All the Binaries Together

A Semantic Approach to ABIs

Andrew Wagner, Amal Ahmed

(Secure Interoperability, Languages, and Compilers)

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"The standard is haunted … by that **Three Letter Demon**. … a contract was forged in blood."
– JeanHeyd Meneide, WG14 C/C++ Compatibility Chair

🔮 What Is an ABI?

🔮 What Is ^in an ABI?

- Data layouts
- Calling conventions
- Name mangling
- \+ *Safety invariants*
- \+ *Ownership*

  …

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- \+ *Ownership*

  …

🤷 Who Cares?

★ **Swift:** *ABI Stability Manifesto*

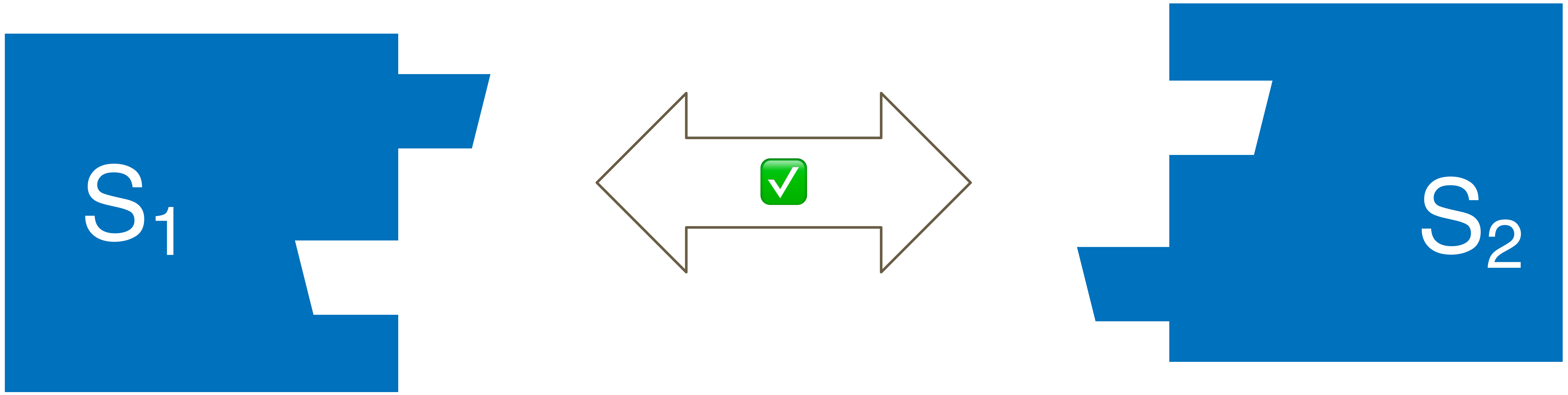
★ **Rust:** *crABI*

★ **C++:** *WG21 ARG*

★ **WASM:** *Component Model*

★ 👊 **You!**

All the Compilers Together



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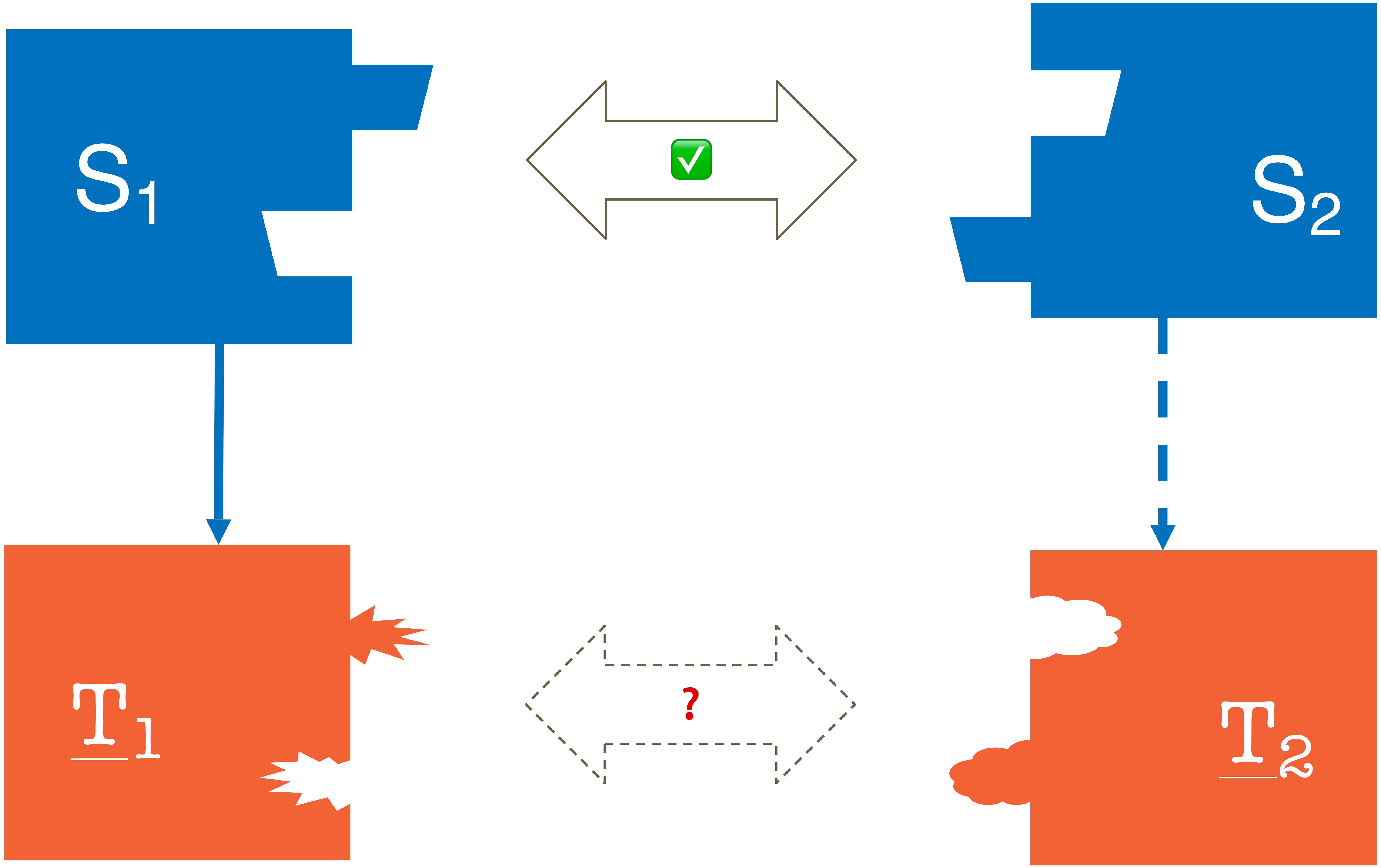
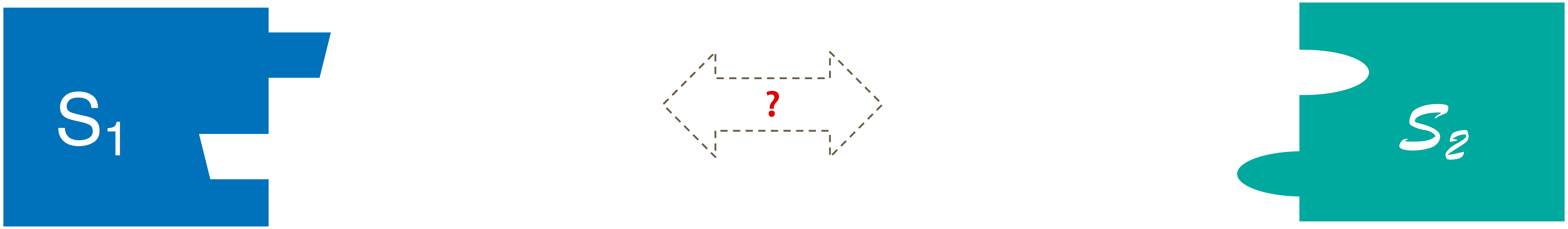


