Exploits as Insecure Compilation

Jennifer Paykin, Eric Mertens, Mark Tullsen, Luke Maurer, Benoît Razet, and Scott Moore

PriSC, January 25 2020

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- **how insecure is it?**

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- **how insecure is it?**
- **with respect to a particular program?**

Definition (Weird Machines)

The computational model made accessible by hacking a particular program.

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1. Idealized, “correct” state machine specification that preserves security properties

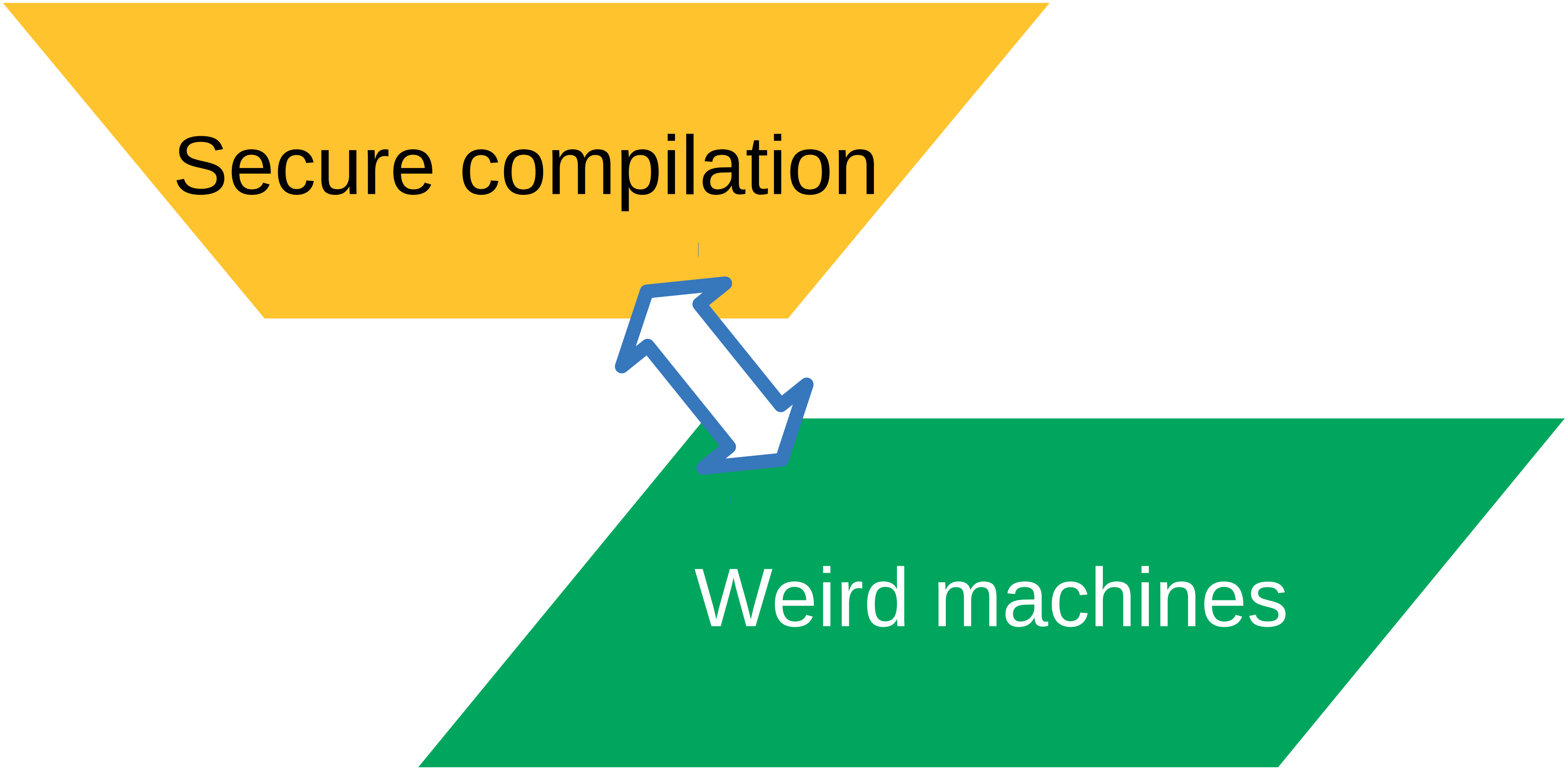
2. Concrete “implementation” model that admits additional behaviors

(Vanegue 2014, Dullien 2017, Bratus & Shubina 2017)

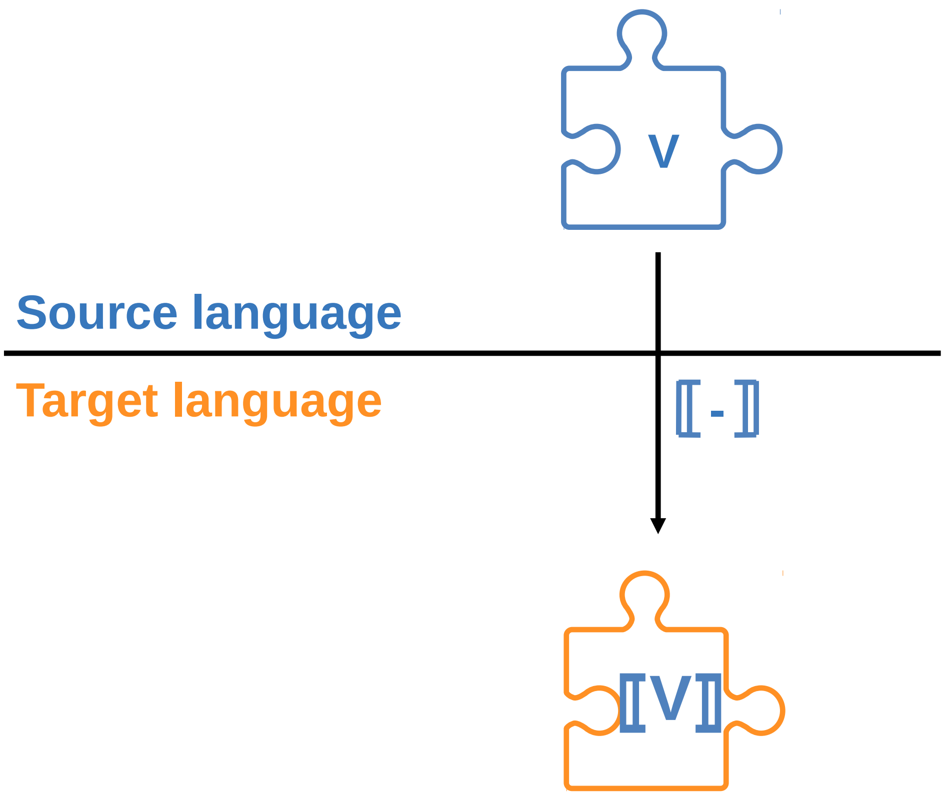
Insecure Compiler

1 program in high-level **source** language
for which security properties are enforced

2 implementation in low-level **target** language
that admits additional behaviors


