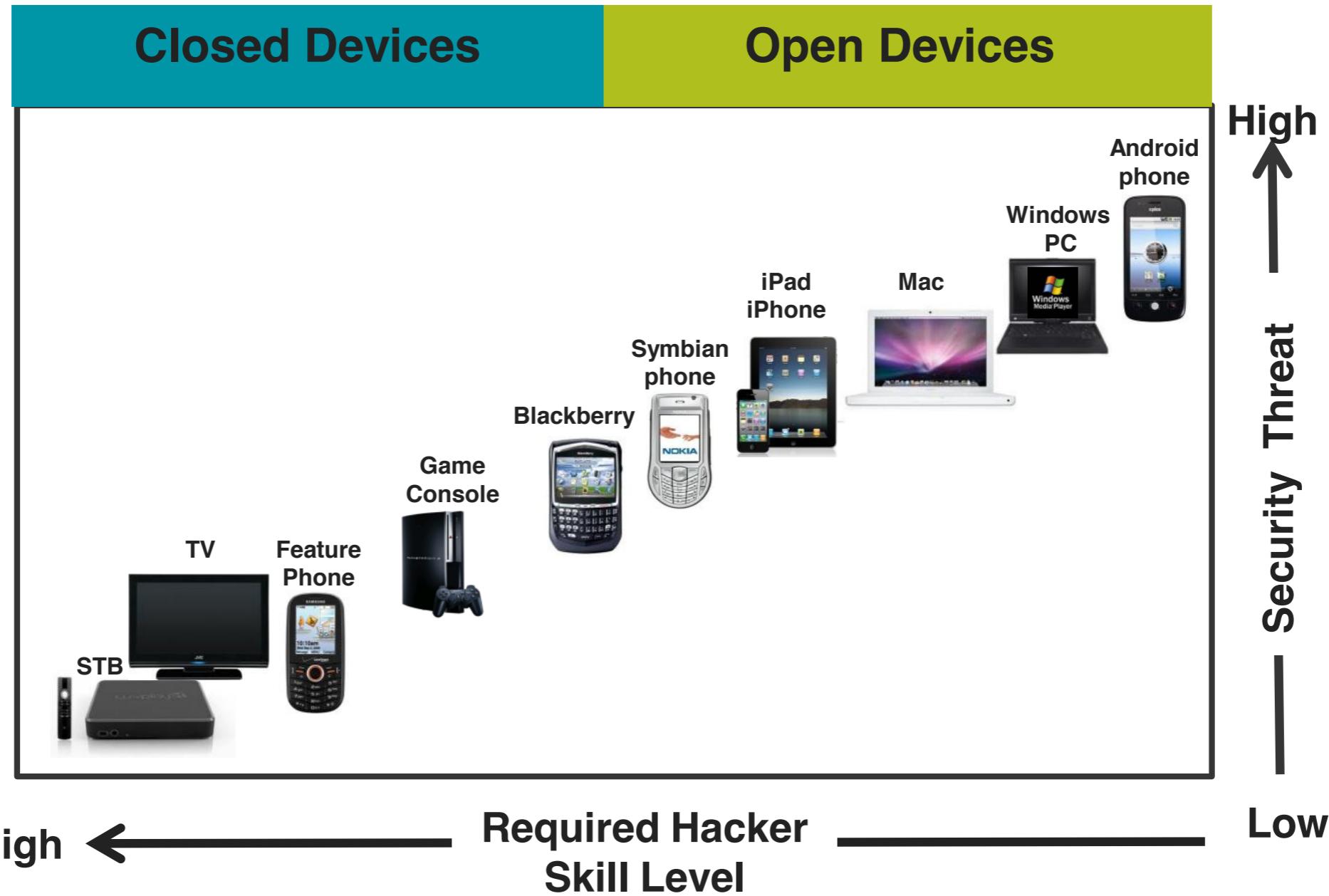


Software Protection

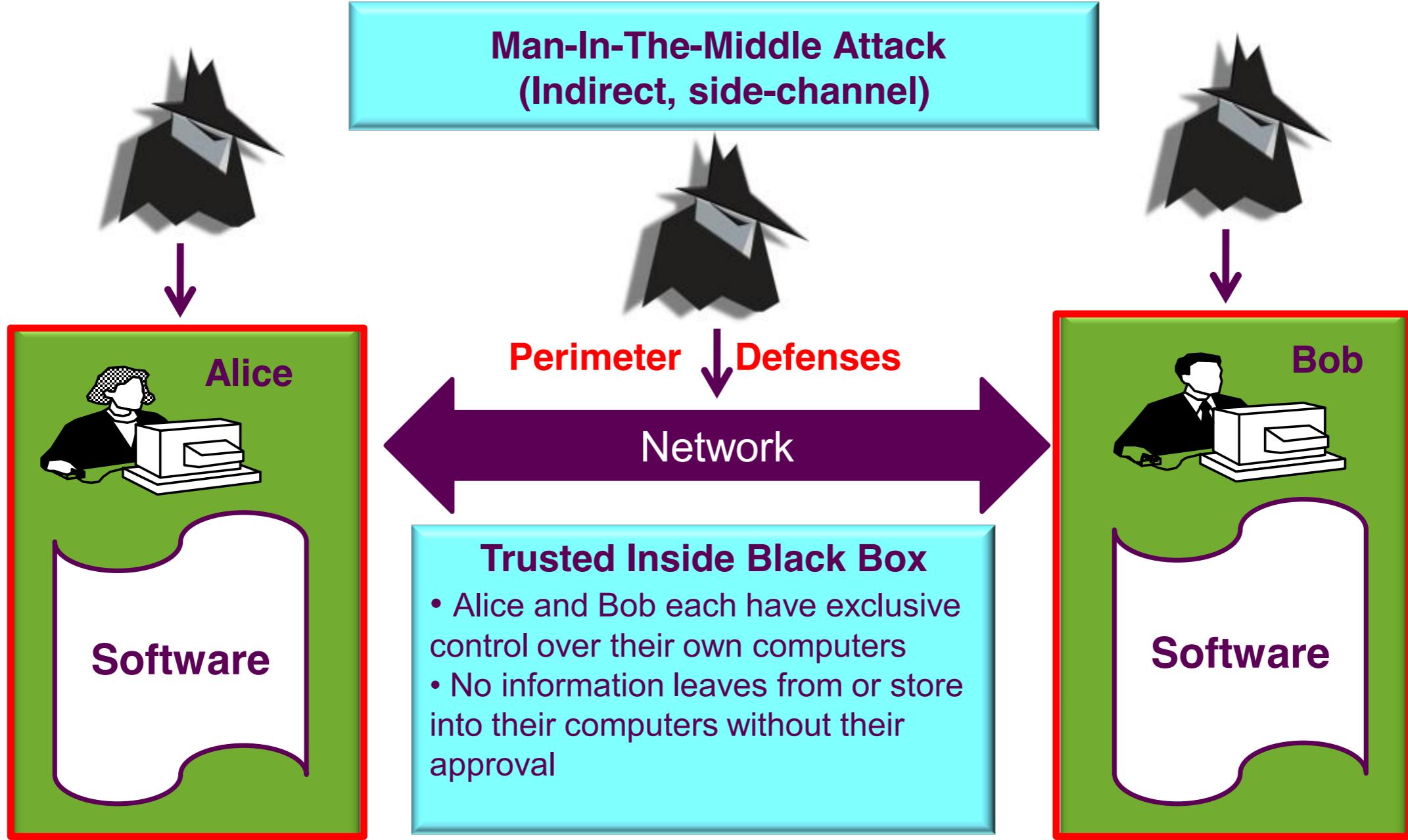
Open platforms pose opportunities & risks



- * Ongoing trend towards openness
- * Open devices/platforms attracts more developers and consumers
- * Unfortunately they decrease the required hacker skill level

Cryptographic Assumption and Traditional Attacks

Black Box Attacks or Grey Box Attacks



White-box Attacks

Attackers have open-end powers to do

- Trace every program instruction
- View the contents of memory and cache
- Stop execution at any point and run an off-line process
- Alter code or memory at will
- Do all of this for as long as they want, whenever they want, in collusion with as many other attackers as they can find

Man-At-The-End Attack

Bob is the Attacker



Alice



Software

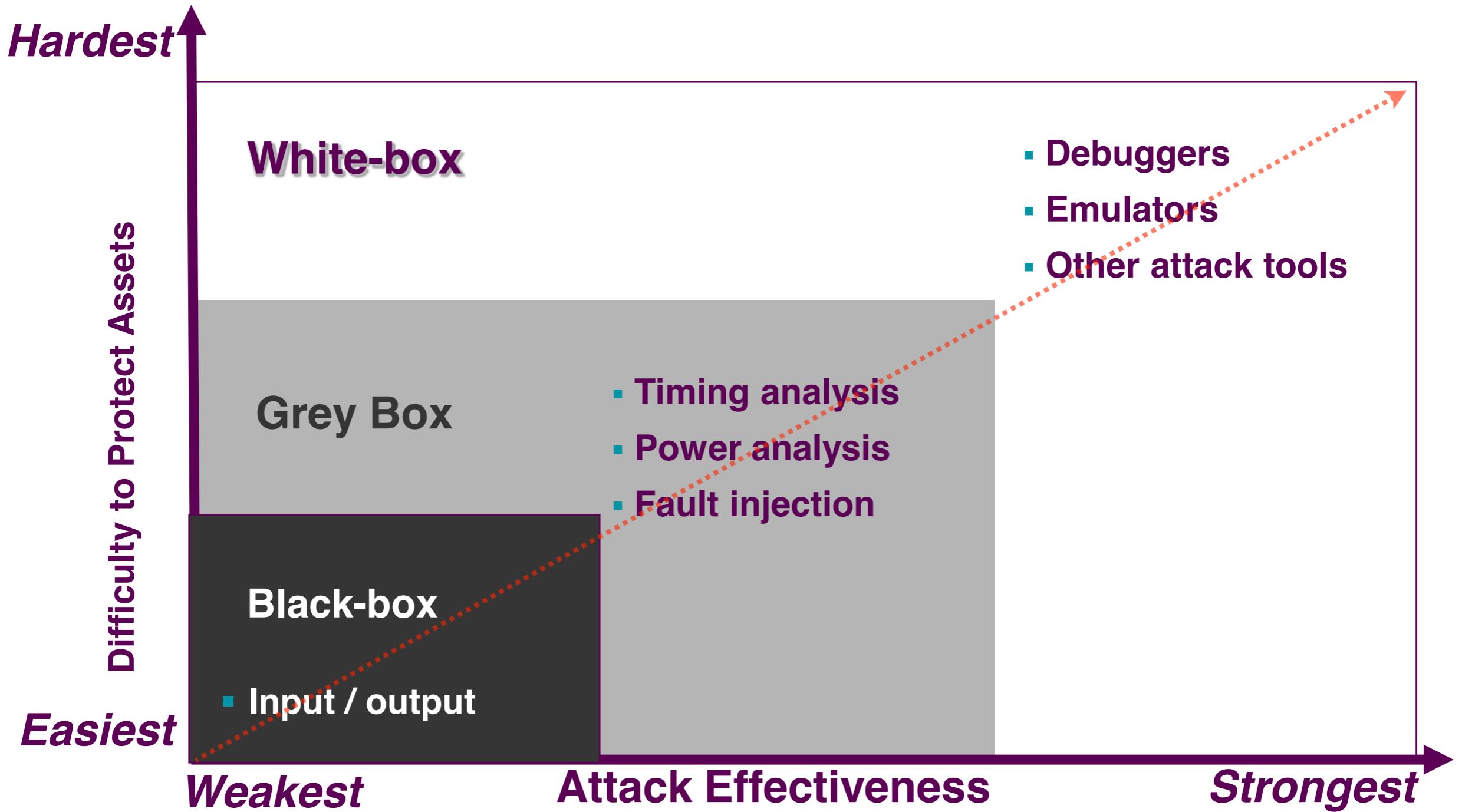
Attacking has much less limitation than protection

Network

- Device and environment are untrusted
- Attacker has direct access to the machine and software no matter whether it's running or not

Software

Attacks



New challenges for information security

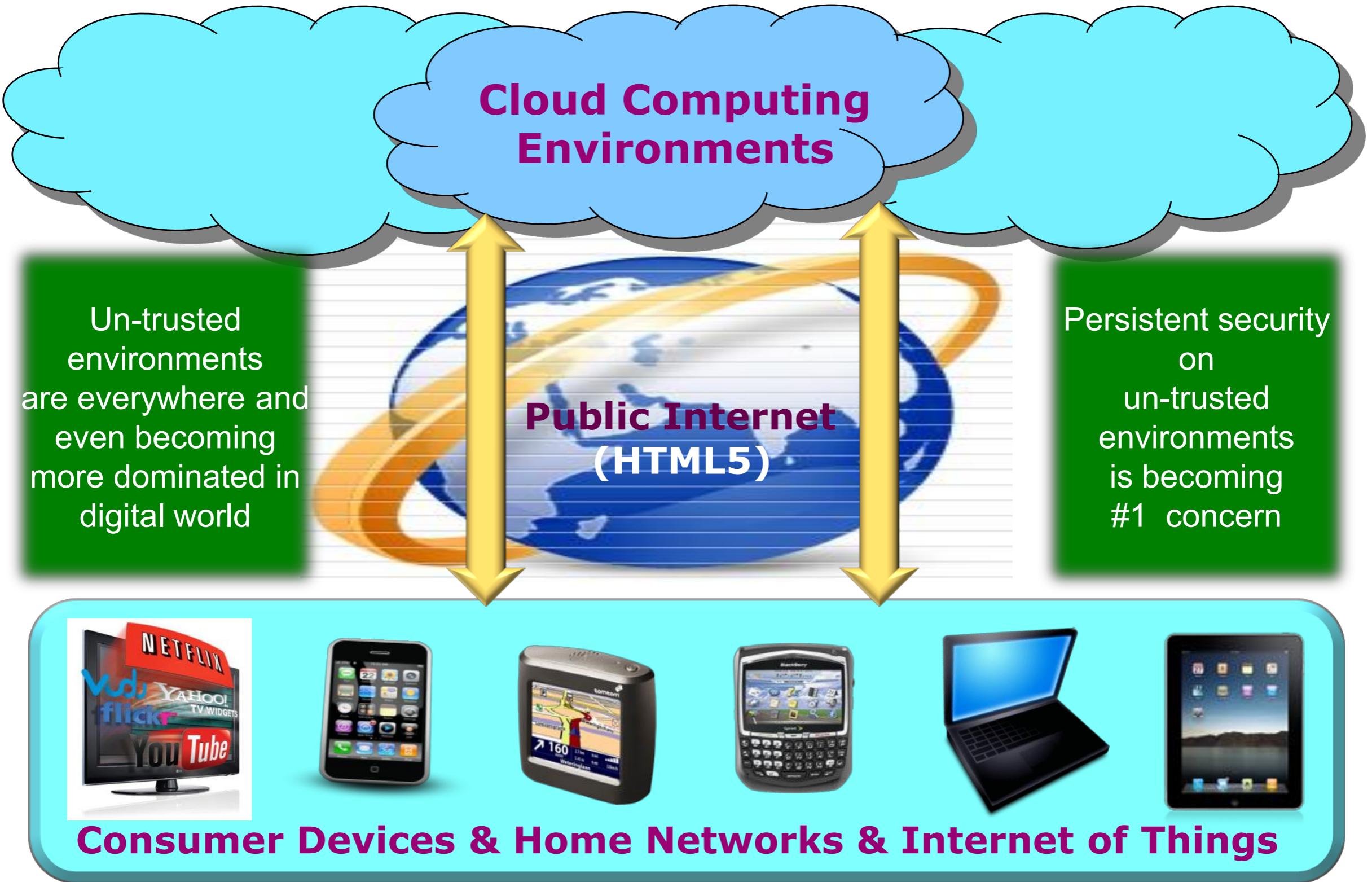
**Traditional security is more about
security of trusted environments**

**White-Box
Security**

**Dynamic
Security**

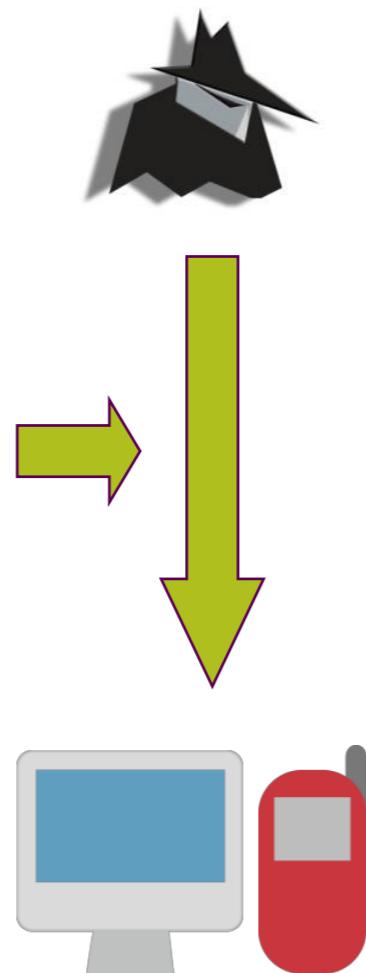
**Digital Asset Protection is More About
Security of Un-Trusted Environments**

Untrusted environments reality

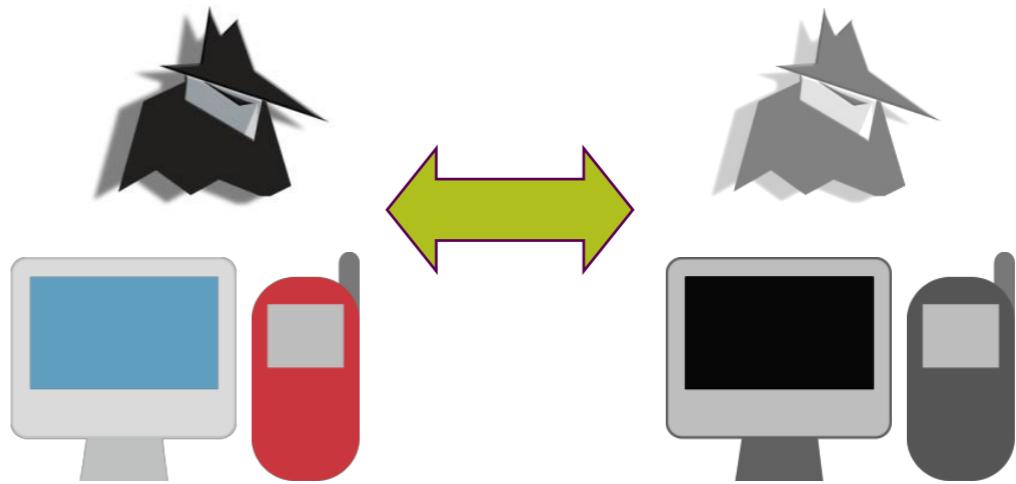


What are the threats?