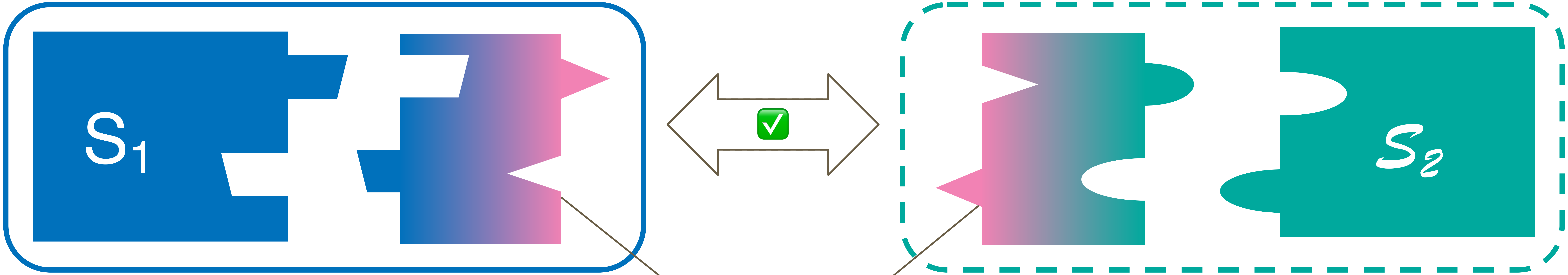
Compiler 1
- **gcc**
- *gcc 9*

Compiler 2
- **clang**
- *gcc 10*

All the Languages Together

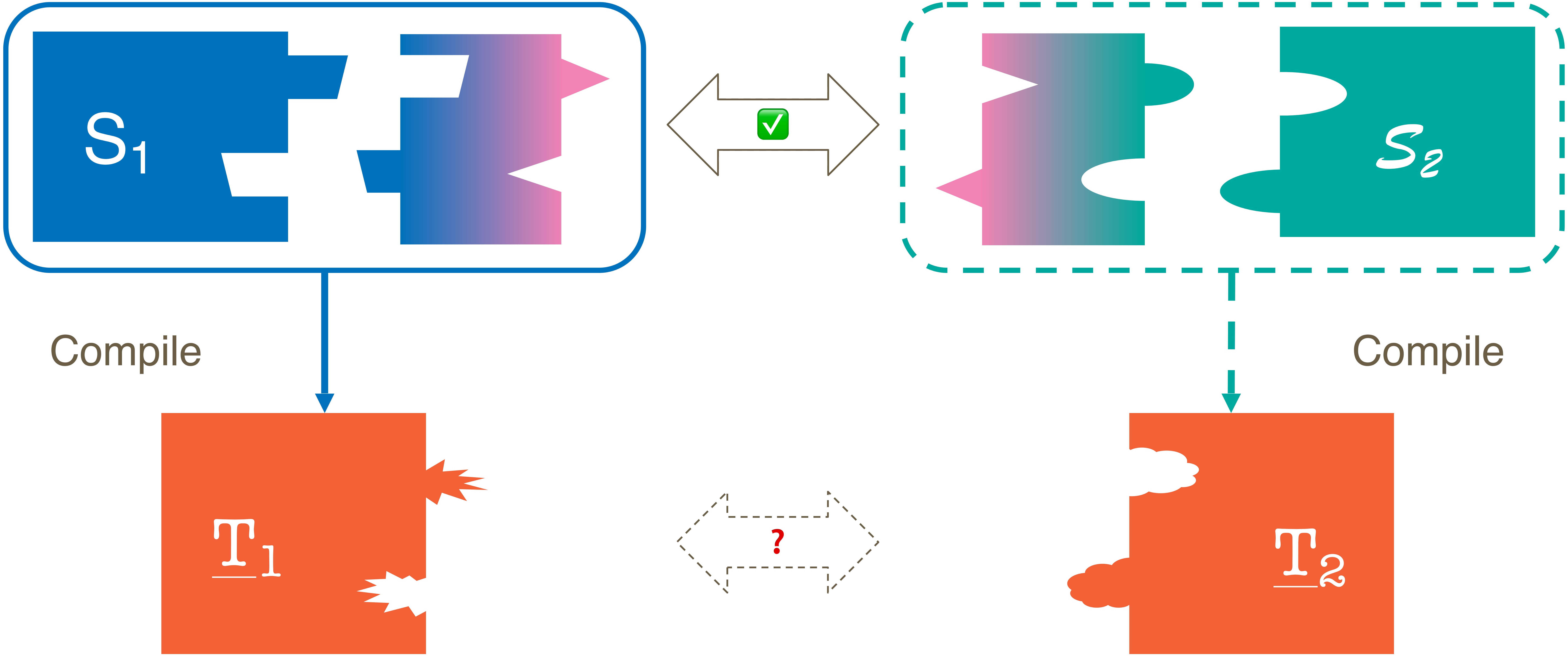


All the Languages Together

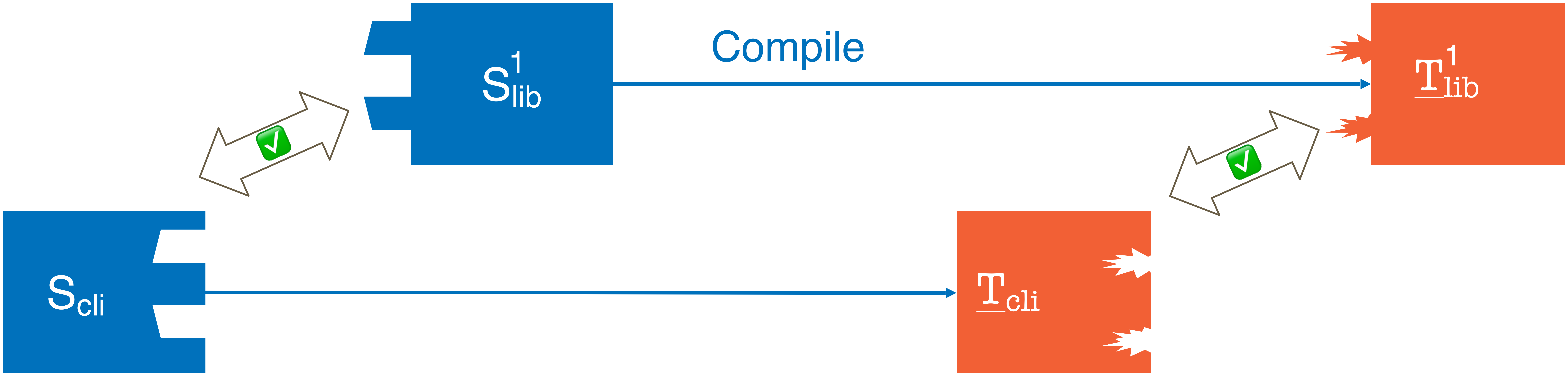


- Multi-Lang. Boundaries [MF07]
- Linking Types [PWA23]
- Probably a C FFI 🙃

All the Languages Together



All the Libraries Together



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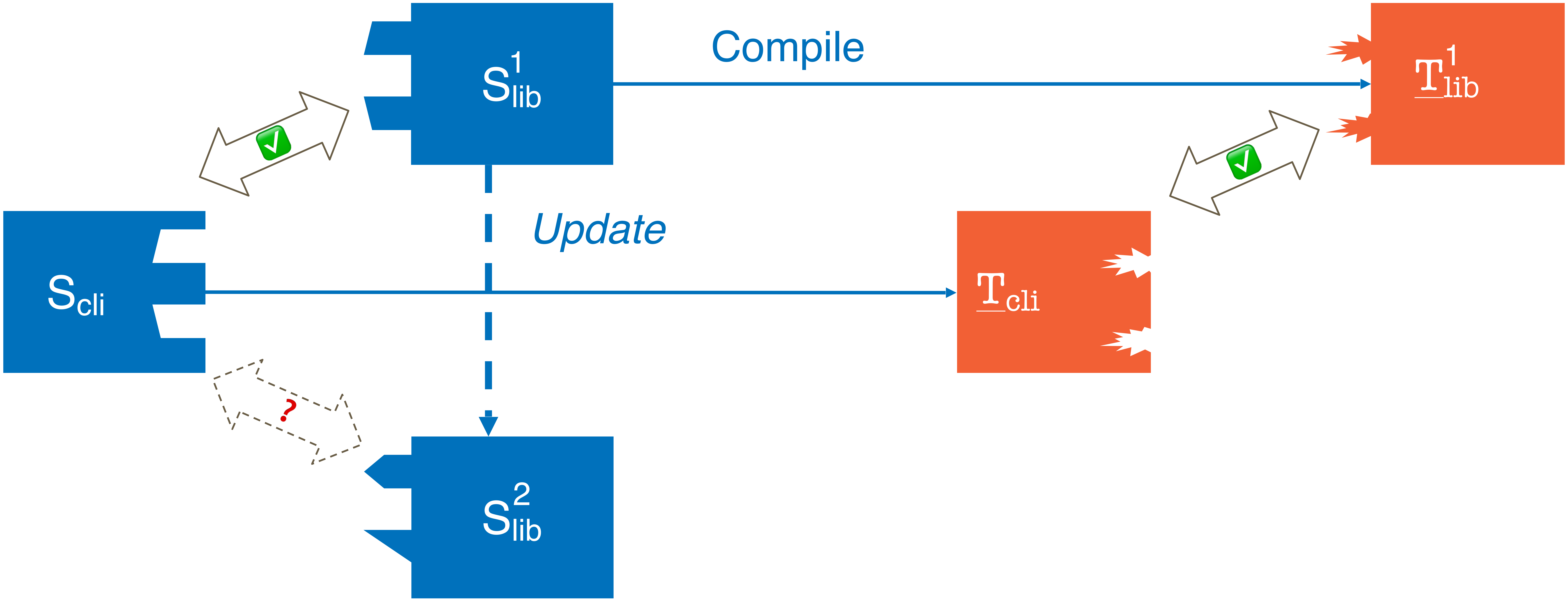
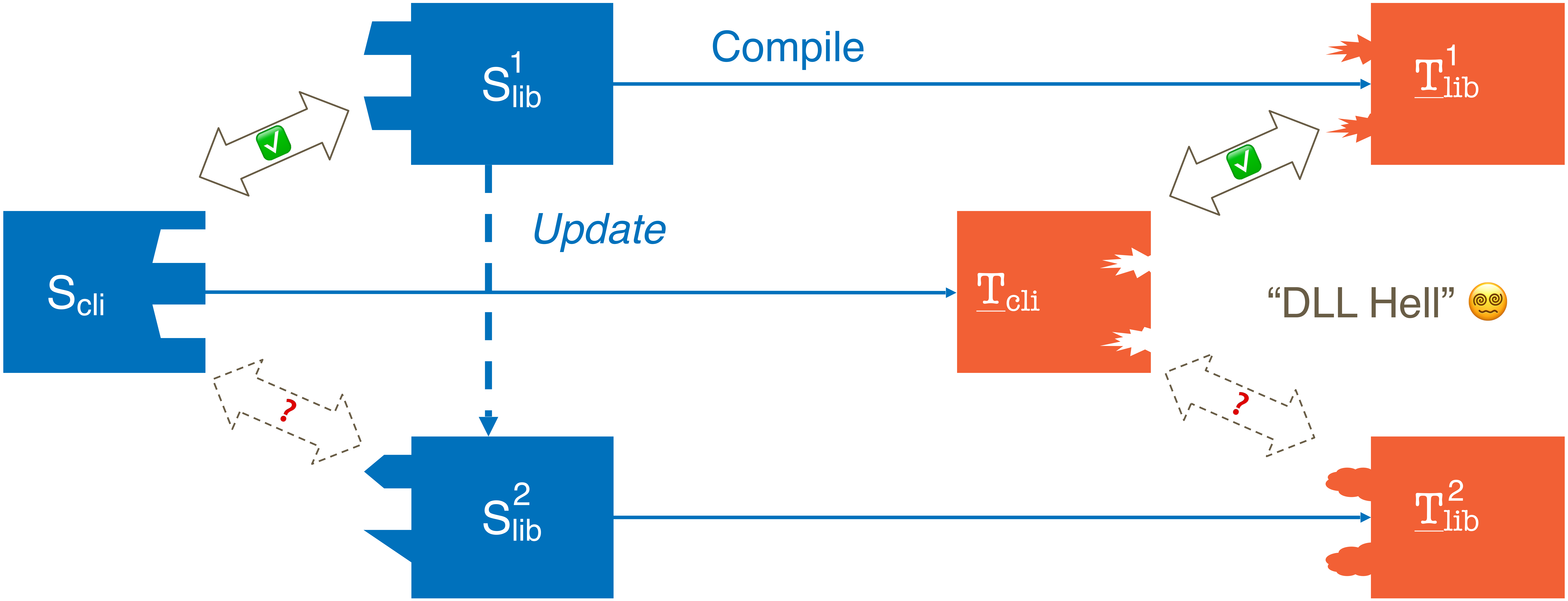


All the Libraries Together



Towards a Formal ABI

- Languages are already grappling with these problems
- Growing dissatisfaction with status quo
- Demand for richer ABIs
- Design decisions, tradeoffs, uncharted territory

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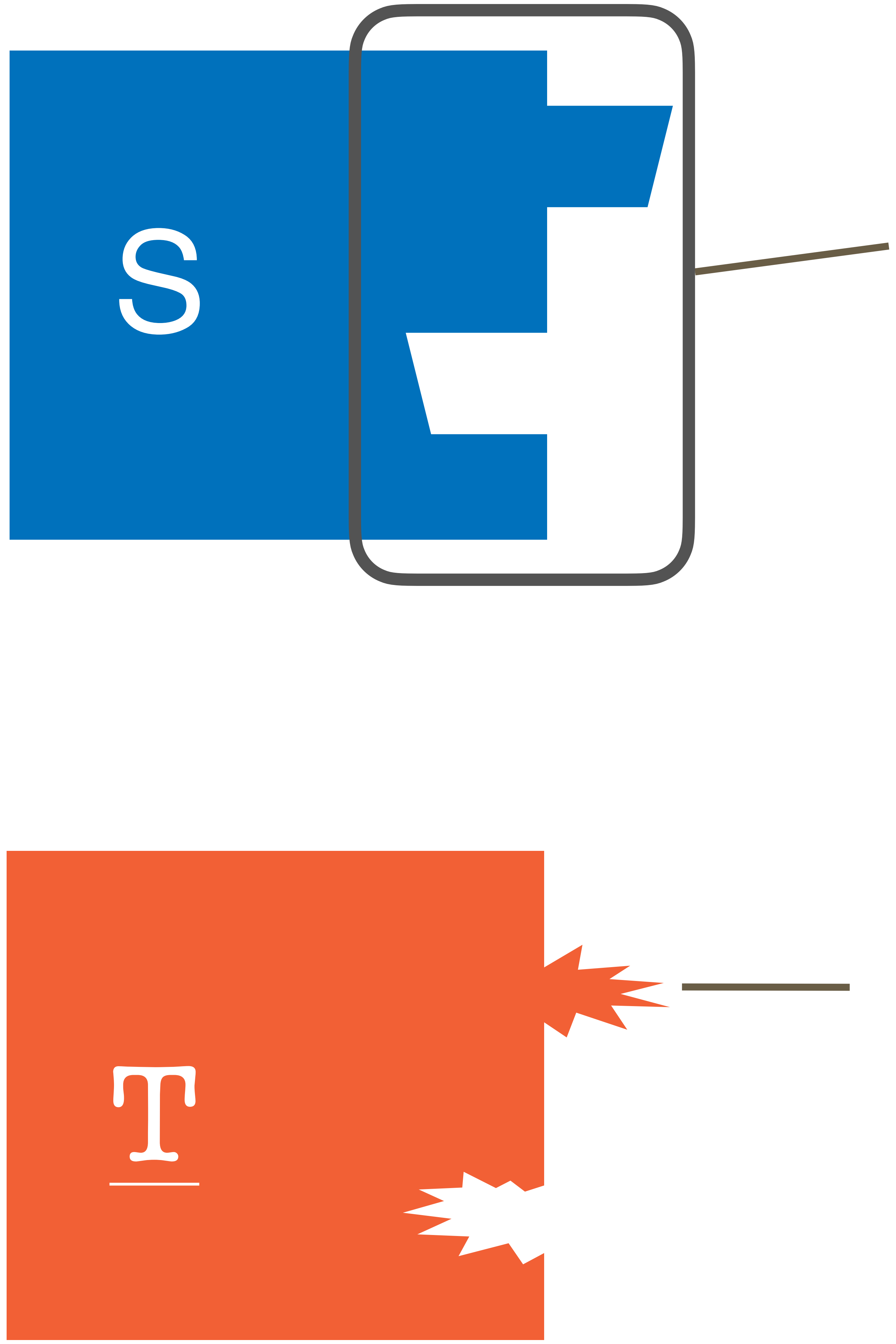
Can we provide a semantic foundation?

