Automatic Enforcement of Expressive Security Policies using Enclaves

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OOPSLA'16

Application-level Security

Application-level Security

```
x = secret_info
//compute with x
…
x = public_info
output x
```

Example Programs

```
x = key
//encrypt with x
encrypt(message, x)
x = 0
output x
```

Encryption

```
x = key
//sign with x
sign(message, x)
x = 0
output x
```

Signature

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Language-based Security

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Language-based Security

Real World Scenario: Application running a real machine

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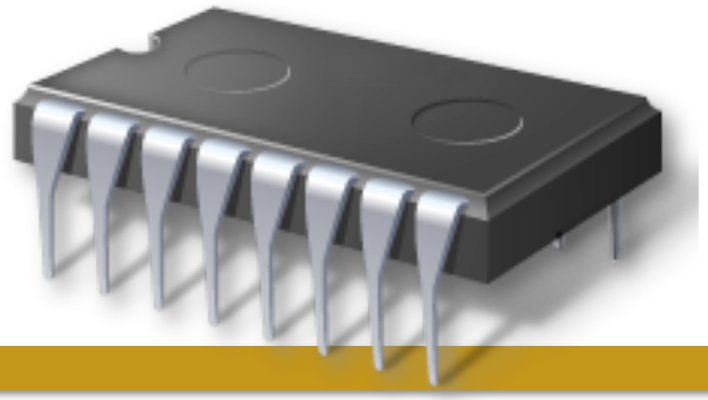
Language-based Security

Operating System



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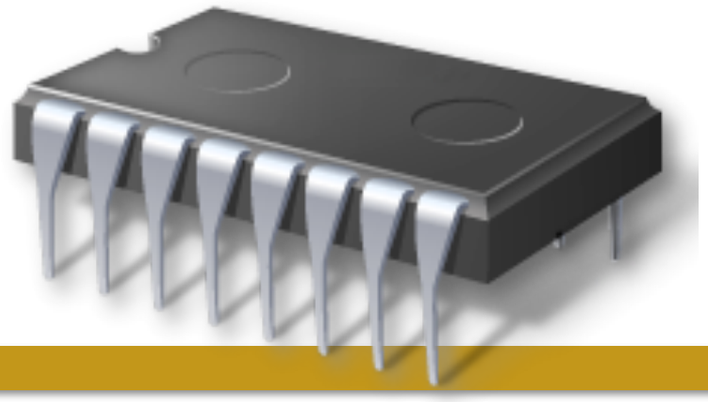

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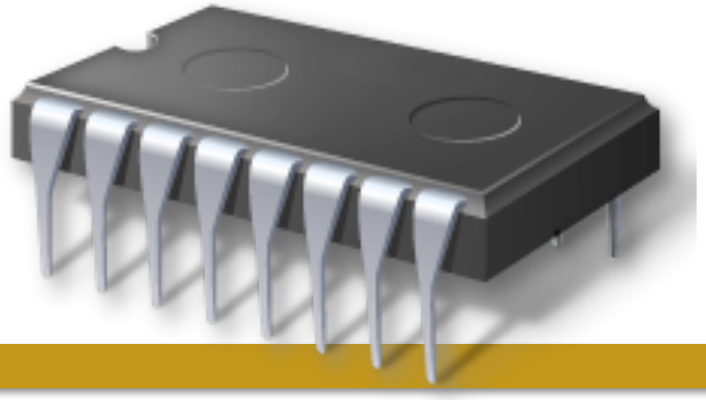

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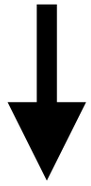

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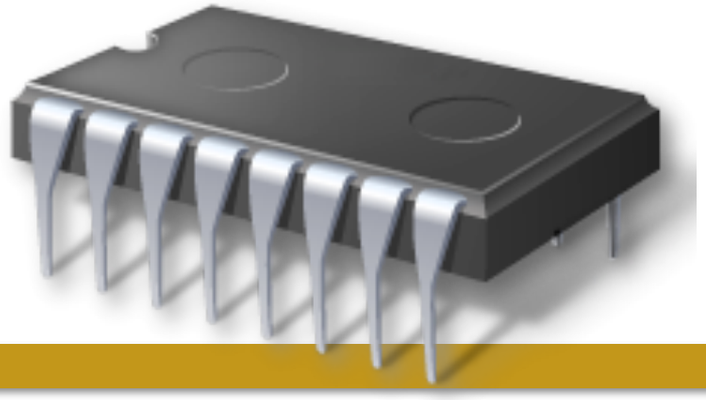

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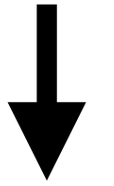

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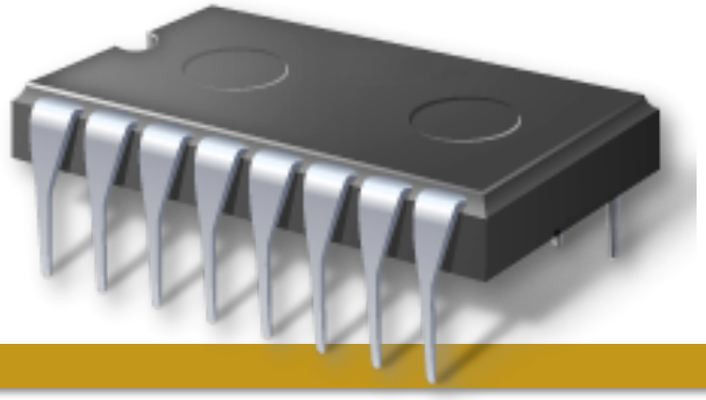

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Question: How to enforce application security guarantees against low-level attackers?

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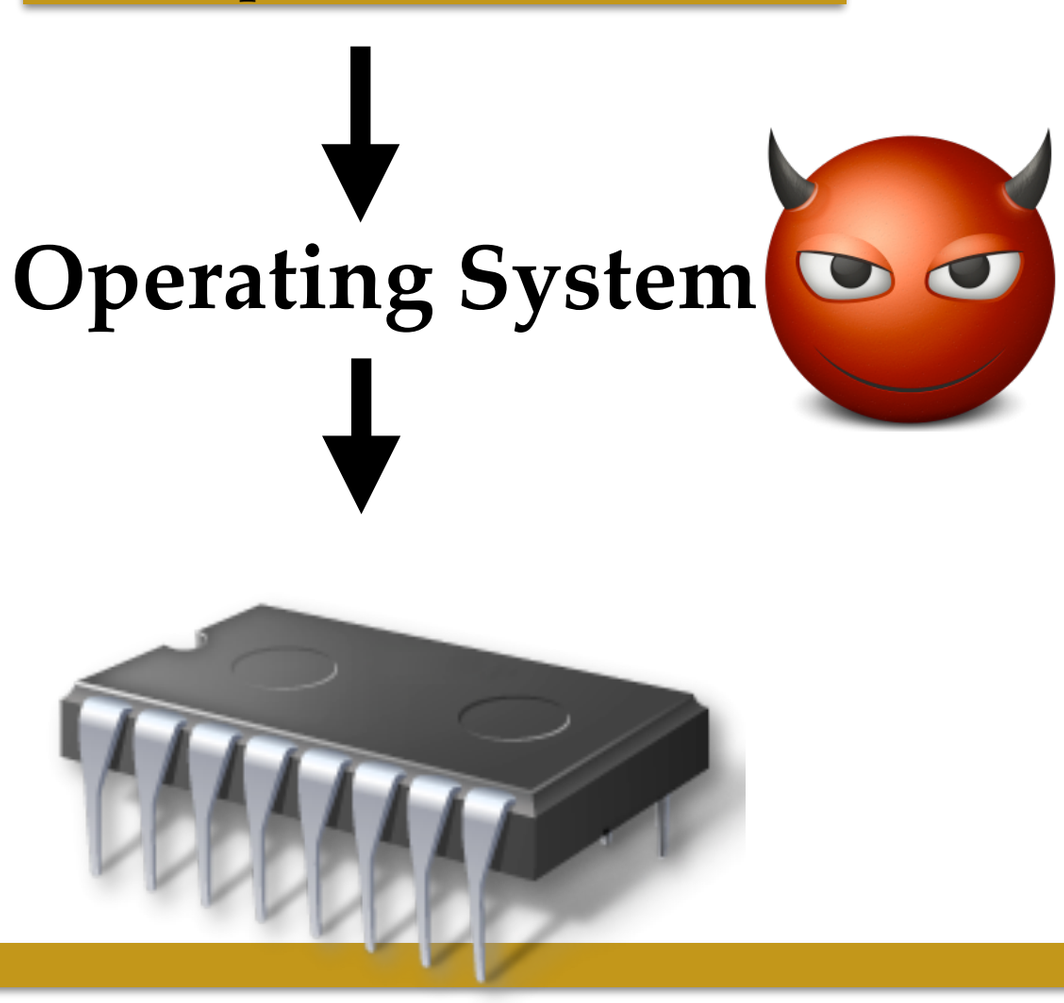

Our Solution

- Extend the Language-based Security with hardware protection mechanisms (Intel SGX, ARM TrustZone)
- Enforce security against low-level attackers

Hardware Protection Mechanisms

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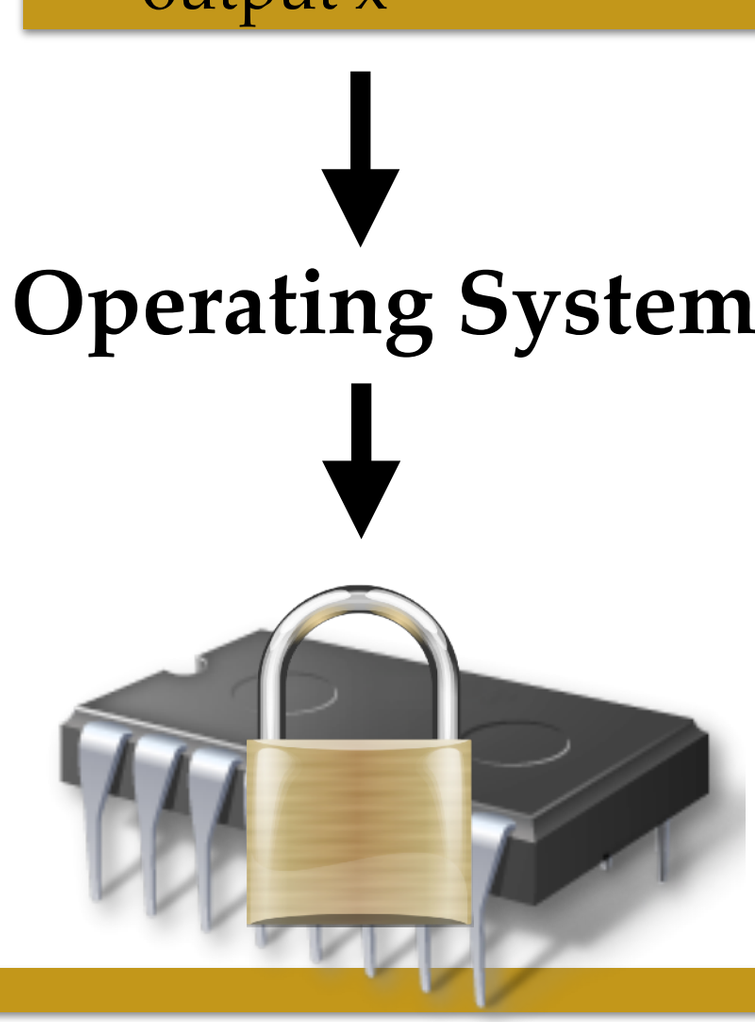

- Intel SGX enables
  - Applications to build enclaves: protected memory containers
    - Isolated execution
    - Restricted access
- ARM TrustZone

Overview of Enclaves

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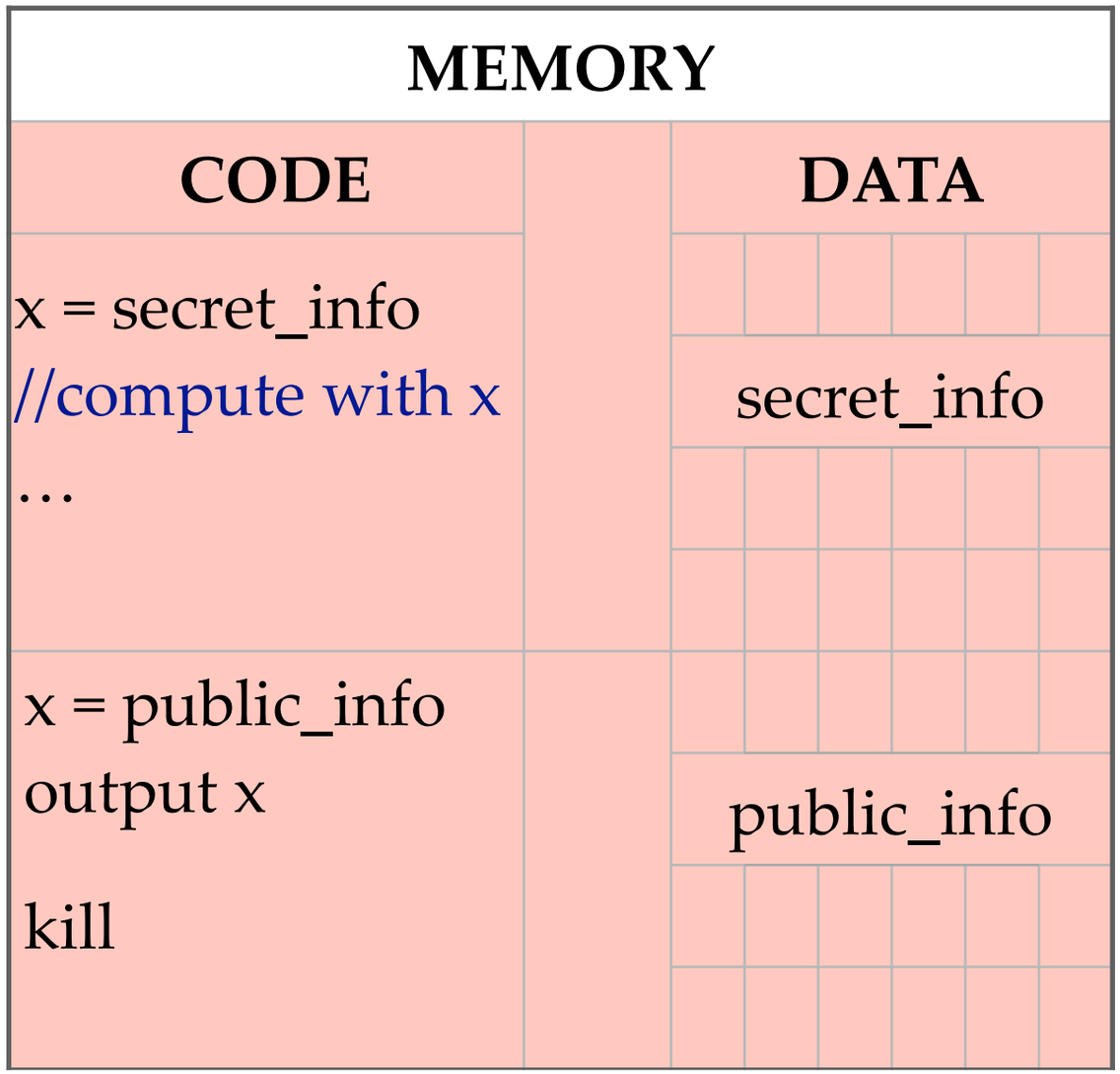
Program



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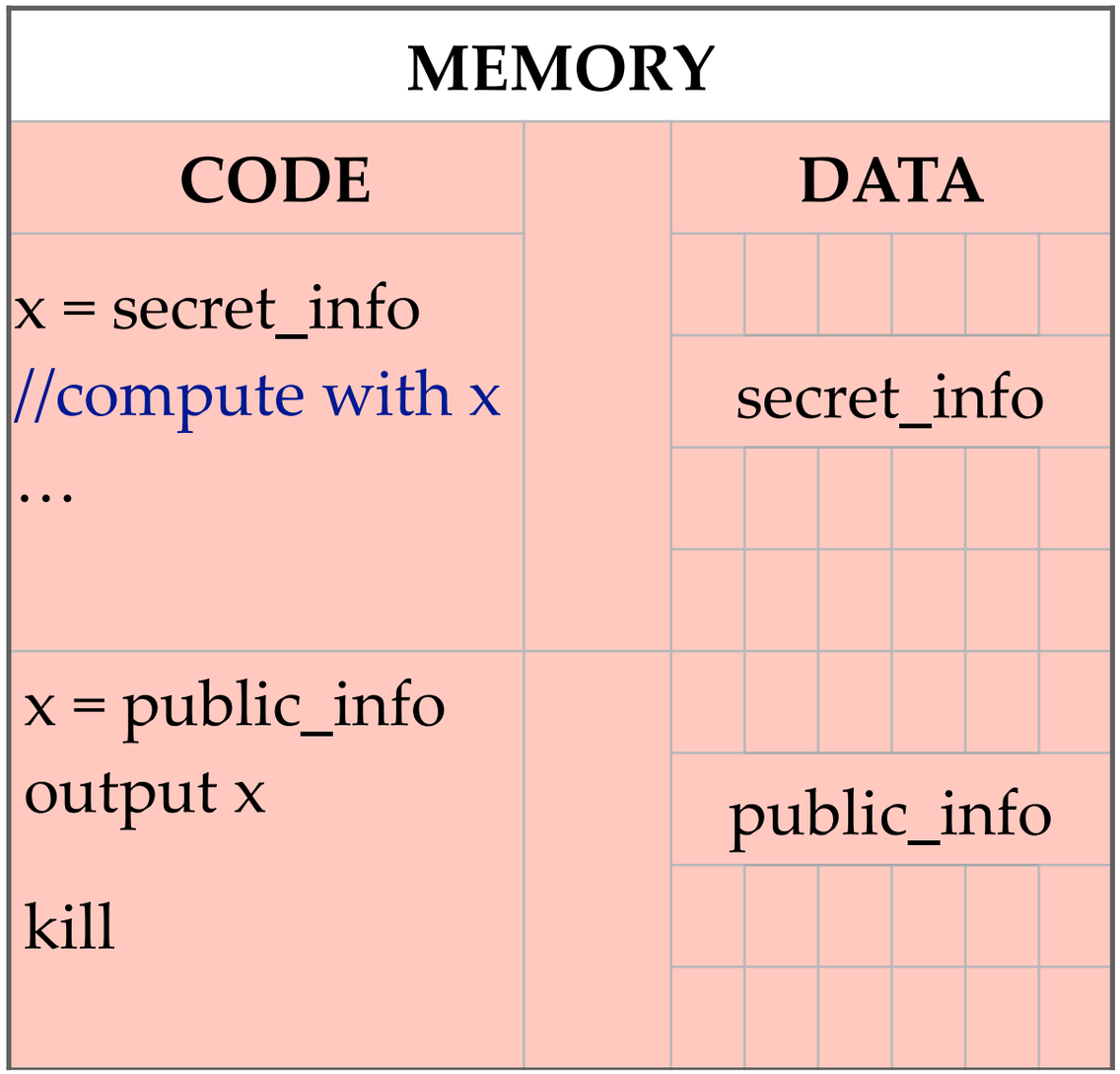

