Compositional Compiler Correctness and Secure Compilation

Where we are & where we want to be

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Northeastern University & Inria Paris

Compiler Verification since 2006…

Leroy '06 : Formal certification of a compiler back-end or: programming a compiler with a proof assistant.

Lochbihler '10 : Verifying a compiler for Java threads.

Myreen '10 : Verified just-in-time compiler on x86.

Sevcik et al.'11 : Relaxed-memory concurrency and verified compilation.

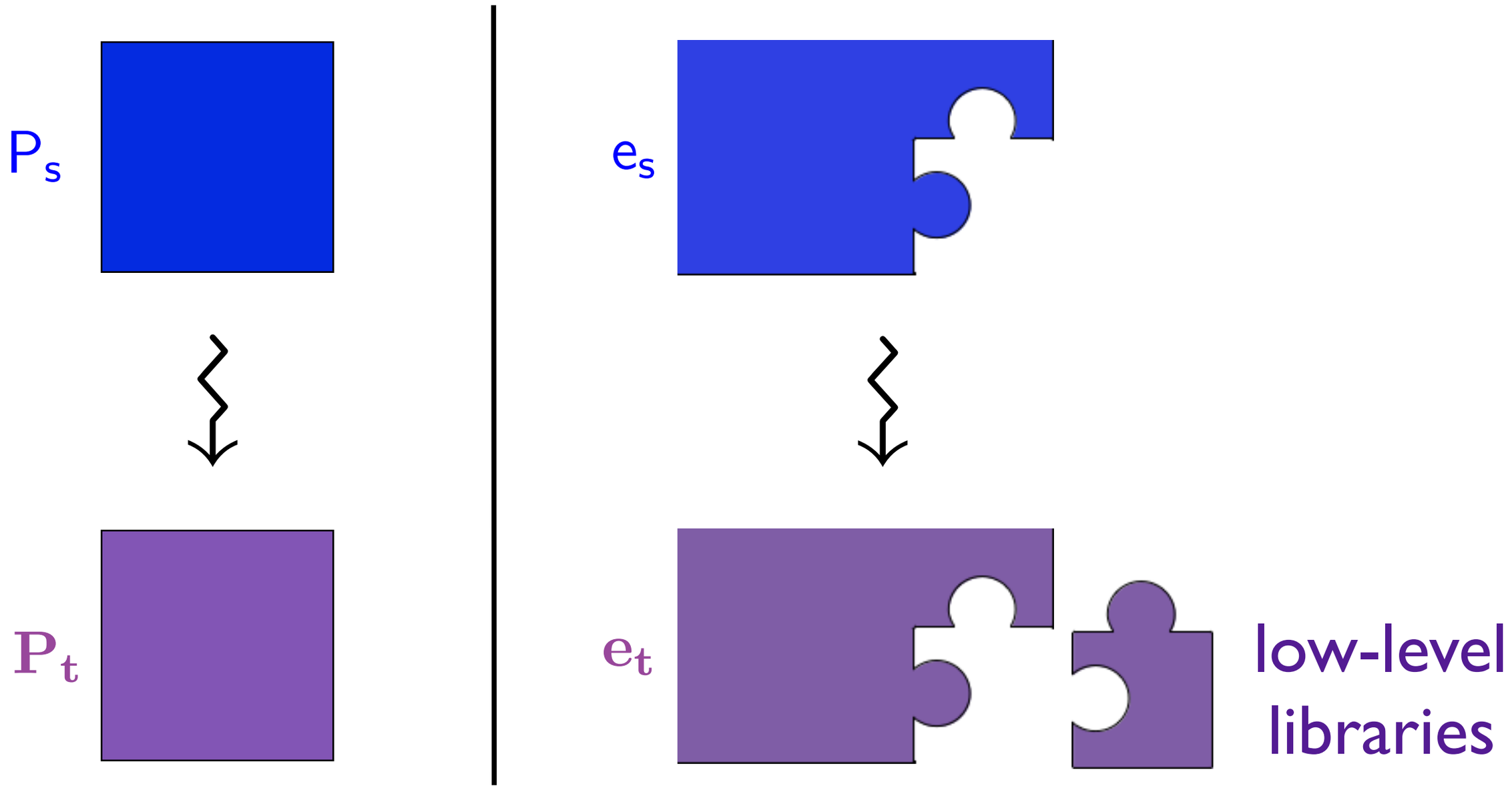
Zhao et al.'13 : Formal verification of SSA-based optimizations for LLVM

Kumar et al.'14 : CakeML: A verified implementation of ML

⋮

Problem: Whole-Program Assumption

Correct compilation guarantee only applies to whole programs!



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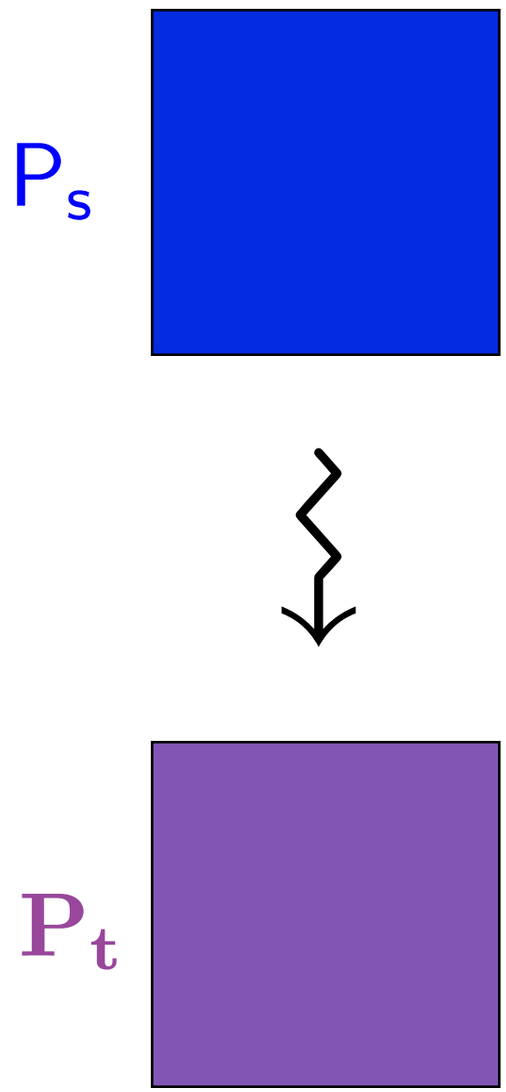
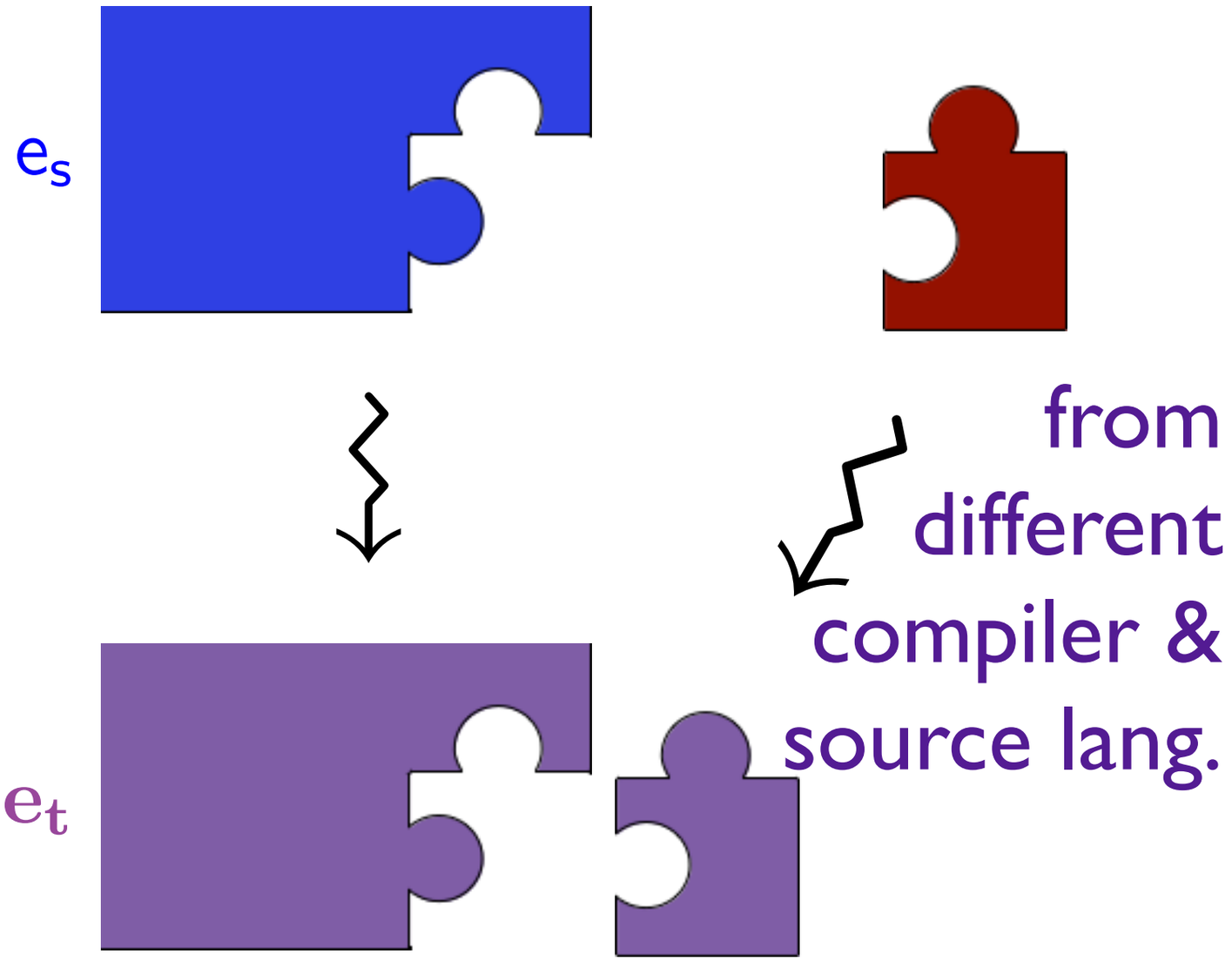
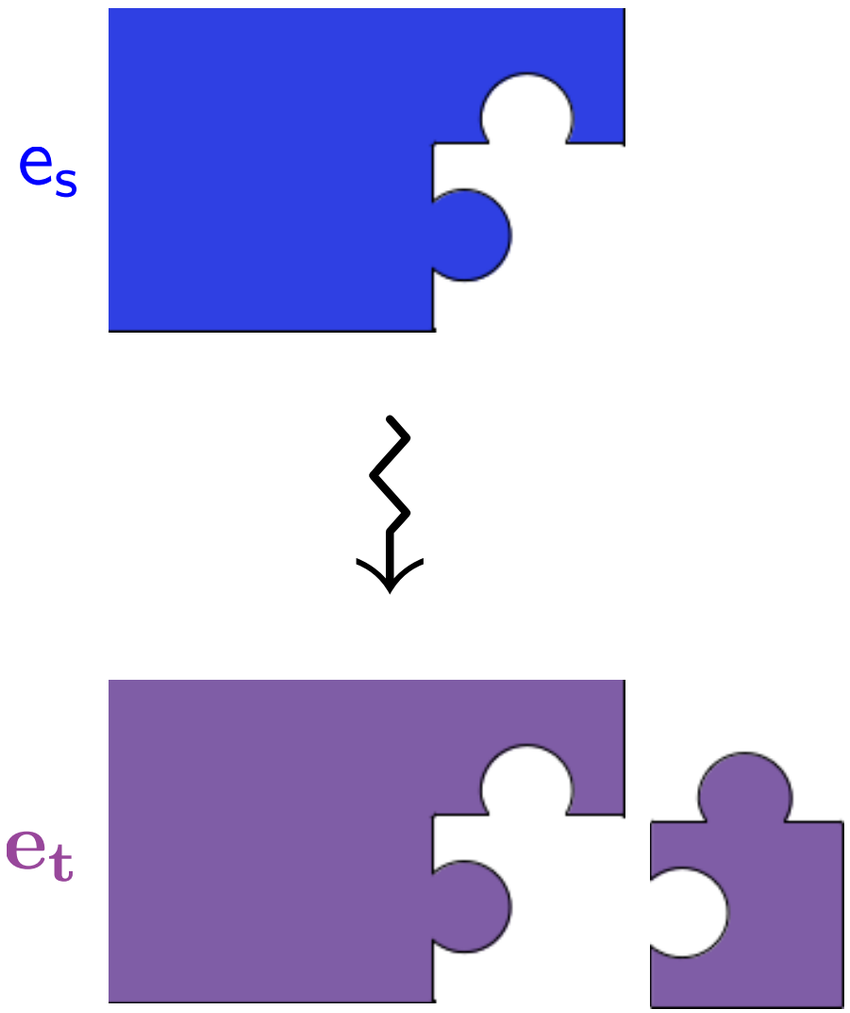




“Compositional” Compiler Verification



This Talk…

- why specifying compositional compiler correctness is hard
- survey recent results
- generic CCC theorem and lessons for formalizing linking & verifying multi-pass compilers

Compiler Correctness

$$s \rightsquigarrow t \implies s \approx t$$

compiles to

behave the same

Compiler Correctness

$$s \rightsquigarrow t \implies s \approx t$$

expressed how?

Whole-Program Compiler Correctness

$$P_s \rightsquigarrow P_t \implies P_t \sqsubset P_s$$

behavior refinement

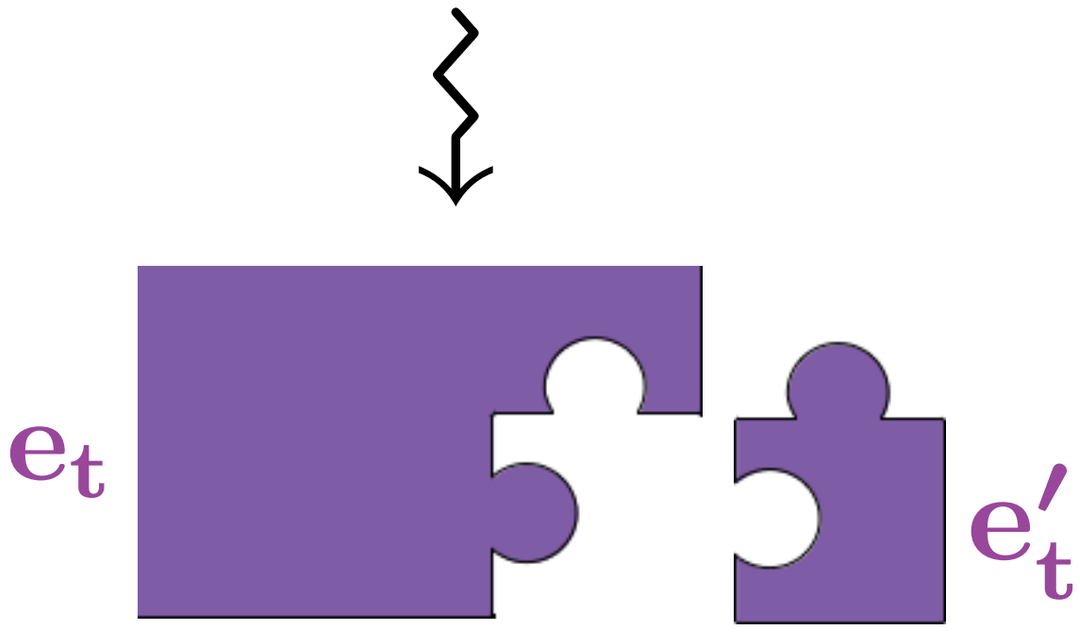
$$\forall n.\ \ P_t \overset{T_t}{\longmapsto}{}^{n}\ P_t' \implies$$

$$\exists m.\ \ P_s \overset{T_s}{\longmapsto}{}^{m}\ P_s' \ \ \wedge\ \ T_t \simeq T_s$$

Correct Compilation of Components?

$e_S \approx e_T$

expressed how?