Secure compilation
Weird machines

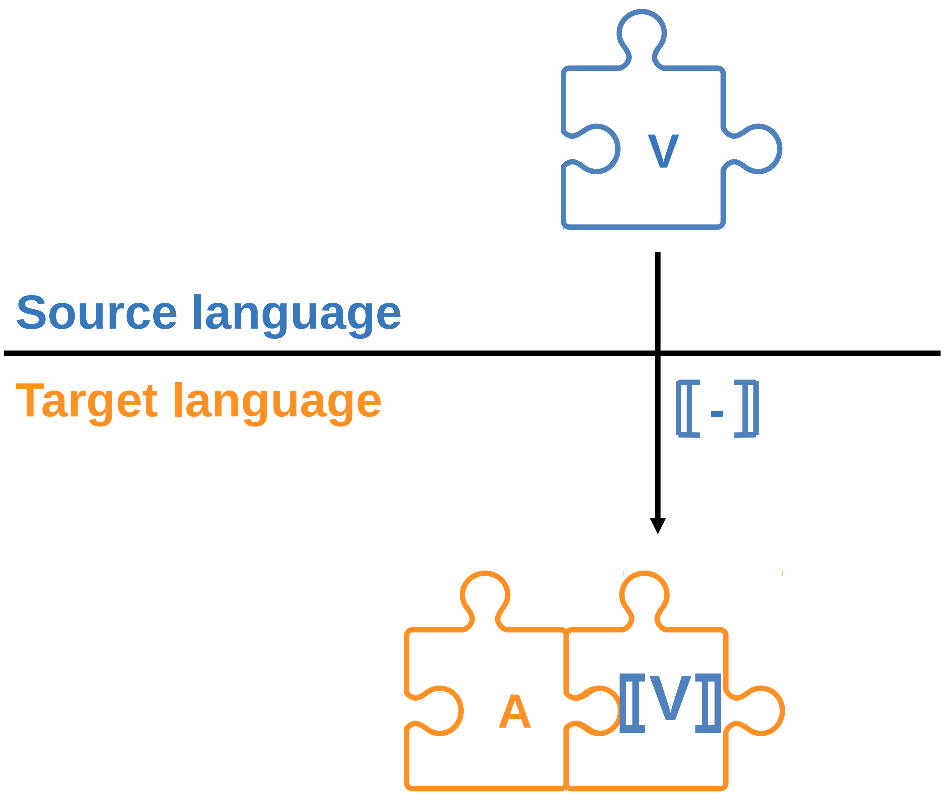
Exploits as violations of secure compilation



Definition

An *exploit*
of a source component **V**

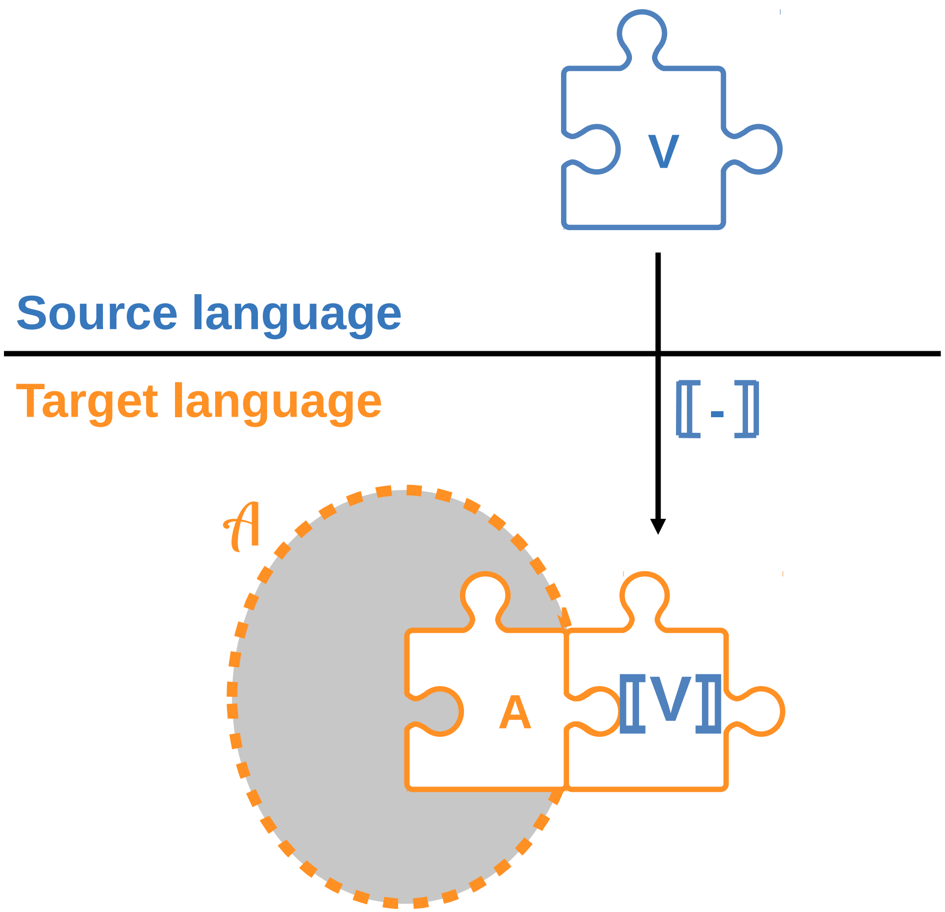
Exploits as violations of secure compilation



Definition

An *exploit*
of a source component **V**
is a context **A**

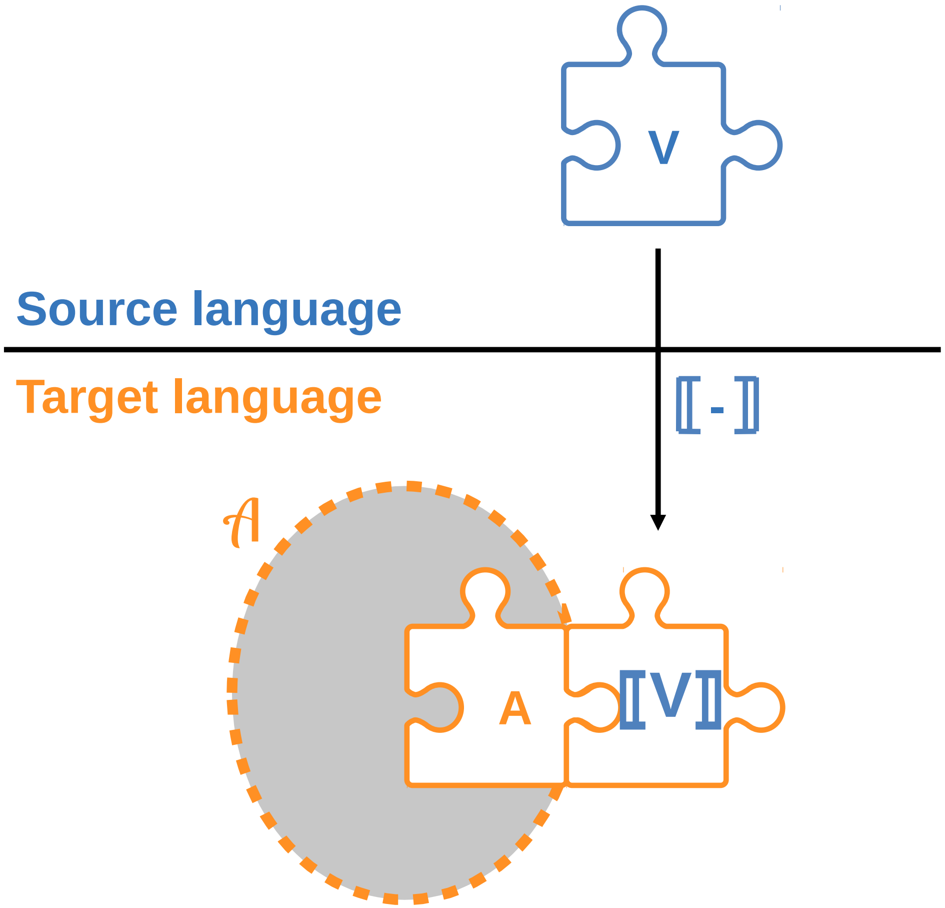
Exploits as violations of secure compilation