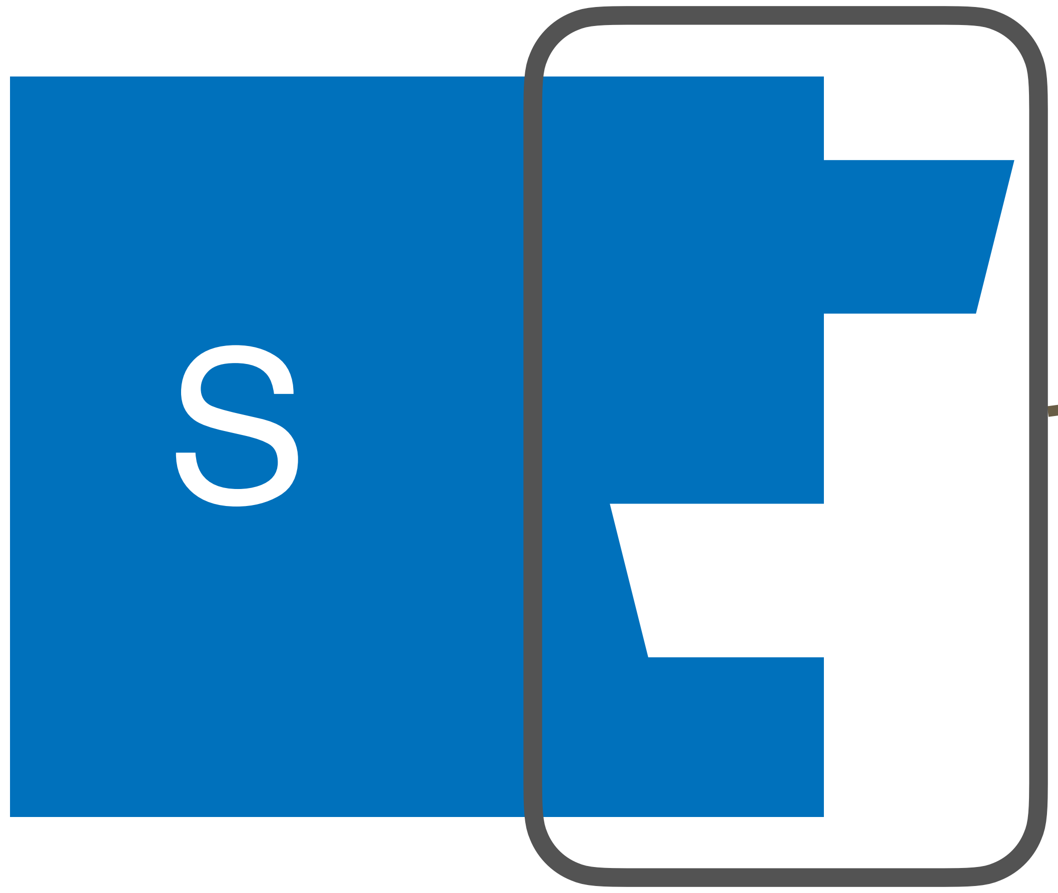
What Is an ABI, Formally?



"This source interface …"

"… describes target programs like this"

What Is an ABI, Formally?



"This source interface …"

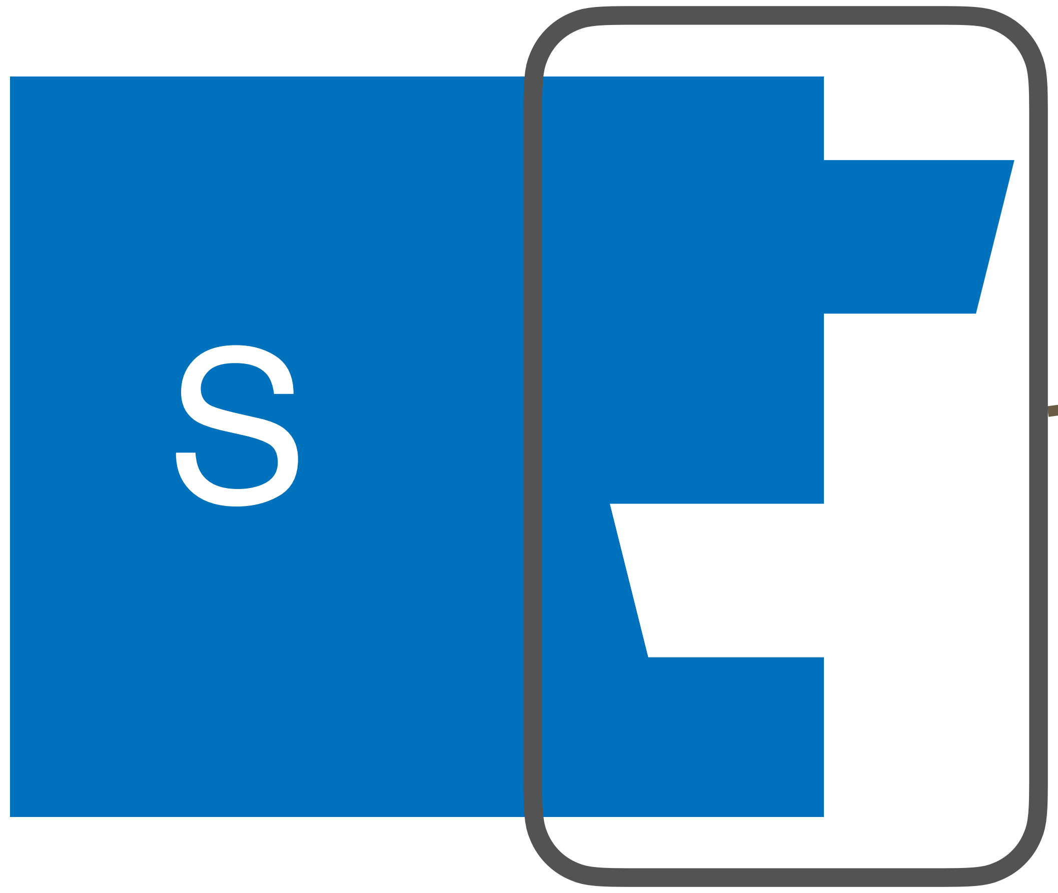
This Type τ

"… describes target programs like this"

Denotes These Programs

$[\![\tau]\!] = \{\, \underline{\mathtt{T}} \mid \ldots \,\}$ — Semantic Typing via Realizability

What Is an ABI, Formally?



"This source interface …"

This Type τ

$\underline{T}$ is **ABI compliant** with τ if

$$\underline{T} \in [\![\tau]\!]$$

"… describes target programs like this"

Denotes These Programs

$[\![\tau]\!] = \{\, \underline{T} \mid \ldots \,\}$ — Semantic Typing via Realizability

$\underline{\mathtt{T}}$ is **ABI compliant** with τ if

$$\underline{\mathtt{T}} \in [\![\tau]\!]$$

Is this a good spec?

$\underline{\mathtt{T}}$ is **ABI compliant** with τ if

$$\underline{\mathtt{T}} \in [\![\tau]\!]$$

Is this a good spec?

1. **Formalization:** Can the spec capture all the pertinent details?
2. **Application:** Can the spec be used in all the relevant scenarios?

Case Study: Reference Counting

- PCF-ish Source
  - Records, variants, higher-order recursive functions
- C-ish Target
  - Block-based memory, pointer arithmetic
- Reference Counting ABI
  - All values are boxed and reference-counted
  - Separation logic specification

Formalization: Semantic Typing via Realizability

$$\Gamma \vdash e : T$$

Formalization: Semantic Typing via Realizability

$\Gamma \vdash e : T$

$$\Gamma \vDash \boldsymbol{e} : T$$

Formalization: Semantic Typing via Realizability

$\Gamma \vdash e : T$

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$$\approx \left\{ \text{“}\textit{Prestate like } \Gamma\text{”} \right\} \boldsymbol{e} \left\{ \boldsymbol{v}.\ \text{“}\boldsymbol{v}\textit{ like } T\text{”} \right\}$$

Formalization: Semantic Typing via Realizability

$\Gamma \vdash e : T$

$$\Gamma \vDash e : T$$

$$\approx \left\{ \text{“Prestate like } \Gamma \text{”} \right\} \; e \; \left\{ v.\ \text{“} v \text{ like } T \text{”} \right\}$$

$(\Gamma = \overline{x : T_x})$

$$\approx \left\{ \star\, \overline{\mathcal{R}[\![T_x]\!](x)} \right\} \; e \; \left\{ \ell.\ \mathcal{R}[\![T]\!](\ell) \right\}$$