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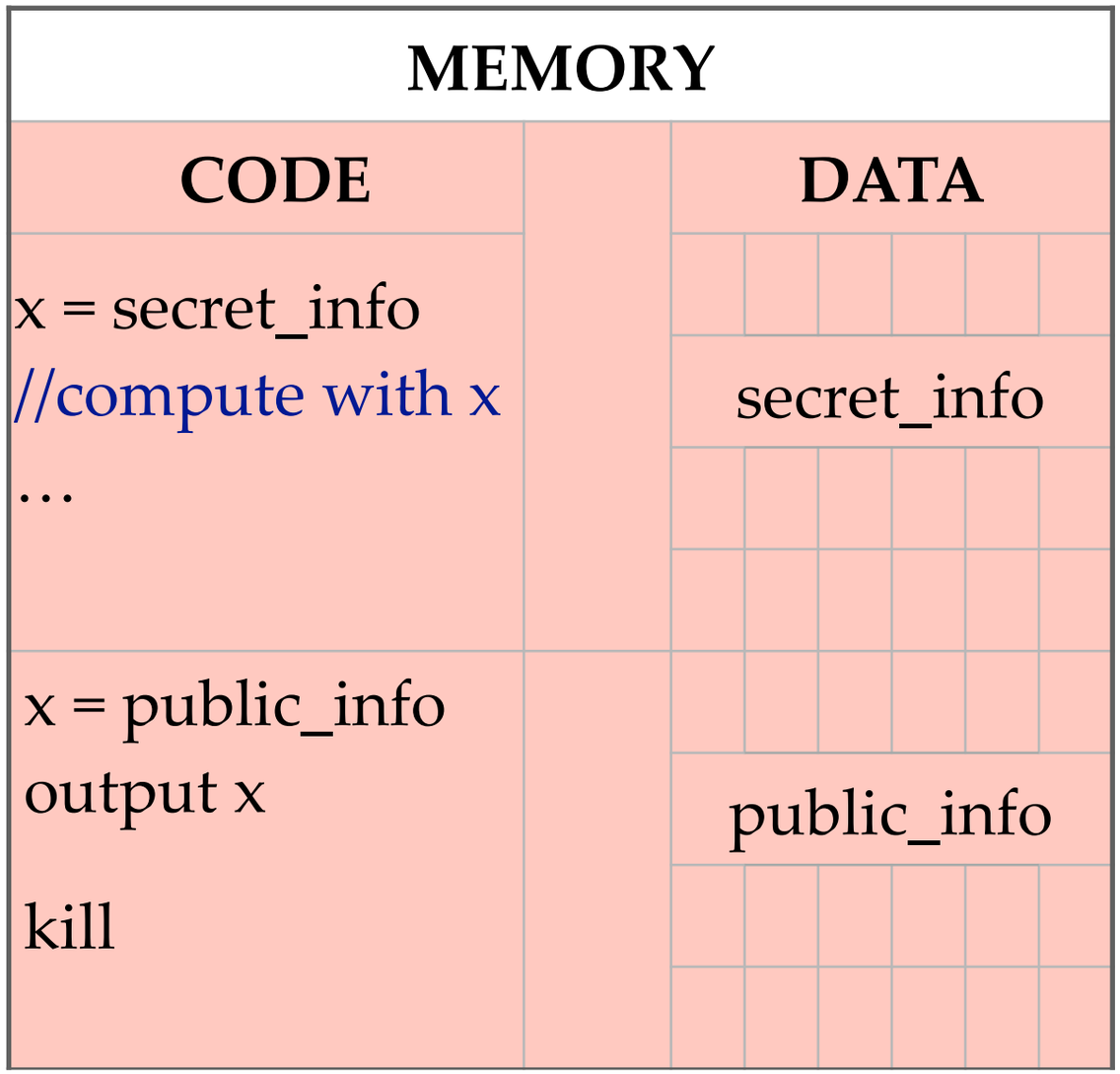

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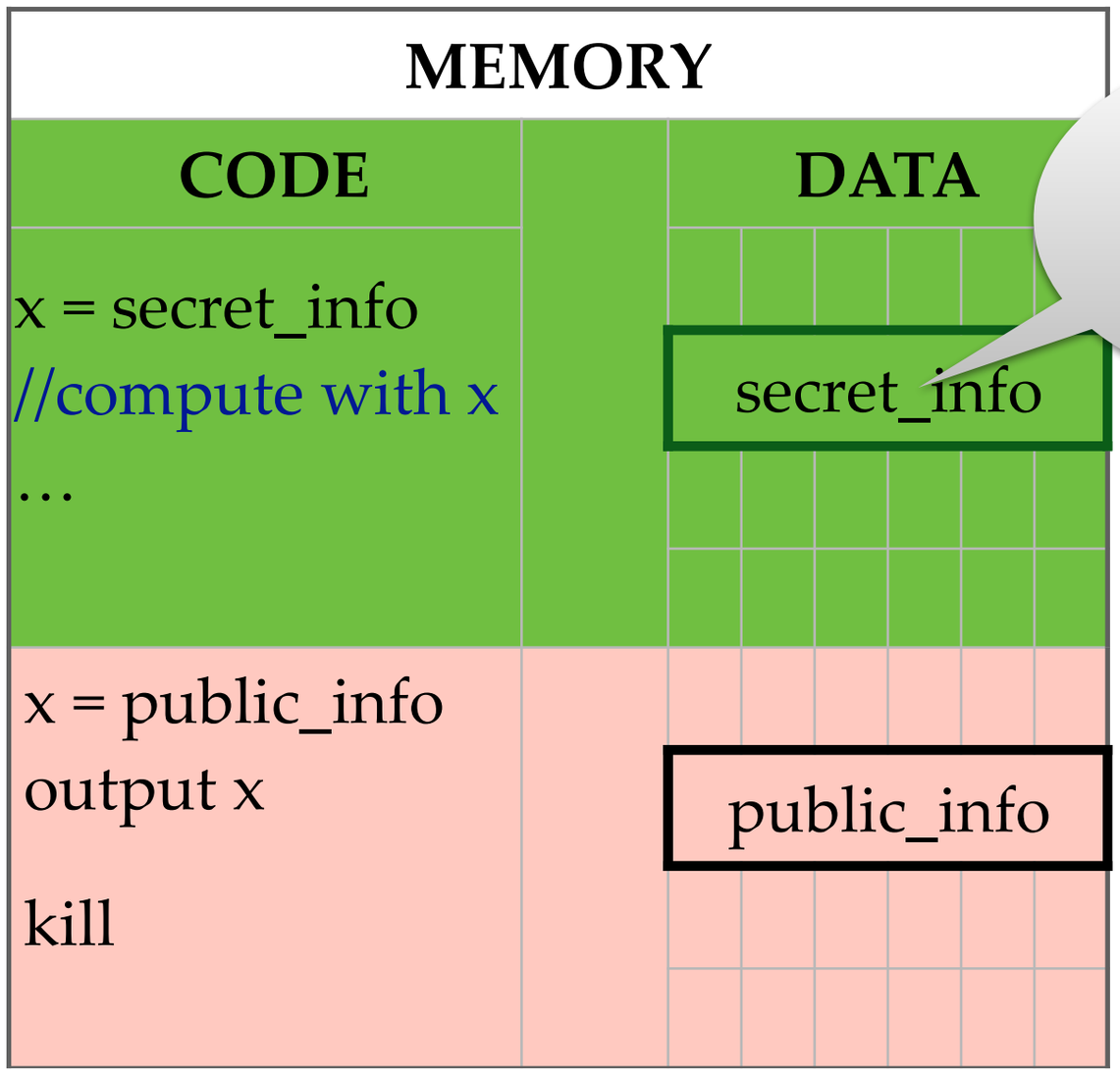

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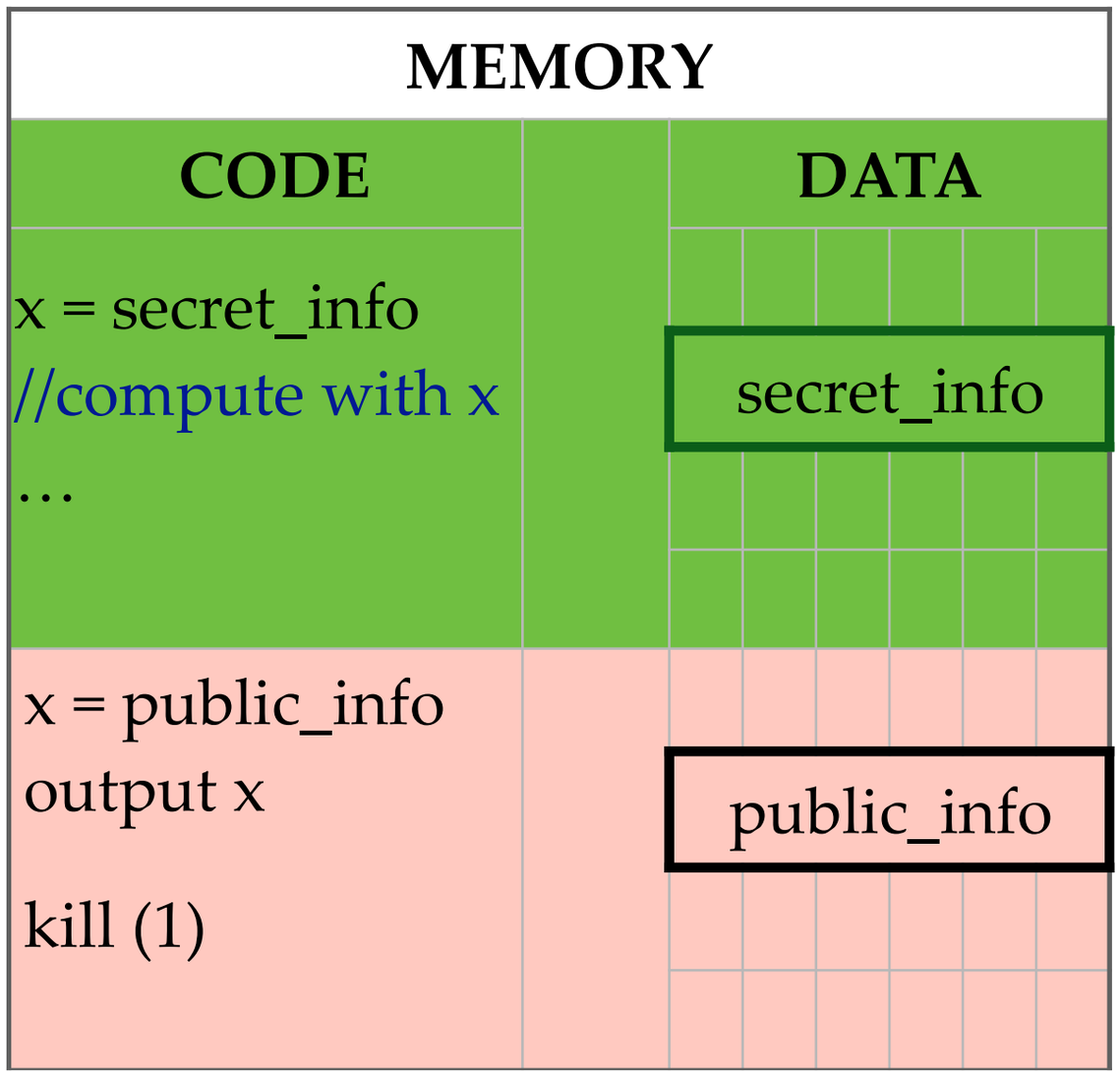

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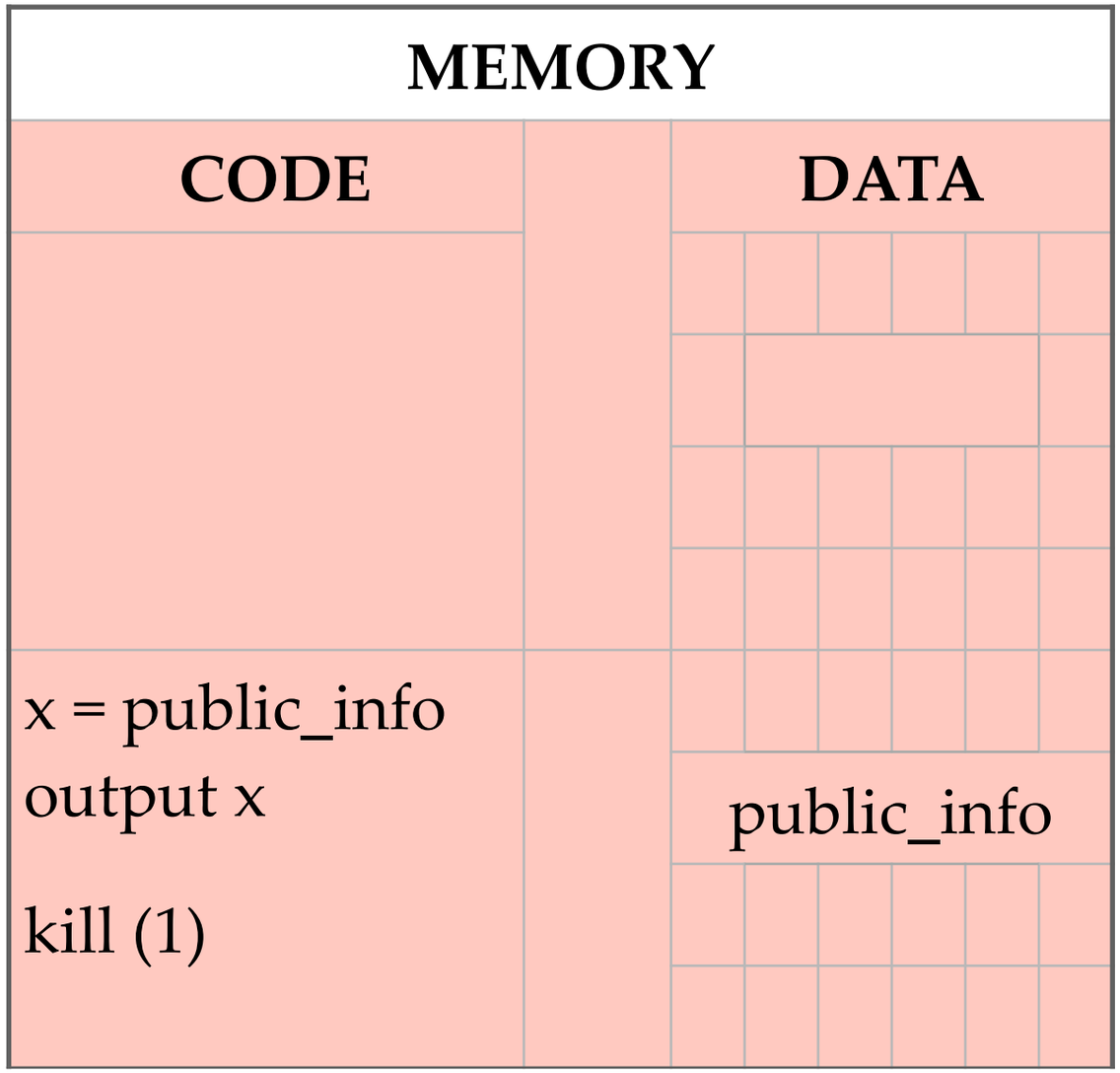

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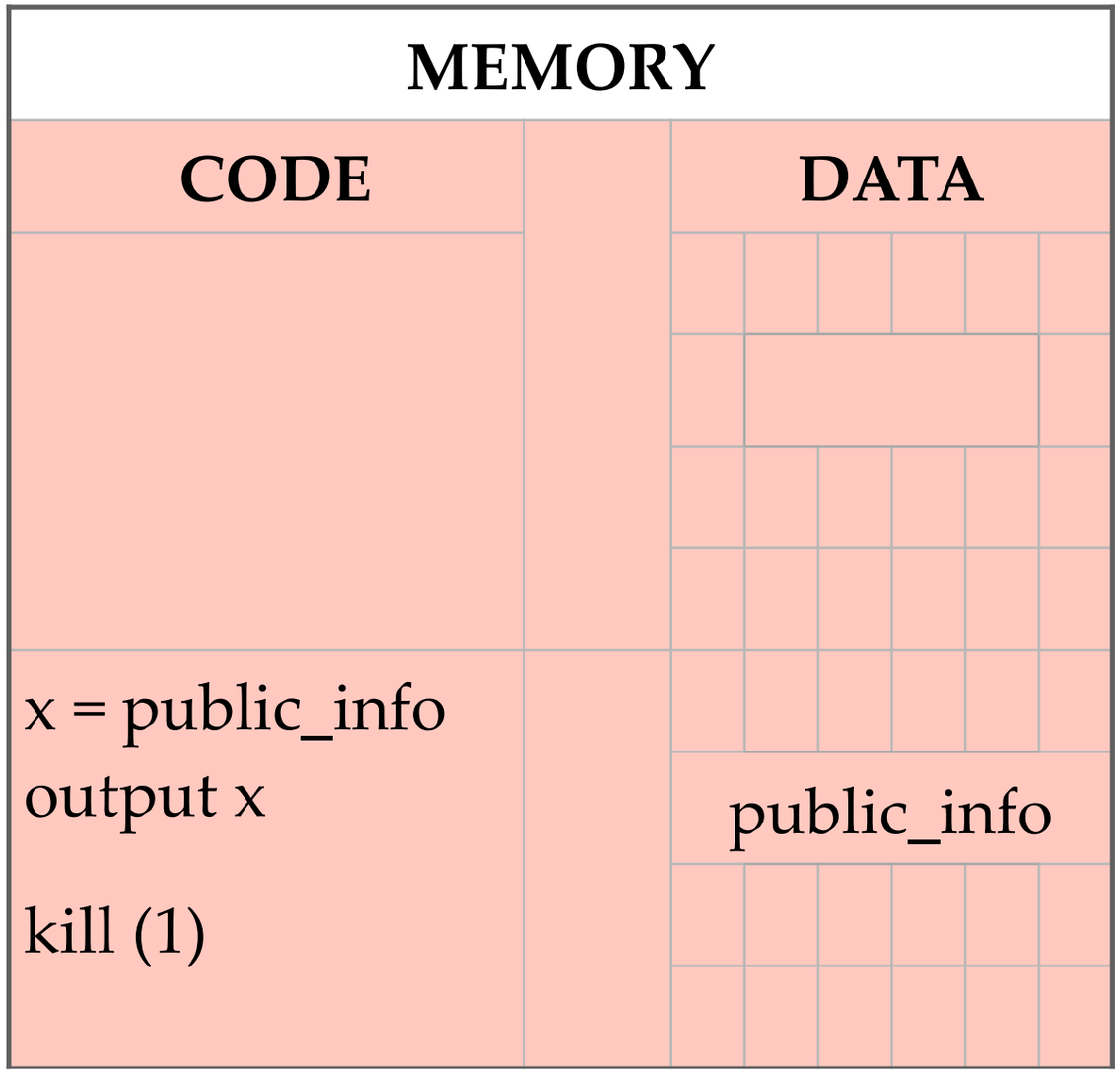

Why are enclaves useful for enforcing security?

