Realistic Realizability:

Specifying ABIs You Can Count On

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What is an ABI?

> **Application Binary Interface (ABI)**
>
> `The run-time contract for using` `a particular API` (or for an entire library), including things like symbol names, **calling conventions**, and type **layout** information.
>
> — Swift

What is an ABI?

Application Binary Interface (ABI)

`The run-time contract for using` `a particular API` (or for an entire library), including things like symbol names, $\underbrace{\textbf{calling conventions}}_{\textbf{Behavior}}$, and type **layout** information.

— Swift

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Application Binary Interface (ABI)

`The run-time contract for using` `a particular API` (or for an entire library), including things like symbol names, **calling conventions**, and type **layout** information.

Behavior

— Swift

```
foo : (Int, Int) -> Int
```

?

```
int foo(int fst, int snd)

int foo(int indir[])

void foo(int indir[], int *ret)
```

Why Use an ABI?

Why Use an ABI? Interoperability

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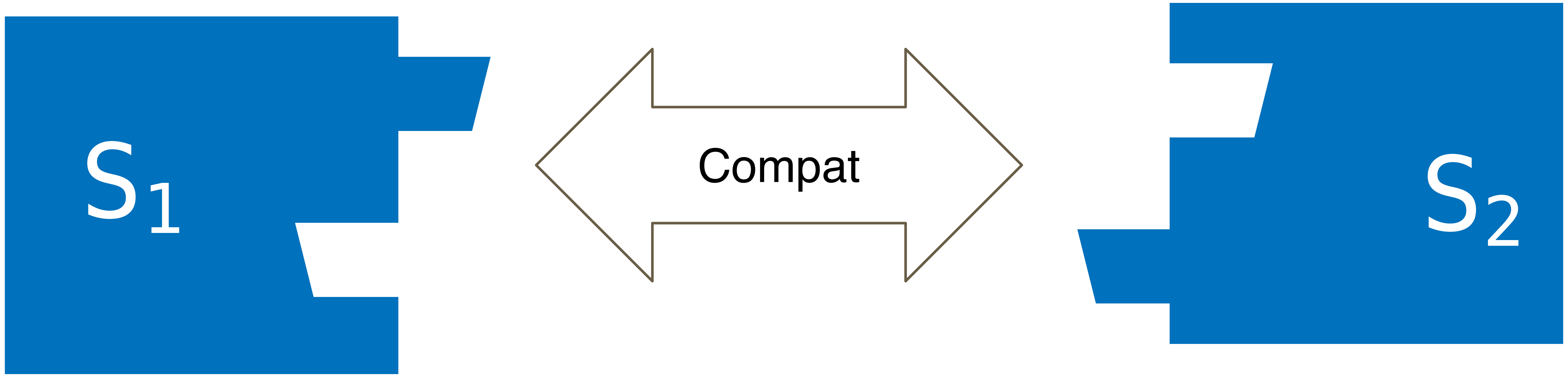

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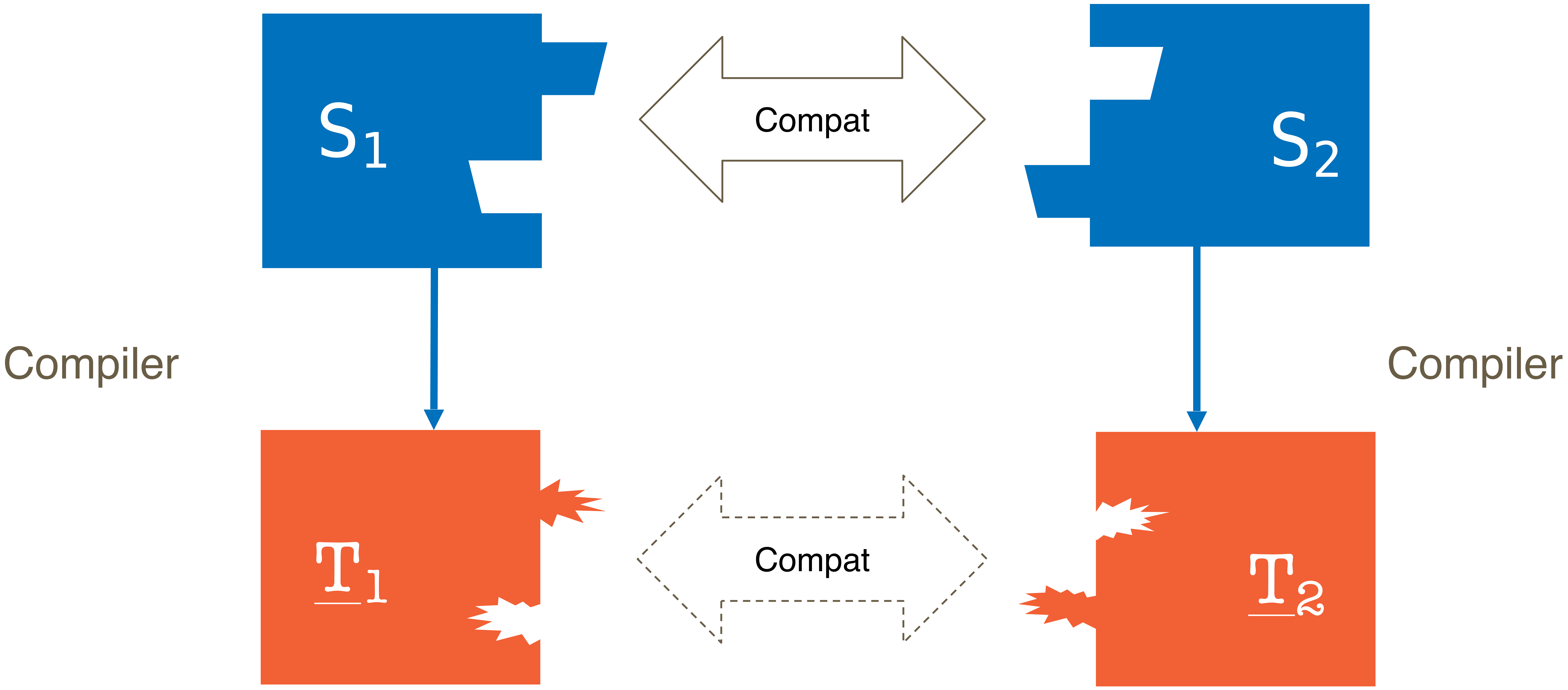
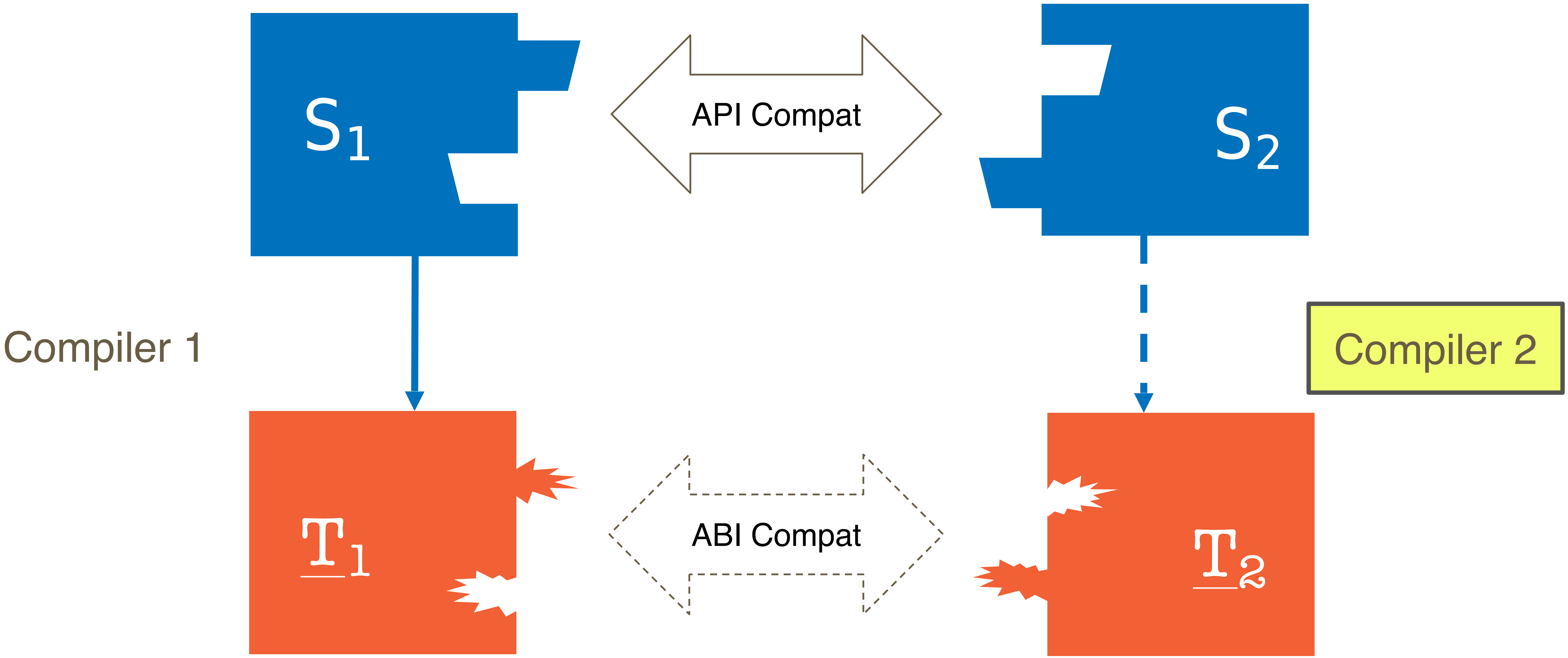
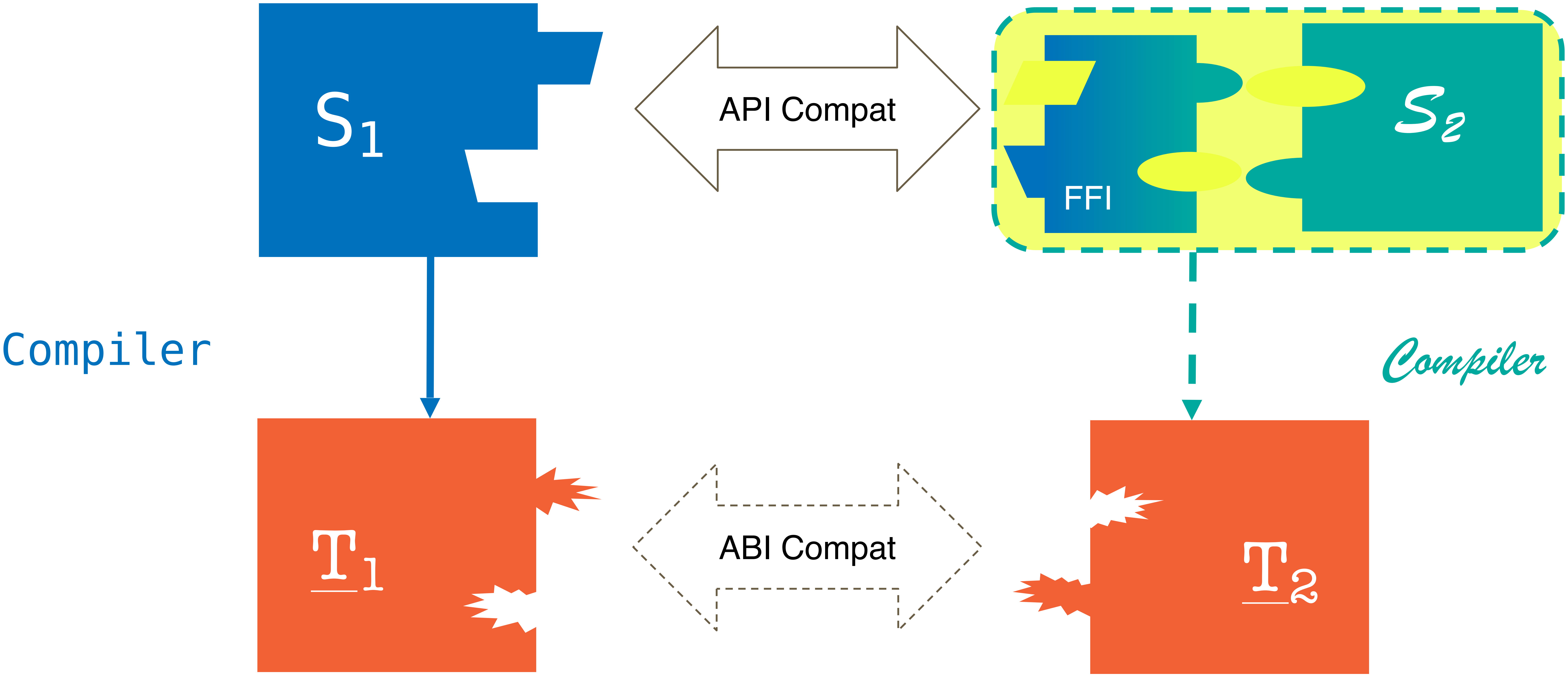


Why Use an ABI? Interoperability for Compilers



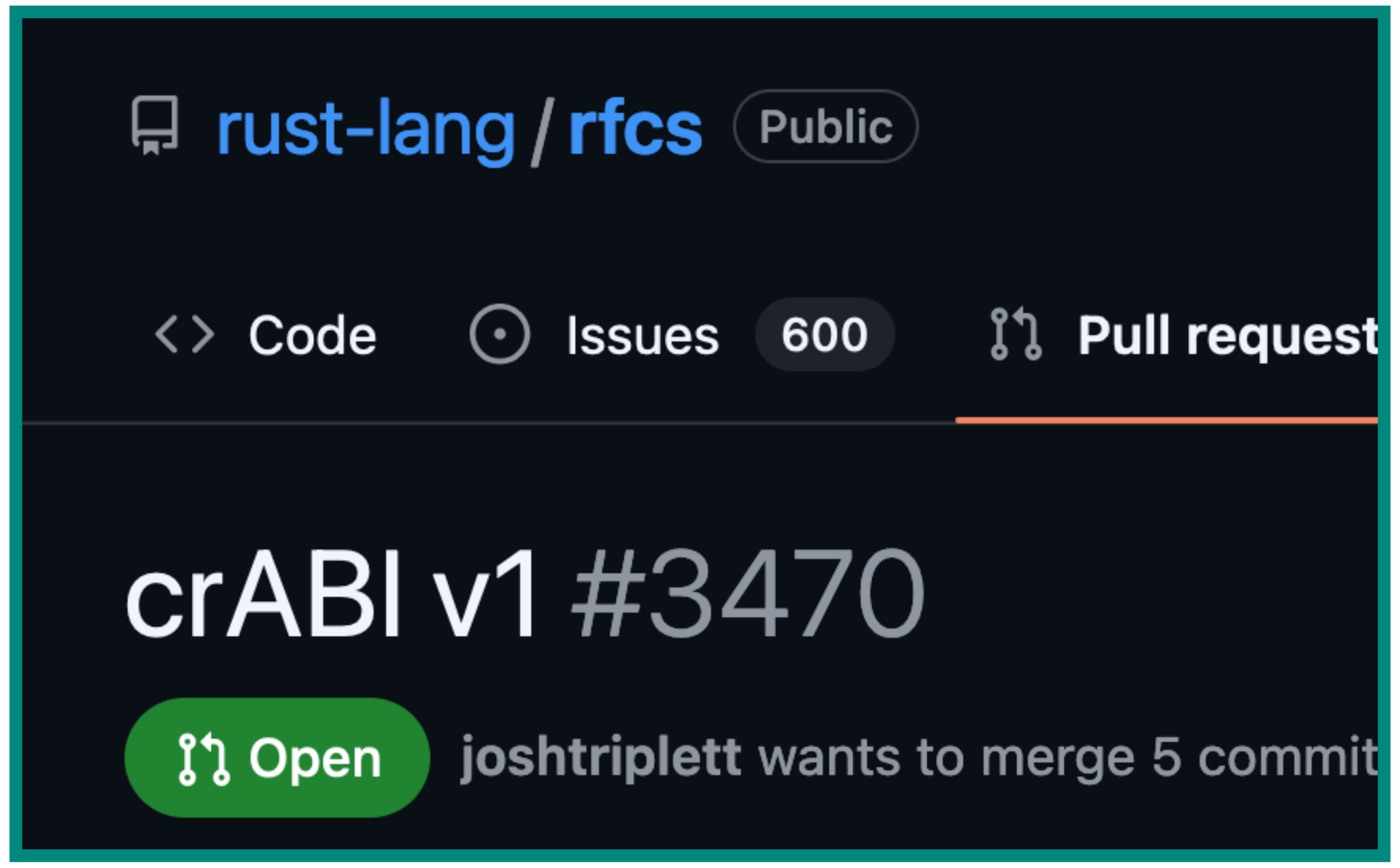
Why Use an ABI? Interoperability for Languages