Formalization: Reference Layout

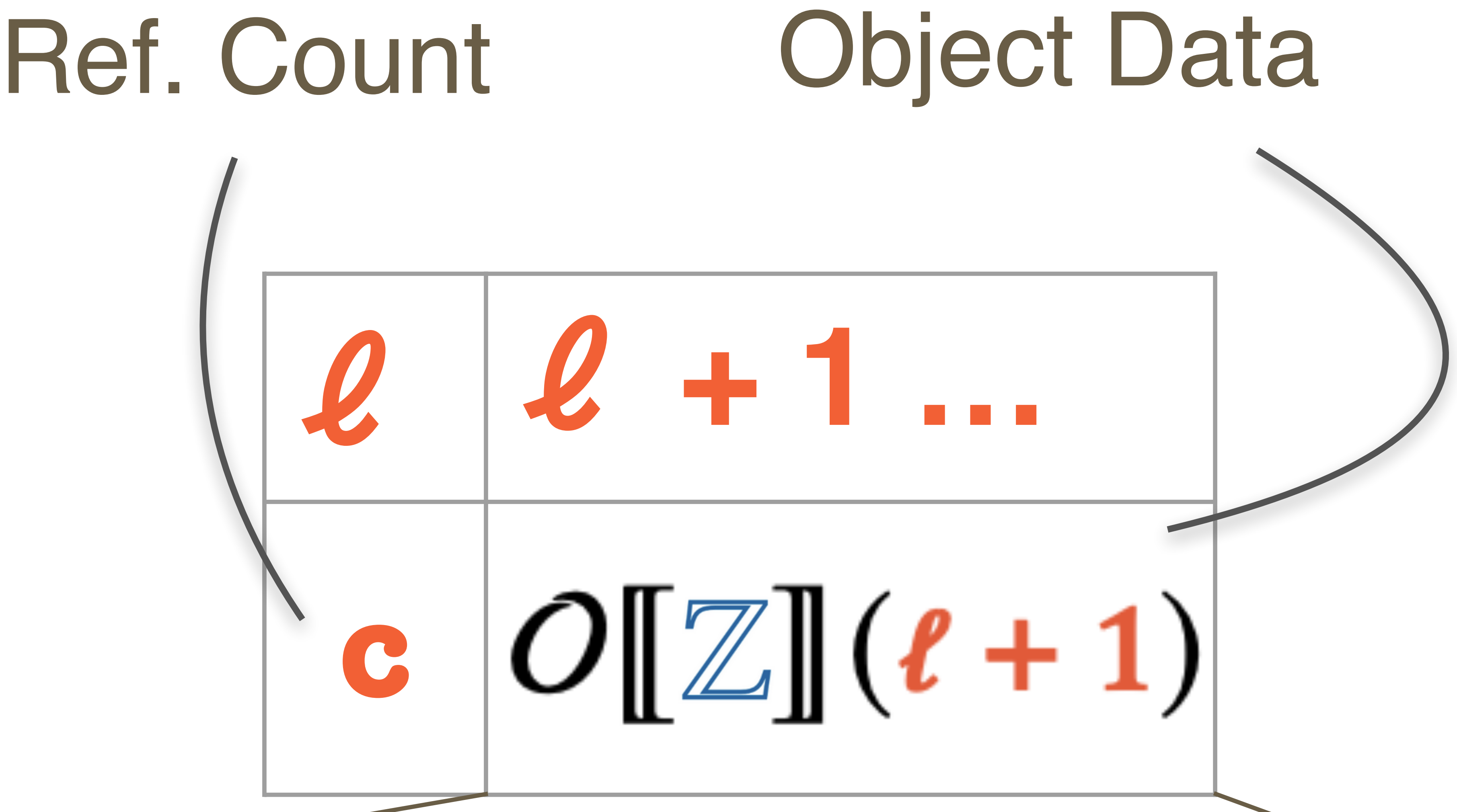
$$\mathcal{R}[\![T]\!](\ell) \approx$$

Ref. Count — Object Data

ℓ	ℓ + 1 ...
c	$\mathcal{O}[\![T]\!](\ell + 1)$

Formalization: Reference Layout

$$\mathcal{R}[\![\mathbb{Z}]\!](\ell) \approx$$



$$\mathcal{O}[\![\mathbb{Z}]\!](\ell + 1) = \exists\, n.\ \ell + 1 \mapsto n$$

Formalization: Reference Layout

$$\mathcal{R}[\![\mathbb{Z}]\!](\ell) \approx$$

	Ref. Count	Object Data
Address	ℓ	$\ell + 1$ ...
Content	c	$\mathcal{O}[\![\mathbb{Z}]\!](\ell + 1)$

$$\mathcal{O}[\![\mathbb{Z}]\!](\ell + 1) = \exists\, n.\ \ell + 1 \mapsto n$$

Also:
Unboxed data
via pointer
tagging

Formalization: Ownership + Sharing

$$\mathcal{R}[\![T]\!](\ell)$$

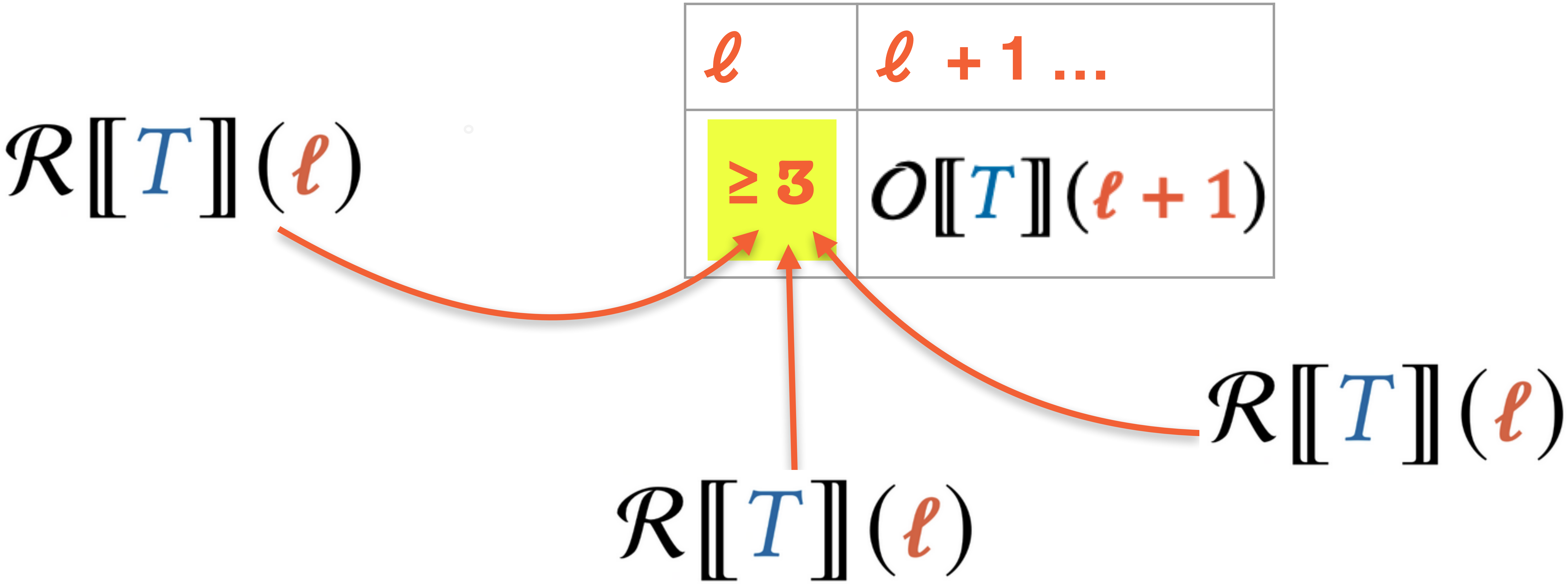
ℓ	$\ell + 1 \ldots$
c	$\mathcal{O}[\![T]\!](\ell + 1)$

Formalization: Ownership + Sharing

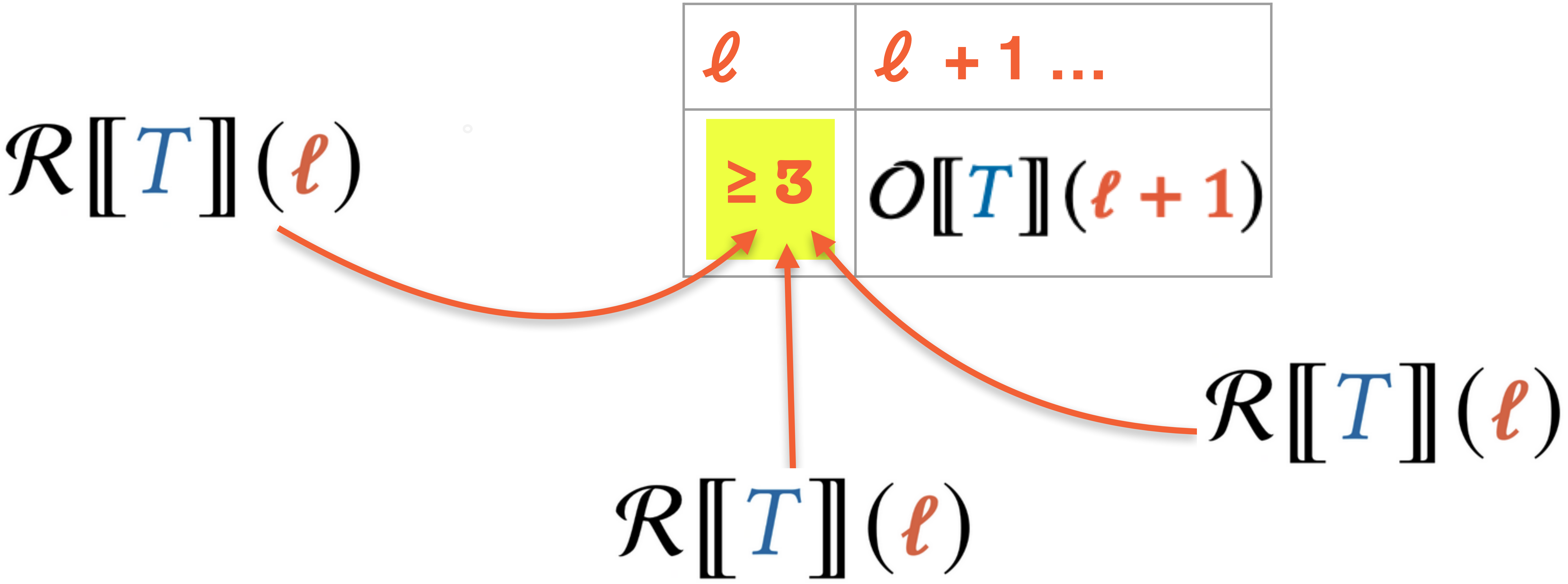
$$\mathcal{R}[\![T]\!](\ell)$$

ℓ	$\ell + 1 \ldots$
≥ 1	$\mathcal{O}[\![T]\!](\ell + 1)$

Formalization: Ownership + Sharing



Formalization: Ownership + Sharing



RC-INCR

$$\left\{\mathcal{R}[\![T]\!](\ell)\right\} \; {+}{+}\ell \; \left\{n.\ \ulcorner n > 1 \urcorner \star \mathcal{R}[\![T]\!](\ell) \star \mathcal{R}[\![T]\!](\ell)\right\}$$

Formalization: Ownership + Sharing

ℓ	$\ell + 1 \ldots$
≥ 3	$\mathcal{O}[\![T]\!](\ell + 1)$

$$\mathcal{R}[\![T]\!](\ell)$$

$$\mathcal{R}[\![T]\!](\ell)$$

$$\mathcal{R}[\![T]\!](\ell)$$

Formalization: Ownership + Sharing

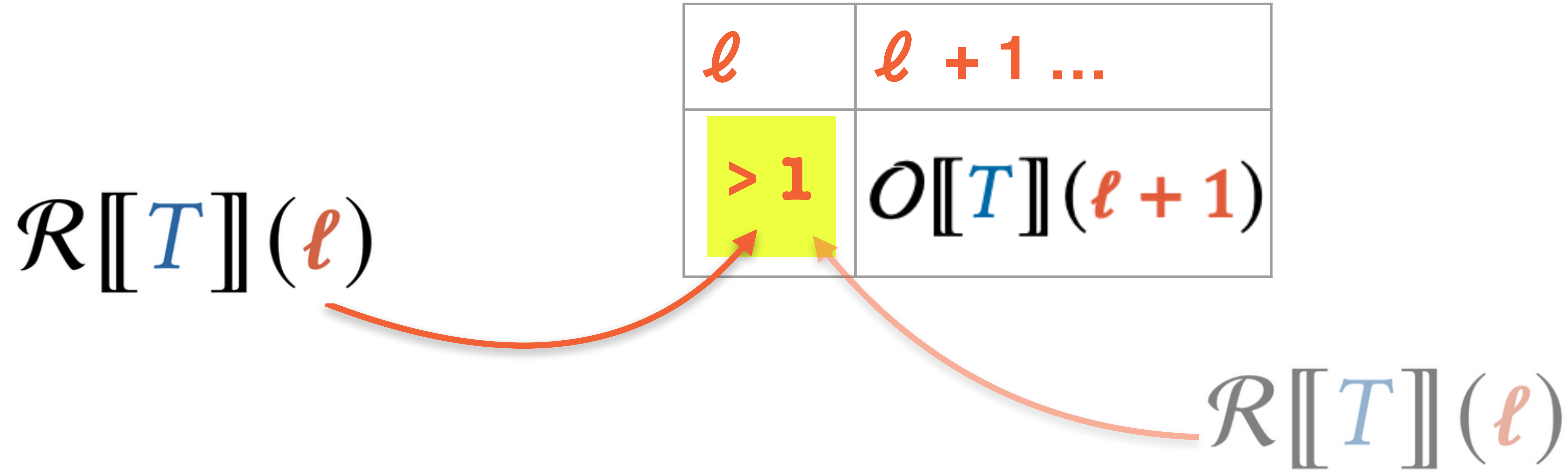
$\mathcal{R}[\![T]\!](\ell)$

ℓ	$\ell + 1 \ldots$
≥ 1	$\mathcal{O}[\![T]\!](\ell + 1)$

RC-DECR

$\{\mathcal{R}[\![T]\!](\ell)\}$ $--\ell$ $\{n.$ $\}$

Formalization: Ownership + Sharing



RC-DECR

$$\left\{\mathcal{R}[\![T]\!](\ell)\right\} \dashrightarrow_{\ell} \left\{n.\, \left(\ulcorner n > 0 \urcorner \wedge \mathsf{emp}\right)\right\}$$

