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

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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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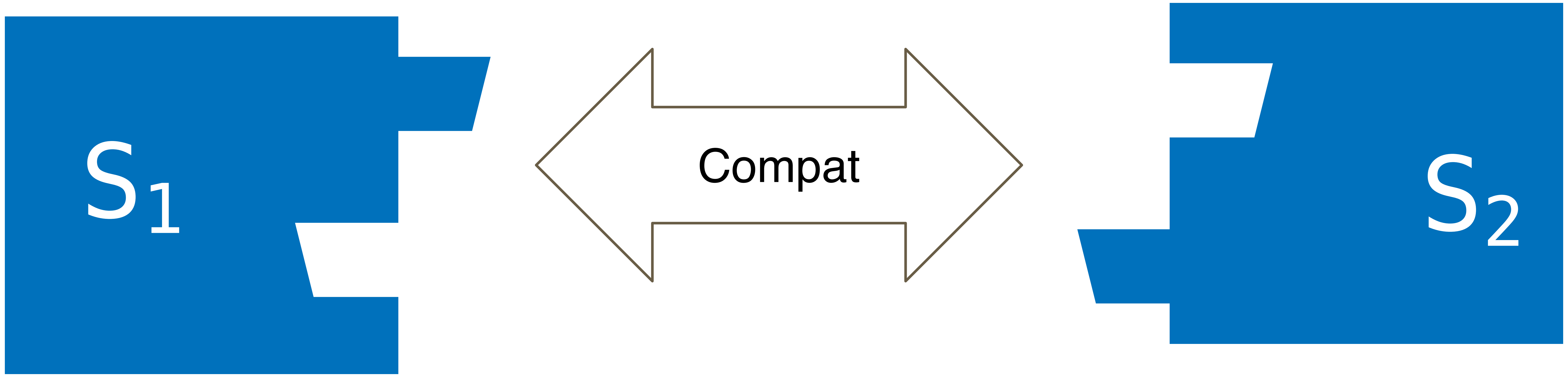

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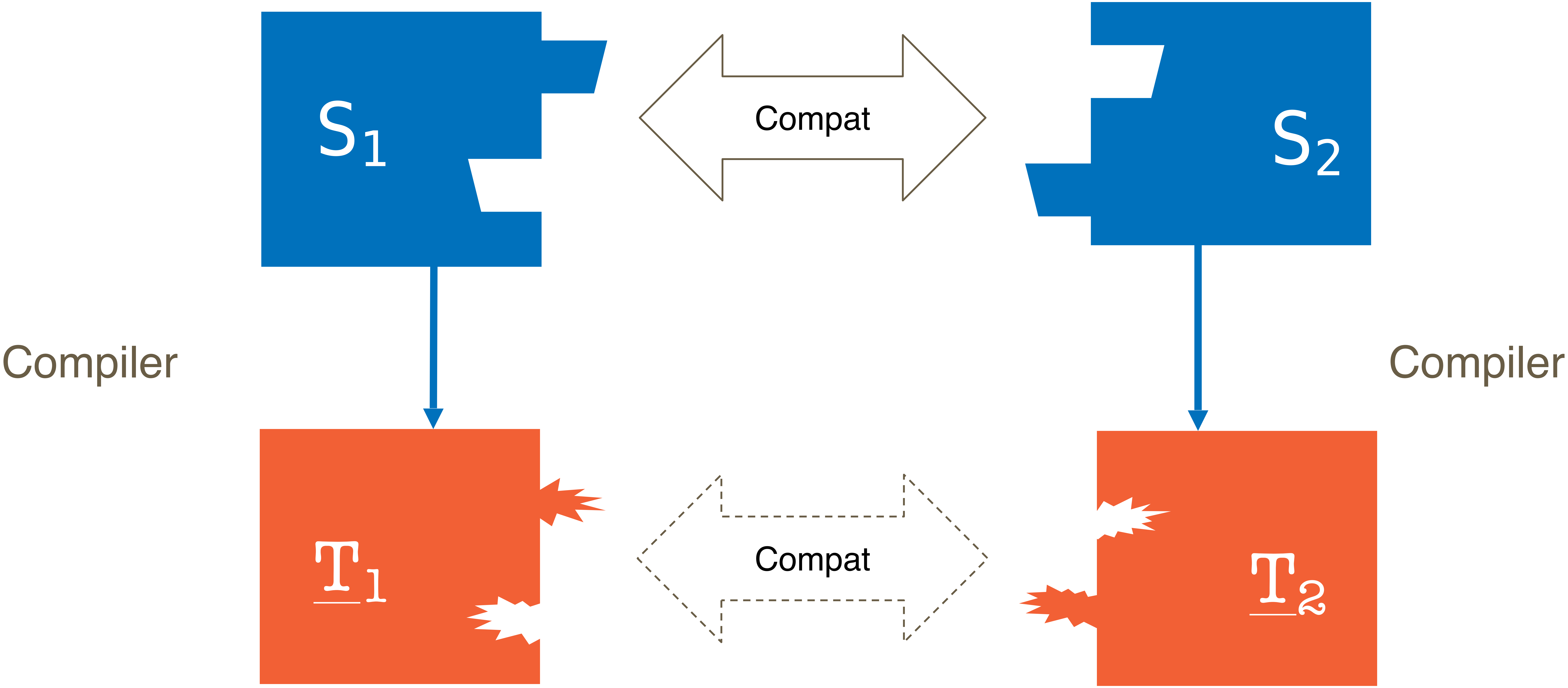
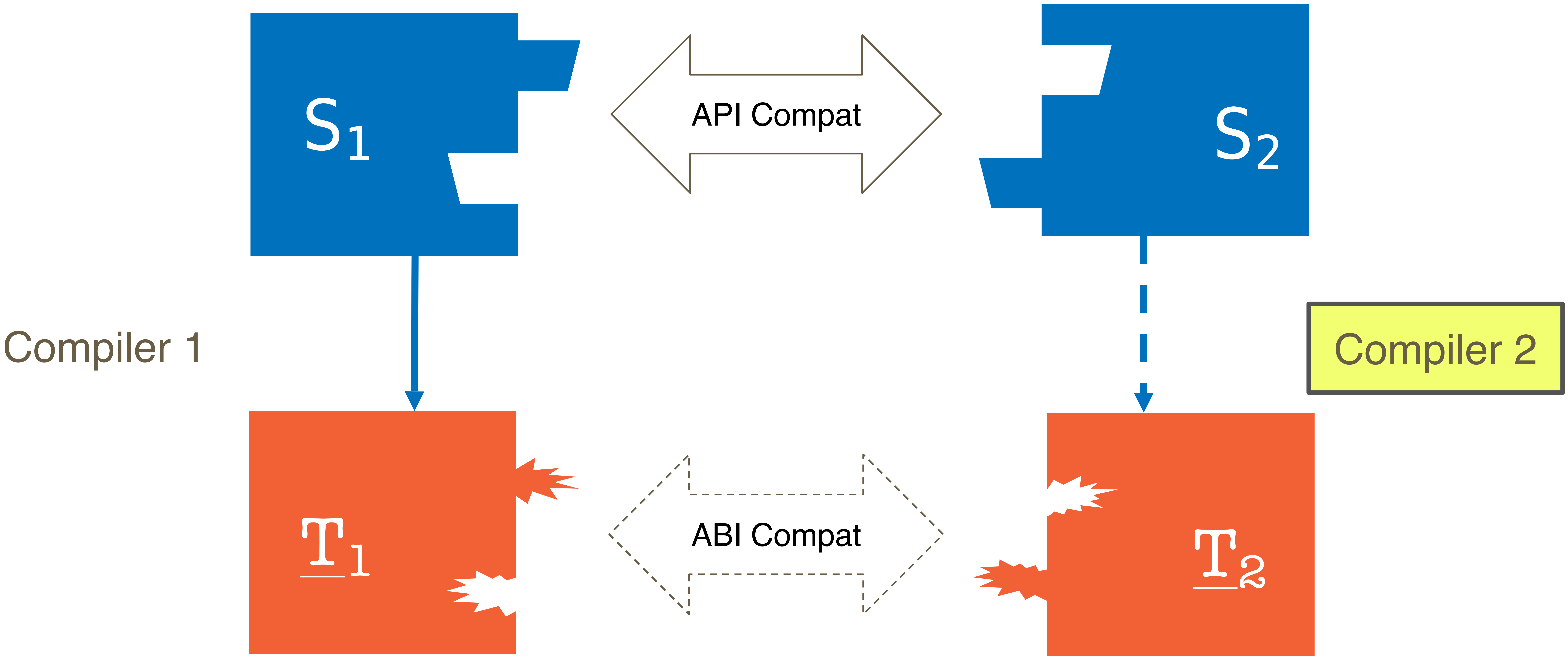
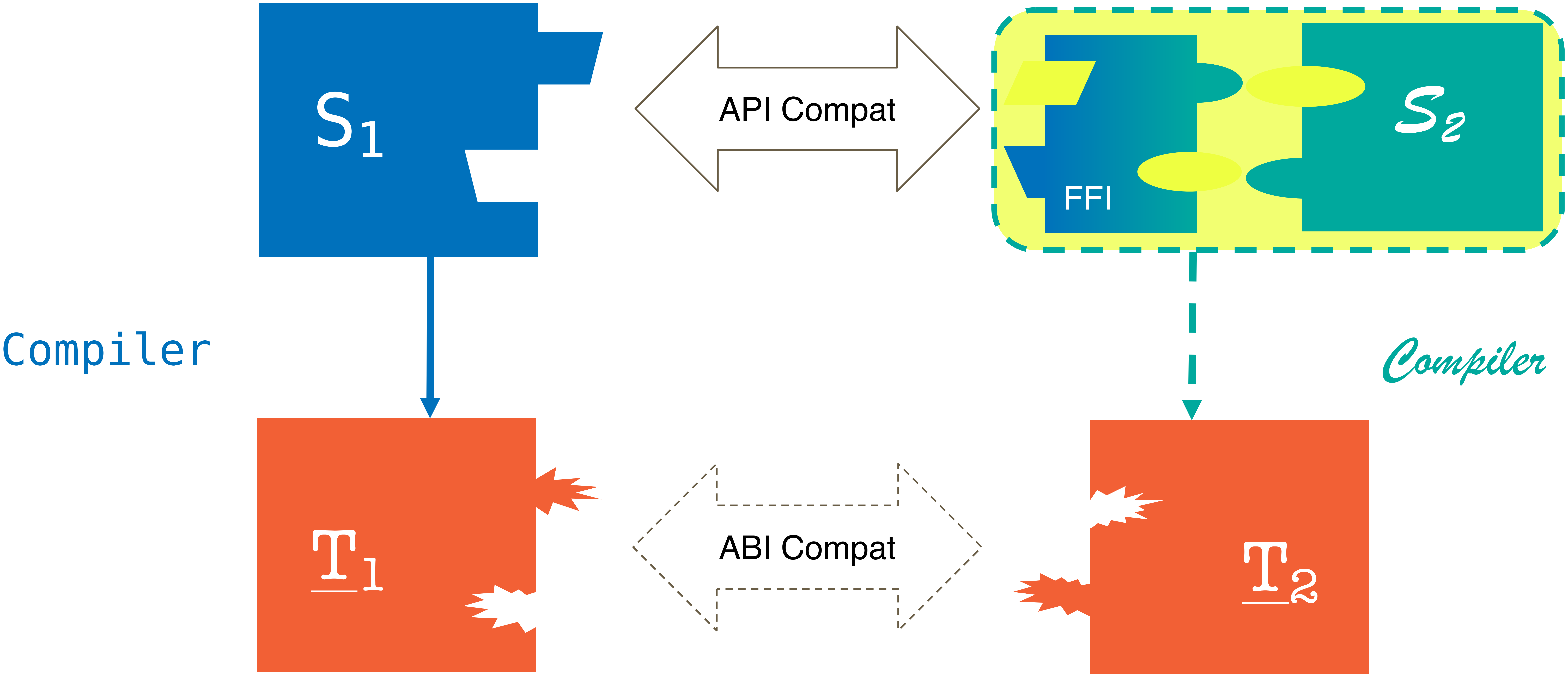


Why Use an ABI? Interoperability for Compilers



Why Use an ABI? Interoperability for Languages



Who is Designing an ABI?

