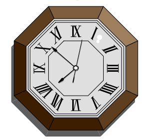


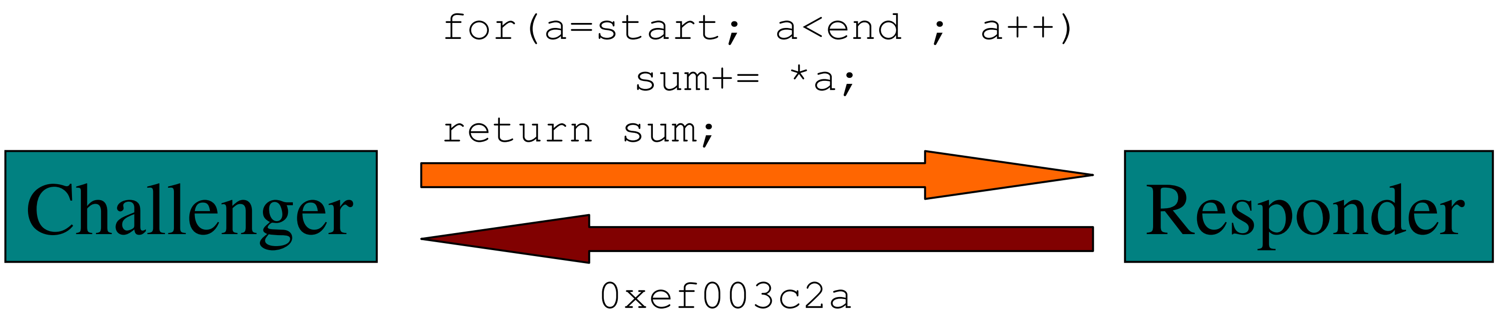
Approach: Software Agents

- Mobile code
- Typically traverses a network to carry out tasks
  (secure deployment requires authentication)
- If run on a known platform, work (execution time) done by an agent can be monitored
- Useful in many scenarios
  - Including *system integrity checking*

TEAS: Basic Idea

Challenge: Agent carries a program to run (many agents)

Response: Program result + *side effects* 

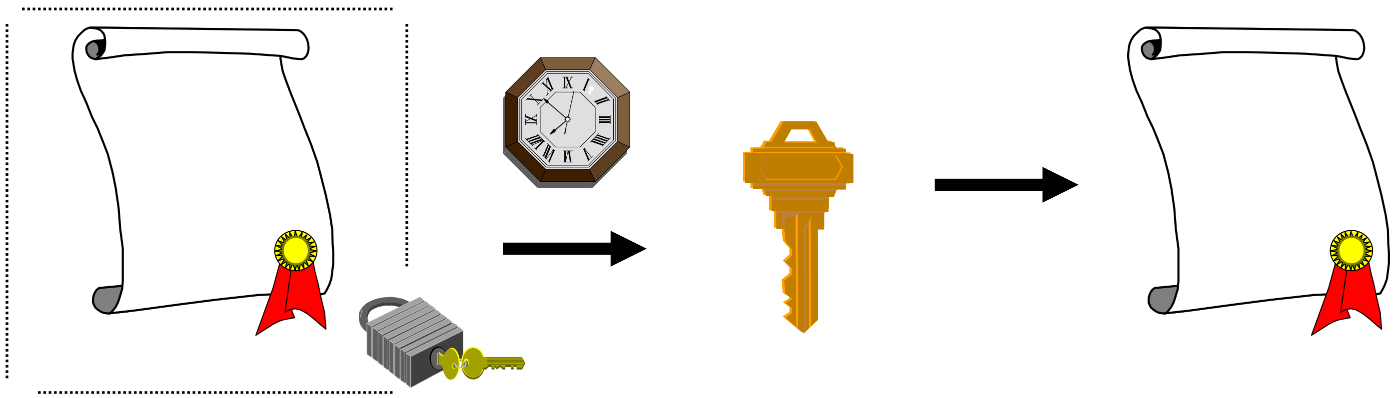


Bounds on execution time can help deter adversary's analysis of the challenge program(s)

Important: Agent may be an *arbitrary* program

Themes

- *“Cryptographic time capsules:”* Sending information into the future



Important: Verifiability (of contents, “time” parameters)

- *Moderately-hard functions:* Not computationally infeasible to solve, but also not easy

Talk Outline

- Definitions, assumptions and system requirements
- TEAS solutions for
  - Offline Adversaries
  - Online Adversaries
- TEAS applications
- Related work
- Summary

Def's, Assumptions & System Requirements

Model:

- Collection of computational nodes in a network
- Two types of nodes:
  - Secure/Trusted hosts
  - Insecure clients
- Uniprocessors. CPU rate C, [C] = cycles/sec
- Memory: Code, data, unused memory and program stack
- Communication: Fairly accurate estimate of transmission delays

  Bandwidth B, [B] = bits/sec

Adversaries

- **Goal:** Provide defense against client nodes being corrupted and/or taken over by an attacker – the *adversary*
- Two adversary classes:
  - *Offline adversaries*: Adversary tries to analyze incoming programs ("agents") *without running them* – recall *static analysis*
  - *Online adversaries*: Adversary is able to run incoming programs
- **Assumption:** Adversary makes *no changes* to the client's hardware
- Client's computing power is known

$\Rightarrow$ no. computation steps $\approx$ absolute time

TEAS Definitions

$(\varepsilon,\mathcal{A})$–TEAS = (Tgen,Tver)

(Two probabilistic algorithms, run at *Challenger*)

Tgen(*params*) $\rightarrow$ $T = ((P_1, o_1, t_1, \pi_1), \ldots , (P_k, o_k, t_k, \pi_k))$

$t_i = | P_i|/B + |o_i|/B + D(P_i)/C$

π_i : "*patience*" threshold

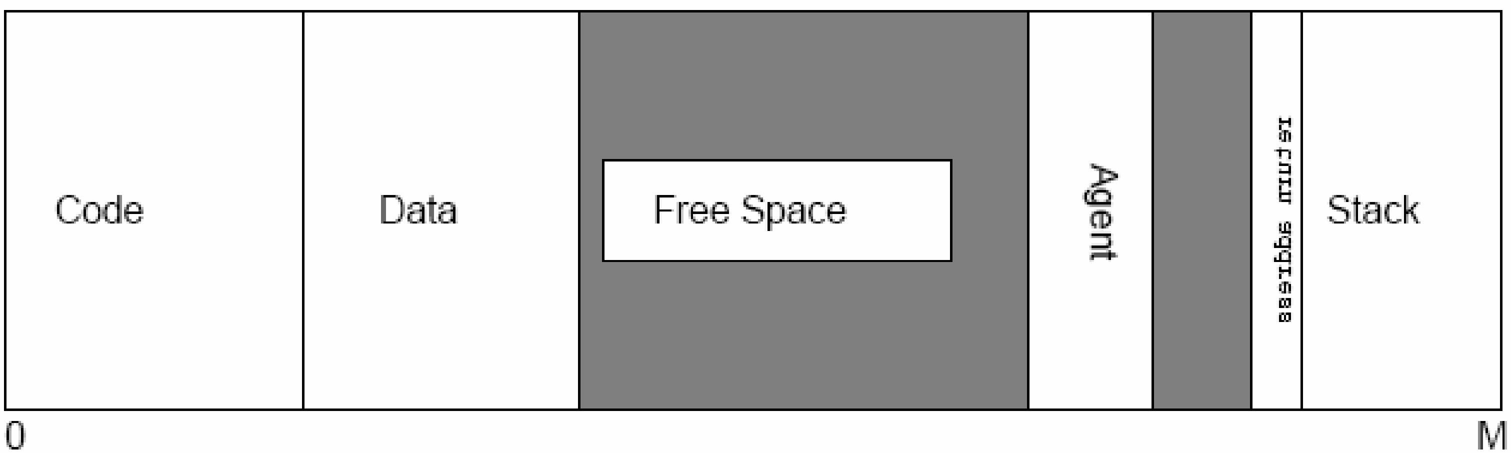
$P_i \rightarrow (o_i', t_i')$ (run at *Responder*)

Tver$(T, (o_i', t_i'), (o_2', t_2'), \ldots , (o_k', t_k')) \rightarrow \{OK, \neg OK\}$

If *Responder* is corrupted (by adv. in $\mathcal{A}$), then probability that Tver outputs OK < ε

System Requirements

- Known *a priori*:
  - The (valid) software that runs on the Responder
  - Responder's HW configuration (memory size, processor speed)
- Ideally, Challenger and Responder are connected by a deterministic, tightly coupled, network with known latencies. (Also more loosely coupled networks.)
- OS: Responder OS allows full and uninterrupted access (i.e., disable interrupts, time-slicing, etc.). Provisioned to receive and execute agents. Examples: real-time computing OSes (mobile phones, computing "appliances," etc.)