Formalization: Ownership + Sharing

$$\mathcal{R}[\![T]\!](\ell)$$

ℓ	$\ell + 1 \ldots$
1	$\mathcal{O}[\![T]\!](\ell + 1)$

RC-DECR

$$\left\{\mathcal{R}[\![T]\!](\ell)\right\} \;{-}{-}\ell\; \left\{n.\,\left(\ulcorner n > 0 \urcorner \land \mathsf{emp}\right)\right\}$$

Formalization: Ownership + Sharing

ℓ	$\ell + 1 \ldots$
0	$\mathcal{O}[\![T]\!](\ell + 1)$

RC-DECR

$$\left\{\mathcal{R}[\![T]\!](\ell)\right\} \dashrightarrow_{\ell} \left\{n.\left(\ulcorner n > 0 \urcorner \land \mathsf{emp}\right) \lor \left(\ulcorner n = 0 \urcorner \star \ell \mapsto 0 \star \mathcal{O}[\![T]\!](\ell + 1)\right)\right\}$$

Formalization: Ownership + Sharing

ℓ	$\ell + 1$ ...
0	$\mathcal{O}[\![T]\!](\ell + 1)$

Formalization: Ownership + Sharing

ℓ	$\ell + 1 \ldots$
1	$\mathcal{O}[\![T]\!](\ell + 1)$

$$\left\{\ell \mapsto 1 \star \mathcal{O}[\![T]\!](\ell + 1)\right\}\ e\ \{Q\}$$

Formalization: Ownership + Sharing

$$\mathcal{R}[\![T]\!](\ell)$$

ℓ	$\ell + 1 \ldots$
1	$\mathcal{O}[\![T]\!](\ell + 1)$

RC-NEW

$$\frac{\left\{\mathcal{R}[\![T]\!](\ell)\right\}\ e\ \left\{Q\right\}}{\left\{\ell \mapsto 1 \star \mathcal{O}[\![T]\!](\ell + 1)\right\}\ e\ \left\{Q\right\}}$$

Formalization: Compound Layout

$$\mathcal{O}[\![T_1 \times T_2]\!](\ell) \approx$$

$$\mathcal{O}[\![T_1 \times T_2]\!](\ell) \triangleq$$

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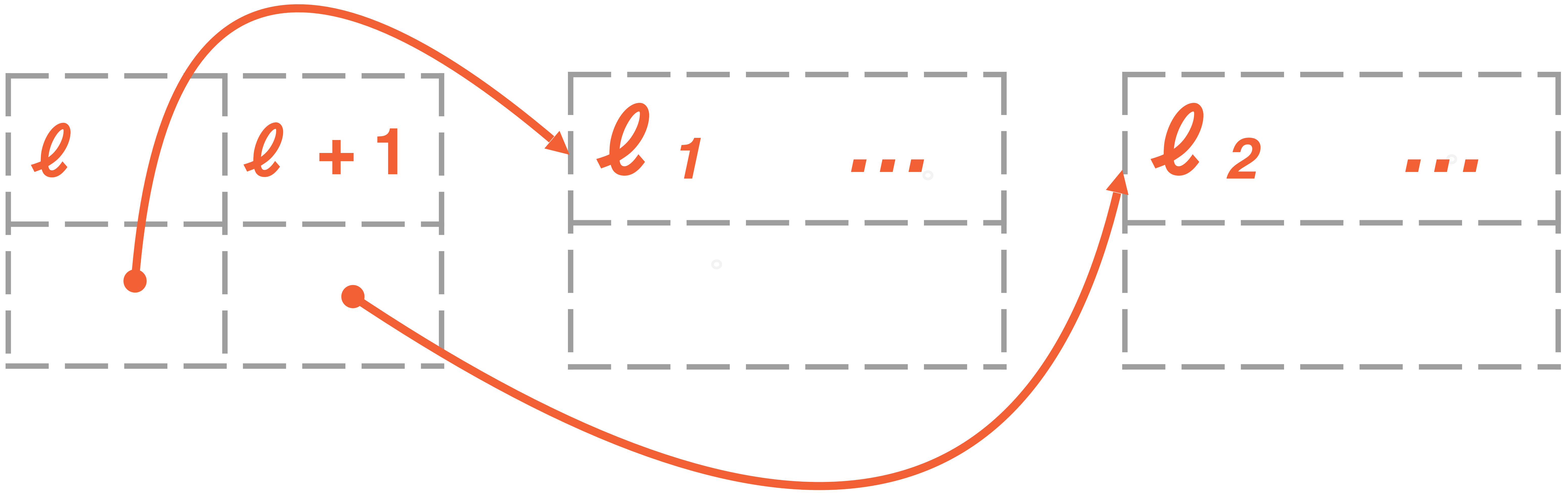
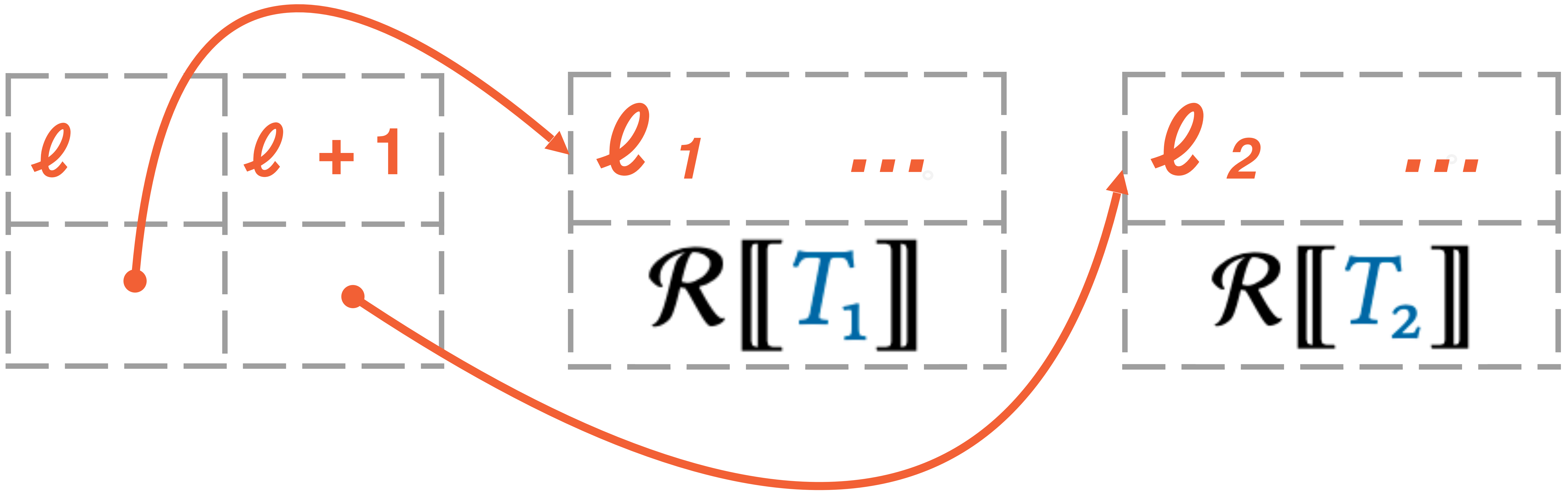


$$\mathcal{O}[\![T_1 \times T_2]\!](\ell) \triangleq \exists\, \ell_1, \ell_2.$$

$$\boxed{\begin{array}{l} \ell \mapsto \ell_1 \\ \star\ \ell + 1 \mapsto \ell_2 \end{array}}$$

Formalization: Compound Layout

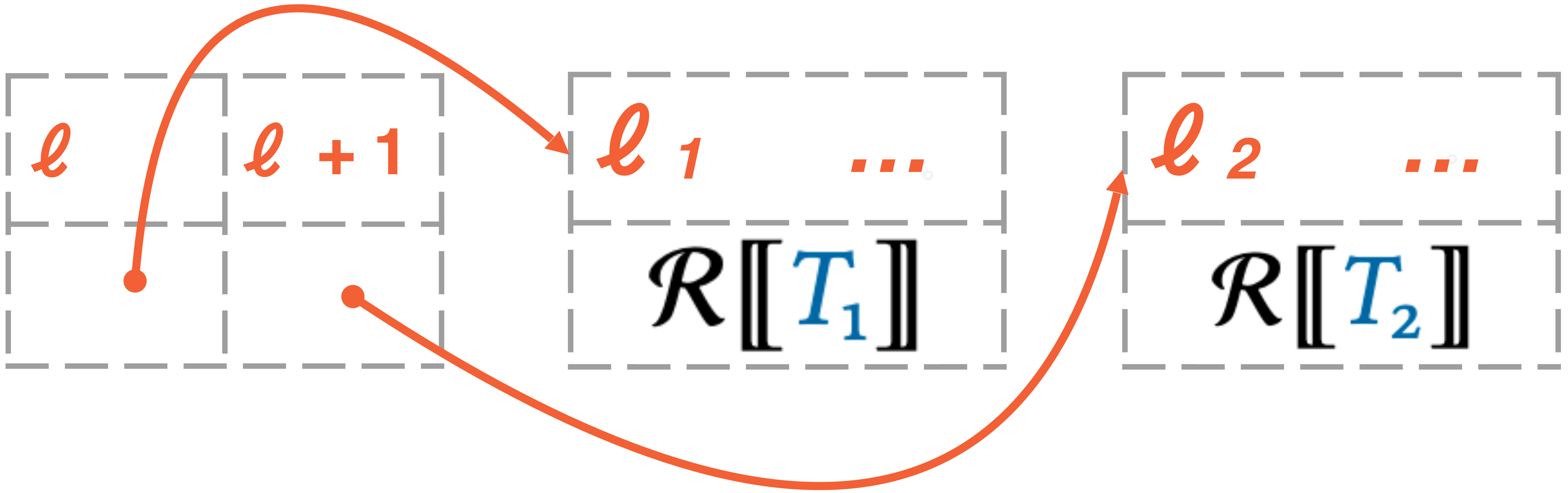
$\mathcal{O}[\![T_1 \times T_2]\!](\ell) \approx$



$$\mathcal{O}[\![T_1 \times T_2]\!](\ell) \triangleq \exists\, \ell_1, \ell_2.\; \boxed{\begin{array}{rl} \ell & \mapsto \ell_1 \\ \star\; \ell + 1 & \mapsto \ell_2 \end{array}} \star \boxed{\mathcal{R}[\![T_1]\!](\ell_1)} \star \boxed{\mathcal{R}[\![T_2]\!](\ell_2)}$$