Swift

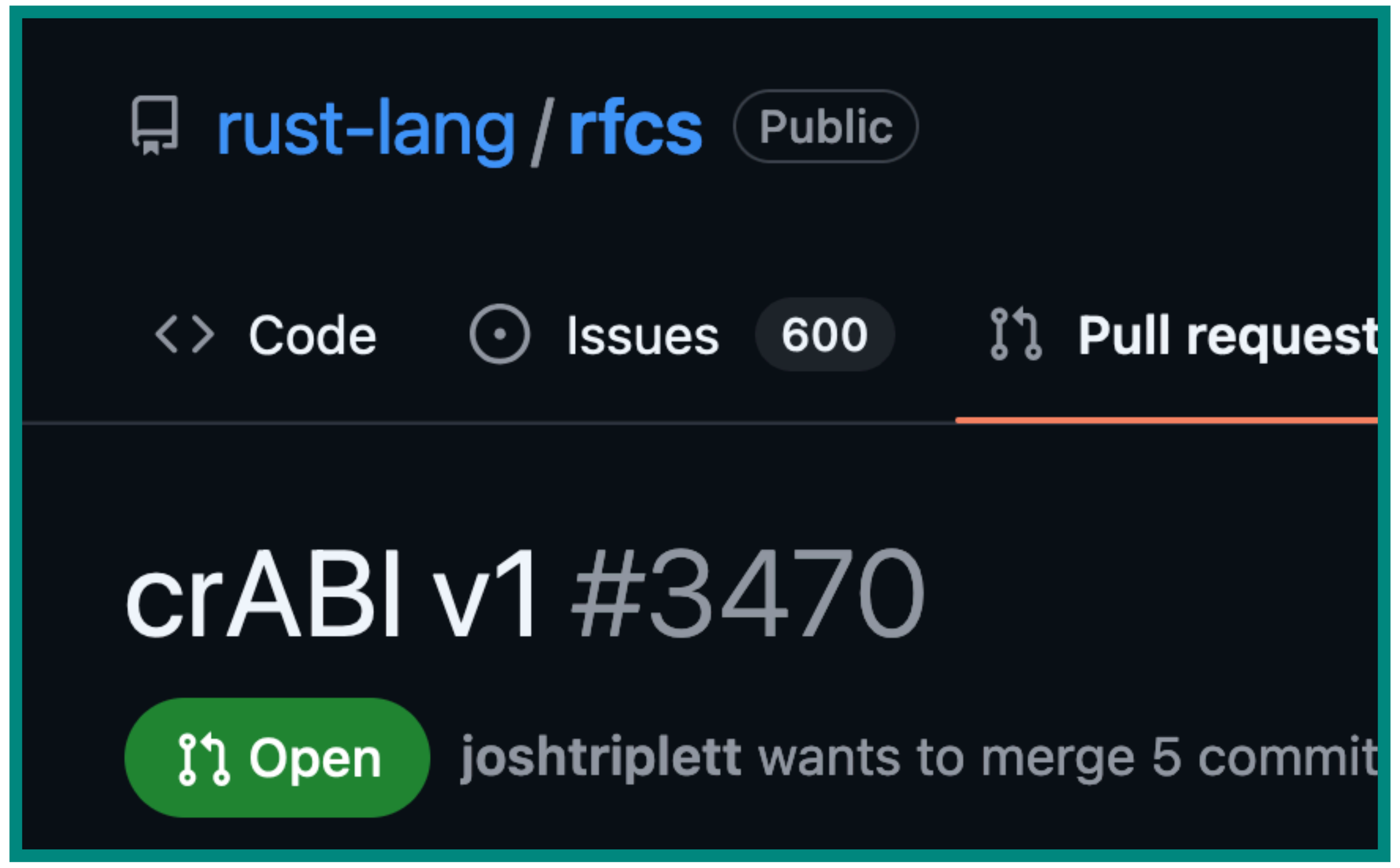
swift / docs / ABIStabilityManifesto.md

dev [docs] Update links to repositories moved to https://github.co

439 lines (230 loc) · 56.2 KB

Swift ABI Stability Manifesto

Rust

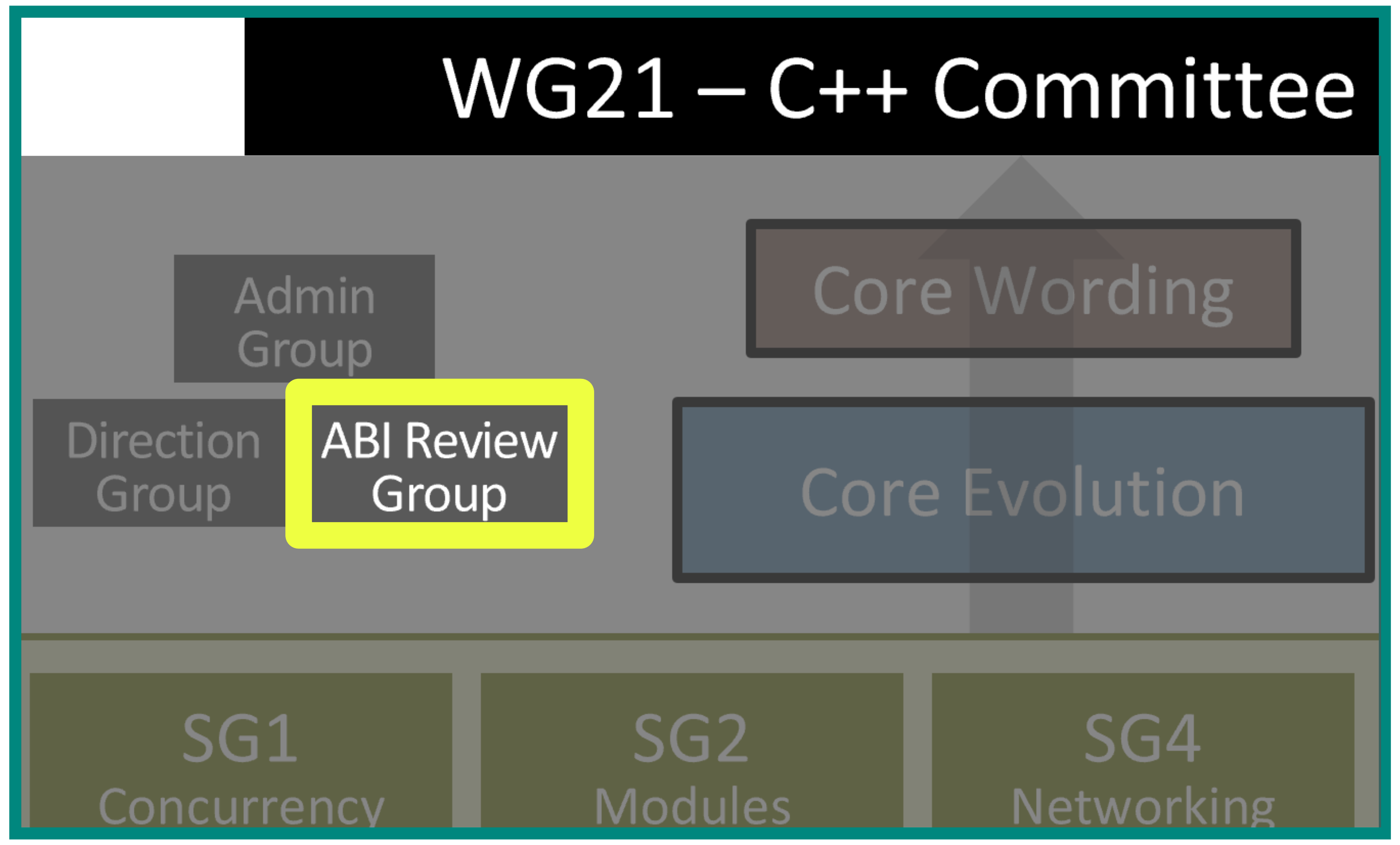


rust-lang / rfcs

crABI v1 #3470

joshtriplett wants to merge 5 commit

C++



WG21 – C++ Committee

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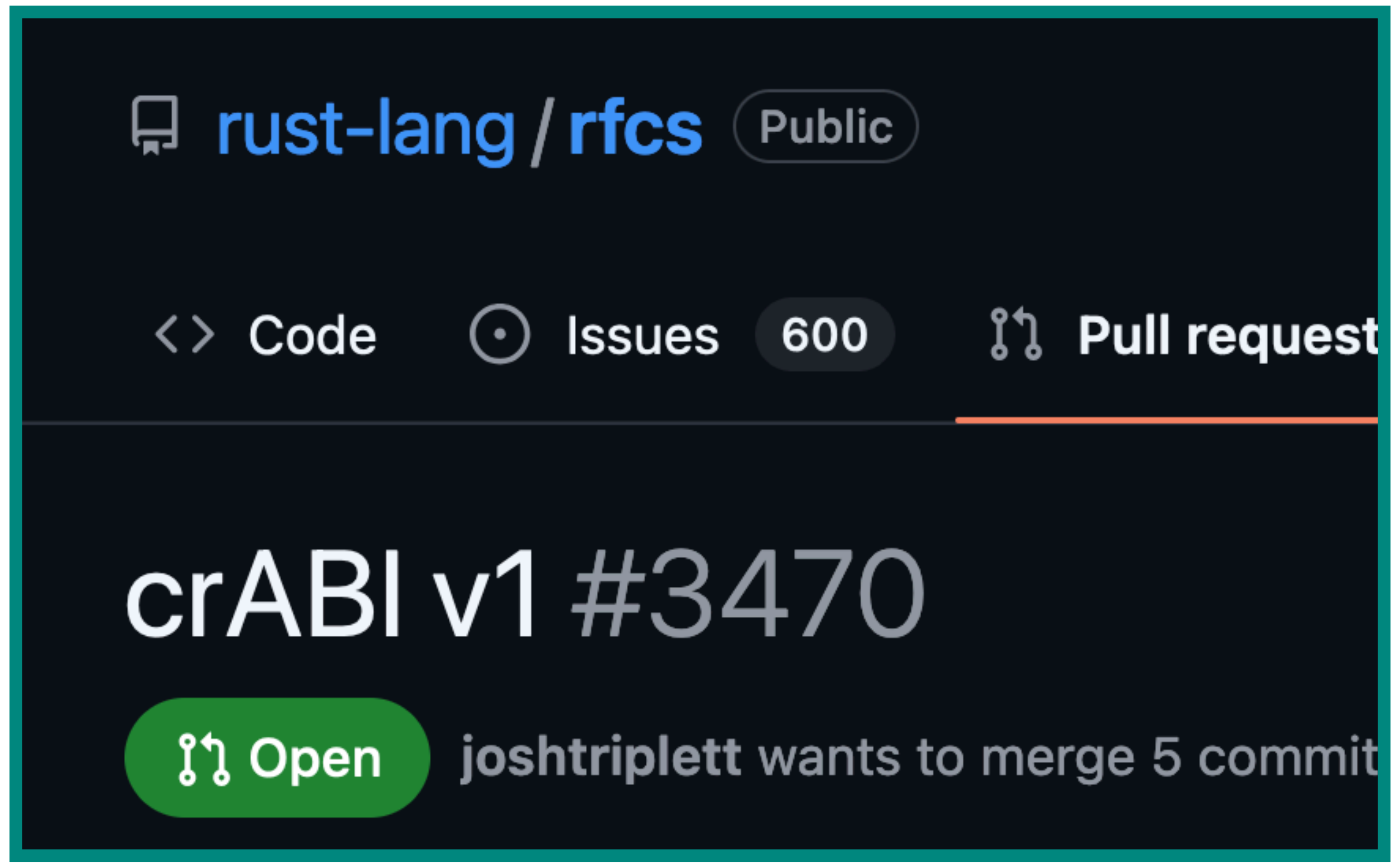

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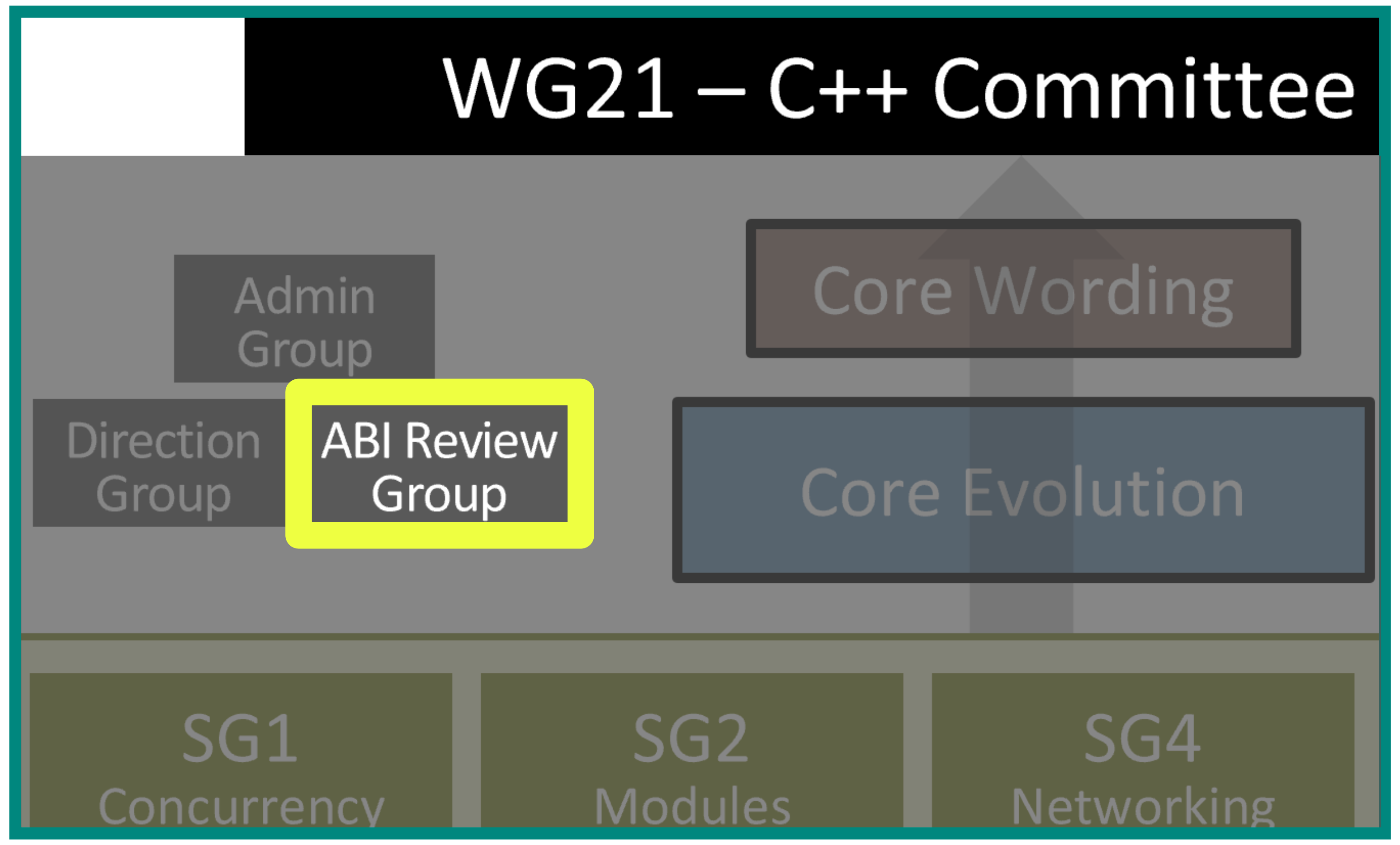

Richer Types → Richer ABIs?

How Should We Specify an ABI?

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

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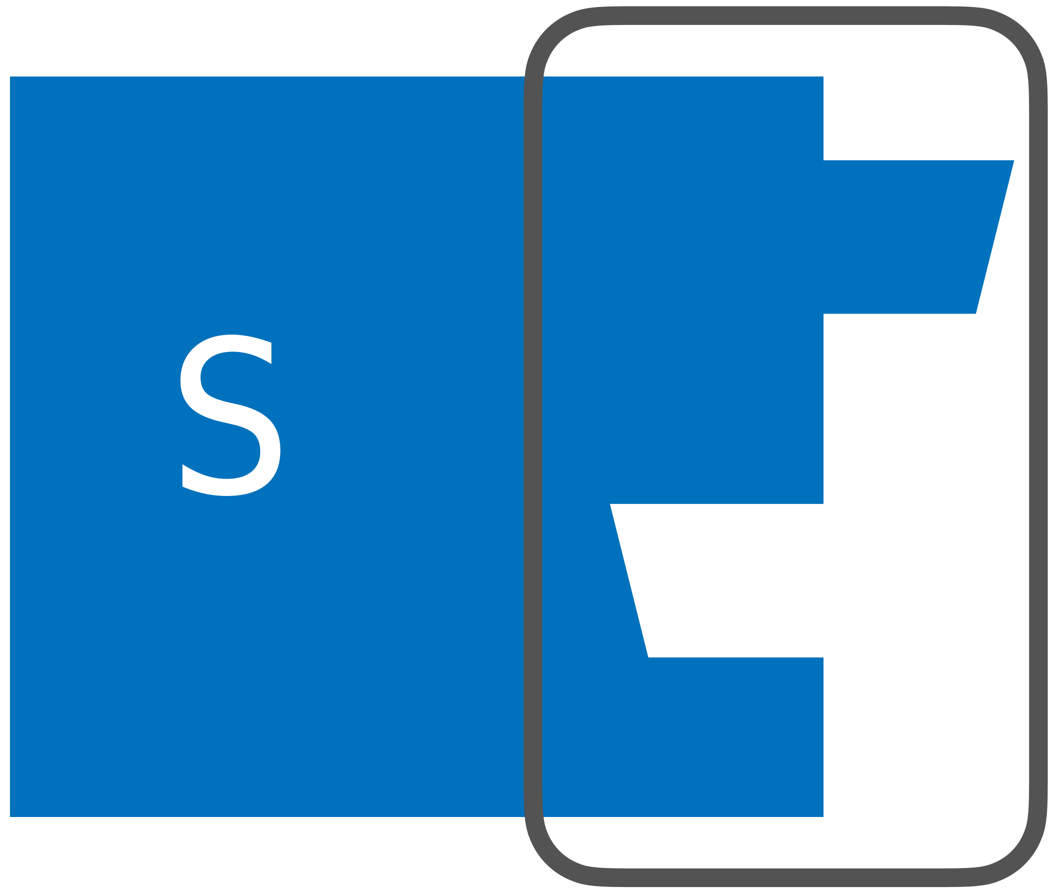

This Type `τ`

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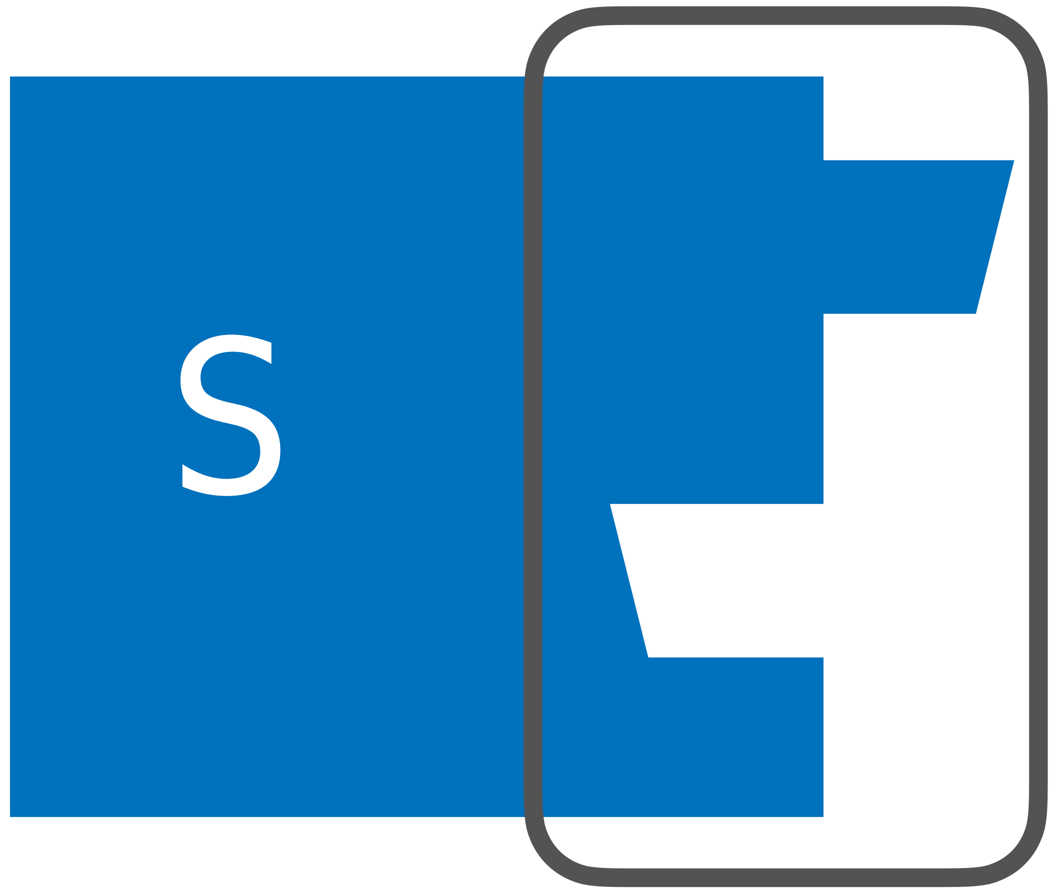

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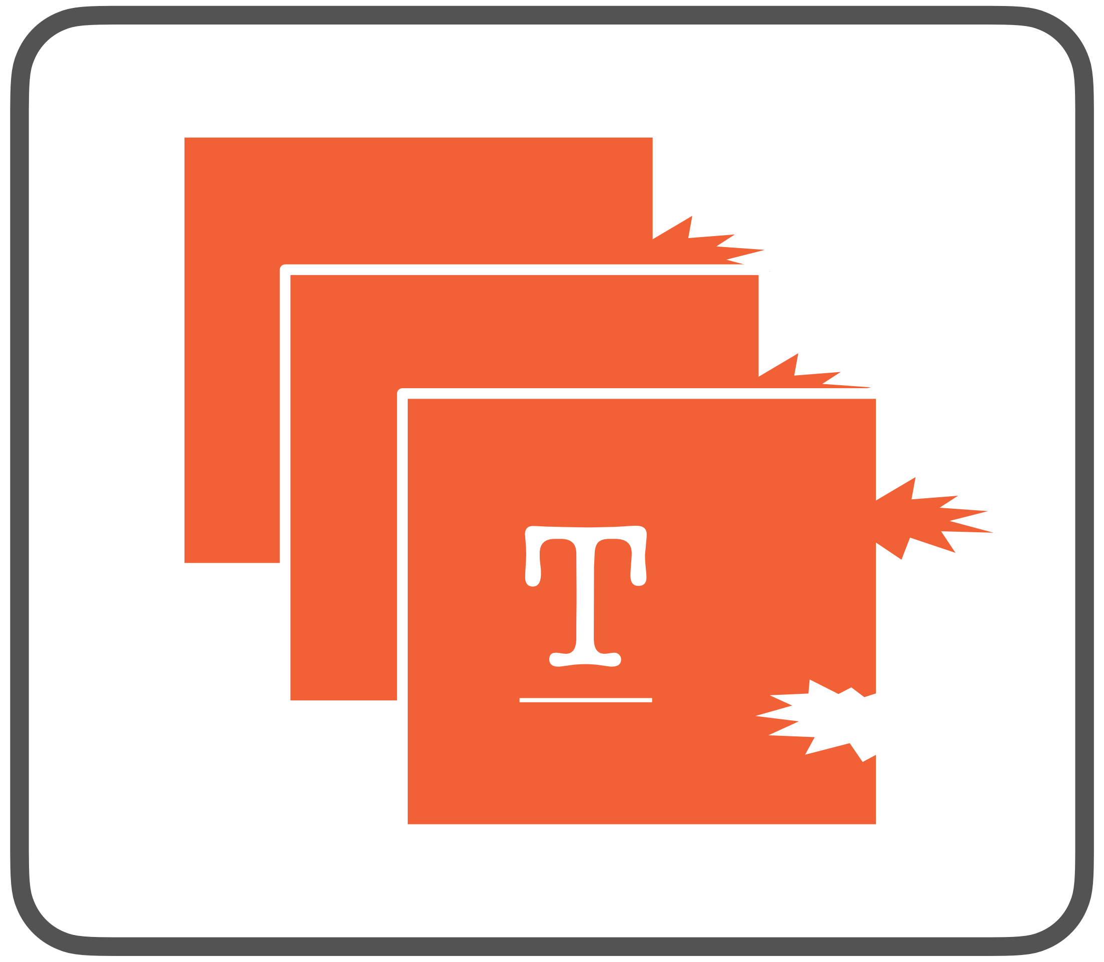