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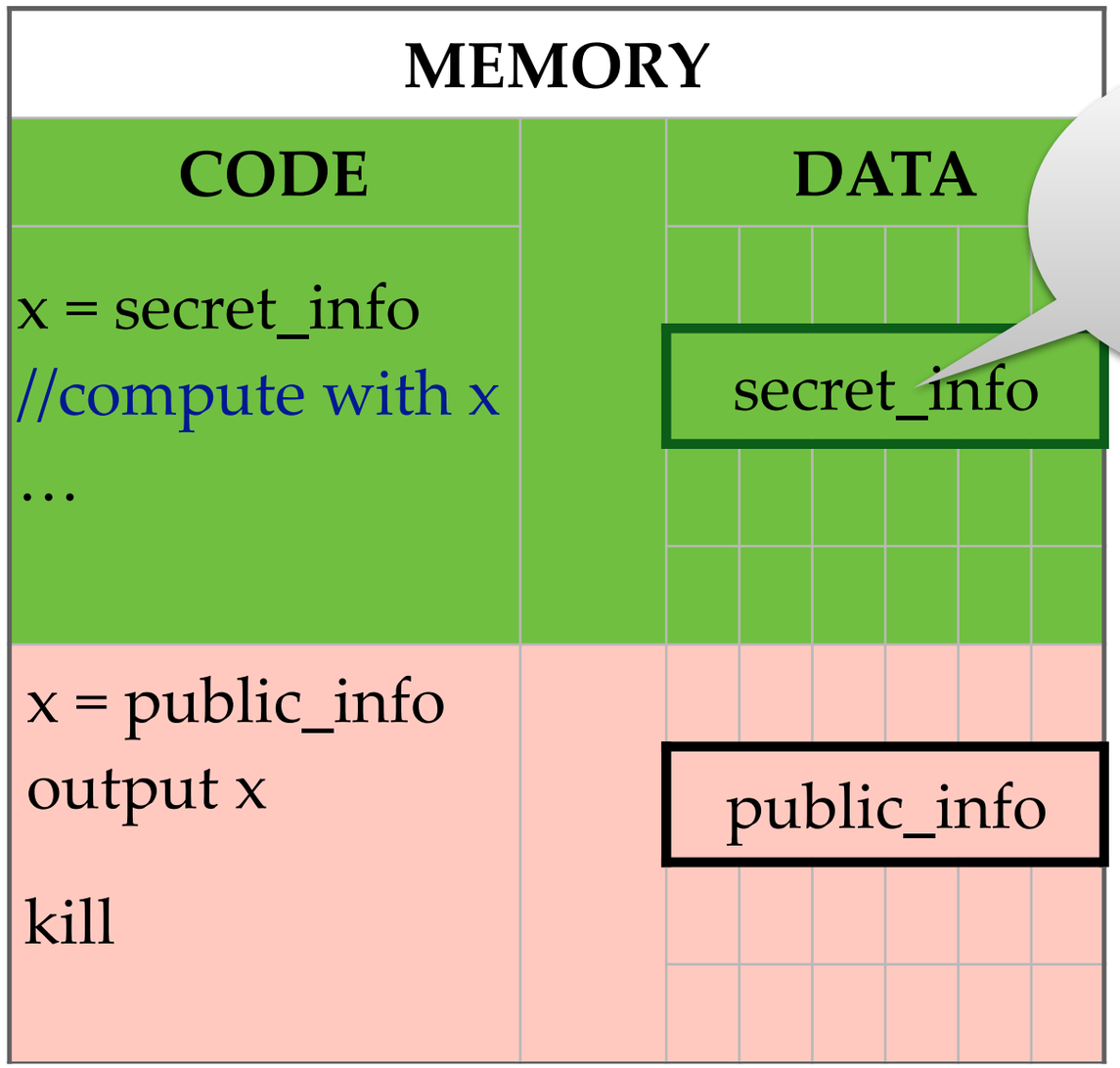
Program



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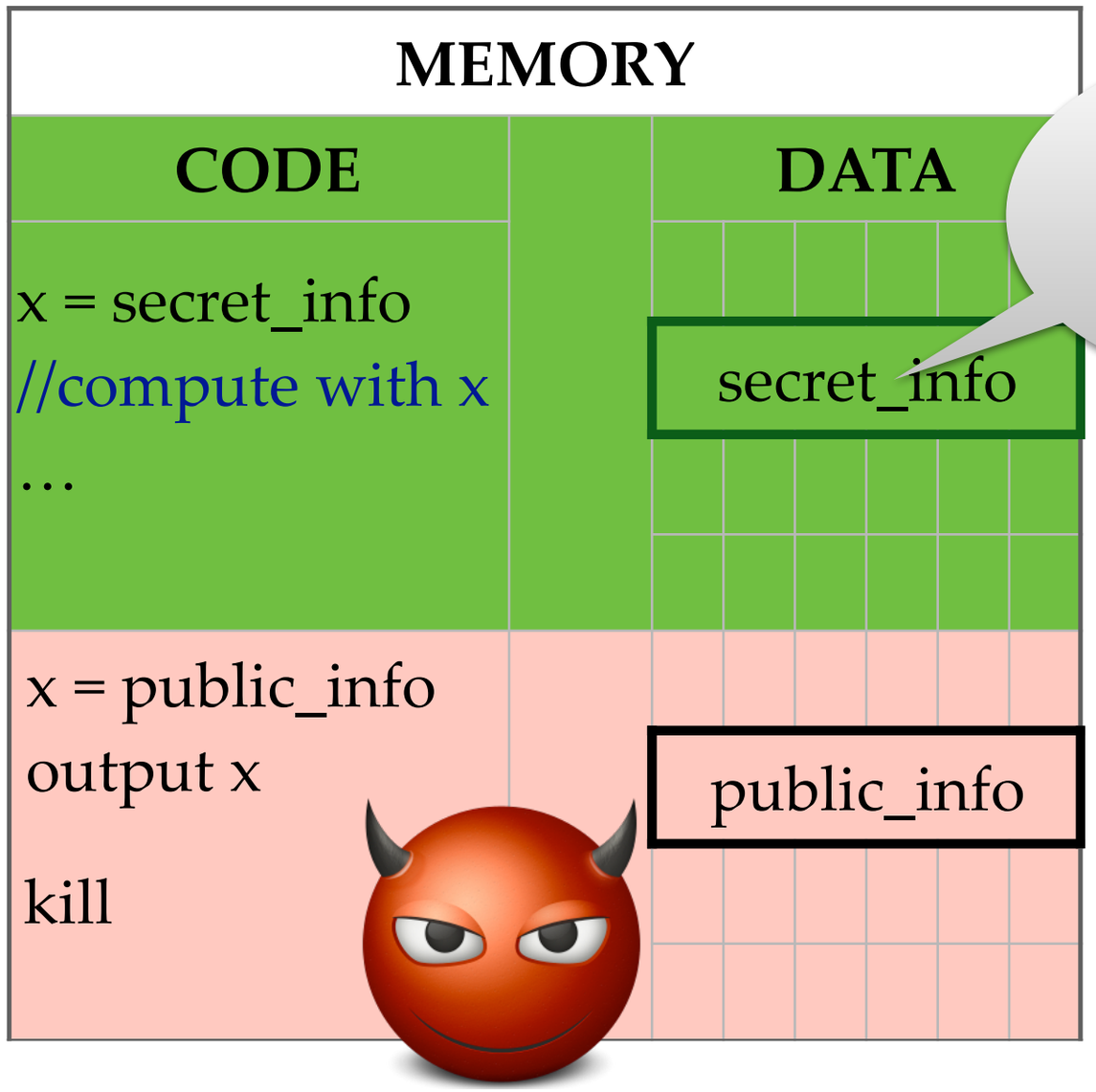

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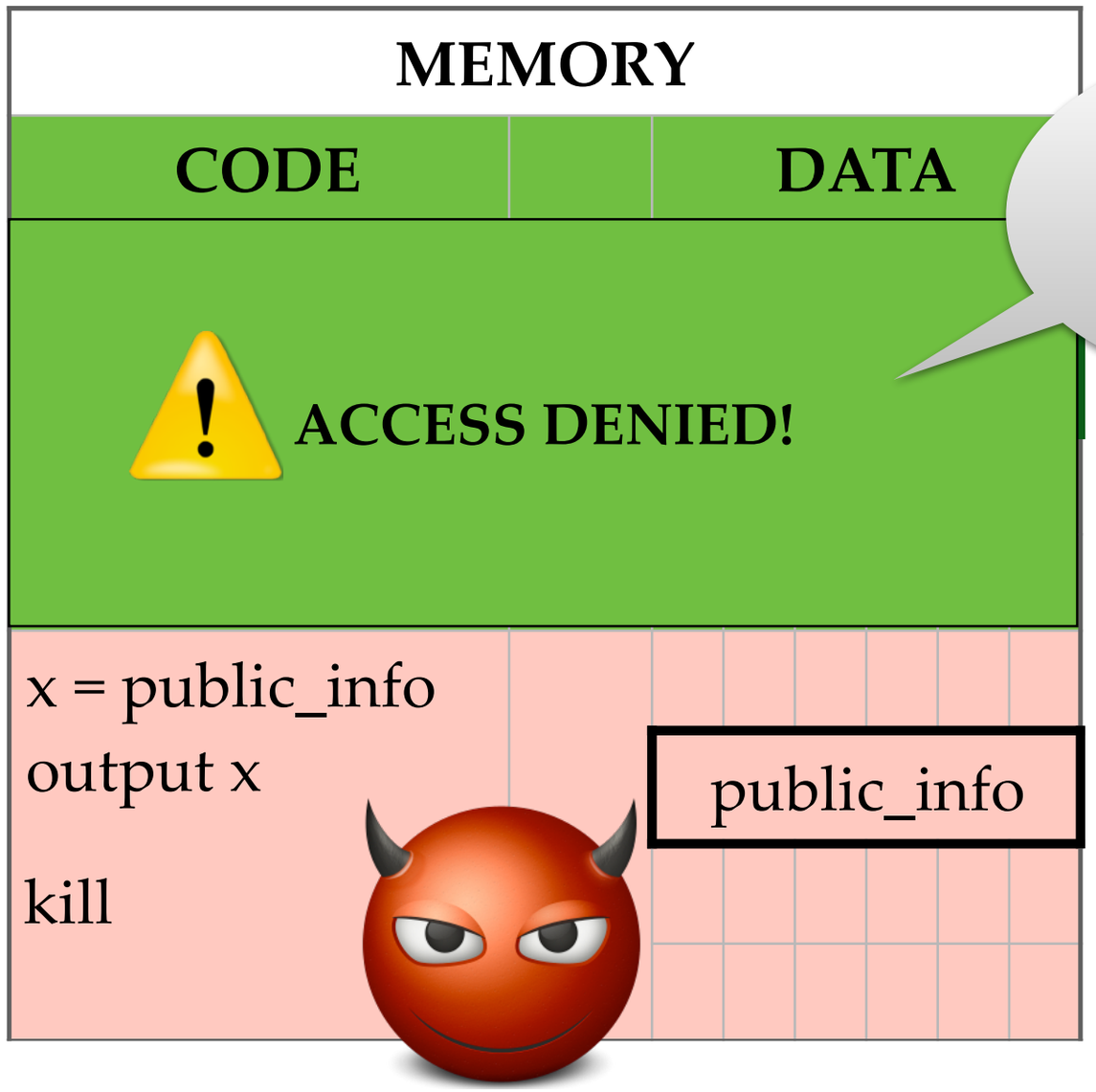

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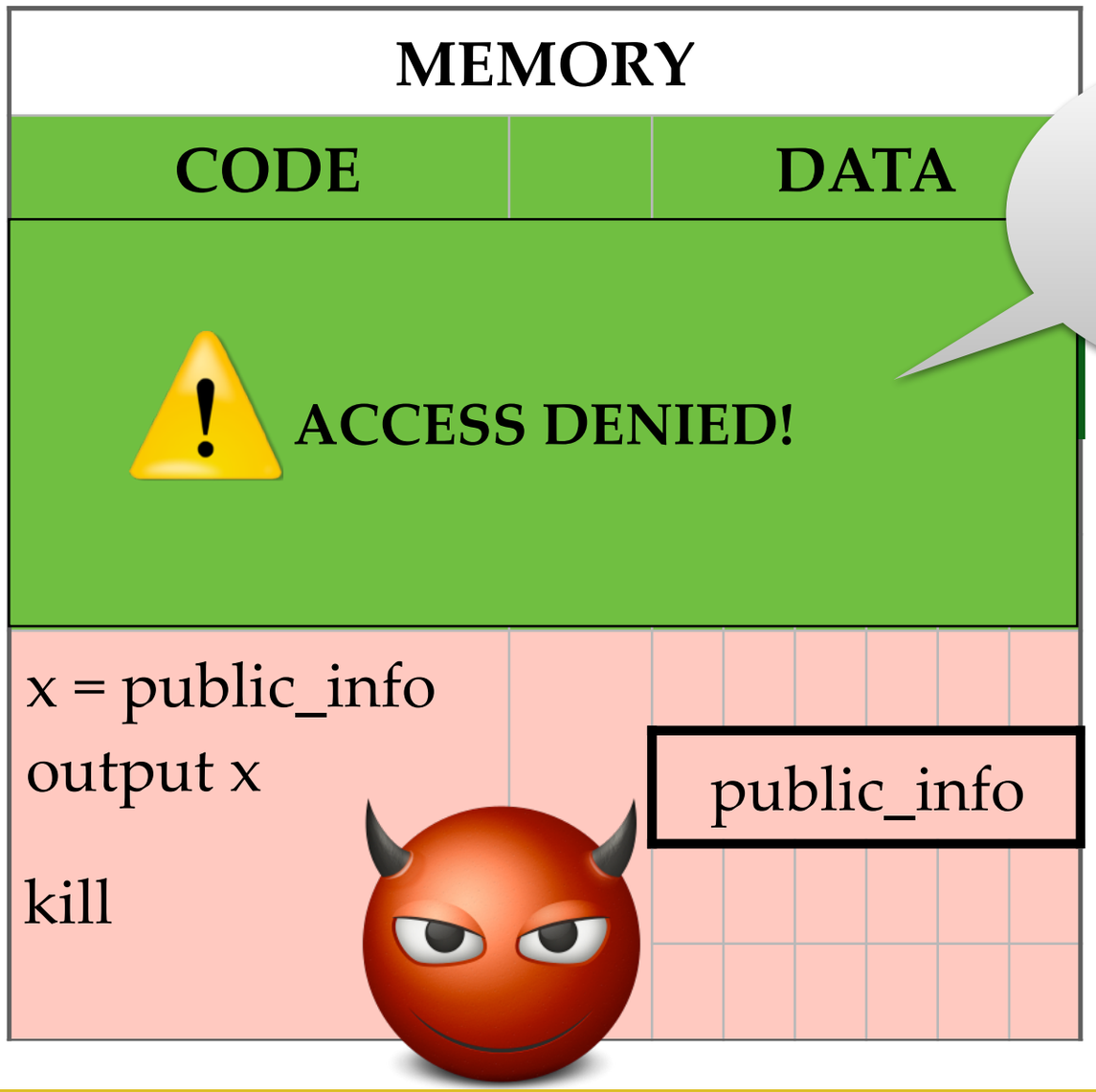

However, enclaves by themselves are insufficient!