Definition

An *exploit* *of a source component* **V** is a context **A** from attack class $\mathcal{A}$

Exploits as violations of secure compilation



Definition

An *exploit*
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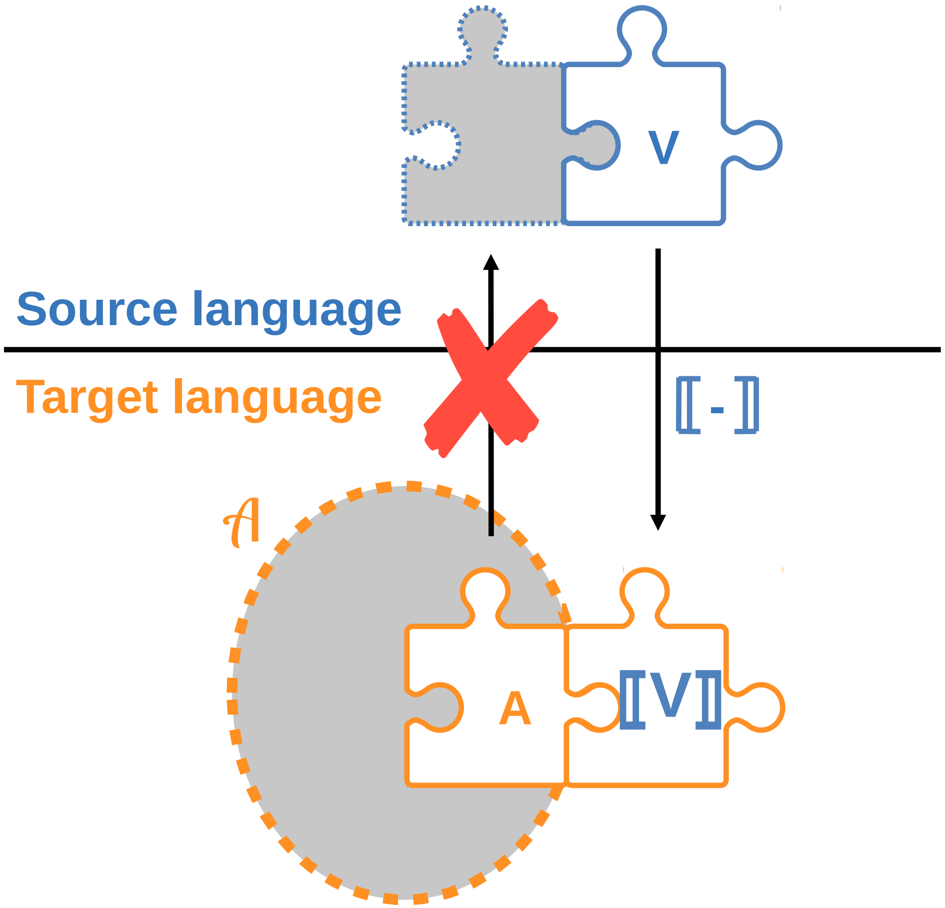
such that
the behavior of **A**[⟦V⟧]

Exploits as violations of secure compilation



Definition

An *exploit*
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is a context **A**
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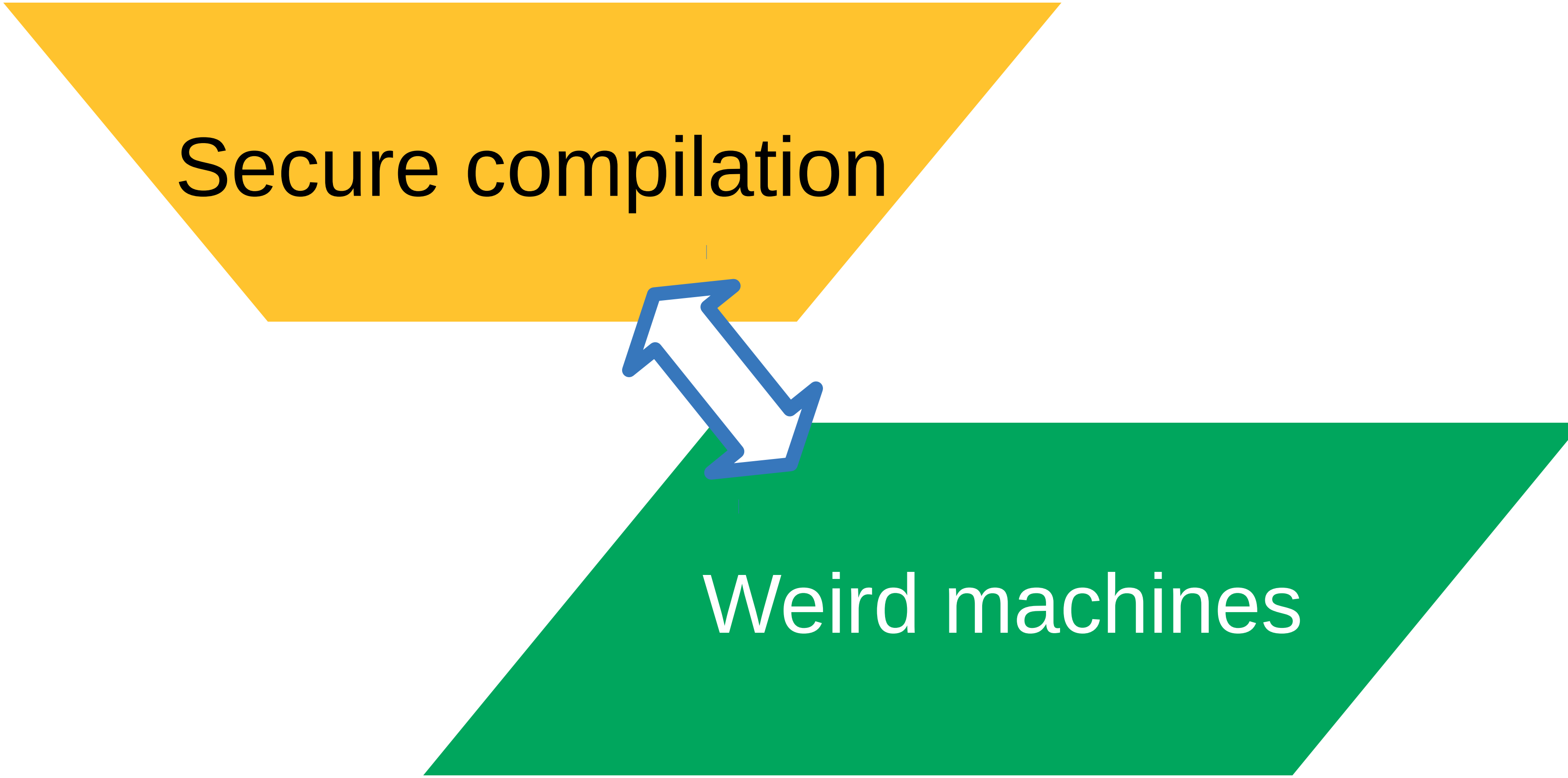
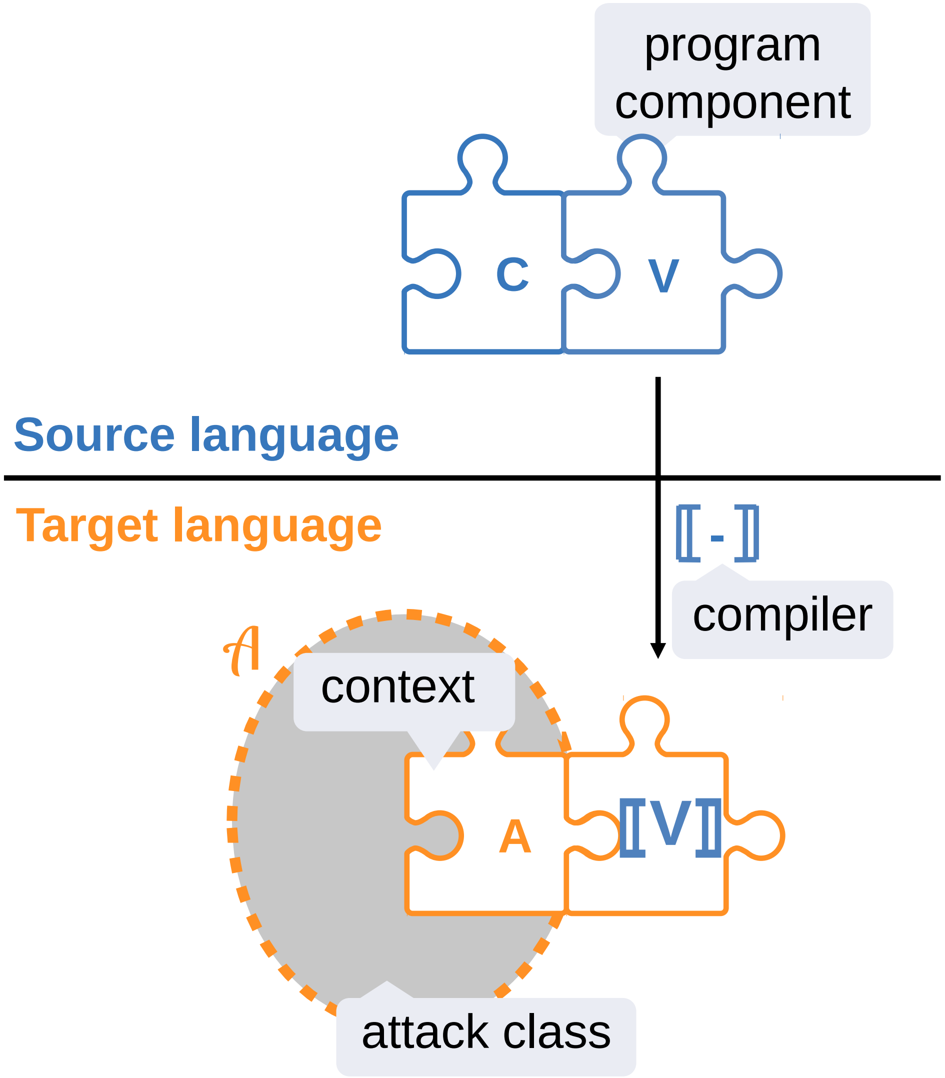
such that
the behavior of **A**[**⟦V⟧**]
cannot be simulated by **V**
in the source language.