Is *Realized By* These Target Programs

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

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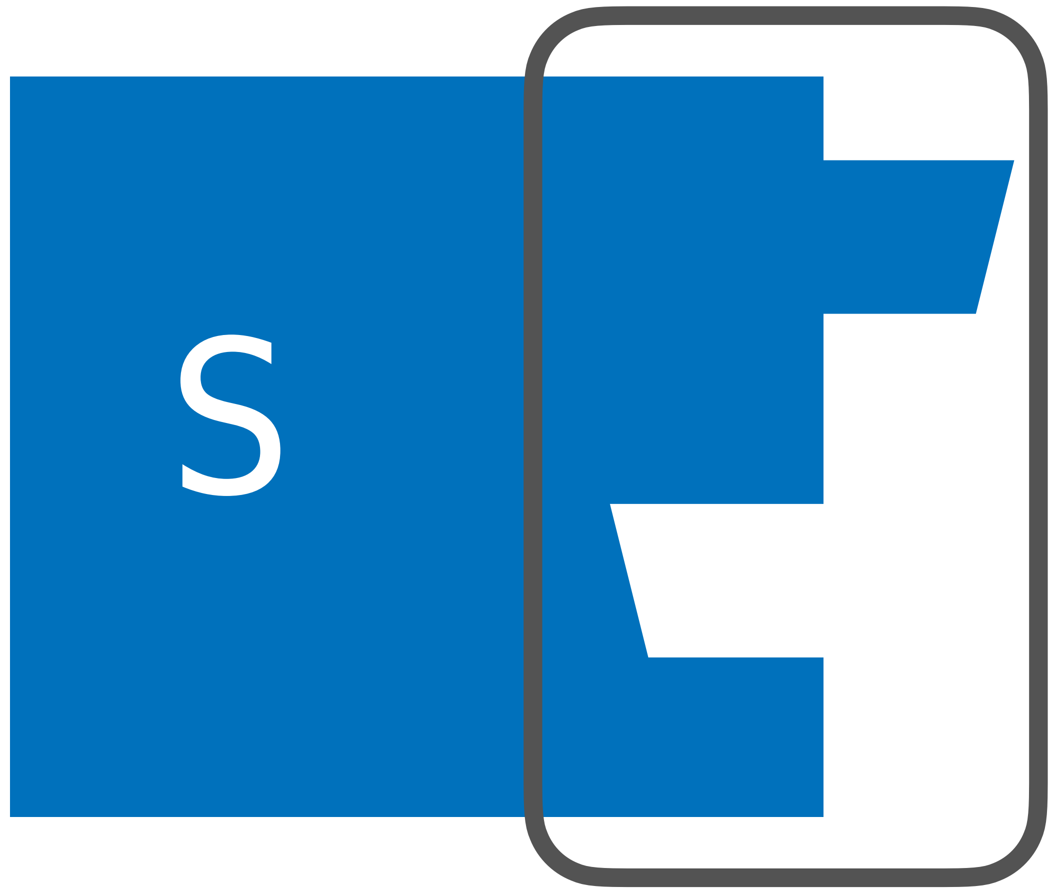

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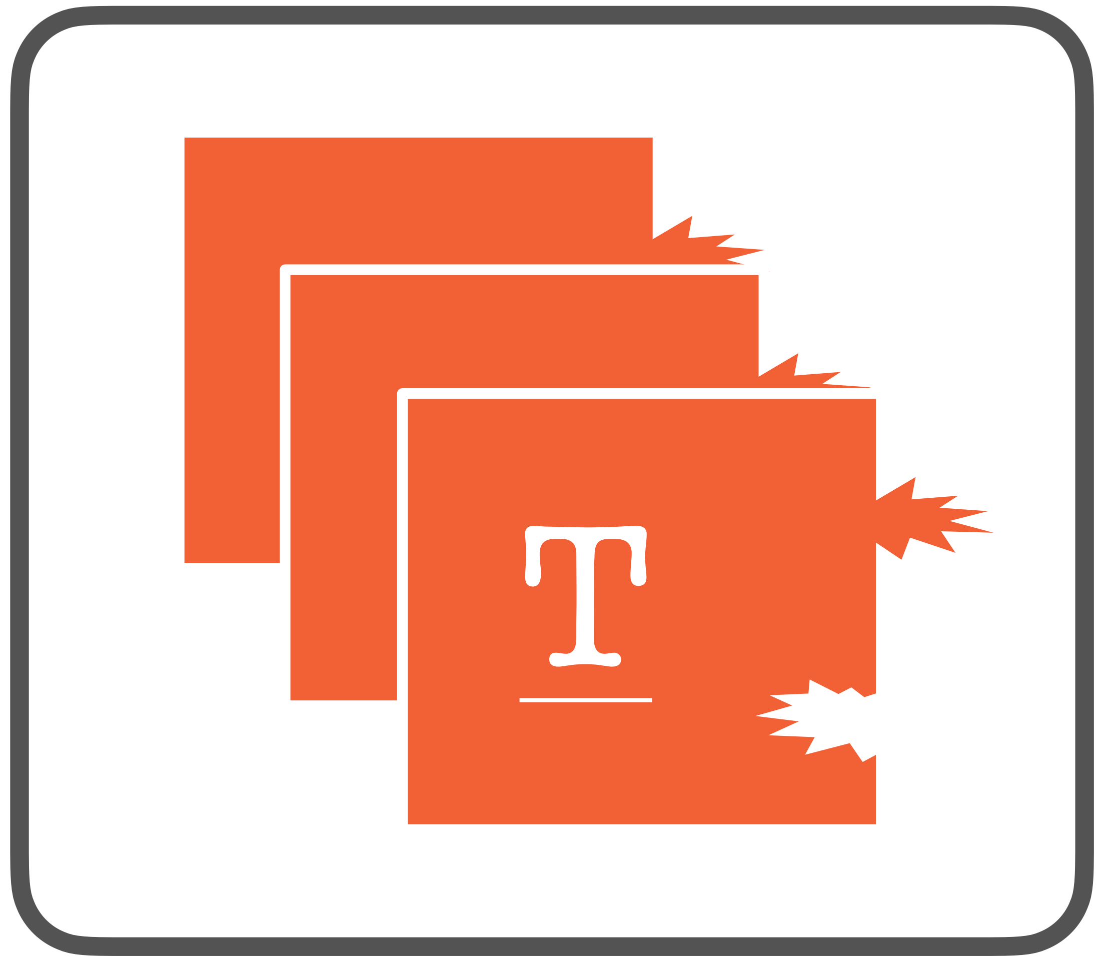

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Semantic Typing using *Realistic Realizability* [Benton06]

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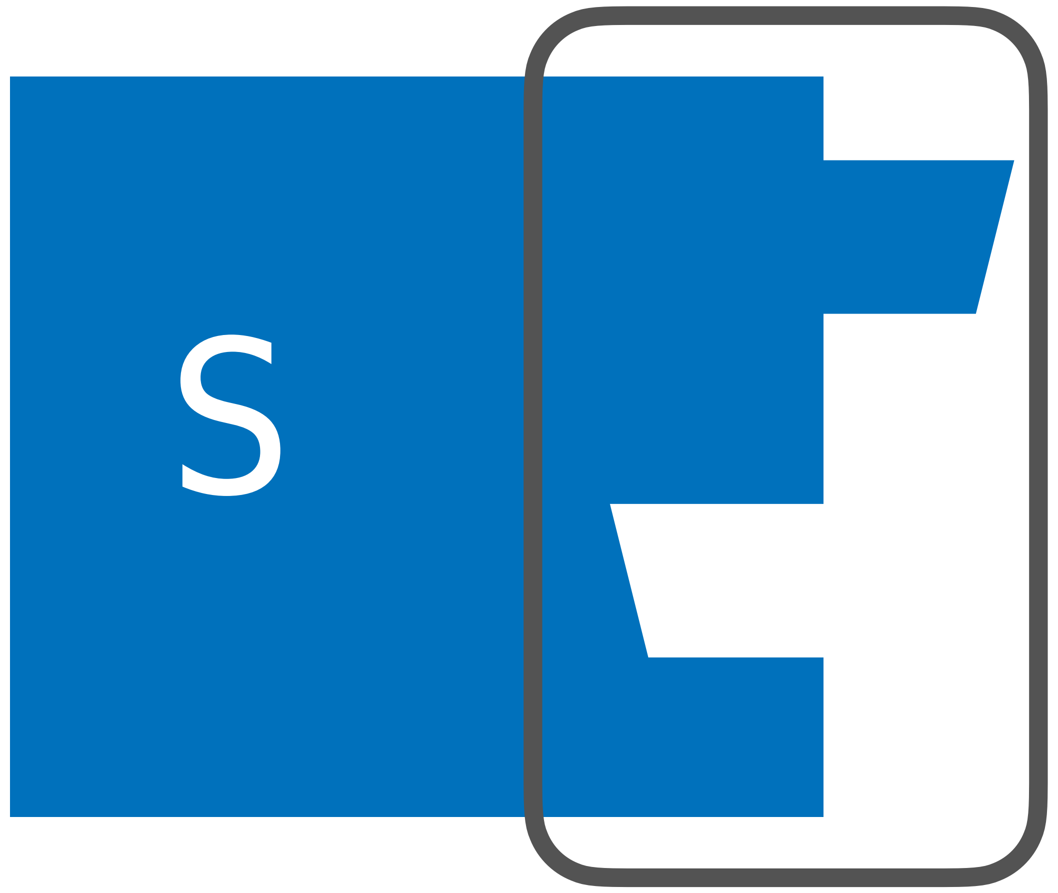
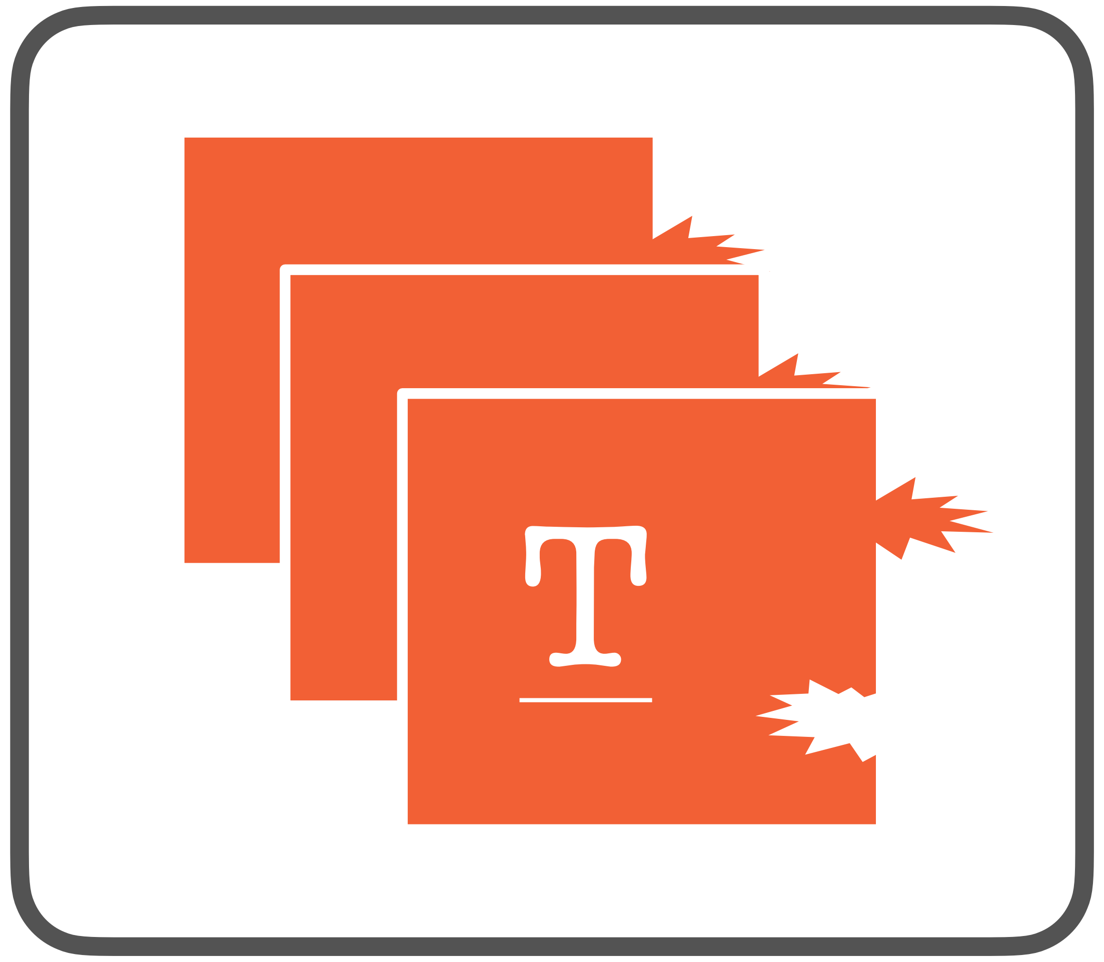


This Type τ

Our Proposal

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

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



Is *Realized By* These Target Programs

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Semantic Typing using *Realistic Realizability* [Benton06]

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
  - Separation logic abstractions for reasoning about RC

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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`

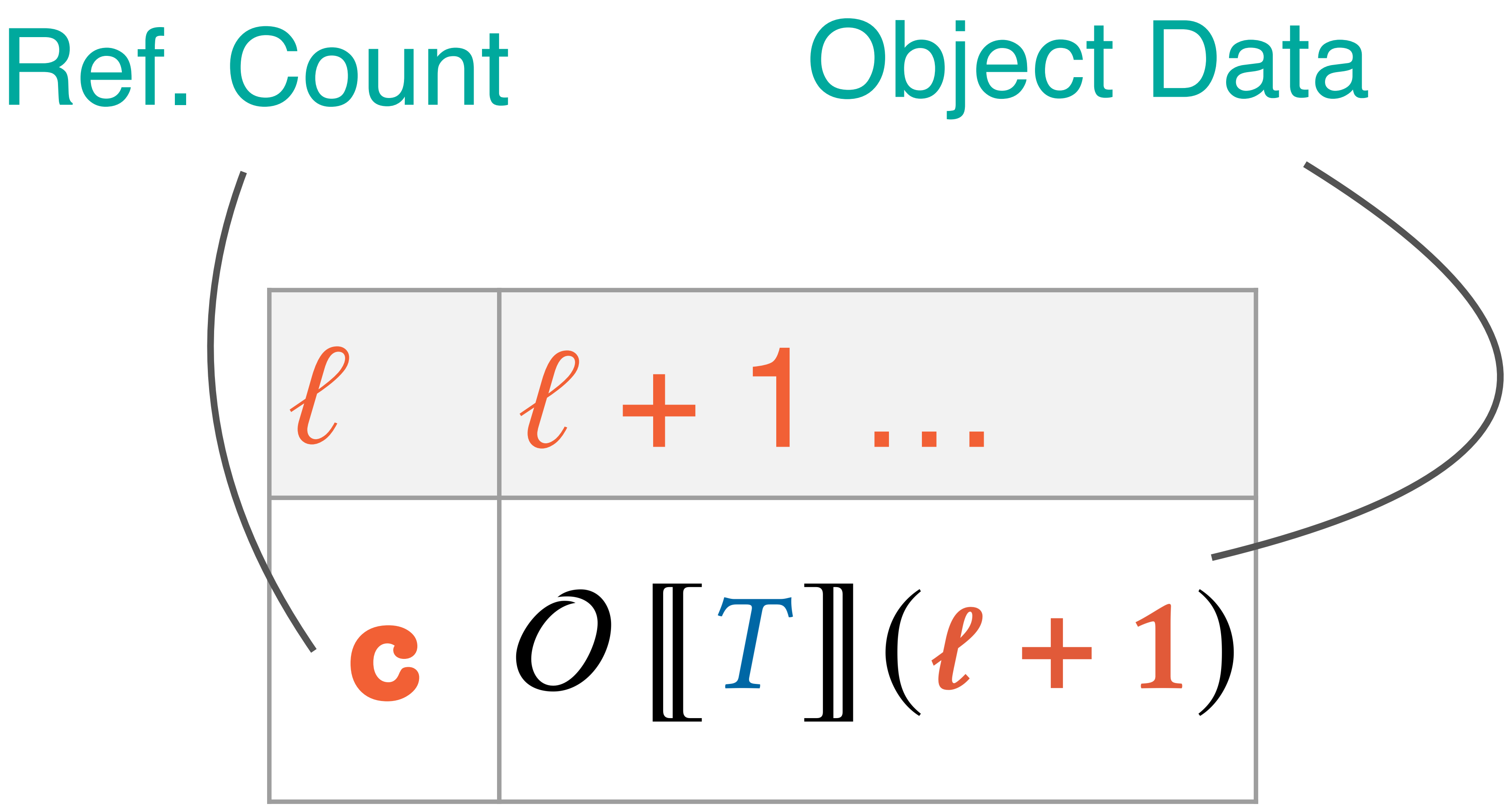
e is **ABI compliant** with τ if

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

References: Layout

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

$$\mathcal{R}[\![T]\!](\ell) \approx \begin{array}{|c|l|}\hline \ell & \ell + 1 \ \dots \\ \hline \mathbf{c} & \mathcal{O}[\![T]\!](\ell + 1) \\ \hline \end{array}$$



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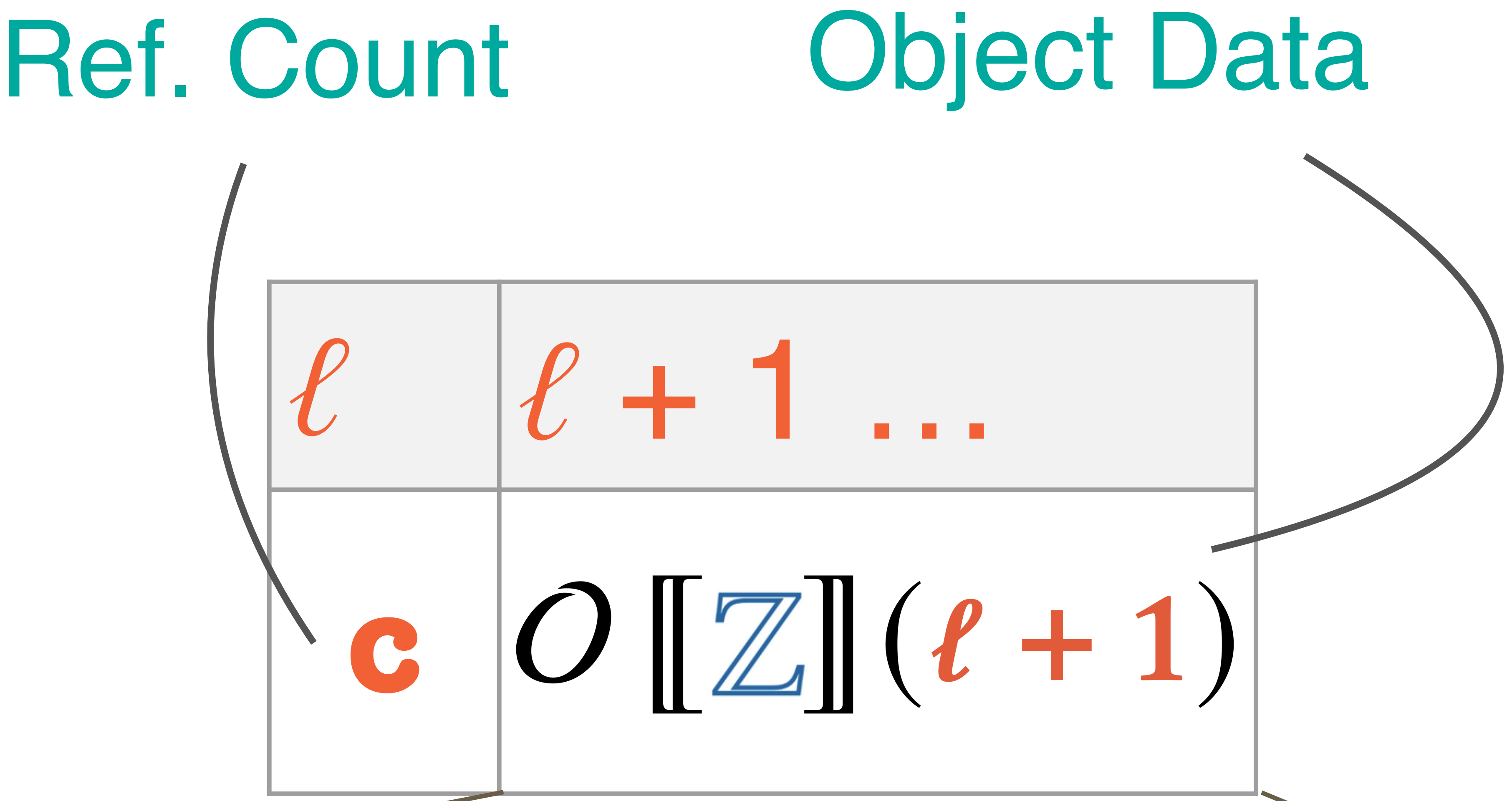
$$\mathcal{R}[\![\mathbb{Z}]\!](\ell) \approx$$