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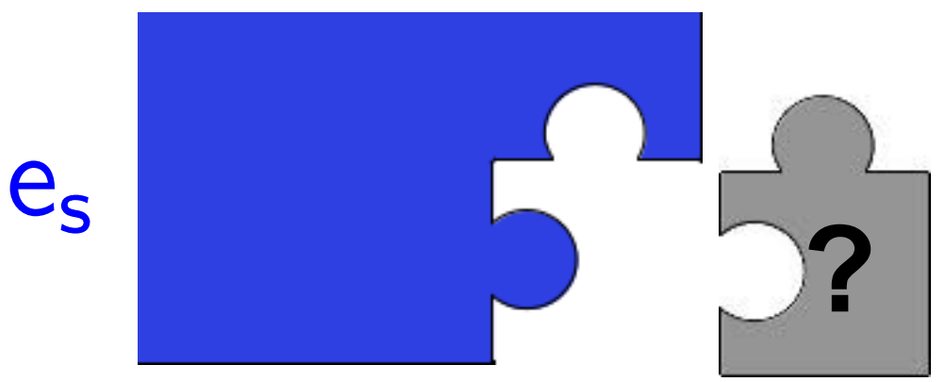
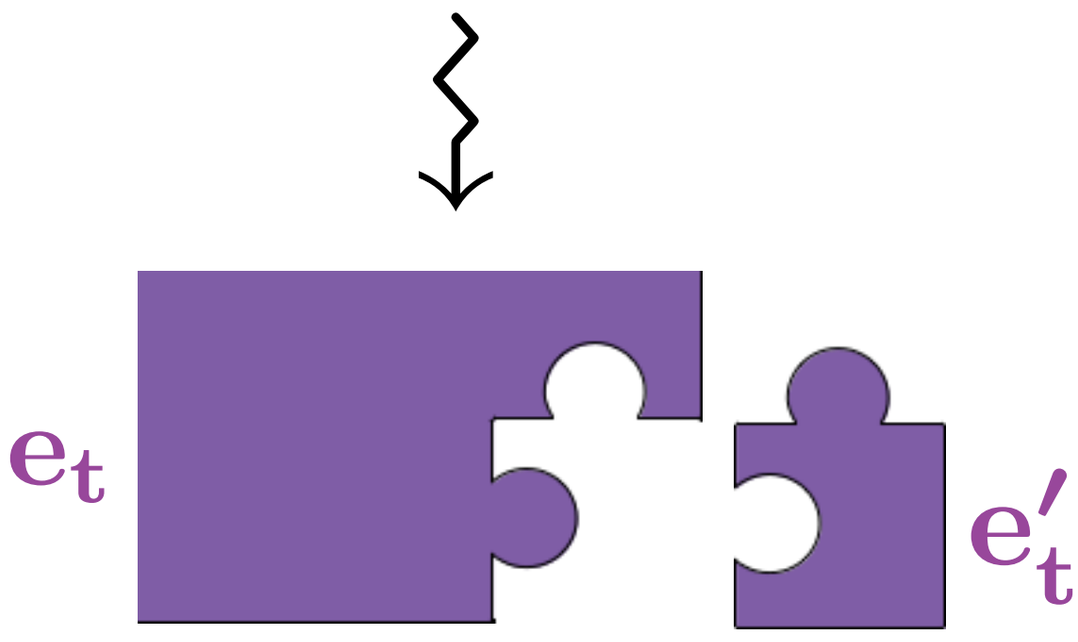
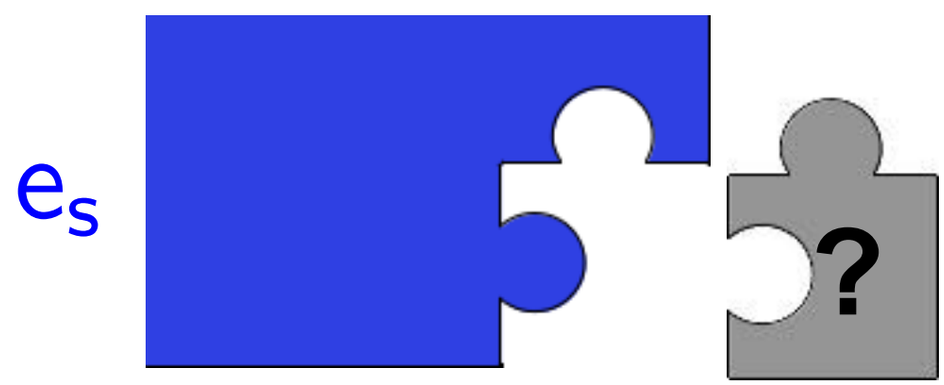


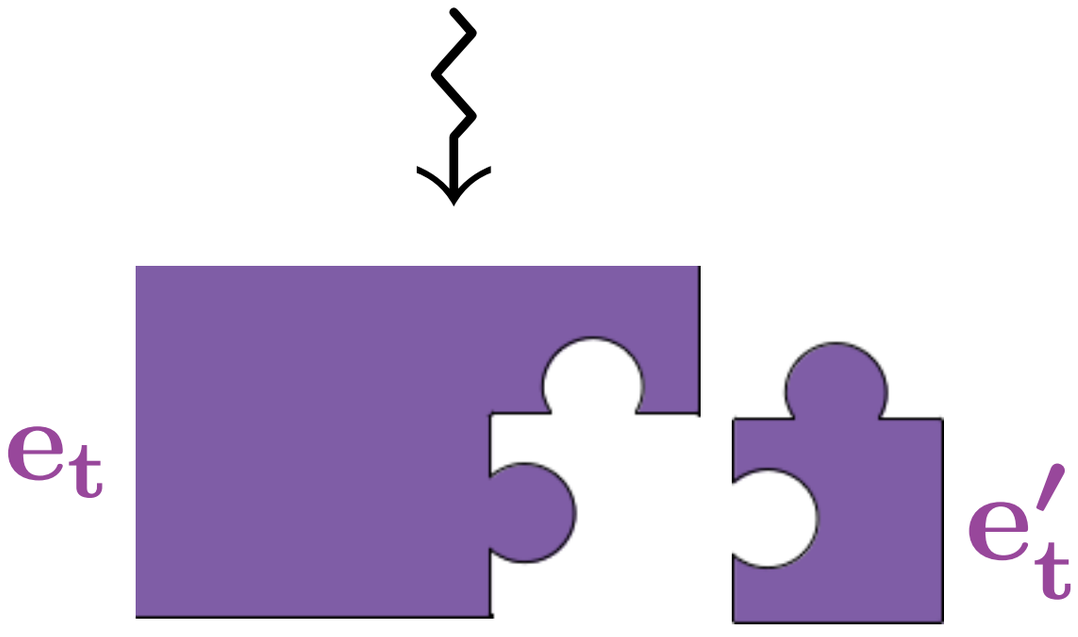


$e_S \approx e_T$

expressed how?

“Compositional” Compiler Correctness





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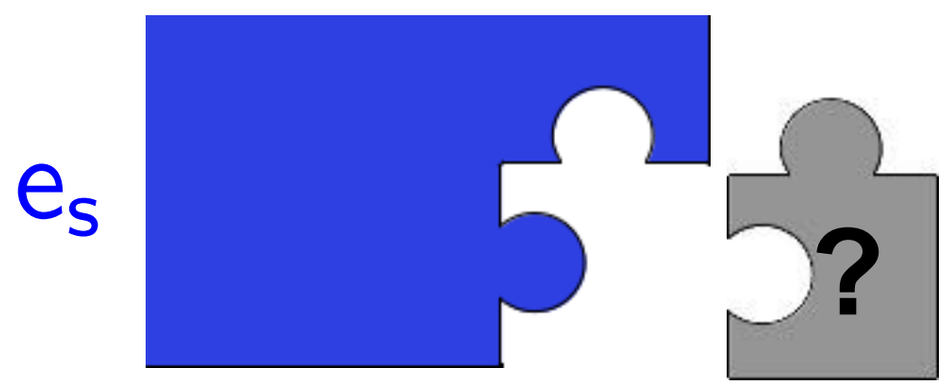
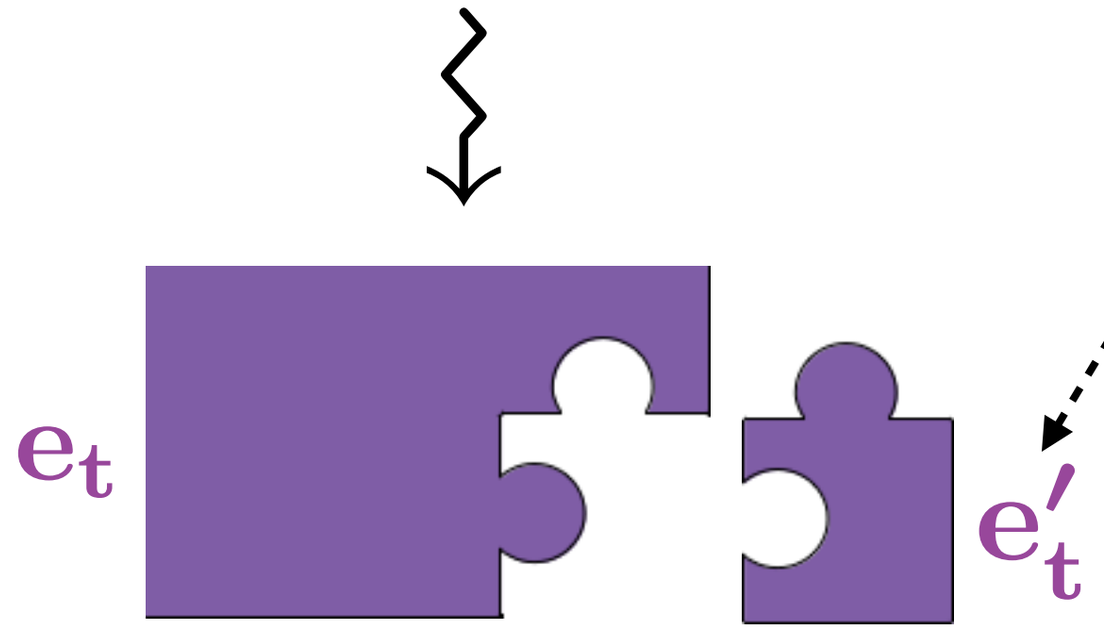
expressed how?

“Compositional” Compiler Correctness





$e_S \approx e_T$

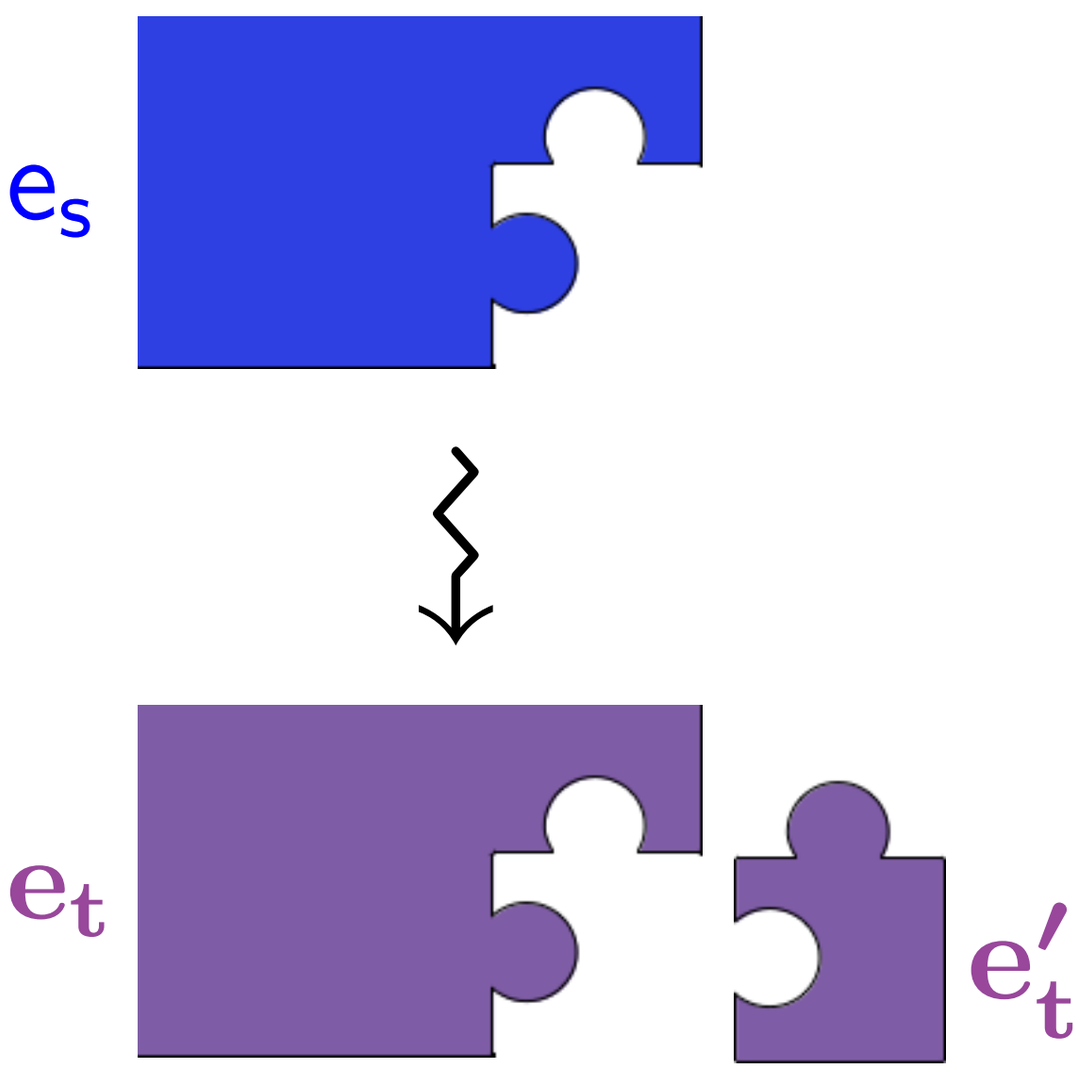
expressed how?

Produced by
- *same compiler,*
- *diff compiler for S,*
- *compiler for diff lang R,*
- *R that’s **very** diff from S?*

Behavior expressible in S?

“Compositional” Compiler Correctness

If we want to verify realistic compilers…



$e_S \approx e_T$

Definition should:

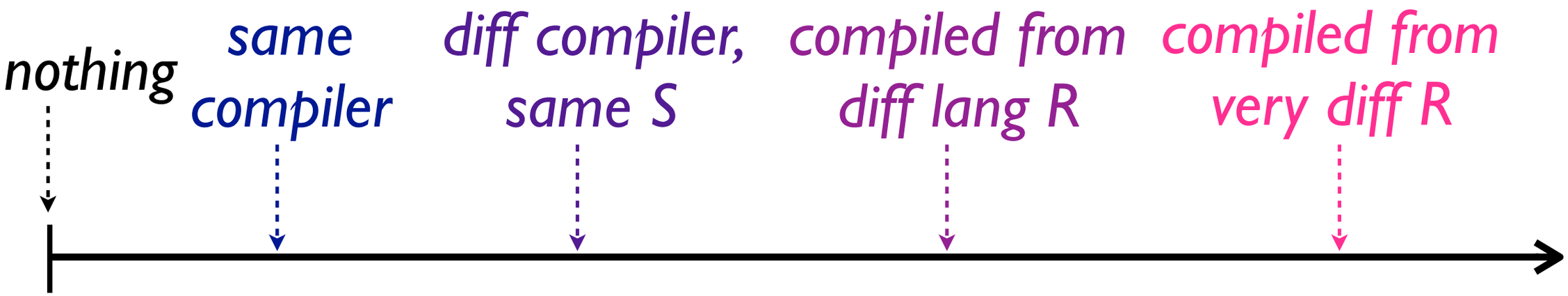
- permit **linking** with target code of arbitrary provenance
- support verification of **multi-pass** compilers

Next: Survey of State of the Art

- Survey of "compositional" compiler correctness results
  - how to express $e_S \approx e_T$

- How does the choice affect:
  - what we can **link** with *(horizontal compositionality)*
  - how we check if some e'_t is okay to link with
  - effort required to prove *transitivity* for **multi-pass** compilers *(vertical compositionality)*
  - effort required to have confidence in theorem statement

What we can link with



CompCert

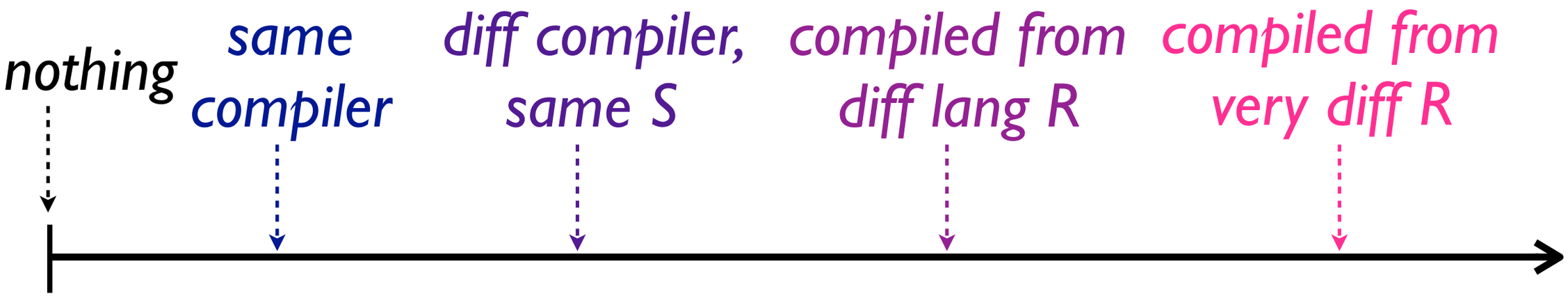
SepCompCert
Kang et al.'16

Pilsner
Neis et al.'15

Compositional CompCert
Stewart et al.'15

Multi-language ST
Perconti-Ahmed'14

What we can link with



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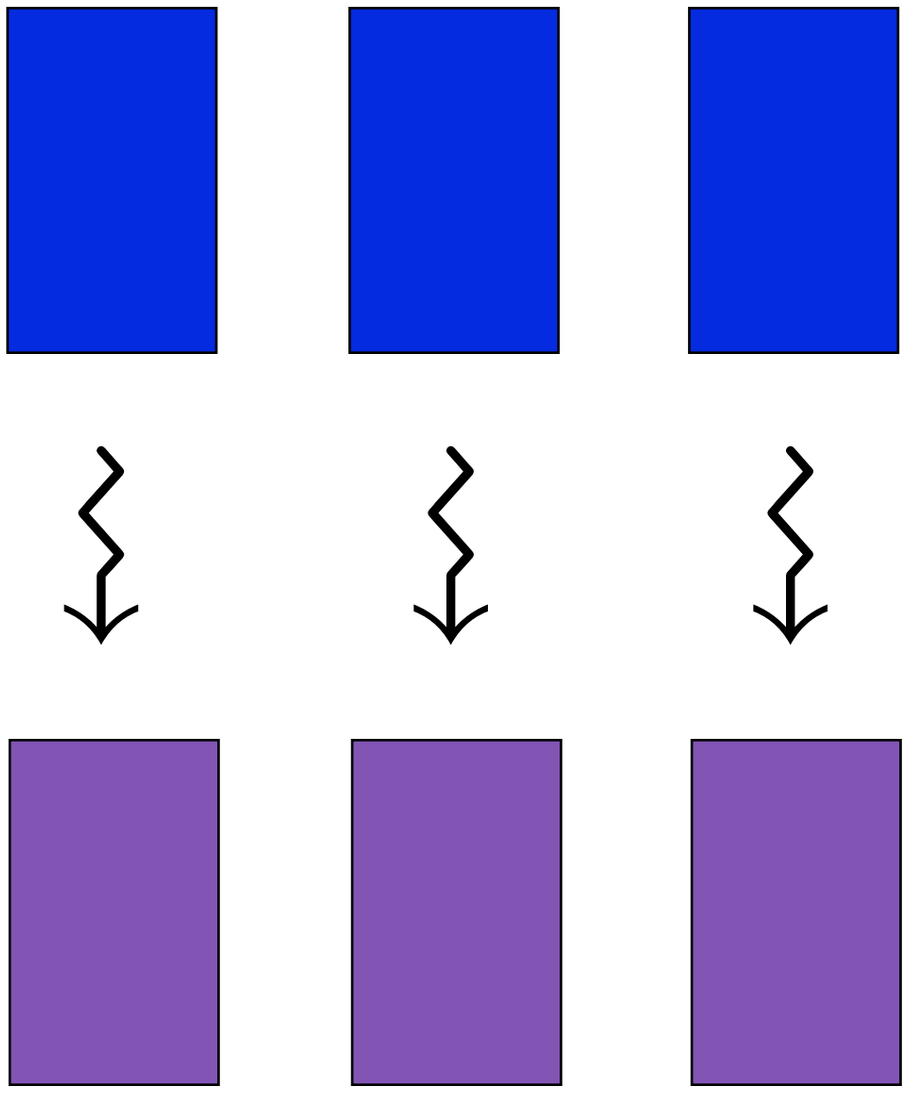
Approach: Separate Compilation