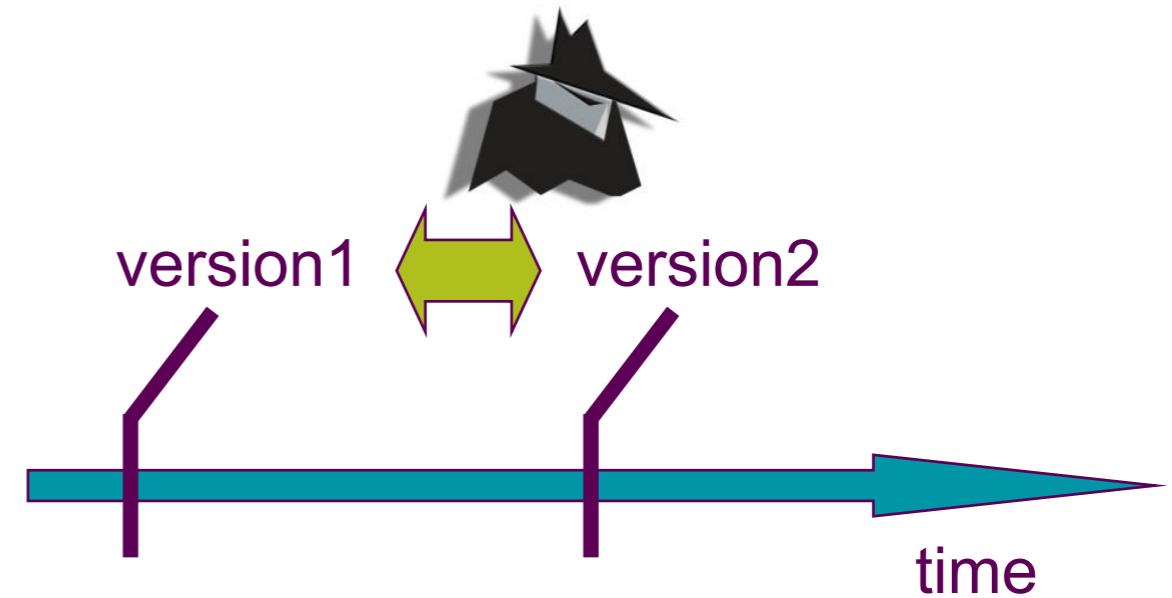
Direct WhiteBox Attack



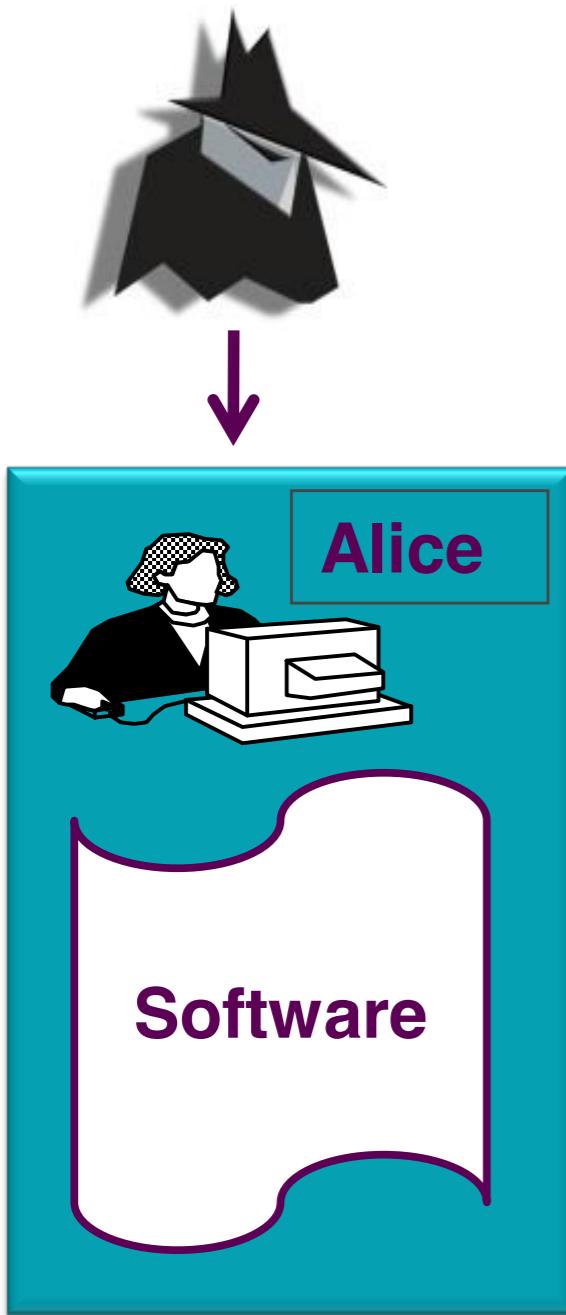
Colluding Attack



Differential Attack



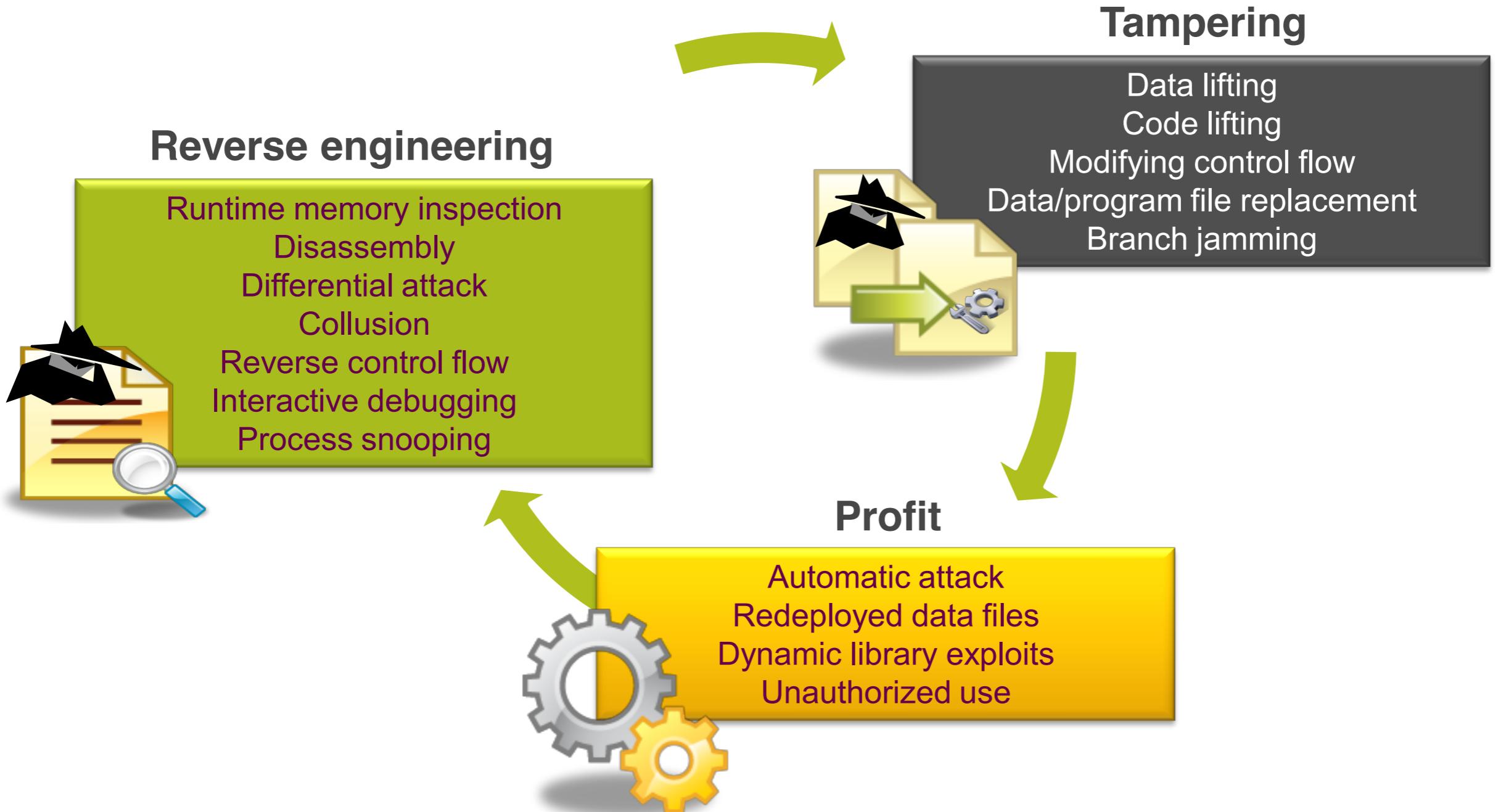
Software Protection Challenges



**How to provide
necessary
trustworthy to
application
software in the
Un-Trusted
Environment**



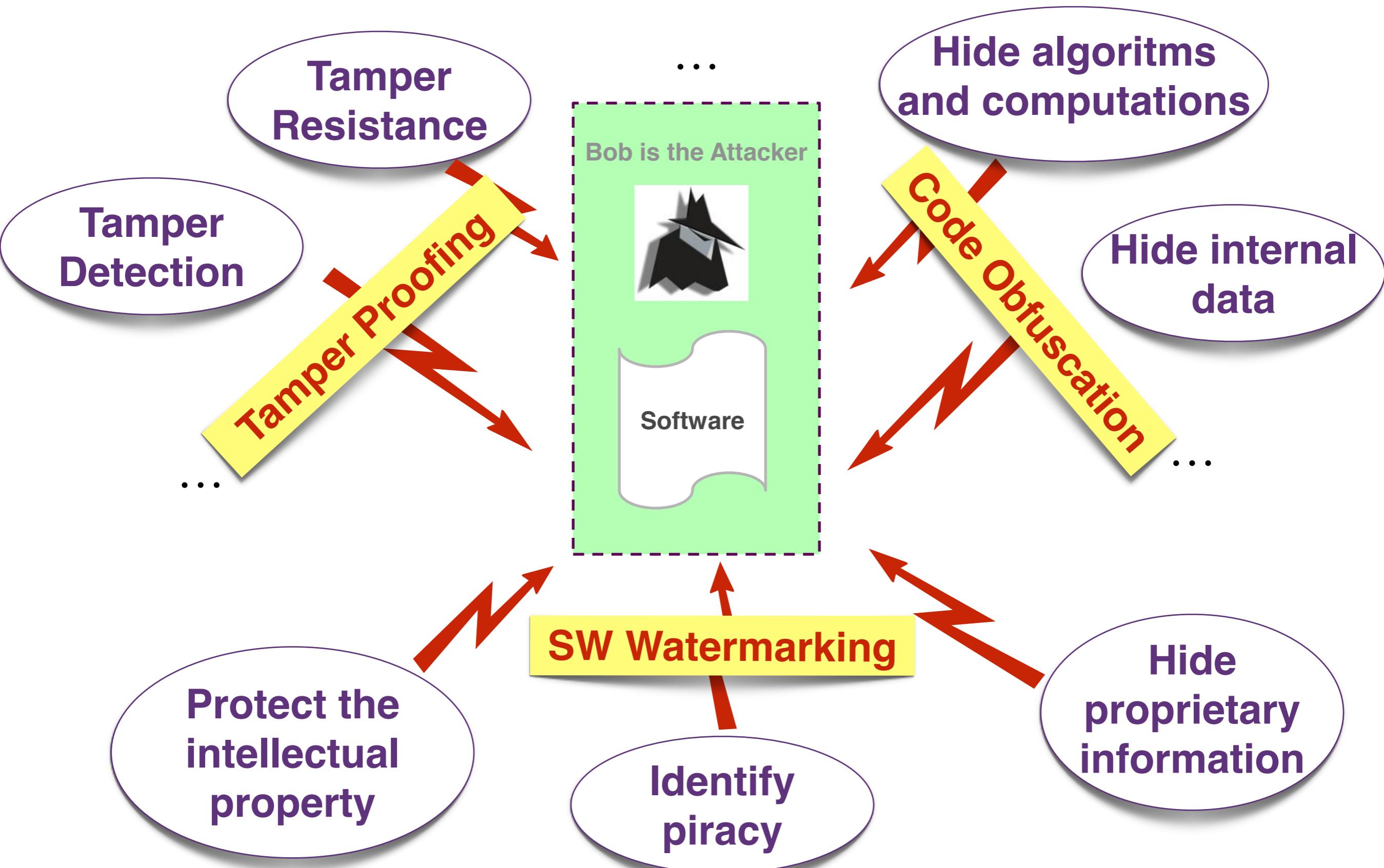
Attacks on Software



Key Objectives of Software Protection

- * Resist static and dynamic **reverse-engineering**
- * Resist **tampering** (i.e. unauthorized modifications)
- * Resist **cloning** (i.e. moving software to a node it is not authorized to run on)
- * Resist **spoofing** (i.e. having software use false identification, such as over a network)
- * Hide both static and dynamic **secrets**, as they are created, moved and used
- * Impede the production and distribution of useful “crack” programs
- * Facilitate timely, intelligent **responses** to crack incidents

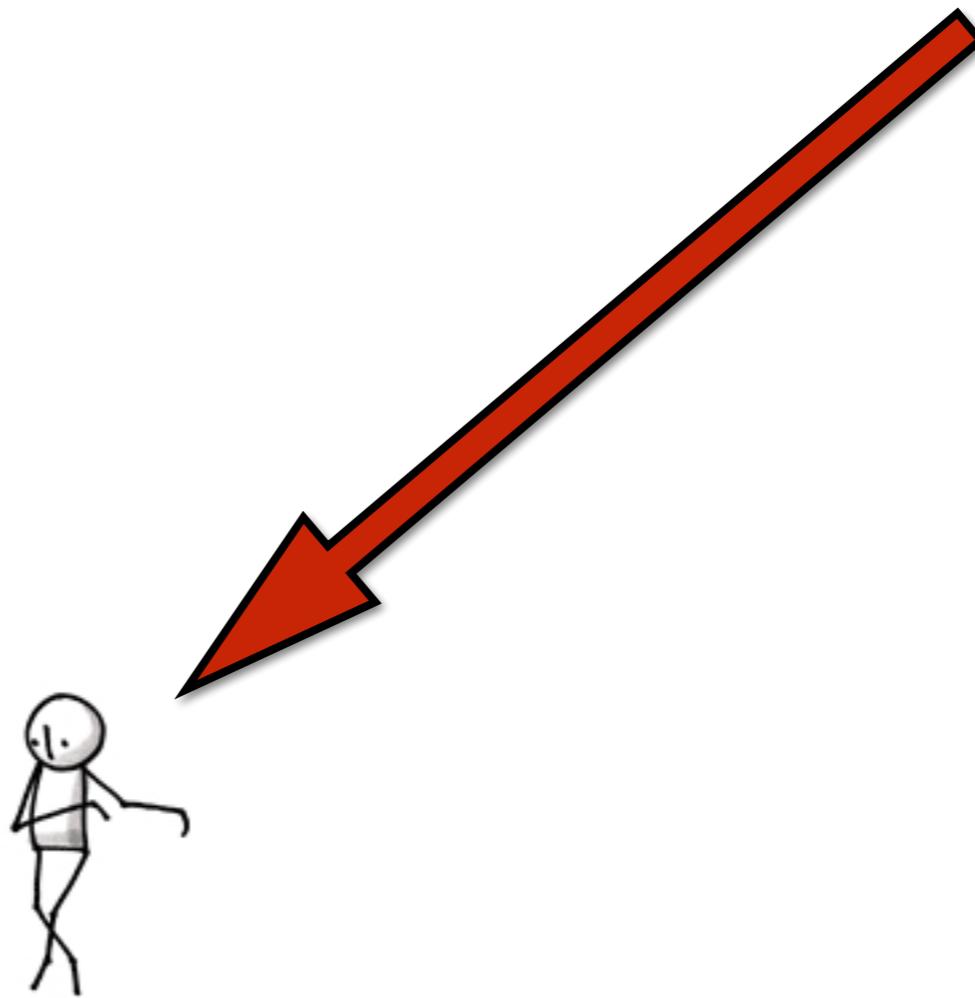
Software Protection



1

Code Obfuscation

Real Code



1

Code Obfuscation



Real Code

Obfuscated
Code

2

Tamper Detection



Original
Code



Tampered
Code



**Detect when tampering
occurs and respond to attack
(checksum)**

3

SW Watermarking



Proprietary
Code



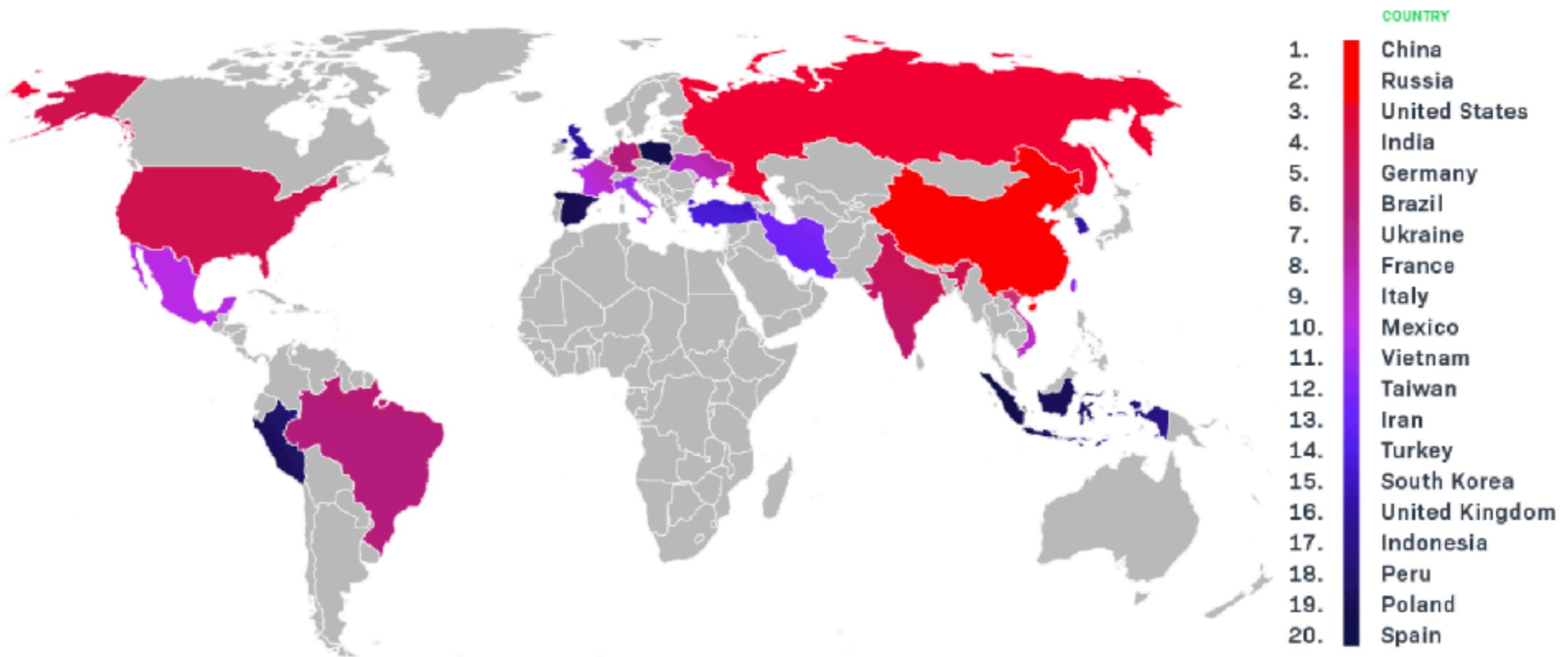
Pirated Copy

Watermarking: Identify illegal copies

**Fingerprint: Identify also the intellectual
property violator**

February 2022

Top 20 Software License Misuse and Piracy Hotspots



Based on aggregate Revenera Compliance Intelligence data as of February 2022.