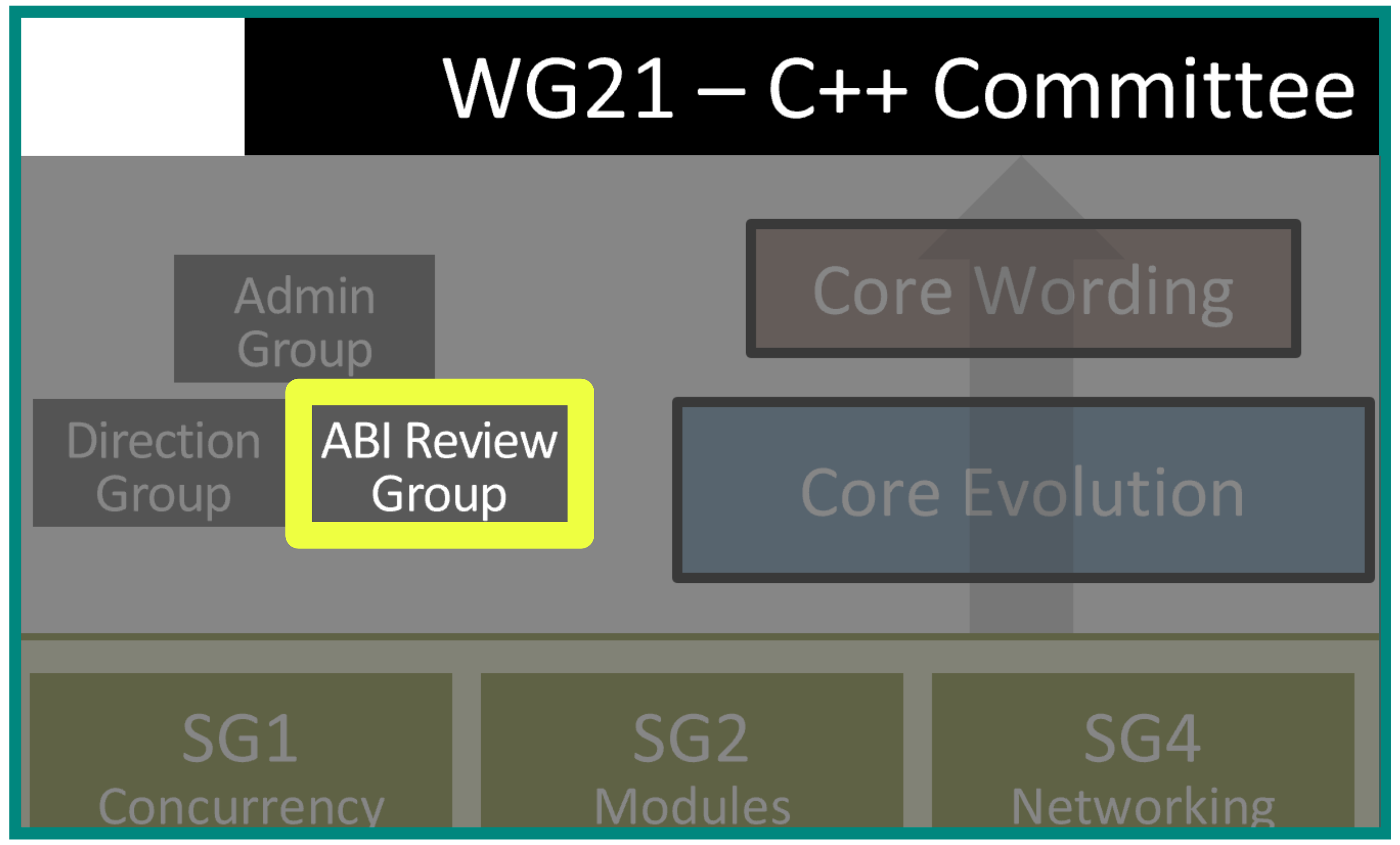
Who is Designing an ABI?

Swift

Rust



C++



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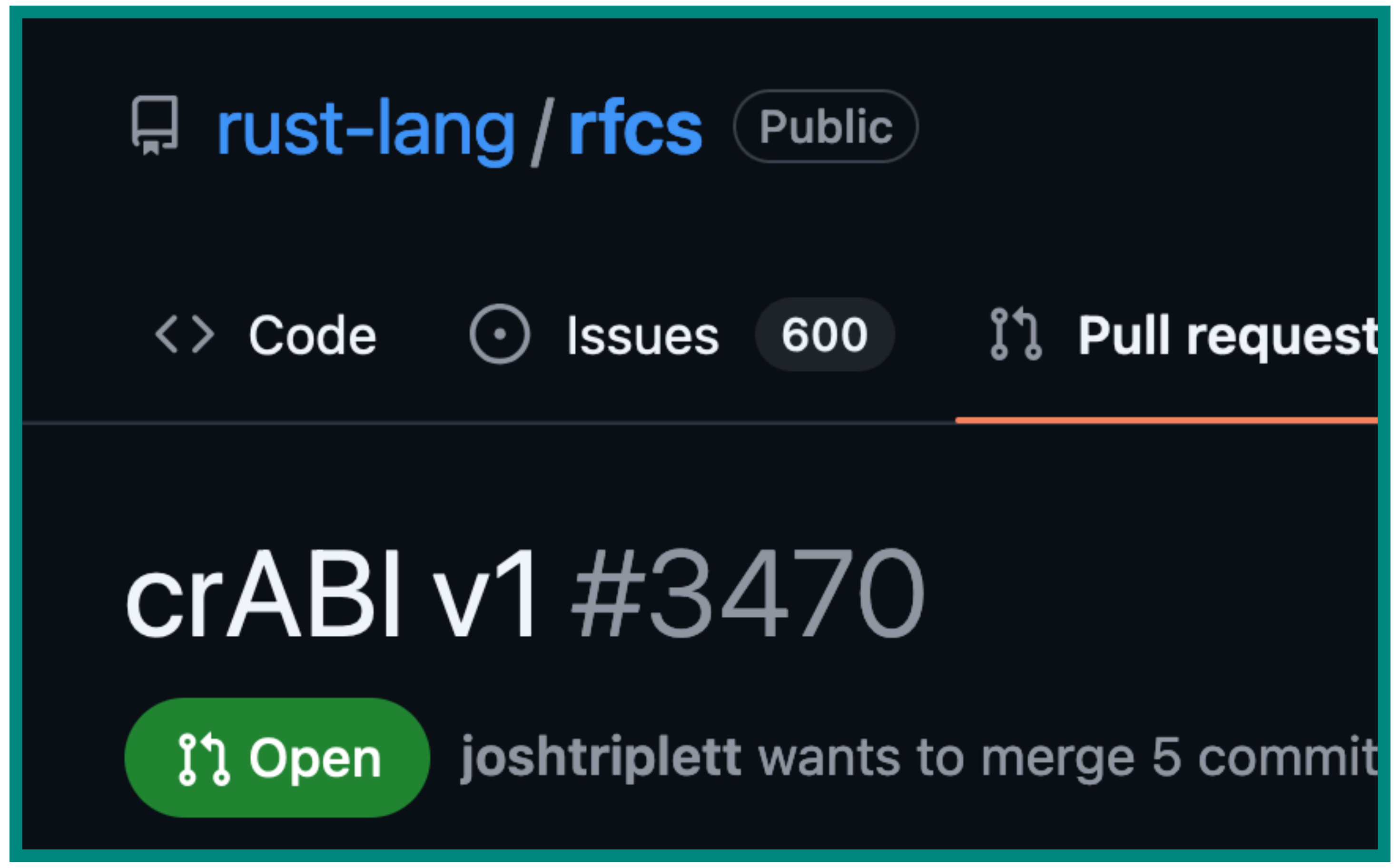

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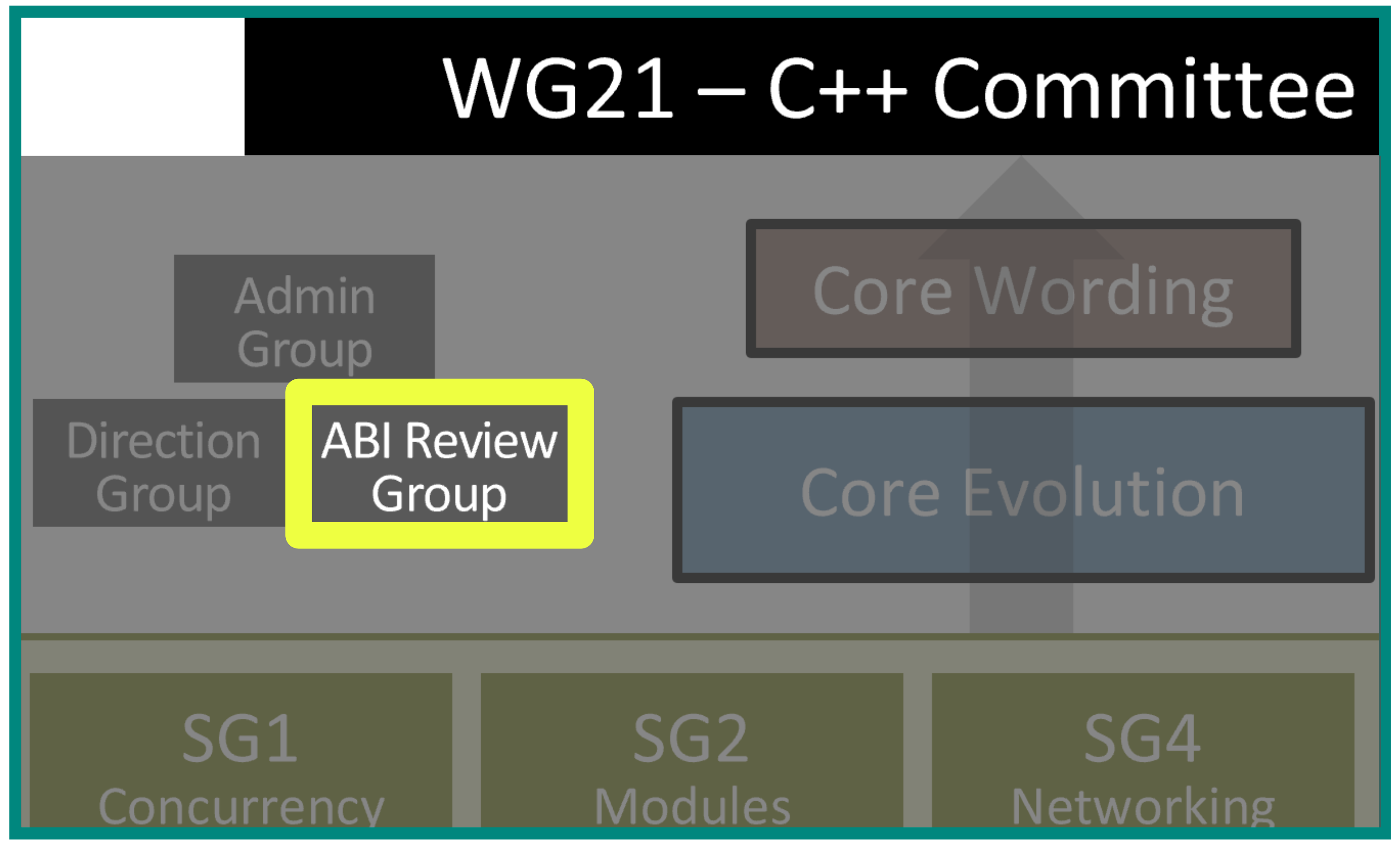

Richer Types → Richer ABIs?

How Should We Specify an ABI?