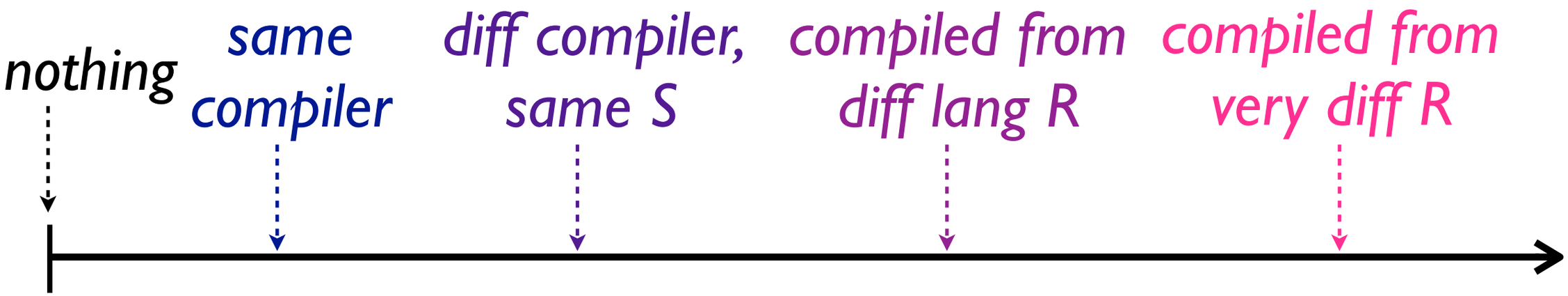
SepCompCert
[Kang et al.'16]



Level A correctness:
exactly same compiler

Level B correctness:
can omit some intra-language (RTL) optimizations

What we can link with



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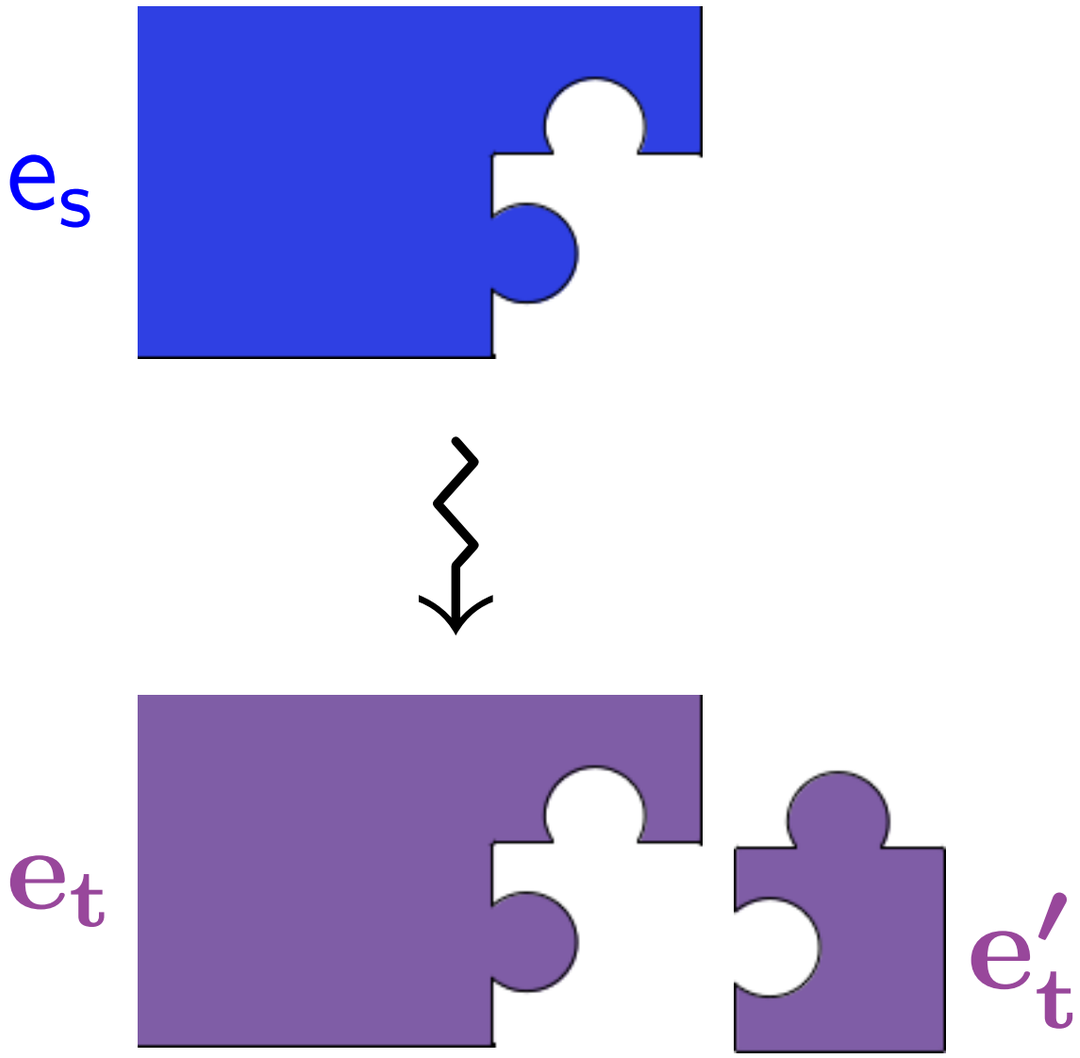
Approach: Cross-Language Relations



Cross-language relation

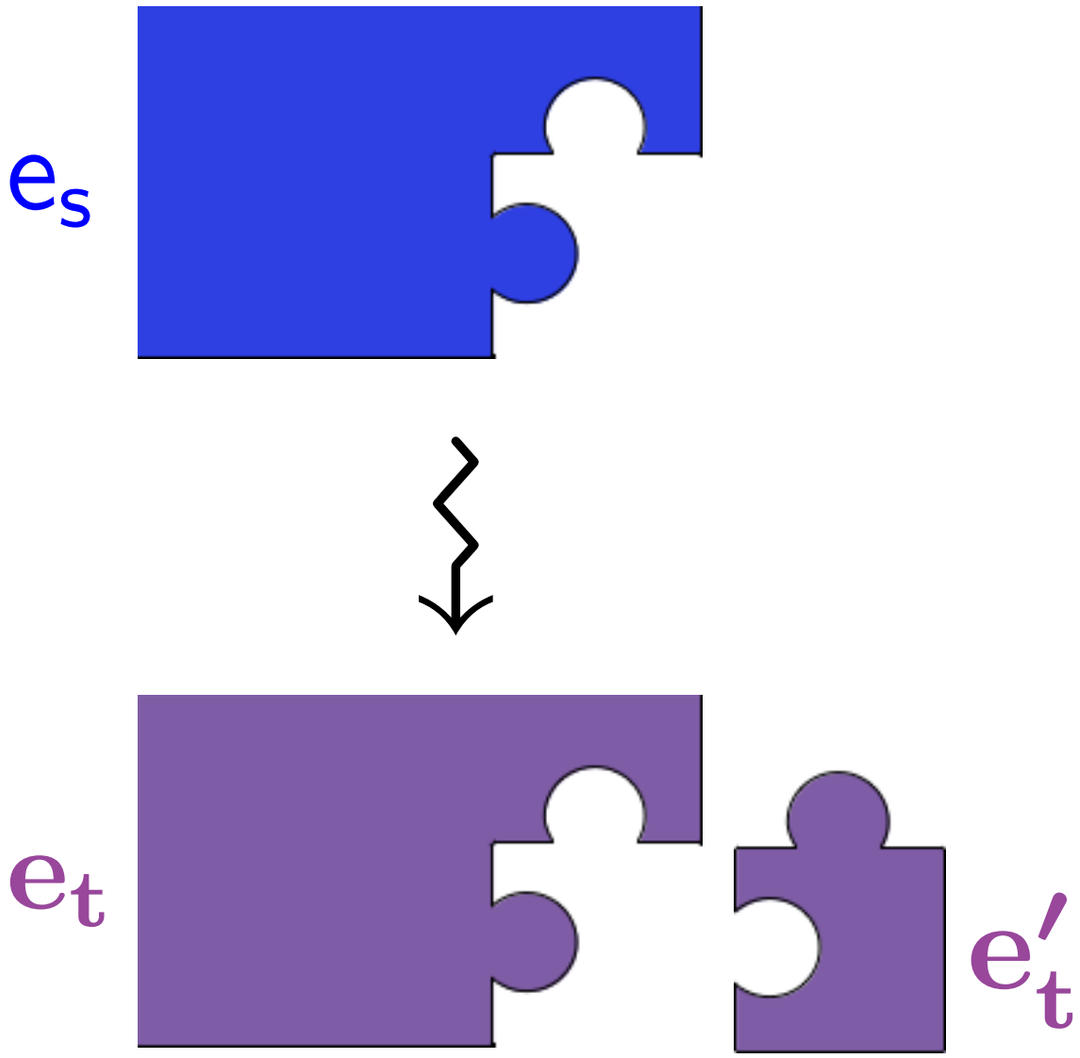
$e_S \approx e_T$

Compiling ML-like langs:

Logical relations

- *[Benton-Hur ICFP'09]*
- *[Hur-Dreyer POPL'11]*

Approach: Cross-Language Relations



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- [illegible]
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No transitivity!

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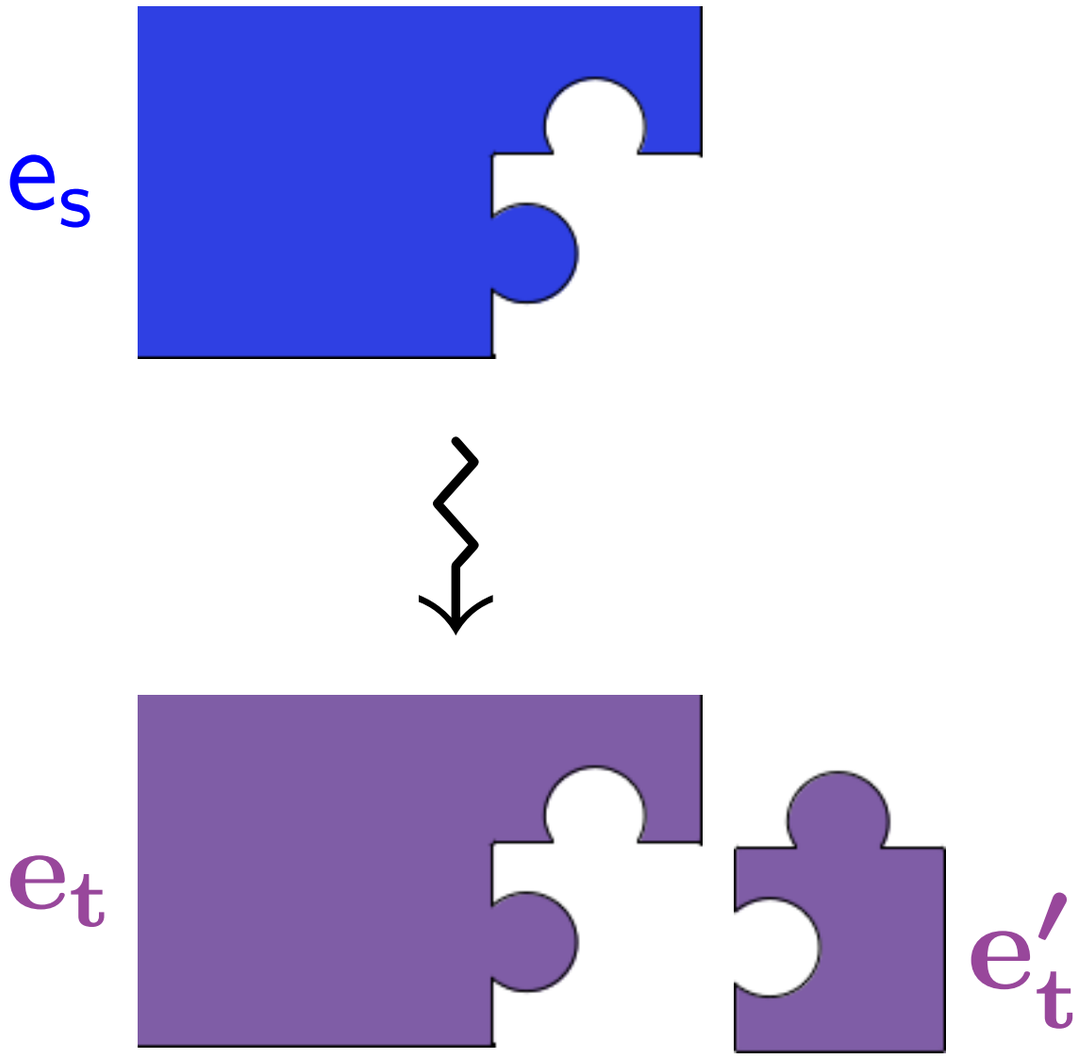

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Parametric inter-language simulations (PILS)

- *[Neis et al. ICFP'15]*

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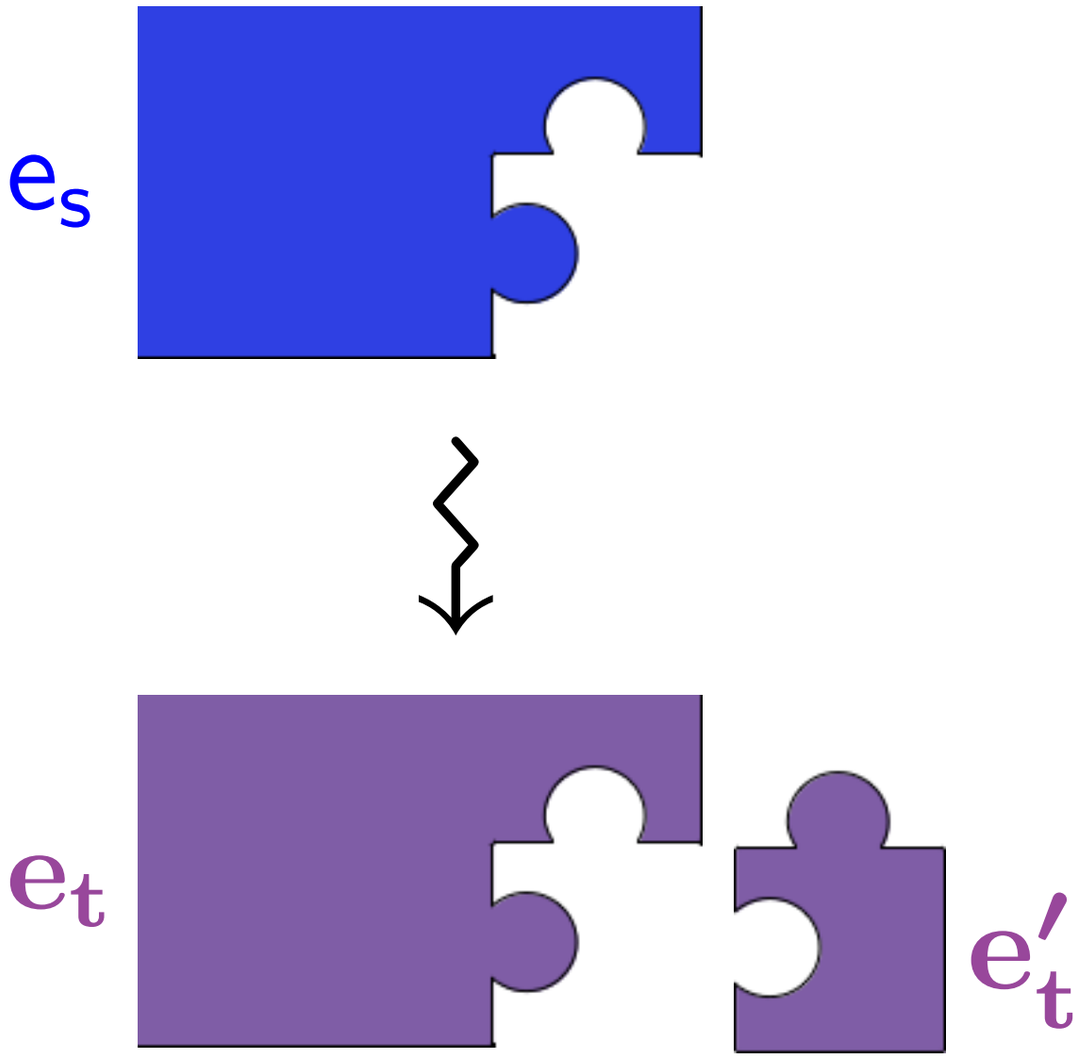

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Logical relations

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No transitivity!