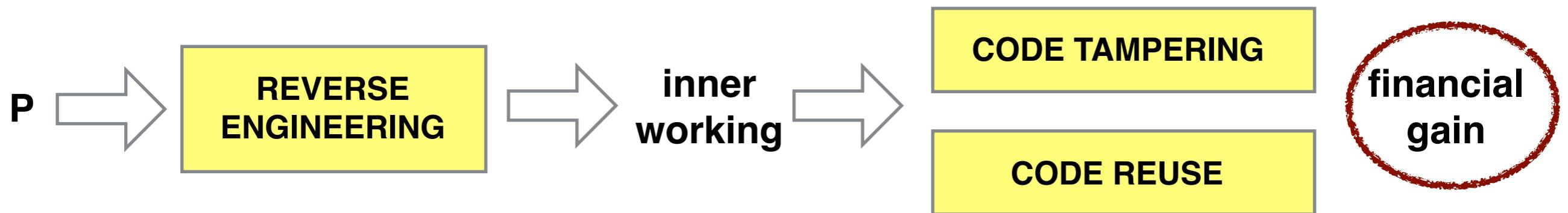
Recent Global Software Survey revealed that 37 percent of software worldwide is unlicensed and the BSA estimated that the commercial value of unlicensed software worldwide was \$46.3 billion.

<https://www.revenera.com/blog/software-monetization/software-piracy-stat-watch/>

SW Protection

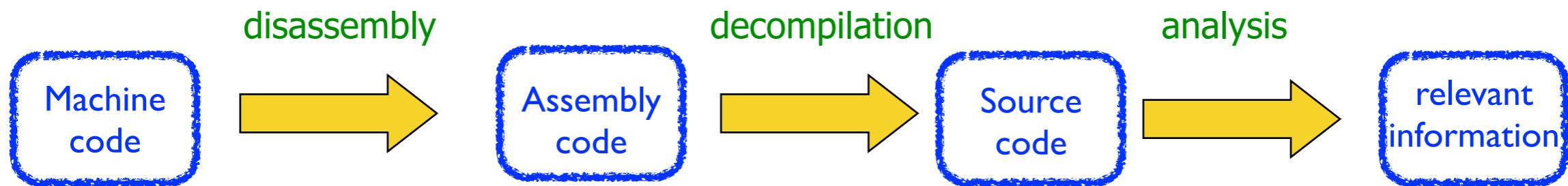
In SW much of the know-how is located in the product itself!

Attacks to (proprietary) programs:



It is estimated that unlicensed software is 37% of all software installed on personal computers. Frontier Economics estimated that the global value of **pirated software in 2022 will be 42\$ - 95\$ billion.**

Reverse Engineering

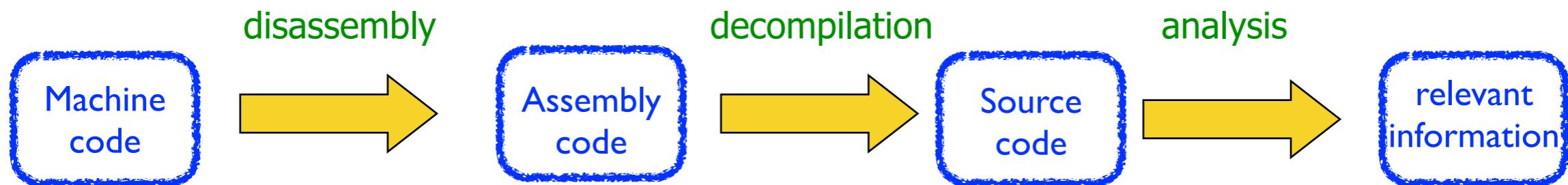


Reverse engineering typically performs **static and dynamic analyses** in order to understand the inner workings of a proprietary program of interest

Given enough time, effort and determination a competent programmer can always reverse engineer any application!!!

Reverse Engineering

Protection Needed at all Levels!!!!

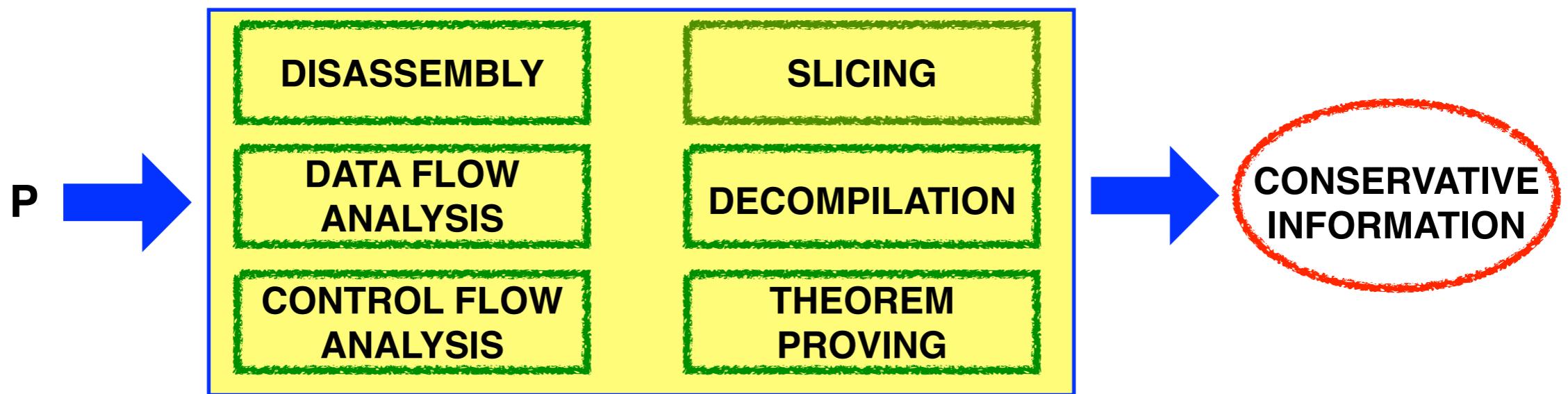


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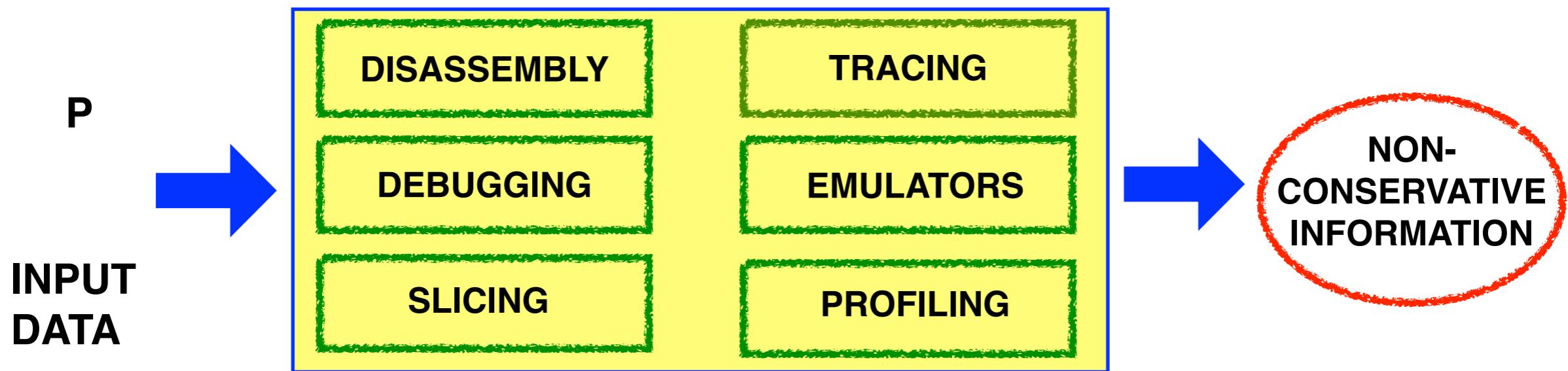
Static Analysis

Static analysis takes as input the program and analyses it without executing it



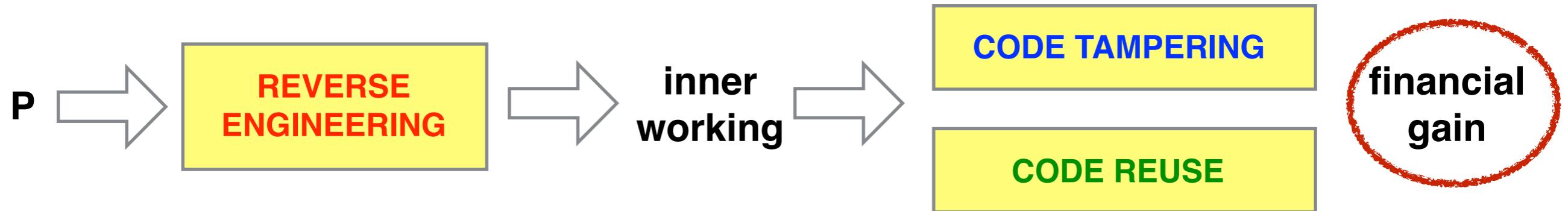
Dynamic Analysis

Dynamic analysis takes as input the program and a sample of input data set and analyses the program by executing it on the considered set of inputs



The accuracy of the generated information depends on the completeness of the input data (coverage problem)

Protection Techniques



* Legal Measures:

- ✓ copyright protects the form but not the idea
- ✓ patents protect also the idea
- ✓ licenses establish client rights and limitations
- ✓ laws are different from state to state
- ✓ costly and time consuming

* **Code Obfuscation**: obstructs reverse engineering

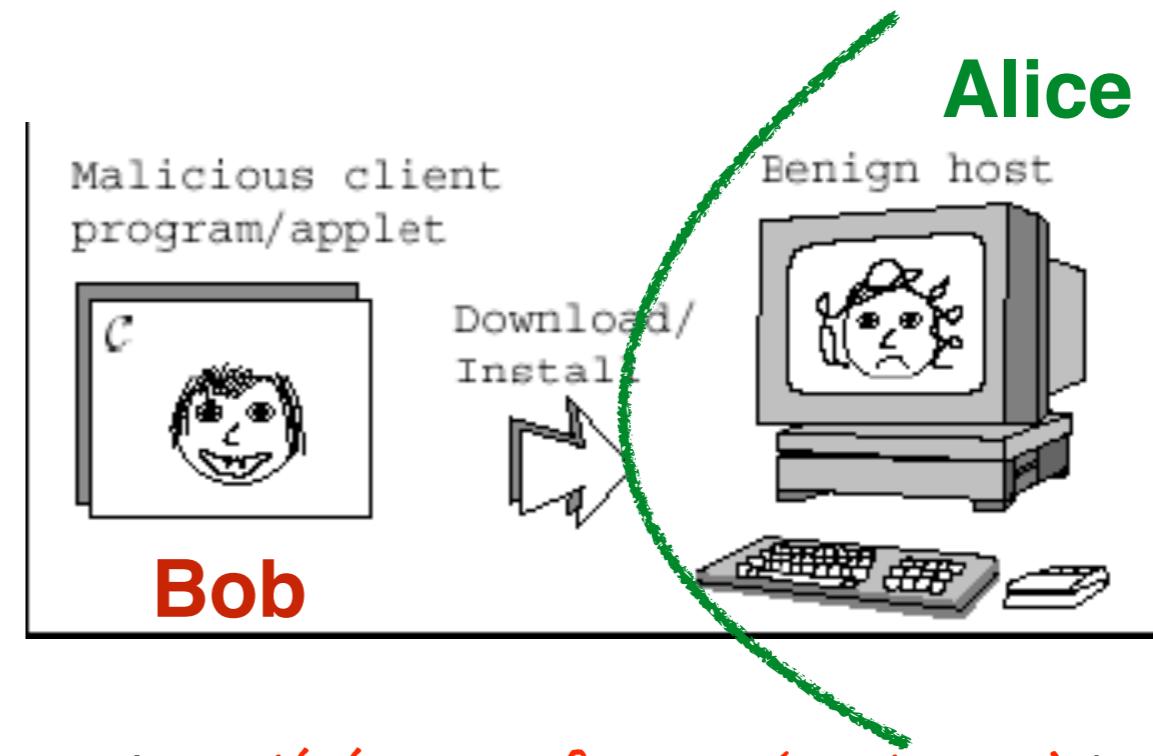
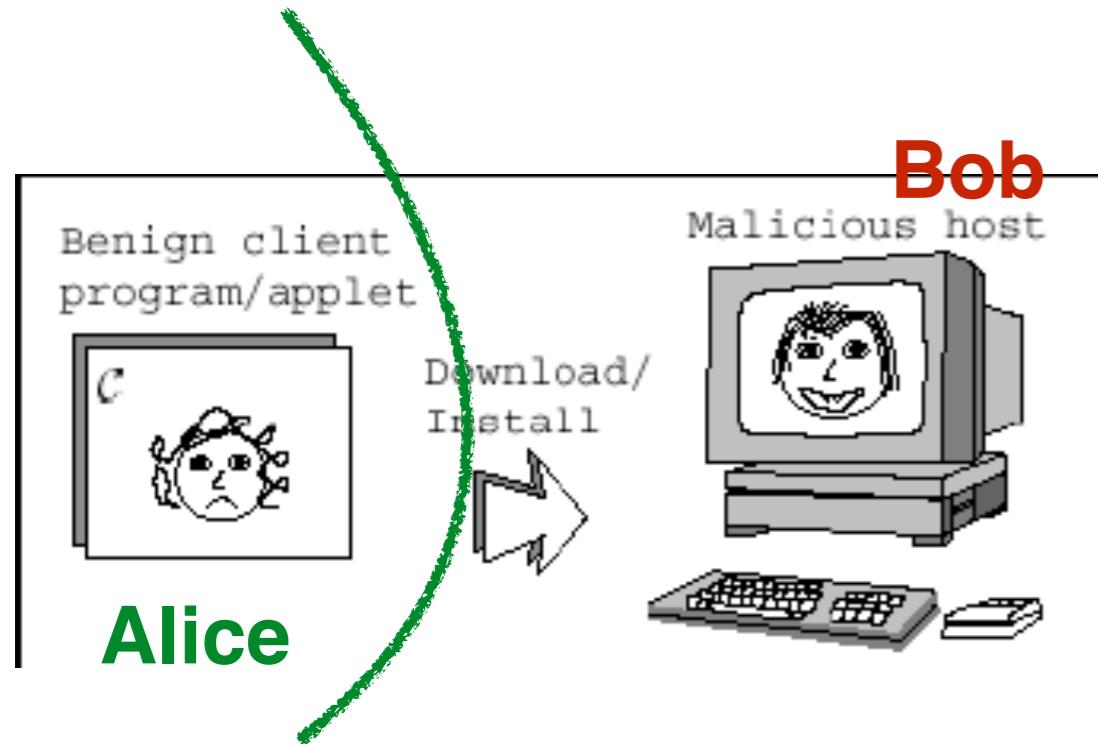
* **SW Watermarking**: insert a mark against theft

* **TamperProofing**: detect integrity violation or illegal modifications

Who is interested in SW protection?

- **Companies**: Microsoft, Apple, Intel, Arxan, Cloakware, Irdeto, Skype.....
- **Academia** researchers have approached the software protection problem from a variety of angles (crypto, recursion theory, programming languages and compilers...)
- **Military** around 2008 the US DoD (Department of Defense) initiated a program to investigate technologies such as obfuscation and tamper proofing in order to protect sensitive weapons system software
- **Bad guys** malware writers recur to obfuscation to avoid automatic detection form anti-malware tools

Malicious Host vs Malicious Software



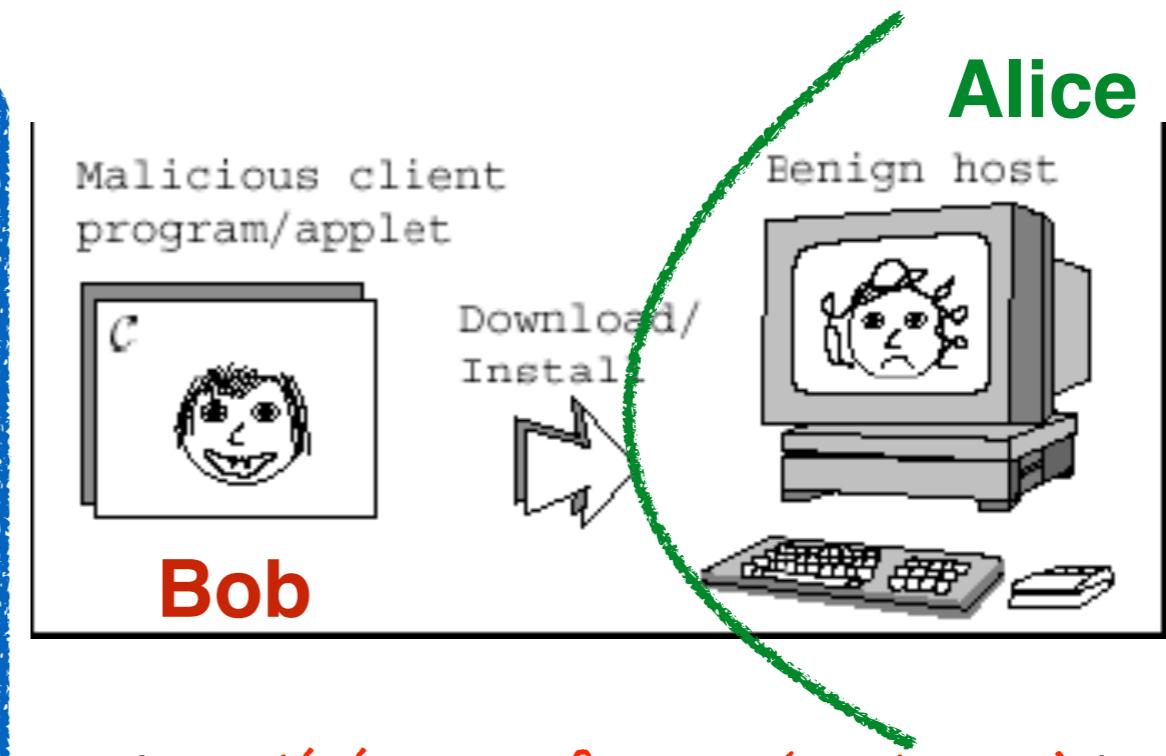
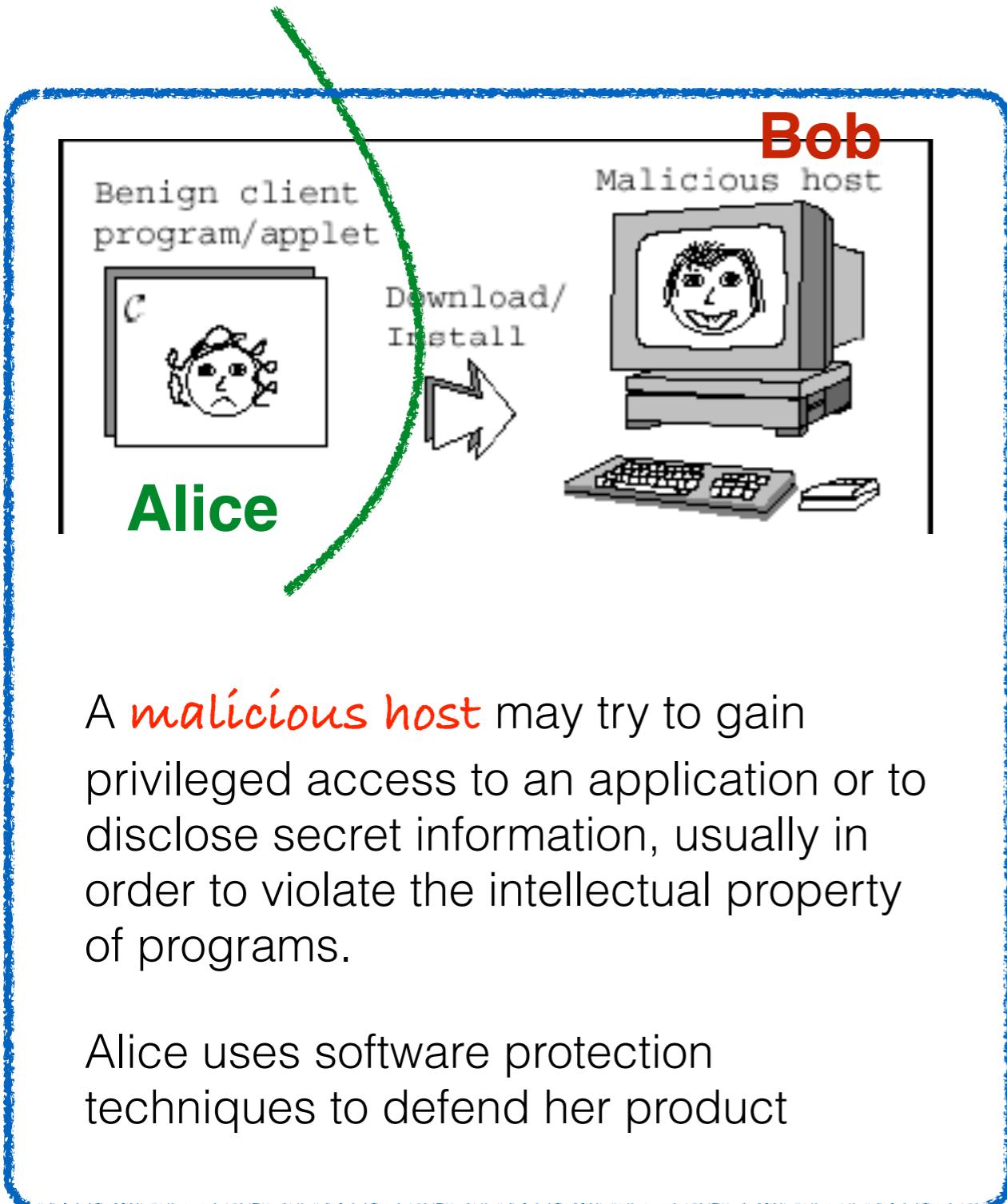
A **malicious host** may try to gain privileged access to an application or to disclose secret information, usually in order to violate the intellectual property of programs.