Formalization: Compound Layout

$$\mathcal{O}[\![T_1 \times T_2]\!](\ell) \approx$$



$$\mathcal{O}[\![T_1 \times T_2]\!](\ell) \triangleq \exists\, \ell_1, \ell_2.\ \begin{pmatrix} \ell \mapsto \ell_1 \\ \star\ \ell + 1 \mapsto \ell_2 \end{pmatrix} \star \mathcal{R}[\![T_1]\!](\ell_1) \star \mathcal{R}[\![T_2]\!](\ell_2)$$

Also:
Records and variants

Formalization: Calling Convention

$$\mathcal{O}[\![T_1 \to T_2]\!](\ell) \triangleq \exists\, f.\, \ell \mapsto f \star$$

Pointer to function

Formalization: Calling Convention

$$\mathcal{O}[\![T_1 \to T_2]\!](\ell) \triangleq \exists\, f.\ \ell \mapsto f \star$$

$$\forall\, \ell_1.\ \{\mathcal{R}[\![T_1]\!](\ell_1)\}\ f(\ell_1)\ \{\ell_2.\ \mathcal{R}[\![T_2]\!](\ell_2)\}$$

Pointer to function

Calling convention:
Caller retain

Formalization: Calling Convention

$$\mathcal{O}[\![T_1 \to T_2]\!](\ell) \triangleq \exists\, f.\ \ell \mapsto f \star$$
$$\forall\, \ell_1.\ \{\mathcal{R}[\![T_1]\!](\ell_1)\}\ f(\ell_1)\ \{\ell_2.\ \mathcal{R}[\![T_2]\!](\ell_2)\}$$

Pointer to function

Calling convention: Caller retain

vs.

$$\forall\, \ell_1.\ \{\mathcal{R}[\![T_1]\!](\ell_1)\}\ f(\ell_1)\ \{\ell_2.\ \mathcal{R}[\![T_2]\!](\ell_2) \star \underbrace{\mathcal{R}[\![T_1]\!](\ell_1)}_{\text{Callee retain}}\}$$

Formalization: Calling Convention

$$\mathcal{O}[\![T_1 \to T_2]\!](\ell) \stackrel{\Delta}{\approx} \exists f.\ \ell \mapsto f \star \forall \ell_1.\ \{\mathcal{R}[\![T_1]\!](\ell_1)\}\ f(\ell_1)\ \{\ell_2.\ \mathcal{R}[\![T_2]\!](\ell_2)\}$$

Pointer to function

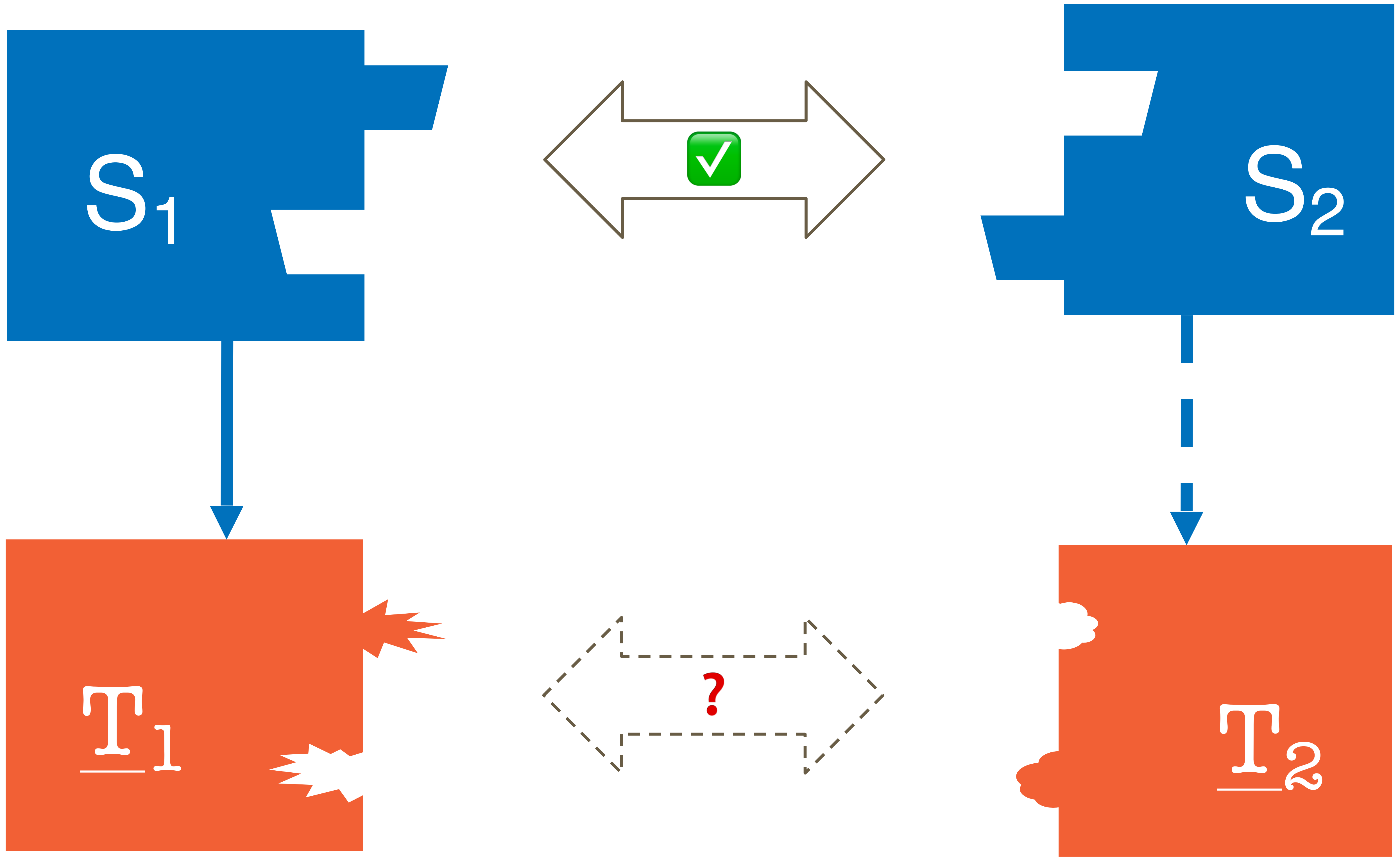
Calling convention:
Caller retain

vs.

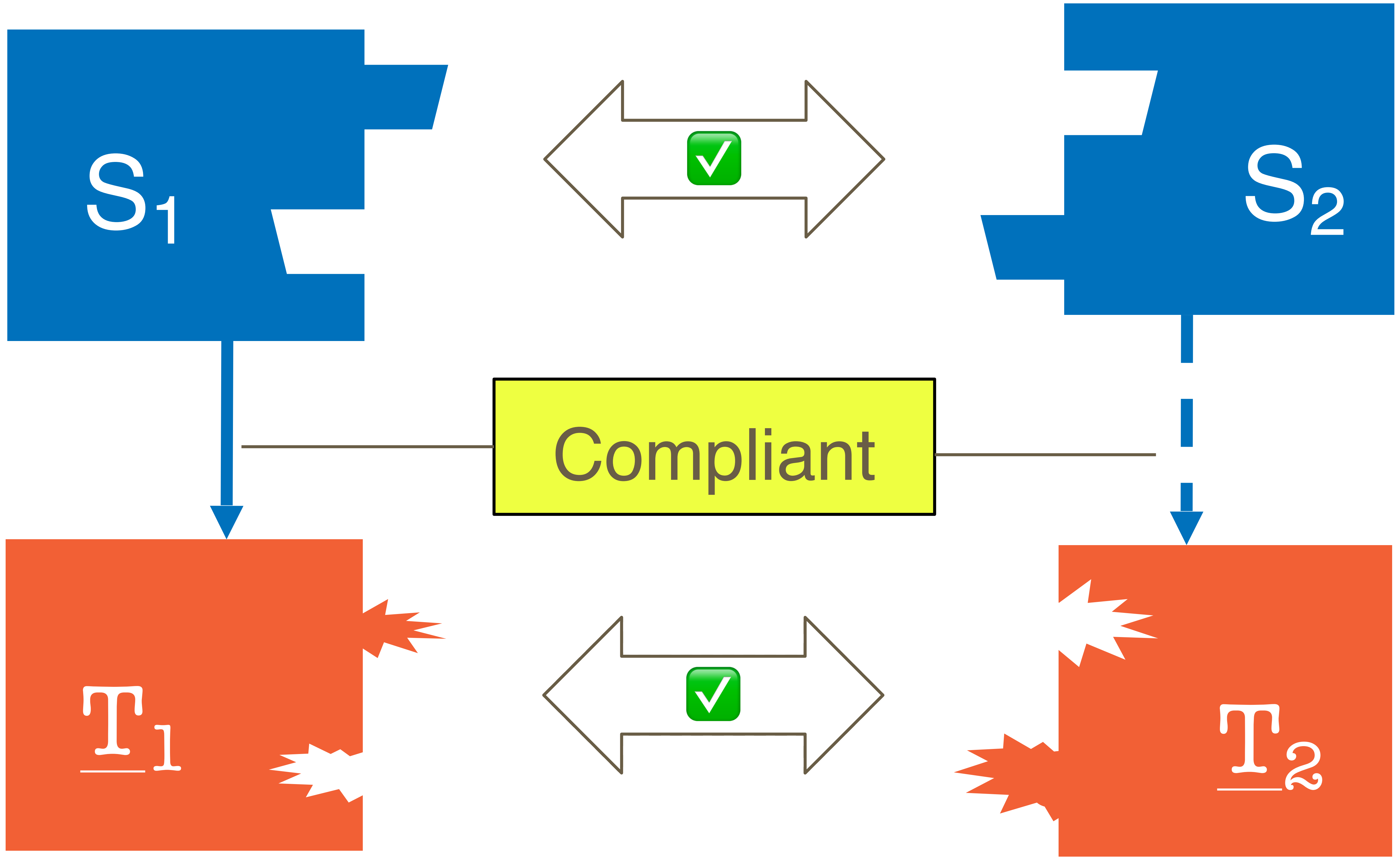
$$\forall \ell_1.\ \{\mathcal{R}[\![T_1]\!](\ell_1)\}\ f(\ell_1)\ \{\ell_2.\ \mathcal{R}[\![T_2]\!](\ell_2) \star \underbrace{\mathcal{R}[\![T_1]\!](\ell_1)}_{\text{Callee retain}}\}$$