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TEAS for Offline Adversaries

- *Offline adversary* tries to analyze incoming programs *without running them.* Also access to inputs and state of Responder.
- Approaches
  1. Undecidability-based protection
  2. (Program analysis) Complexity-based protection

Complexity-based Protection

- **Program analysis background:** Behavior of program P (output values) may be determined through *global data-flow analysis*
  - Extract P's *control flow graph* (CFG) G_P
  - Convert G_P to a *reducible* flow graph G'_P
  - Perform global data flow analysis on G_P (or G'_P)
- Let n be some static measure of |P|
  - Extraction of CFG has complexity $\Omega(n)$
  - Rises to superlinear ($\Omega(n^2)$ or higher) with certain types of branches
  - CFG may not be reducible
  - Note: Only *deterministic* program analysis [Gulwani *et al.*]

Complexity-based Protection (cont'd)

- Program P : $P(x) \rightarrow y$, *fast* execution time
  - E.g., check memory locations, configuration values
- Global Data Flow problems ($\Omega(|P|^2)$ worst case)
  - "Reaching Definitions (Def-Use):" For each use of a variable, determine all the definitions that reach that variable
- $\Rightarrow$ Analysis (much) more expensive than execution
- Since we are crafting the agent, it is possible to avoid "in-practice" analysis!
- **Strategy:** Generate TEAS instance with sufficiently many such programs (k)

Complexity-based Protection: Example

$C = 10^9$ cycles/sec, 1 instruction/cycle; $B = 10^6$ bytes/sec

$|P| = 10^3$ instructions, 4 bytes/inst.

Linear dynamic runtime $\Rightarrow$ $10^3 / 10^9 =$ 0.000001 sec

Communication $4 * 10^3 / 10^6 + 4/10^6 =$ 0.004004 sec

$\Rightarrow t \geq 0.004005$ sec

$\Omega(n^2)$ analysis $\Rightarrow$ 0.01 sec computation time

$\Rightarrow t' \geq 0.014005$ sec

≈ 3.5

TEAS Agent Creation

- Need a large library of agents
  - To prevent agents being “learned” by adversary
- Creation of agents by hand is possible, but tedious and error prone
- Can agents be created automatically?
  - YES, via *program blinding*

Automatic Agent Generation

- *Program blinding*: Combine a small (hand-written) program with a *random*, obliviously generated one

  $$P^* \leftarrow P \otimes P^R$$

  "cross-over" operation: P* "inherits" some of P's properties

- P* is difficult to predict:
  (ε,n)-*semantically uncertain*: given P and input x, $\mathcal{A}$ can't determine $y \leftarrow P(x)$ after n steps of analysis with prob. better than ε

- *Input-sensitive* blinded programs

Automatic Agent Generation (cont'd)

- Make sure that blinded programs are
  1. "hard," e.g., contain an irreducible CFG, and
  2. "input-sensitive," i.e., blinded program's output depends on original program's input (e.g., a register or memory location value)

- **Experiments:** VRM, 8 registers, P = LOADr0([A]), r1 $\leftarrow$ P
  Ran blinding 10^5 times for programs of size 25, 50, 100

# instructions	n	n^2	n^3	foward jmps	backward jmps
25	687	48	1	2.5	1.9
50	422	59	1	5.3	4.2
100	282	26	1	10.7	9.6

Example TEAS Construction

- p^n_{irred} : probability that random program of size n contains an irreducible CFG (estimated in several ways)
- **Tgen** generates instances that include $((1 - p^n_{irred}), n)$-uncertain agents
- $(\varepsilon, \mathcal{A}_{off})$–TEAS: Tgen blinds target program with k terminating random programs s.t.
  1. every program is input-sensitive, and
  2. k such that $(1 - p^n_{irred})^k < \varepsilon$

Tver:

if $\exists\, P_i^*$ s.t. $o_i \neq o_i'$ OR $t_i'/\, t_i > \pi_i$ then output $\neg$OK