Ref. Count

Object Data

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

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

More in Paper:
Unboxed types

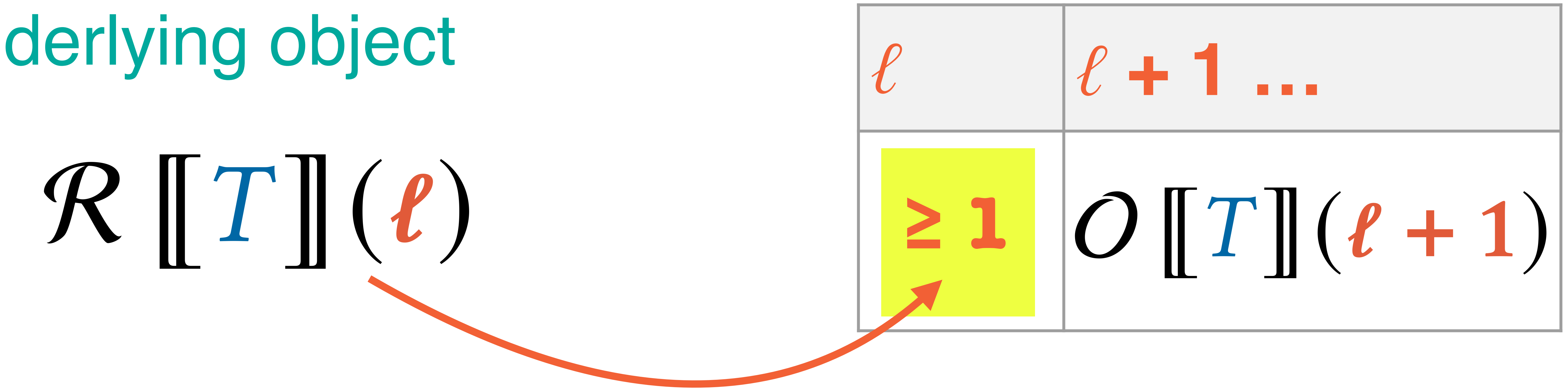
References: Ownership + Sharing

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

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

References: Ownership + Sharing

Single reference represents one share of underlying object

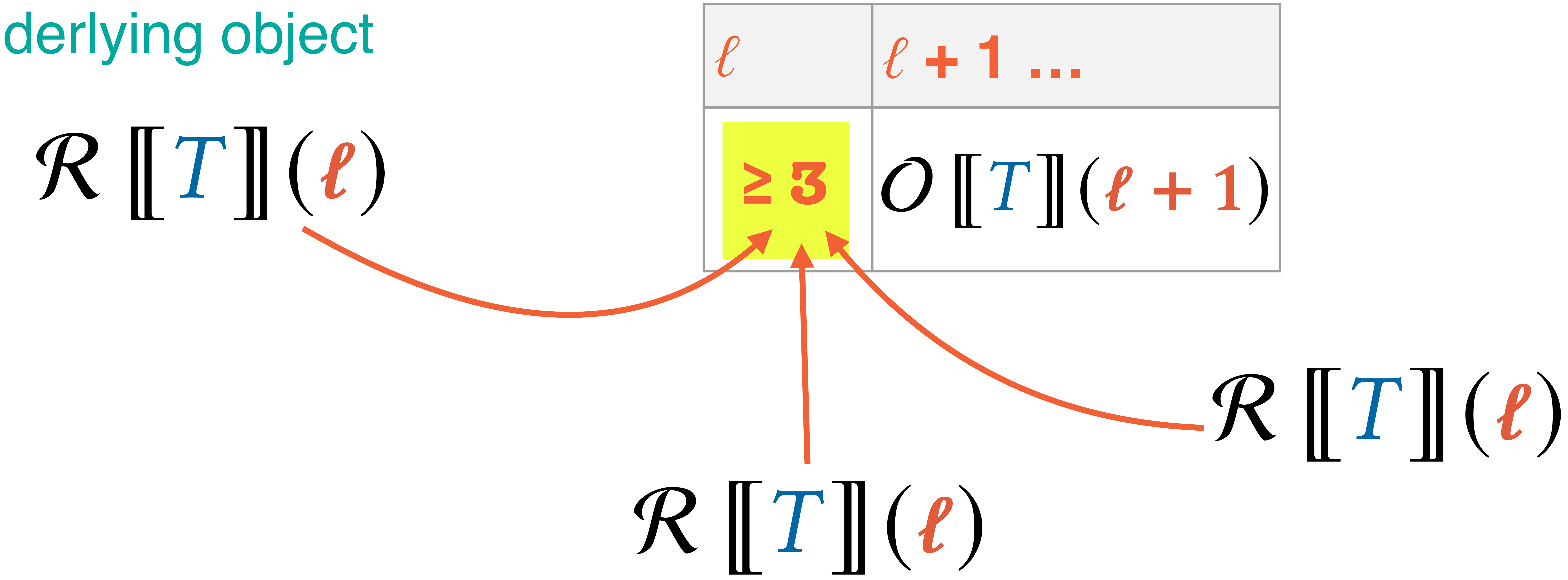


$$\mathcal{R}\,[\![T]\!](\boldsymbol{\ell})$$

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

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

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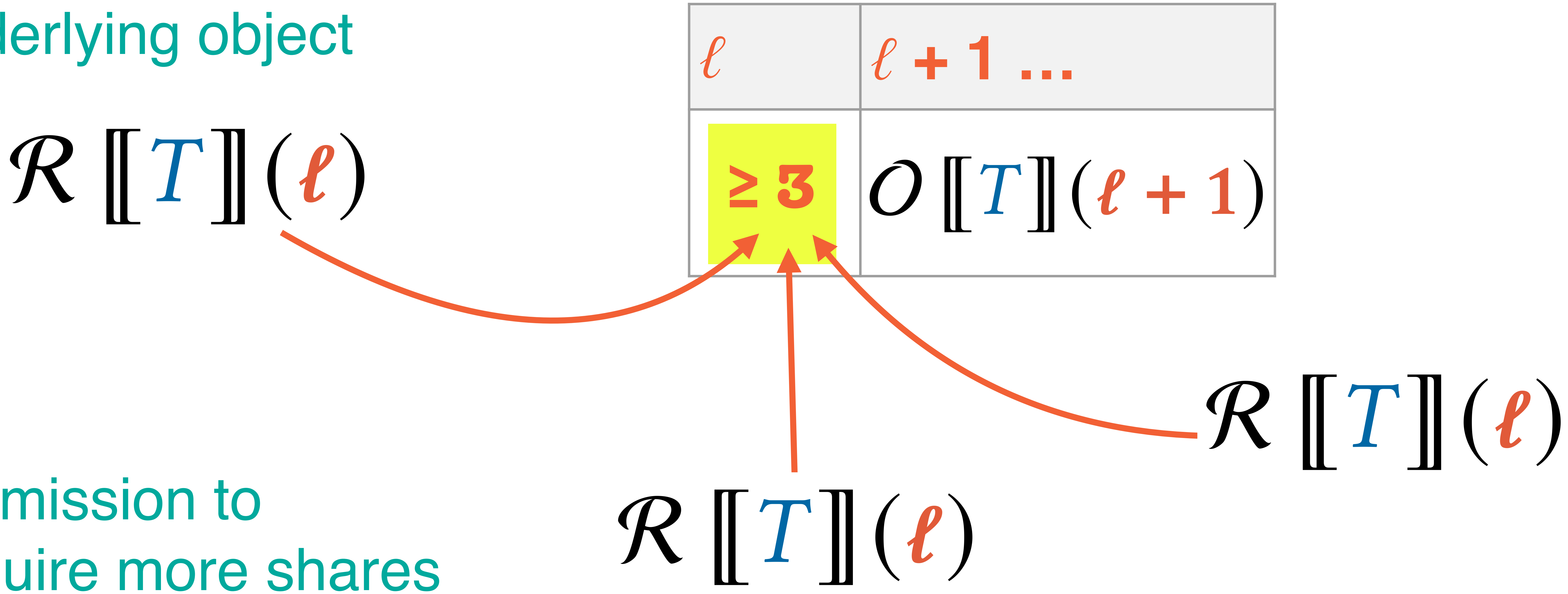

ℓ	$\ell + 1$ ...
≥ 3	$\mathcal{O}[\![T]\!](\ell + 1)$

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

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

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

Reference confers permission to increment count & acquire more shares

RC-INCR

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

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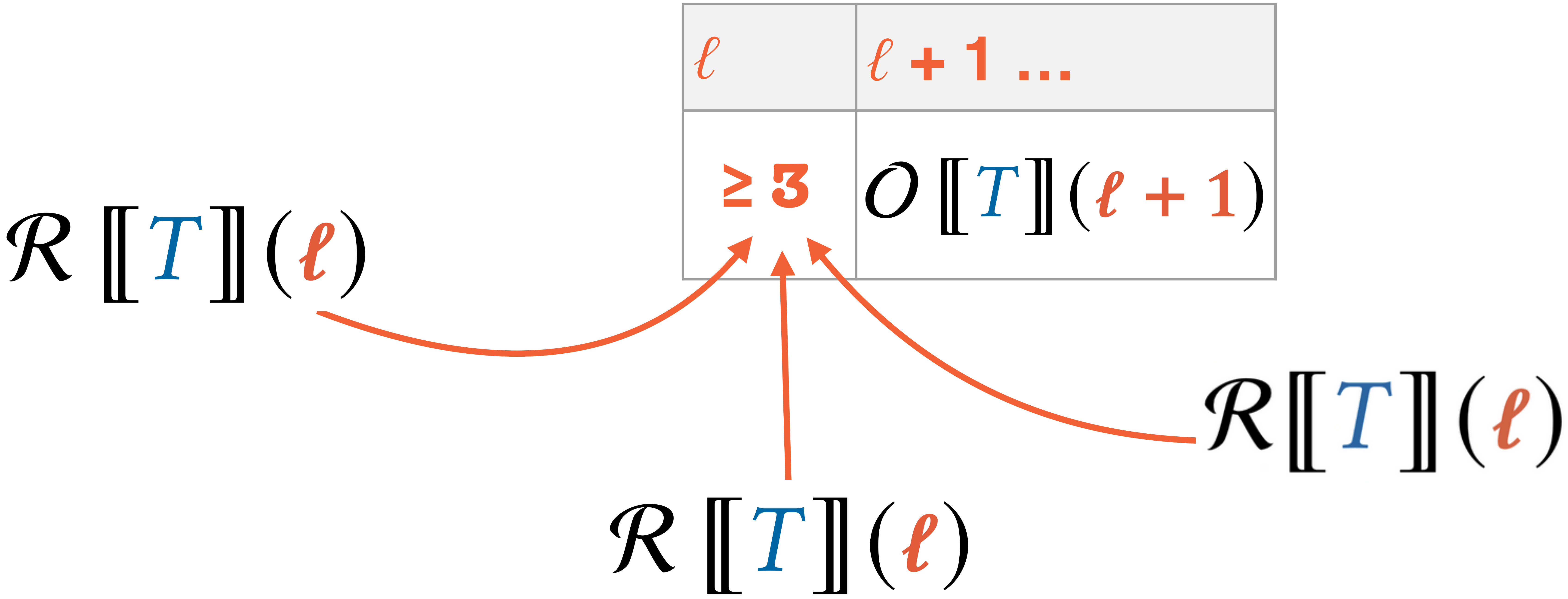

ℓ	$\ell + 1$ ...
≥ 3	$\mathcal{O}[\![T]\!](\ell + 1)$

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

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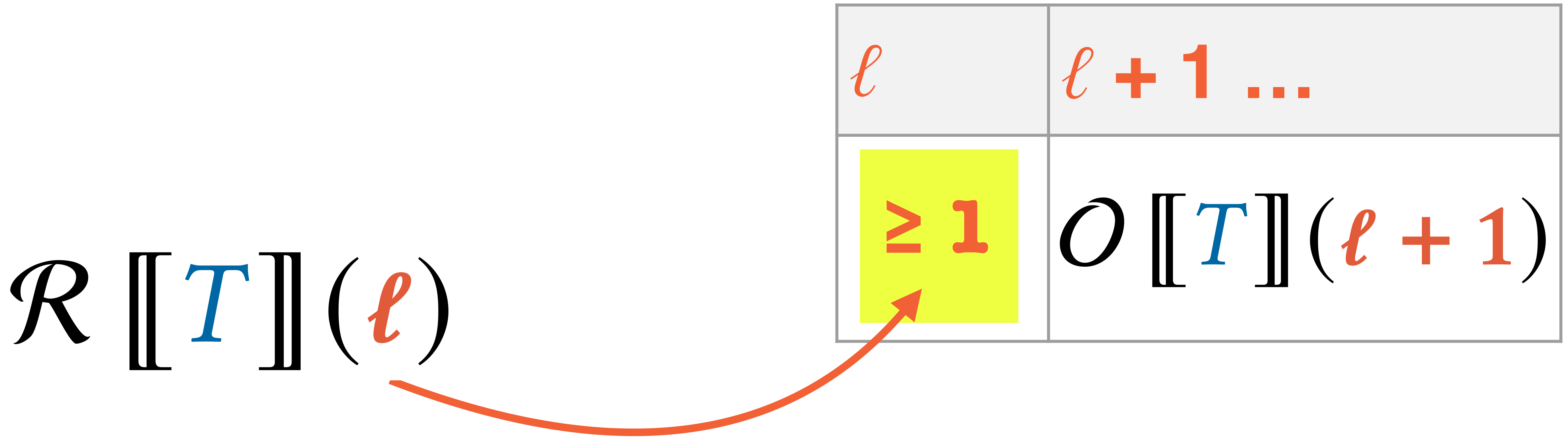


$$\mathcal{R}\,[\![T]\!](\ell)$$

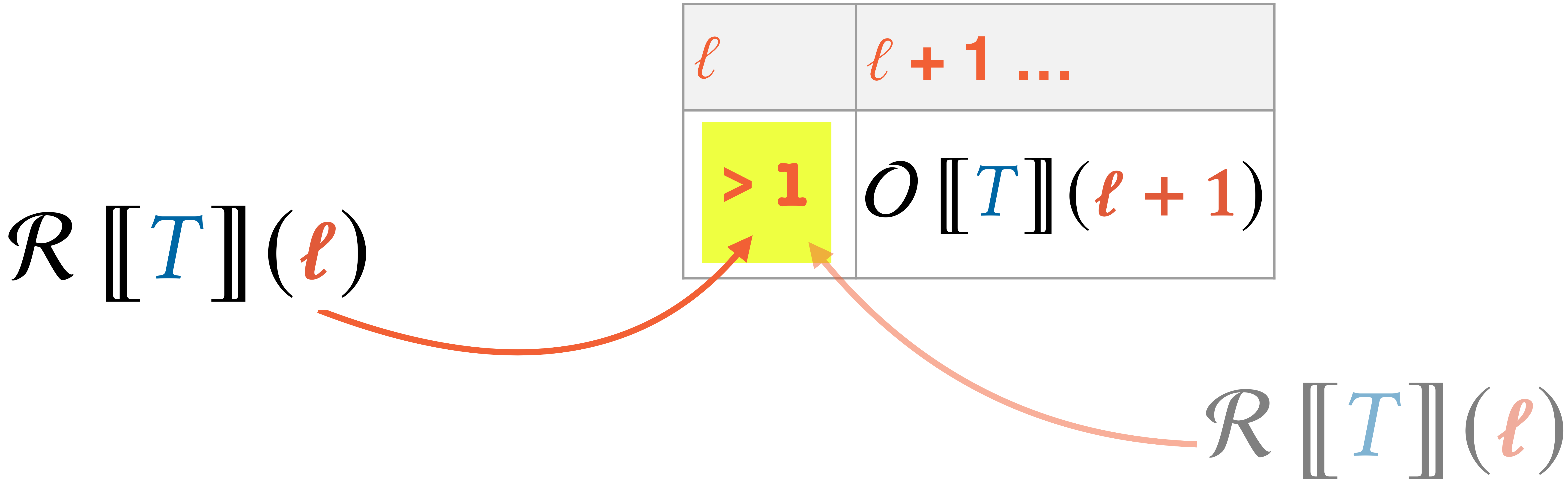
ℓ	ℓ + 1 ...
≥ 1	$\mathcal{O}\,[\![T]\!](\ell + 1)$

Reference confers permission to decrement count & release shares

RC-DECR

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

References: Ownership + Sharing



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

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

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

Reference confers permission to decrement count & release shares

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

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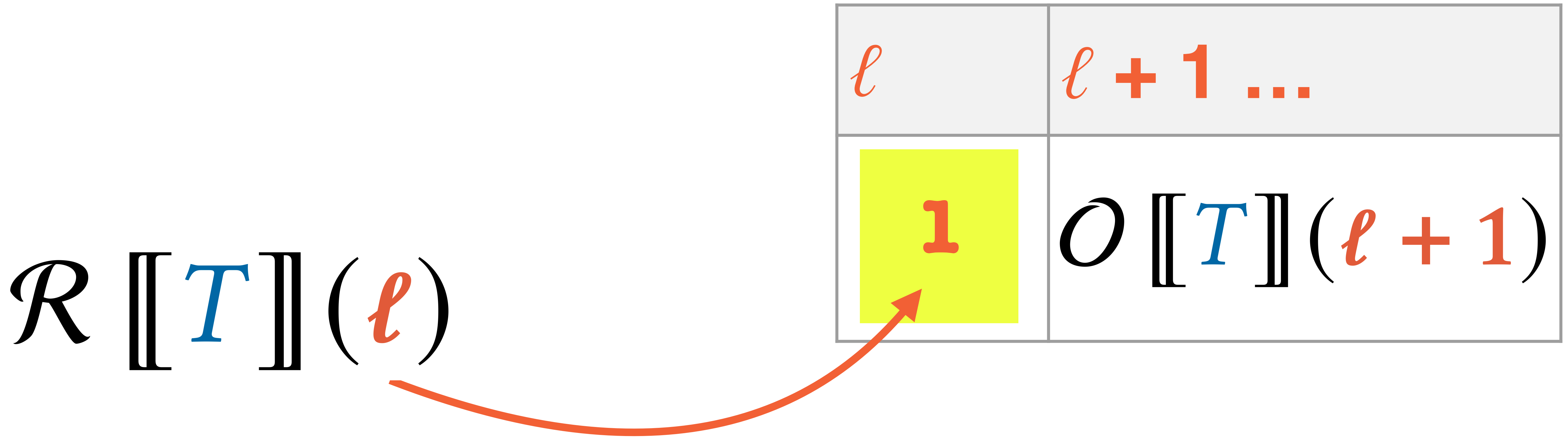