Alice uses software protection techniques to defend her product

A **malicious software (malware)** is a program with a malicious intent that propagates with no user consent and produces some damage.

Alice adds **protective layers** to prevent someone from entering, to detect that someone has entered, or to stop someone from doing harm once they've entered

Malicious Host vs Malicious Software



Software Protection

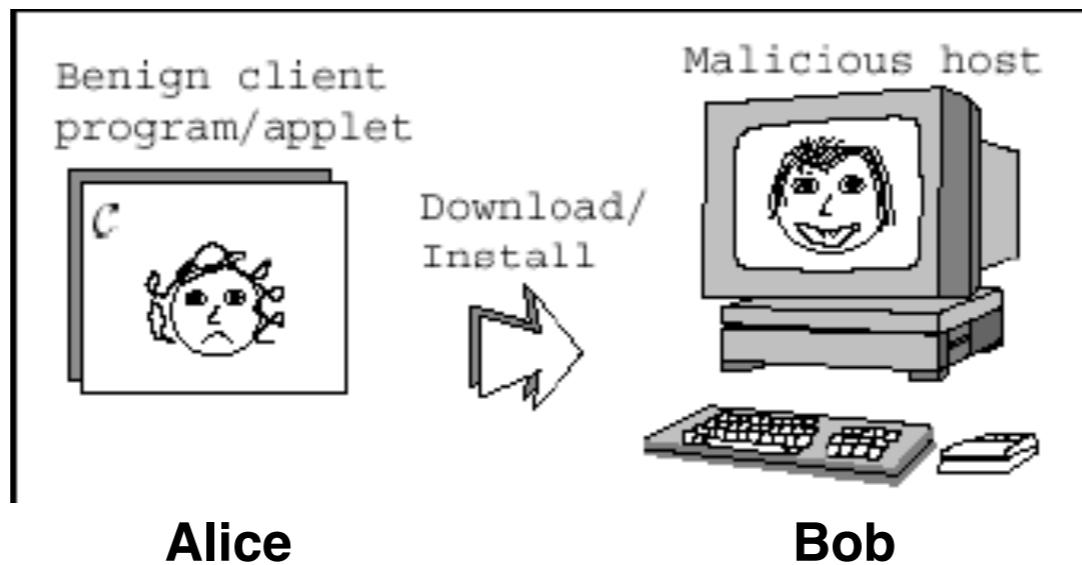
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Alice adds **protective layers** to prevent someone from entering, to detect that someone has entered, or to stop someone from doing harm once they've entered

Software Protection

Consider a benign developer Alice that sells a benign program to Bob to run. Assume that the program contains some secrets S and that Bob can get some economic advantage over Alice by extracting such secret.

Cryptography, namely encrypting the code does not work in this case because Bob needs to execute the program at hence, at some point, it must be in clear text.



There is no limit to what Bob can do on the program of Alice once he has access to it

Software Protection

Software protection has a lot in common with **Steganography**, the branch of cryptography that studies how to transfer a secret stealthily (prisoners' problem).

In a typical defense scenario Alice:

- ✓ adds **tamper-protection** to prevent Bob from modifying it
- ✓ adds **confusion** to her code to make it more difficult for Bob to analyze
- ✓ **marks** the code to assert her intellectual property rights

Obstruct Reverse Engineering

Technical protections: Obstruct the reverse engineering process

- ✓ HW devices
- ✓ Code encryption
- ✓ (Partial) Serves side execution
- ✓ *Obfuscation*

HW Devices



Alice protects her code by relating its execution to the presence of certain **hardware features**, when the dedicated hardware is not present the

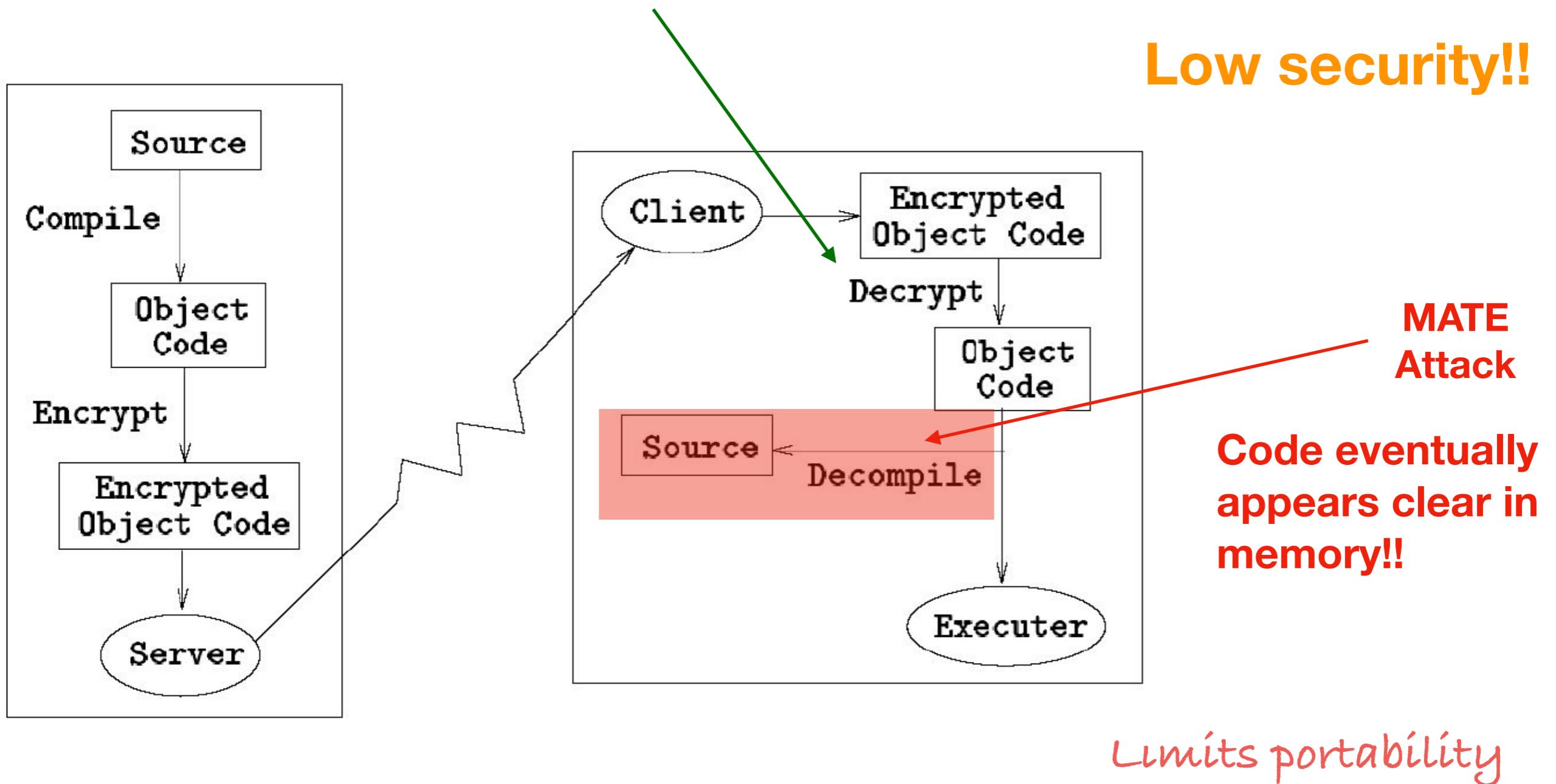
Application refuses to run or runs in a restricted mode

Typical example: **dongle** -- small hardware device that plugs into the serial or USB port on a computer

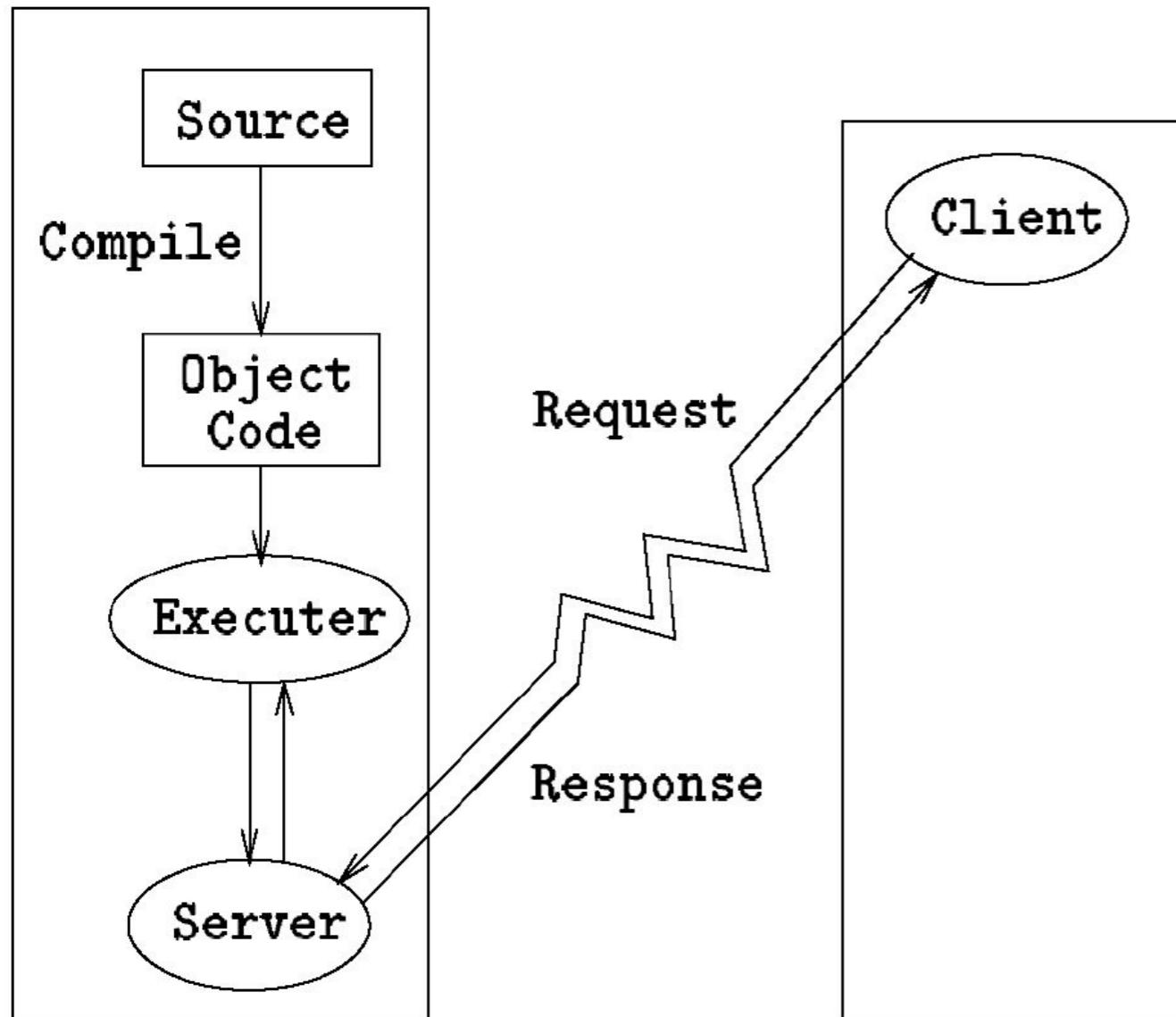
These physical devices are not convenient in a mobile code environment since they **limit portability**

Encryption

Decryption keys hold via dongles or Internet



Remote Execution



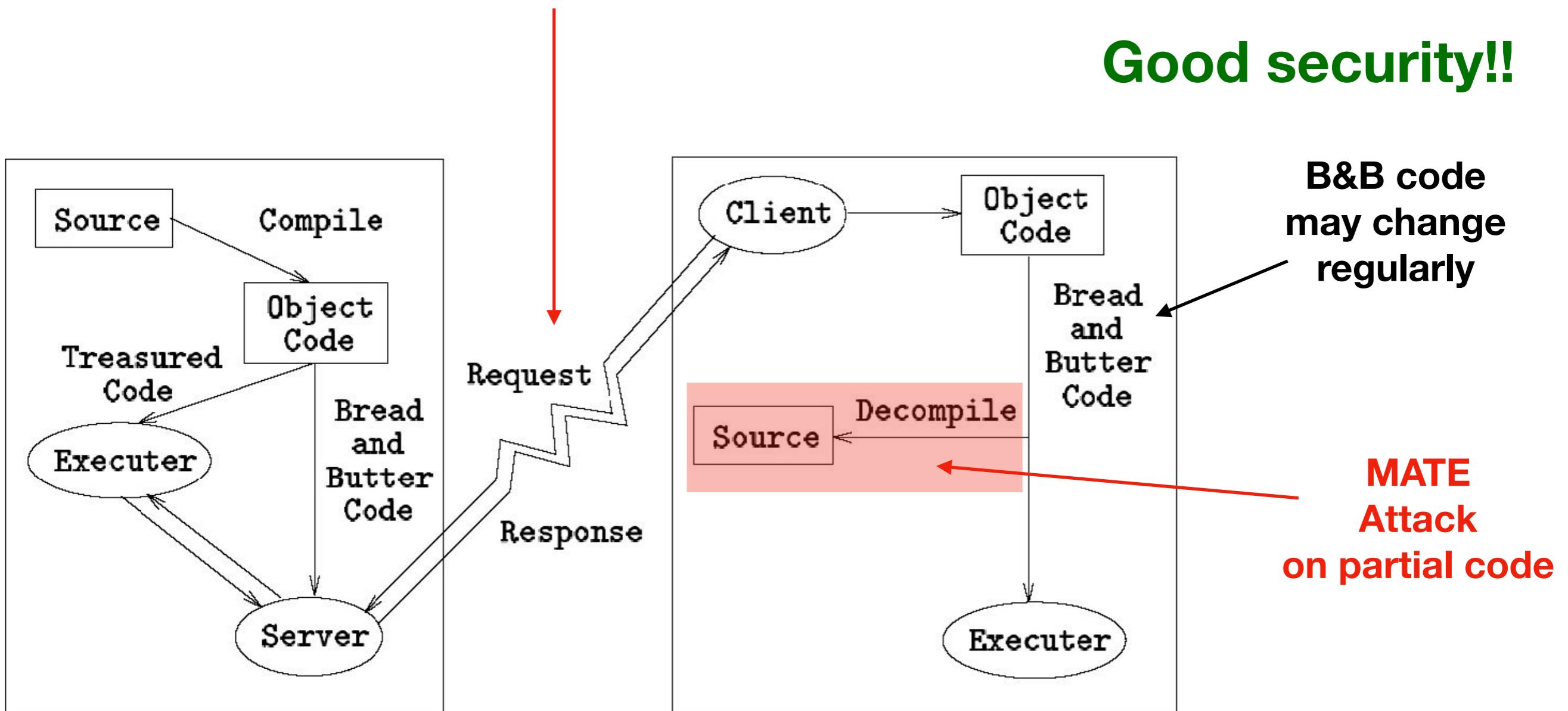
Highly secure!!

- No code disclosure
- All secrets in house
- Requires connection client-server
- High bandwidth

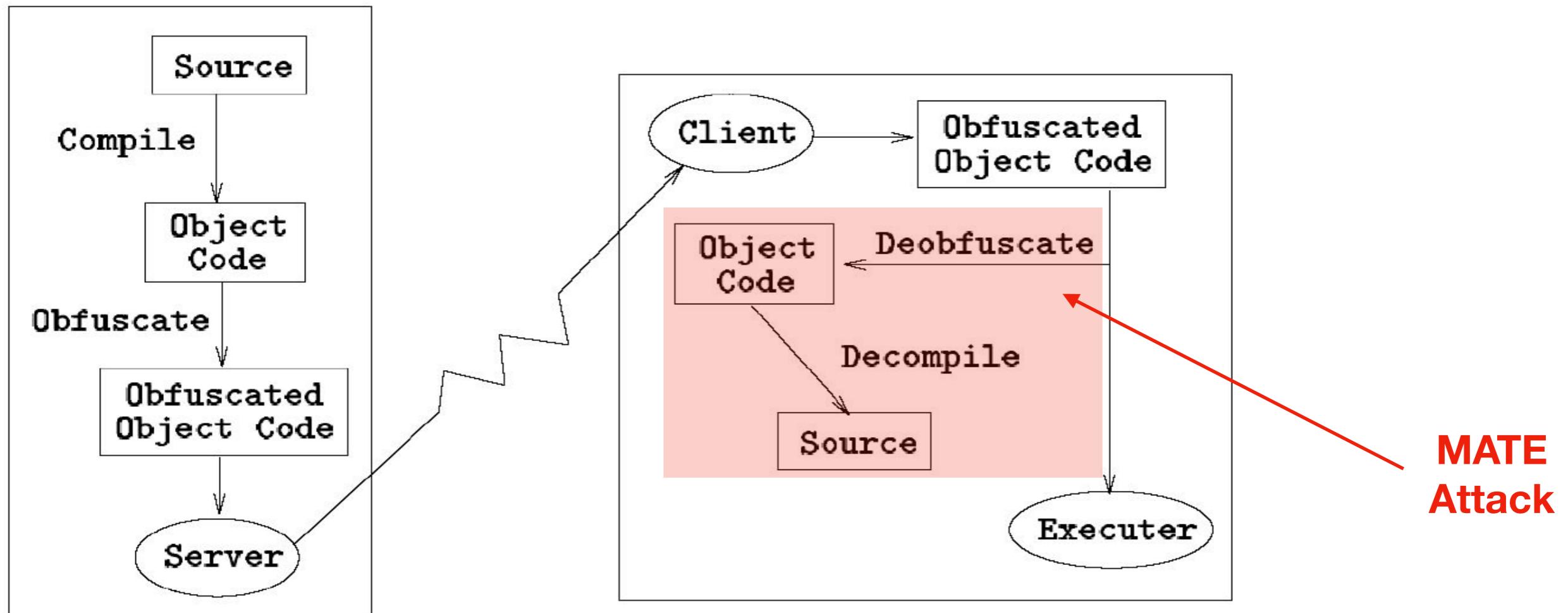
Remote Execution

Partial Remote Execution

Continuous communication



Software Protection: Full Code Deployed



with low diversification

→ High Risk!!