`The run-time contract for using a particular API`

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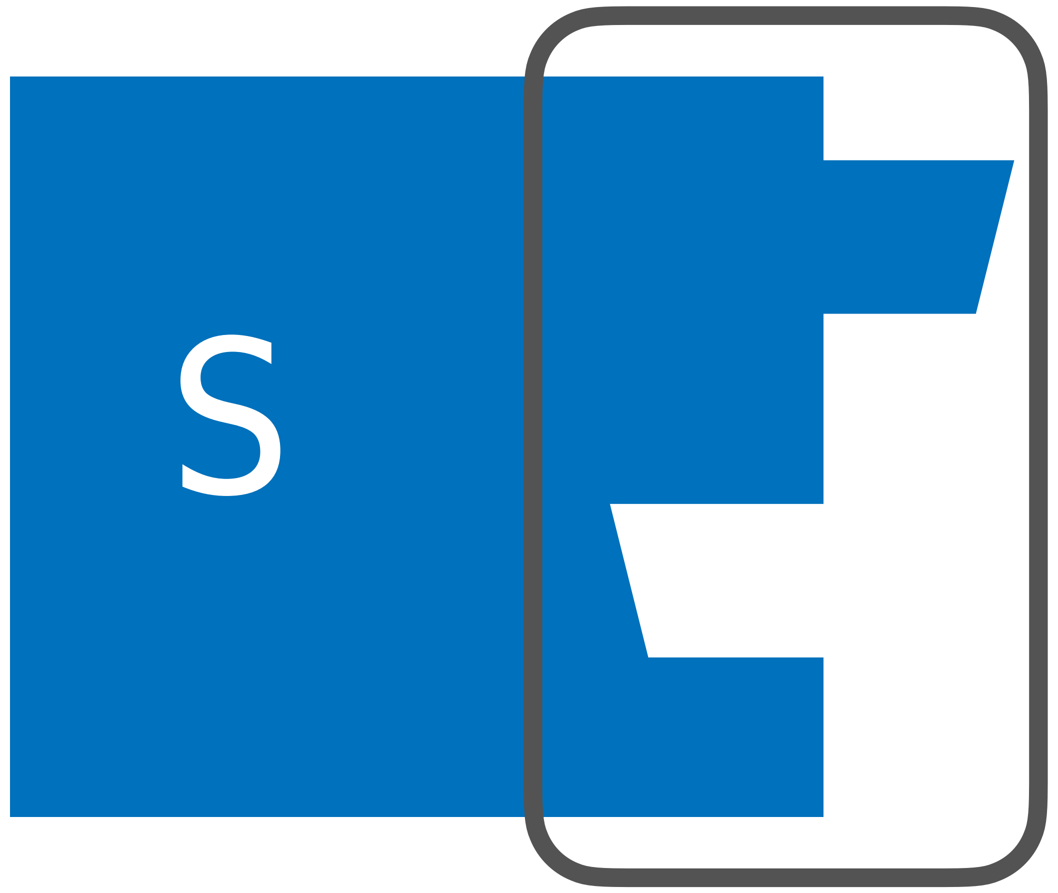
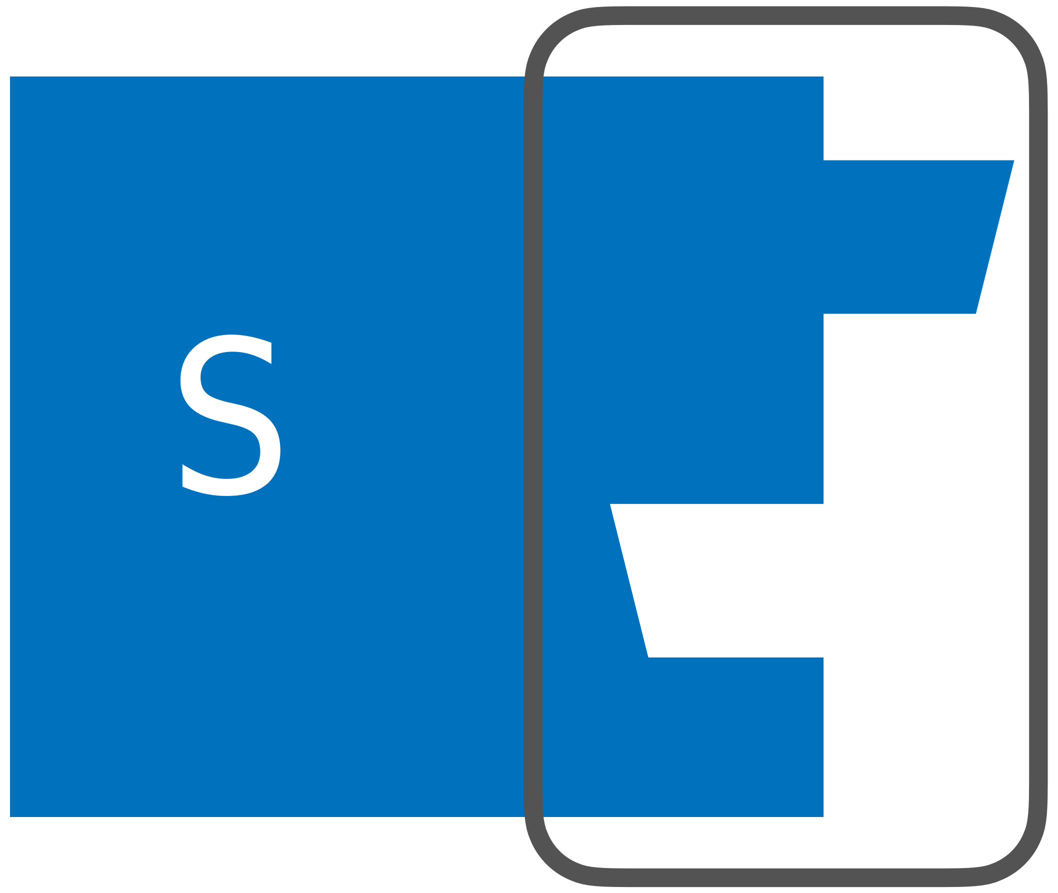


`The run-time contract for using a particular API`

This Type τ

How Should We Specify an ABI?

The run-time contract for using a particular API



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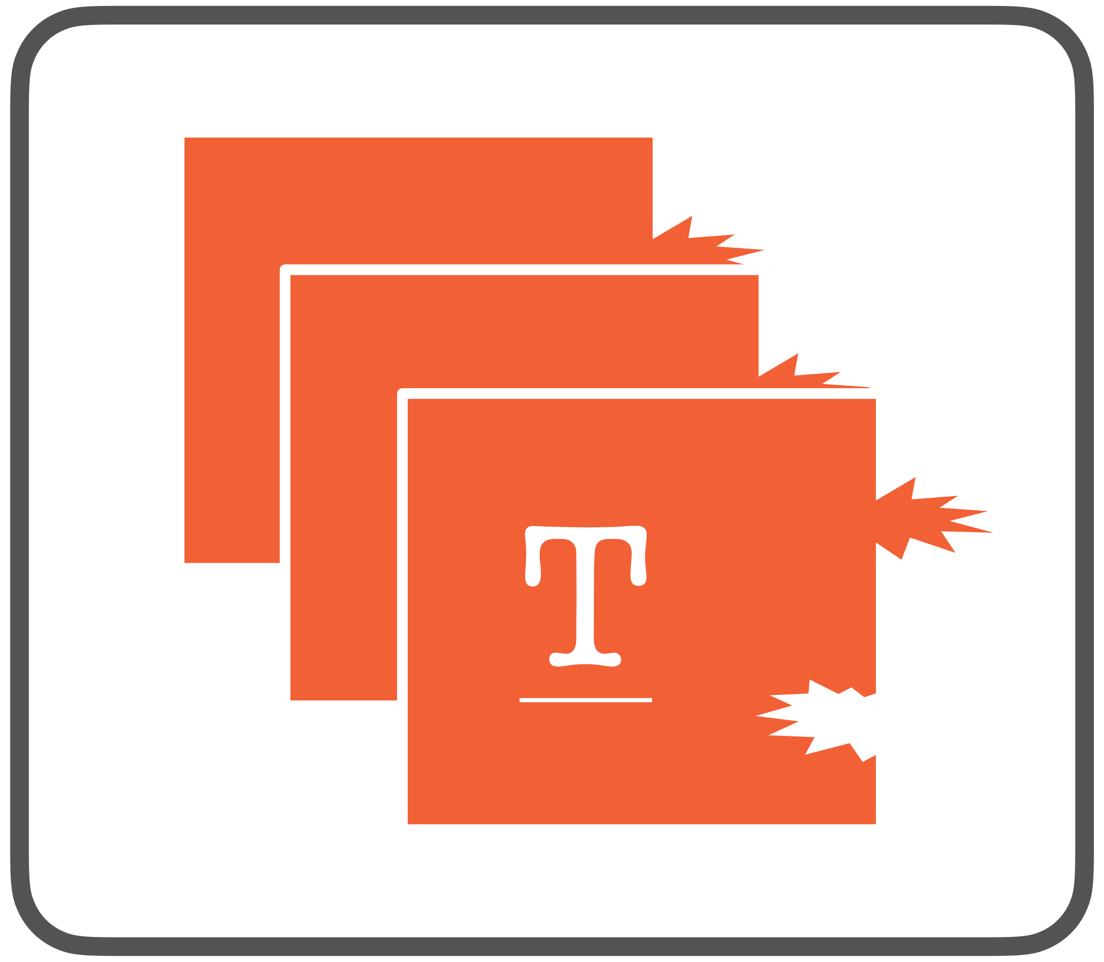

Is *Realized By* These Target Programs

$[\![\tau]\!] = \{ \underline{e} \mid \dots \}$

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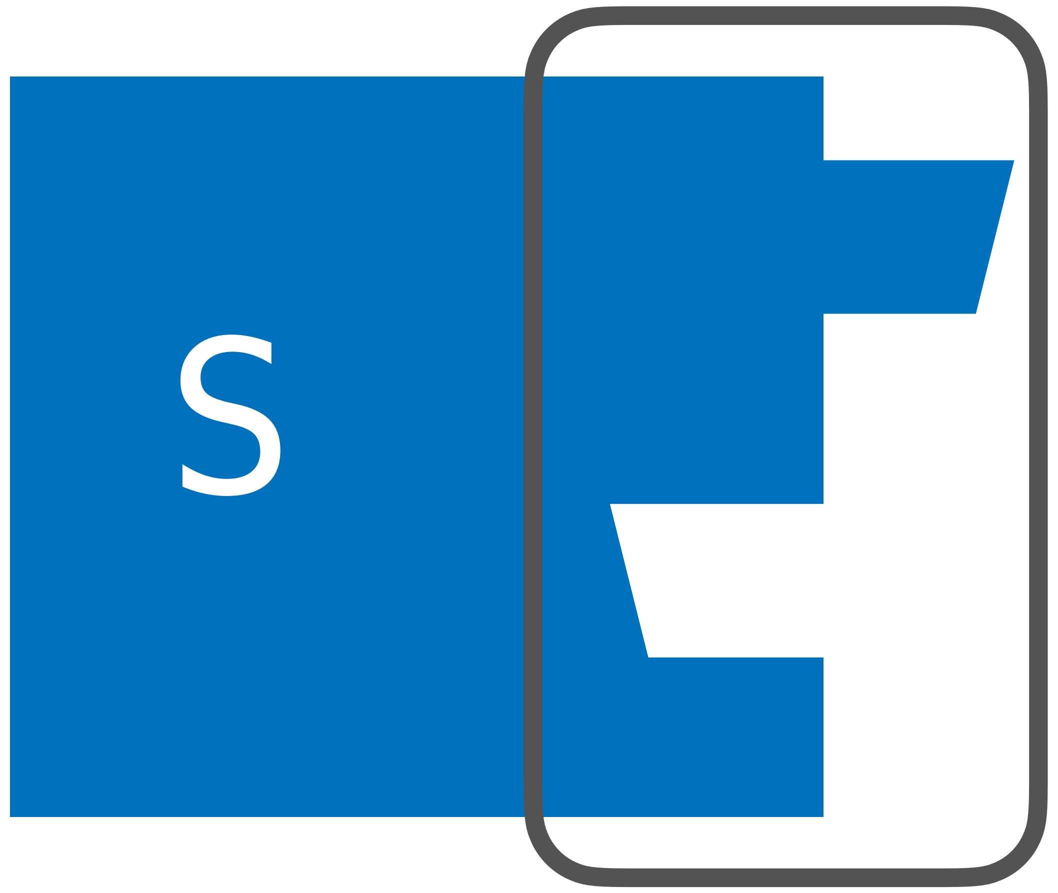

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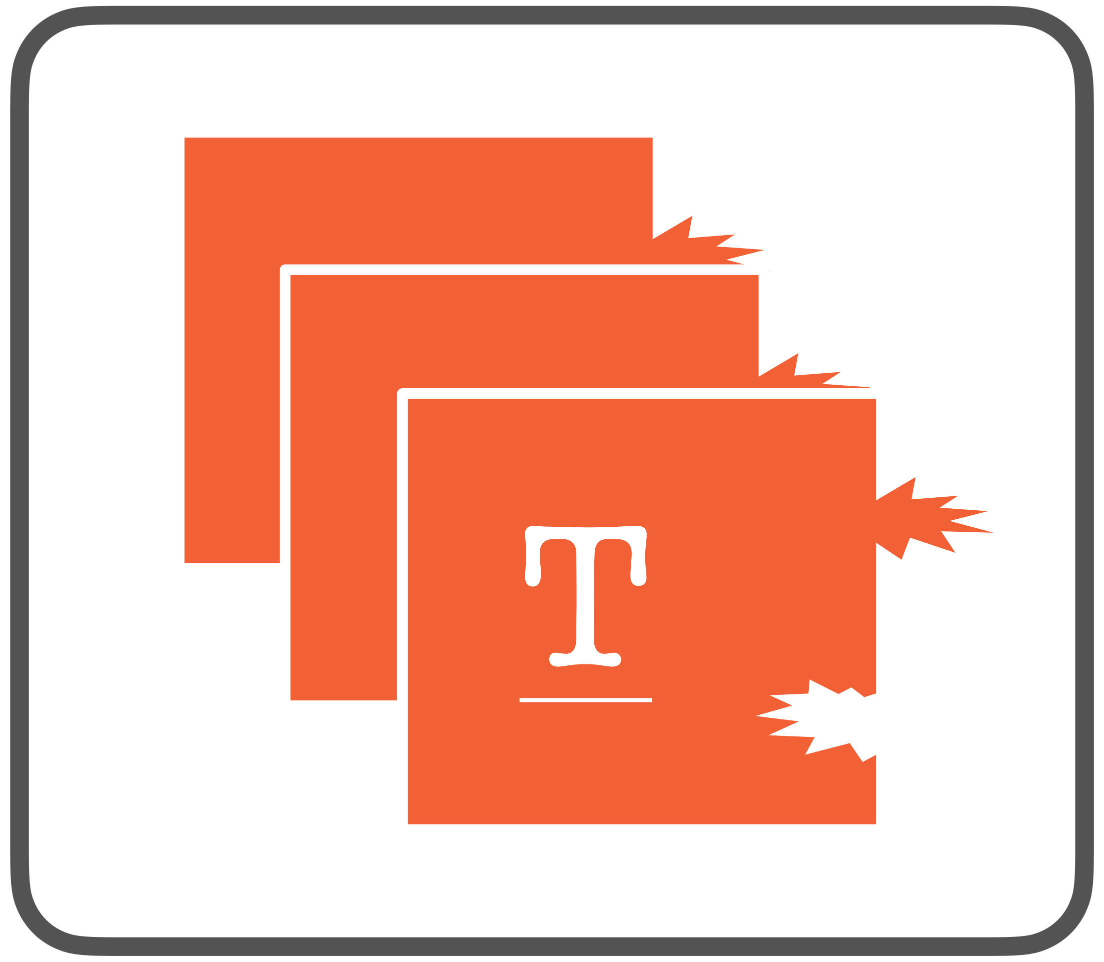

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Semantic Typing using *Realistic Realizability* [Benton06]

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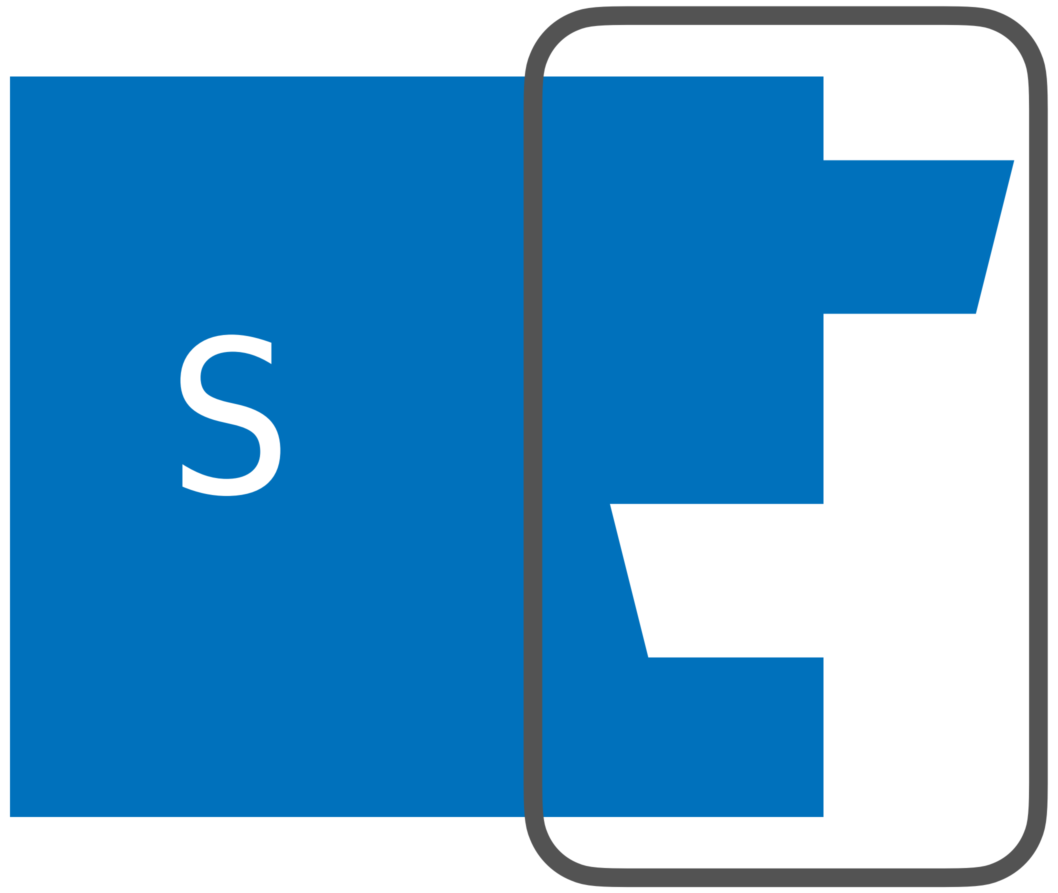