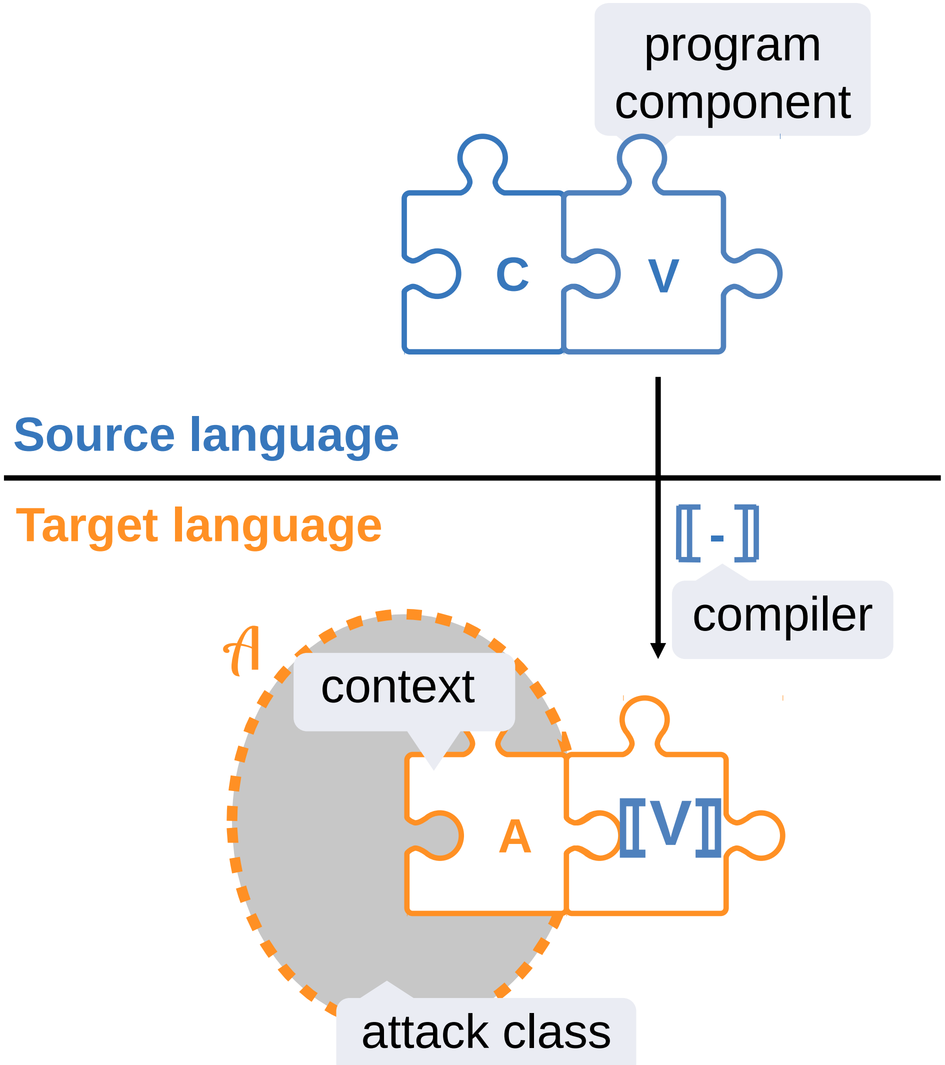
Hypothesis:
Definitions match intuitions

Framework



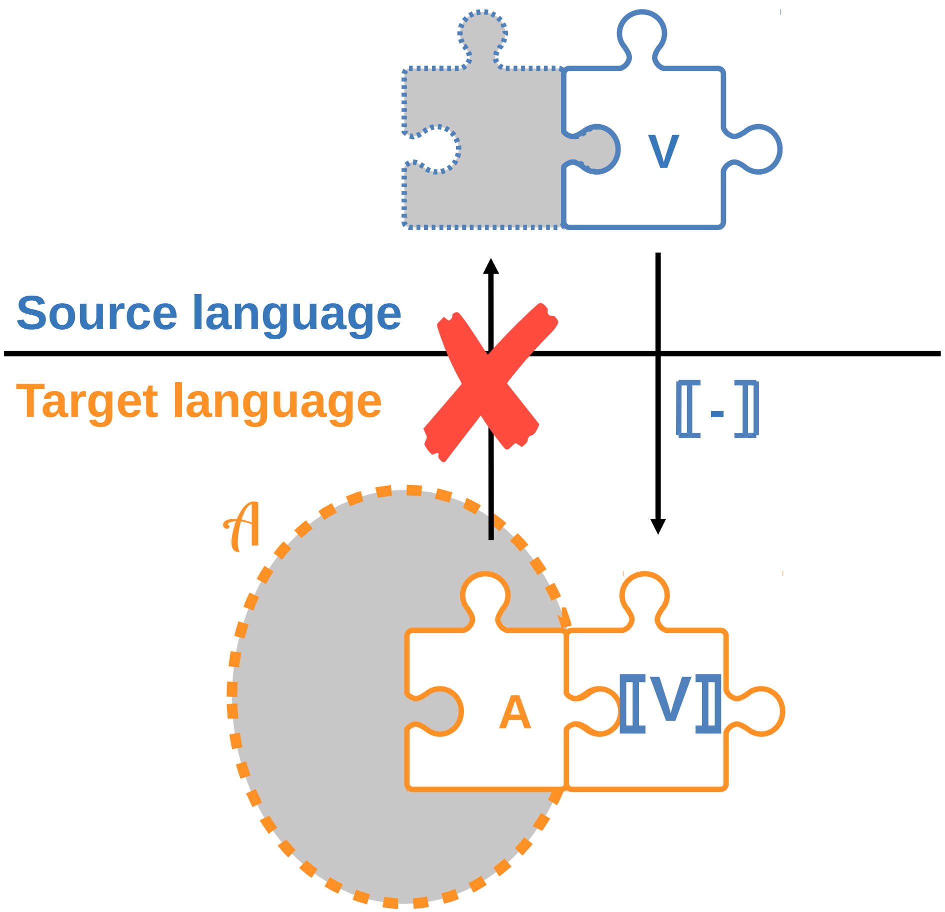
Exploit type	return-oriented programming (ROP)
Source	C
Compiler	clang
Target	assembly
Component	complete C program
Context	command-line input
Attack class	command-line input
Behavior	output traces