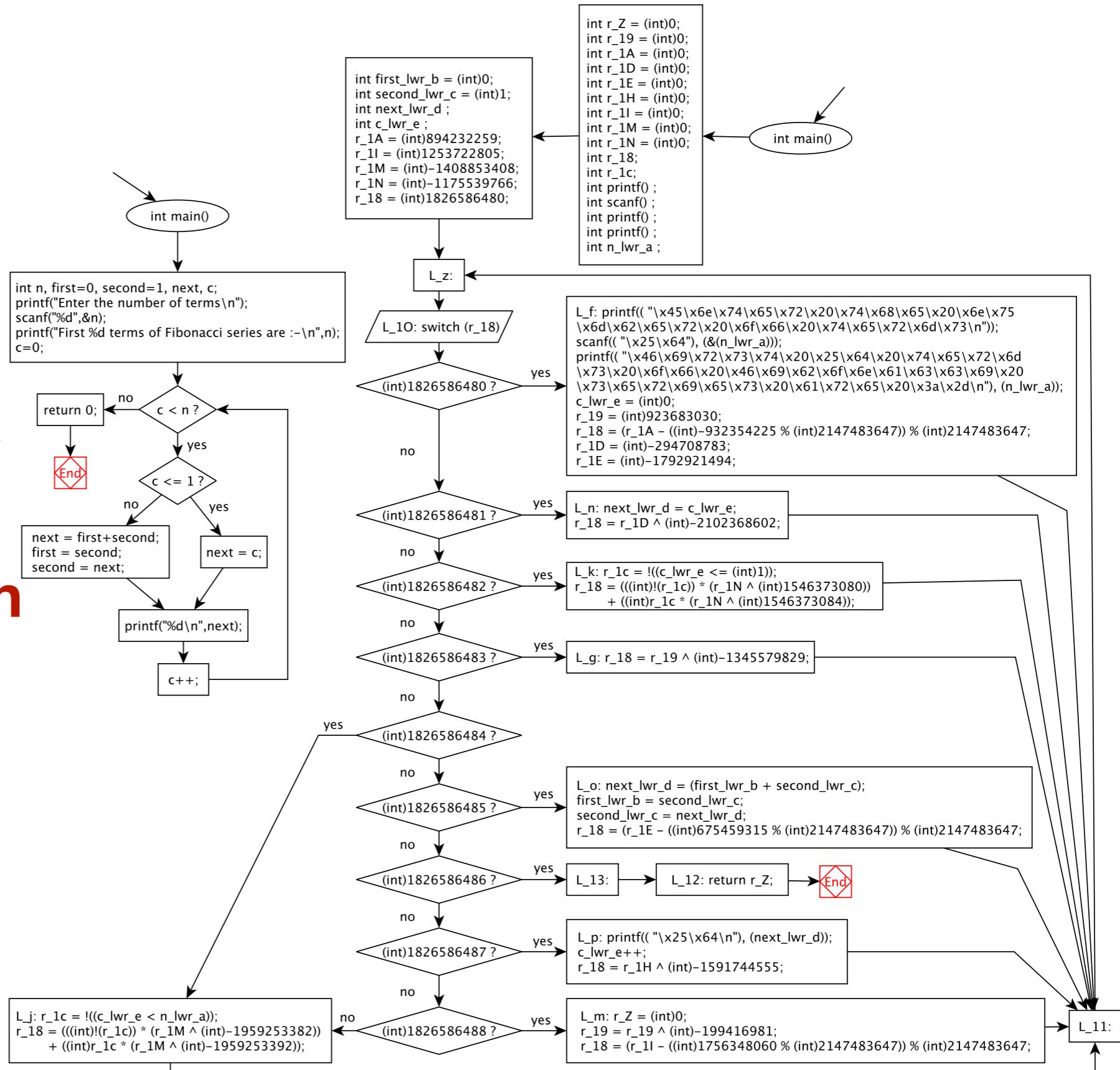
Possible Solutions

- ✓ **Continuous diversification by obfuscation**
- ✓ **Hybrid solutions**
 - ✓ Partial execution
- ✓ **Combination with other protection techniques**
 - ✓ watermarking/fingerprinting
 - ✓ tamper proofing

Code Obfuscation

Methods

- Renaming
- Encryption
- Control flow
- Data flow
- Virtualisation



Code Obfuscation

Method

- Renaming
- Encryption
- Control flow
- Data flow
- Virtualisation



Can defeat
automatic
analysis fixed tool

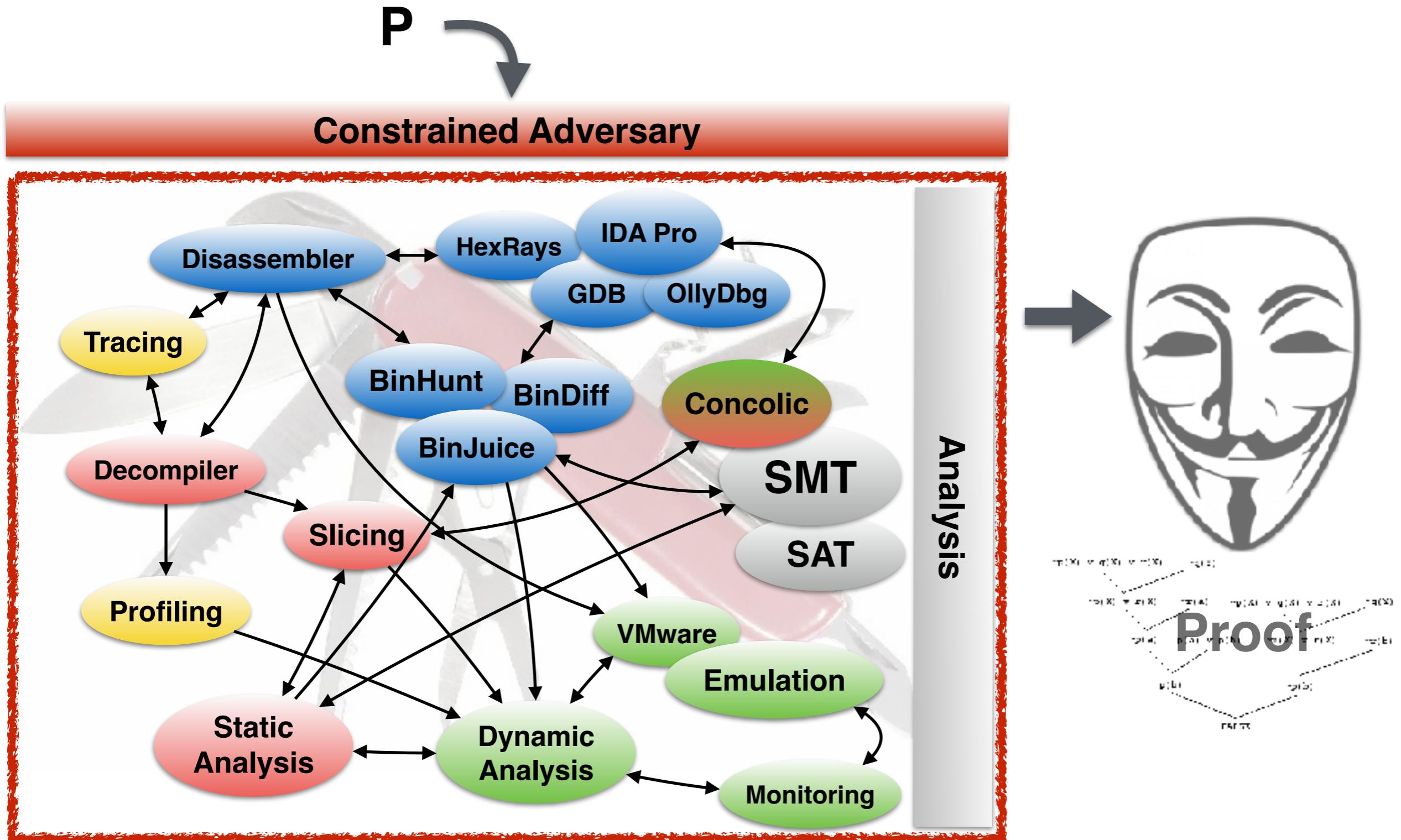


Cannot defeat all
attacks!!!

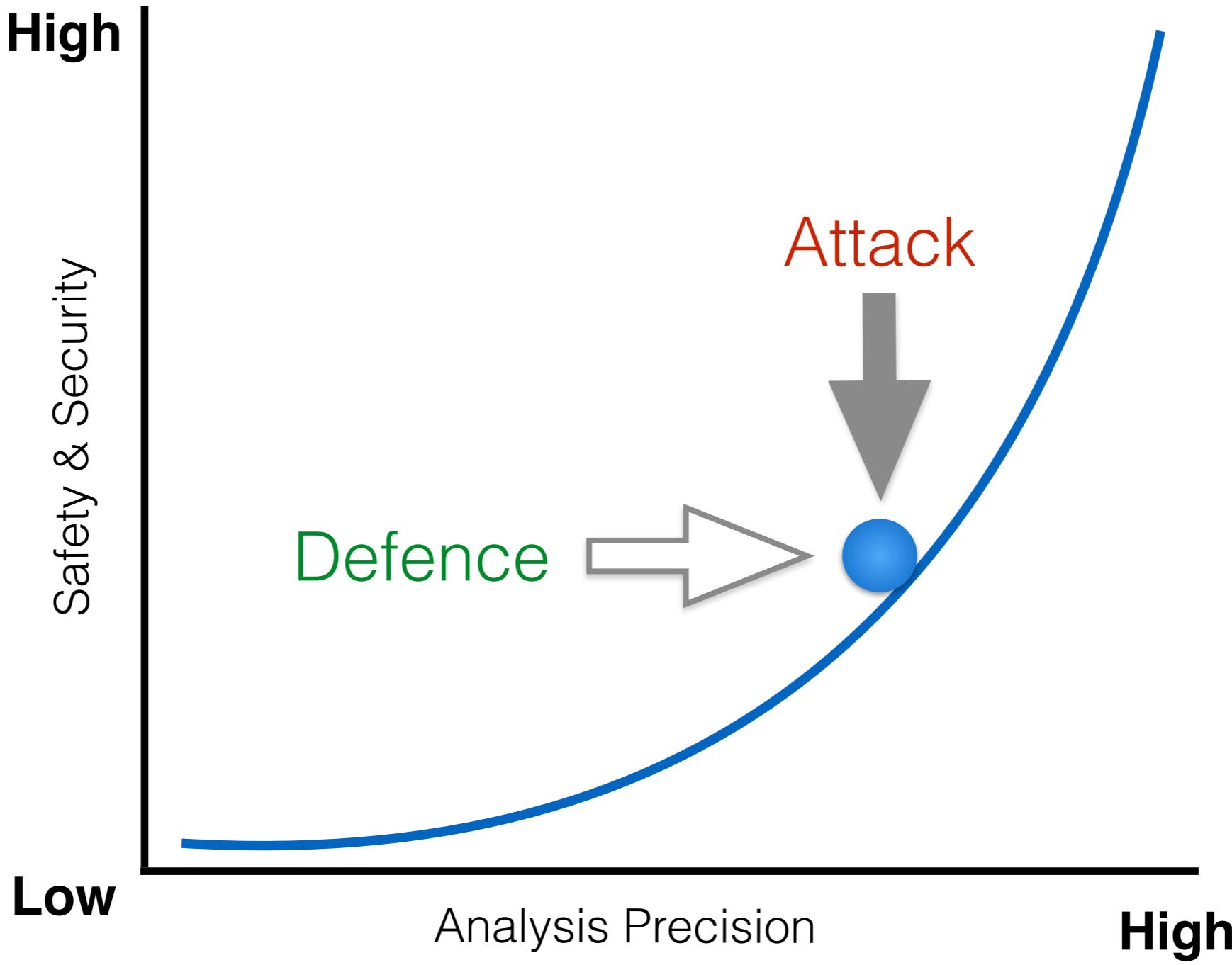


Make human analysis harder!