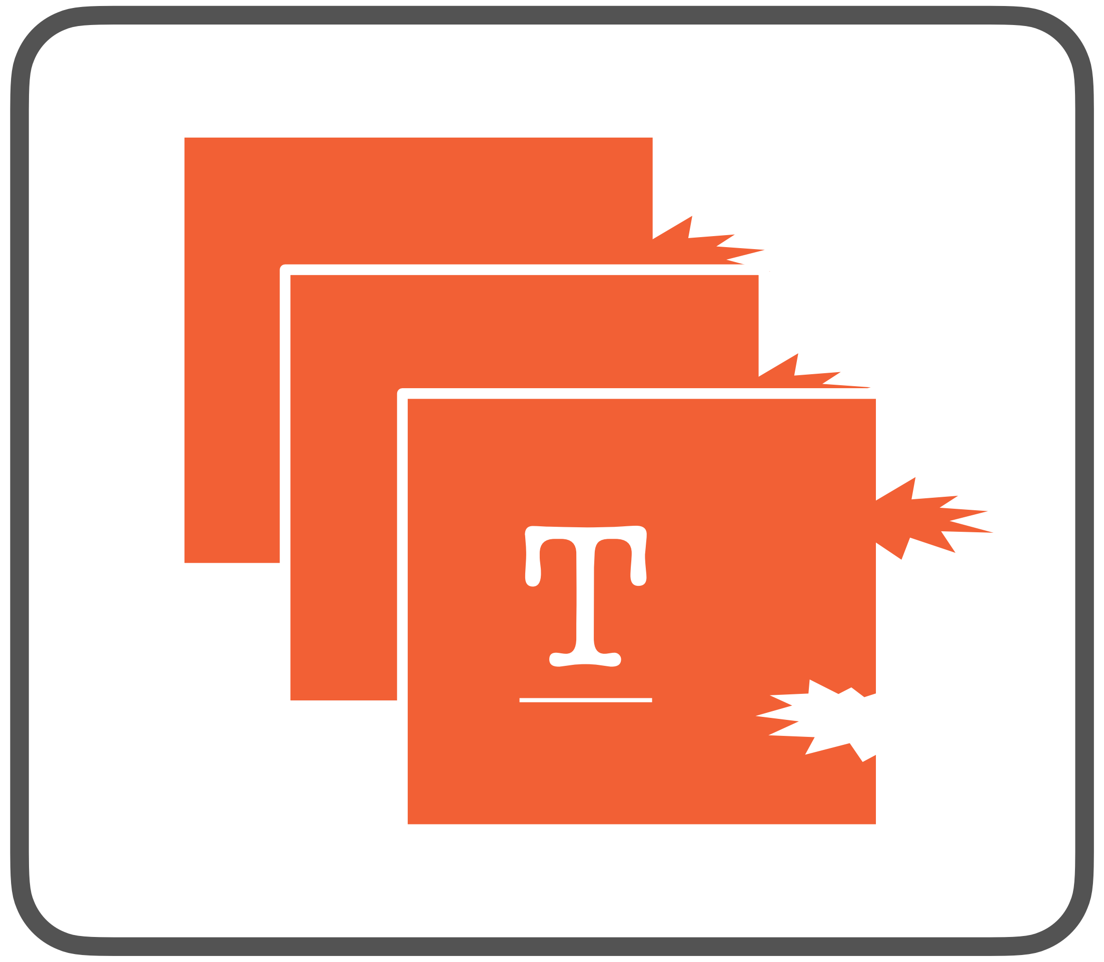
`The run-time contract for using a particular API`

This Type τ

Our Proposal

e is **ABI compliant** with τ if

$e \in [\![\tau]\!]$



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Case Study

- `Functional Source Language`
    - Recursive records and variants, higher-order recursive functions
- C-like Target
    - Block-based memory, pointer arithmetic
- Automatic Reference Counting (ARC) Implementation
    - Values are boxed and reference-counted
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Layout + Behavior

`The run-time contract for using a particular type`

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Layout + Behavior

The run-time contract for using a particular type

e is **ABI compliant** with τ if

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References: Layout

Location ℓ is a reference to an object that behaves like type T

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

Ref. Count Object Data

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

References: Layout

Location ℓ is a reference to an object that behaves like type T

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

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

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

More in Paper:
Unboxed types

References: Ownership + Sharing

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

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

References: Ownership + Sharing

Single reference represents one
share of underlying object

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

ℓ	ℓ **+ 1 ...**
≥ 1	$\mathcal{O}\,[\![T]\!](\boldsymbol{\ell}+1)$

References: Ownership + Sharing

Single reference represents one share of underlying object

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

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

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Reference confers permission to increment count & acquire more shares

RC-INCR

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

References: Ownership + Sharing

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

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Reference confers permission to decrement count & release shares

RC-DECR

$$\left\{\mathcal{R}[\![T]\!](\boldsymbol{\ell})\right\} \; \texttt{--}\boldsymbol{\ell} \; \left\{\boldsymbol{n}. \qquad \right\}$$

References: Ownership + Sharing

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

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

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RC-DECR

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

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References: Ownership + Sharing

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

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RC-DECR

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

Calling Conventions

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

Pointer to function

Calling Conventions

$$
\begin{aligned}
&\mathcal{O}\,[\![T_1 \longrightarrow T_2]\!](\ell) \triangleq \exists\, f.\ \ell \mapsto f \star \\
&\qquad \forall\, \ell_1.\ \left\{\mathcal{R}\,[\![T_1]\!](\ell_1)\right\}\ f(\ell_1)\ \left\{\ell_2.\ \mathcal{R}\,[\![T_2]\!](\ell_2)\right\}
\end{aligned}
$$

Pointer to function

Calling convention:
Caller increment

Calling Conventions

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

Pointer to function

Calling convention:
Caller increment

vs.

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

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More in Paper:
Recursive closures

Aggregate Layout

$$\mathcal{O}\,[\![\mathsf{struct\ Point}\ \{x : \mathbb{Z}, y : \mathbb{Z}\}]\!](\ell)$$

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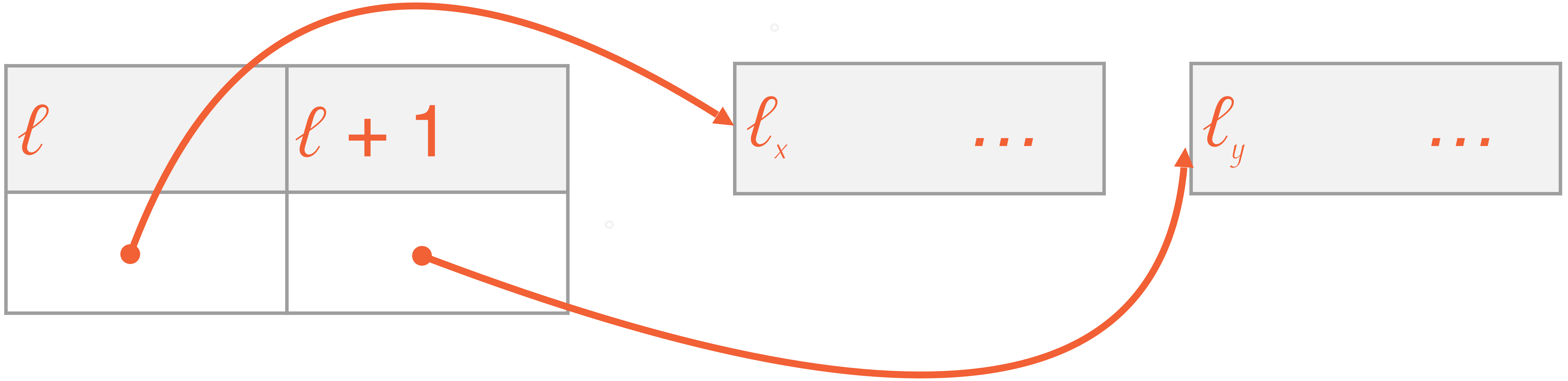
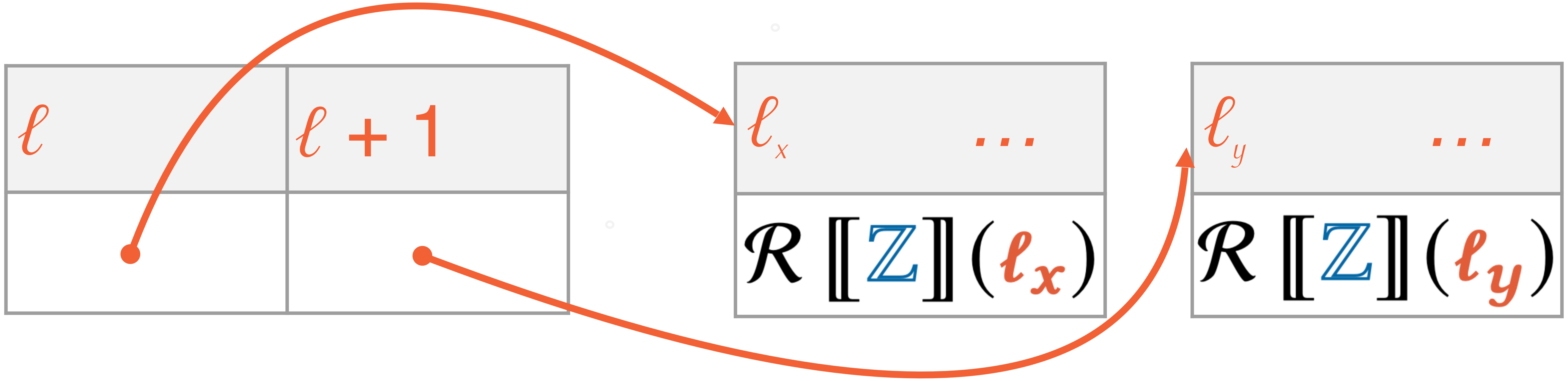


$$\boxed{\exists\, \ell_x, \ell_y.\ \underbrace{\ell \mapsto \ell_x \star \ell + 1 \mapsto \ell_y}_{\text{Physical footprint}}}$$

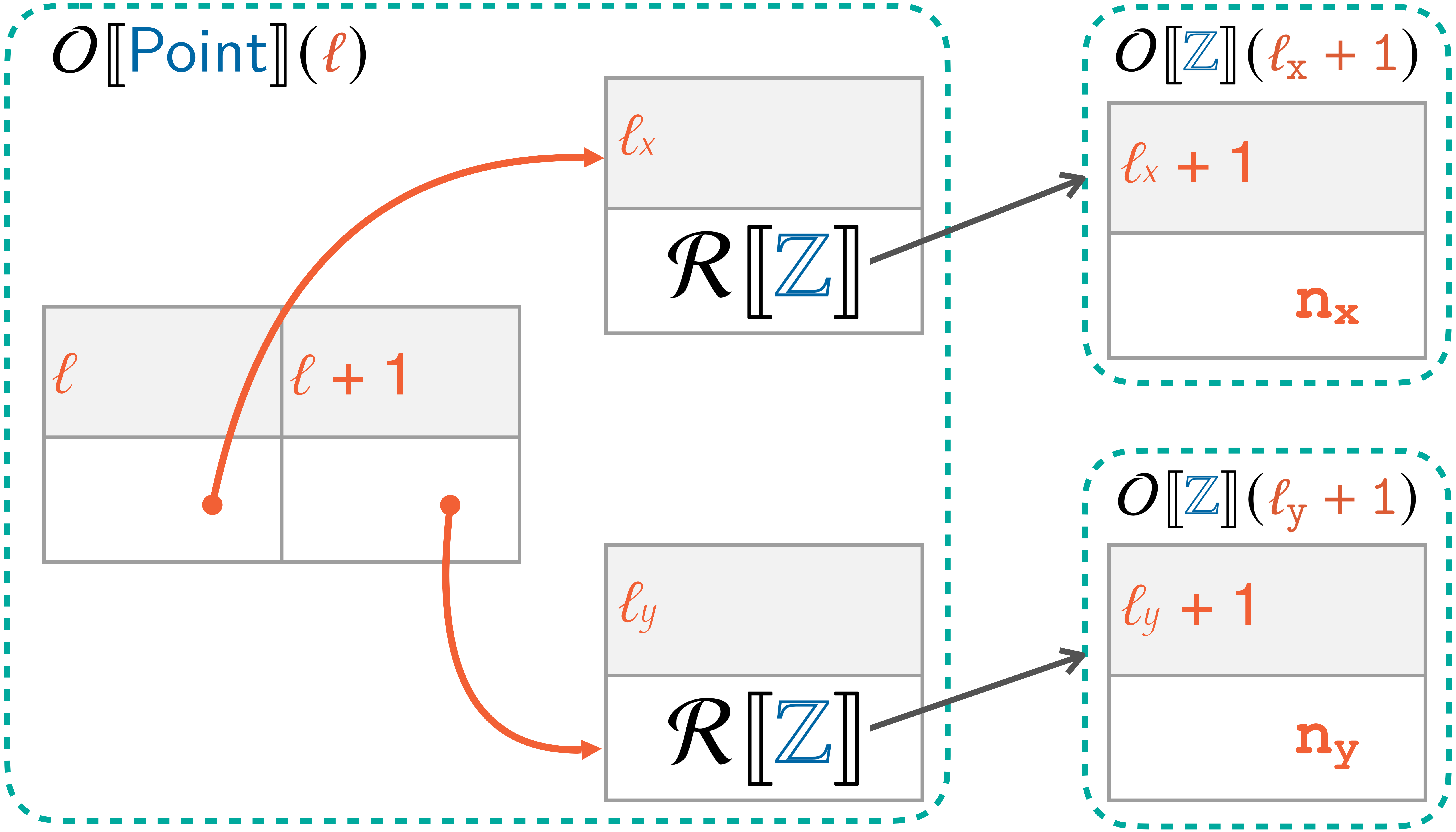
Aggregate Layout

$$\mathcal{O}[\![\text{struct Point}\ \{x : \mathbb{Z}, y : \mathbb{Z}\}]\!](\ell)$$



$$\exists\, \ell_x, \ell_y.\ \underbrace{\ell \mapsto \ell_x \star \ell + 1 \mapsto \ell_y}_{\text{Physical footprint}} \star \underbrace{\mathcal{R}[\![\mathbb{Z}]\!](\ell_x) \star \mathcal{R}[\![\mathbb{Z}]\!](\ell_y)}_{\text{Logical footprint includes permission to access fields}}$$