Framework



Exploit type	Spectre (Patrignani and Guarnieri 2020)
Source	non-speculative semantics
Compiler	no-op
Target	speculative semantics
Component	program in memory
Context	memory, cache, PC, etc...
Attack class	prepare cache, invoke function, query cache...
Behavior	timing information

Exploits as violations of secure compilation



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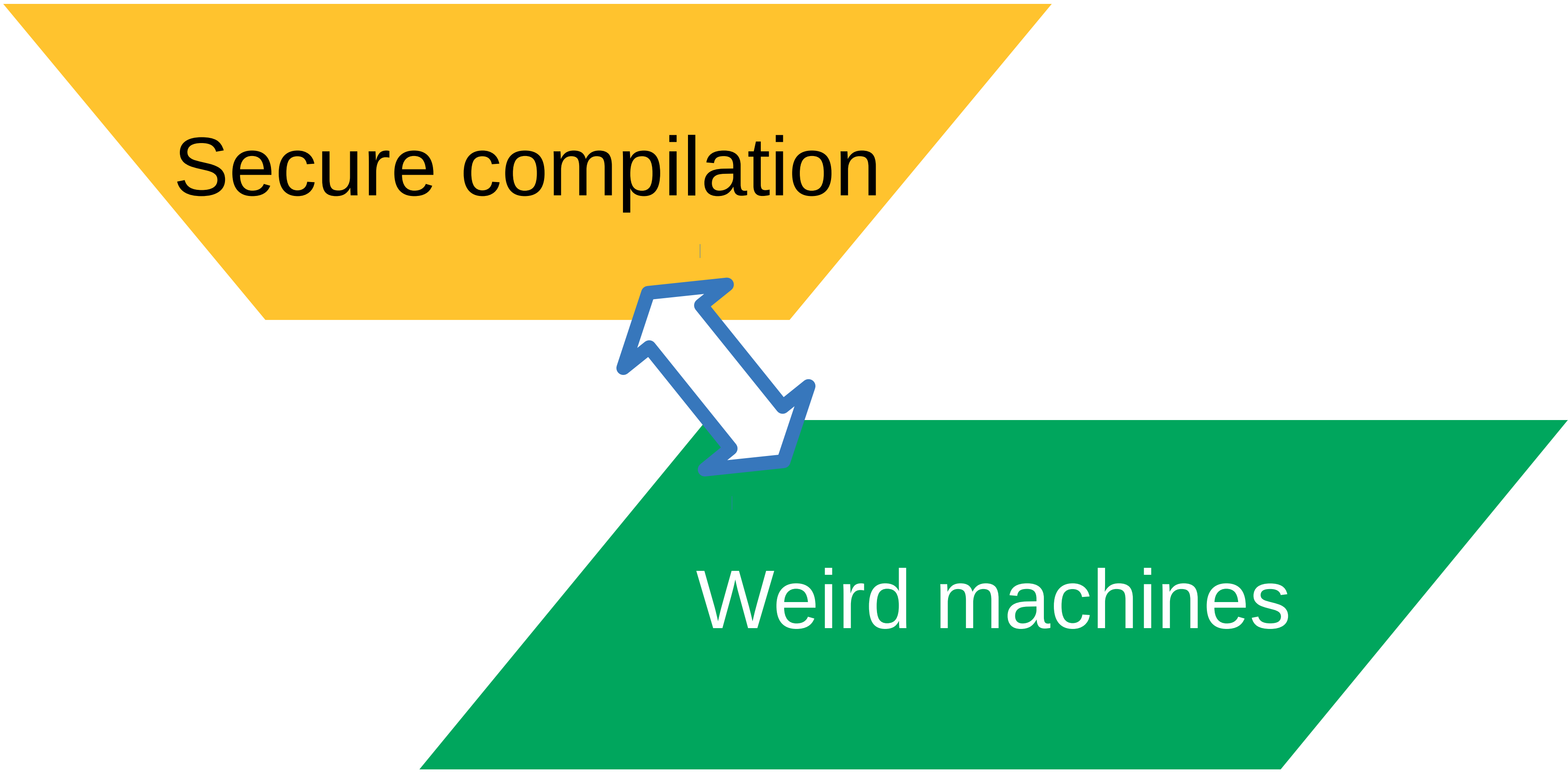

Constructive procedure to answer:

Is **A** an exploit of **V**?

Robust Property Preservation

Definition (Abate et al 2019)

A compiler satisfies *robust hyper-property preservation* (RHP) if, ∀ source programs **V** and ∀ hyper-properties H ⊆ B:

$$(\forall \mathbf{C}^{\mathbf{S}}.\ \text{Behavior}(\mathbf{C}^{\mathbf{S}}[\mathbf{V}]) \in H) \Rightarrow$$
$$(\forall \mathbf{C}^{\mathbf{T}}.\ \text{Behavior}(\mathbf{C}^{\mathbf{T}}[[\![\mathbf{V}]\!]]) \in H)$$

* approx: behaviors = sets of traces, so H is a set of (set of traces)

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$$(\forall C^T.\ \mathrm{Behavior}(C^T[[\![V]\!]]) \in H)$$

Theorem (Abate et al 2019)

A compiler satisfies RHP iff ∀ source programs **V:**

$$\forall C^T, \exists C^S.\ \mathrm{Behavior}(C^S[V]) = \mathrm{Behavior}(C^T[[\![V]\!]]).$$

* approx: behaviors = sets of traces, so H is a set of (set of traces)

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Definition

An exploit of a source programs V is a context $A \in \mathcal{A}$ such that

$\neg\exists C^S . \text{Behavior}(C^S [V]) = \text{Behavior}(C^T[[\![V]\!]])$.