Understanding is Interpreting

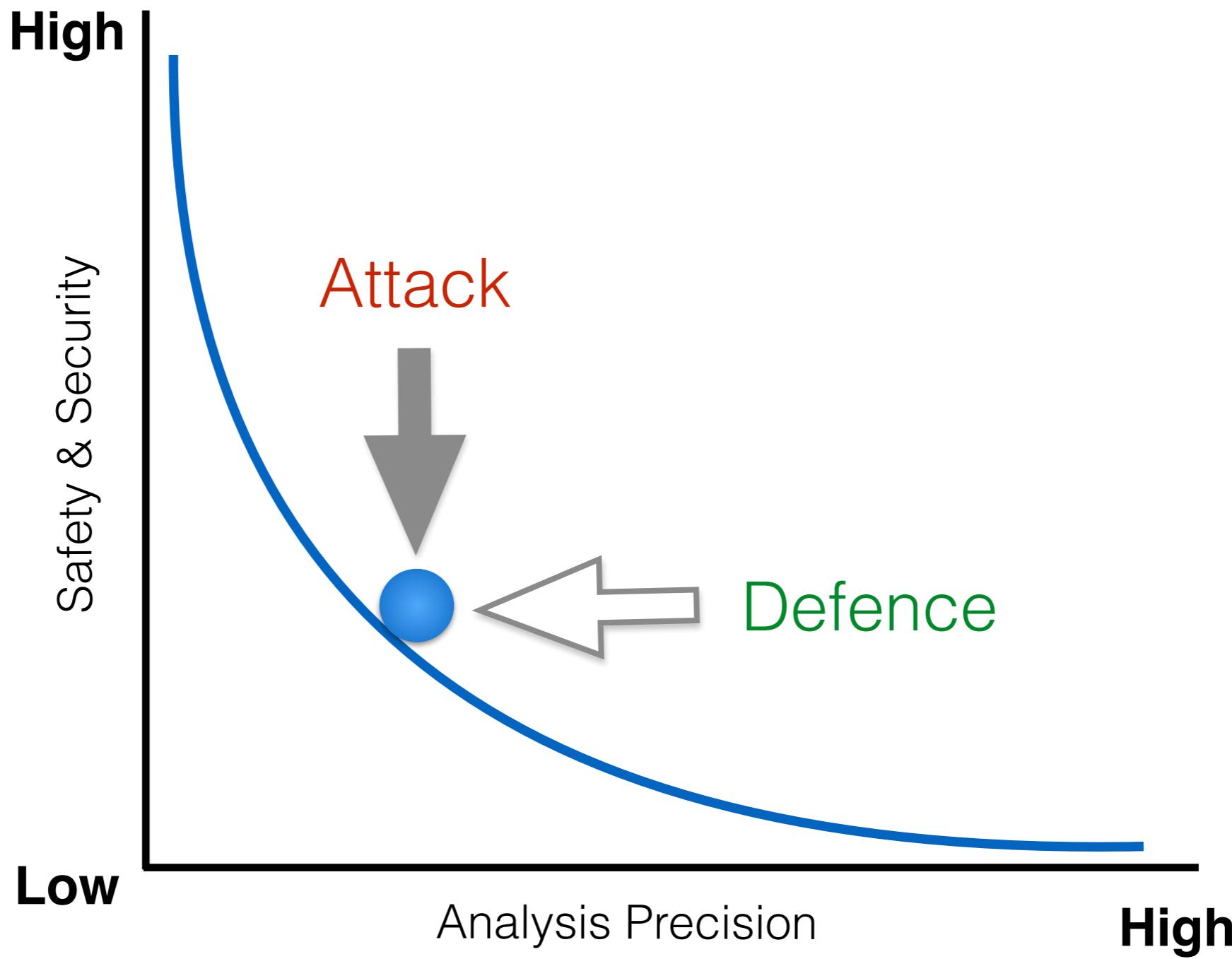


Code Debugging



The attacker exploits bugs

Software Protection

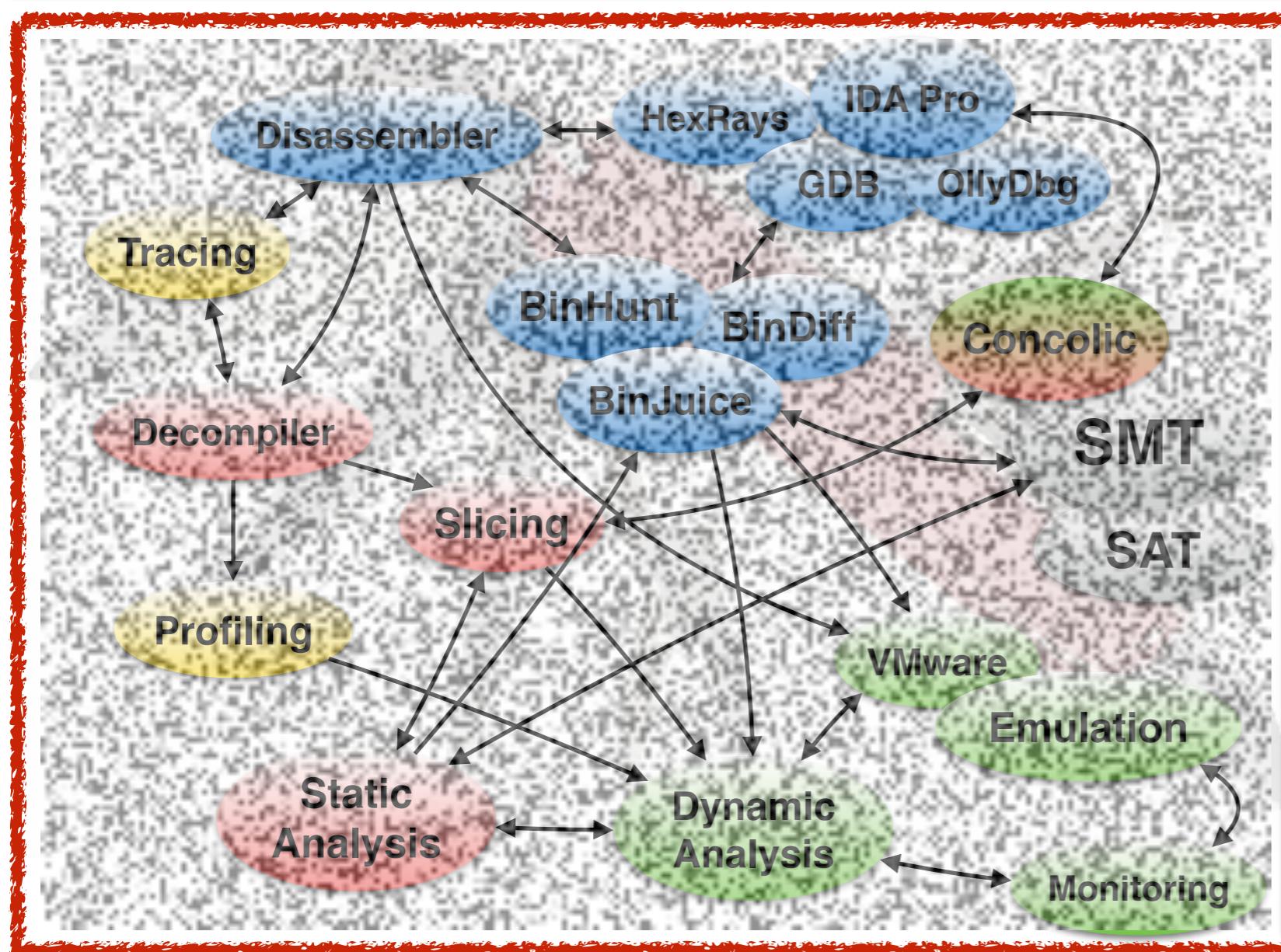


The attacker reverse engineer code

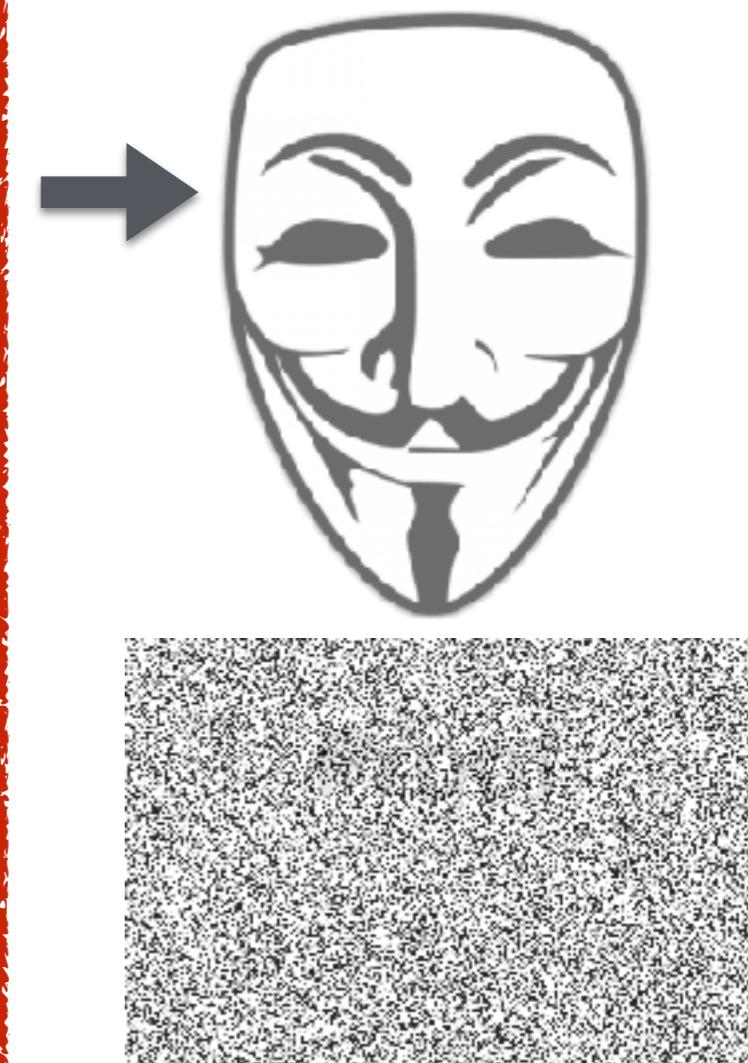
Protecting is obscuring Interpreters

$O(P)$

Constrained Adversary

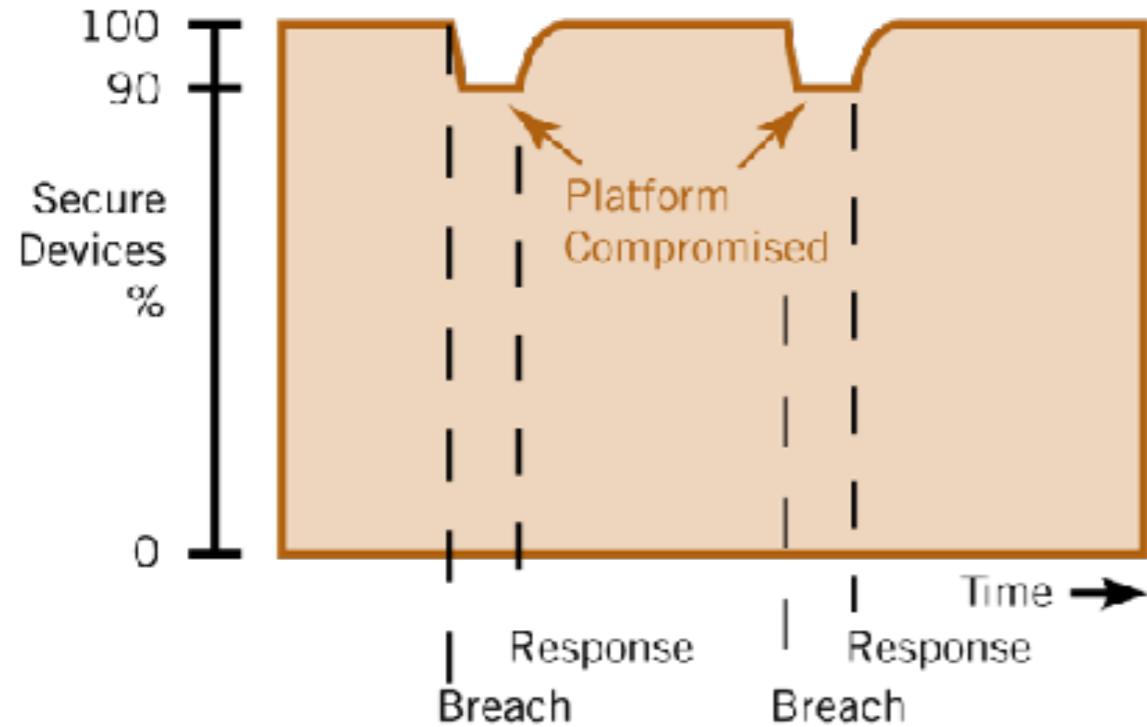


Analysis



Mitigation

- Strong attack response
- Reduces duration of attack

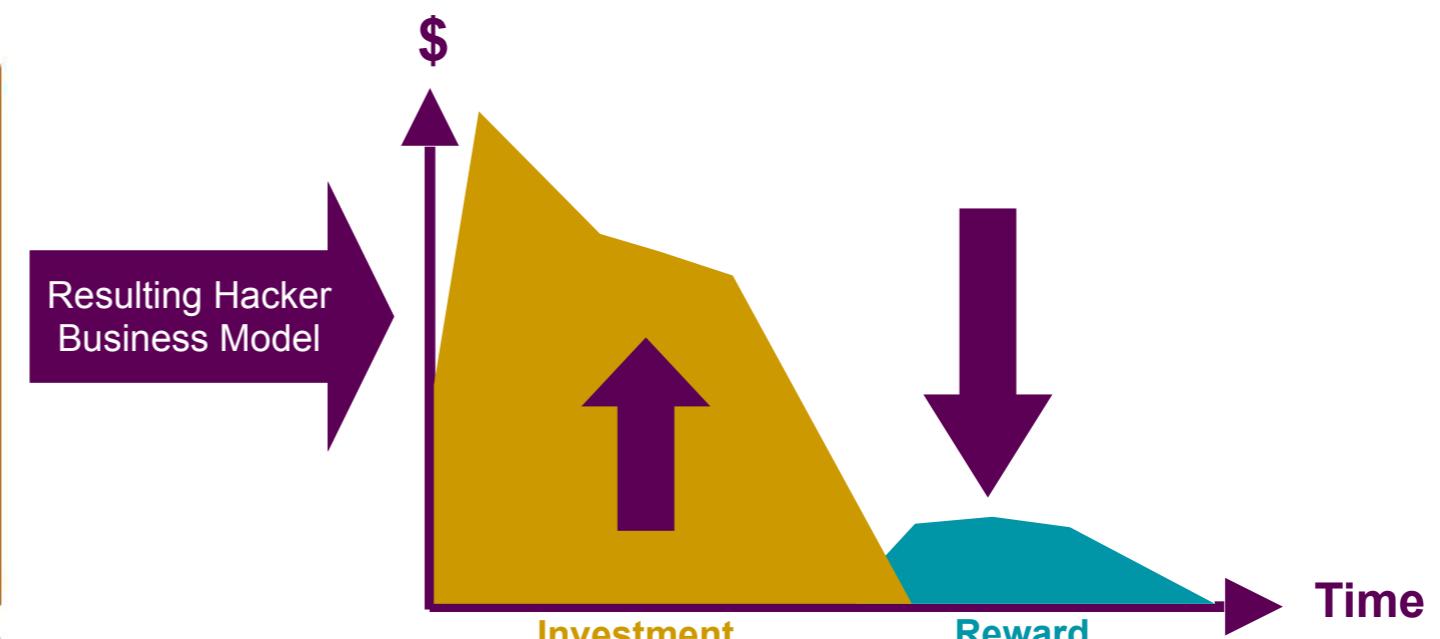


Tamper resistance

Raises cost of attack

Diverse production

Reduces scope of attack



Software Diversity Benefits

Minimise scope of attack -- Prevent automated attacks

Provide rapid recovery in the event of an attack

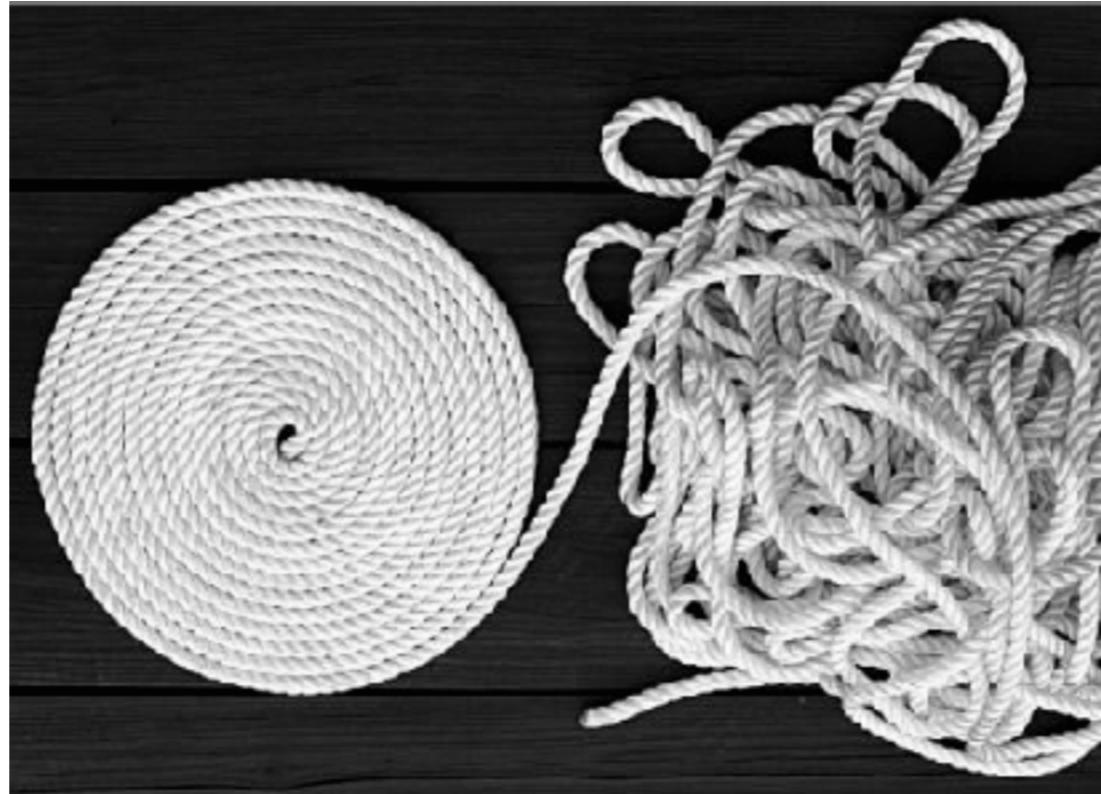
Make the business unattractive to the hacker

Code Obfuscation

[Collberg et al. POPL 1998]

A program transformation $O: \text{Programs} \longrightarrow \text{Programs}$ is a code obfuscation if:

- O preserves the observational behavior of programs
- O is potent, makes the program more complex to analyse



Code Obfuscation

The **level of security** from reverse engineering that an obfuscator adds to an application depends on:

- ✓ the **sophistication of the obfuscating transformation**
- ✓ the **power of the deobfuscator**
- ✓ the **amount of resources** (time and space) available to the deobfuscator
- ✓ Observe that:
 - ✓ it is difficult to measure the goodness/efficiency of an obfuscation
 - ✓ obfuscation can **never completely protect** an application

Evaluating Code Obfuscation

An obfuscating transformation T is evaluated according to:

- **potency**: how much obscurity obfuscation T adds to the program (max)
- **resilience**: how difficult T is for a deobfuscator to undo (max)
- **cost**: how much computational overhead (time and space) T adds to the obfuscated application (min)
- **stealth**: how well code introduced by T fits in with the original code (max)

$$\text{Quality}(T) = \text{potency} + \text{resilience} + \text{cost} + \text{stealth}$$



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concerning Coronavirus / Covid 19

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August 11 – 16 , 2019, Dagstuhl Seminar 19331

Software Protection Decision Support and Evaluation Methodologies

Organizers

Christian Collberg (University of Arizona – Tucson, US)

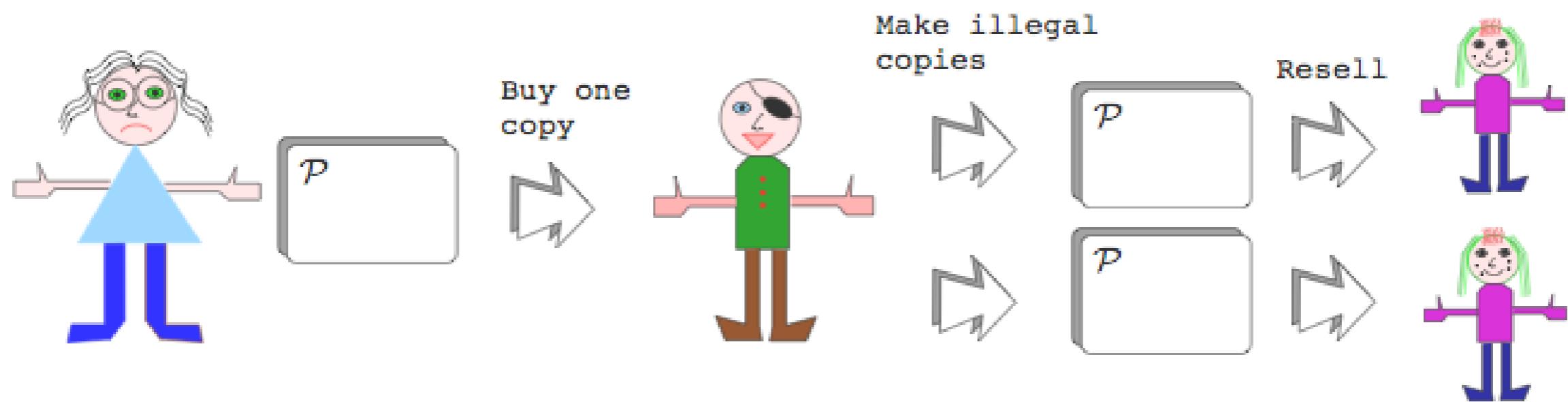
Mila Dalla Preda (University of Verona, IT)

Bjorn De Sutter (Ghent University, BE)

Brecht Wyseur (NAGRA Kudelski Group SA – Cheseaux, CH)



SW Piracy



SW Watermarking: idea

- * Embed a unique identifier in a program to trace SW pirates
- * Watermarking:
 - ✓ Discourages theft
 - ✓ Allows us to prove theft
- * Fingerprinting
 - ✓ Trace violators
- * Algorithms and procedure that are:
 - ✓ hard to destroy
 - ✓ stealthy
 - ✓ high bit-rate
 - ✓ little performance overhead.

Steganography

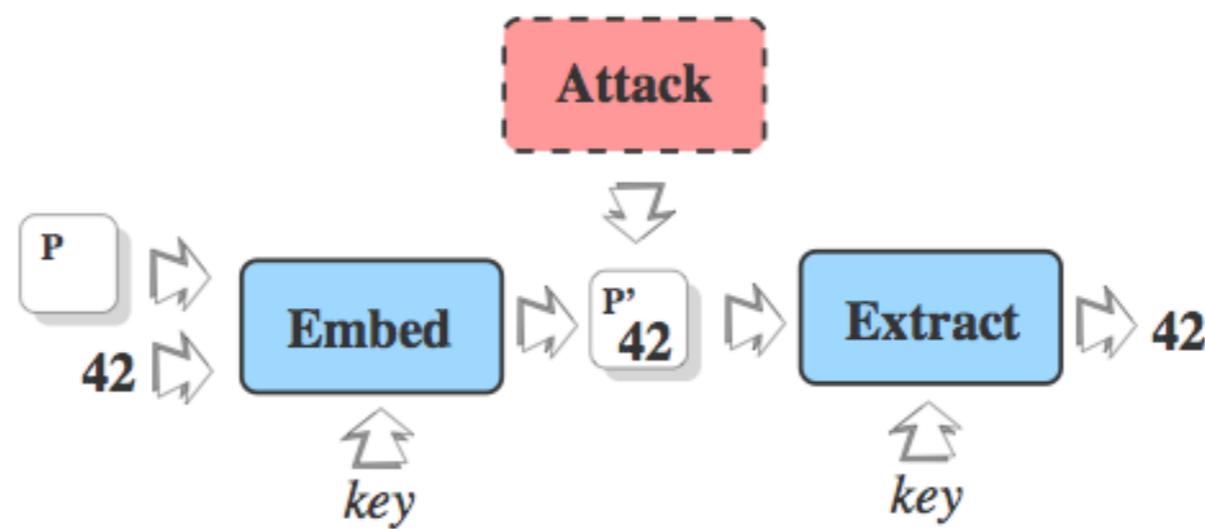
- * Steganography is the art and science of writing **hidden messages** in such a way that no one apart from the intended recipient knows of the existence of the message.
- * Steganography means "covered, or hidden writing"
 - ✓ The Histories of Herodotus: Demeratus sent a hidden message about a forthcoming attack to Greece by writing a wooden panel which was covered in a wax.
 - ✓ Hidden messages on paper written with secret inks
- * Important: **steganography hides the fact that the message exists!!**
- * Watermarking and fingerprints are examples!