Enclaves are Insufficient

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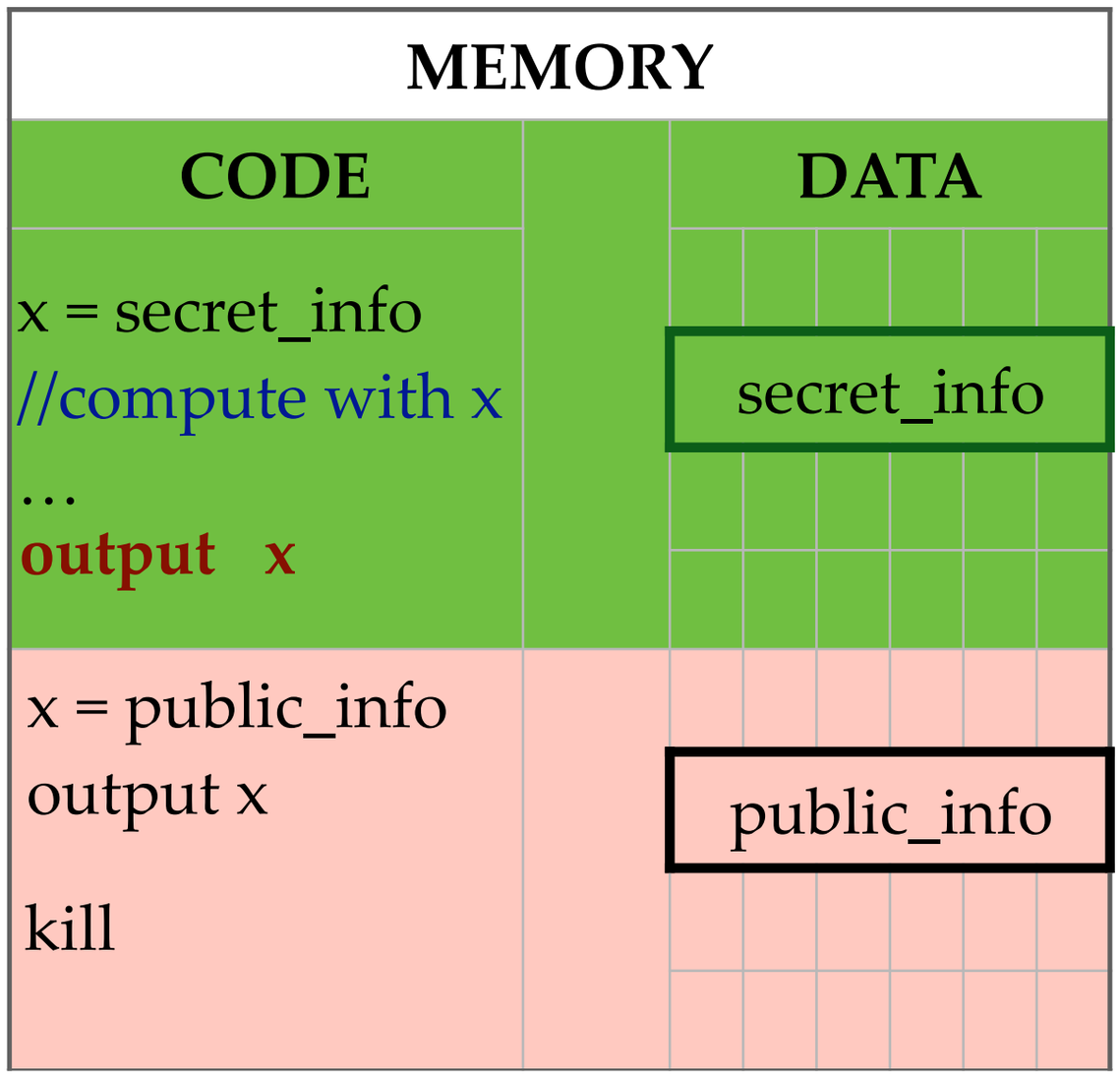

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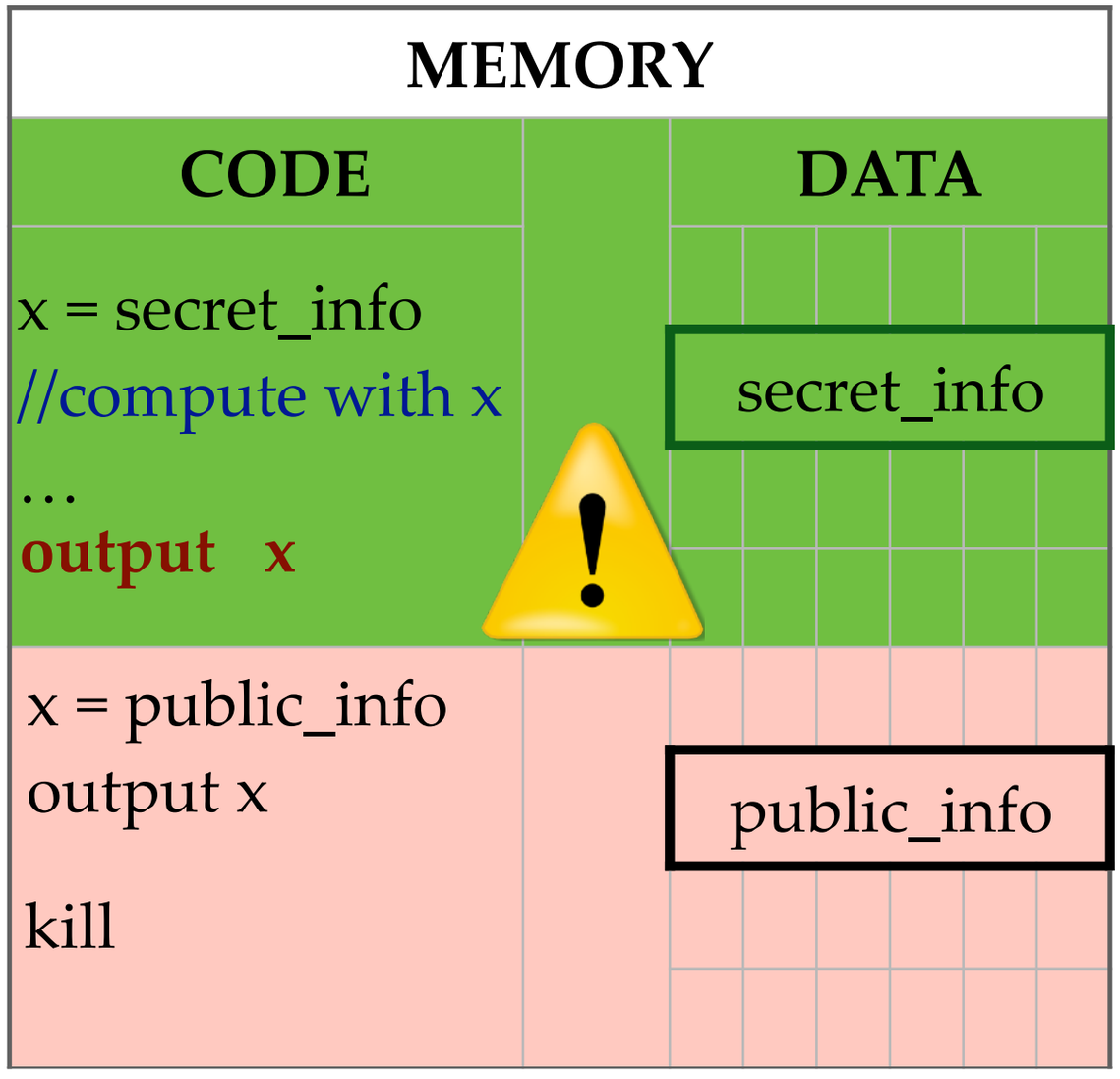

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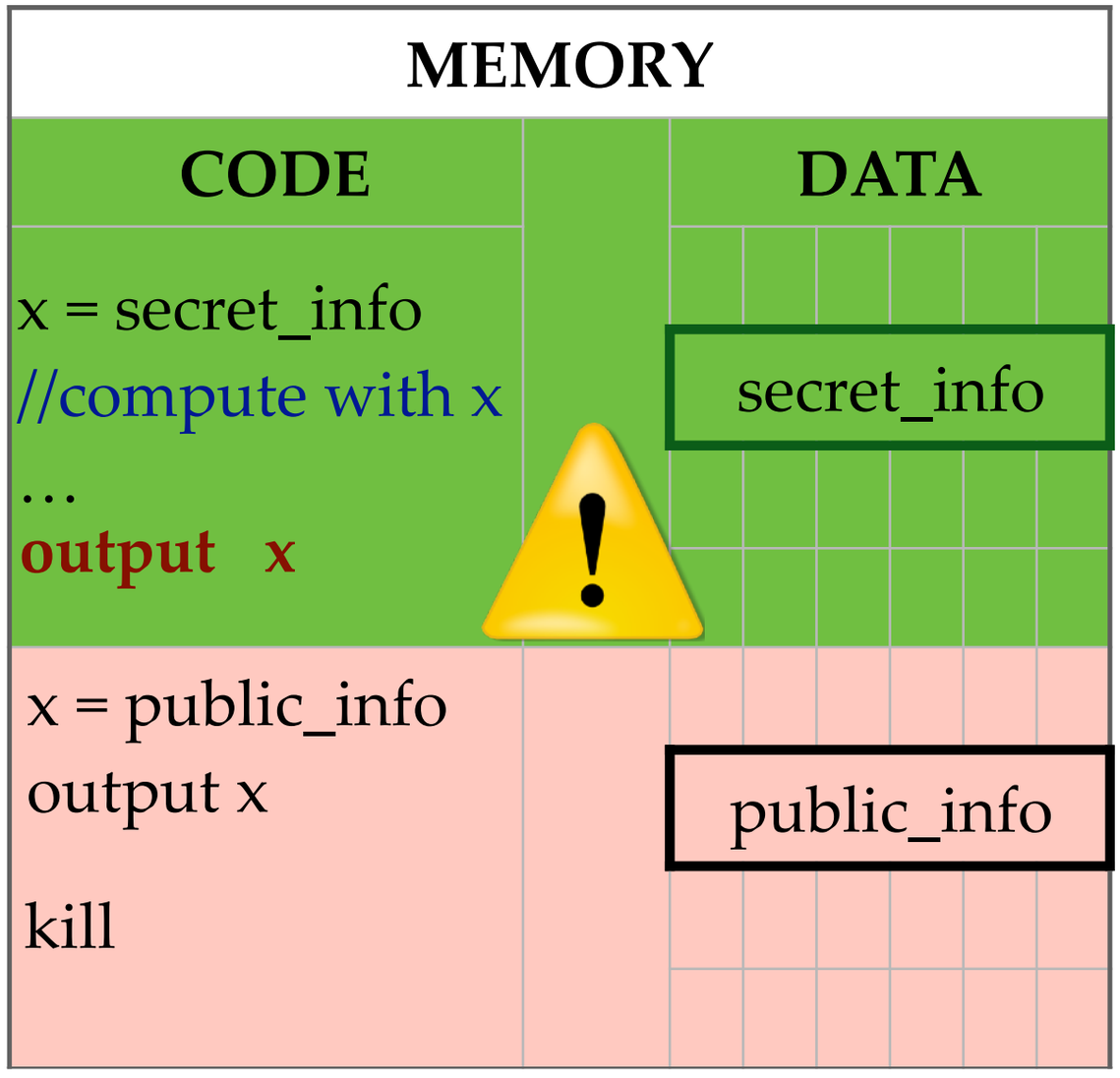

Extend the language-based security mechanisms with enclaves!

IMPE

- An expressive formal calculus
- Extends a standard imperative calculus with
  - Enclaves
  - First-class functions
  - Security policies
    - Express application-specific security requirements

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- Confidentiality levels
  - form a linear order

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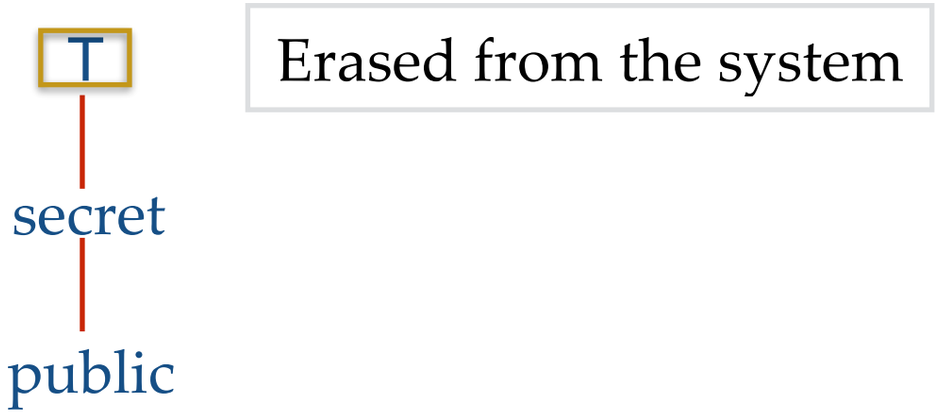

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- Erasure policy : change of confidentiality level during the program execution

Erased from the system

- e.g. secret_info : 

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Security policies are enforced w.r.t. a threat model

	Attacker	Observe Output	Modify Non-Enclave Memory	Modify Enclave Memory	Example
	Passive	✔	✘	✘	Network monitoring
	Non-Enclave Active	✔	✔	✘	Malware

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When is a program secure against these attackers?

Security

- Formally defined as a non-interference property
  - Public outputs are not influenced by private inputs
- Parameterized by the kind of attacker

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Security against weaker attacker $\not\Rightarrow$ security against powerful attacker

Security Against Passive Attacker

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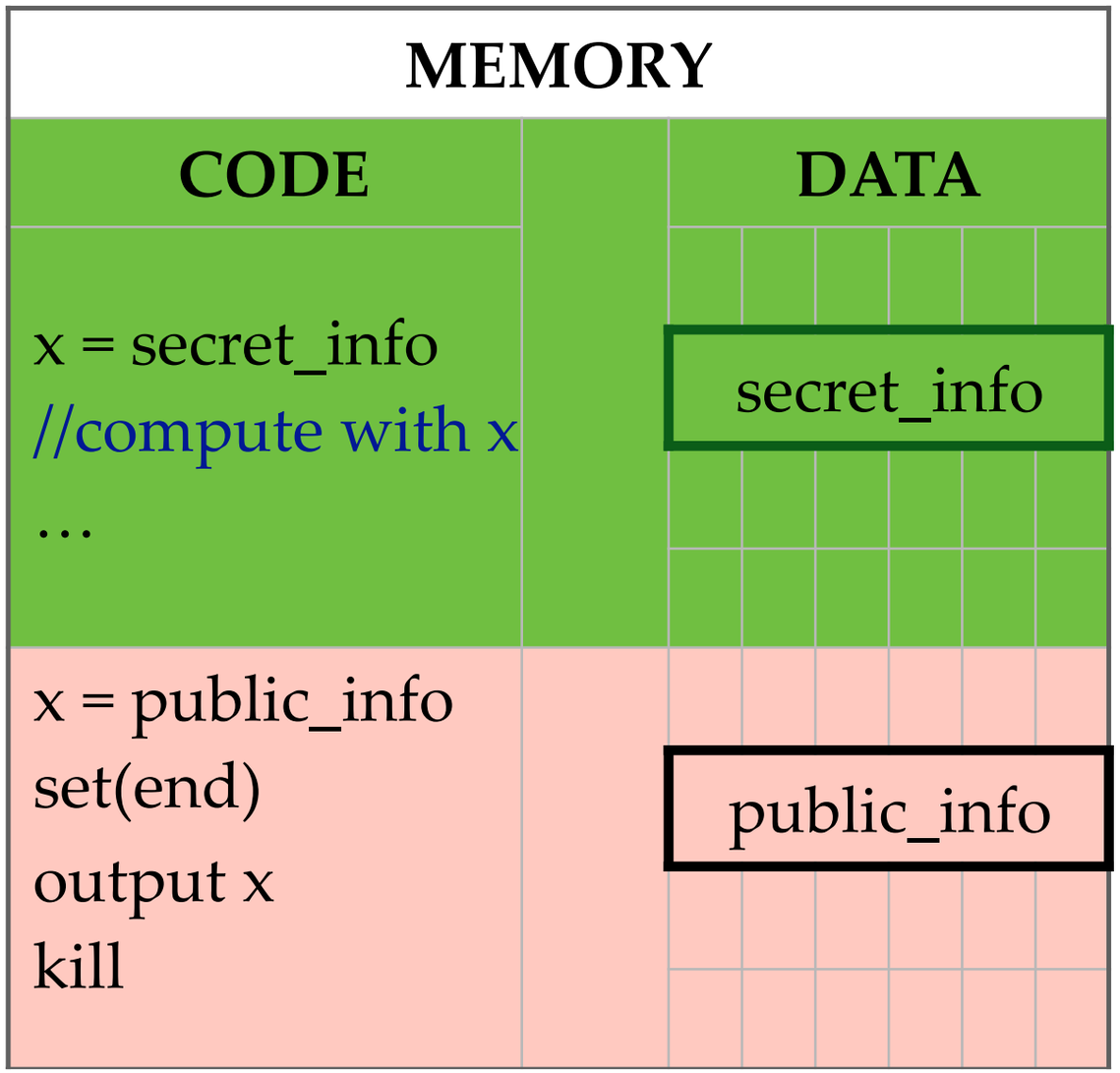