$\mathcal{R}[\![T]\!](\ell)$

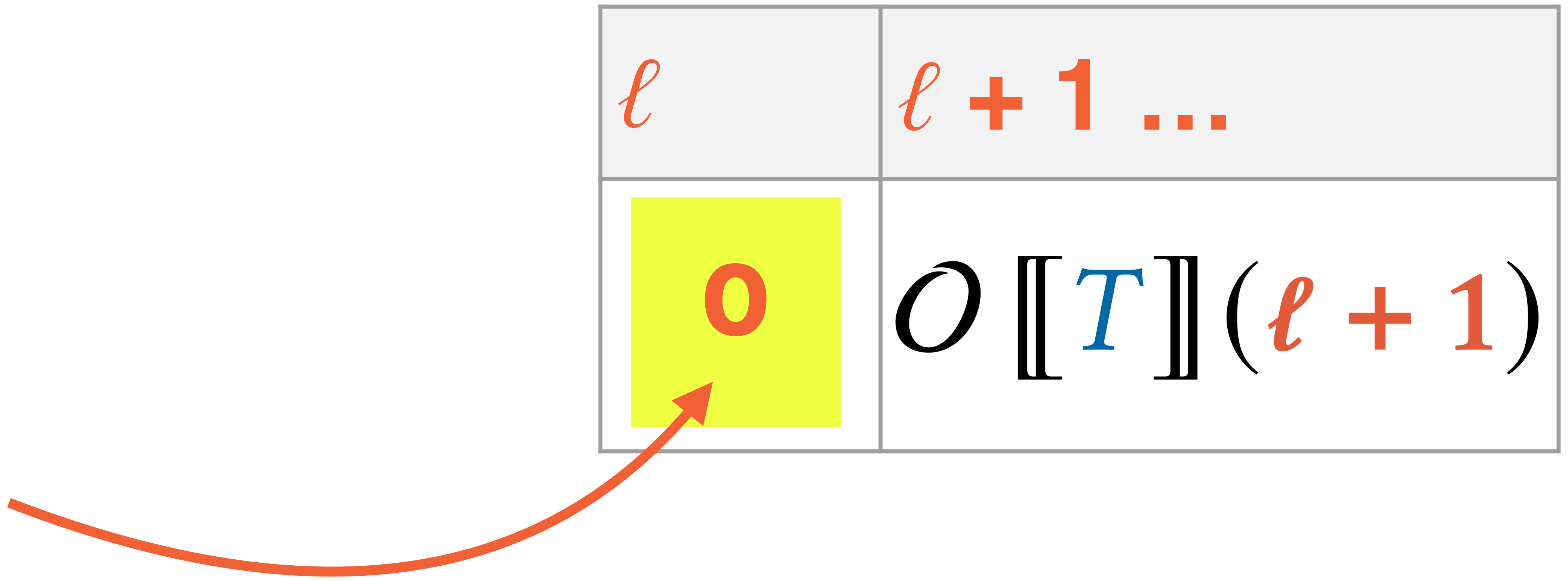
ℓ	$\ell + 1 \ldots$
1	$\mathcal{O}[\![T]\!](\ell + 1)$

Reference confers permission to decrement count & release shares

RC-DECR

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

References: Ownership + Sharing



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

Reference confers permission to
decrement count & release shares

RC-DECR

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

Calling Conventions

$$\mathcal{O}\llbracket T_1 \rightarrow T_2 \rrbracket(\ell) \triangleq \exists f.\, \ell \mapsto f \star$$

Pointer to function

Calling Conventions

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

Pointer to function

Calling convention:
Caller increment

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Pointer to function

Calling convention:
Caller increment

vs.

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

Calling Conventions

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

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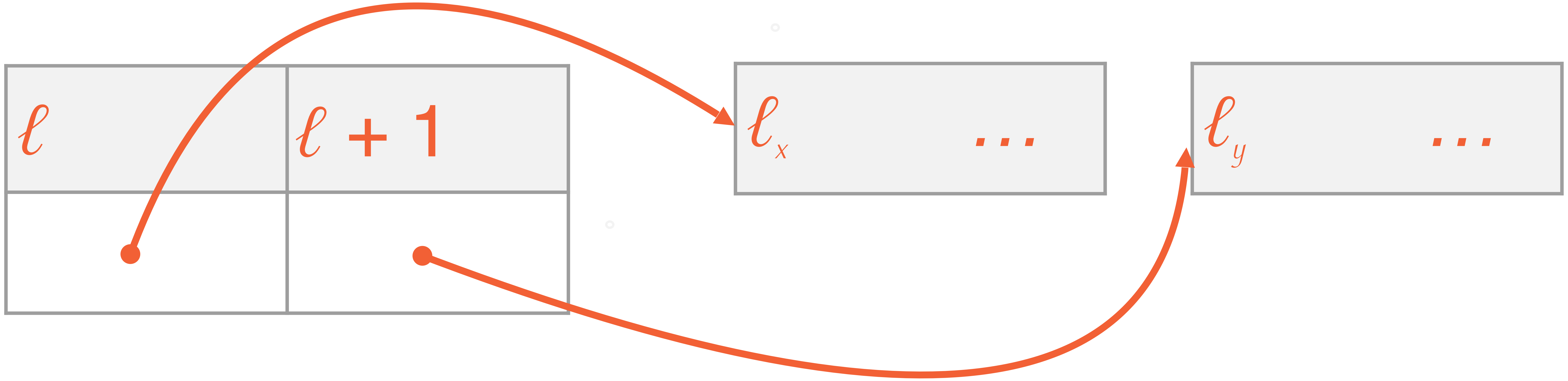
More in Paper:
Recursive closures

Aggregate Layout

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

Aggregate Layout

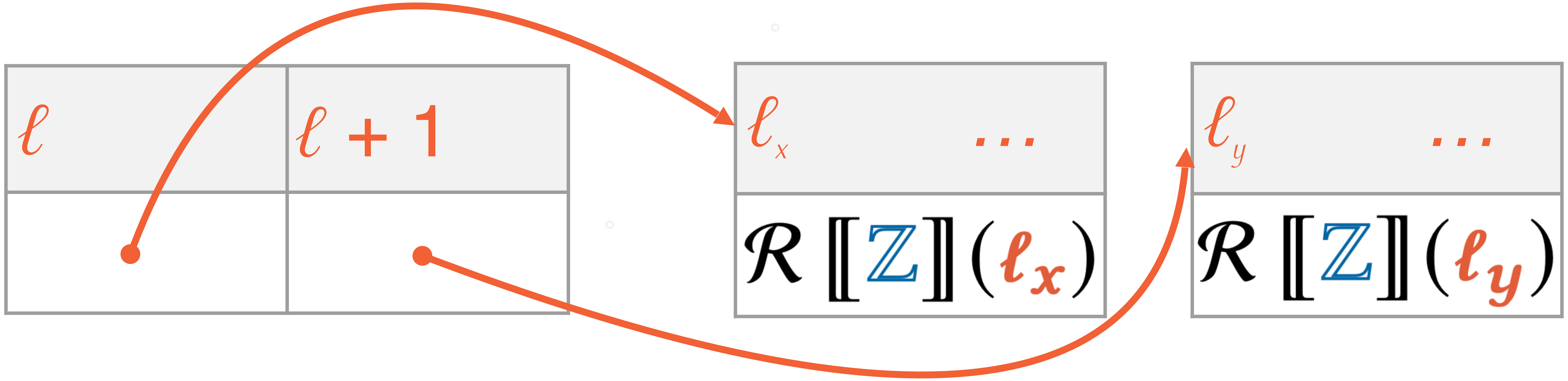
$$\mathcal{O}\,[\![\text{struct Point}\ \{x : \mathbb{Z}, y : \mathbb{Z}\}]\!](\ell)$$



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

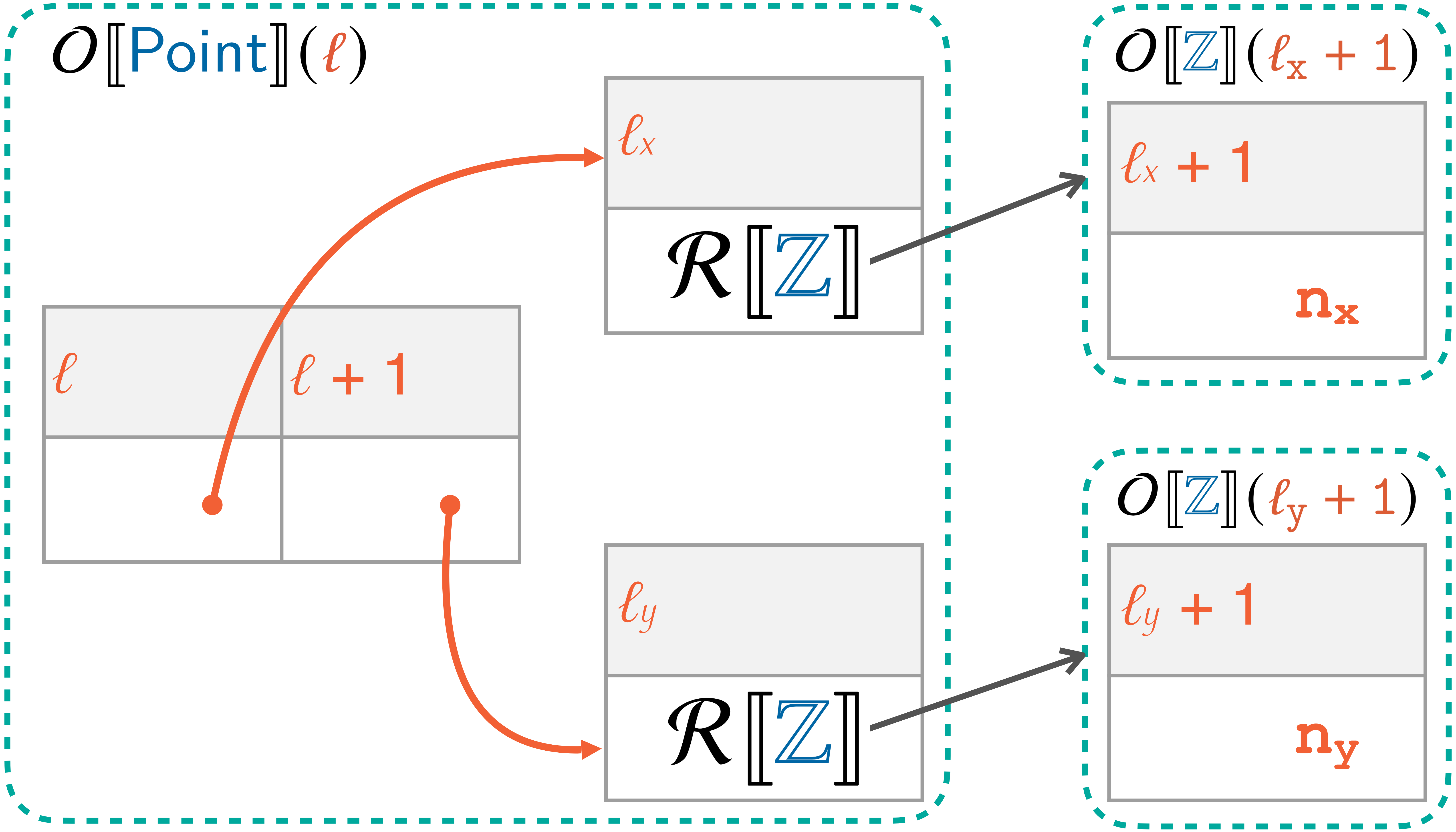
Aggregate Layout

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



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

Resource Graphs



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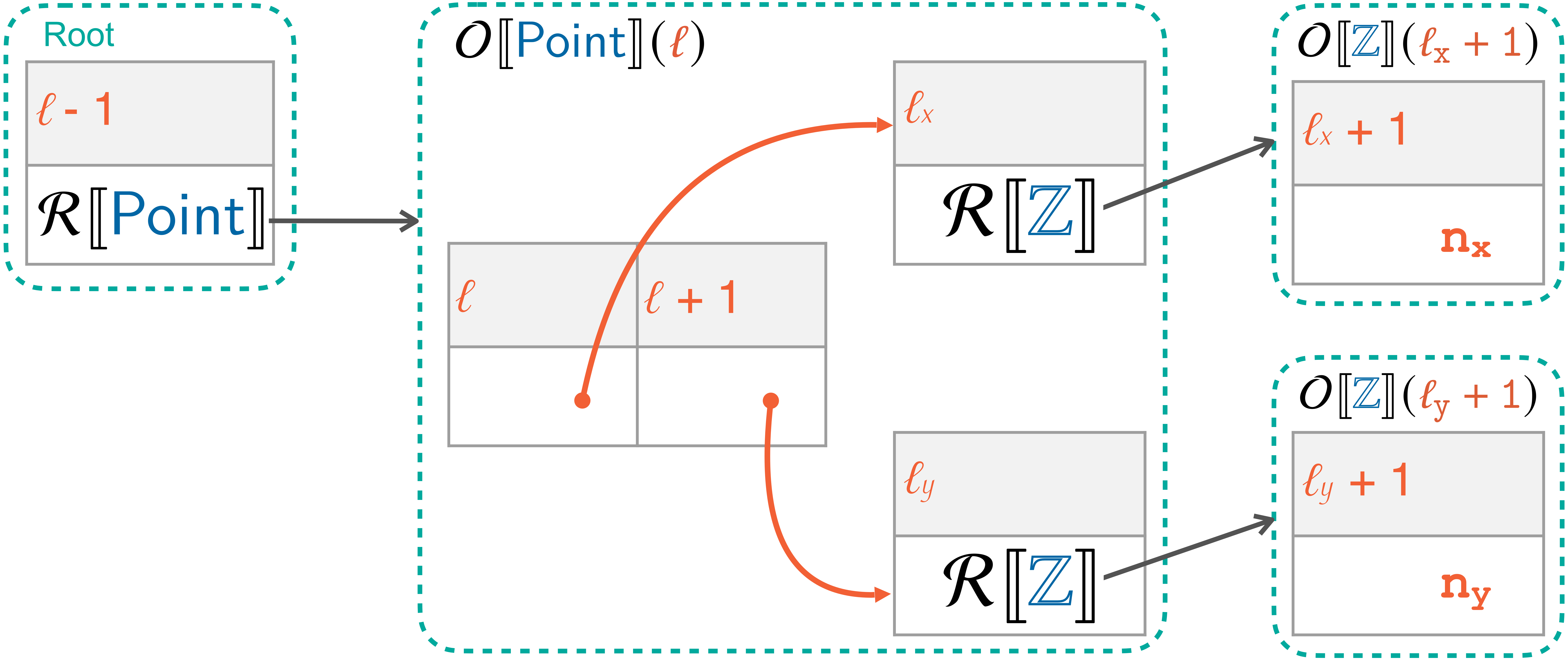

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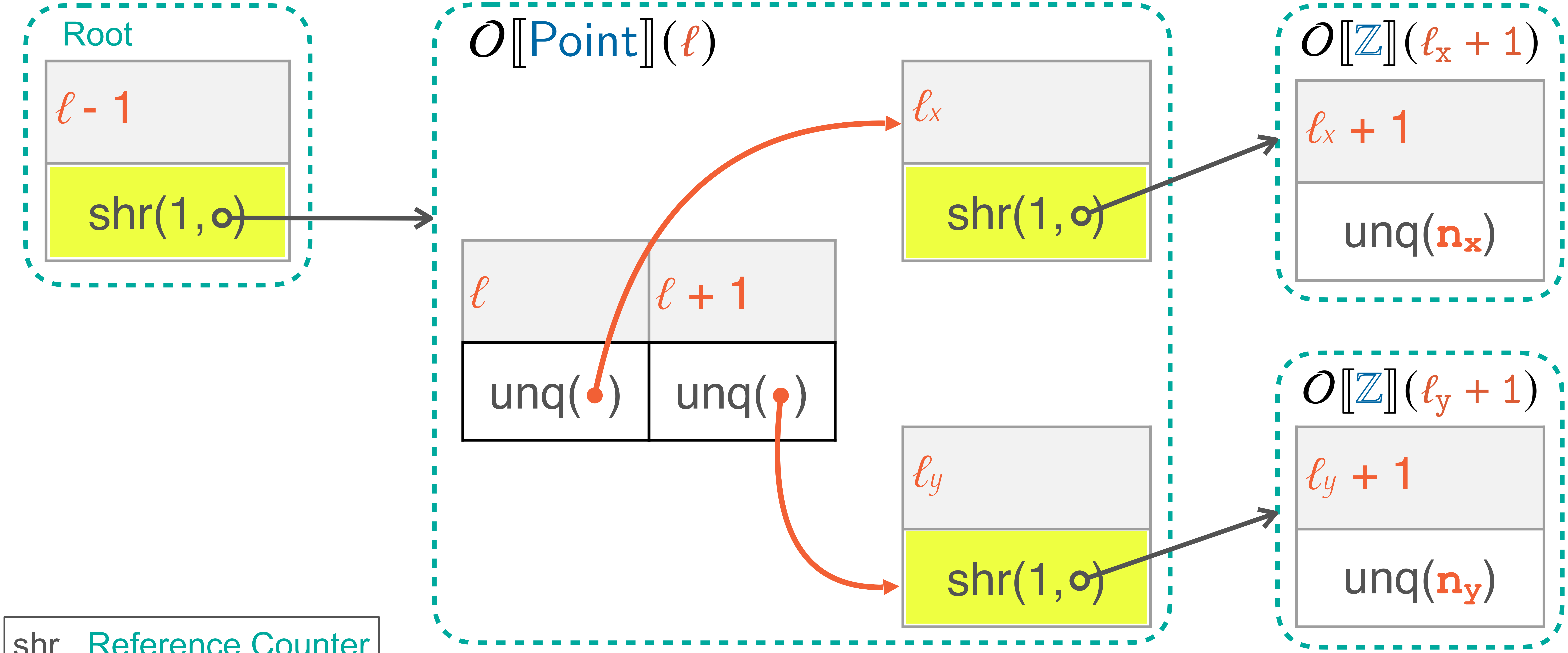
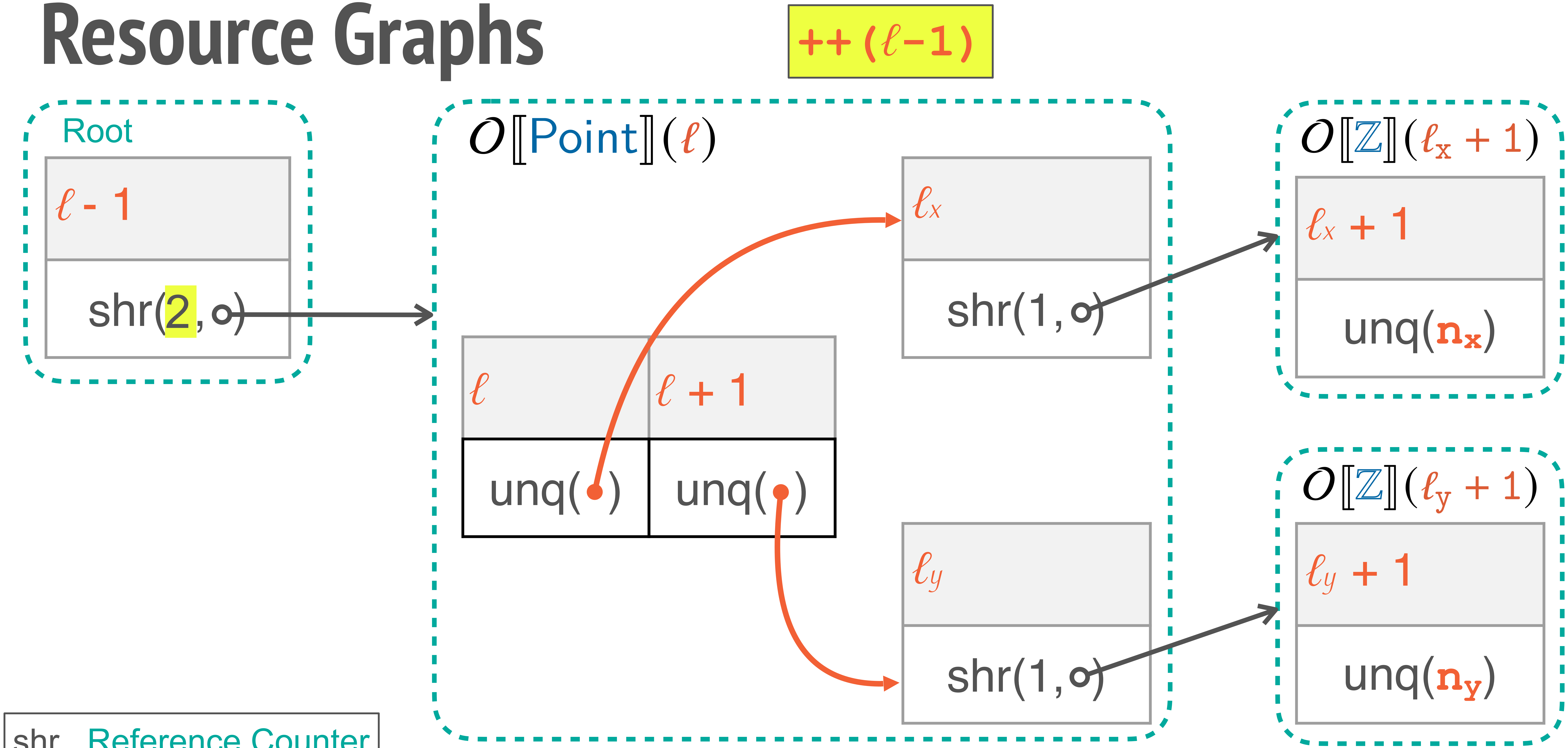