Parametric inter-language simulations (PILS)

- [illegible]

Prove transitivity, but requires effort!

Cross-Language Relation (Pilsner)

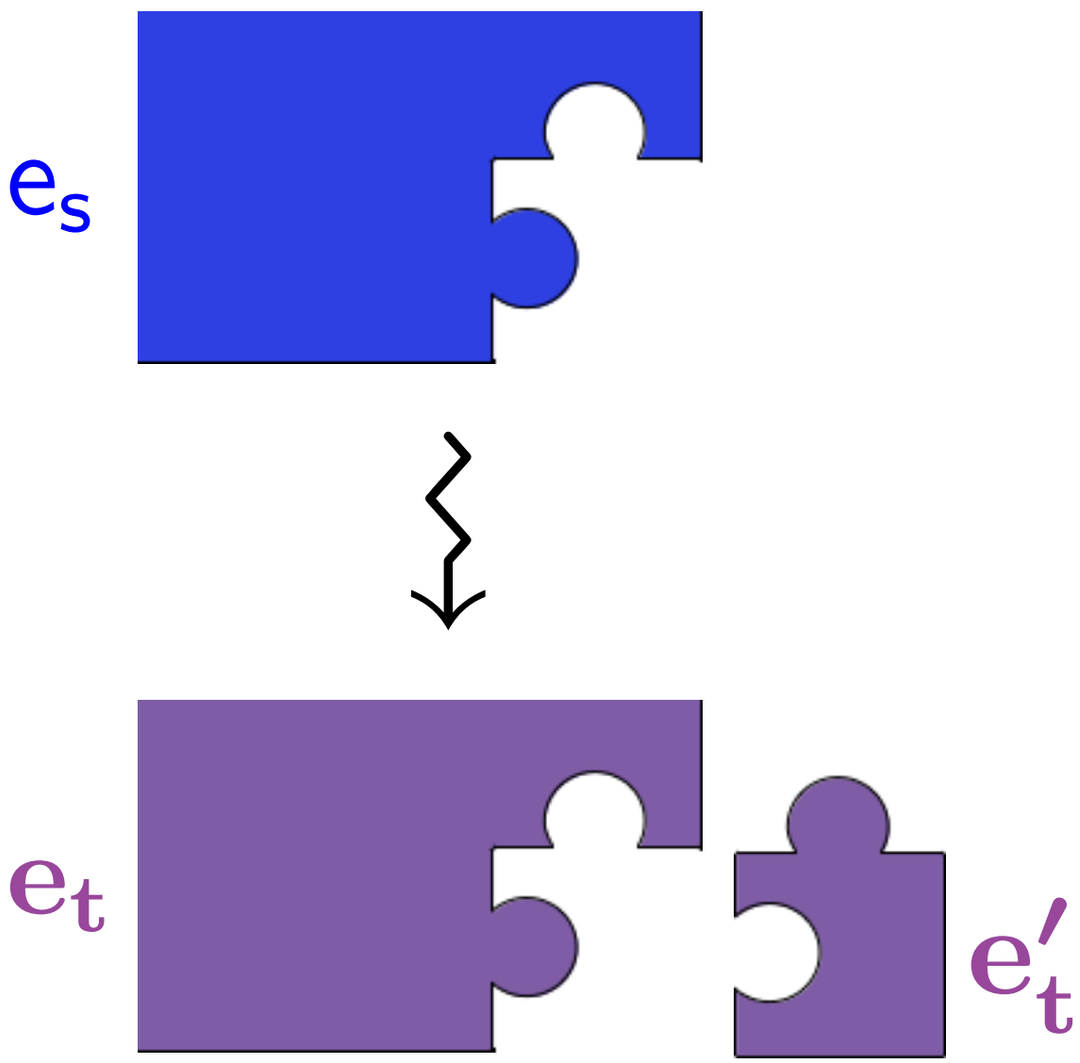
$$\mathsf{x} : \tau' \vdash \mathsf{e_s} : \tau \rightsquigarrow \mathbf{e_t} \implies \mathsf{x} : \tau' \vdash \mathsf{e_s} \simeq \mathbf{e_t} : \tau$$

cross-language relation

$$\forall \mathsf{e'_s}, \mathbf{e'_t}.\ \vdash \mathsf{e'_s} \simeq \mathbf{e'_t} : \tau' \implies \vdash \mathsf{e_s}[\mathsf{e'_s}/\mathsf{x}] \simeq \mathbf{e_t}[\mathbf{e'_t}/\mathbf{x}] : \tau$$

Cross-Language Relation (Pilsner)

Have $\mathsf{x} : \tau' \vdash \mathsf{e_s} \simeq \mathbf{e_t} : \tau$



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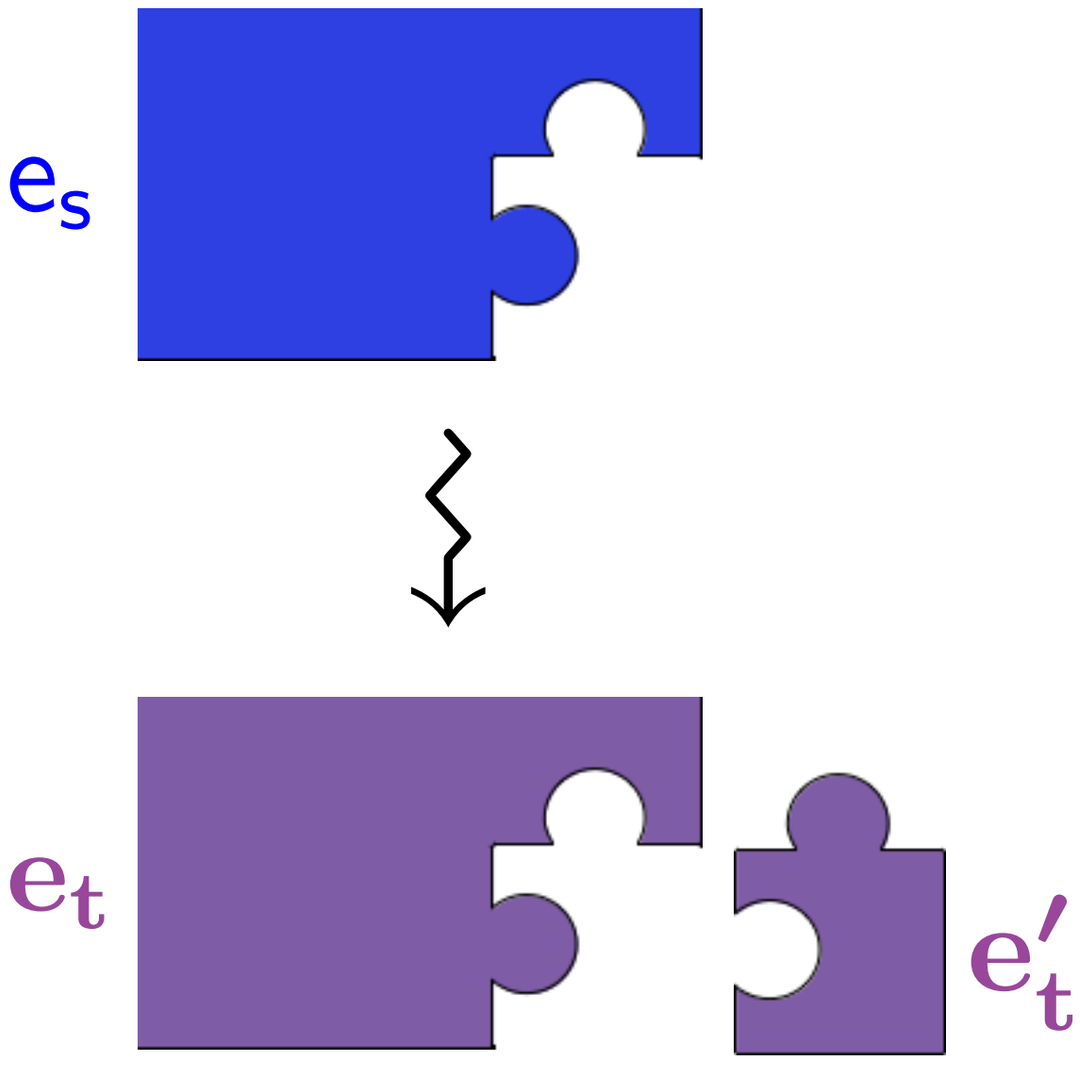

Have $x : \tau' \vdash e_s \simeq e_t : \tau$

Does the compiler correctness theorem permit linking with e'_t *?*

Cross-Language Relation (Pilsner)

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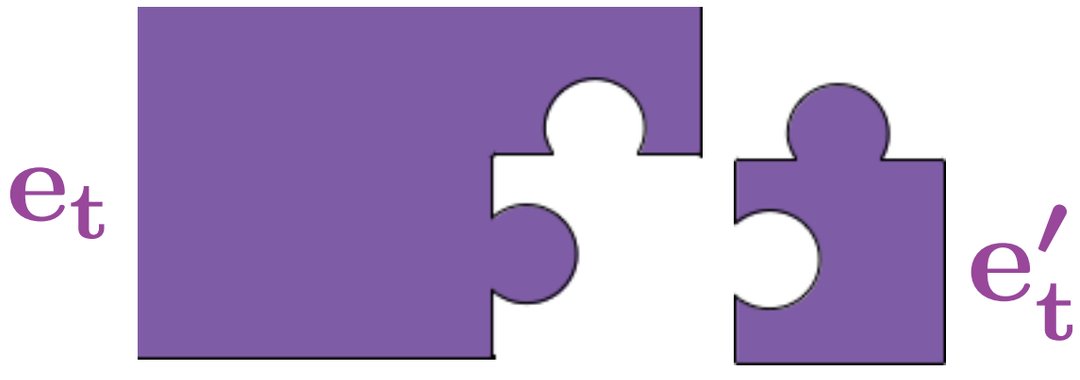

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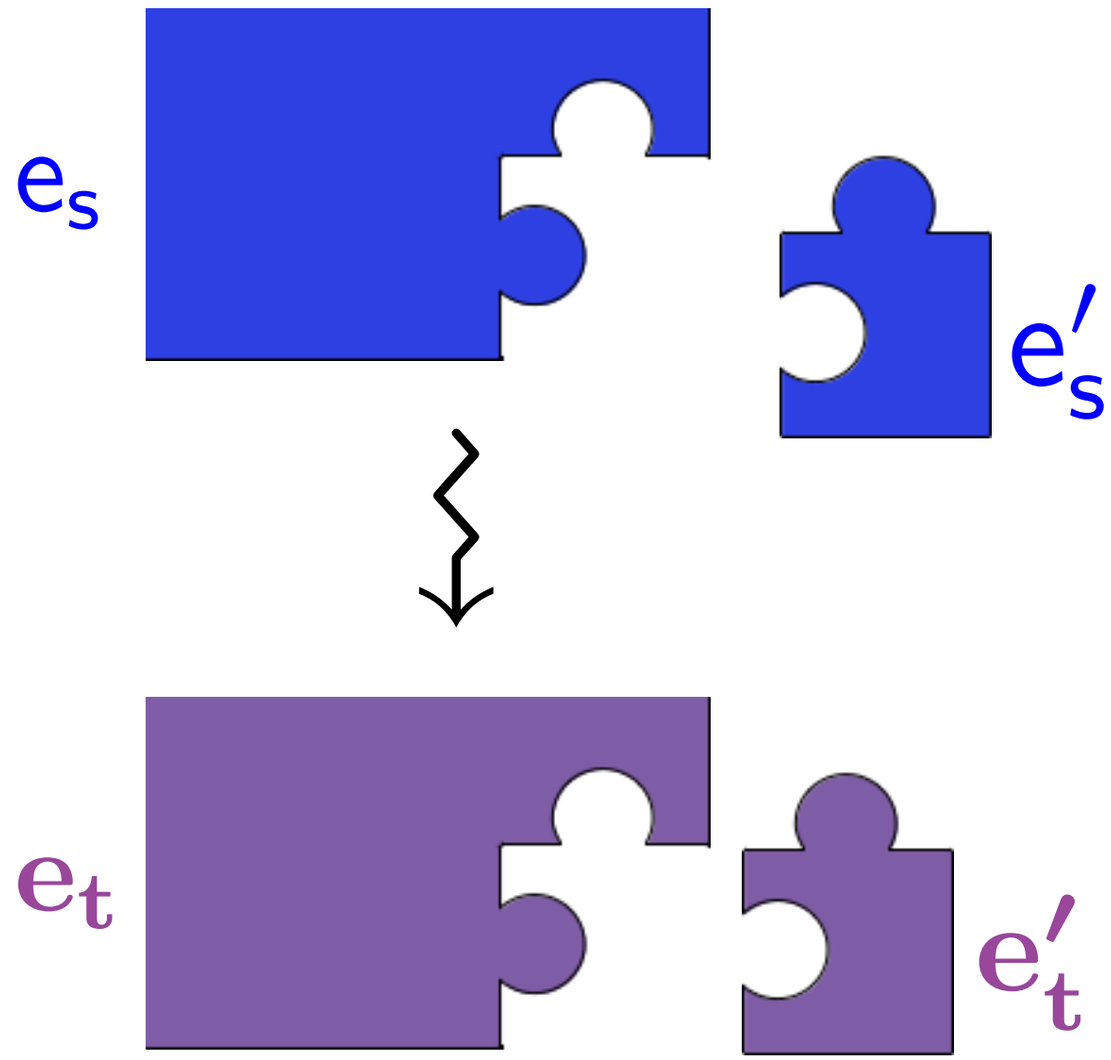

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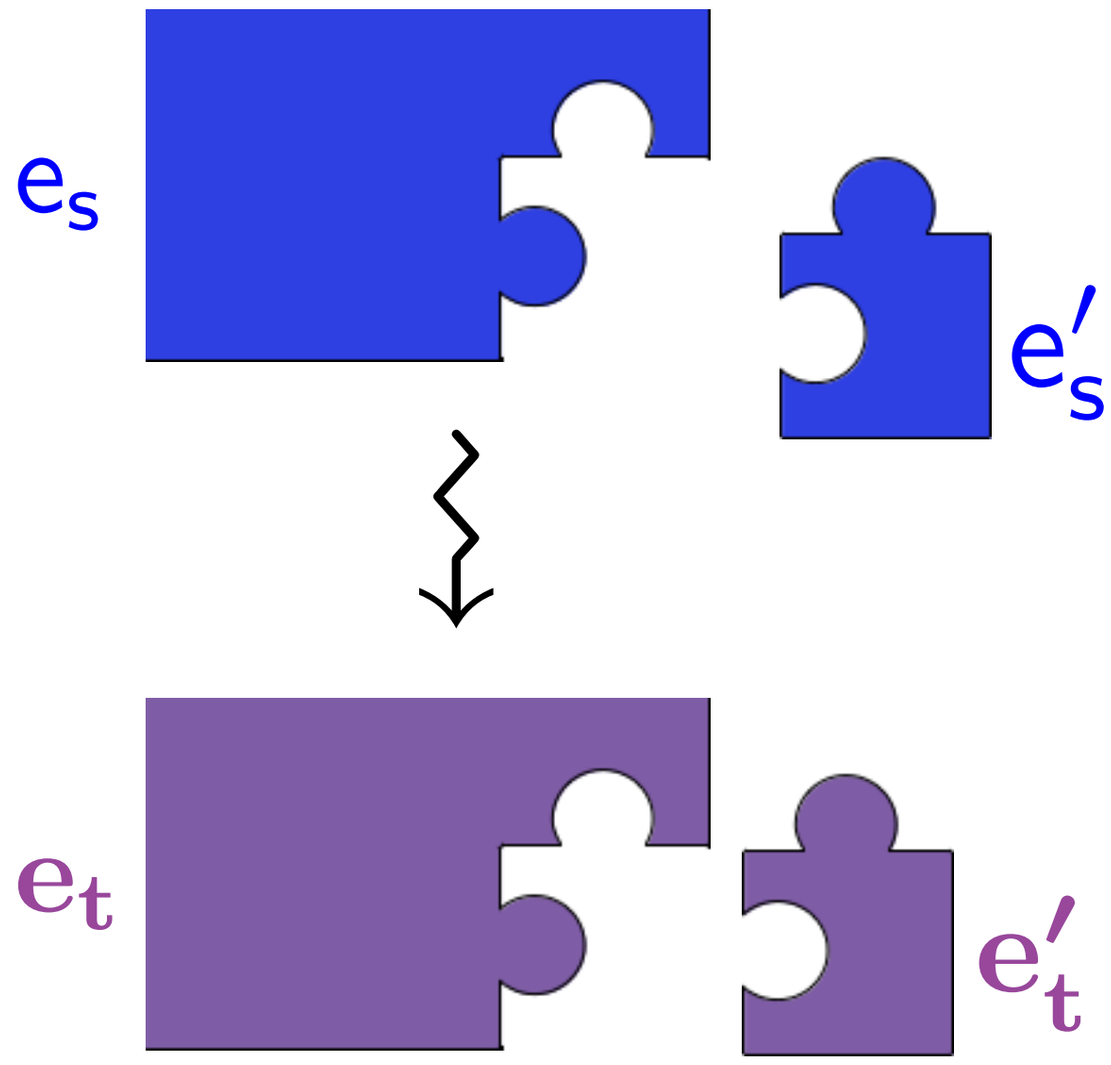