Security Against Non-enclave Active Attacker

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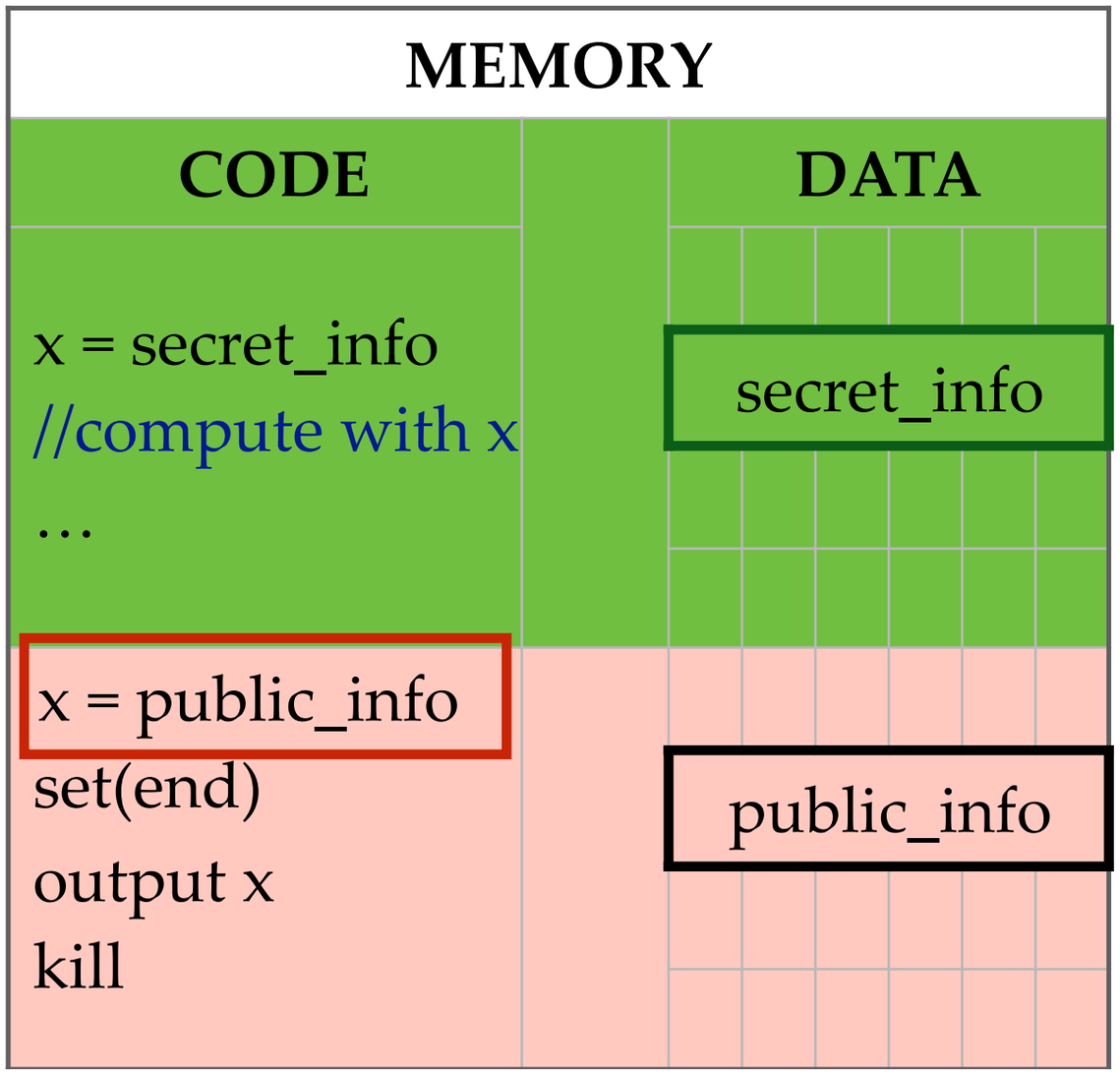

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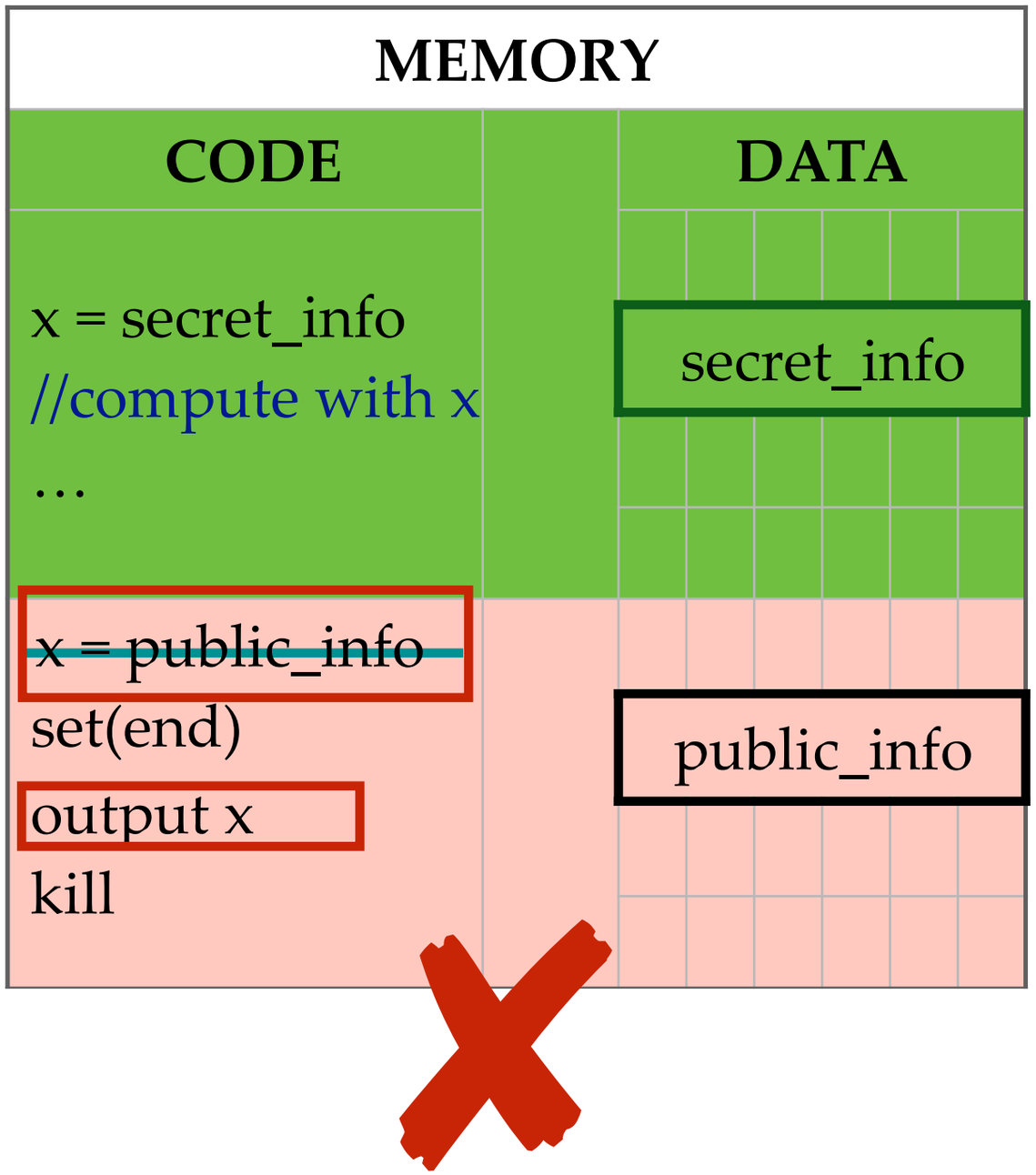

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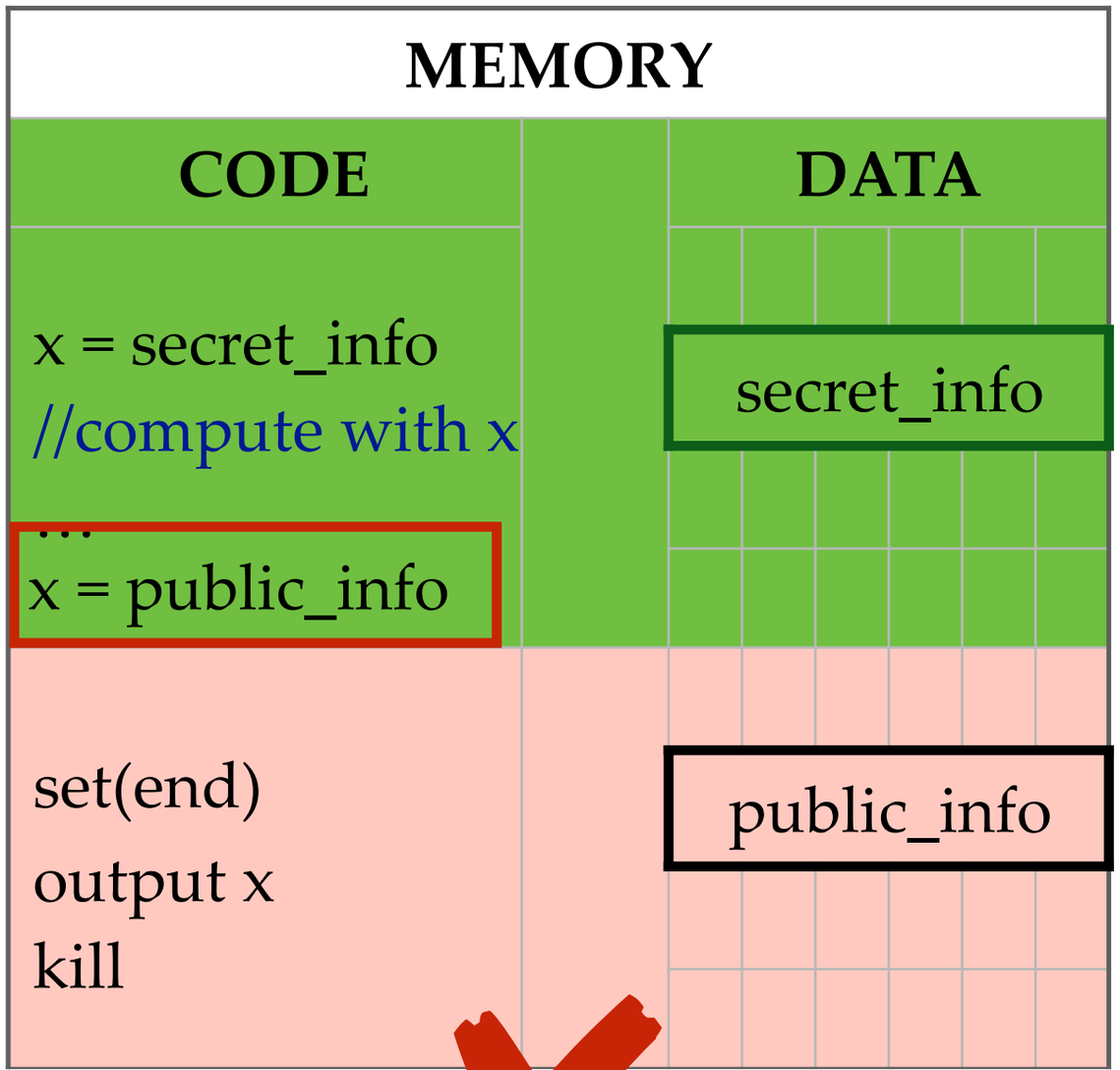

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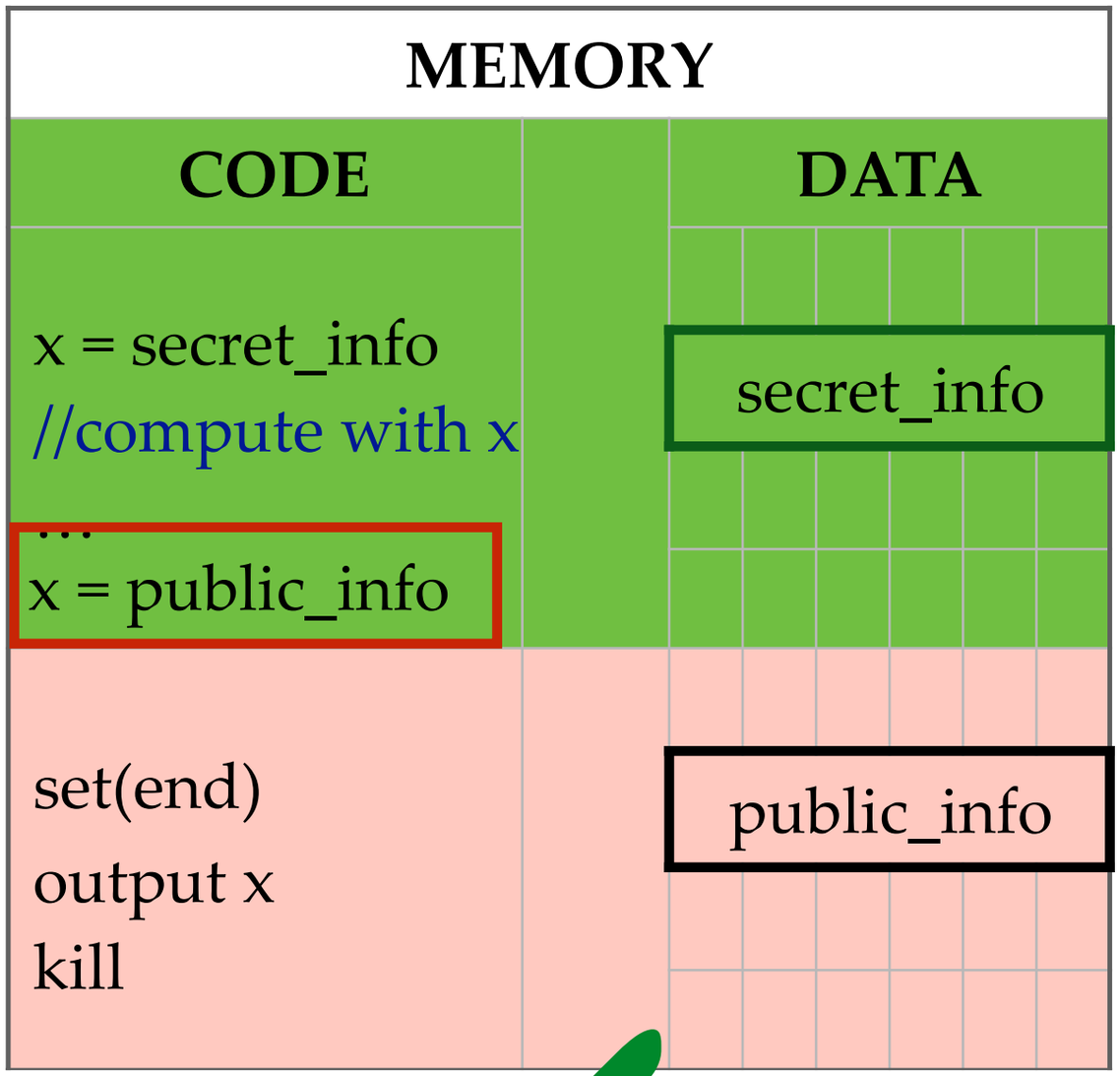

Enforcing Security

- Security Type System
  - secret information is placed only in enclaves
  - code that manipulates the secret information is placed in the same enclave

Enforcing Security

- **Theorem:** Well-typed IMPE programs are secure against
  - Passive attacker
  - Non-enclave active attacker

Enforcing Security

- **Theorem:** Well-typed IMPE programs are secure against
  - Passive attacker
  - Non-enclave active attacker
- Is the program secure for **enclave active attacker**?

Security Against Enclave Active Attacker

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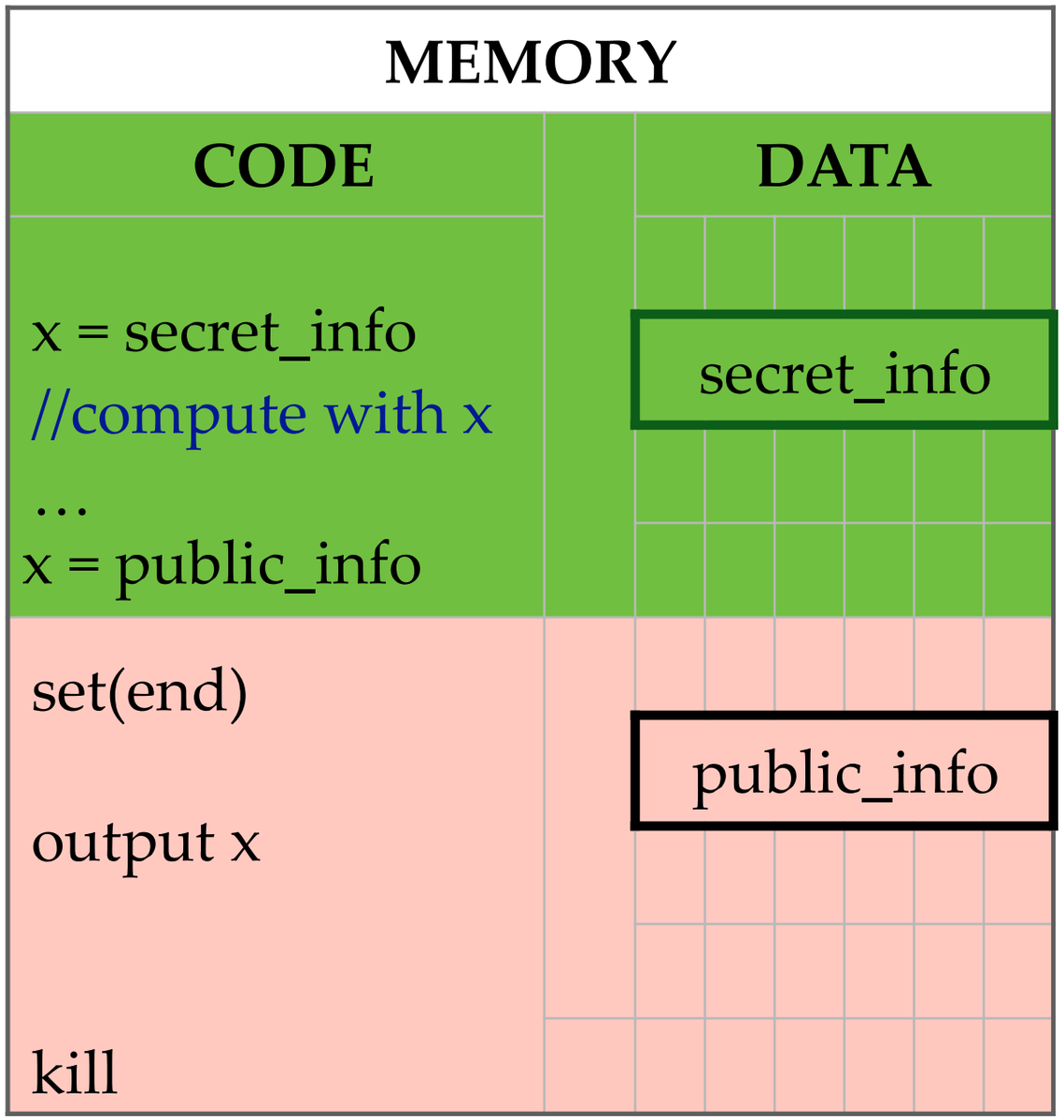