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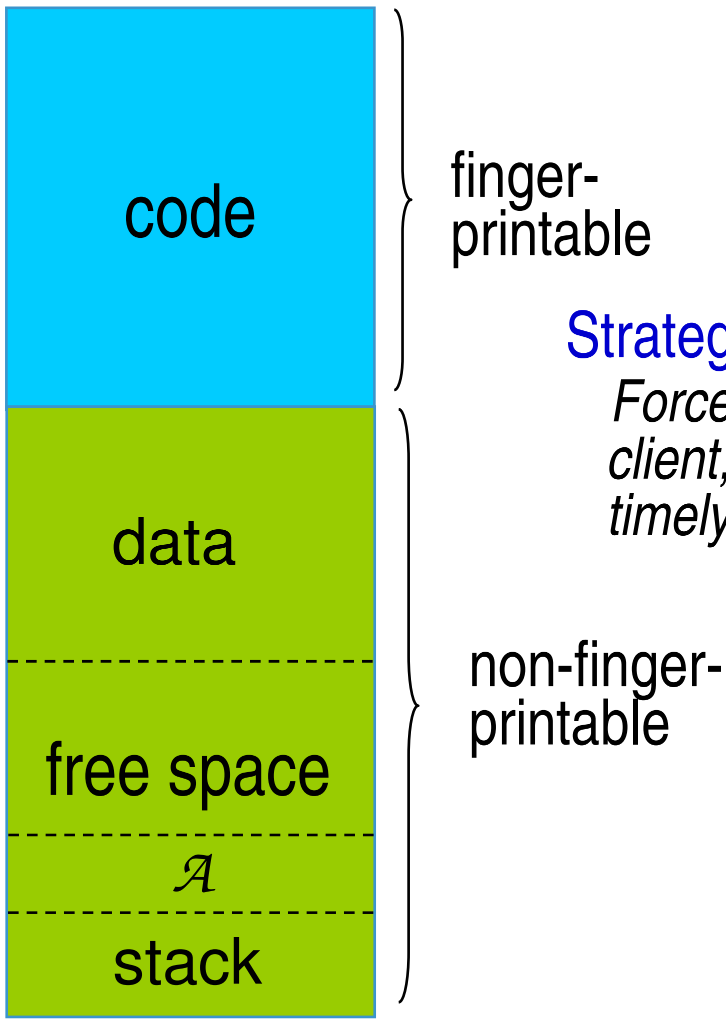
TEAS for Online Adversaries

- The “*interpreter*” attack: Dynamic (runtime) interpretation of an agent

```
/* agent fragment:

   LOAD (0xfc00), r0;
   STORE r0, (0x1200);
   JMP 0x0100;
 */

instr = GET_INSTR(pc);
op1 = GET_OP1(pc);
op2 = GET_OP2(pc);

switch (instr) {
LOAD:    if (protected(op1))
                 op2 = *(translate(op1));
         else
                 op2 = *op1;
         break;
STORE:   if (protected(op1))
                 *(translate(op1)) = op2;
         else
                 *op1 = op2;
         break;
JMP:     if (protected(op1))
                 pc = translate(op1);
         else
                 pc = op1;
         break;

...

}
```

Loads and stores from/to protected areas are avoided, with very small overhead

TEAS for Online Adversaries (cont'd)



Strategy: Perform "adversary fragmentation"

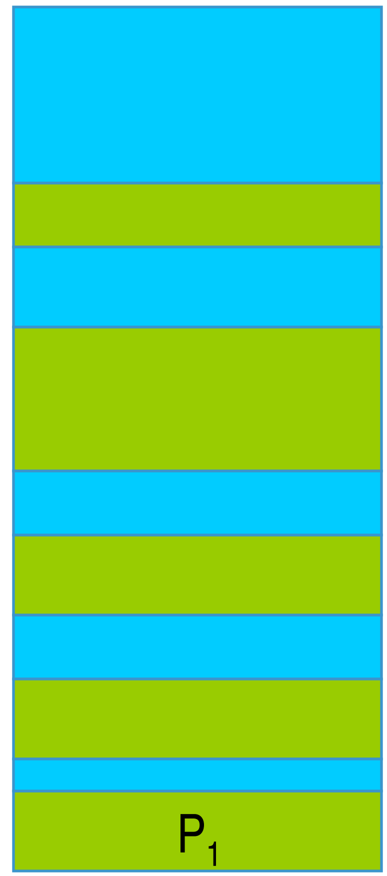
Force the adversary to relinquish control of the client, or not be able to respond to queries in a timely manner

“Adversary Fragmentation”