Also:
Closures

Application: Compiler Compliance



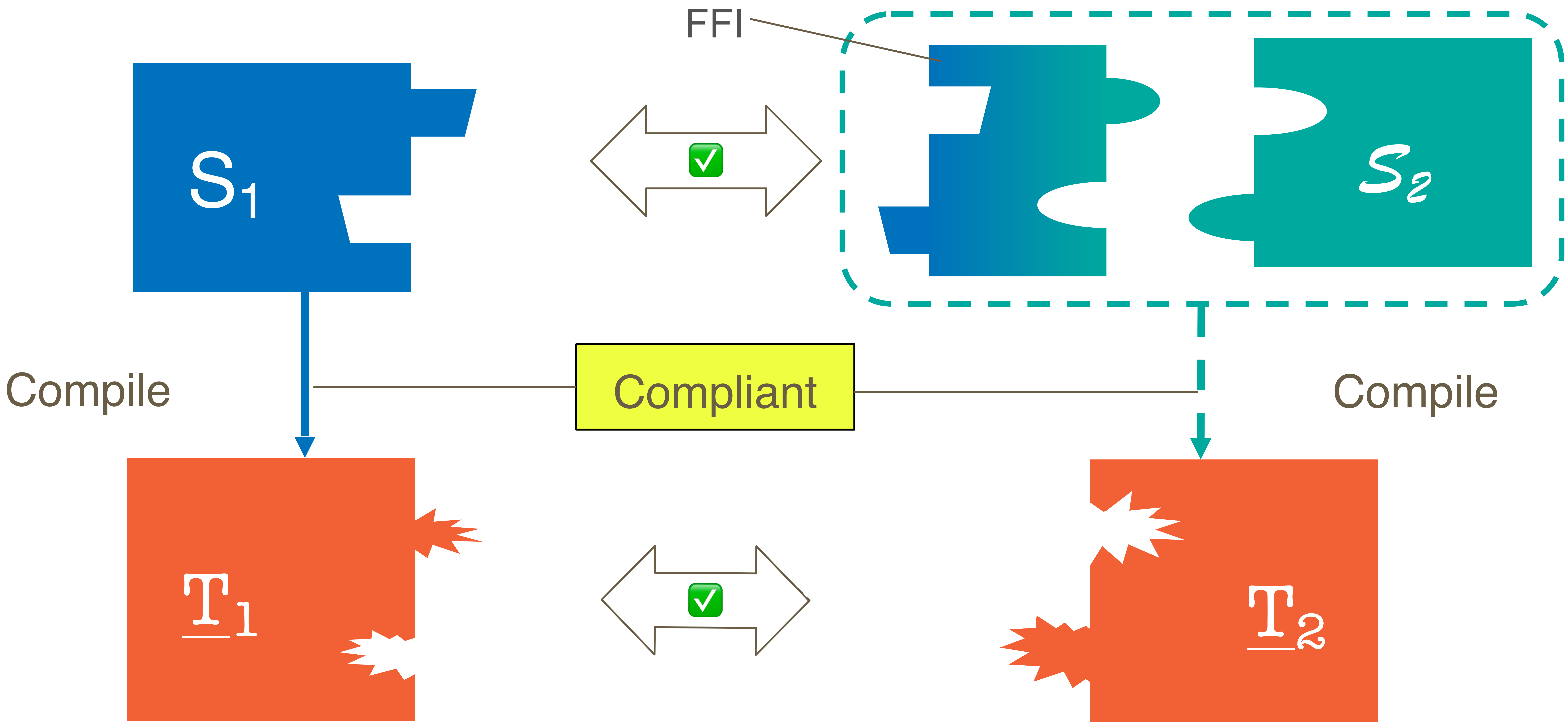
Application: Compiler Compliance



$\rightsquigarrow$ is an **compliant compiler** if

$S : \tau$ *and* $S \rightsquigarrow T$ *implies* $T \in [\![\tau]\!]$

Application: FFI Safety



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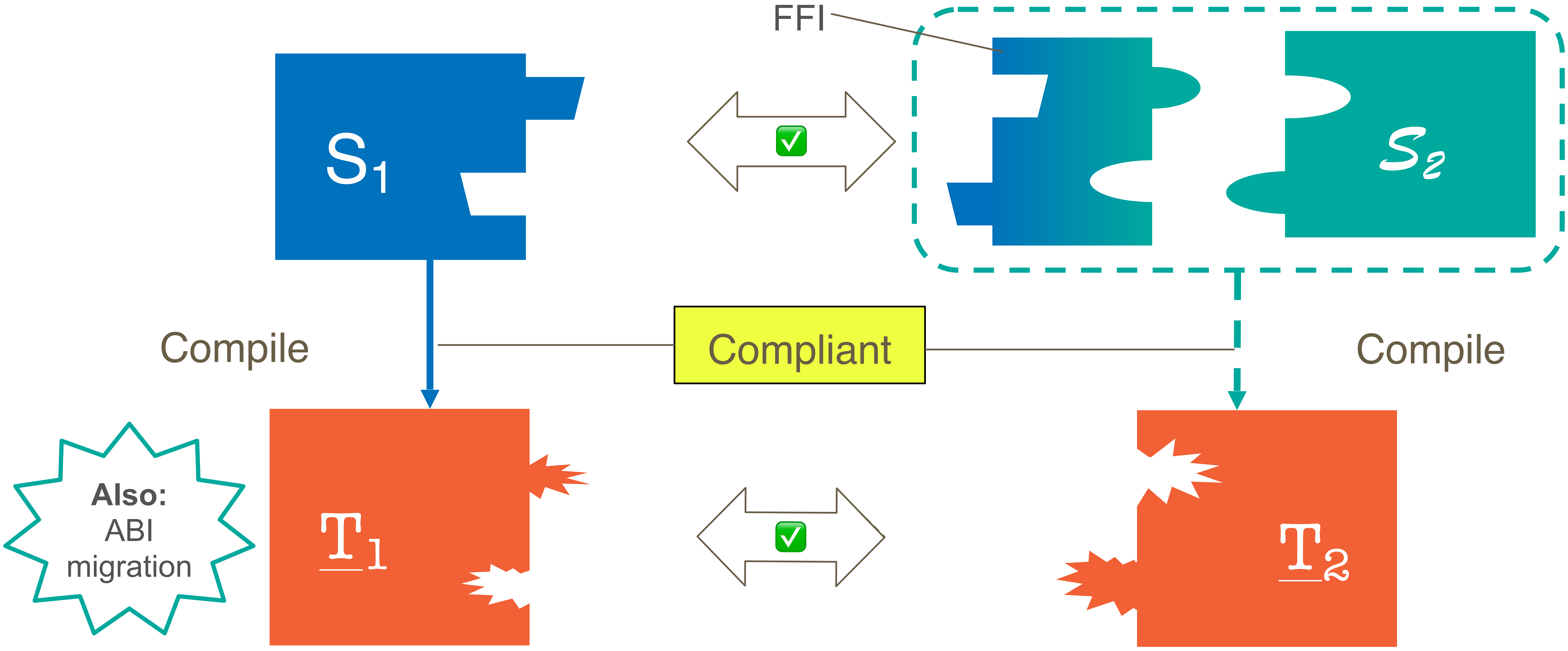
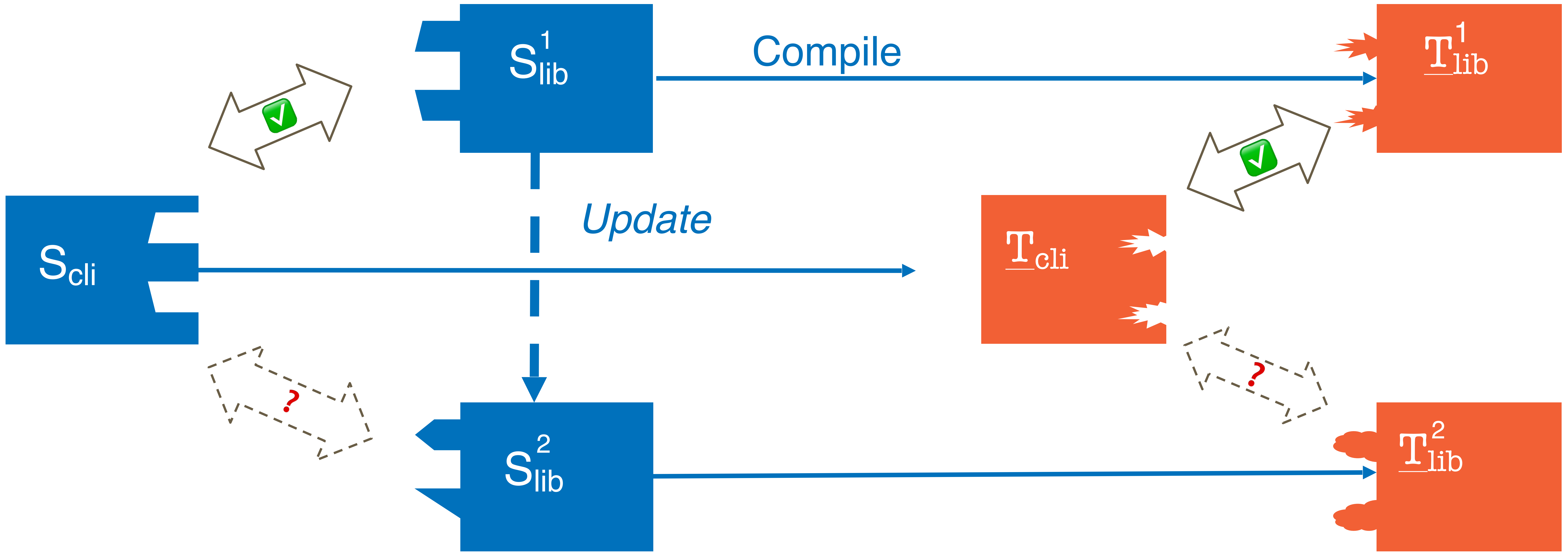
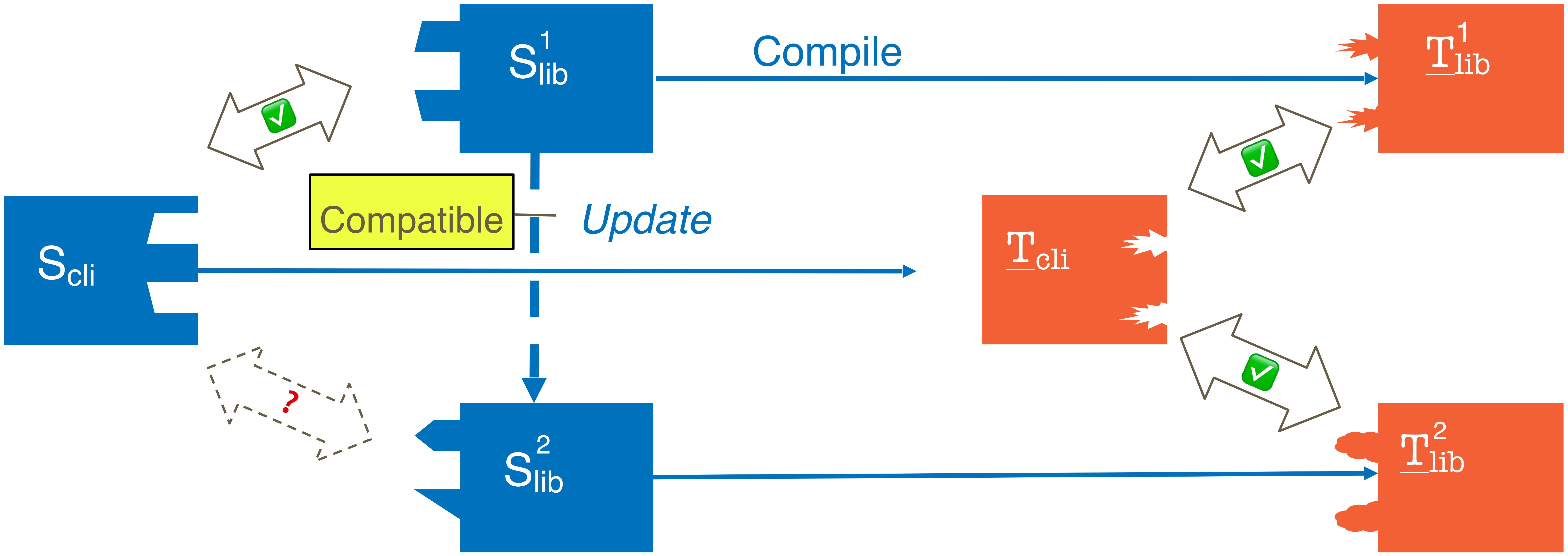