Resource Graphs



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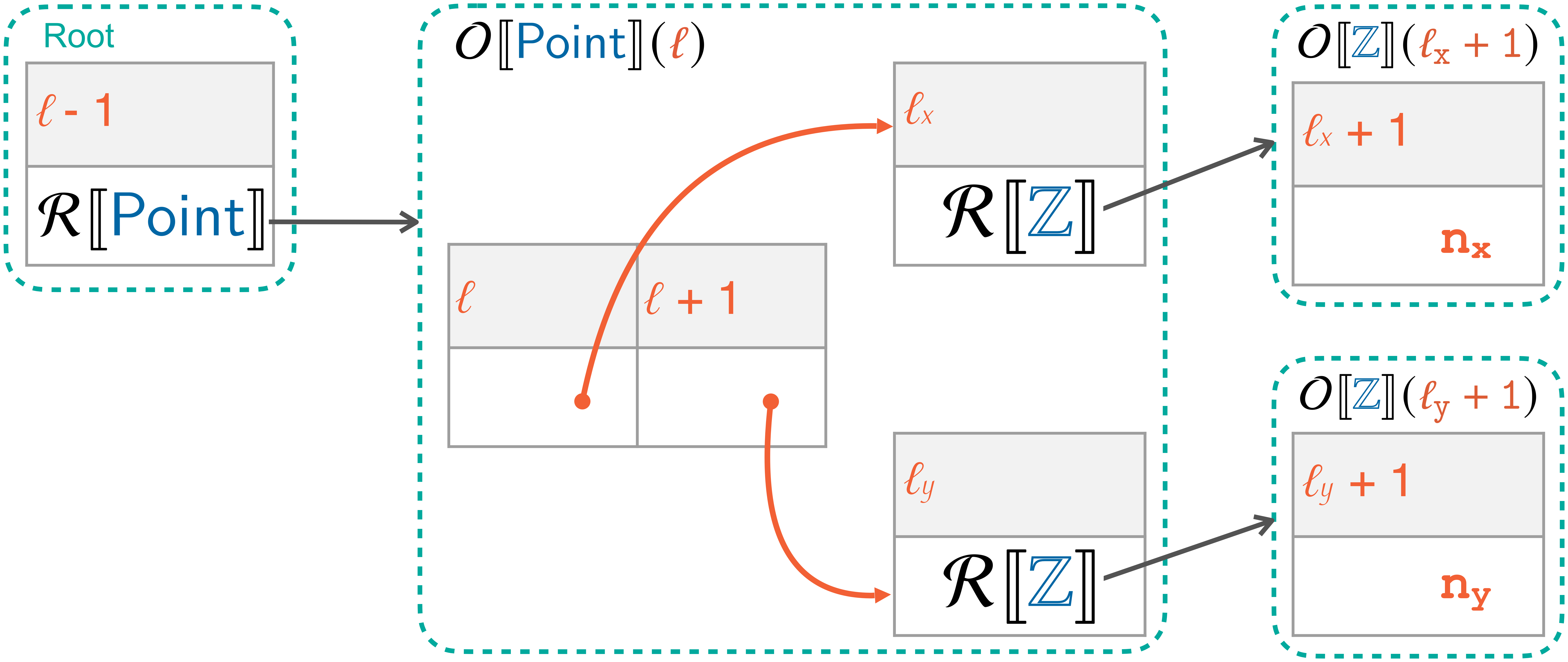

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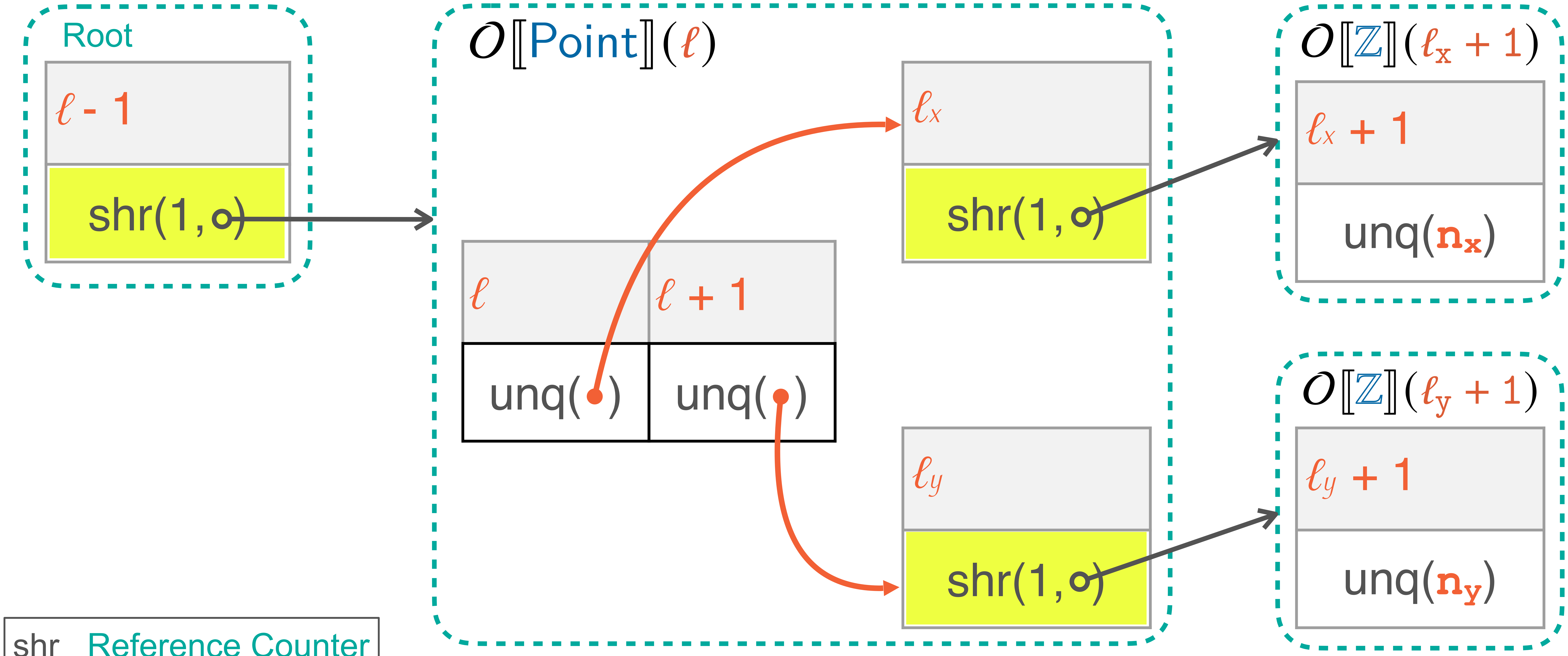
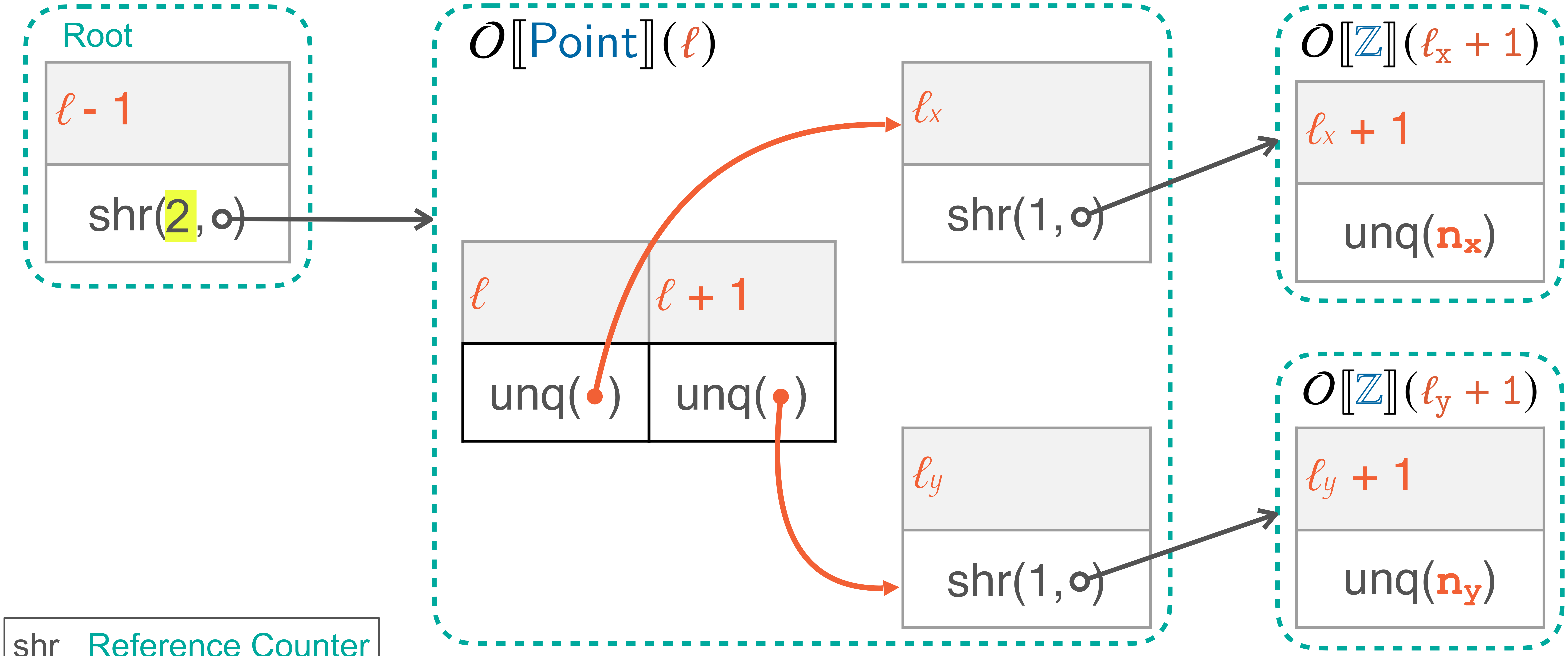


shr	Reference Counter
unq	Plain Old Data

Resource Graphs

++(ℓ−1)



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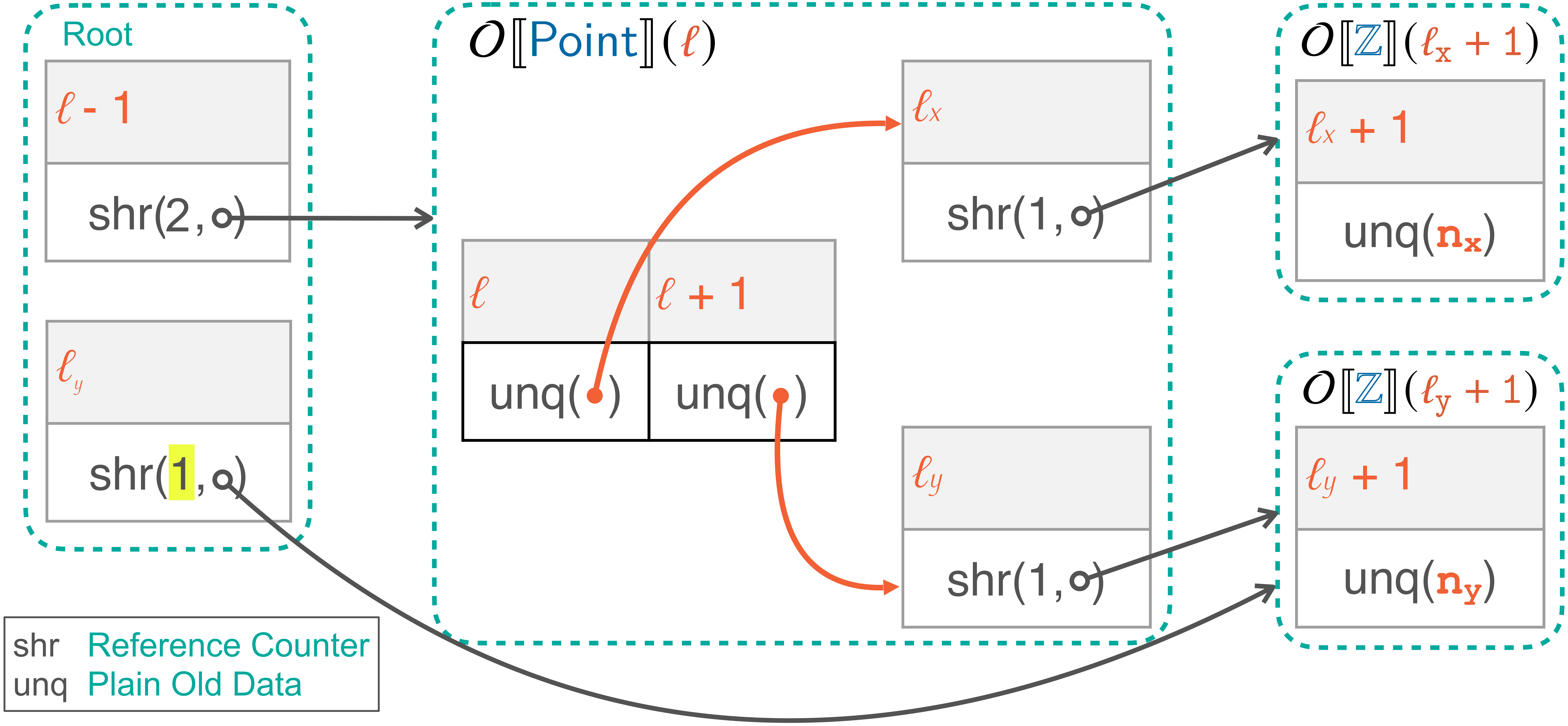
Resource Graphs

`++(ℓ−1) ; ++ℓy`



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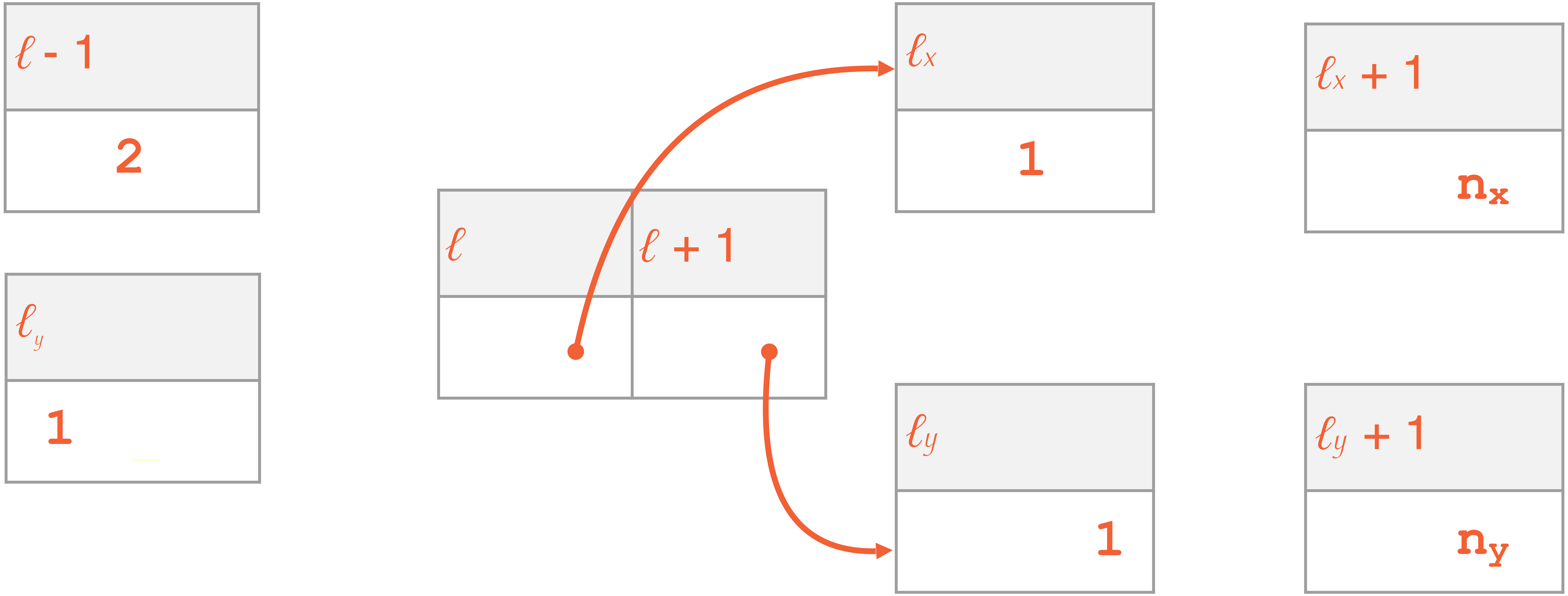