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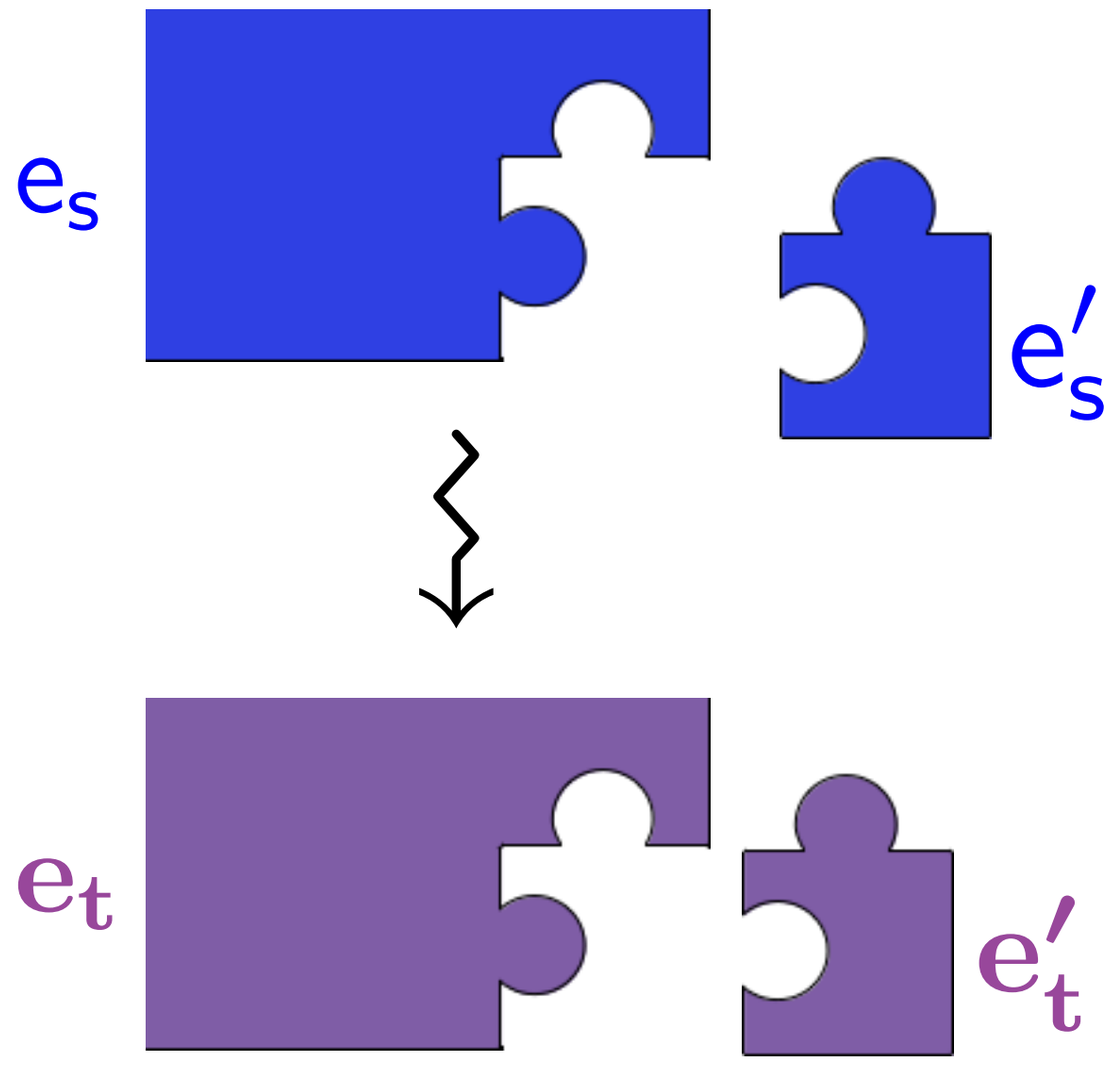

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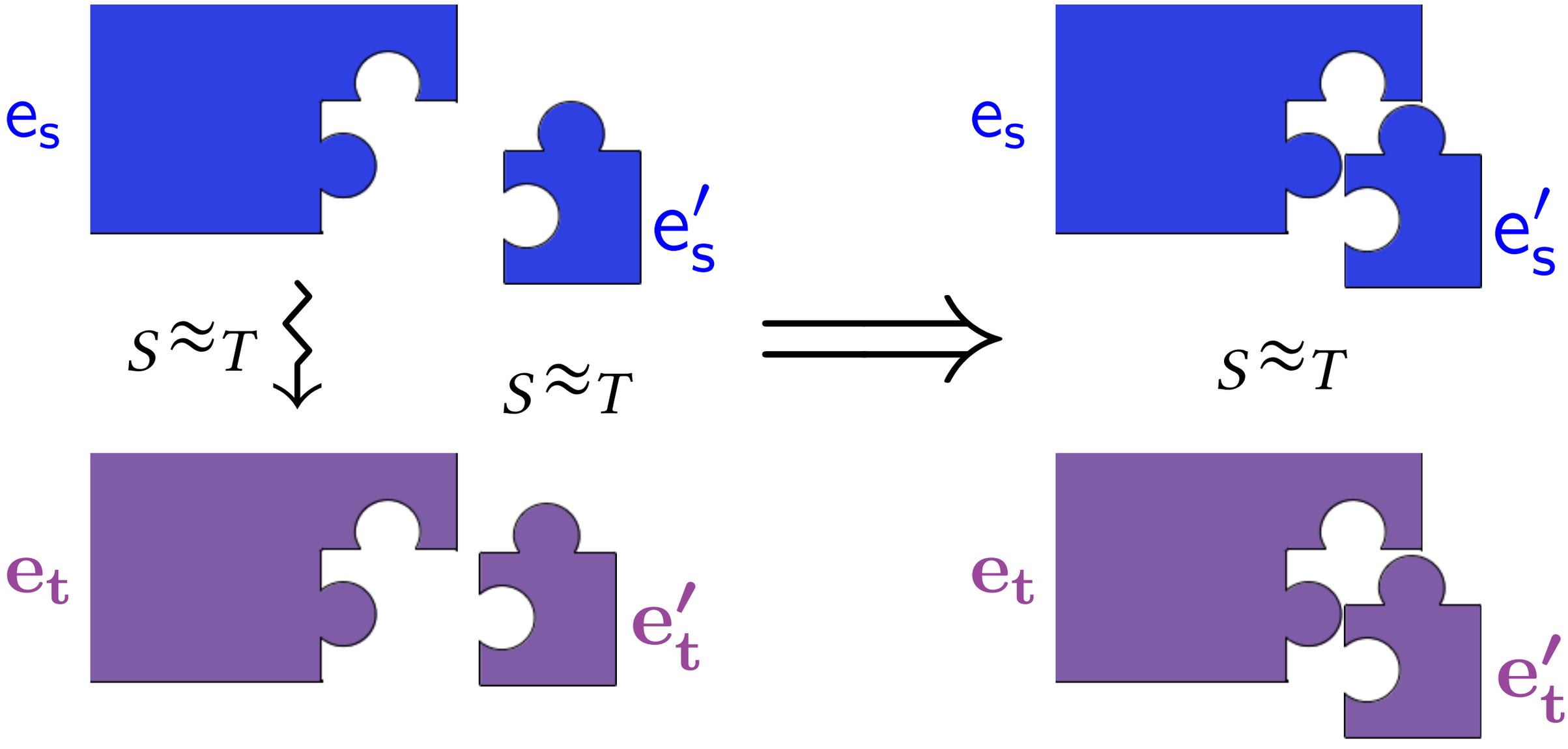
- Need to come up with e'_s -- not feasible in practice!
- Cannot link with e'_t whose behavior cannot be expressed in source.