Watermarking



- * Watermarks were first introduced in Bologna by Fabriano, in 1282
- * Watermarks appeared on British stamps from 1840
- * The term "**digital watermark**" was first coined in 1992 by Tirkel and Osborne, in their paper: A.Z.Tirkel, G.A. Rankin, R.M. Van Schyndel, W.J.Ho, N.R.A.Mee, C.F.Osborne. "Electronic Water Mark". DICTA 93, Macquarie University. p.666-673

Watermarking



Embed an integer W in program P such that

- W is resilient against automated attacks
- W is stealthy
- W is large (high bitrate)
- the overhead (space and time) is low

Watermarking

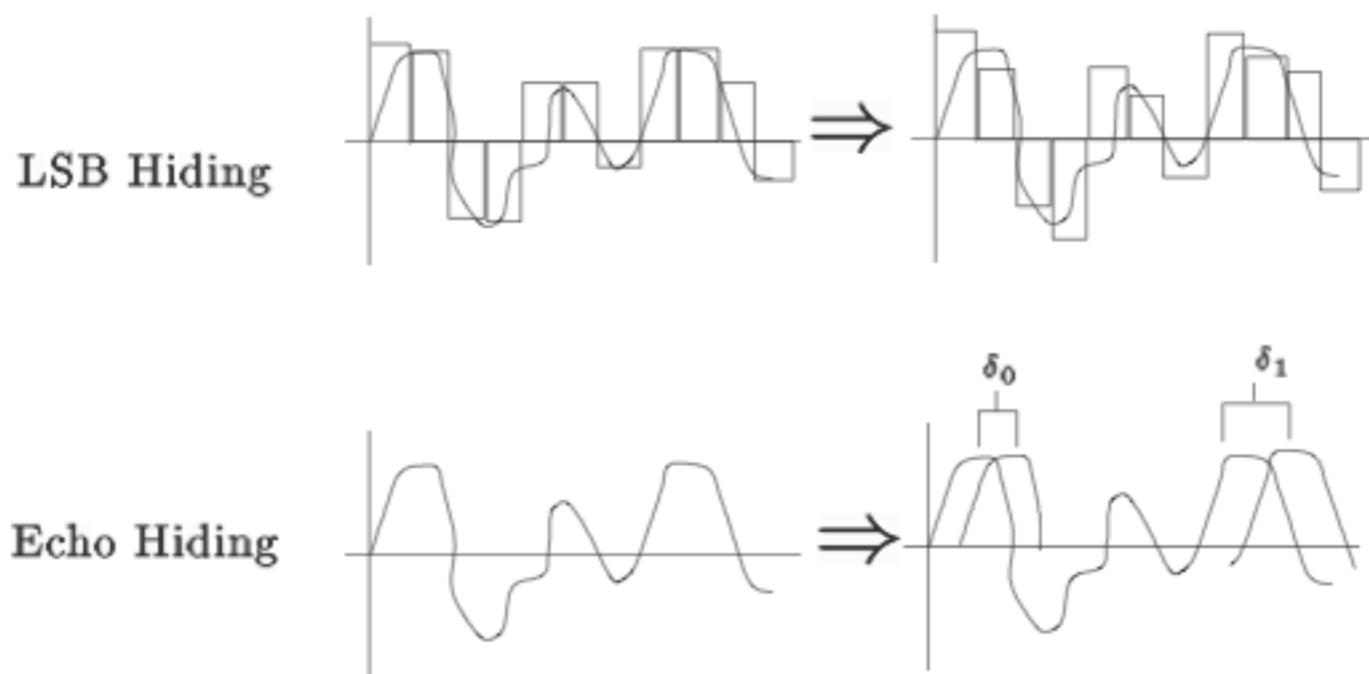


```
Embed: Init_RND( $\mathcal{K}$ );  
repeat  $n \approx 10000$  times  
   $i \leftarrow \text{RND}(); j \leftarrow \text{RND}();$   
  fix brightness :  $a_i \leftarrow a_i + \delta; b_j \leftarrow b_j - \delta;$ 
```

```
Extract: Init_RND( $\mathcal{K}$ );  $S' \leftarrow 0;$   
repeat  $n \approx 10000$  times  
   $i \leftarrow \text{RND}(); j \leftarrow \text{RND}();$   
  sum brightness :  $S' \leftarrow S' + a_i - b_j;$ 
```

- $\sum_i^n (a_i - b_i) \gg 0 \Rightarrow \text{watermark!}$
- Bit-rate: 1 bit per image.

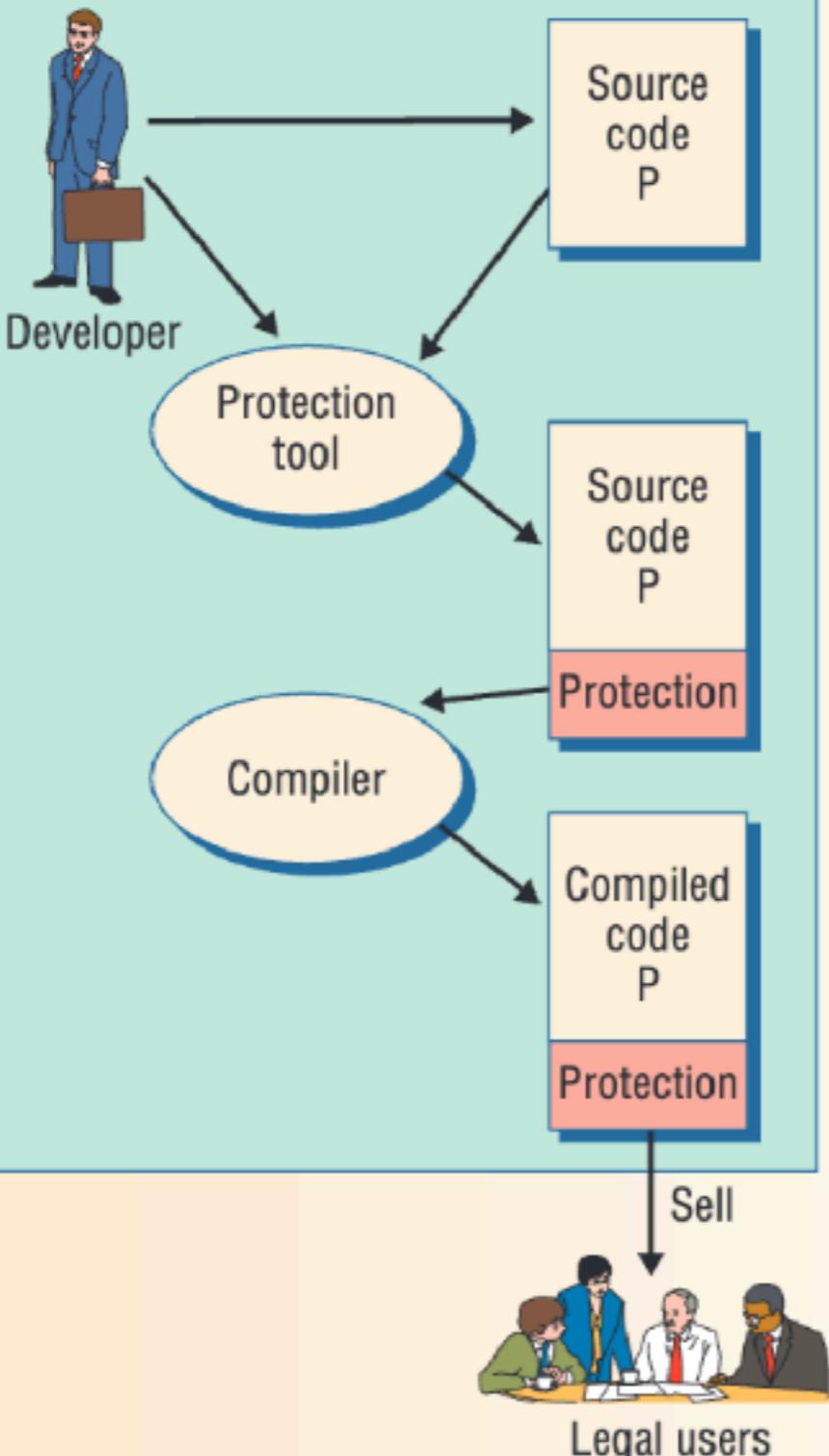
Audio Watermarking



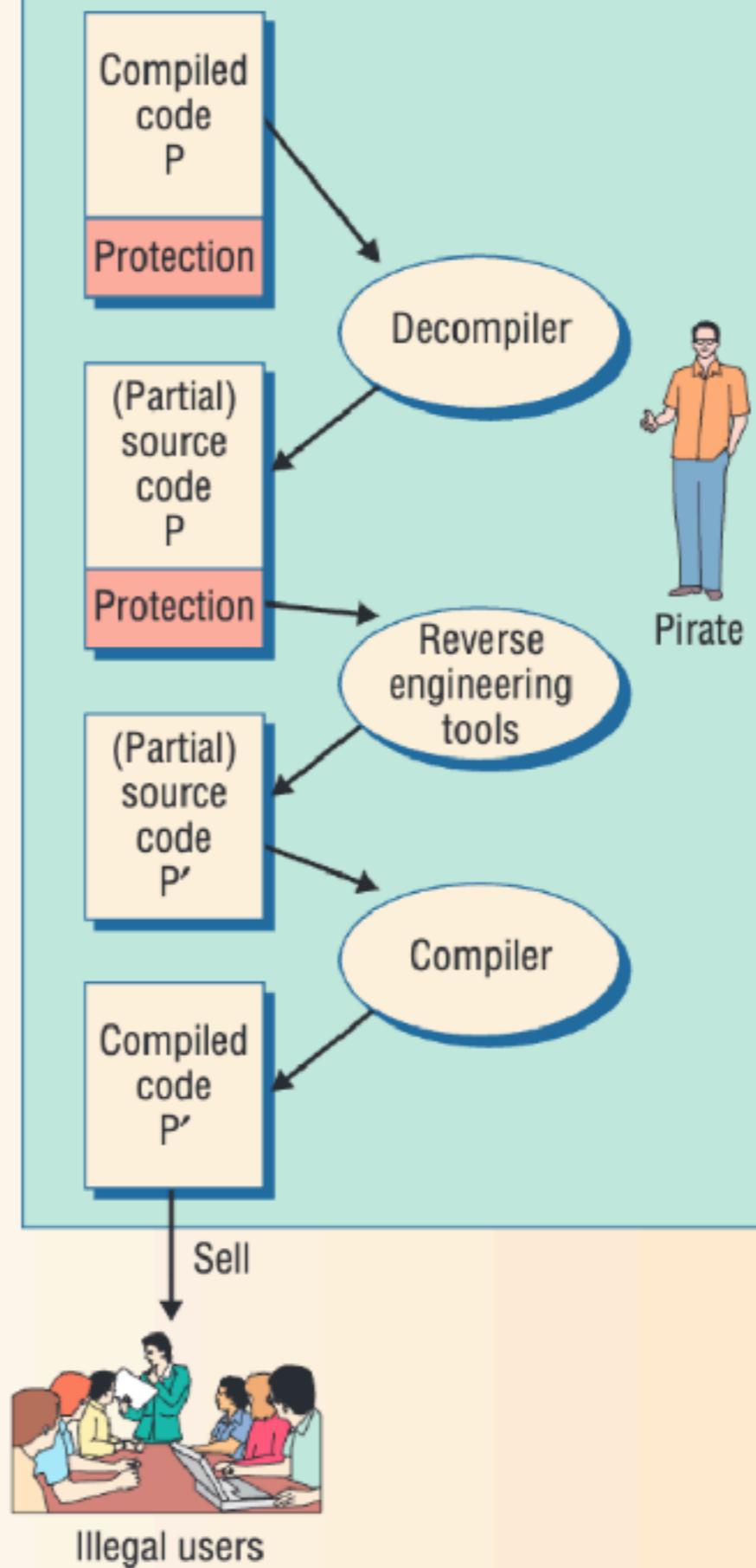
Text Watermarking

Hard-Copy	<p>I saw the best minds of my generation, starving hysterical naked</p>
White-Space	I saw the best minds of my generation, starving hysterical naked
Syntactic	It was the best minds of my generation that I saw, starving hysterical naked
Semantic	I observed the choice intellects of my generation, starving hysterical nude

Software vendor



Software pirate



SW Tampering: idea

- * goal: ensure that the program executes *as intended* even in presence of an adversary
- * it should *detect* when tampering occurs and *respond* to the attack
- * related to obfuscation and software watermarking

```
if (license-expired()) {           if (false) {  
    printf ("pay m1!!!");          printf ("pay m1!!!");      program crashes  
    abort();                      abort();  
}
```

- * Sw developer's revenue depends on their programs executing as aspected, while the adversary's revenue depends on modifying the semantics of these programs to execute the way they wanted to

What is tamper proofing?

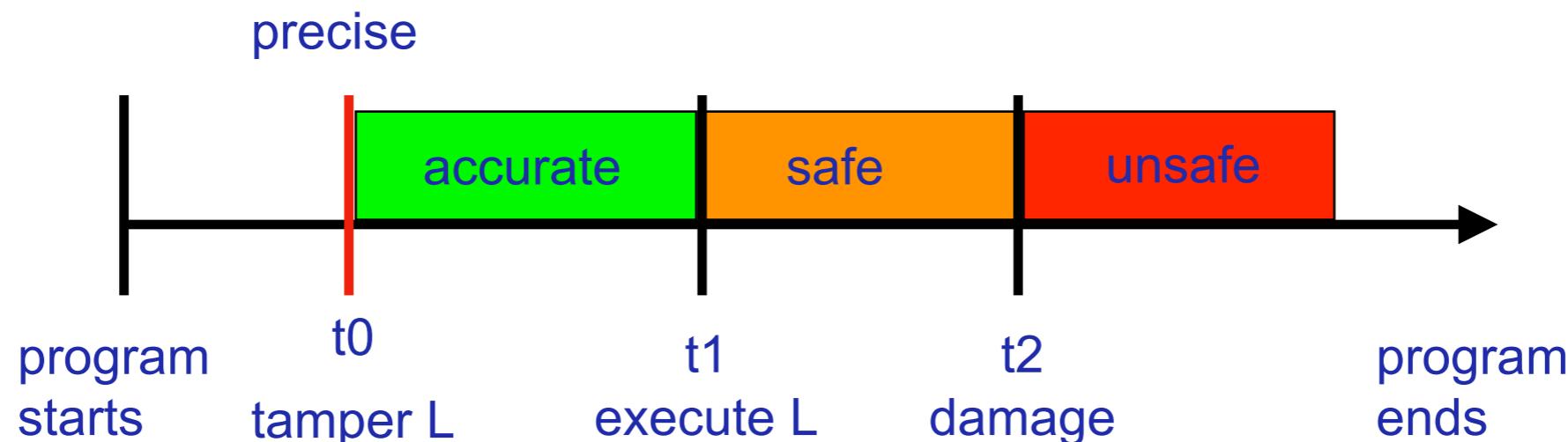
- * Ensure that programs executes as intended, even in the presence of an adversary who tries to disrupt, monitor, or change the execution
- * A tamper-proofing algorithm:
 - * **CHECK**: that monitors the health of the system by testing a set of invariants and returning **true** if nothing suspicious is found
 - * **RESPOND**: queries **CHECK** to see if P is running as expected, and if it's not, issues a **tamper response** (e.g. terminating the program)

Checking for Tampering

CHECK tests a set of invariant

- * **Code checking**: check that P's code hashes to a known value
- * **Result checking**: test that the result of computation is correct.
Checking the validity of the computation result is often computationally cheaper than performing the computation itself
- * **Environment checking**: the hardest thing for a program to check is the validity of its execution environment.
 - ◆ Running under an emulator
 - ◆ Operating system
 - ◆ ...

Precision



- ✓ **Precise**: the checker detects the attack immediately after the modification has taken place
- ✓ **Accurate**: the checker detects the attacks before the modified code is executed
- ✓ **Safe**: the checker waits until after the modified code has been executed, but before the first interaction event (before damage)
- ✓ **Unsafe**: the checker identifies the attack after the damage has taken place...

Respond Scenarios

- ✓ Terminate the program
- ✓ Restore the program (patch the code)
- ✓ Run incorrect results / deteriorate performance
- ✓ Report an attack
- ✓ Punish the attacker: destroy code / system (malware!!)

Attack: Program Analysis

```
n := n0;                                n := n0;  
{n0=n,n0>=0}  
i := n;                                i := n;  
{n0=i,n0=n,n0>=0}  
while (i <> 0 ) do  
    j := 0;                            while (i <> 0 ) do  
        j := 0;                        {n0=n,i>=1,n0>=i}  
        while (j <> i) do  
            j := j + 1;                  j := 0;  
            {n0=n,j>=0,i>=1,n0>=i}  
        od;                            while (j <> i) do  
            j := j + 1;                  {n0=n,j>=0,i>=j+1,n0>=i}  
            {n0=n,j>=1,i>=j,n0>=i}  
        od;                            j := j + 1  
        {n0=n,i=j,i>=1,n0>=i}      {n0=n,j>=1,i>=j,n0>=i}  
        i := i - 1;                    od;  
        {i+1=j,n0=n,i>=0,n0>=i+1}  
    od  
    {n0=n,i=0,n0>=0}
```

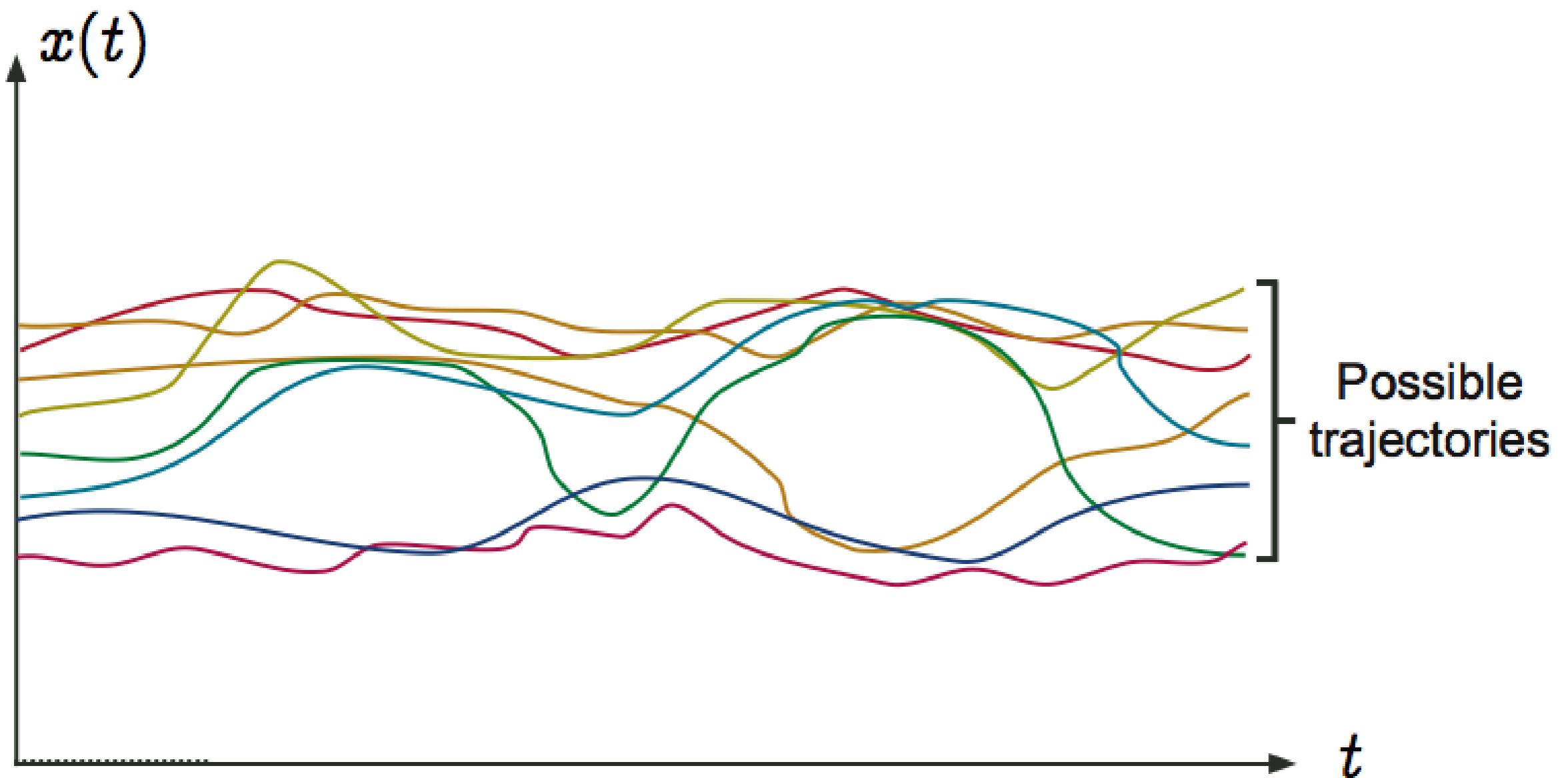
Attack: Program Analysis

Example of static analysis (safety)

```
{n0>=0} ←  
    n := n0;  
{n0=n, n0>=0}  
    i := n;  
{n0=i, n0=n, n0>=0}  
    while (i <> 0) do  
        {n0=n, i>=1, n0>=i}  
        j := 0;  
{n0=n, j=0, i>=1, n0>=i}  
        while (j <> i) do  
            {n0=n, j>=0, i>=j+1, n0>=i}  
            j := j + 1 ← j < n0 so no upper overflow  
{n0=n, j>=1, i>=j, n0>=i}  
    od;  
{n0=n, i=j, i>=1, n0>=i}  
    i := i - 1 ← i > 0 so no lower overflow  
{i+1=j, n0=n, i>=0, n0>=i+1}  
od  
{n0=n, i=0, n0>=0}
```

n0 must be initially nonnegative
(otherwise the program does not terminate properly)