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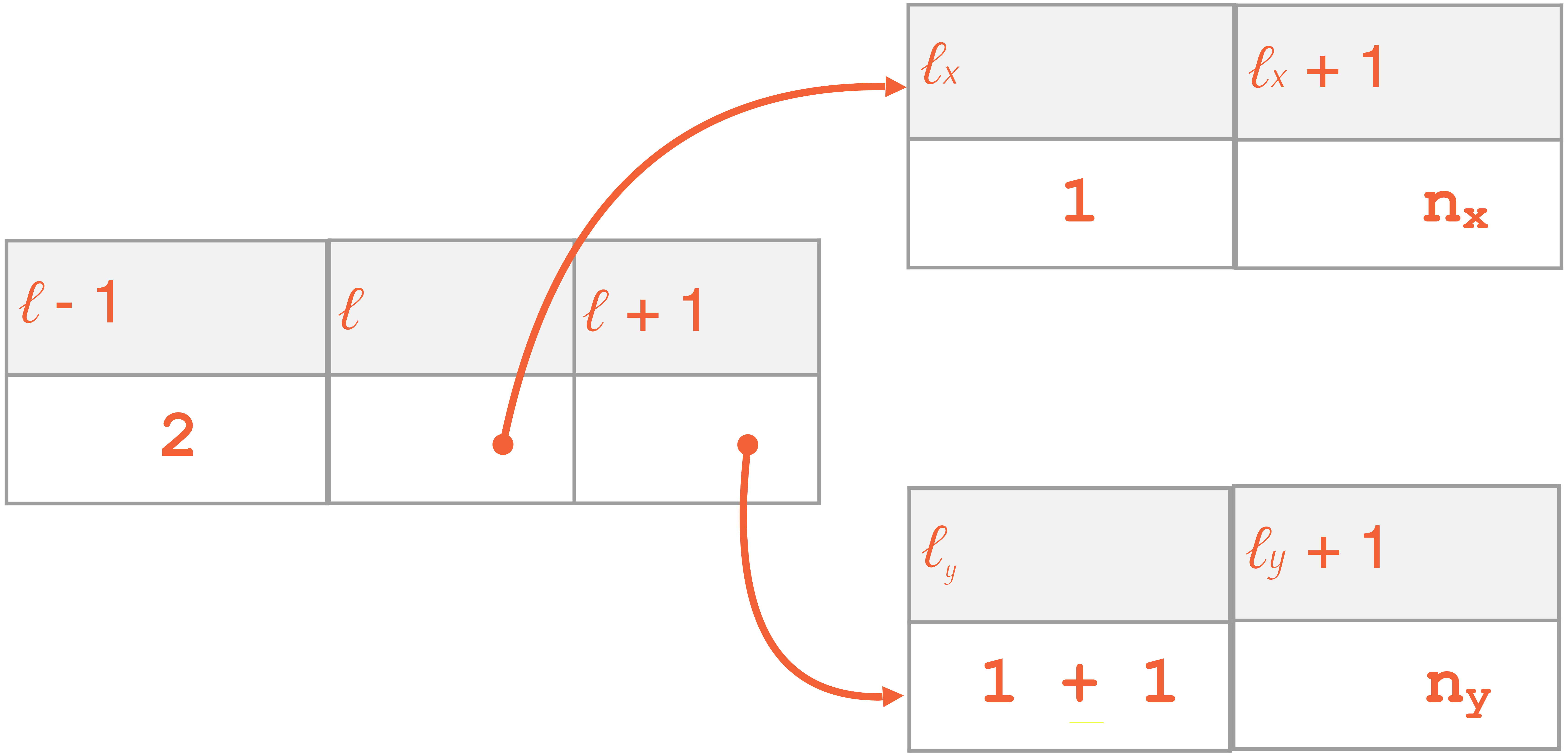
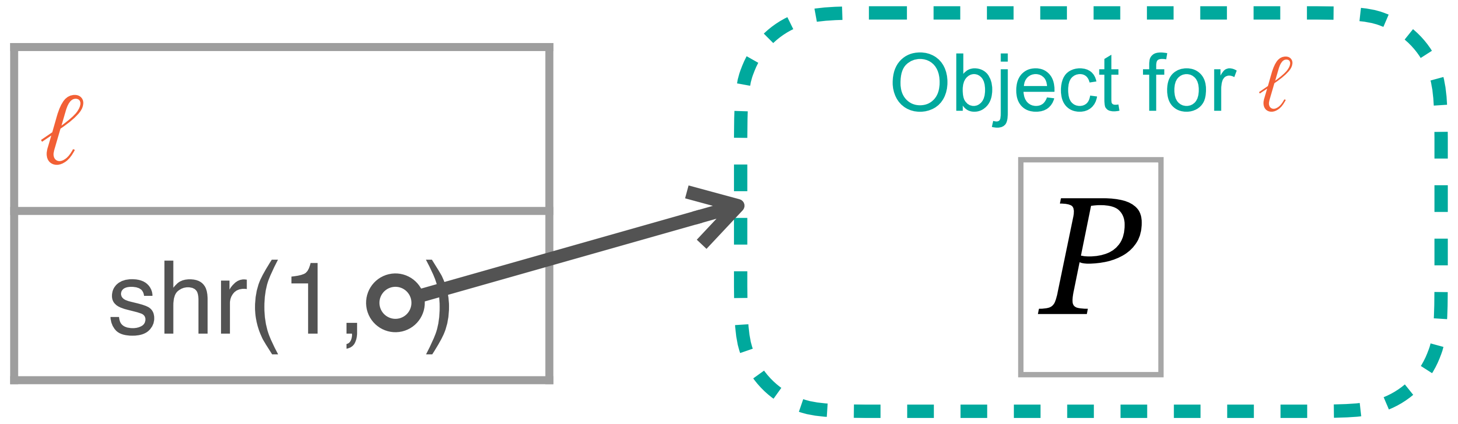


Modalities

Modalities

Jump Modality: It is possible to “jump” from ℓ to an object that satisfies P

$$@_{\ell}\, P \;\approx$$



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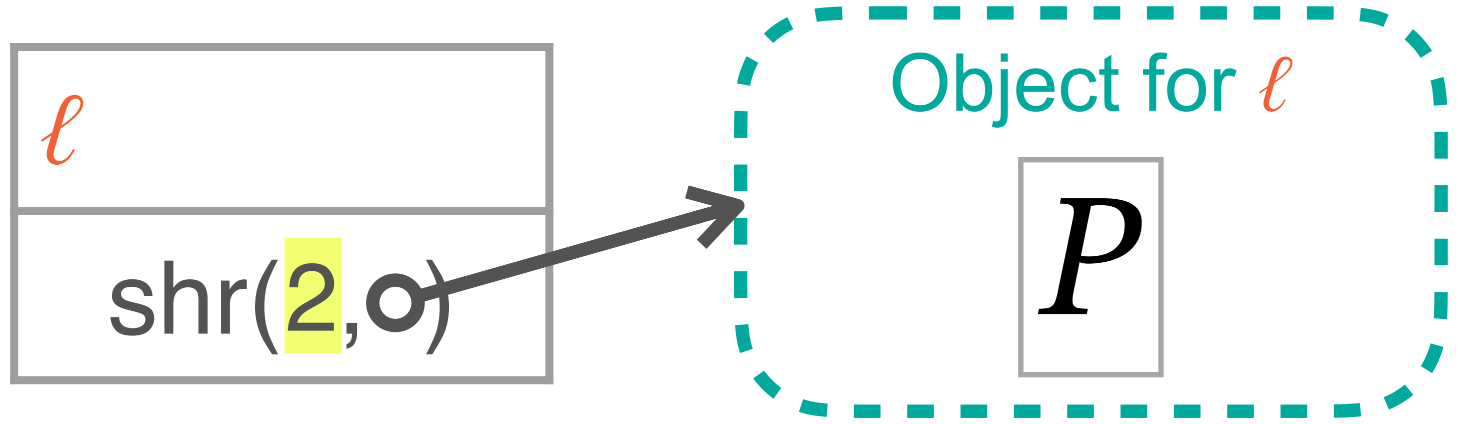
$$@_\ell P \star @_\ell P \approx$$



Composition sums counters at the root, not in objects

Modalities

Jump Modality: It is possible to “jump” from ℓ to an object that satisfies P

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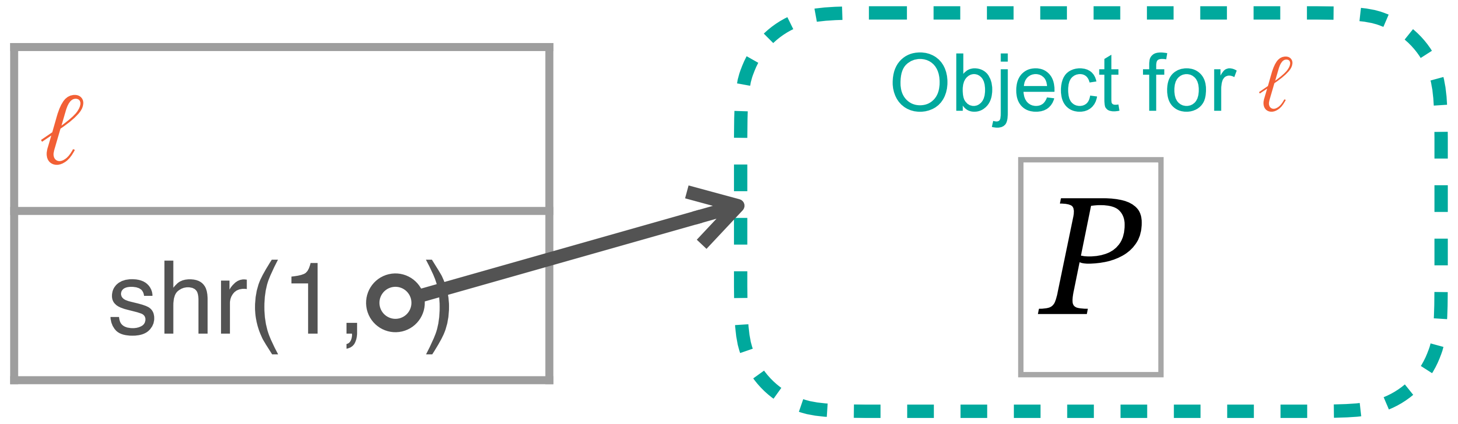

$$\boxed{\mathcal{R}[\![T]\!](\ell) \triangleq @_{\ell}\, \mathcal{O}[\![T]\!](\ell + 1)}$$

Modalities

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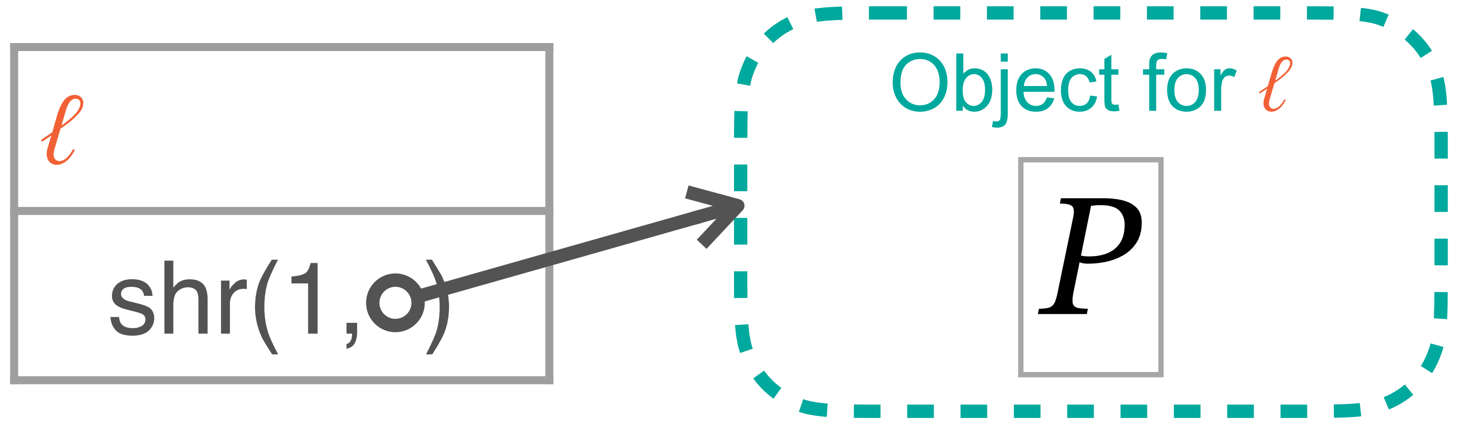

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Reachability Modality $\diamond P$: It is possible to reach P via some set of jumps

Allows reading and incrementing from deeply nested objects

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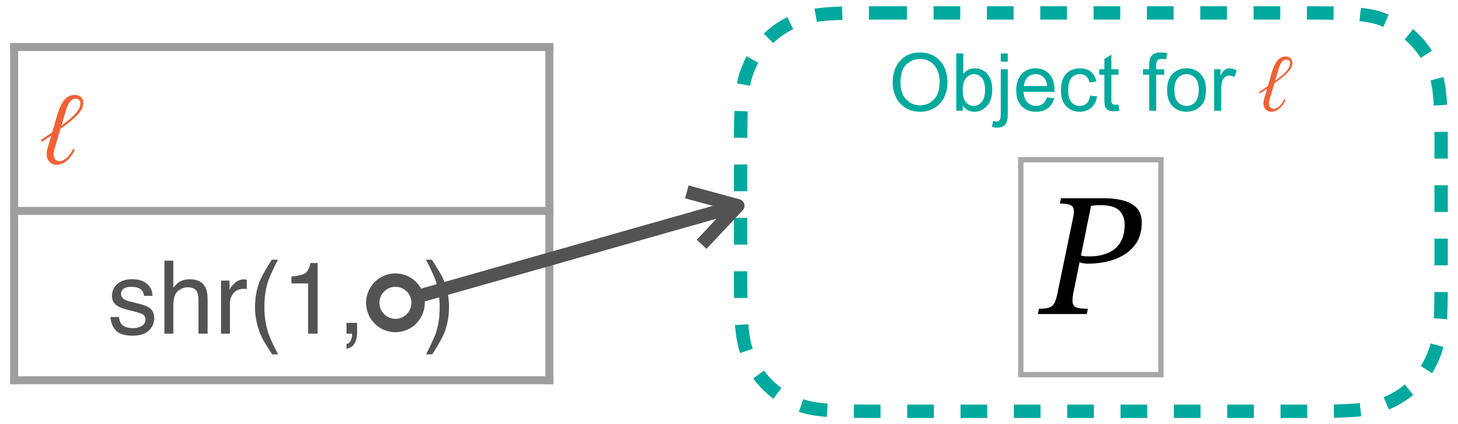