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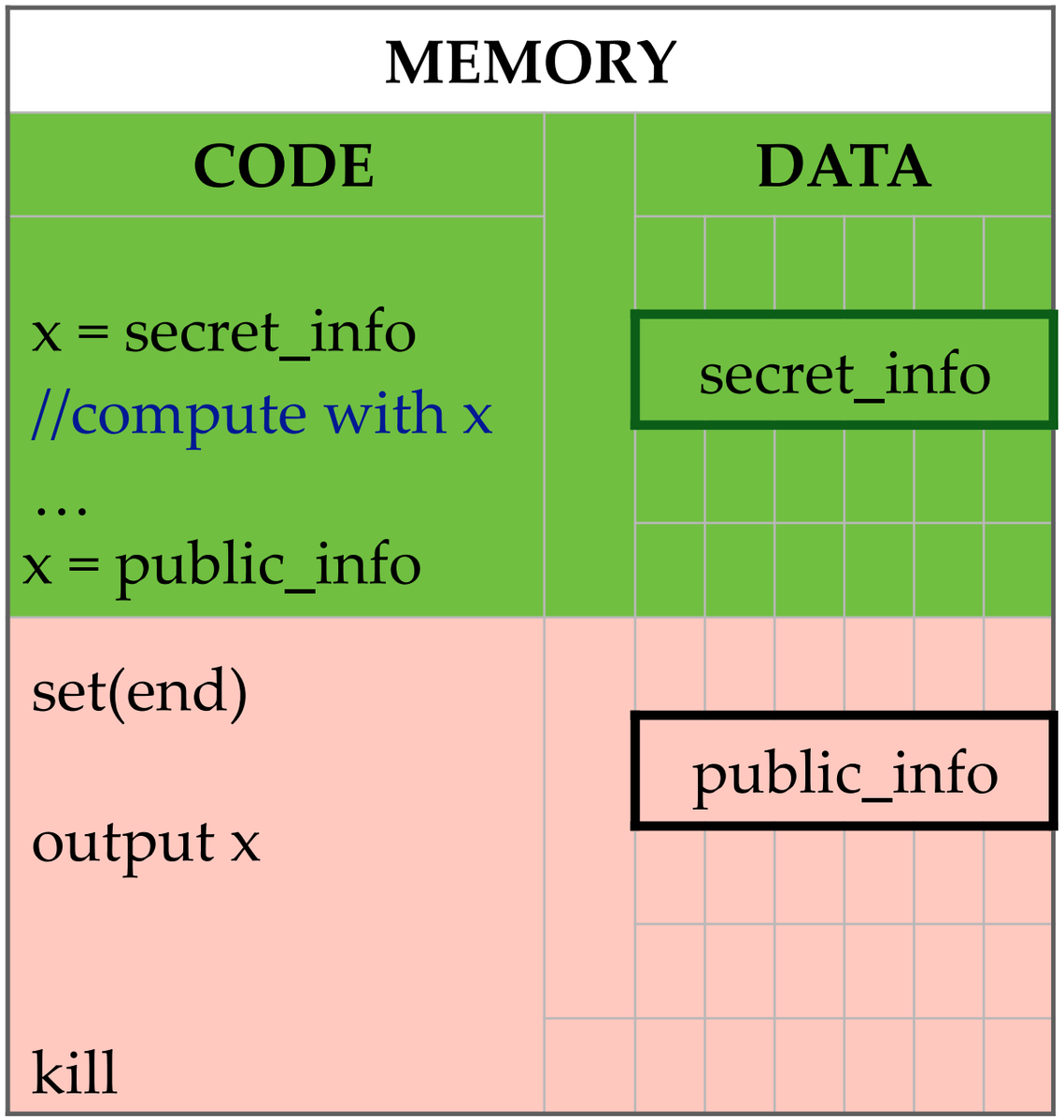

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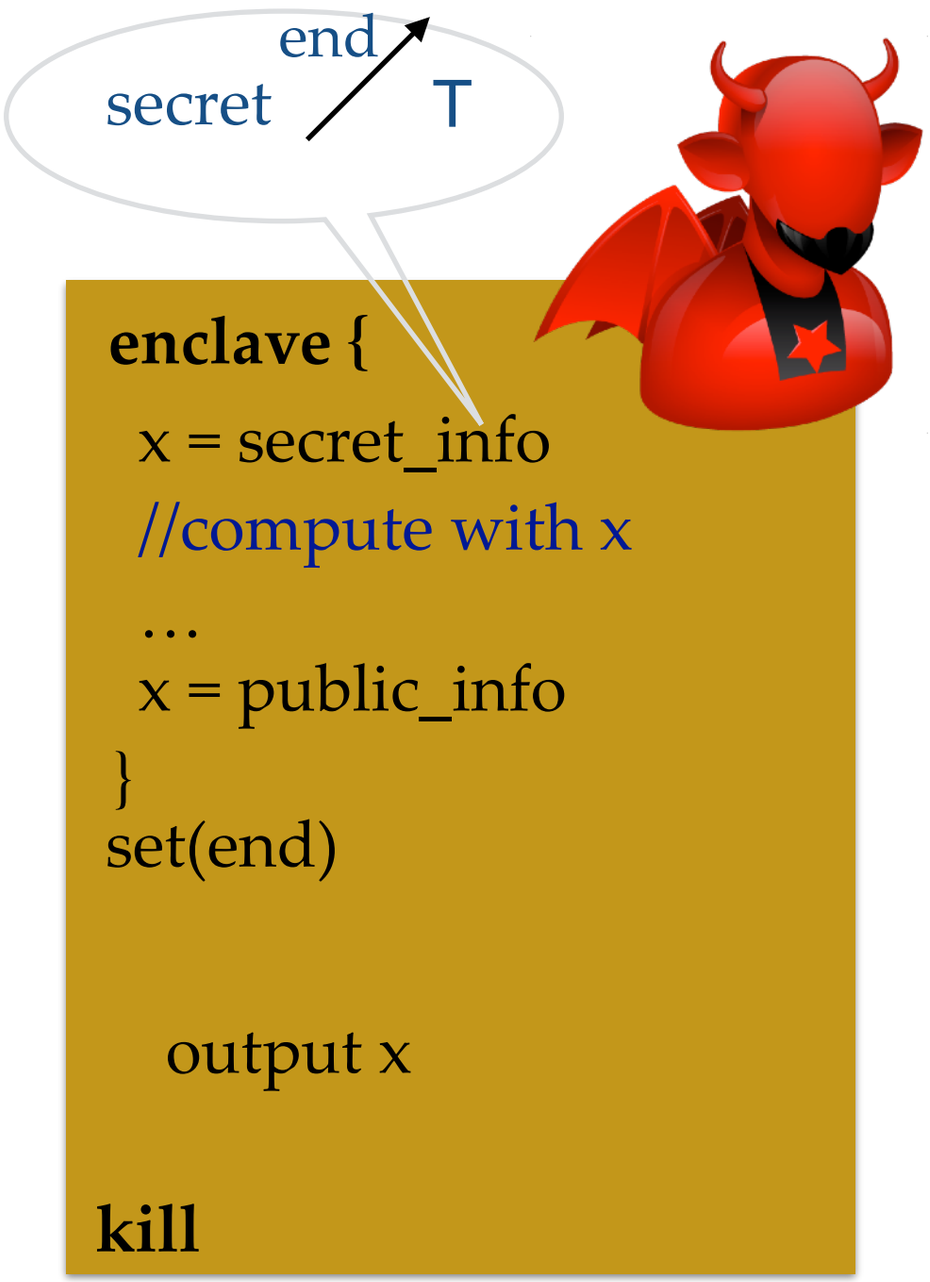