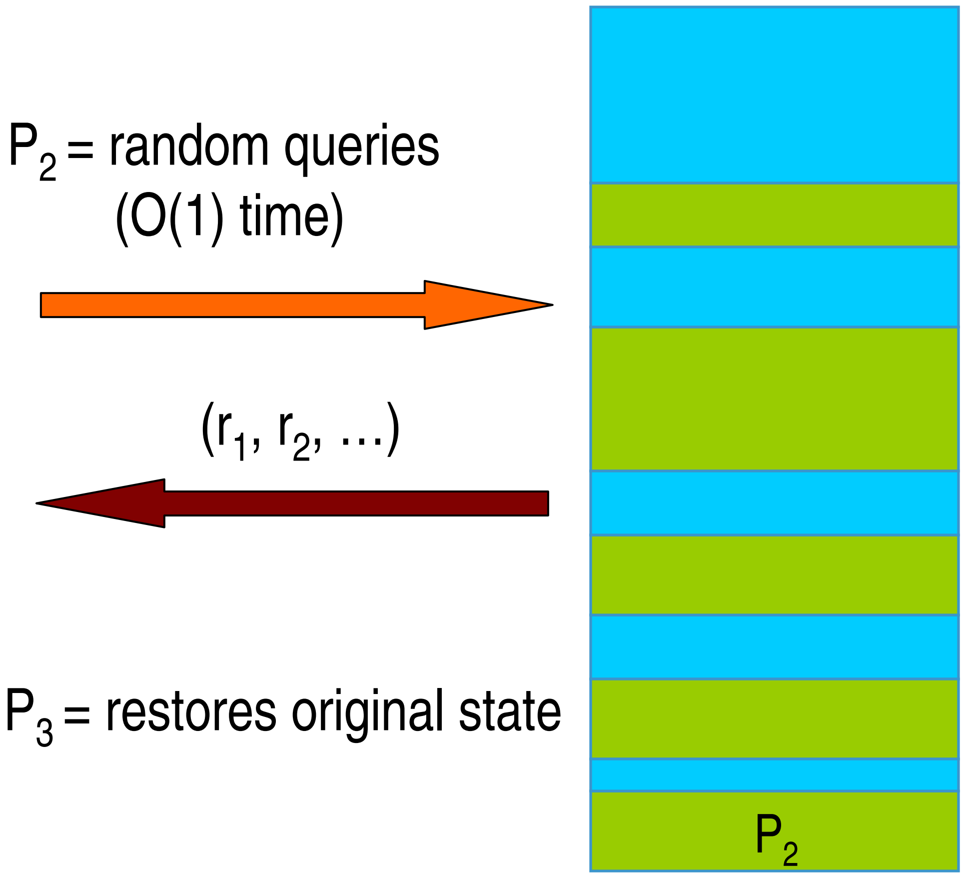
$(1/|M|, \mathcal{A}_{on})$–TEAS = (P_1, P_2, P_3)

P_1 = random permutation of memory

```
a2 = seed;
for(i = 0; i < N; i++) {
      a1 = random(a2);
      a2 = random(a1);
      t = M[a1];
      M[a1] = M[a2];
      M[a2] = t;
}
```



Adversary Fragmentation (cont'd)



If $\mathcal{A}$ executes P_2, then Responder under control of P_2

Otherwise, $\mathcal{A}$ computes perm. for each query
$\Rightarrow$ time bound violation

or tries to keep track of addresses
$\Rightarrow$ out of memory!

TEAS Applications

Monitor integrity of

- Mobile devices such as cell phones
  - Has phone been hacked?
- Set-top boxes and cable modems
  - E.g., detect reconfiguration to bypass service license
- Wireless basestation components
  - Detect black/grey market cards or reconfigurations
- Remote sensors perhaps deployed in hostile environments
  - Ascertain veracity of data

Related Work

Other software-only schemes for integrity verification:

- *Genuinity* [Kemell-Jamieson, Usenix'03]: Checksum of (virtual) memory addresses and machine-specific register values; host also computes the checksum and times the response.
- [Shankar-Chew-Tygar, Usenix Security'04]: Genuinity is vulnerable to fast simulation ("interpreter") attack, below 35%.
- *SWATT* [Seshadri-Perrig-van Doorn-Khosla, ISCC'04]: Also checksum of probabilistic memory traversal. Focuses on embedded microcontrollers, with fixed processor speeds and small memory sizes; requires knowledge of entire state being checked, and tight coupling between host and client.

Summary

- Malware is pernicious
  - Degrades and destroys system integrity
- A new method to help stop it: TEAS
  - Software-only
    - Amenable to legacy systems that might now be vulnerable
  - Challenge/response framework
    - Challenges are *arbitrary* programs sent as agents
    - Hard problems from complexity of program analysis
    - Challenges are timed
- New technique called *program blinding*
  - Aids in creating large libraries of agents
- Many application areas identified

References

- J. Garay and L. Huelsbergen, "Software Integrity Protection Using Timed Executable Agents," *ASIACCS 2006*.

  Available from

  `http://www.bell-labs.com/user/garay`

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Questions and Answers

Undecidability-based Protection

- Use undecidability of non-trivial program properties (Rice's theorem)
- **Example:** Compute the number of instructions a TEAS agent executes – non-computable *a priori*
- **Challenge:** Automatic methods for generating agents with given undecidability properties