Robust Property Preservation

Definition

An exploit of a source program **V** is a context **A** ∈ $\mathcal{A}$ such that

$$\forall \mathbf{C^S} \,.\, \text{Behavior}(\mathbf{C^S}[\mathbf{V}]) \neq \text{Behavior}(\mathbf{C^T}[[\![\mathbf{V}]\!]]).$$

Robust Property Preservation

Definition

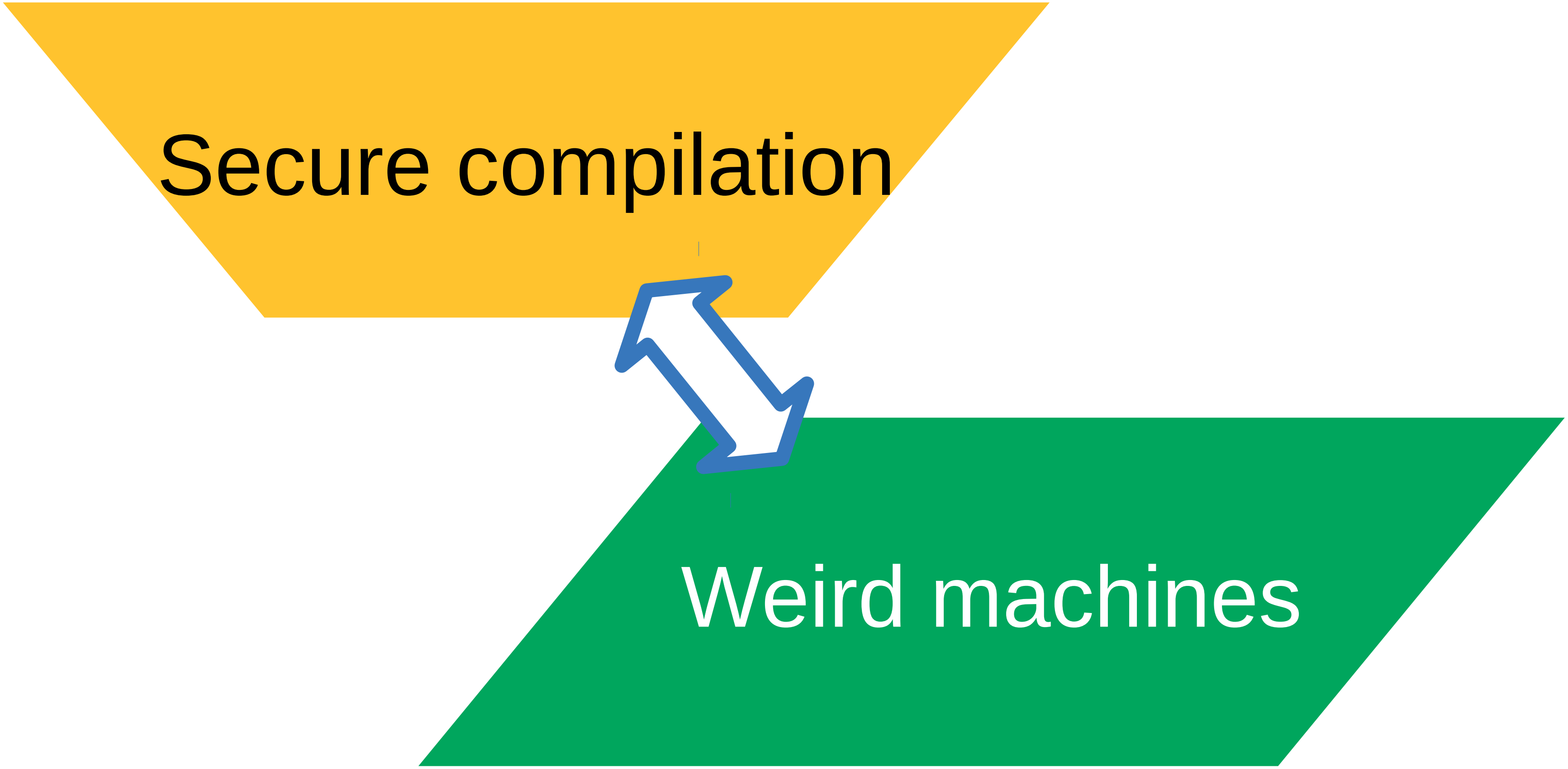
An exploit of a source program $\mathbf{V}$ is a context $\mathbf{A} \in \mathcal{A}$ such that

$$\forall \mathbf{C}^{\mathbf{S}} .\ \text{Behavior}(\mathbf{C}^{\mathbf{S}}\ [\mathbf{V}]) \neq \text{Behavior}(\mathbf{C}^{\mathbf{T}}[[\![\mathbf{V}]\!]]).$$

Theorem

$\mathbf{A}$ is an exploit of $\mathbf{V}$ iff RHP is violated:
$\exists$ hyper-property $H \subseteq B$ such that

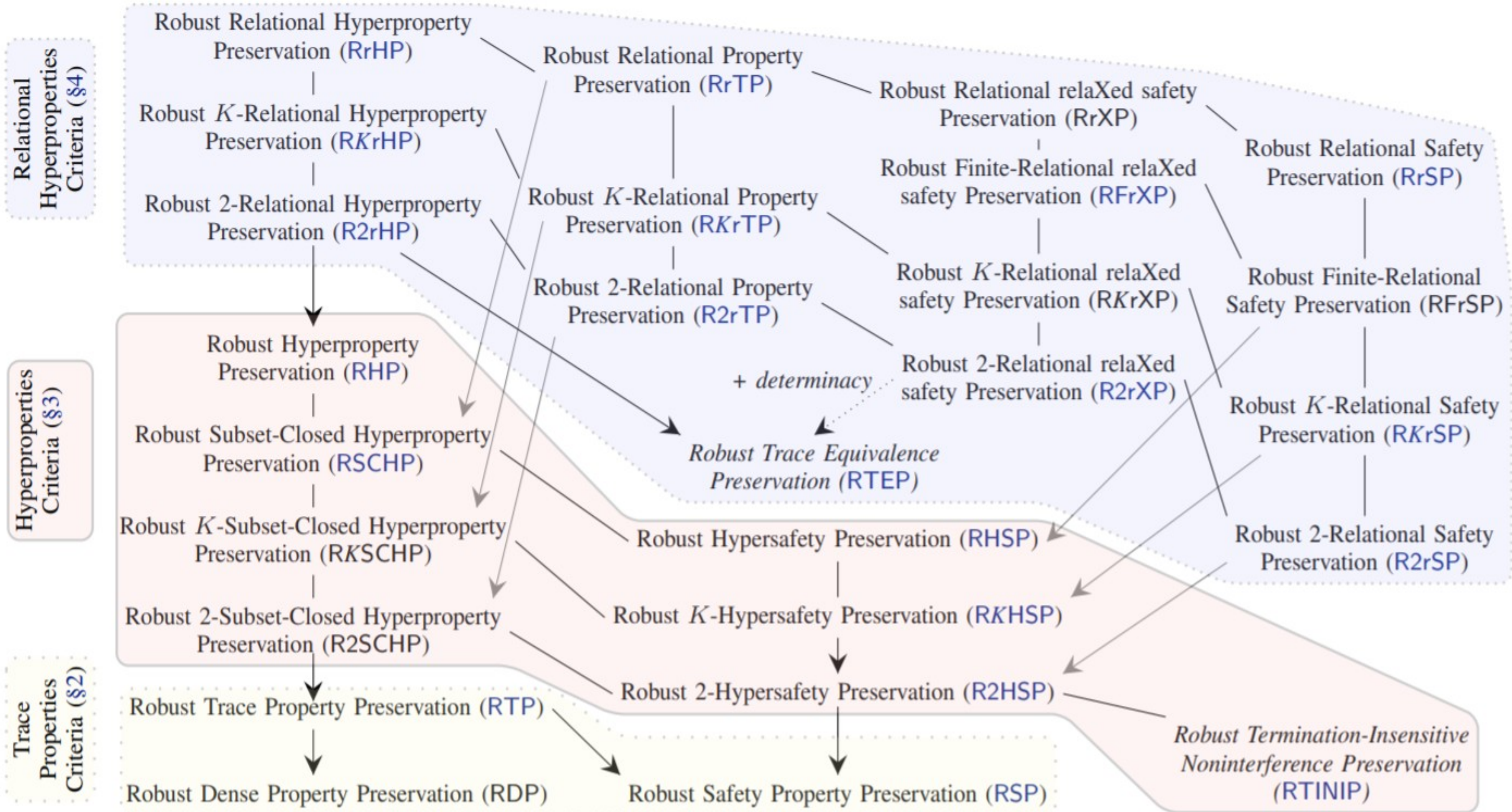
$$(\forall \mathbf{C}^{\mathbf{S}}.\ \text{Behavior}(\mathbf{C}^{\mathbf{S}}[\mathbf{V}]) \in H)$$
$$\text{but} \quad \text{Behavior}(\mathbf{A}[[\![\mathbf{V}]\!]]) \notin H)$$



different security properties

= different attack classes

Hierarchy of robust property preservation classes



Abate et al. 2019

Hierarchy of exploit classes

1 identify a class of security properties of interest

2 identify property-free characterization

3 exploit class is negation of property-free characterization

CFI?