Application: Library Compatibility



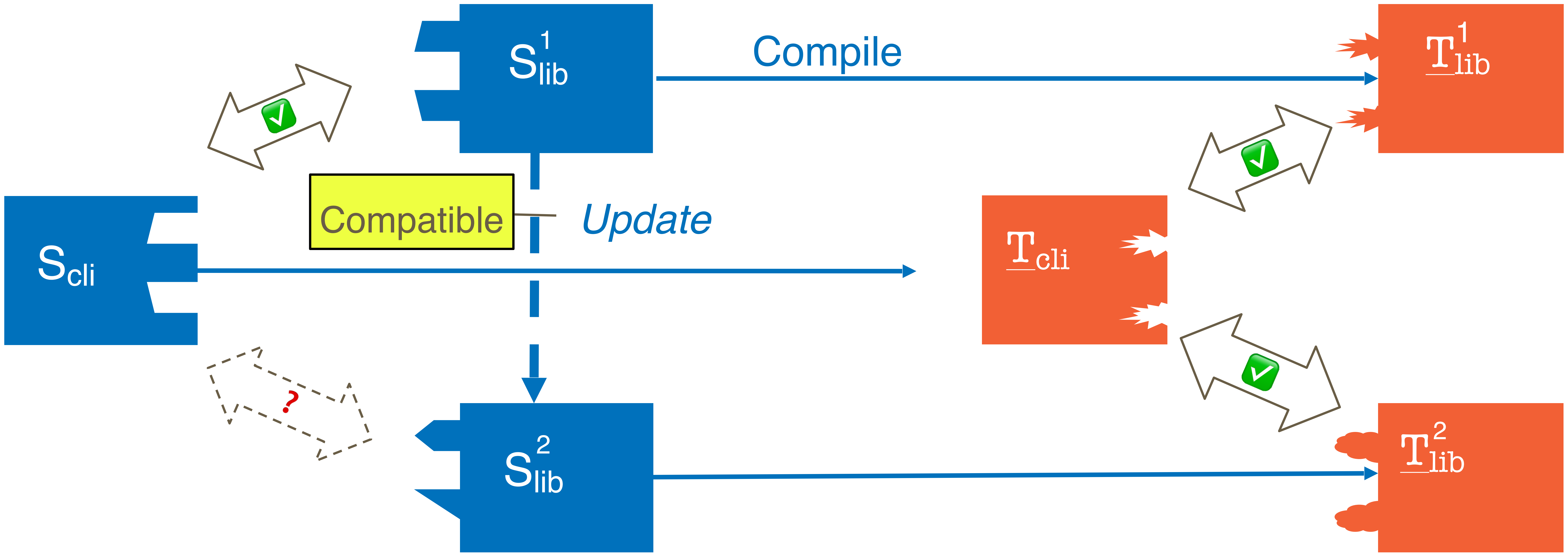
Application: Library Compatibility

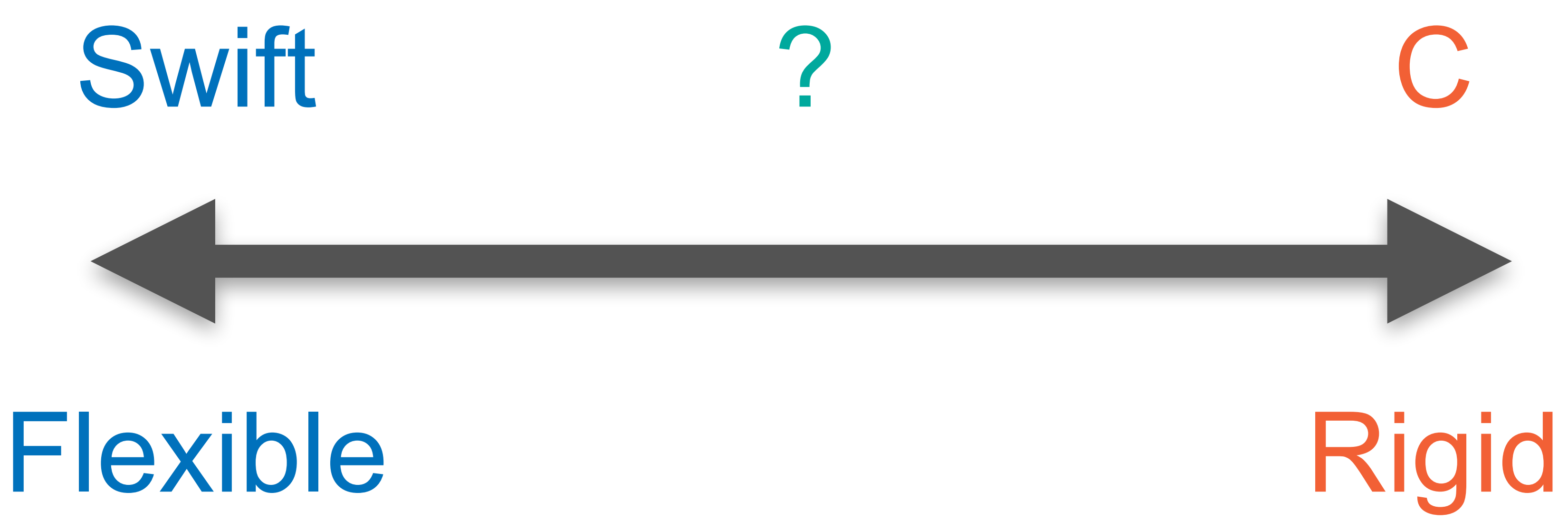


τ_2 is an **compatible update** from τ_1 if

$$\underline{T} \in [\![\tau_2]\!] \quad \textit{implies} \quad \underline{T} \in [\![\tau_1]\!]$$

Application: Library Compatibility





τ_2 is an **compatible update** from τ_1 if

$\underline{T} \in [\![\tau_2]\!]$ *implies* $\underline{T} \in [\![\tau_1]\!]$

Next Steps

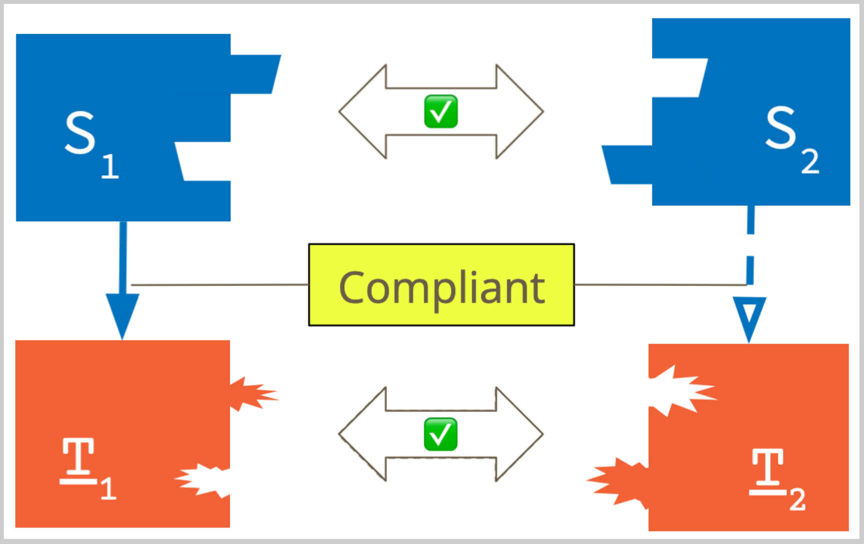
- ★ Wrapping up case study
  - ✦ Variations on design
- ★ Idiosyncrasies of Swift ABI
  - ✦ Resilient type layouts, reabstraction (polymorphism)
- ★ Rust ABI over Wasm
  - ✦ Component Model (prev. Interface Types) building blocks

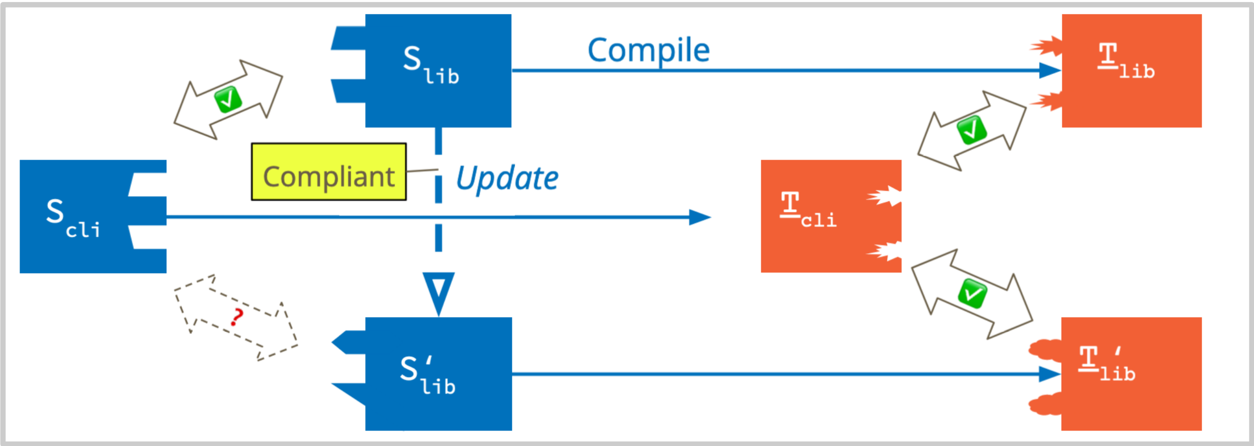
Takeaways

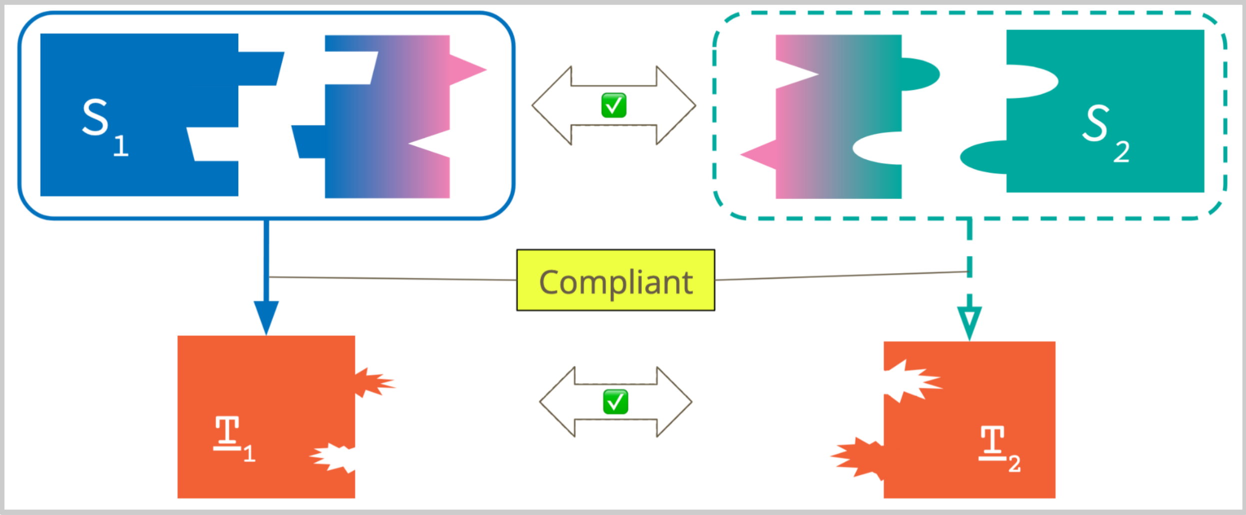
Formalization

$$\underline{T} \in [\![\tau]\!]$$

Application







Let's Chat!

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