shr	Reference Counter
unq	Plain Old Data

Resource Graphs



`++(ℓ-1)`

Root

ℓ - 1

shr(2, ∘)

$\mathcal{O}[\![\text{Point}]\!](\ell)$

ℓ

unq(•)

$\ell + 1$

unq(•)

ℓ_x

shr(1, ∘)

ℓ_y

shr(1, ∘)

$\mathcal{O}[\![\mathbb{Z}]\!](\ell_x + 1)$

$\ell_x + 1$

unq($\mathtt{n_x}$)

$\mathcal{O}[\![\mathbb{Z}]\!](\ell_y + 1)$

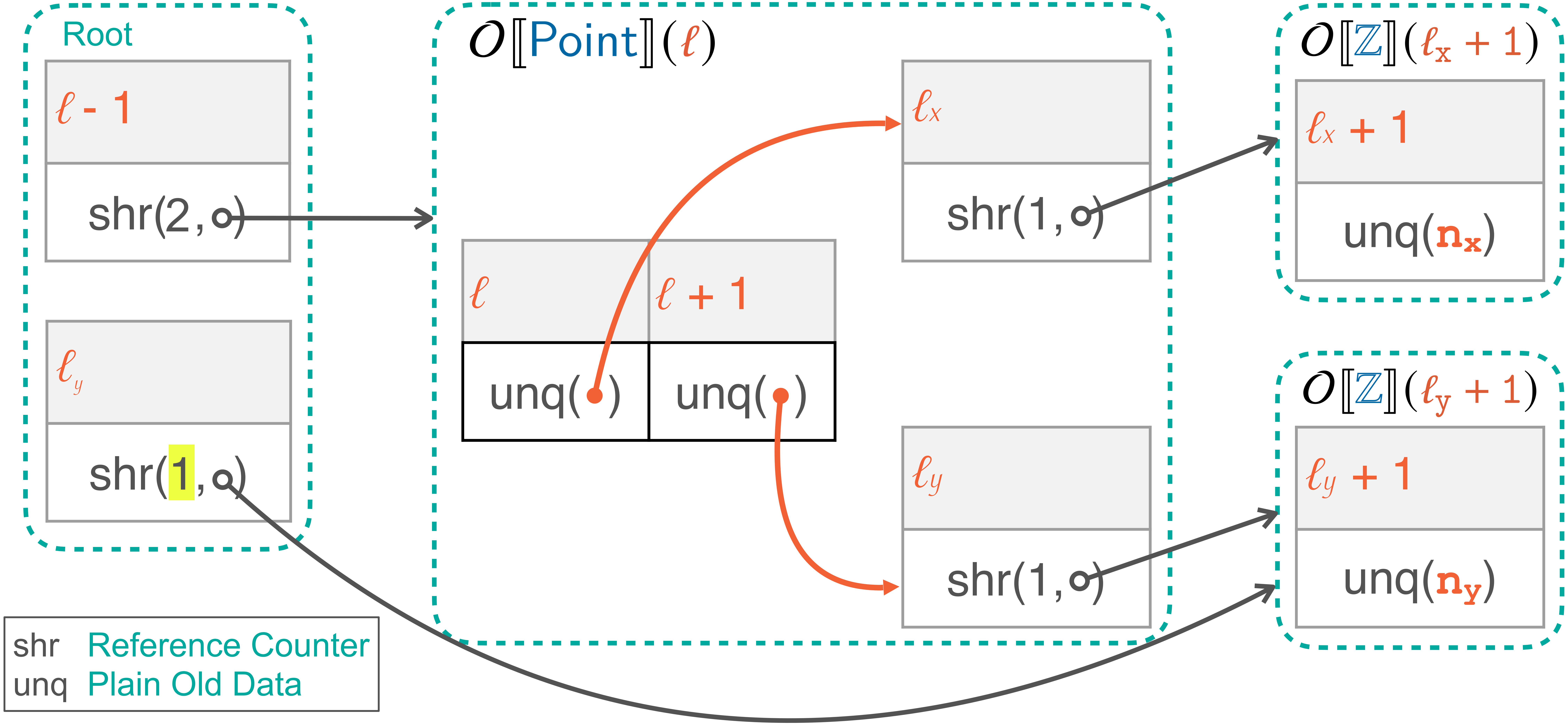
$\ell_y + 1$

unq($\mathtt{n_y}$)

shr	Reference Counter
unq	Plain Old Data

Resource Graphs

$++(\ell-1)\,;\ \boxed{++\ell_y}$



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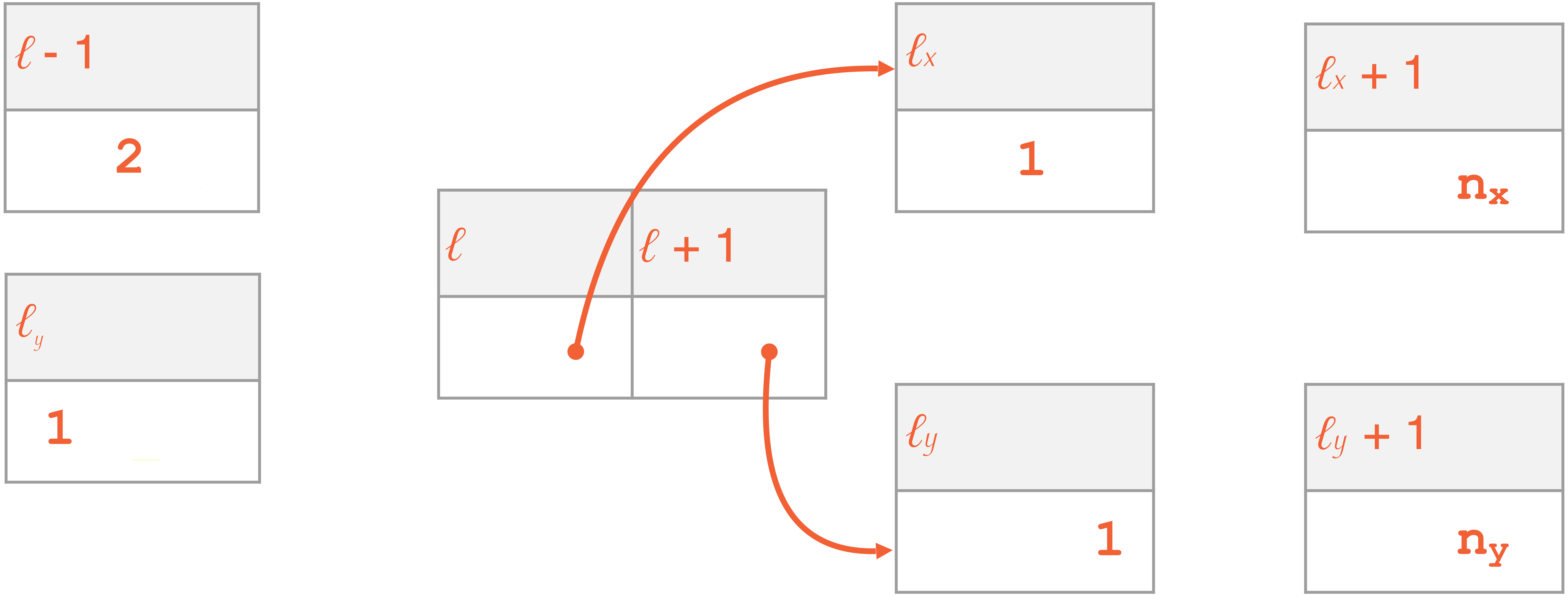


ℓ - 1

2

ℓ_y

1

ℓ

$\ell + 1$

ℓ_x

1

ℓ_y

1

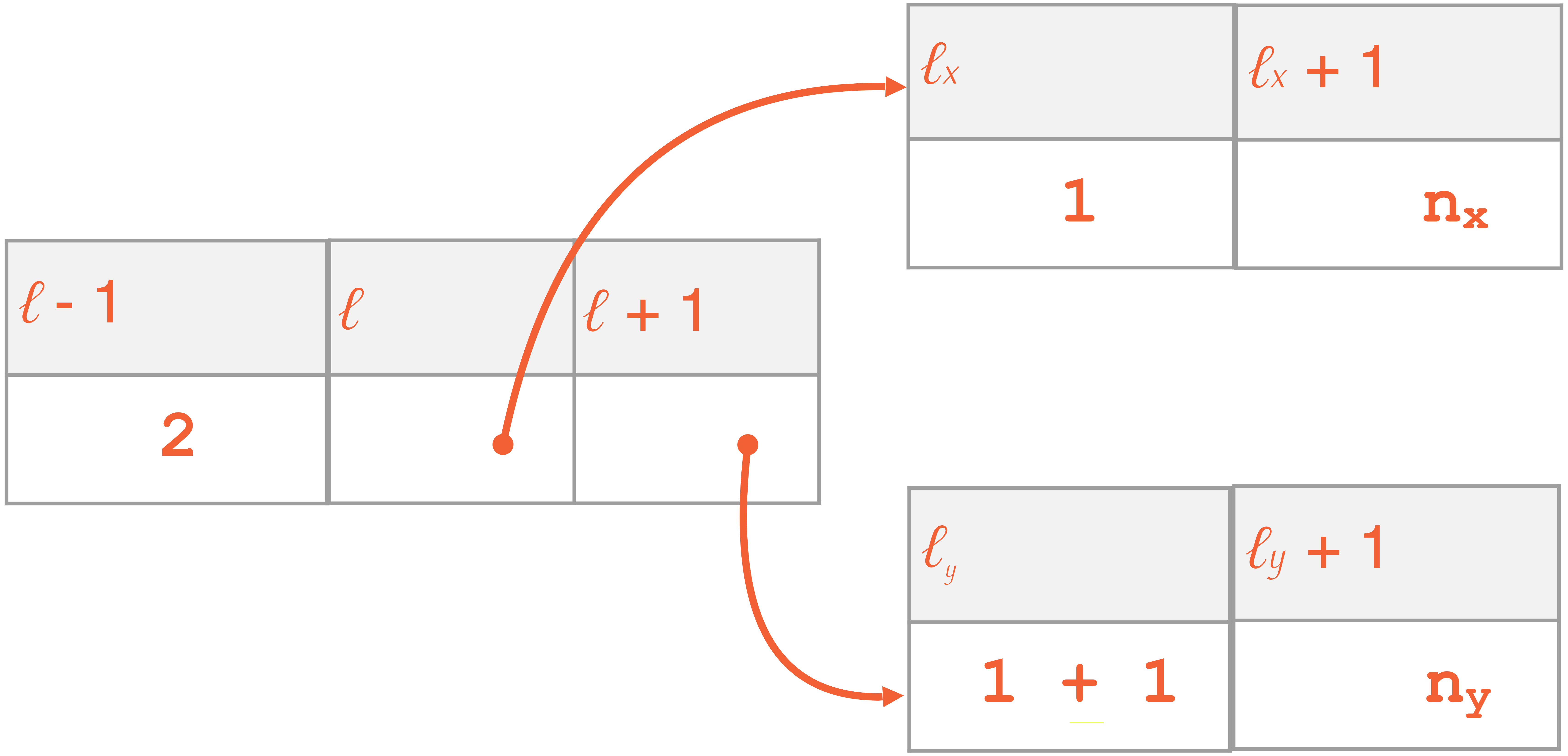
$\ell_x + 1$

$\mathbf{n_x}$

$\ell_y + 1$

$\mathbf{n_y}$

Resource Graphs



$\ell - 1$

2

ℓ

$\ell + 1$

ℓ_x

1

$\ell_x + 1$

$\mathbf{n_x}$

ℓ_y

$1 + 1$

$\ell_y + 1$

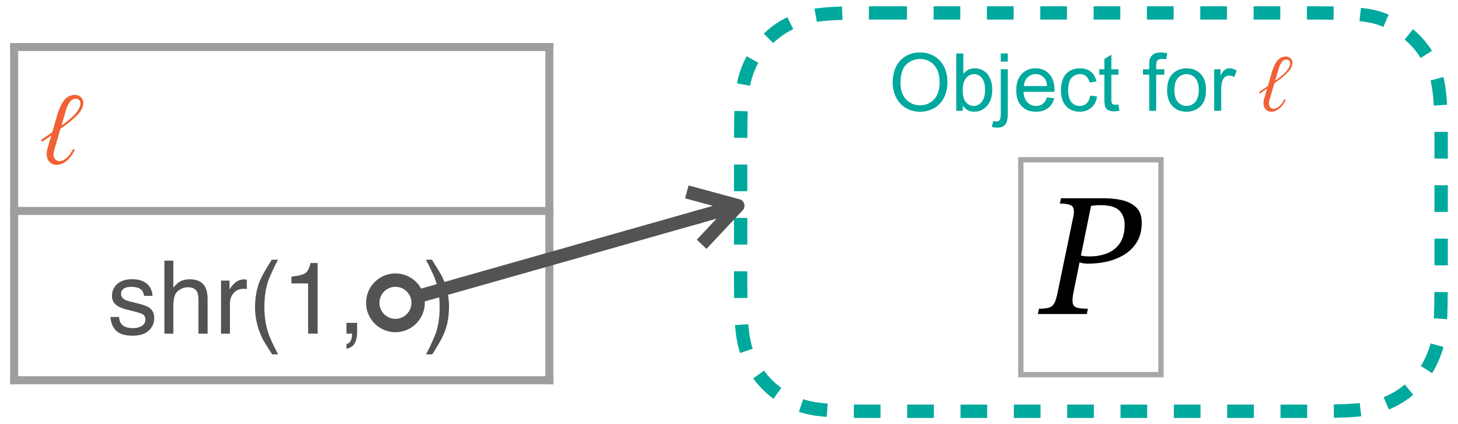
$\mathbf{n_y}$

Modalities

Modalities

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

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



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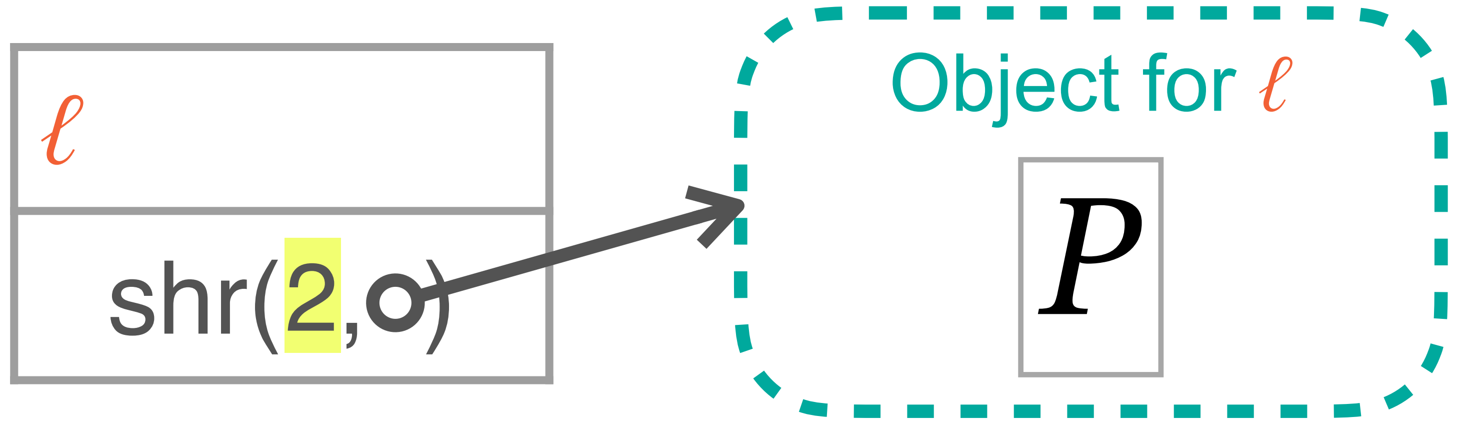
$$@_{\ell} P \star @_{\ell} P \approx$$