Full abstraction?

Trace Property Preservation

Definition

A *trace exploit* of a source program **V** is a context **A** $\in \mathcal{A}$ such that

$$\exists\, t \in \text{Behavior}(\mathbf{A}[[\![\mathbf{V}]\!]]).$$

$$\forall\, \mathbf{C^S},\ t \notin \text{Behavior}(\mathbf{C^S}[\mathbf{V}])$$

Trace Property Preservation

Definition

A *trace exploit* of a source program $\mathbf{V}$ is a context $\mathbf{A} \in \mathcal{A}$ such that

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Theorem

- trace exploits ⊆ hyperproperty exploits.
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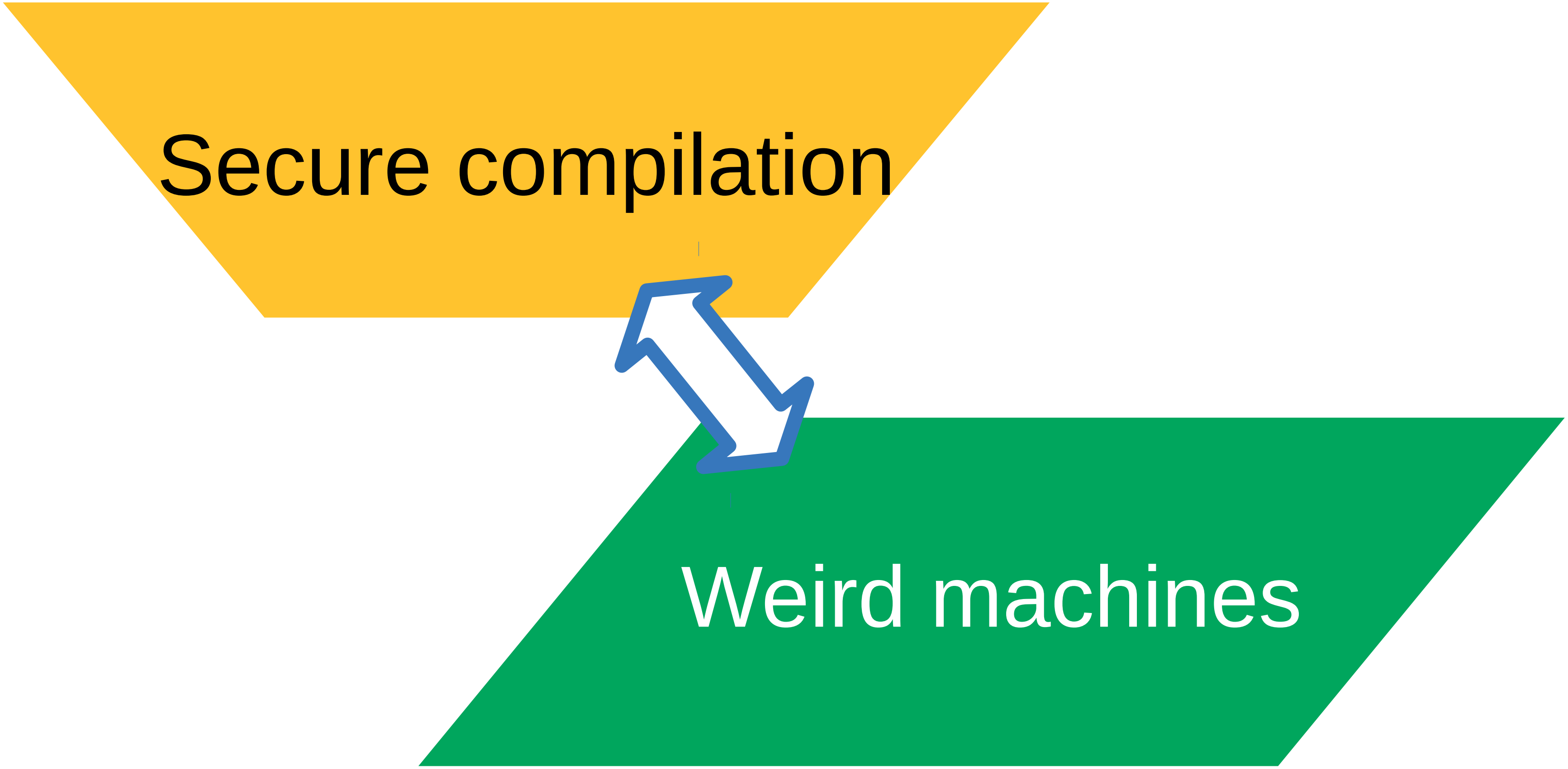
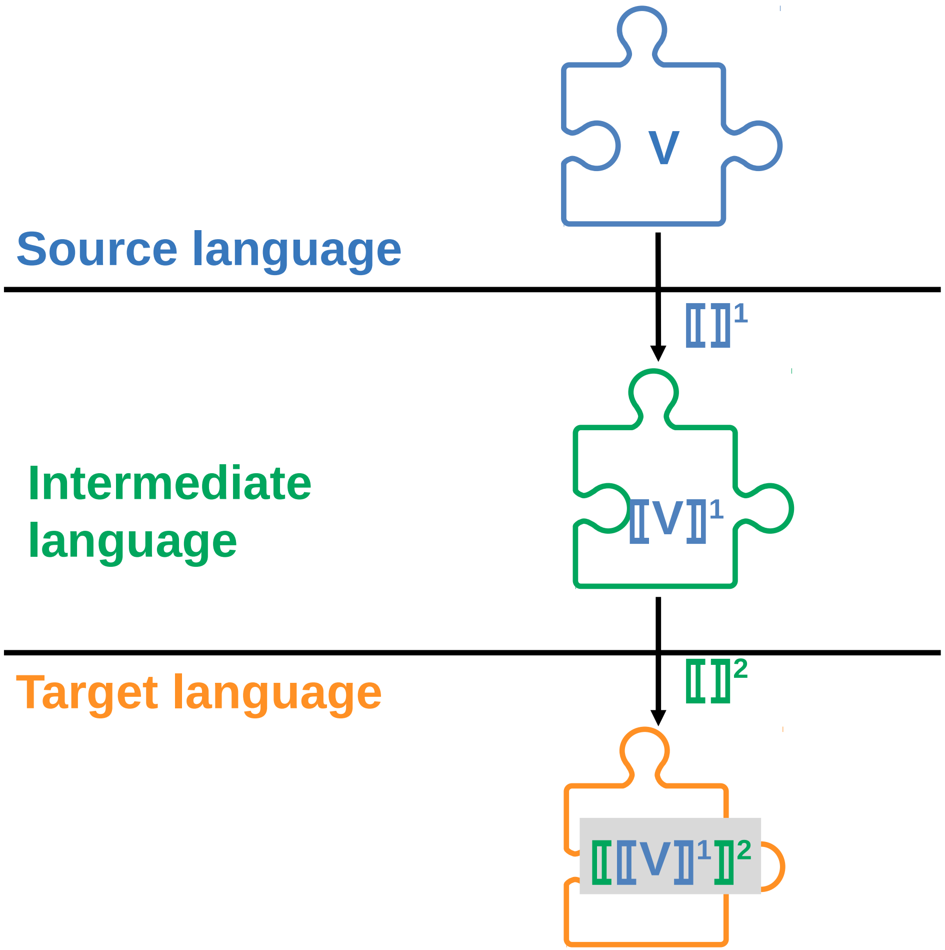
- e.g. side-channel attacks
- Trace exploits “more programmable” than hyperproperty exploits.