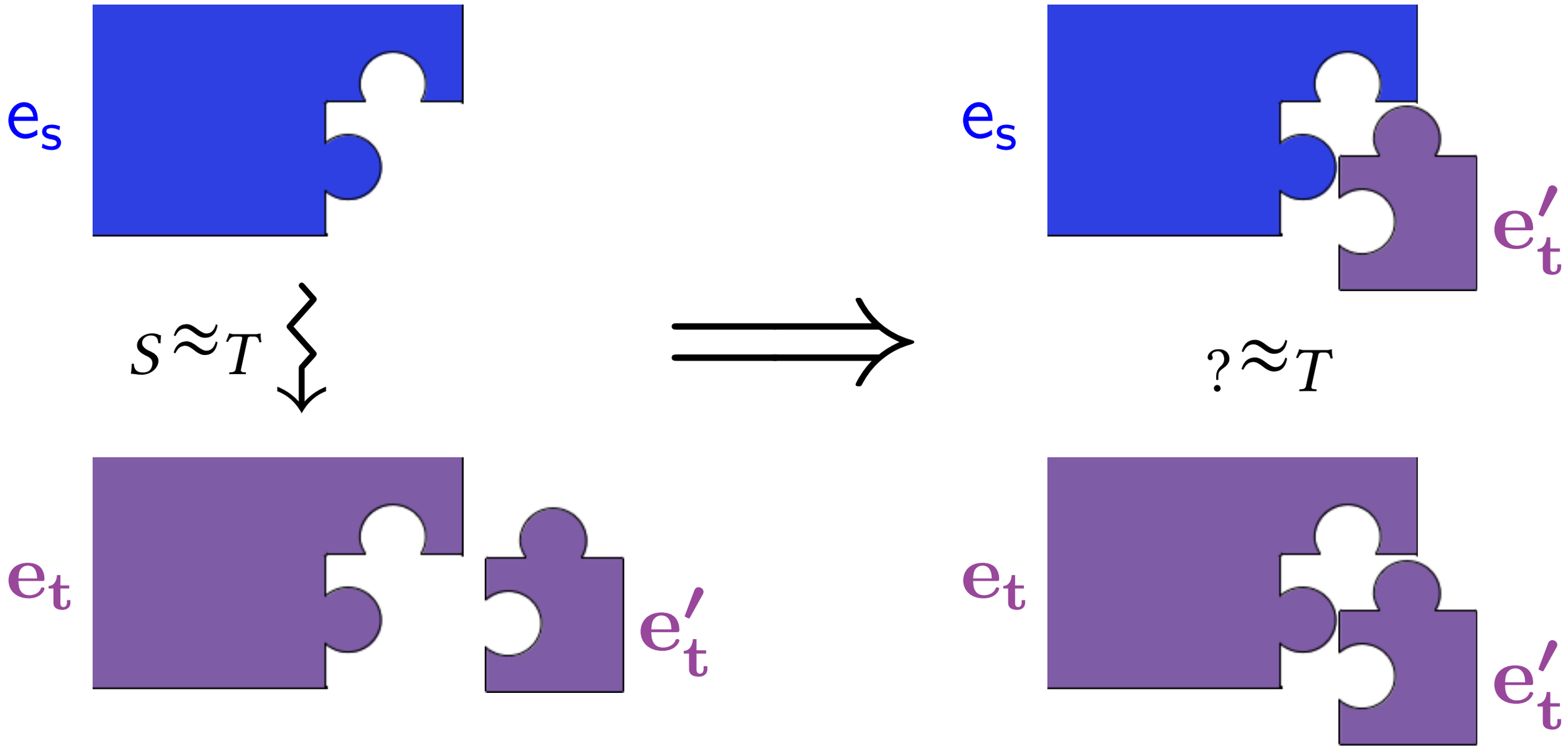
Horizontal Compositionality

Linking

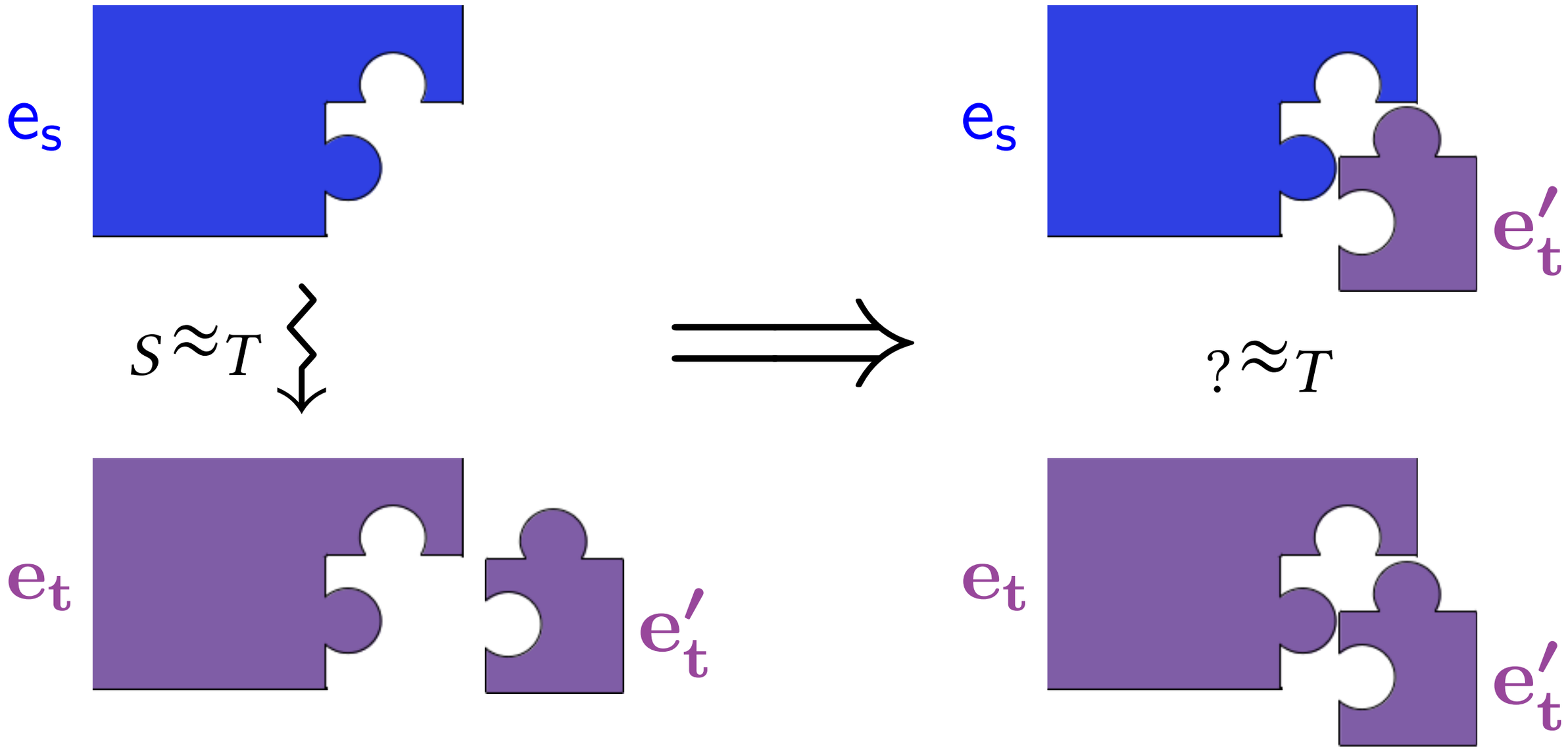
Horizontal Compositionality



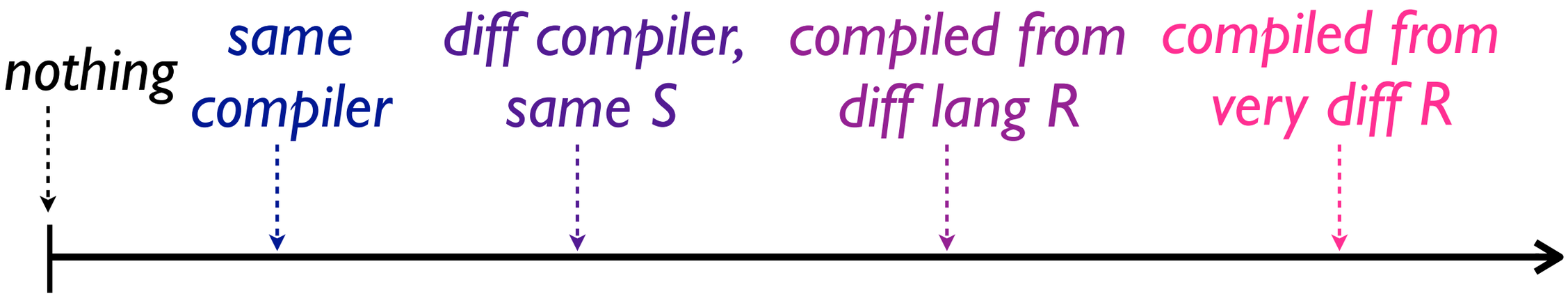
Linking



Source-Independent Linking



What we can link with



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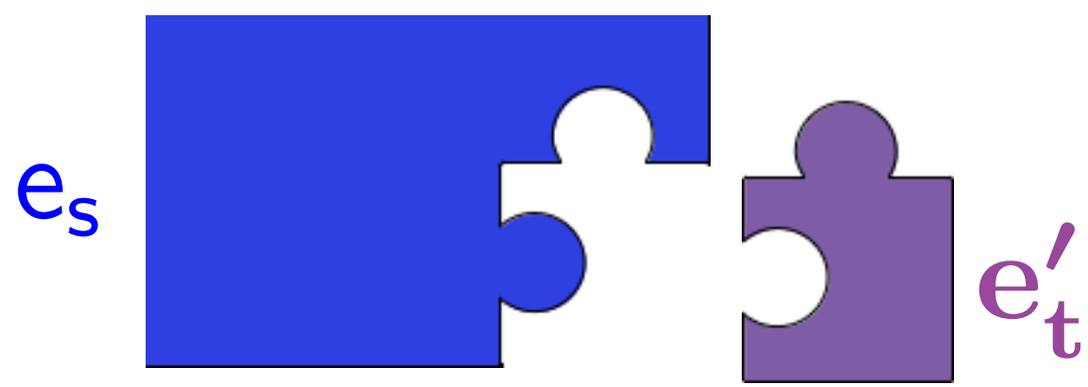
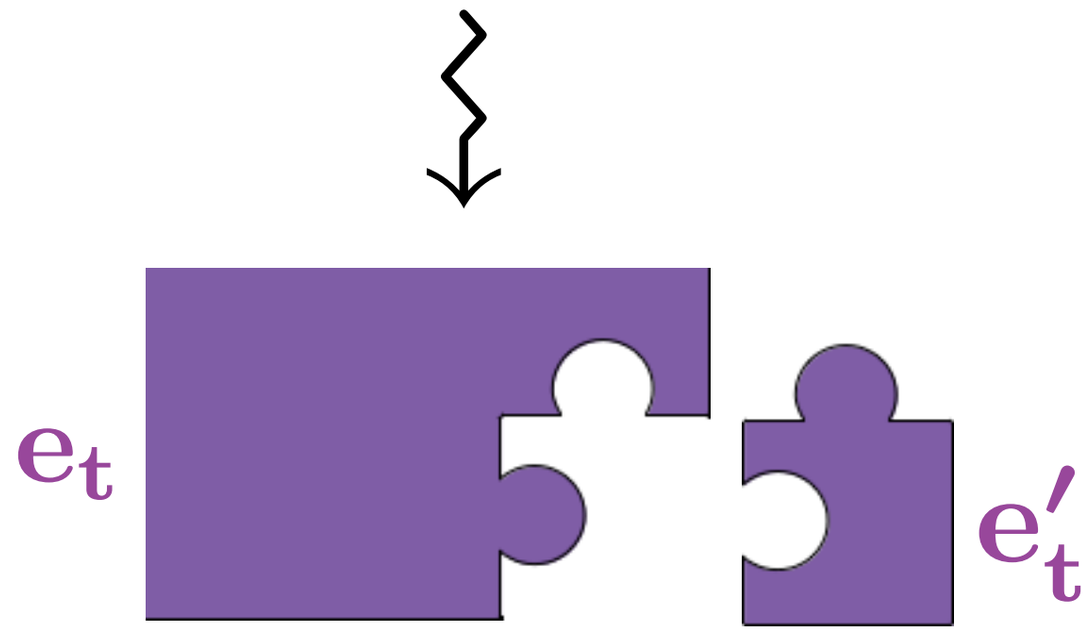
Correct Compilation of Components?



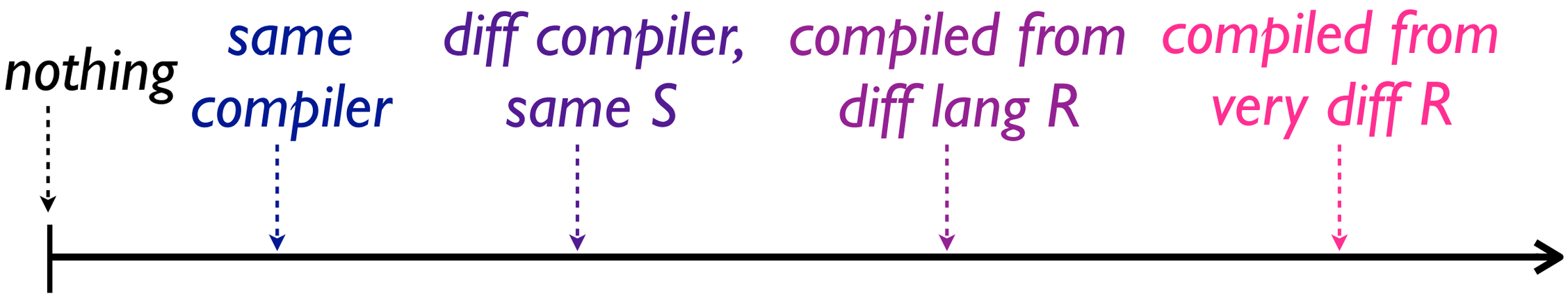


$e_S \approx e_T$

expressed how?

Need a semantics
of source-target
interoperability:
- *interaction semantics*
- *source-target multi-language*

What we can link with



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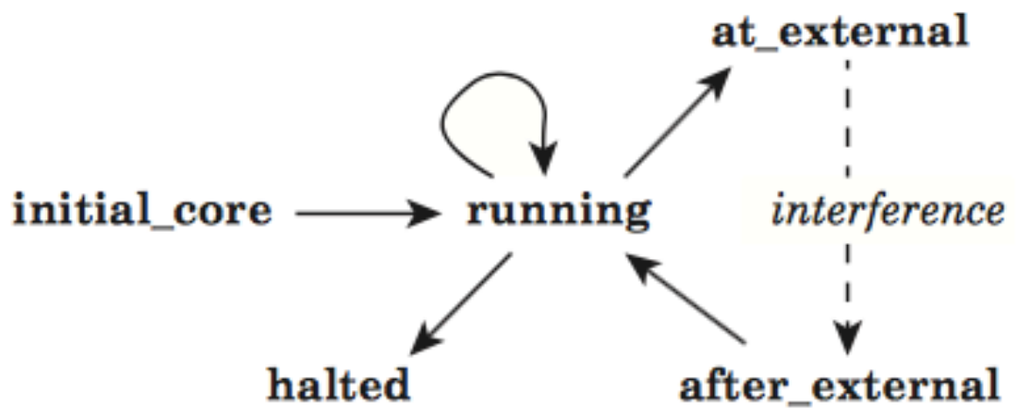
Approach: Interaction Semantics

Compositional CompCert

[Stewart et al.'15]

- Language-independent linking



$$
\begin{array}{l}
\mathsf{Semantics}\ (G\ C\ M : \mathsf{Type}) : \mathsf{Type} \triangleq \\
\left\{\begin{array}{lcl}
\mathsf{initial\_core} & : & G \to \mathcal{V} \to \mathsf{list}\ \mathcal{V} \to \mathsf{option}\ C \\
\mathsf{at\_external} & : & C \to \mathsf{option}\ (\mathcal{F} \times \mathsf{list}\ \mathcal{V}) \\
\mathsf{after\_external} & : & \mathsf{option}\ \mathcal{V} \to C \to \mathsf{option}\ C \\
\mathsf{halted} & : & C \to \mathsf{option}\ \mathcal{V} \\
\mathsf{corestep} & : & G \to C \to M \to C \to M \to \mathsf{Prop}
\end{array}\right.
\end{array}
$$

Figure 2. Interaction semantics interface. The types G (global environment), C (core state), and M (memory) are parameters to the interface. $\mathcal{F}$ is the type of external function identifiers. $\mathcal{V}$ is the type of CompCert values.

Approach: Interaction Semantics

Compositional CompCert

[Stewart et al.'15]

- Language-independent linking
- Structured simulation: support rely-guarantee relationship between the different languages while retaining vertical compositionality

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  - uniform CompCert memory model across all languages
  - not clear how to scale to richer source langs (e.g., ML), compilers with different source/target memory models
- Structured simulation: support rely-guarantee relationship between the different languages while retaining vertical compositionality

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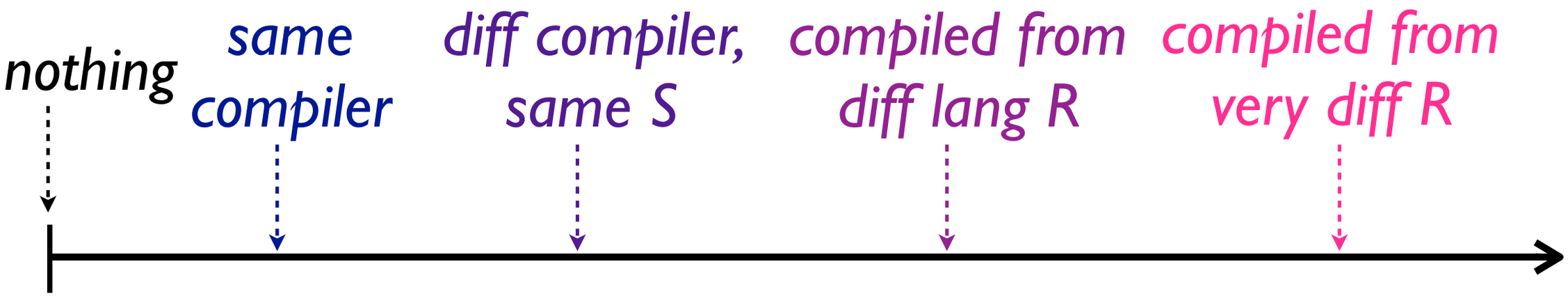
  - not clear how to scale to richer source langs (e.g., ML), compilers with different source/target memory models

- Structured simulation: support rely-guarantee relationship between the different languages while retaining vertical compositionality

  - transitivity relies on compiler passes performing restricted set of memory transformations

What we can link with



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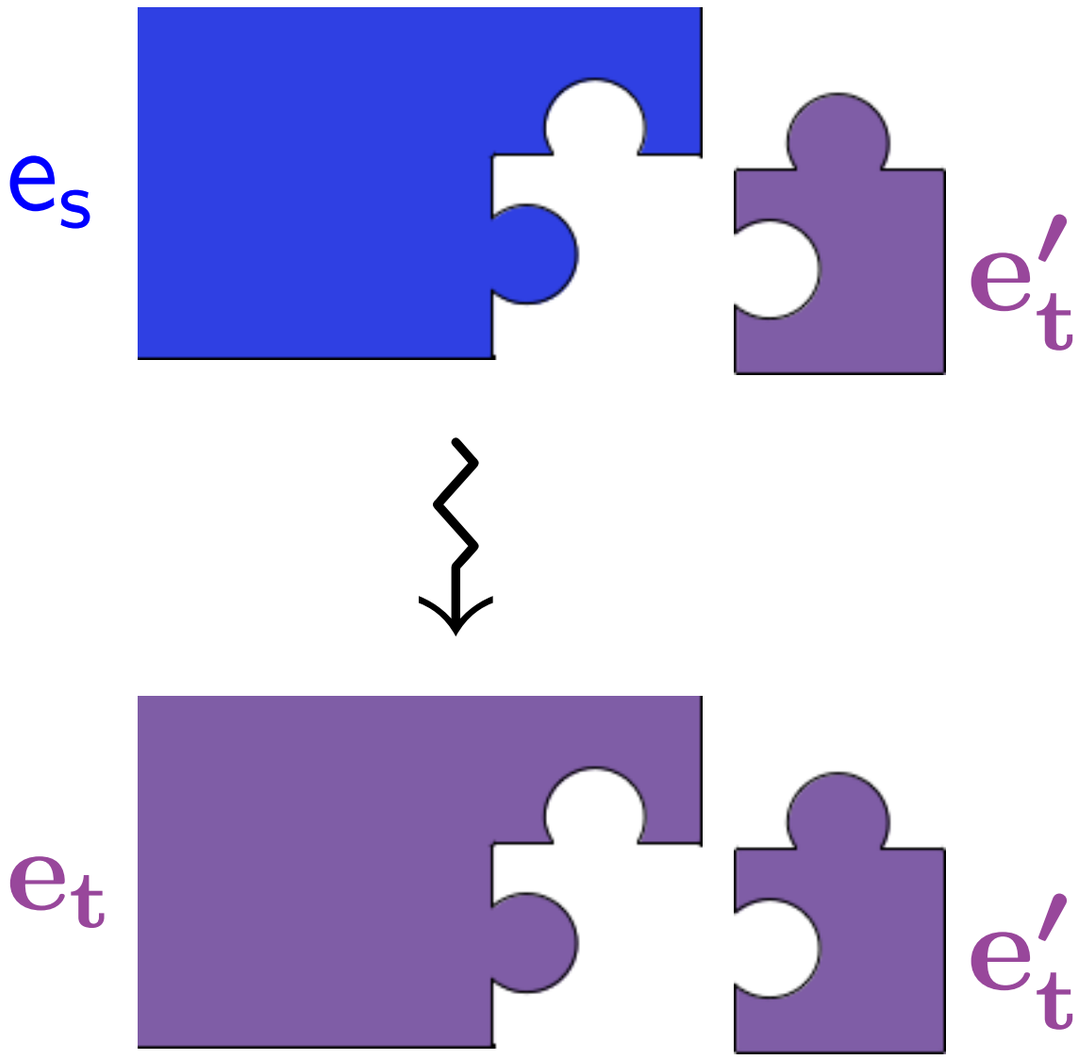
Compositional CompCert
Stewart et al.'15

Multi-language ST
Perconti-Ahmed'14

Approach: Source-Target Multi-lang.

[Perconti-Ahmed'14]



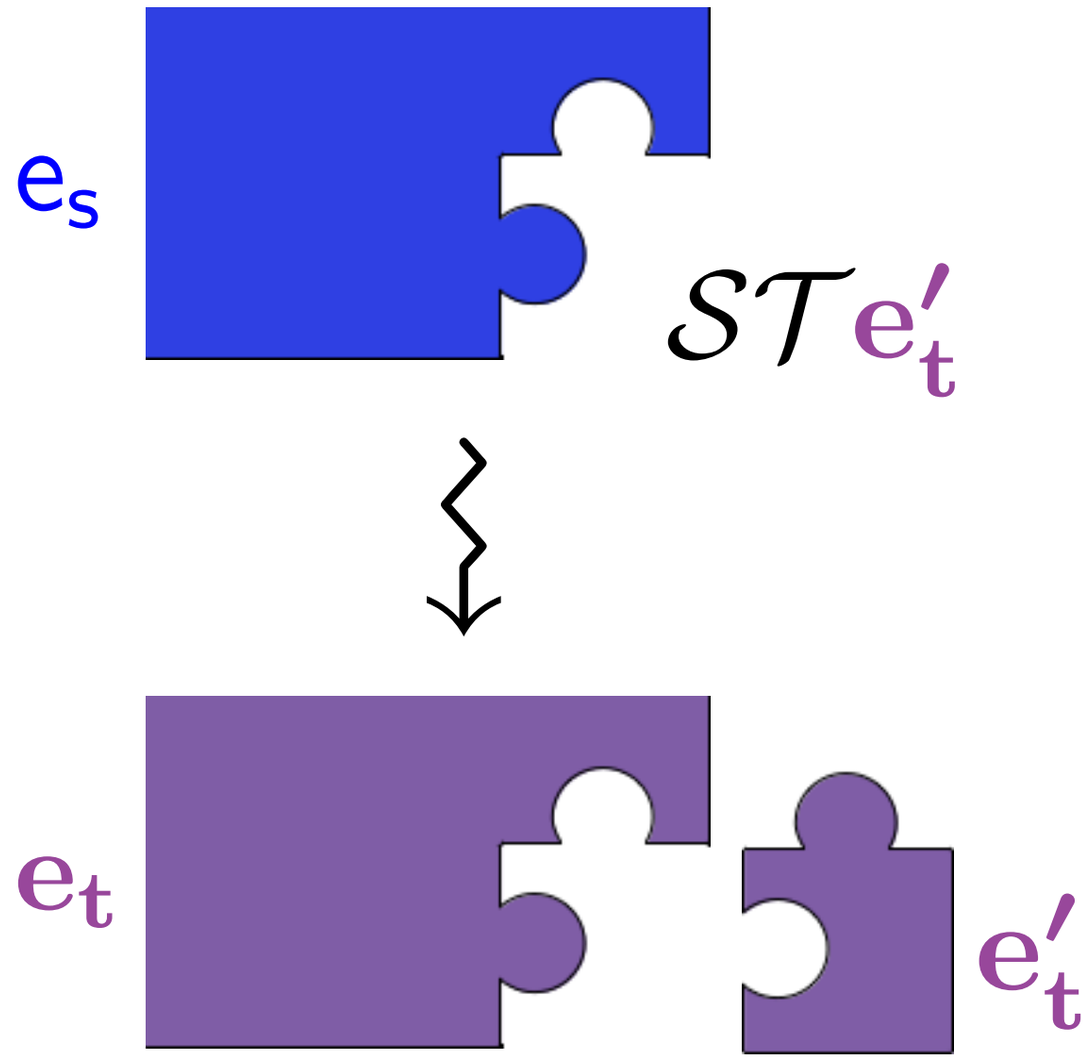
Specify semantics of source-target interoperability:

$\mathcal{ST}\,e_t \qquad \mathcal{TS}\,e_s$

Multi-language semantics: a la Matthews-Findler '07

Approach: Source-Target Multi-lang.