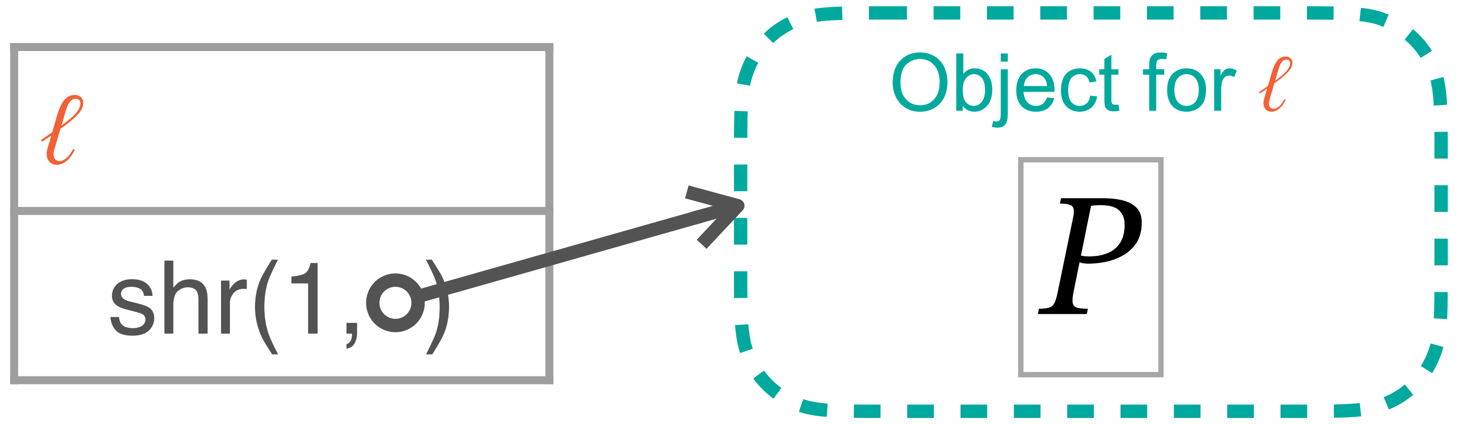


Composition sums counters at the root, not in objects

Modalities

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

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



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

Modalities

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

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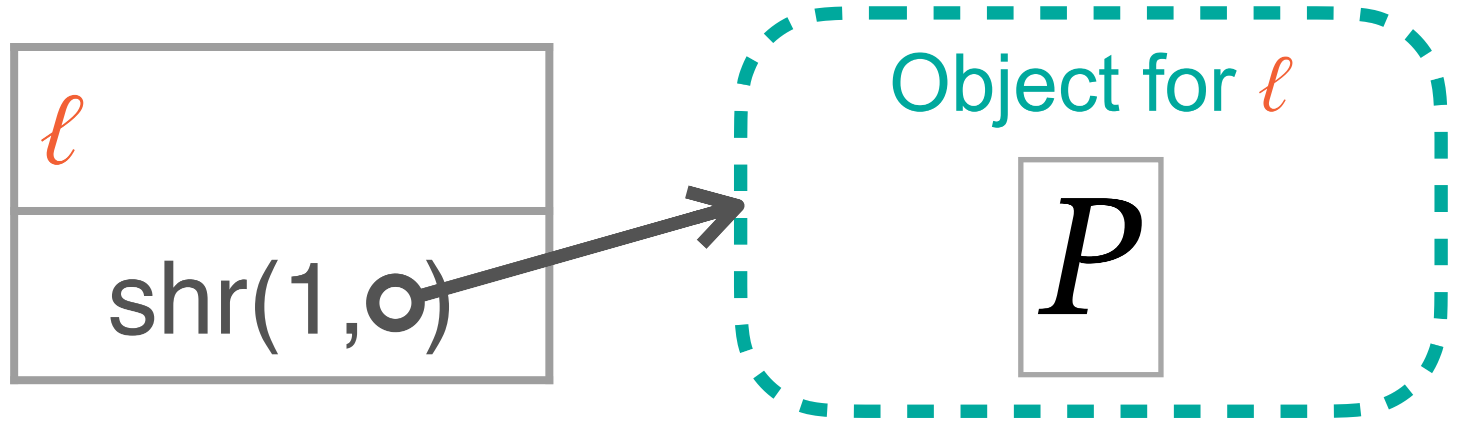


$$\boxed{\mathcal{R}[\![T]\!](\ell) \triangleq @_{\ell}\, \mathcal{O}[\![T]\!](\ell + 1)}$$

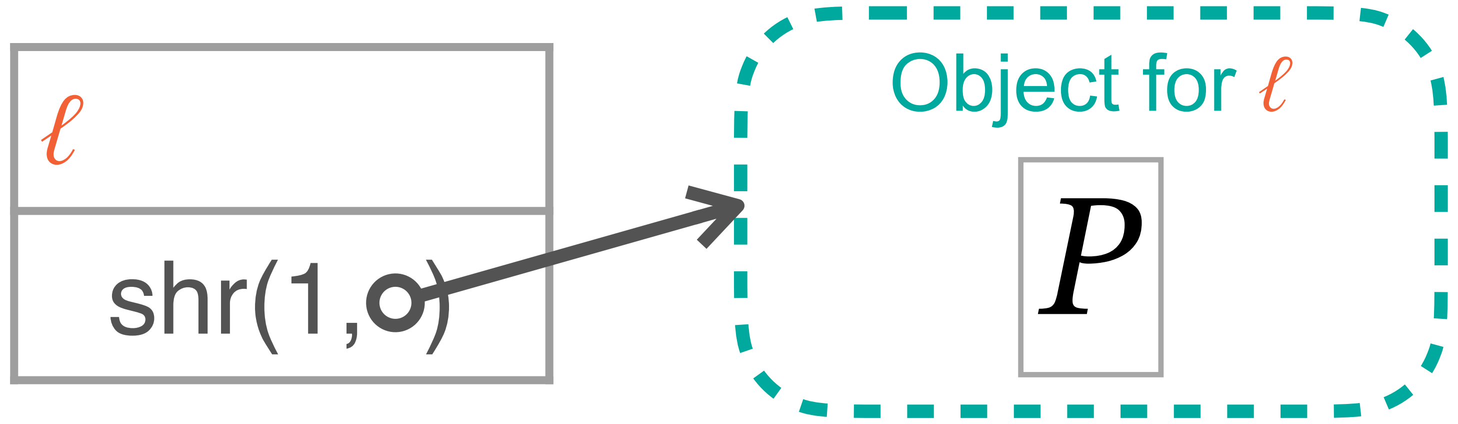
Reachability Modality $\diamond P$: It is possible to reach P via some set of jumps

Allows reading and incrementing from deeply nested objects

Modalities

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

$$@_\ell P \approx$$



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

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

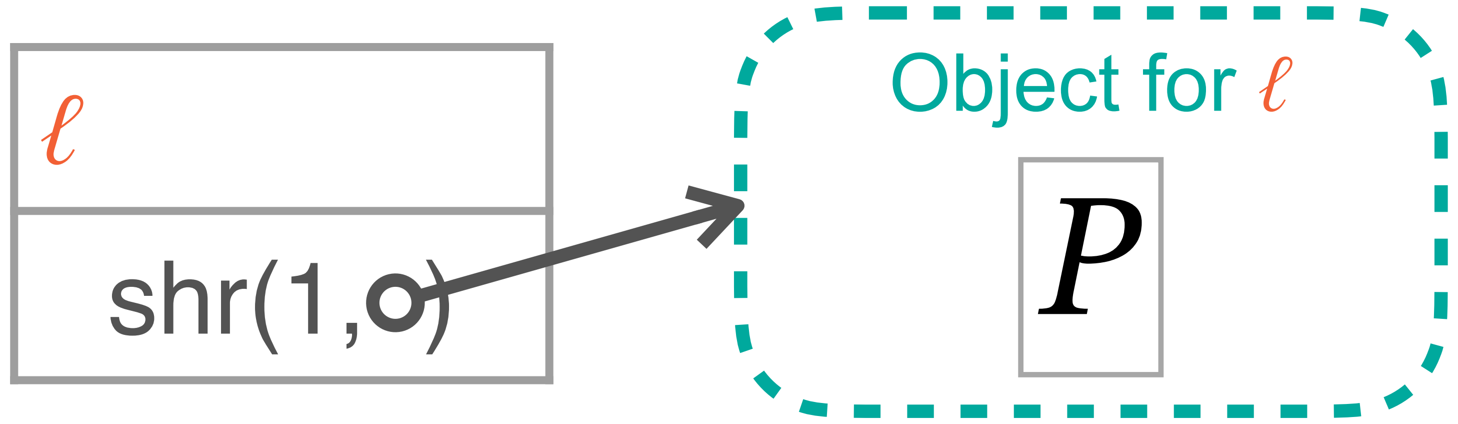
Allows reading and incrementing from deeply nested objects

$$\boxed{\begin{array}{l}\text{@-INCR}\\ \dfrac{}{\{ @_\ell P \} \mathbin{{+}{+}}\ell \{ n. \ulcorner n > 1 \urcorner \star @_\ell P \star @_\ell P \}}\end{array}}$$

Modalities

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

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



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

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

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

Like C ABI

Rigid Layout

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

Like C ABI

No reordering

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

Rigid Layout

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

Like C ABI

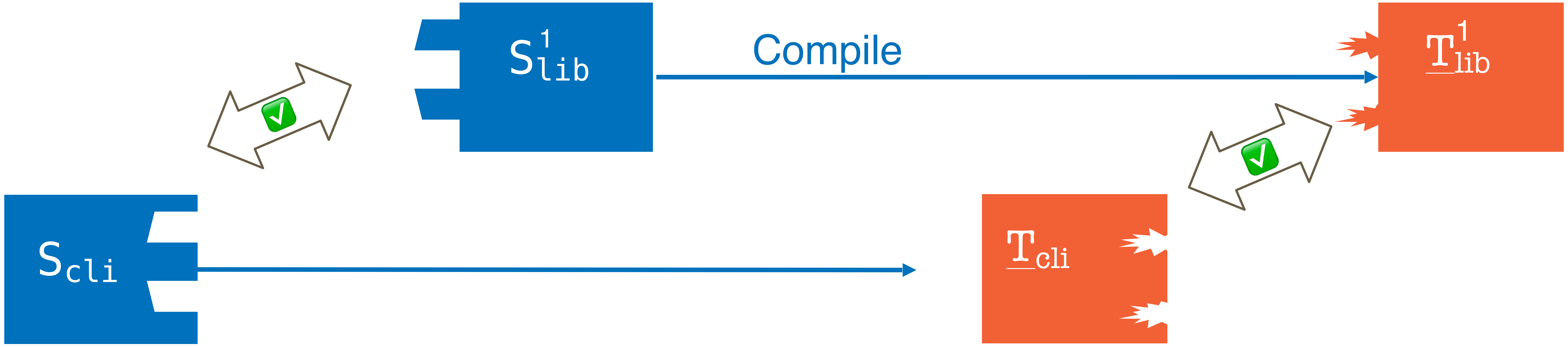
No reordering

$$\text{struct Point}\ \{x:\mathbb{Z}, y:\mathbb{Z}\} \overset{\text{upd}}{\nRightarrow} \text{struct Point}\ \{y:\mathbb{Z}, x:\mathbb{Z}\}$$

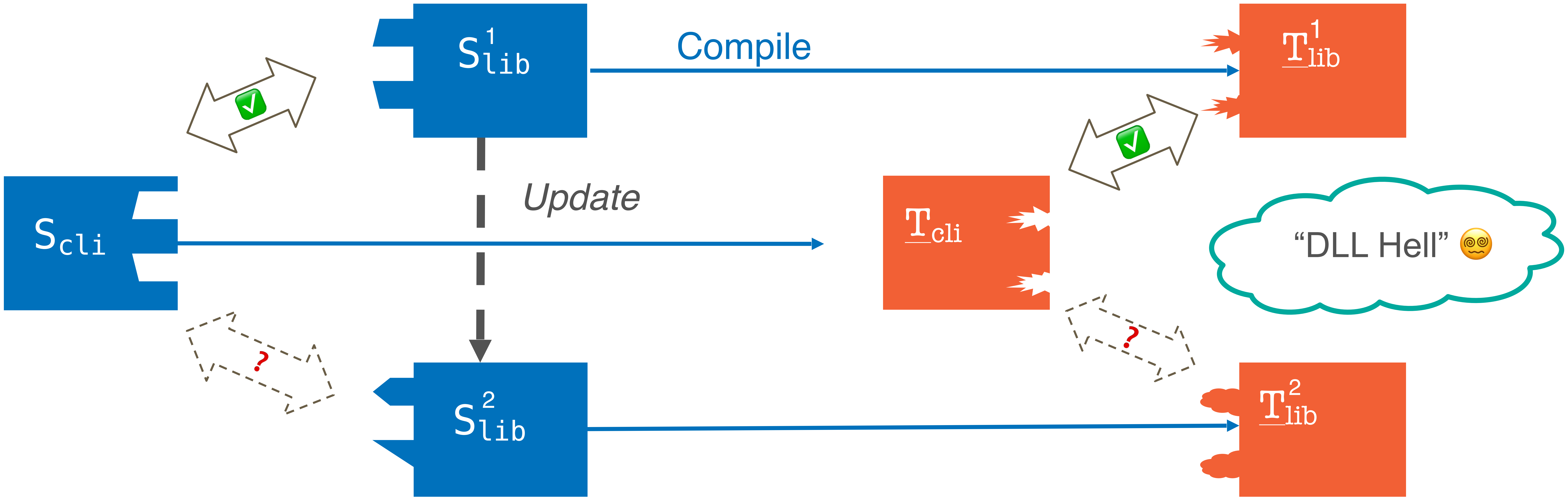
No extensibility

$$\text{struct Point}\ \{x:\mathbb{Z}, y:\mathbb{Z}\} \overset{\text{upd}}{\nRightarrow} \text{struct Point}\ \{x:\mathbb{Z}, y:\mathbb{Z}, z:\mathbb{Z}\}$$