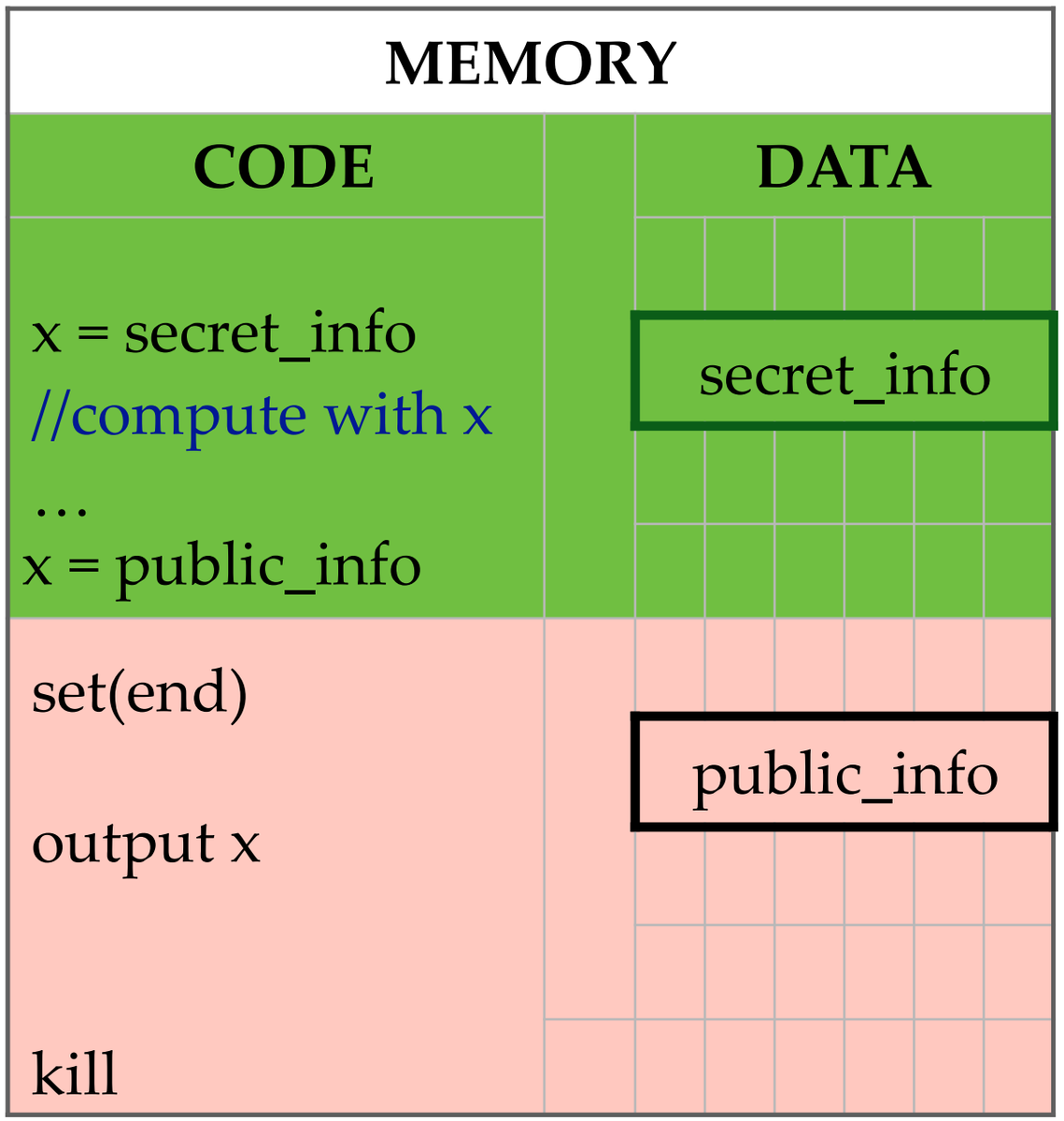

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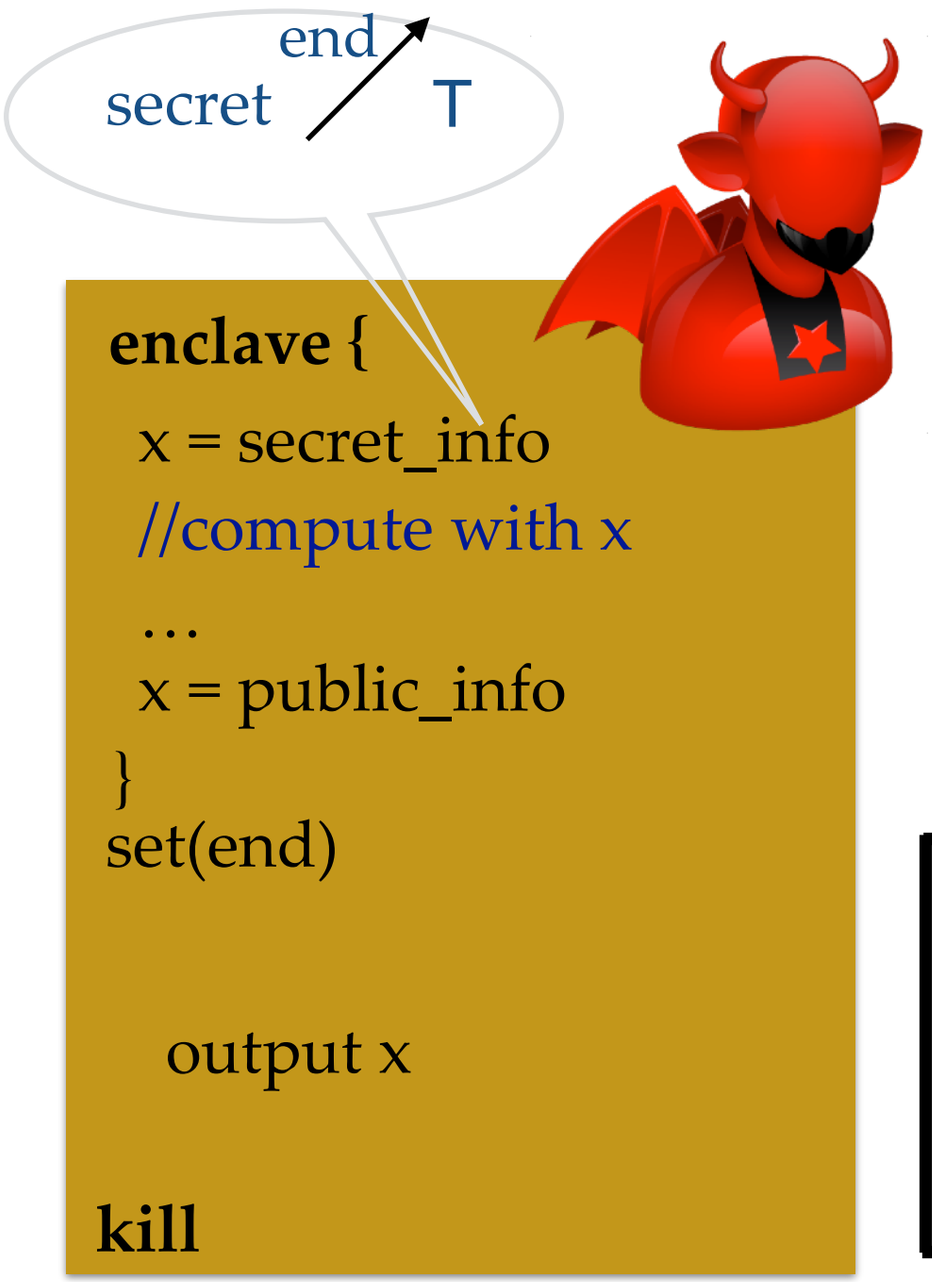
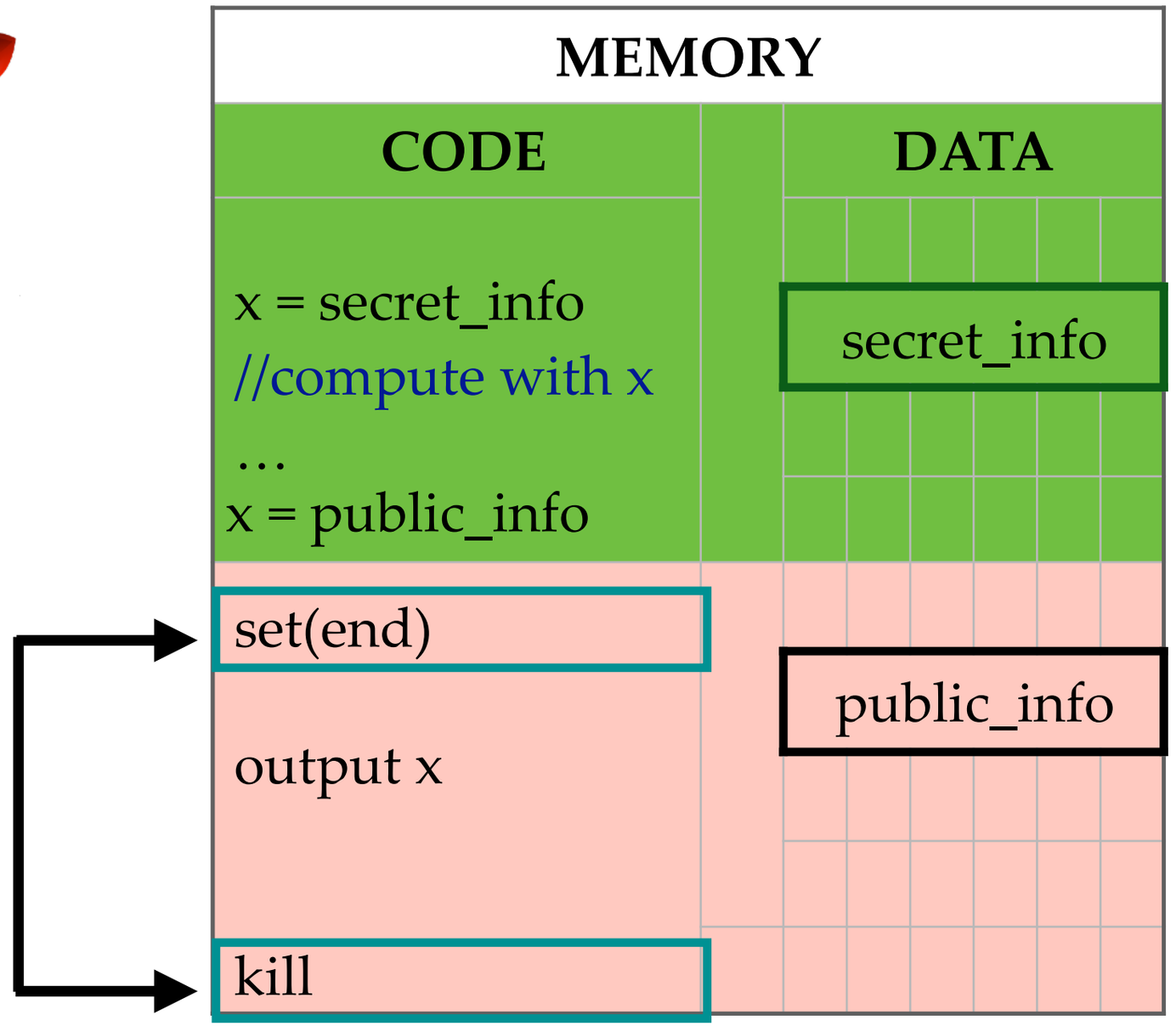
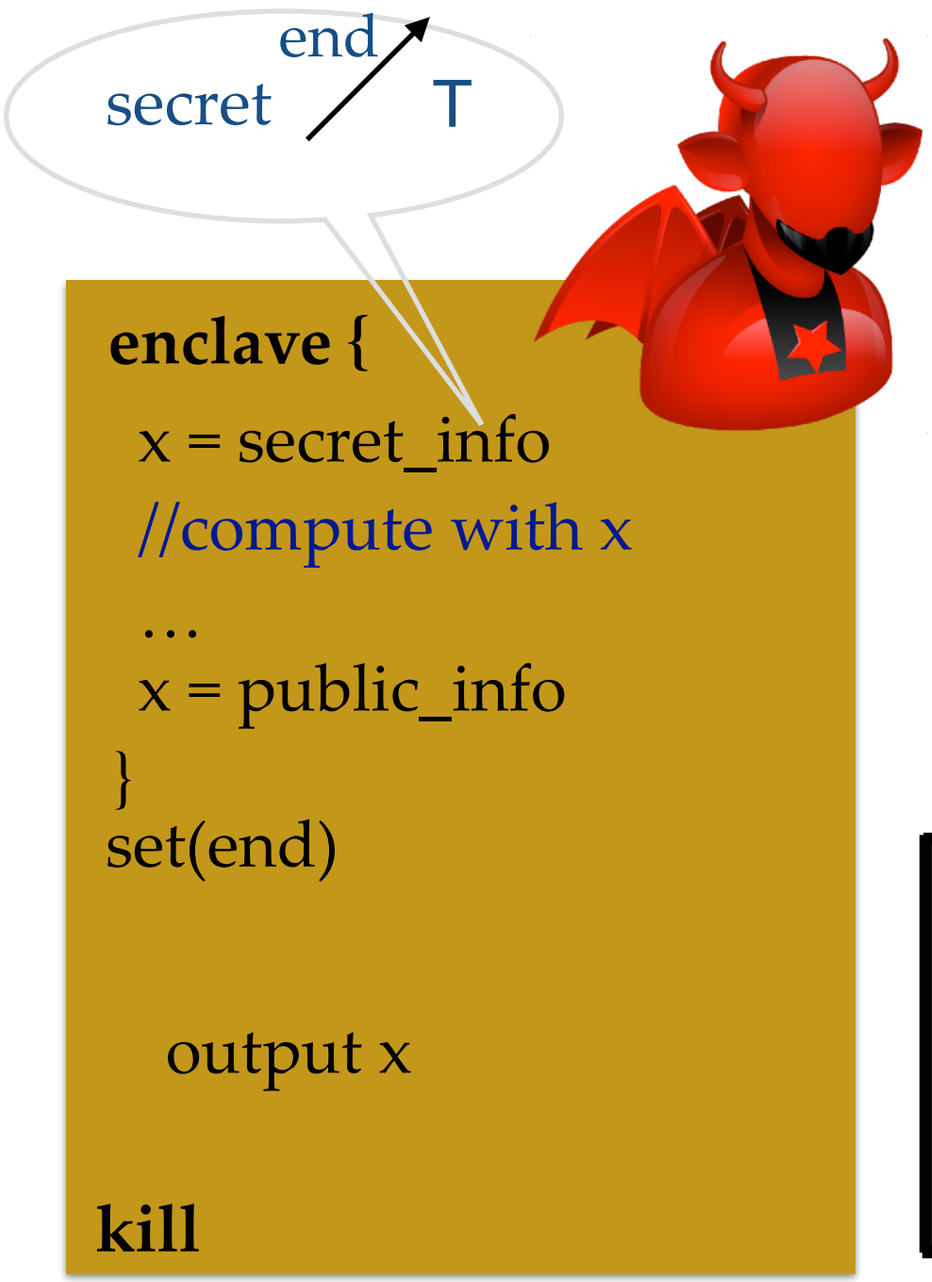
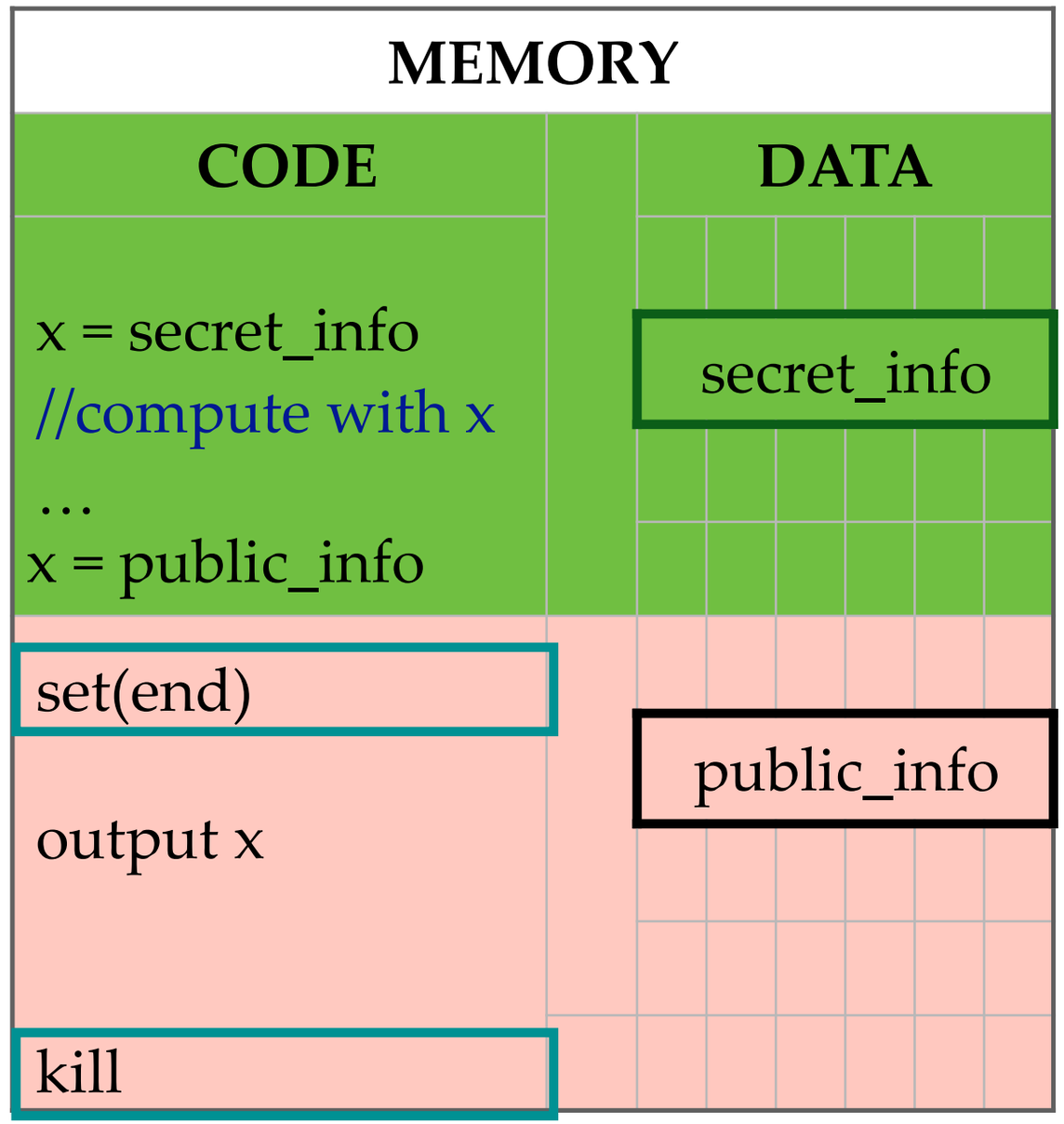




- Window of vulnerability

Security Against Enclave Active Attacker





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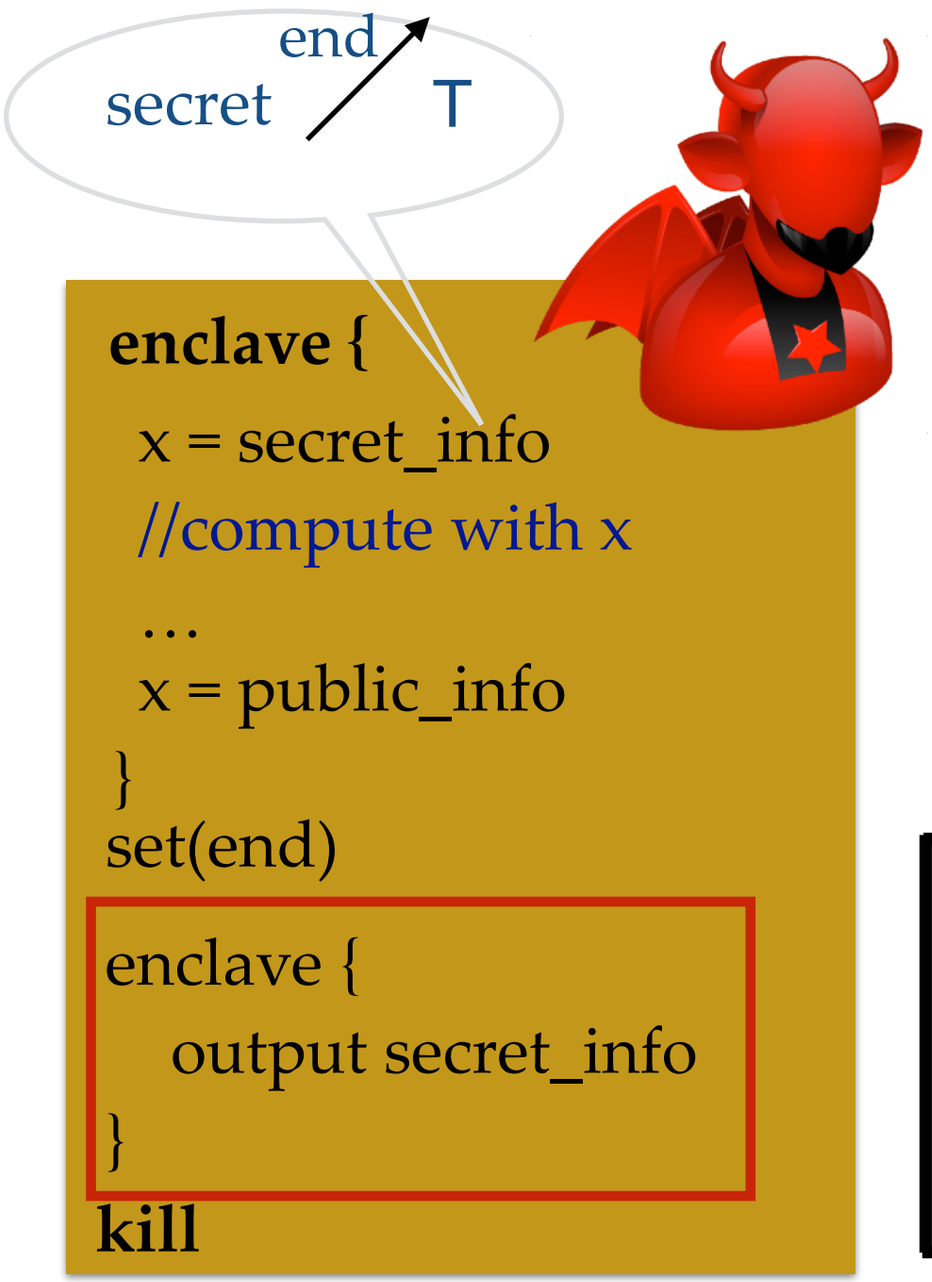
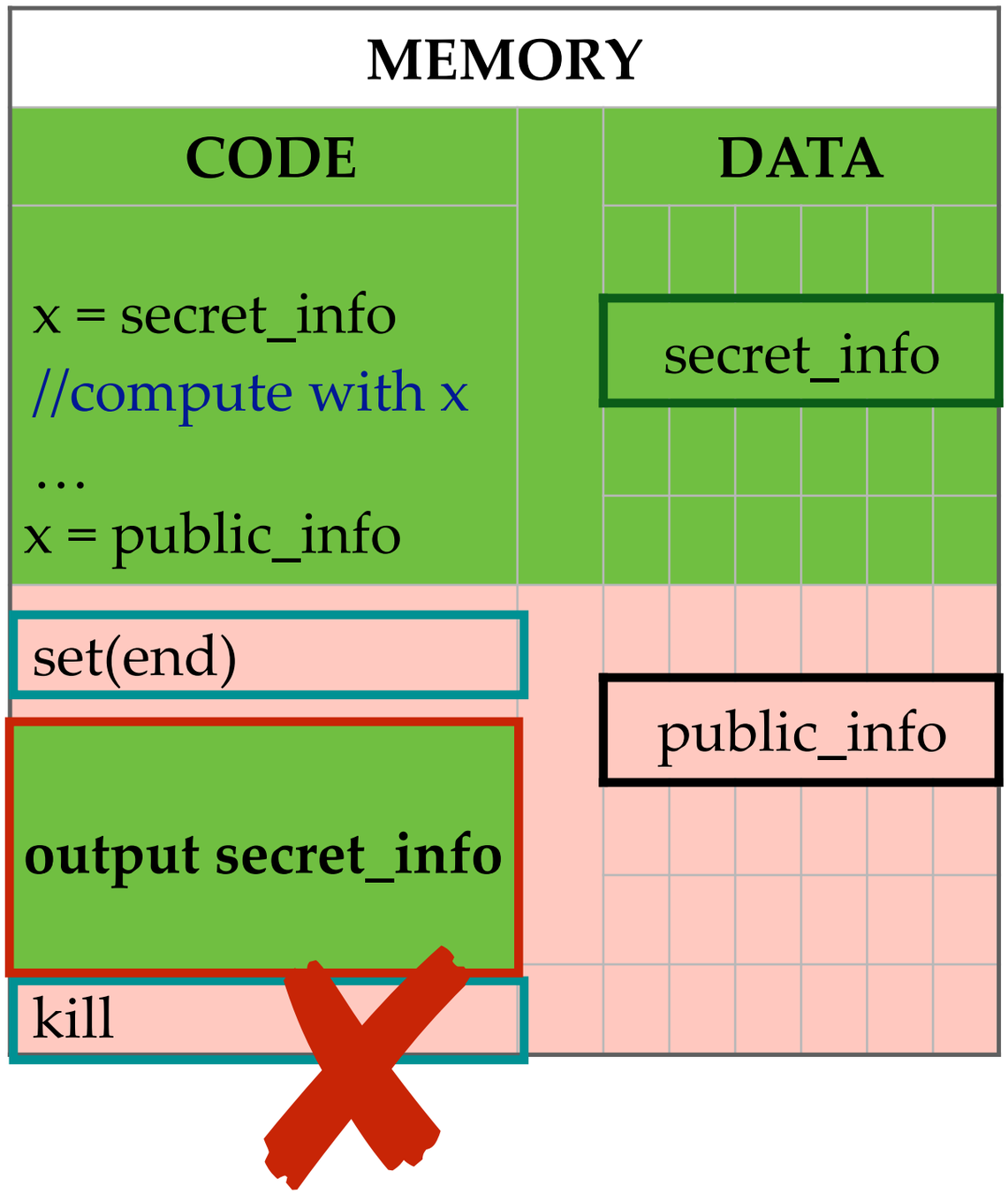
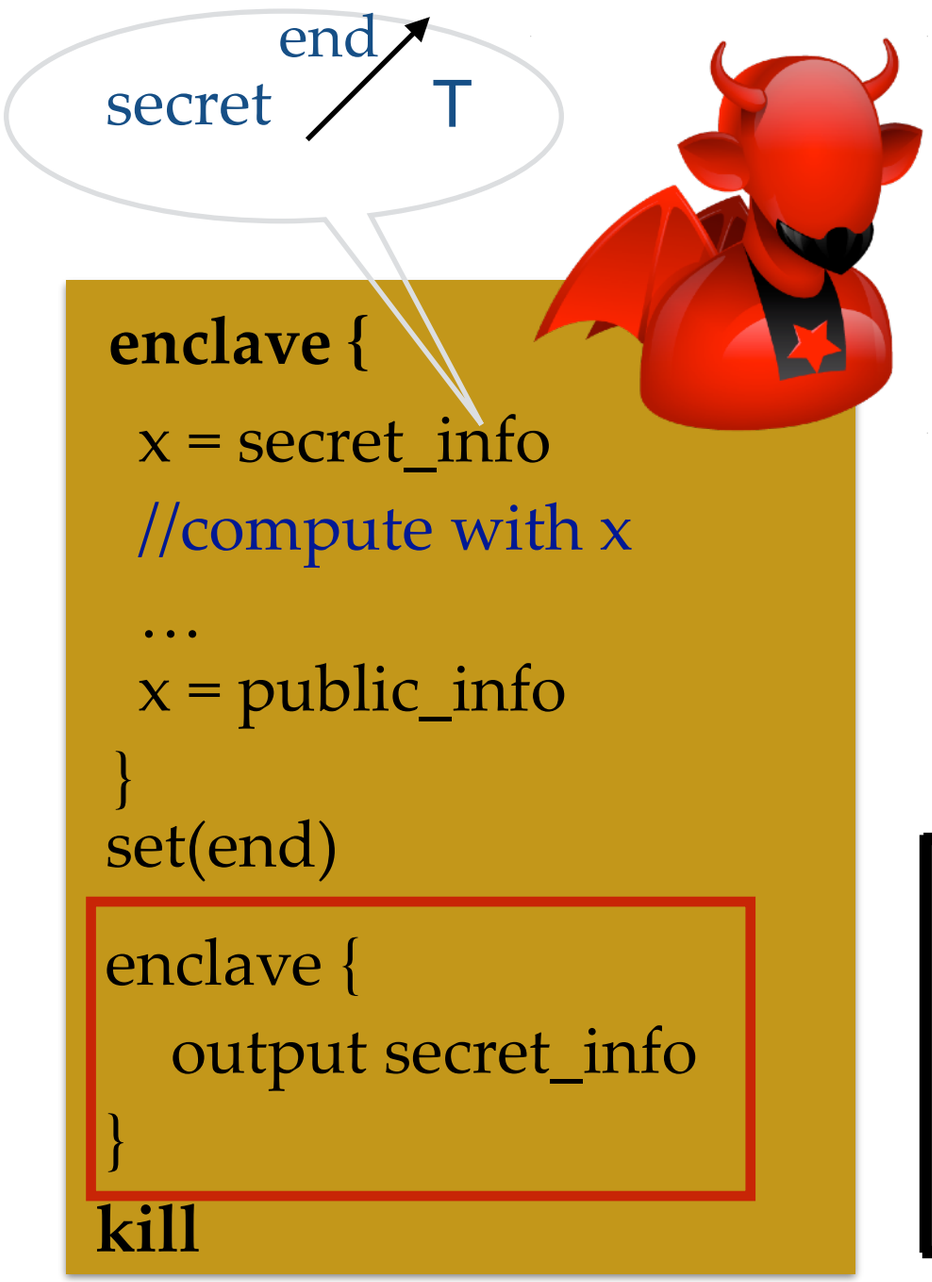
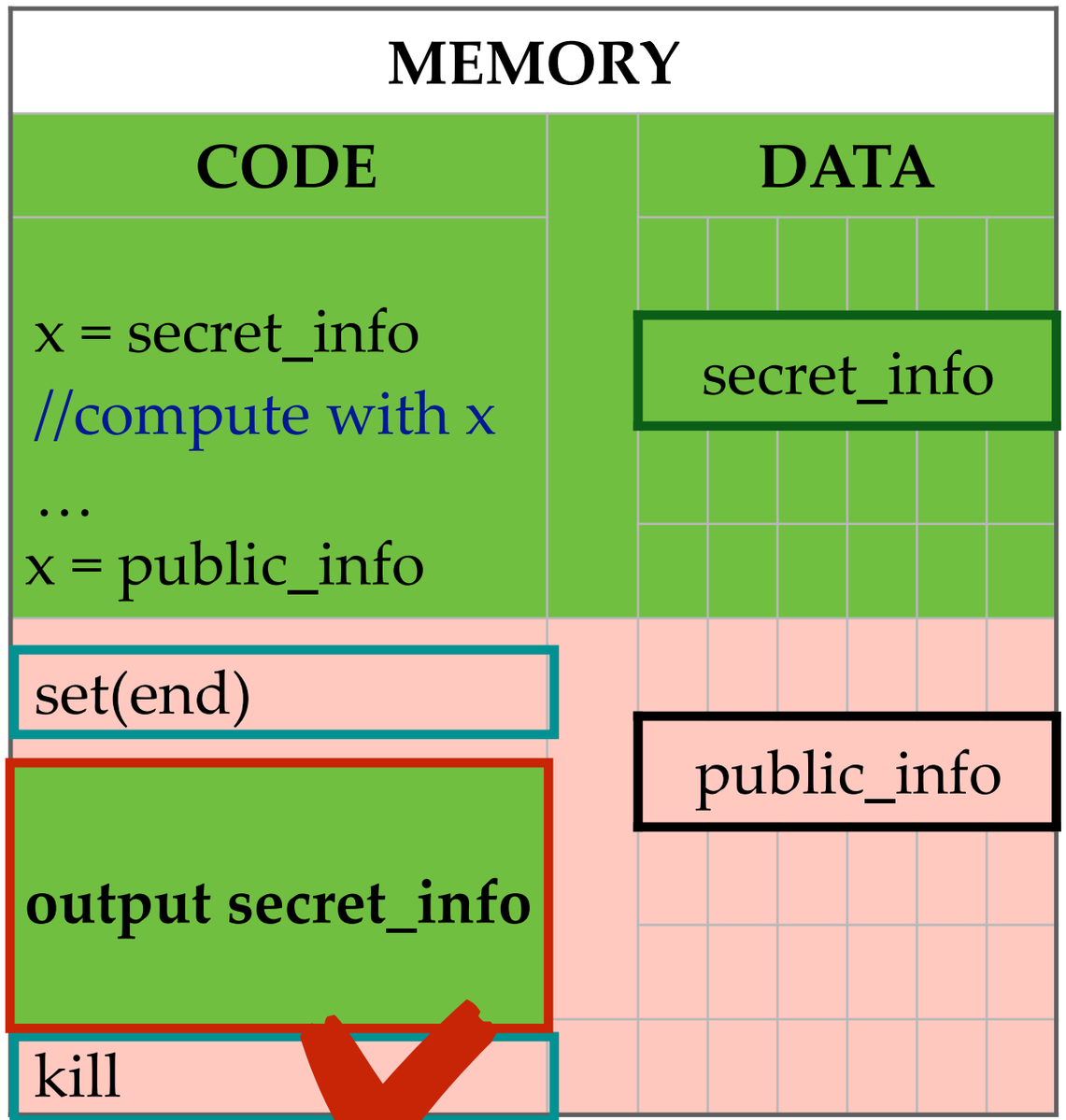