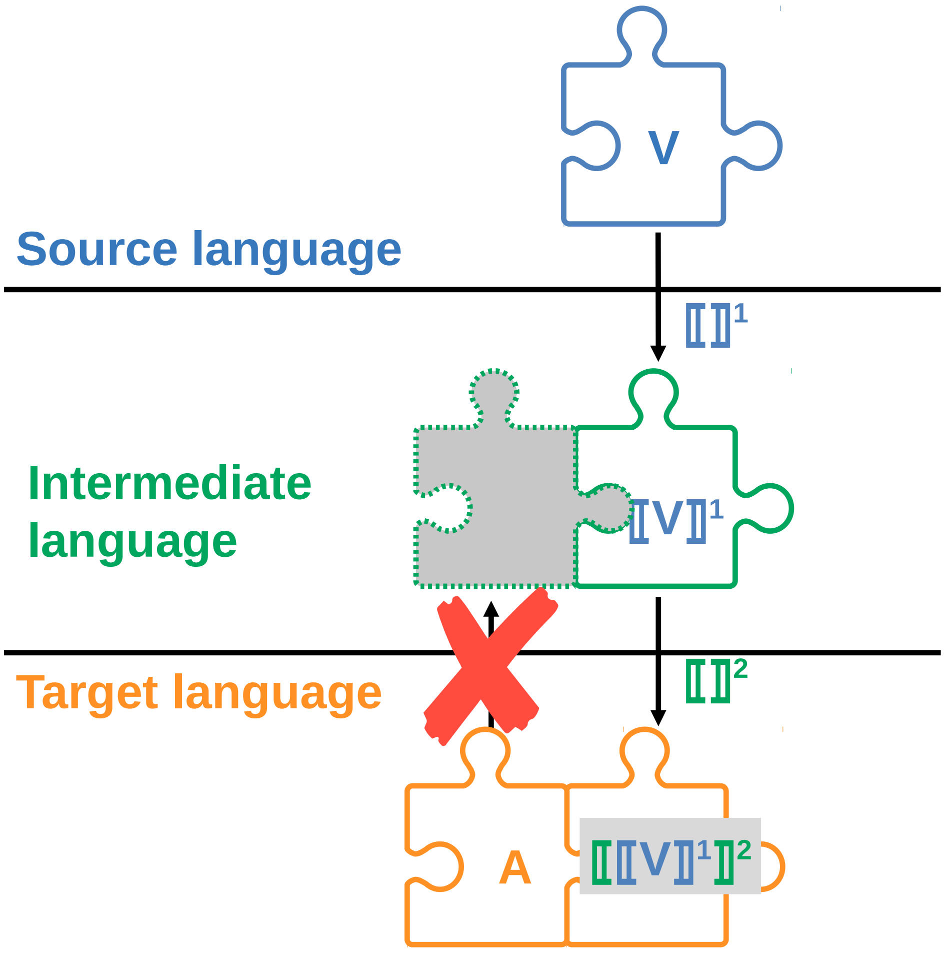


exploits compose
through compiler stages

Compositionality through compiler stages



Compositionality through compiler stages



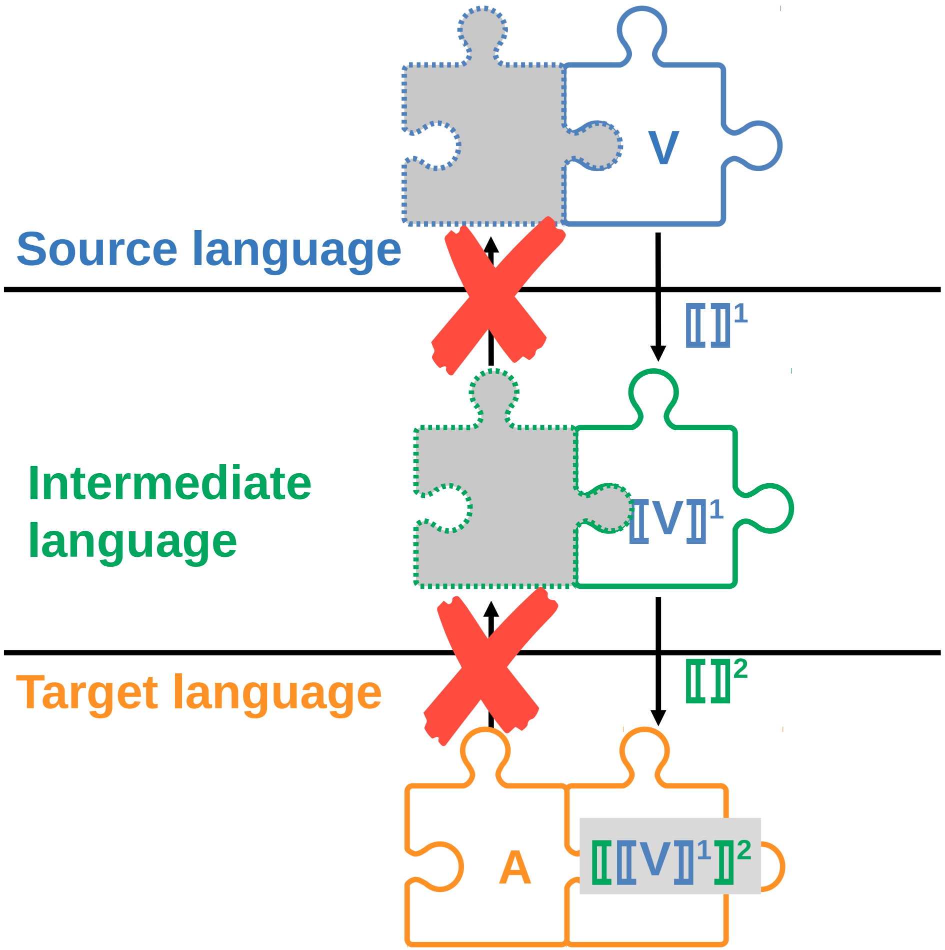
Theorem

If **A** is an exploit of $[\![V]\!]^1$ such that

- $[\![\;]\!]^1$ is correct for **V**; and
- behaviors are invertible,

then **A** is an exploit of **V**.

Compositionality through compiler stages



Theorem

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Takeaways in the paper...

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1 "Obvious" applications of secure compilation

- value in formalizing application strategy?

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1

“Obvious” applications of secure compilation

- value in formalizing application strategy?

2

Non-traditional “programming languages” and “compilers”

- no-op compilers with different operational semantics
- source language as state machines

Takeaways in the paper...

1 "Obvious" applications of secure compilation

- value in formalizing application strategy?

2 Non-traditional "programming languages" and "compilers"

- no-op compilers with different operational semantics
- source language as state machines

3 Trace-relating compilers

- source behaviors different from target behaviors
- behaviors need not be sets of traces

Next steps...

Study counterexamples to secure compilation

- while trying to design a secure compiler
- determine programmability of exploits in design
- given an insecure compiler, help designing mitigations

|galois|

Weird Machines as Insecure Compilation

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