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Allows reading and incrementing from deeply nested objects

$$\textsc{@-Incr}\quad \frac{}{\{\, @_\ell P \,\}\ {+}{+}\ell\ \{\, n.\ \ulcorner n > 1 \urcorner \star @_\ell P \star @_\ell P \,\}}$$

Modalities

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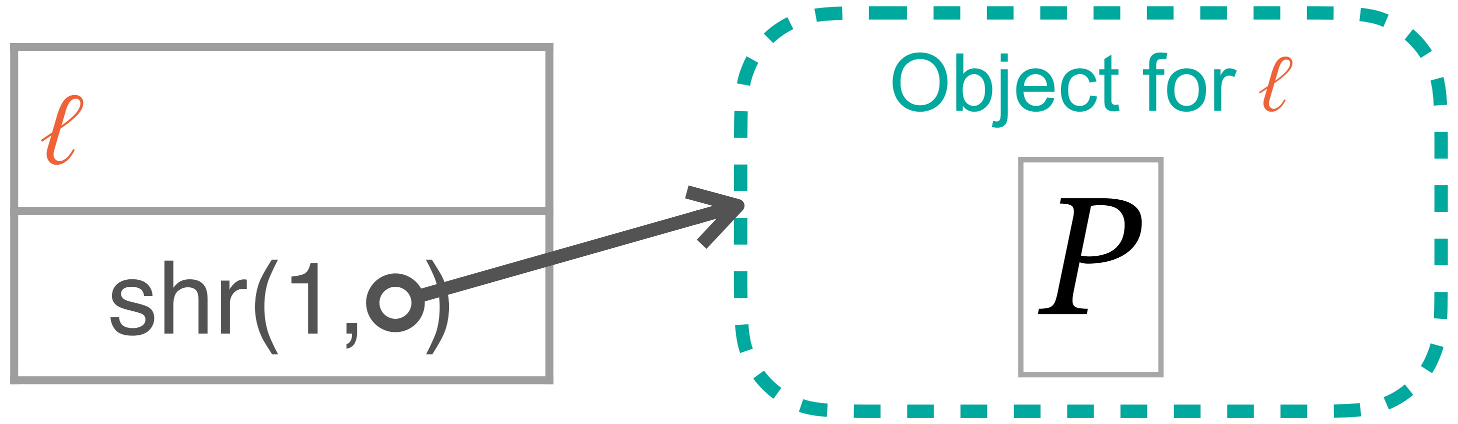

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Reachability Modality $\diamond P$ **:** It is possible to reach P via some set of jumps

Allows reading and incrementing from deeply nested objects

@-INCR-◇

$$\frac{Q \vdash \diamond @_\ell\, P}{\{\ Q\ \}\ {+}{+}\ell\ \{n.\ \ulcorner n > 1 \urcorner \star\ Q\ \star @_\ell\, P\}}$$

Rigid Layout

$$\mathcal{O}\,[\![\text{struct Point}\ \{x : \mathbb{Z}, y : \mathbb{Z}\}]\!](\ell)$$
$$= \exists\, \ell_x, \ell_y.\ \ell \mapsto \ell_x \star \ell + 1 \mapsto \ell_y \star \mathcal{R}\,[\![\mathbb{Z}]\!](\ell_x) \star \mathcal{R}\,[\![\mathbb{Z}]\!](\ell_y)$$

Like C ABI

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Like C ABI

No reordering

$$\textsf{struct Point}\ \{x : \mathbb{Z}, y : \mathbb{Z}\} \overset{\textsf{upd}}{\not\Rightarrow} \textsf{struct Point}\ \{y : \mathbb{Z}, x : \mathbb{Z}\}$$

Rigid Layout

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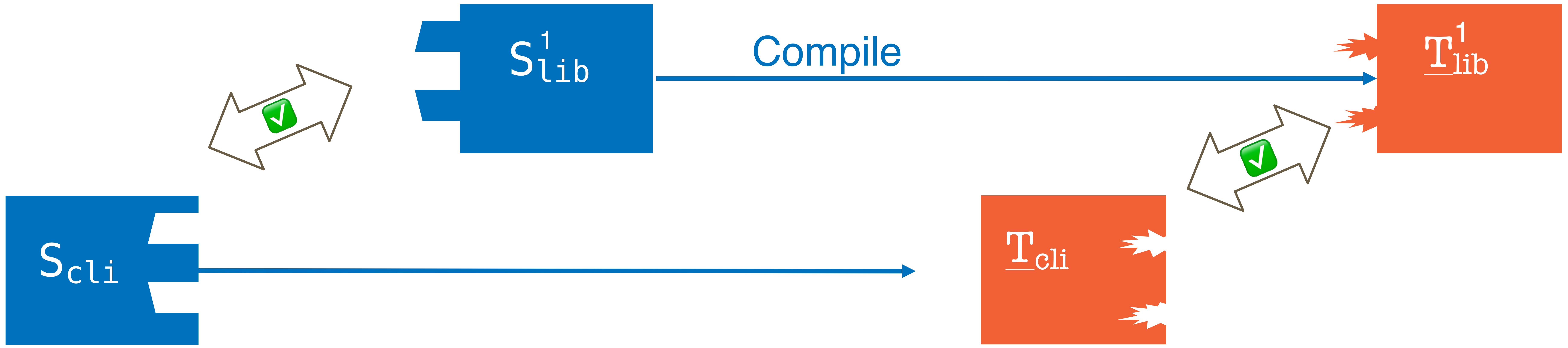
No extensibility

$$\mathsf{struct\ Point}\ \{x:\mathbb{Z}, y:\mathbb{Z}\} \overset{\mathsf{upd}}{\not\Rightarrow} \mathsf{struct\ Point}\ \{x:\mathbb{Z}, y:\mathbb{Z}, z:\mathbb{Z}\}$$

Library Evolution



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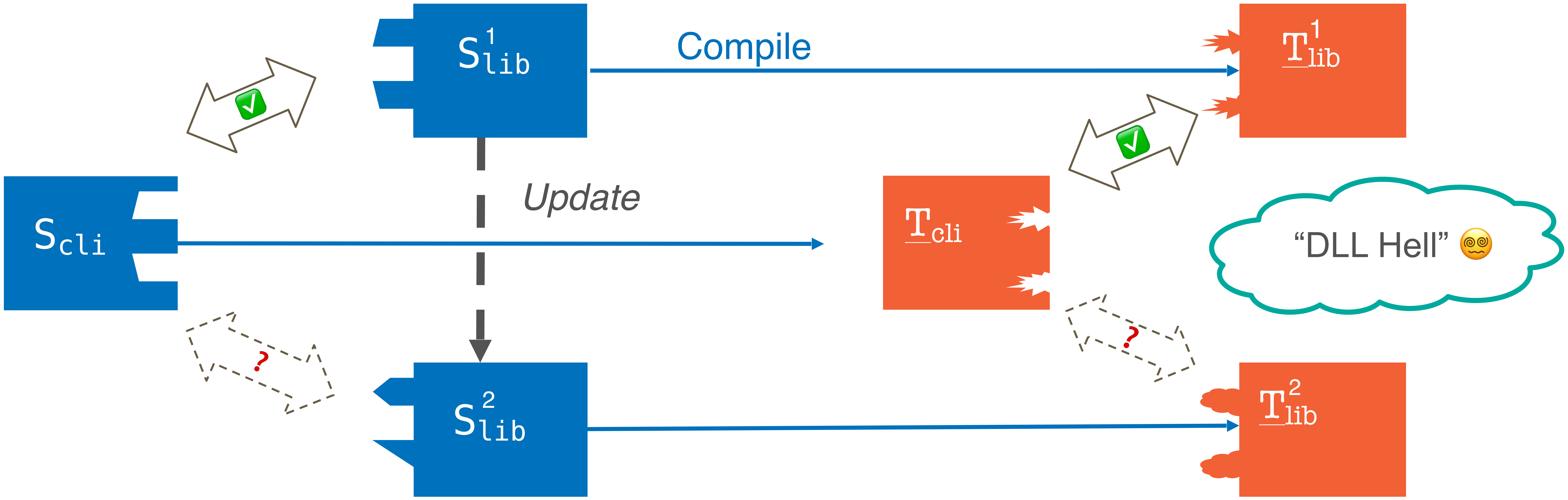

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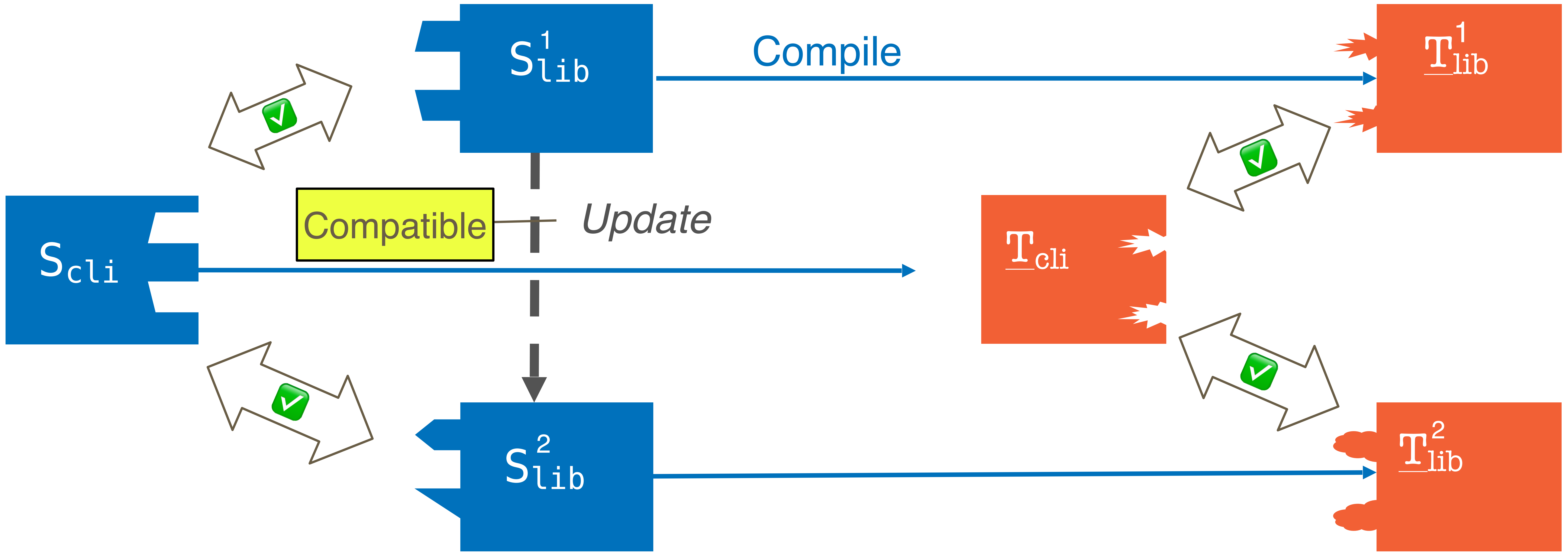
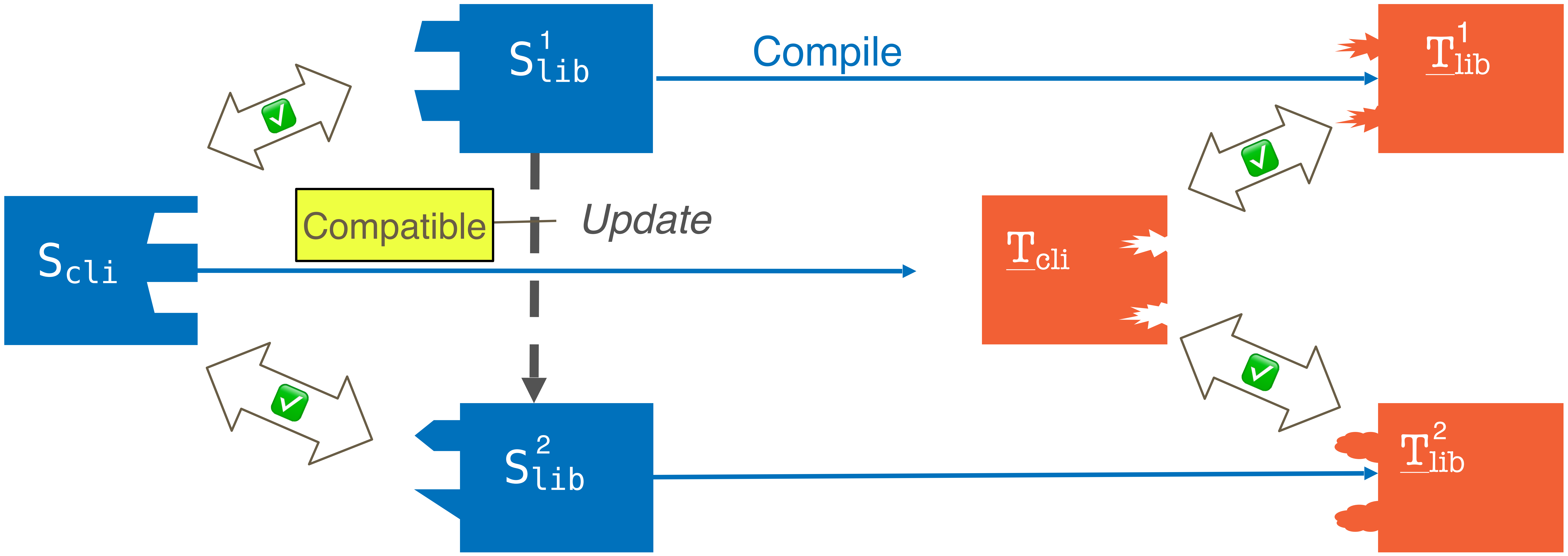