- Window of vulnerability

Security Against Enclave Active Attacker





- Window of vulnerability
- **Smaller the window, better the security**

Enforcing Security against Enclave Active Attackers

- **Theorem:** Well-typed IMPE programs are secure against enclave active attacker

- Only for attacks launched after the enclaves (containing the data to be erased) are killed

Recap

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- Well-typed IMPE programs are:
  - Secure against passive attacker
  - Secure against non-enclave active attacker
  - Partially secure against enclave active attacker

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  - For non-enclave active attacker
    - enclave code is assumed to have no vulnerabilities
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Trivial solution: Place entire application inside an enclave

- Increases trusted computing base (TCB)
  - For non-enclave active attacker
    - enclave code is assumed to have no vulnerabilities
  - More enclave code = more assumptions
- Increases window of vulnerability
  - Can't kill an enclave until the end
  - Data to be erased lives longer

How to Partition Program into Enclaves?

Using multiple enclaves:

- Fine-grained partitioning leads to smaller enclaves
  - Reduces the lifetime of data to be erased
- Tedious and error-prone

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We can automatically infer enclave placement!

Enclave Inference as Constraint Satisfaction

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Program w/out Enclaves

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- Sensitive data should be in some enclave
- A killed enclave cannot be accessed

constraints

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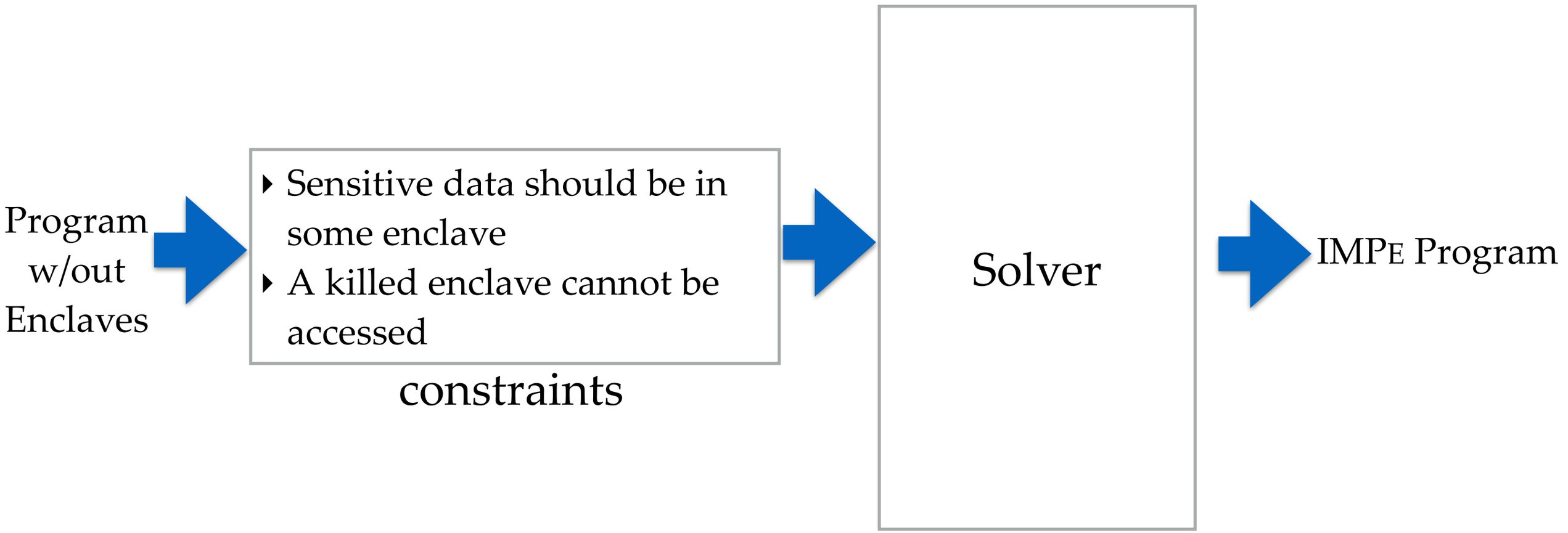
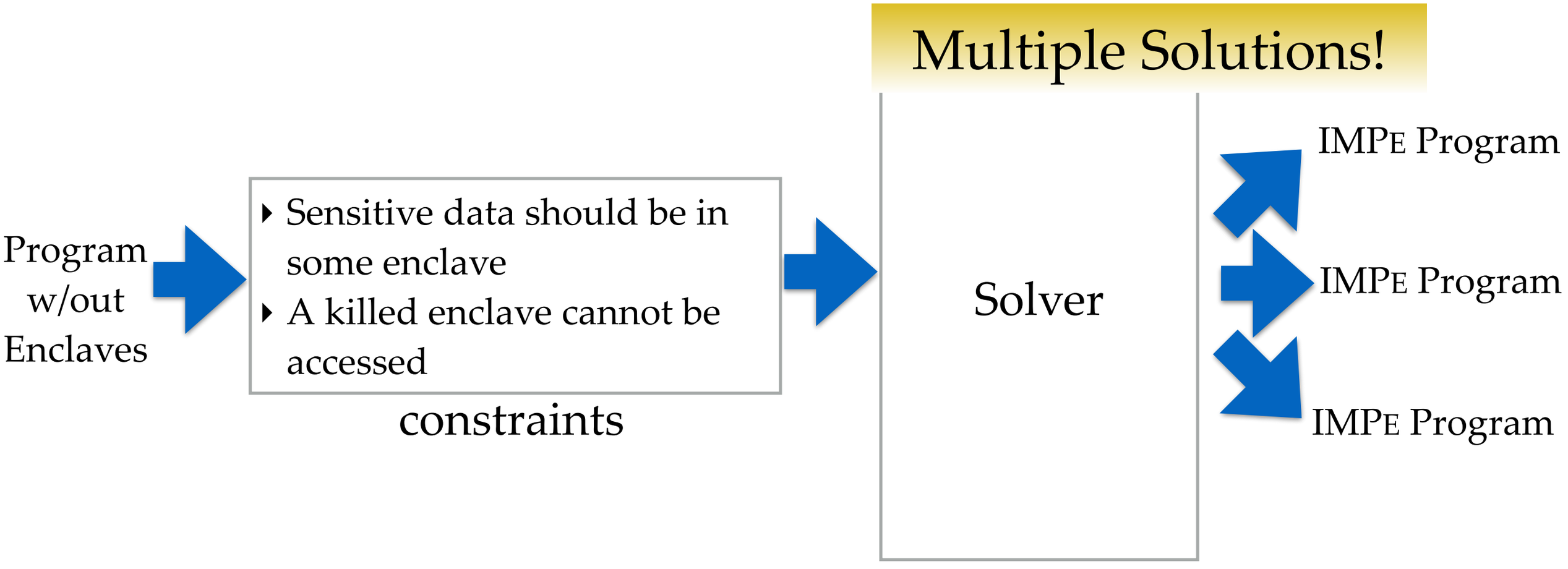
Solver

Enclave Inference as Constraint Satisfaction



Solution is a well-typed IMPE program

Enclave Inference as Constraint Satisfaction



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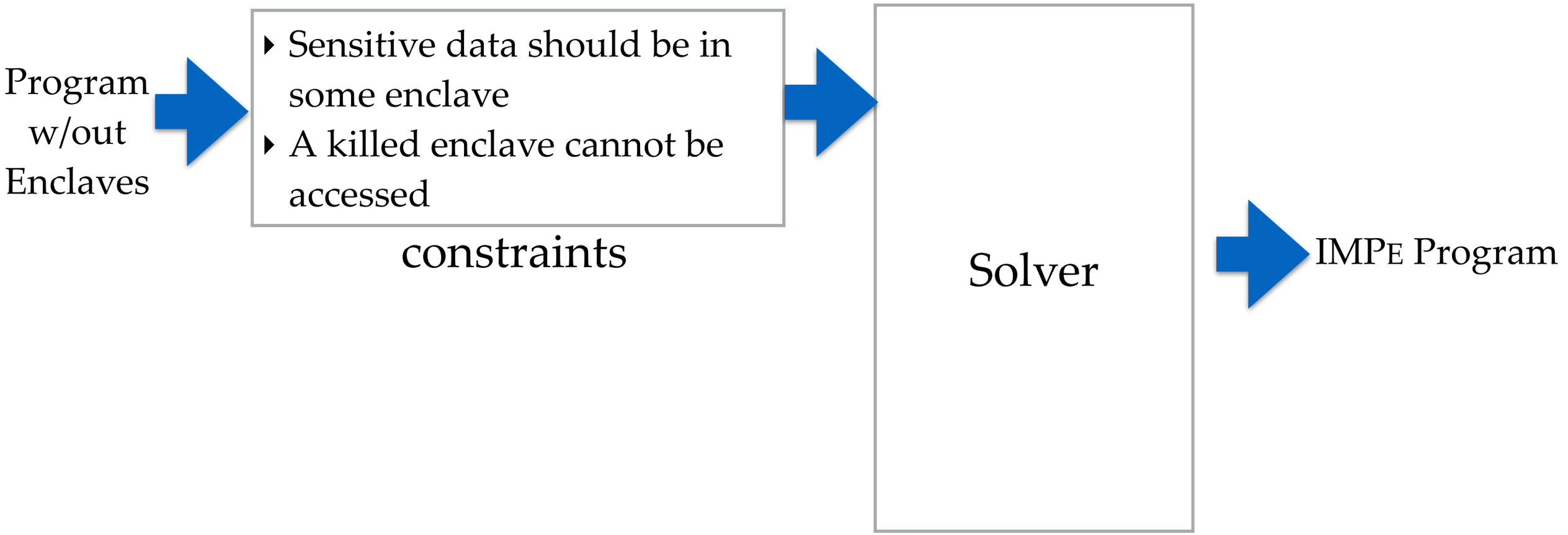
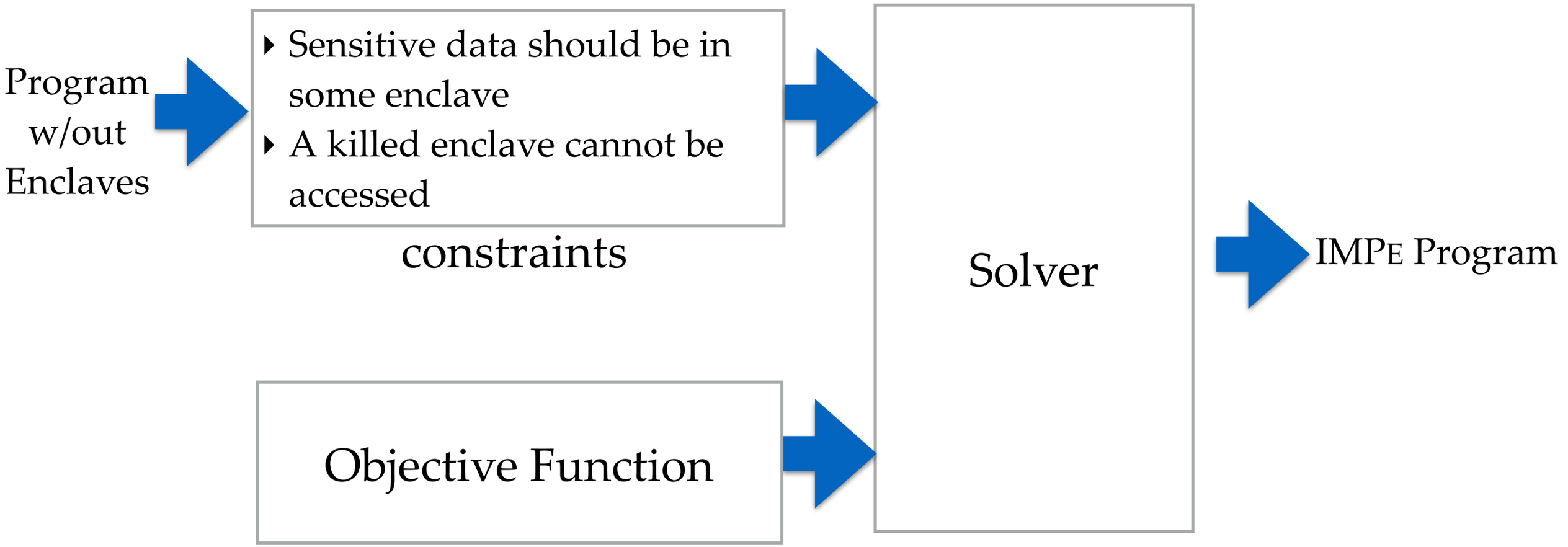
Enclave Inference as Constraint **Optimization**



Enclave Inference as Constraint **Optimization**



Example Objective Functions

1. Minimize the TCB

   - Reduce the number of statements inside enclaves

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1. Minimize the TCB

   - Reduce the number of statements inside enclaves

2. Minimize the window of vulnerability

   - Place code and data in as many different enclaves as possible

   - Kill an enclave as soon as possible

Summary

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1. Strong information-flow guarantees using hardware protection mechanisms (enclaves)

2. Automatically infer enclave placement in an application relieving the programmers' burden