[Perconti-Ahmed'14]



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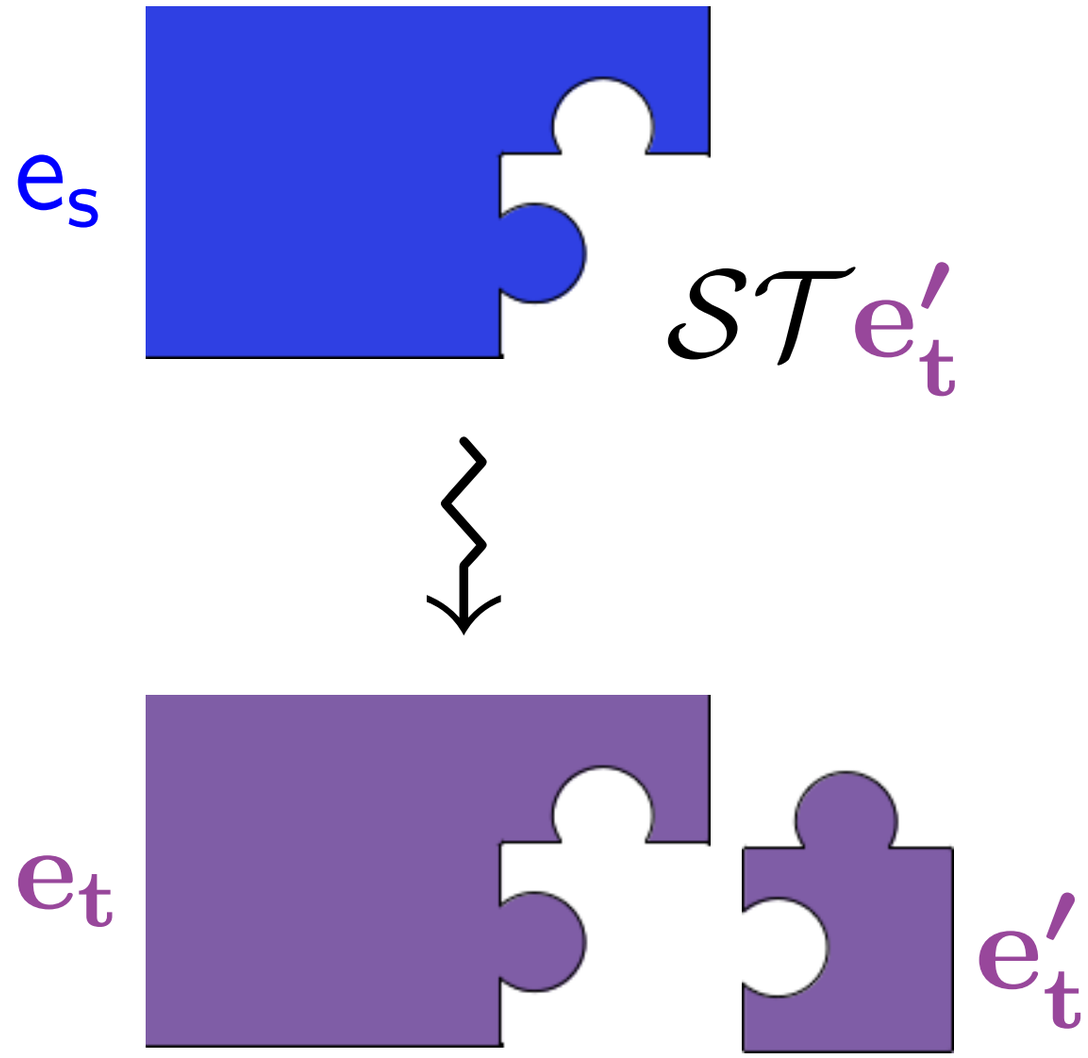
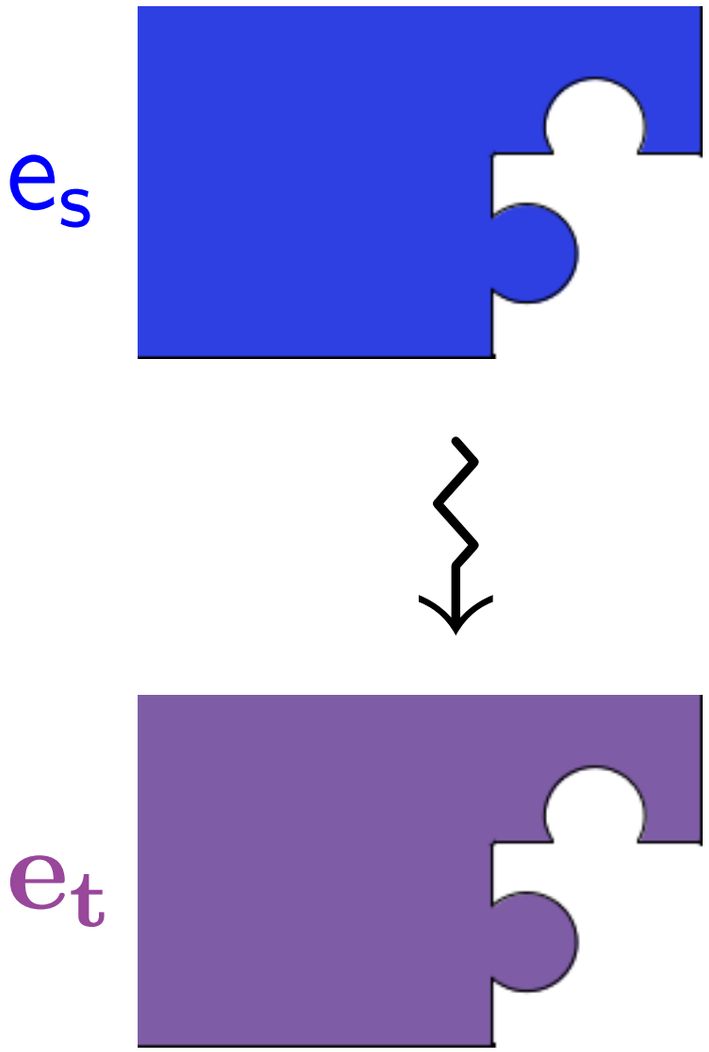


$$\mathcal{TS}(e_s\ (\mathcal{ST}\,e'_t)) \approx^{ctx} e_t\ e'_t$$

Approach: Source-Target Multi-lang.

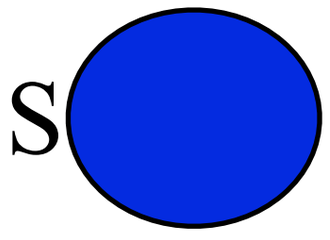
[Perconti-Ahmed'14]

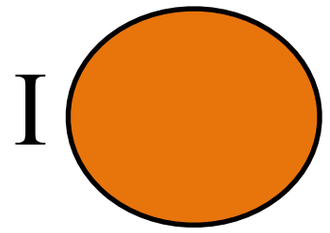


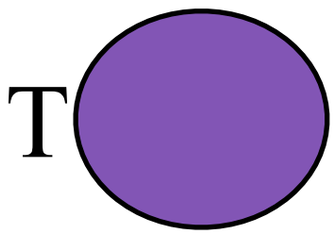
$$e_S \approx e_T \stackrel{\text{def}}{=\!=}$$

$$e_S \approx^{ctx} \mathcal{ST}\, e_T$$

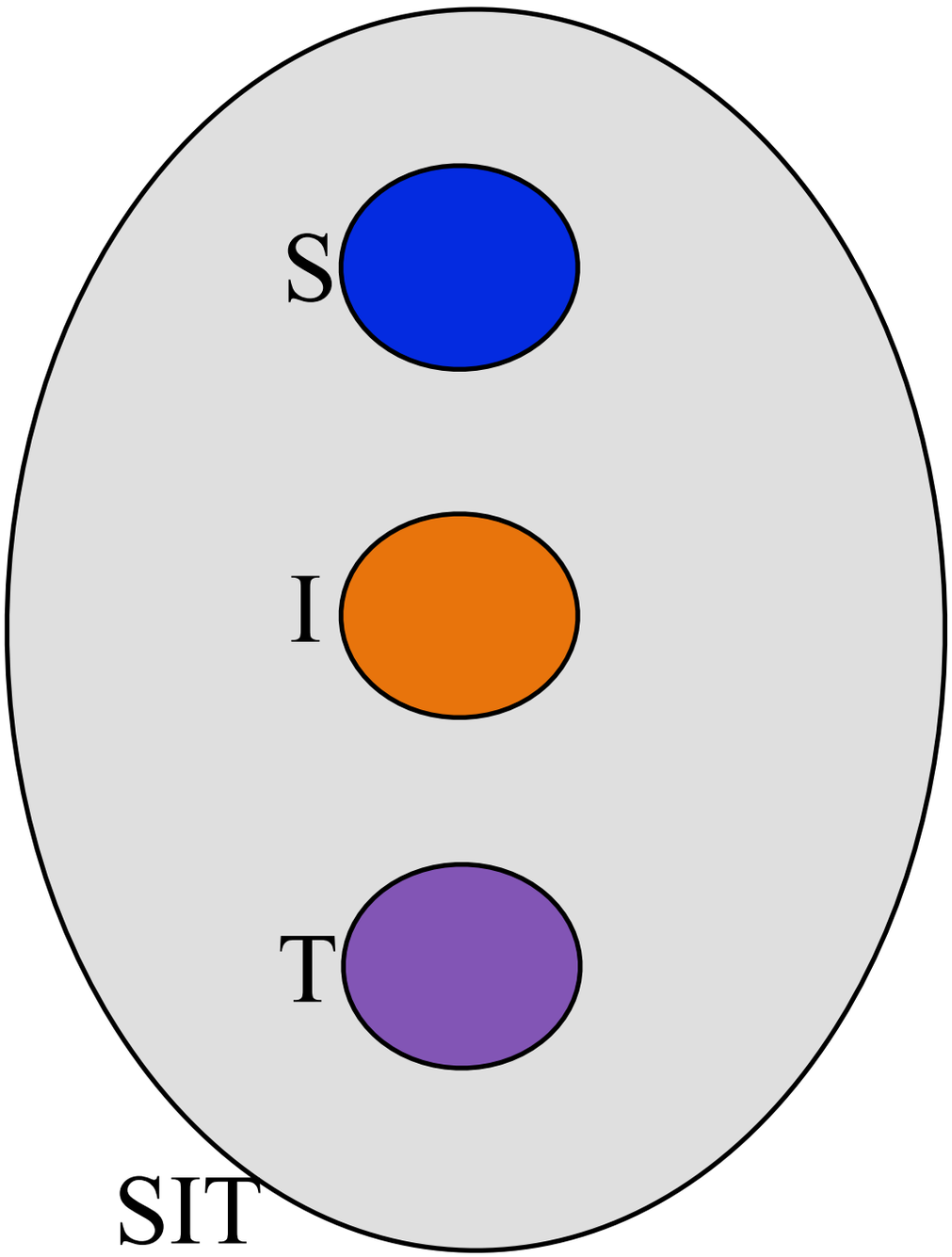
Multi-Language Semantics Approach







Multi-Language Semantics Approach



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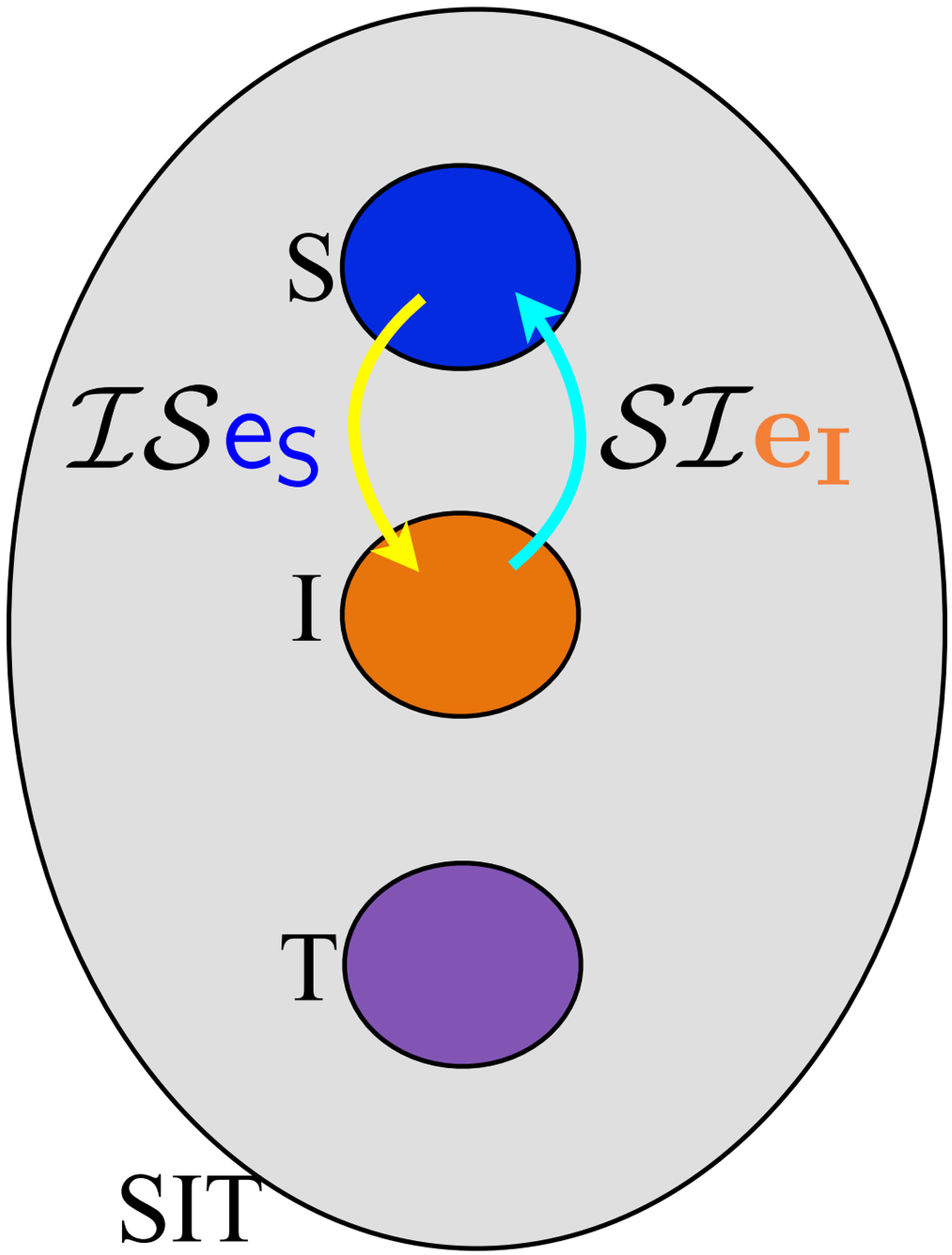