τ_2 is an **ABI compatible update** from τ_1 if

$$[\![\tau_2]\!] \subseteq [\![\tau_1]\!]$$

Library Evolution



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Resilient Layout

Like Swift ABI

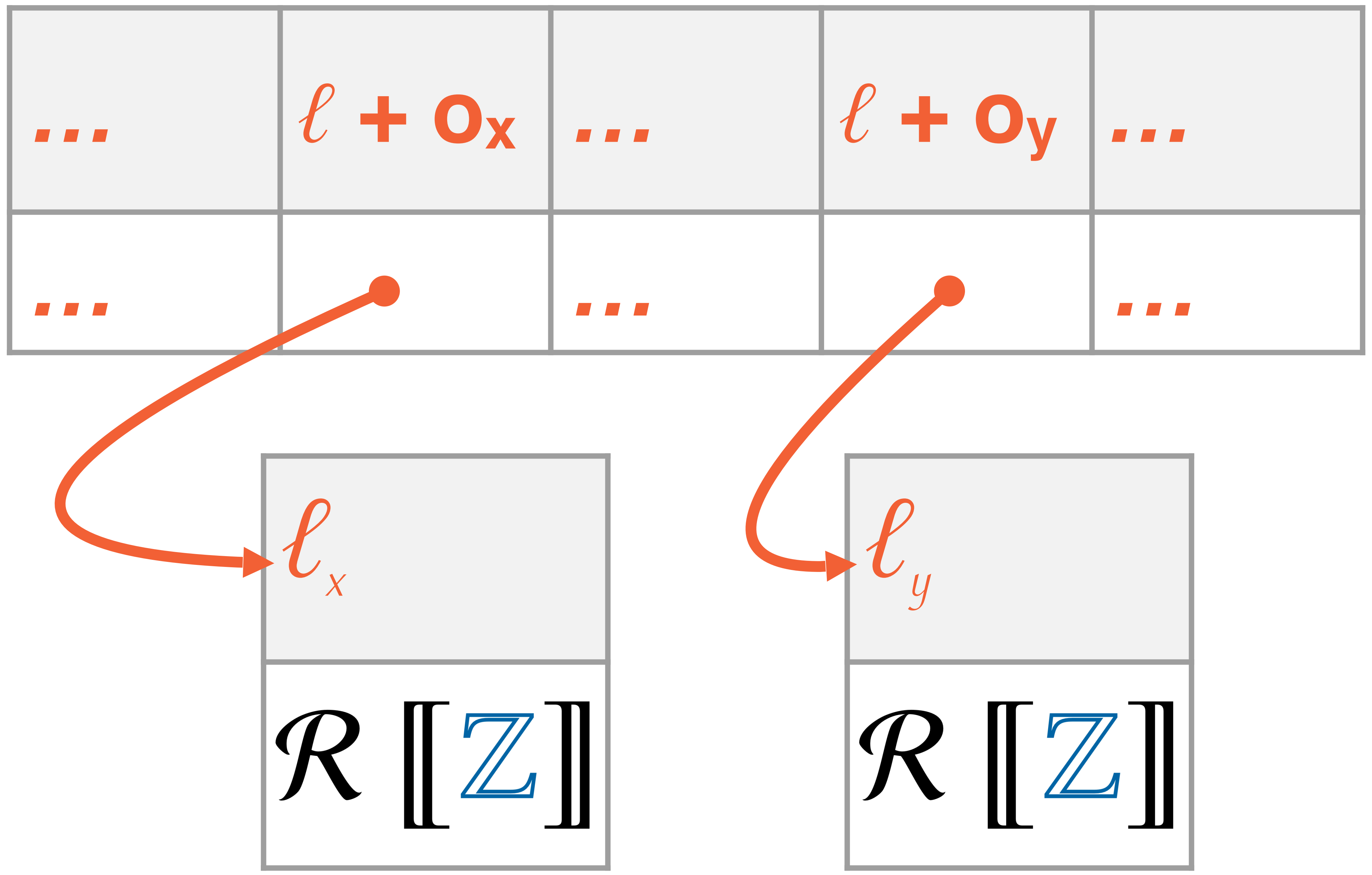
Resilient Layout

Like Swift ABI

Client Using `Point`

...	o_x	...	o_y	...
	?		?	

Offset Table



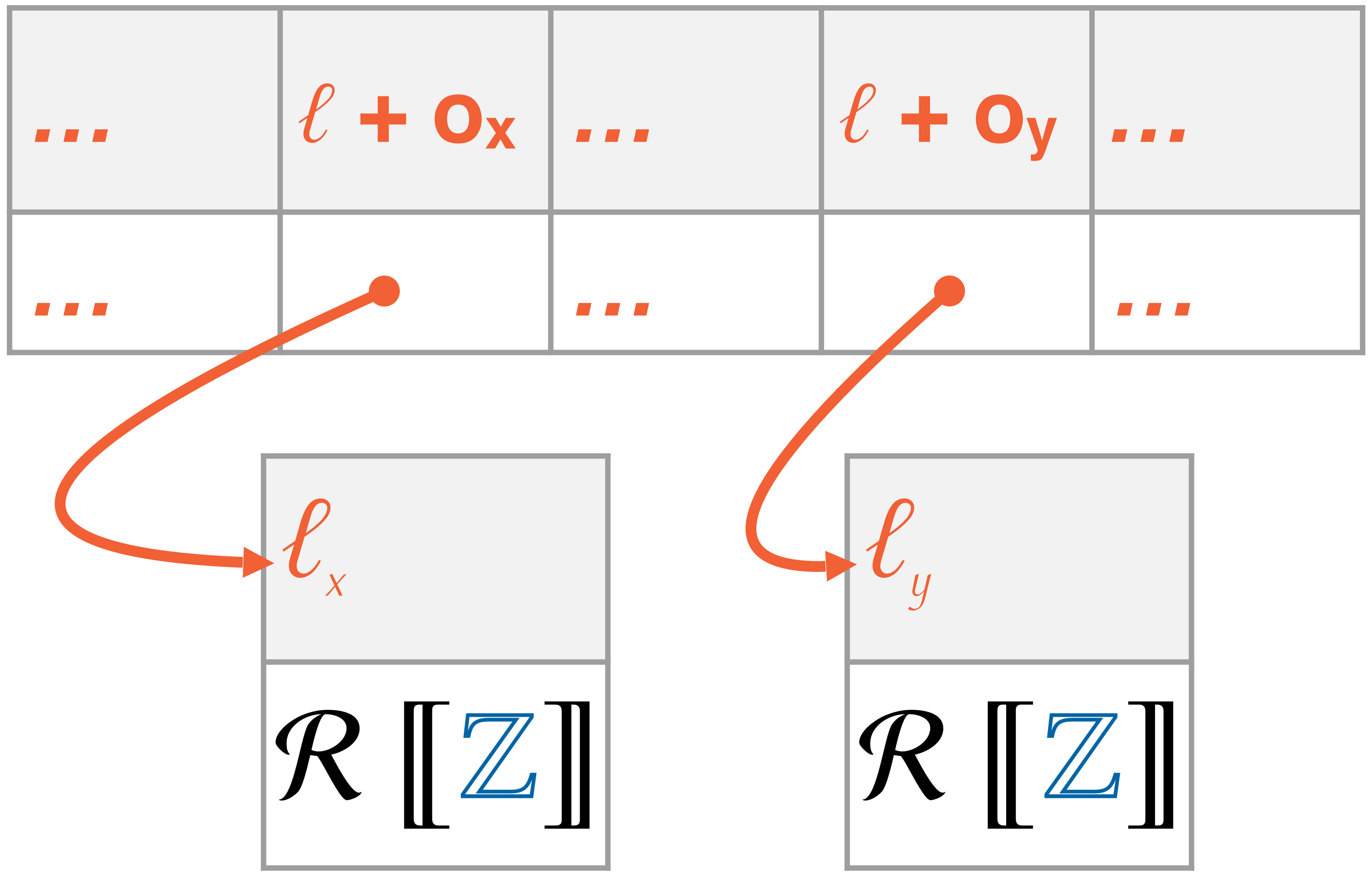
Resilient Layout

Like Swift ABI

Client Using `Point`

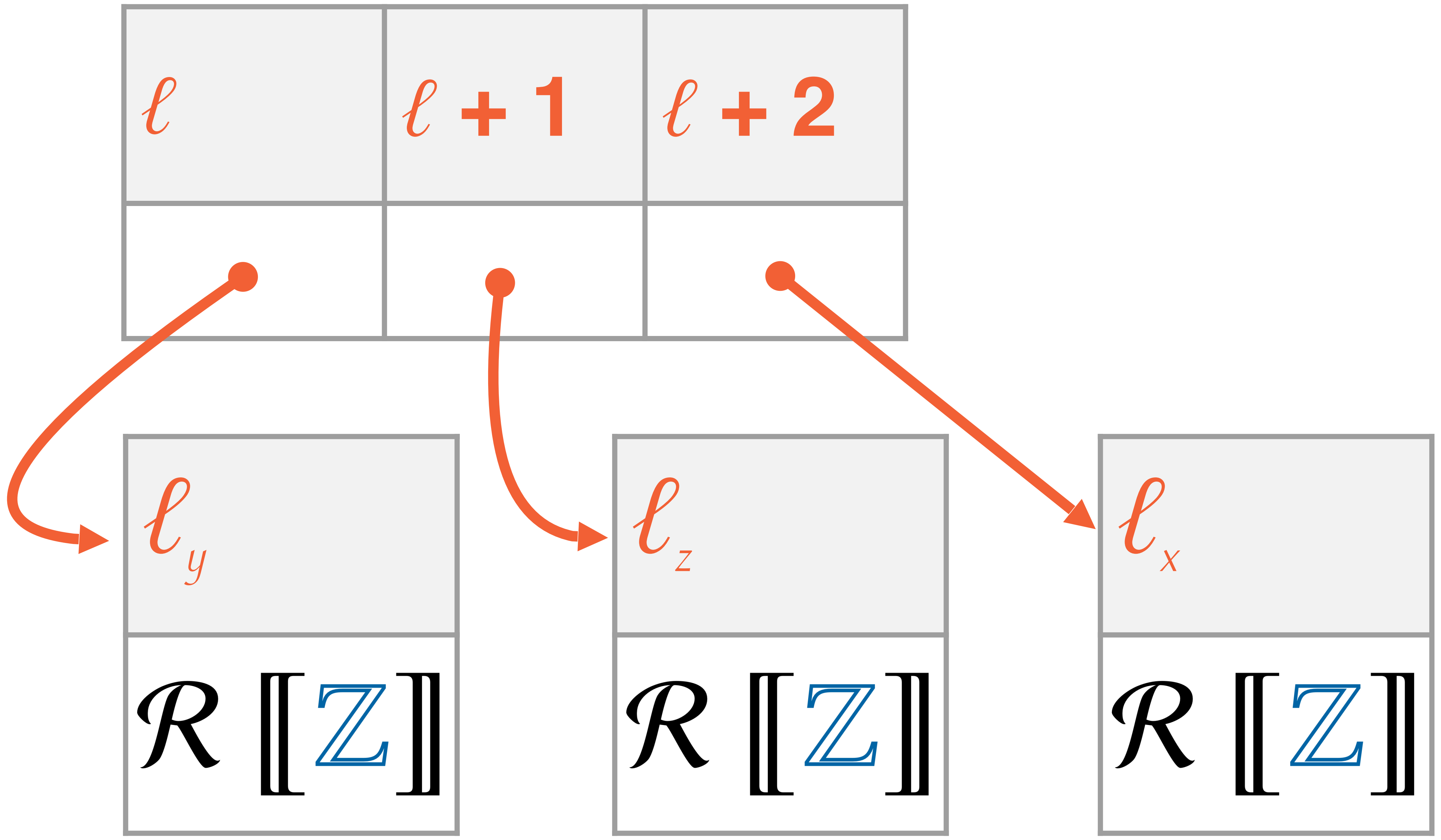
…	O_x	…	O_y	…
	?		?	

Offset Table



Library Providing `Point`

O_x	O_y	O_z
2	0	1



More in the Paper

- Variations: Unboxed types, calling conventions, layout optimizations
- Theorems: Safety & memory reclamation, compiler compliance, type evolution

Next Steps

- Ongoing: `Rust`-like ABI over `Wasm` with ownership and borrowing
- Application: Verified FFI

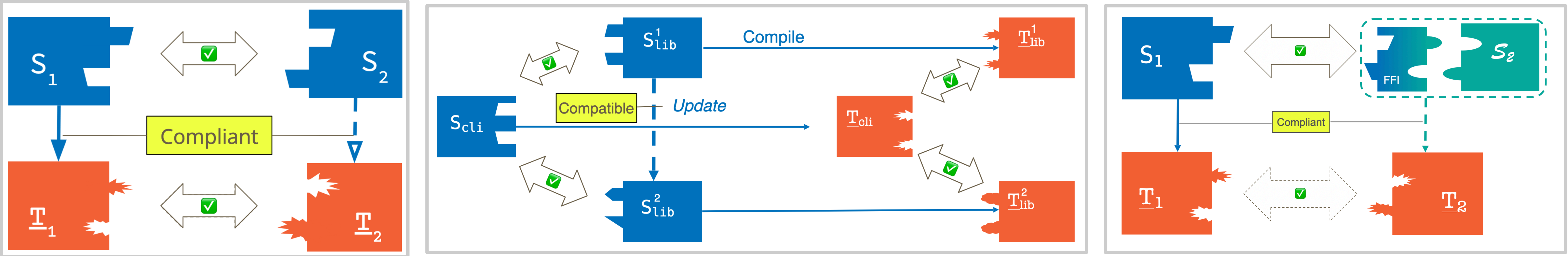
Takeaways

The Methodology

ABI Spec with Realistic Realizability

$e \in [\![\tau]\!]$

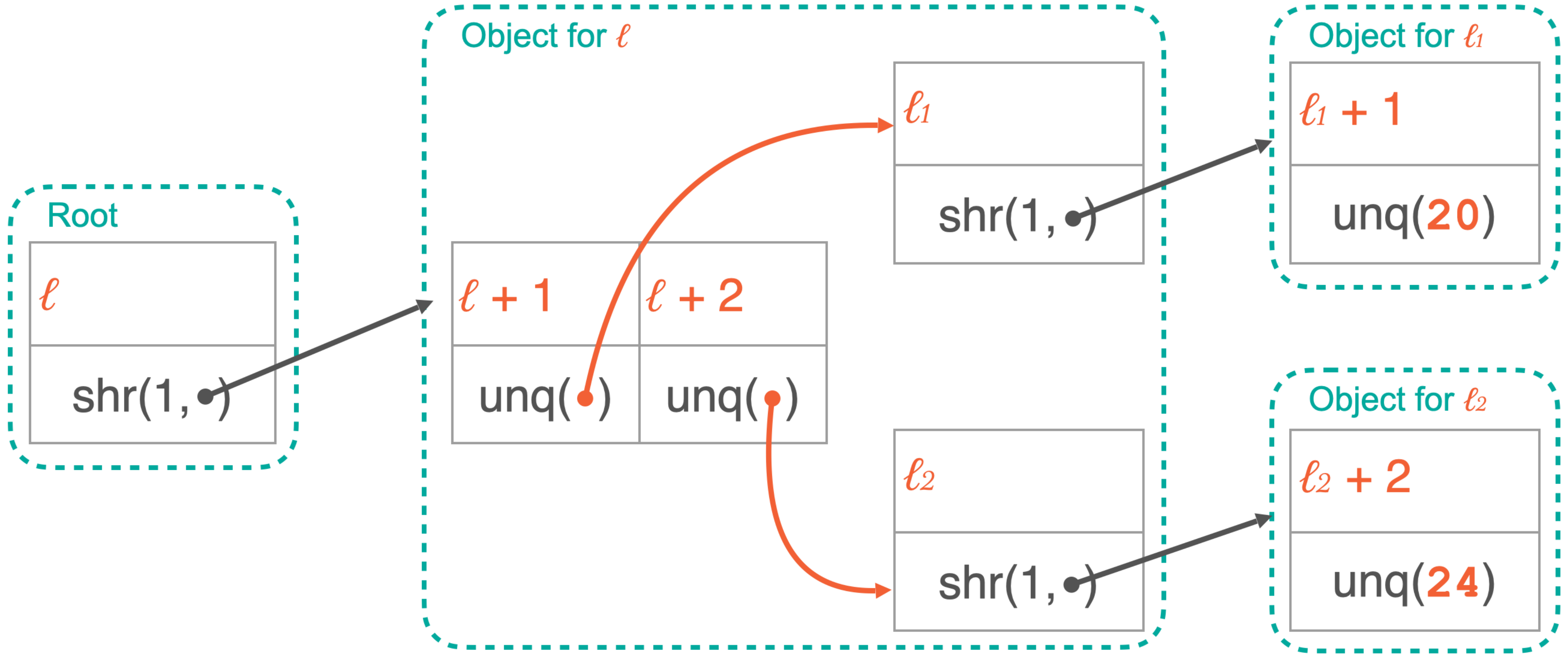
Compiler Compliance, Library Evolution, FFI Safety*



The Case Study

Graph-Based Resources for RC

$@_{\ell}\, P \quad \diamond P$



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