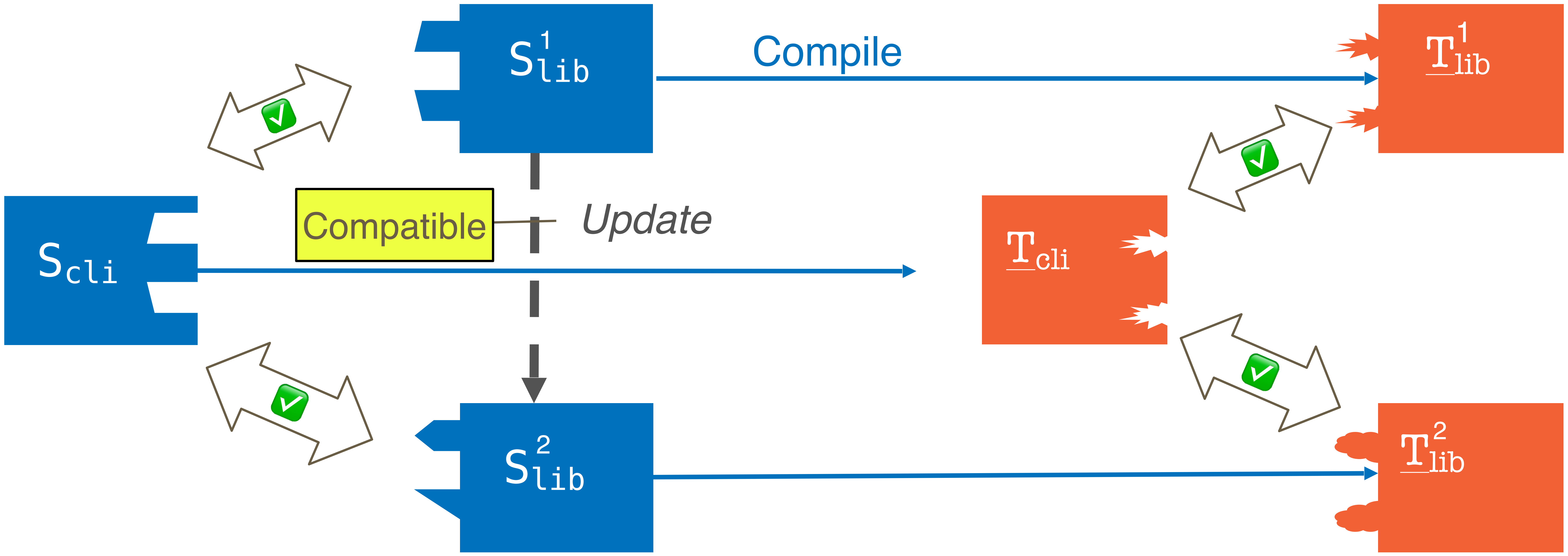
Library Evolution



Library Evolution



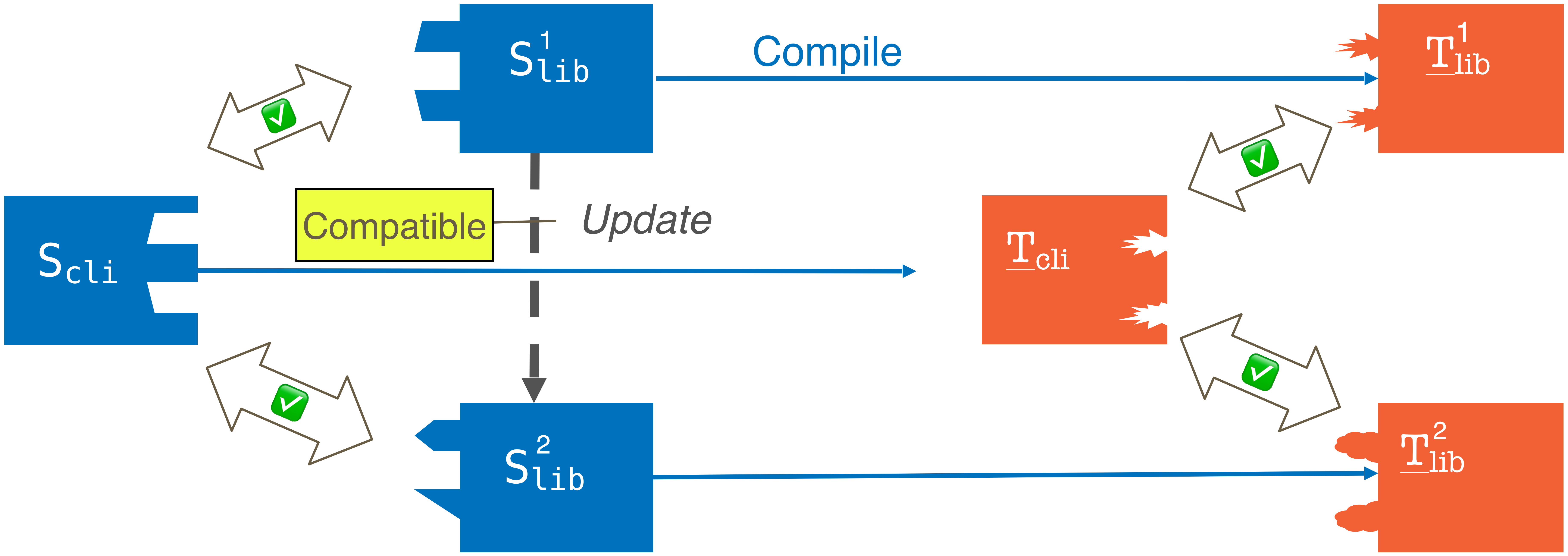
Library Evolution

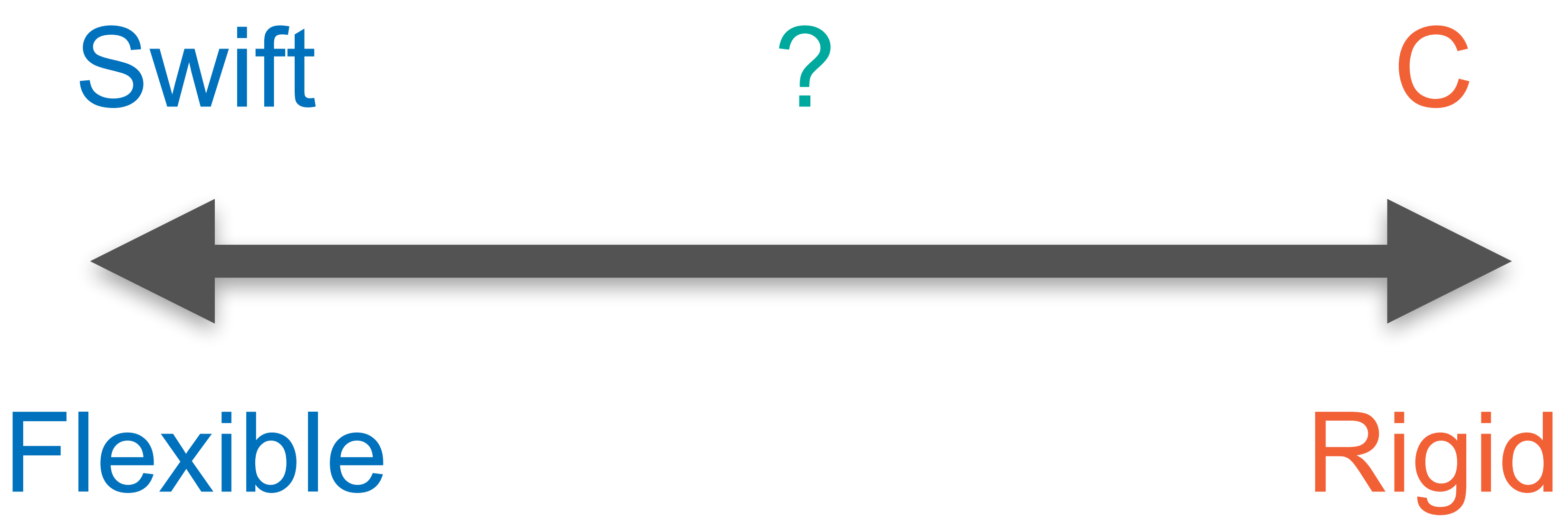


τ_2 is an **ABI compatible update** from τ_1 if

$$\llbracket \tau_2 \rrbracket \subseteq \llbracket \tau_1 \rrbracket$$

Library Evolution





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

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

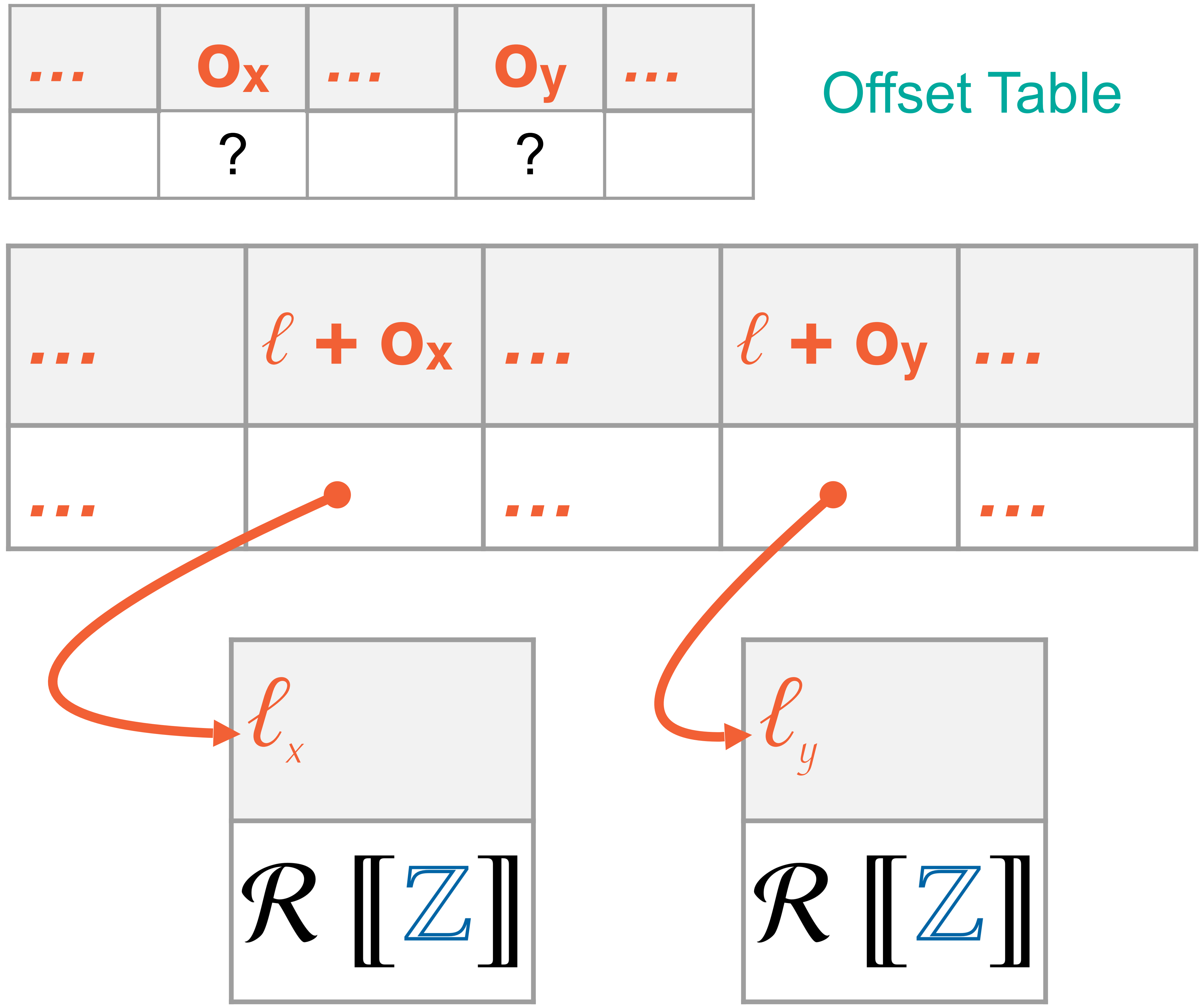
Resilient Layout

Like Swift ABI

Resilient Layout

Like Swift ABI

Client Using `Point`



Offset Table

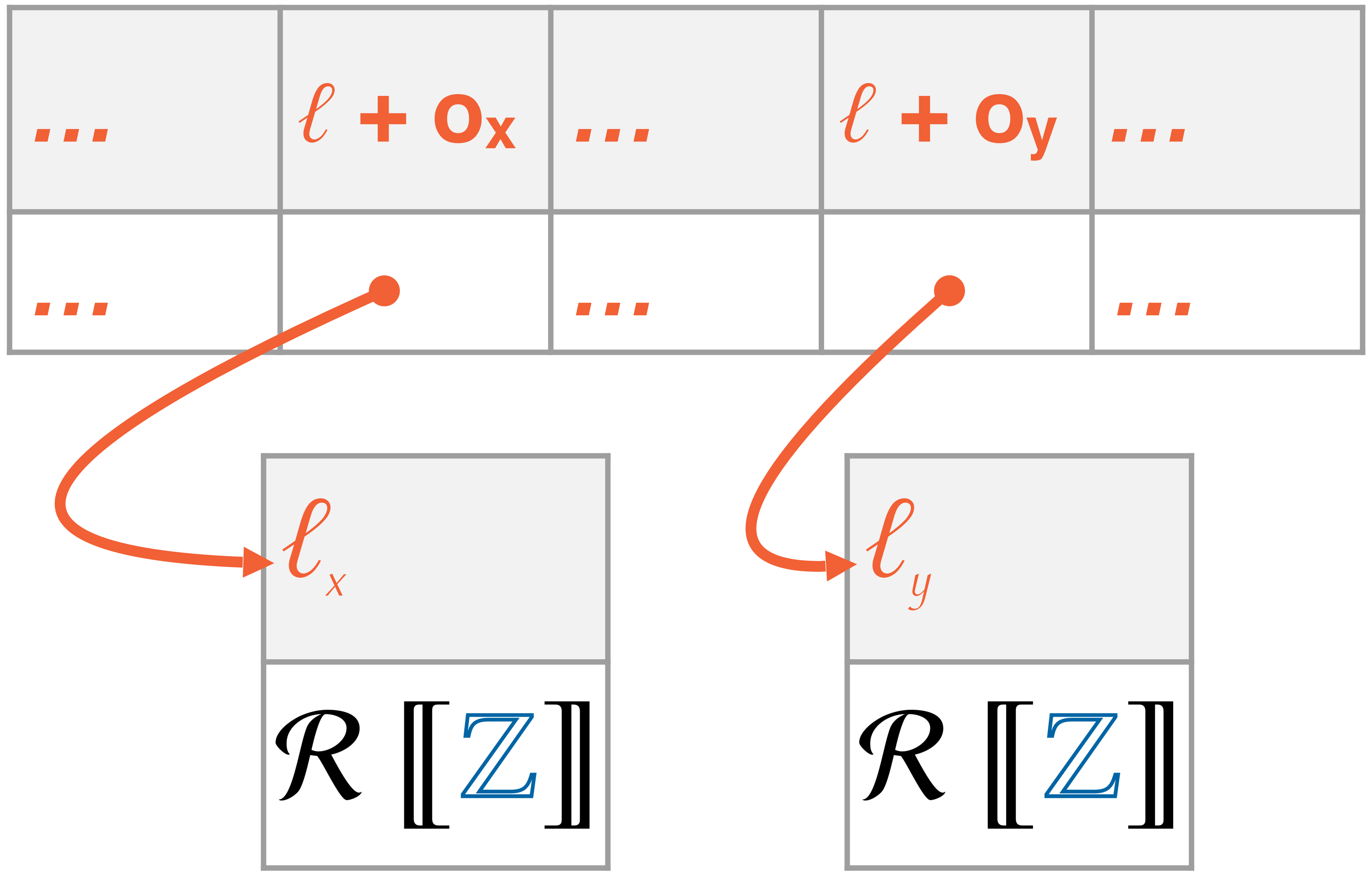
Resilient Layout

Like Swift ABI

Client Using `Point`

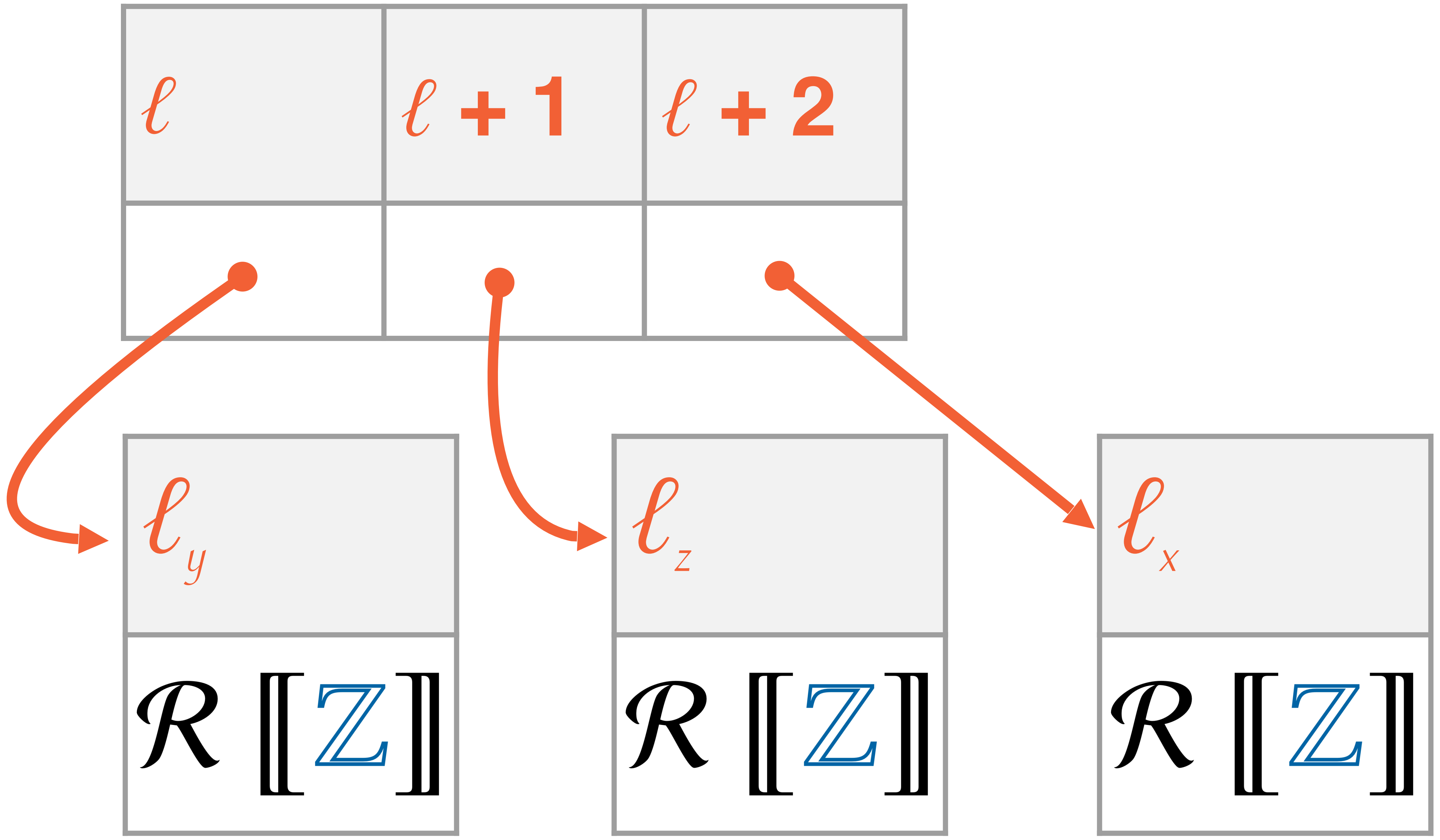
…	O_x	…	O_y	…
	?		?	

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

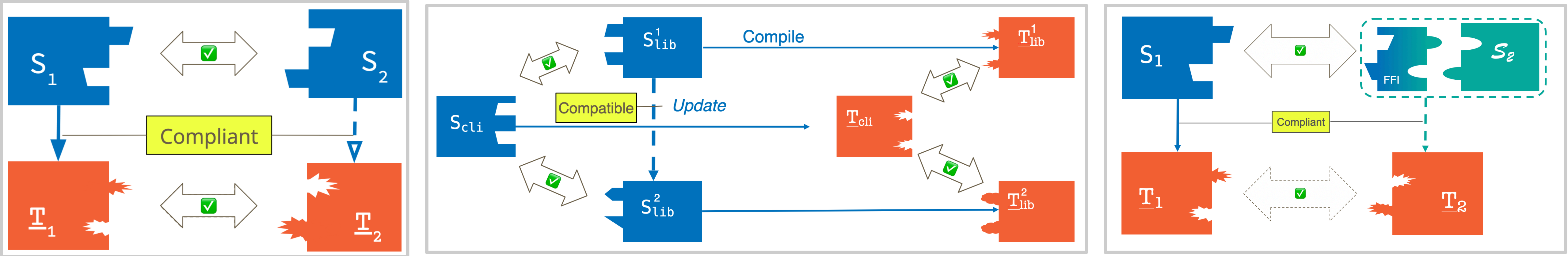
Takeaways

The Methodology

ABI Spec with Realistic Realizability

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

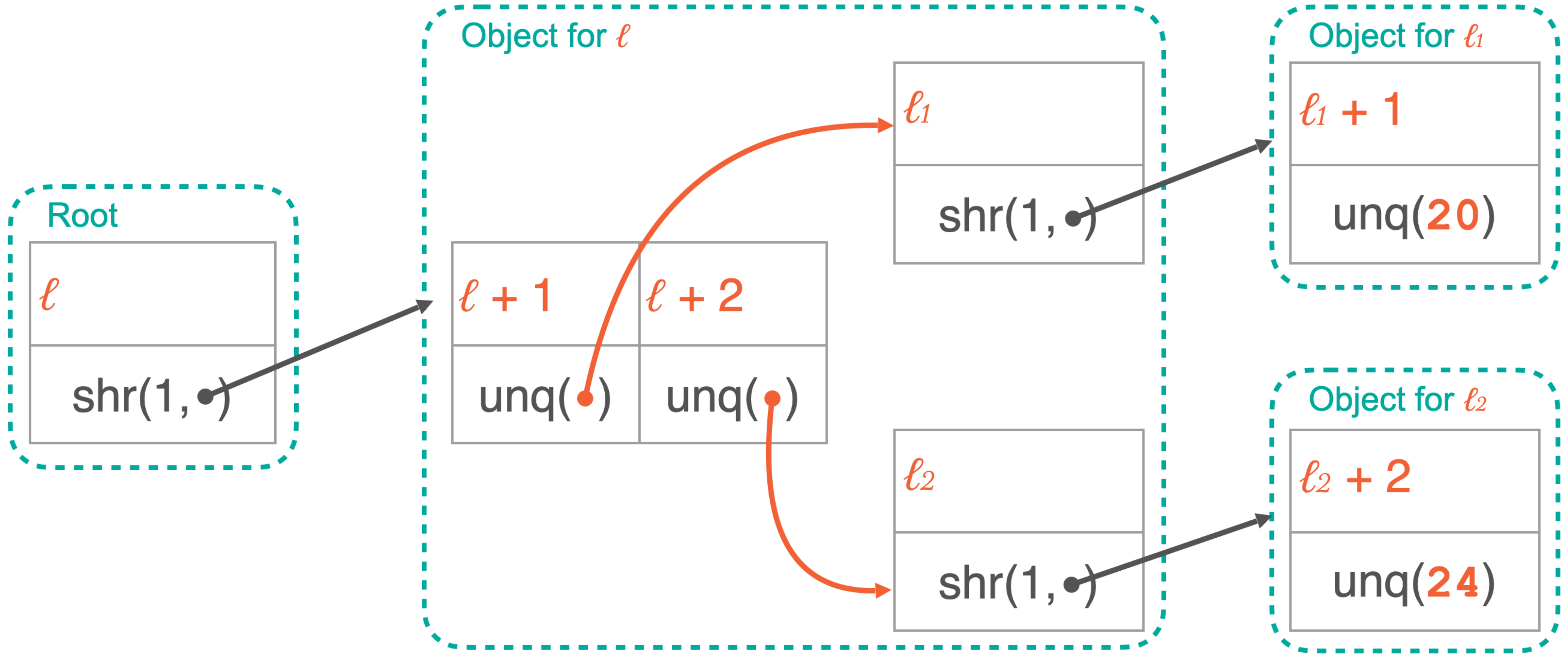
Compiler Compliance, Library Evolution, FFI Safety*



The Case Study

Graph-Based Resources for RC

$@_\ell P \quad \diamond P$



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