Possible Behaviors



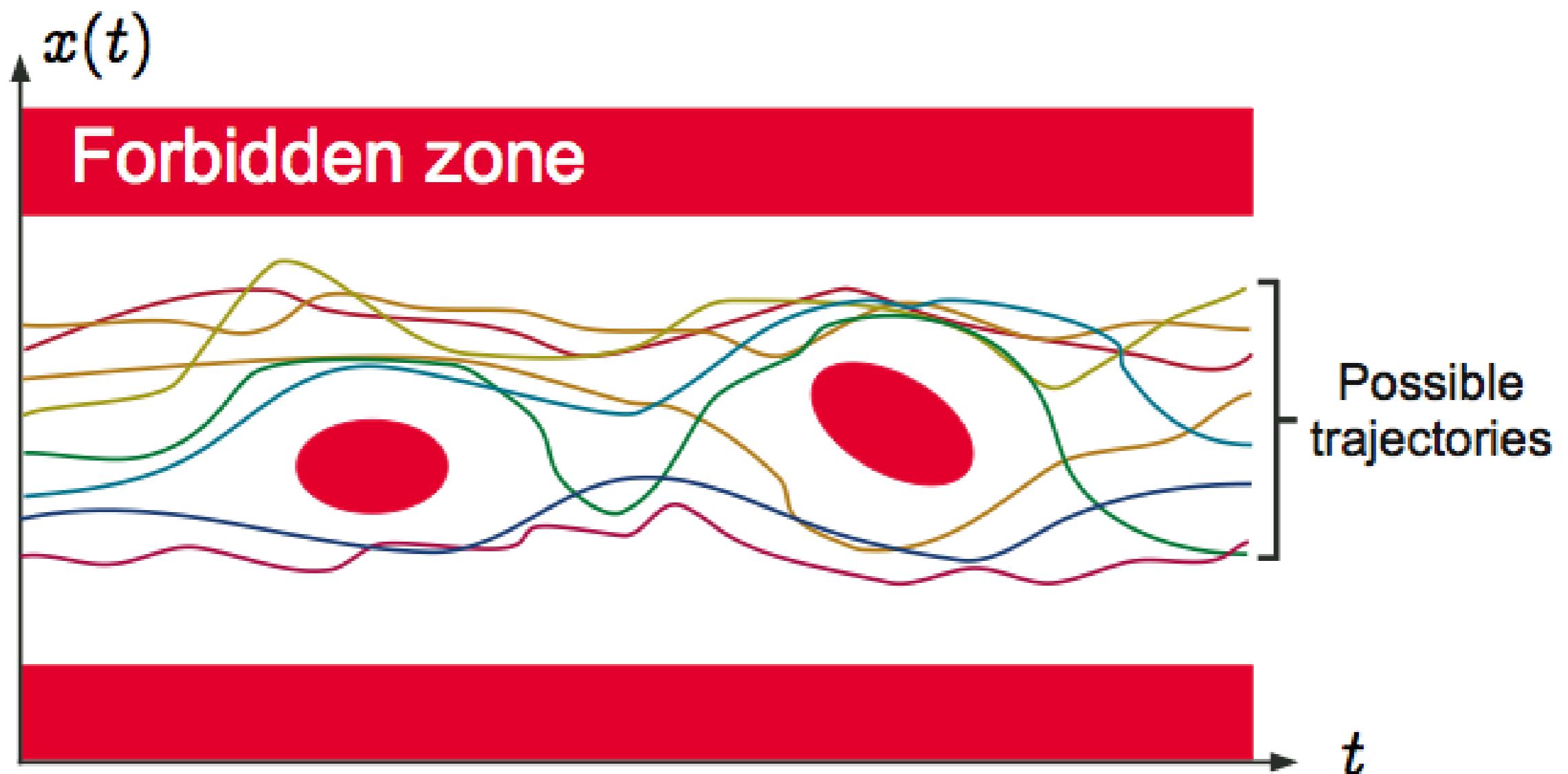
Semantics

- * The **concrete semantics** of a program formalizes (is a mathematical model of) the set of all its possible executions in all possible execution environments.
- * The concrete mathematical semantics of a program is an **infinite** mathematical object, **not computable**;
- * All non trivial questions on the concrete program semantics are **undecidable**

Safety Properties

- * The *safety properties* of a program express that no possible execution in any possible execution environment can reach an erroneous state
- * A *safety proof* consists in proving that the intersection of the program concrete semantics and the forbidden zone is empty
- * *undecidable problem* (the concrete semantics is not computable)
- * *impossible* to provide completely automatic answers with finite computer resources and neither *human interaction* nor *uncertainty* on the answer

Safety Properties



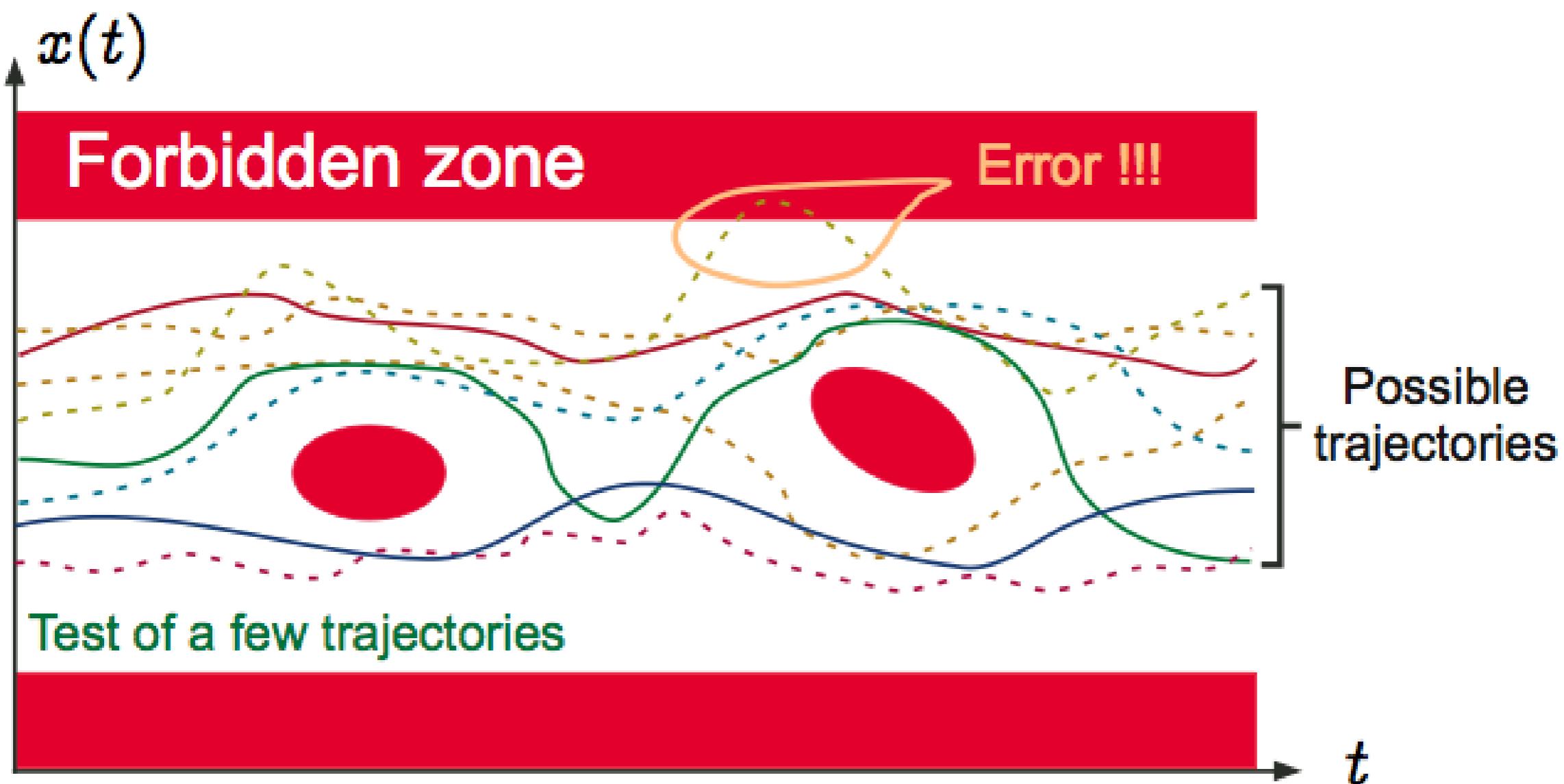
Dynamic Analysis

Testing, Debugging

- * Consists in considering a subset of the possible executions
- * Not a correctness proof
- * *Absence of coverage* is the main problem

Dynamic Analysis

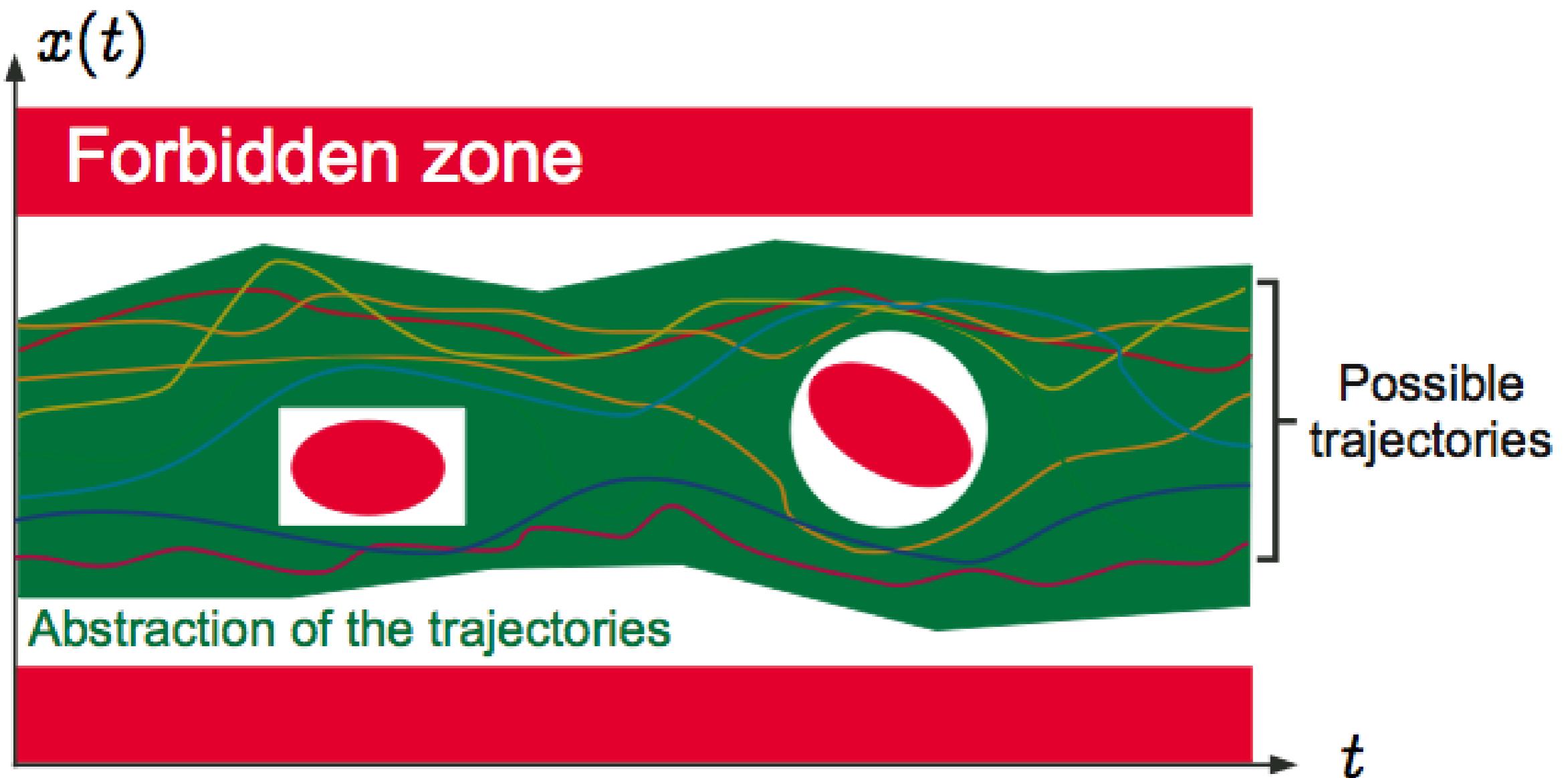
Testing, Debugging



Abstract Interpretation

- * Consists in considering an *abstract semantics*, that is to say a superset of the concrete semantics of the program
- * Hence the abstract semantics *covers all possible concrete cases*
- * *Correct*: if the abstract semantics is safe (does not intersect the forbidden zone) then so is the concrete semantics

Abstract Interpretation



Formal Methods

Formal methods are abstract interpretations, which differ in the way to obtain the abstract semantics

*Model checking:

The abstract semantics is given manually by the user in the form of a *finitely model of the program execution*. Can be computed automatically, by techniques relevant to static analysis.

*Deductive methods:

The abstract semantics is specified by *verification conditions*. The user must provide the abstract semantics in the form if inductive arguments (e.g. invariants). Can be computed automatically, by techniques relevant to static analysis

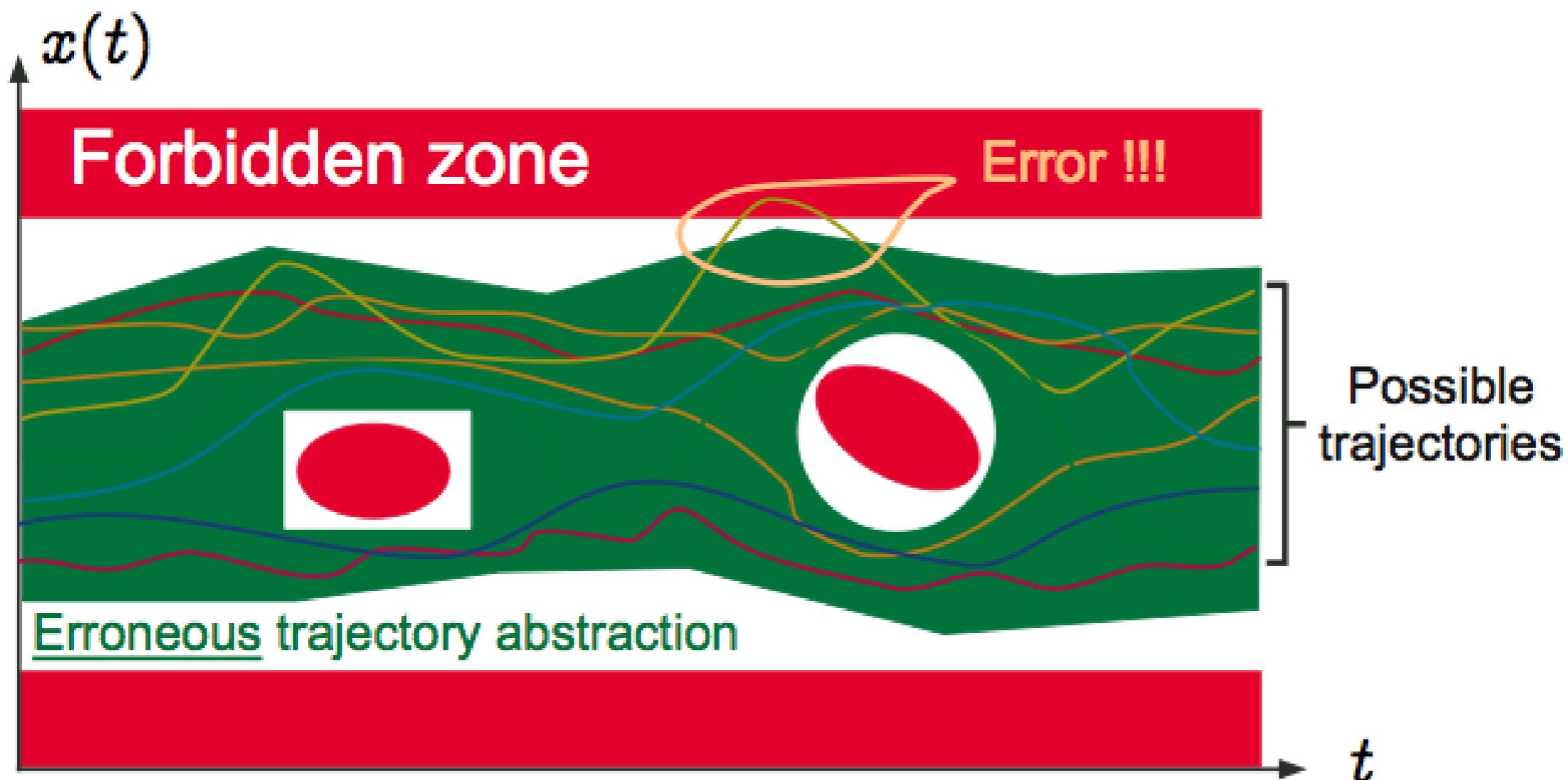
*Static analysis:

The abstract semantic is computed automatically from the program text according tho *predefined abstractions* (that can sometimes be tailored automatically/manually by the user)

Required properties of the abstract semantics

- ***Sound** so that no possible error can be forgotten
- ***Precise** enough (to avoid false alarms)
- *As **simple/abstract** as possible (to avoid combinatorial explosion phenomena)

Erroneous/Unsound Abstraction



Imprecision & false alarms