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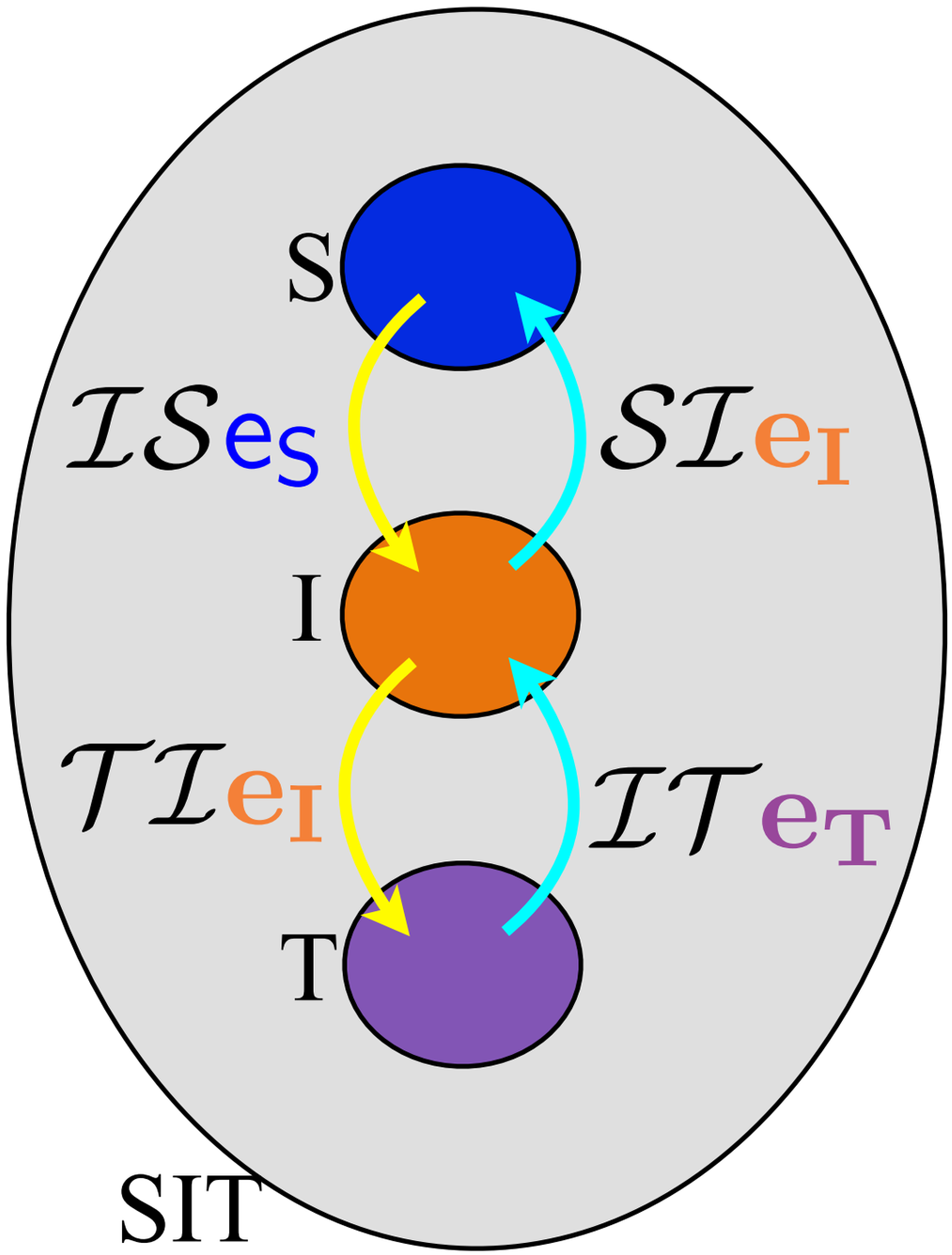

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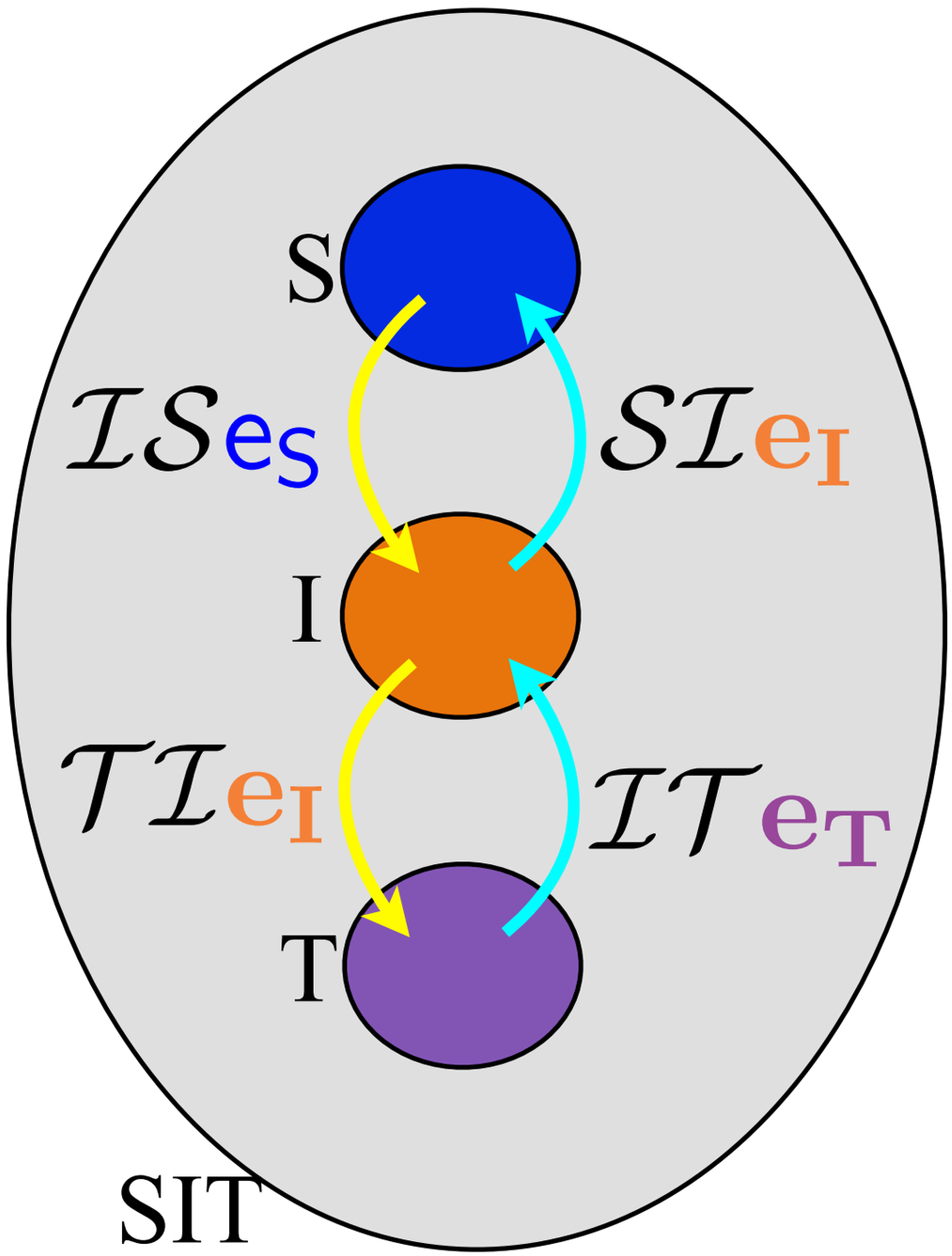
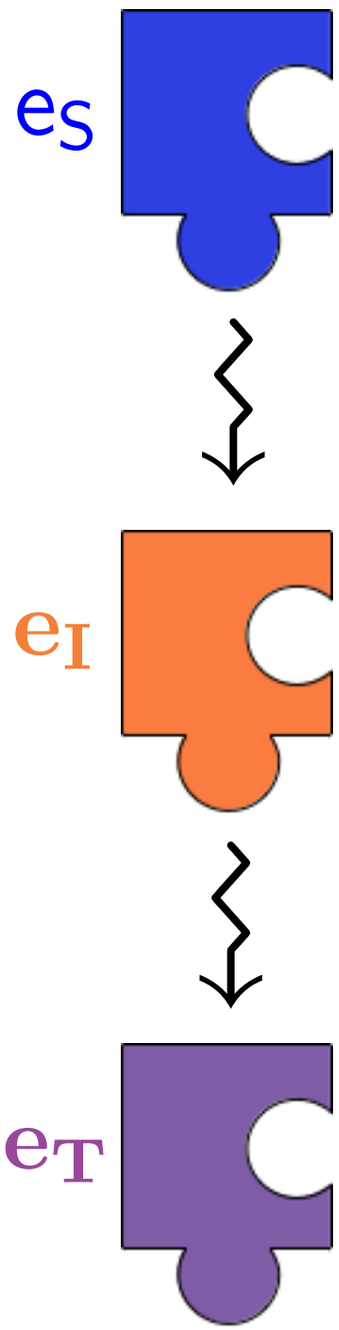


Compiler Correctness

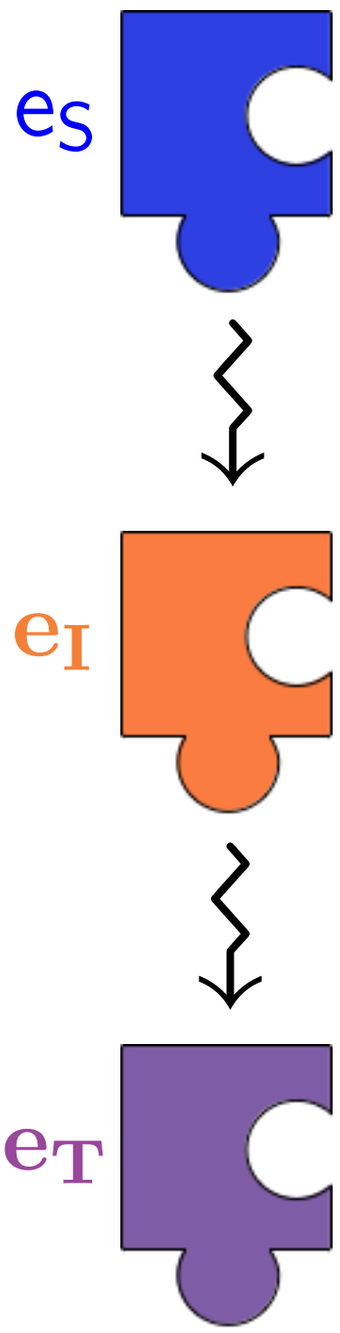


$\mathrm{e_S} \approx^{ctx} \mathcal{SI}\mathrm{e_I}$

$\mathrm{e_I} \approx^{ctx} \mathcal{IT}\mathrm{e_T}$

Multi-Lang. Approach: Multi-pass ✓

Compiler Correctness



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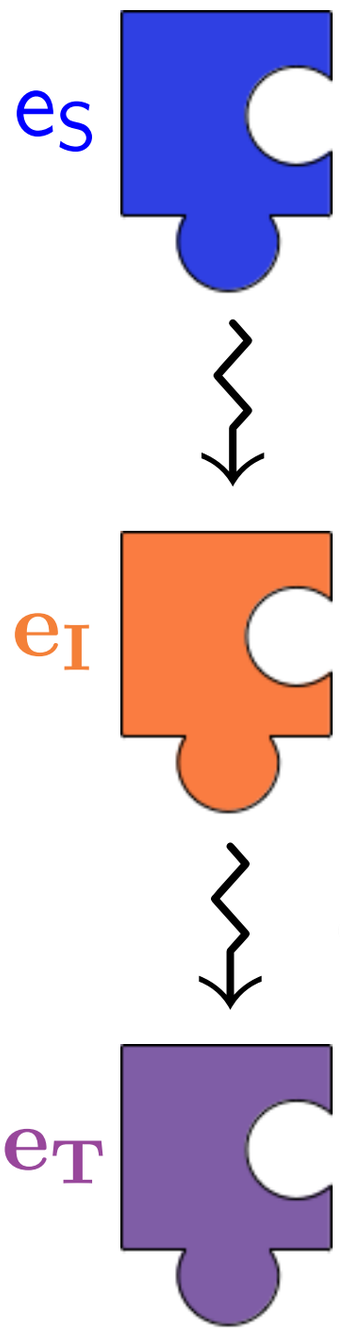

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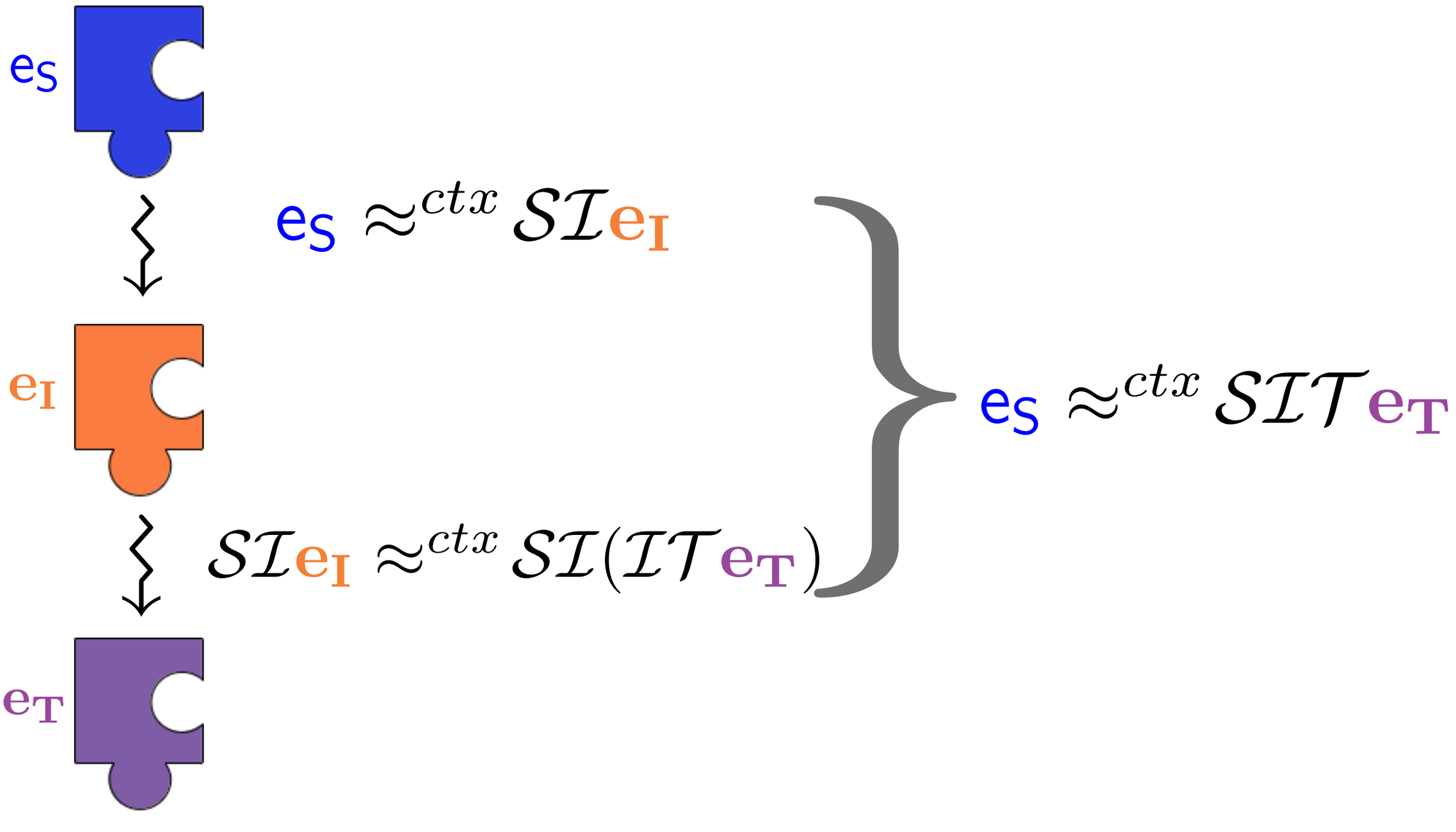
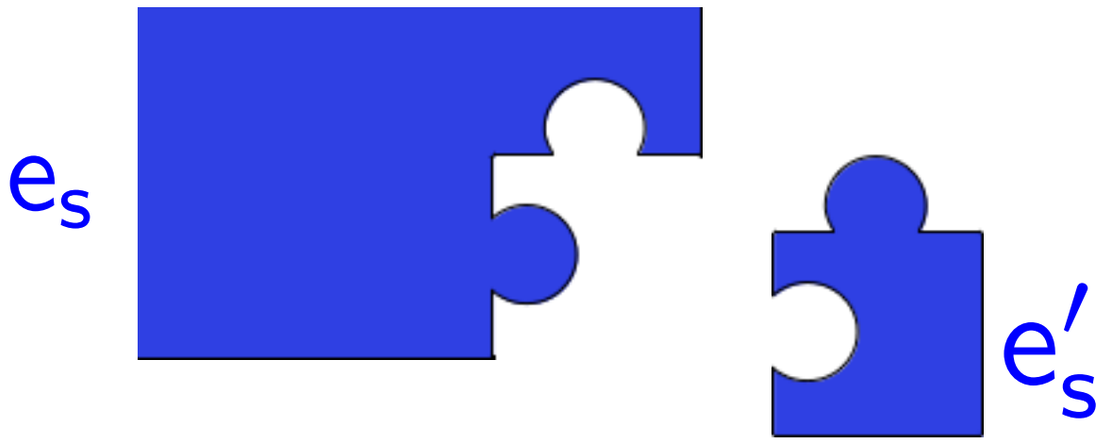
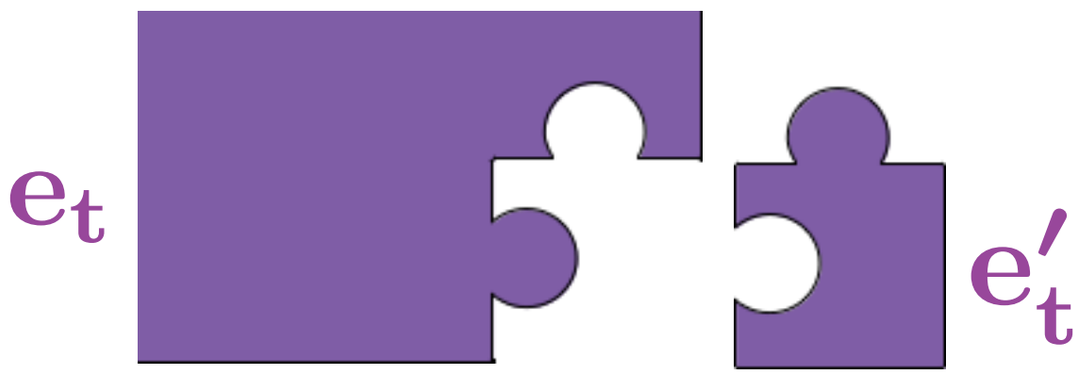


Multi-Lang. Approach: Linking ✓





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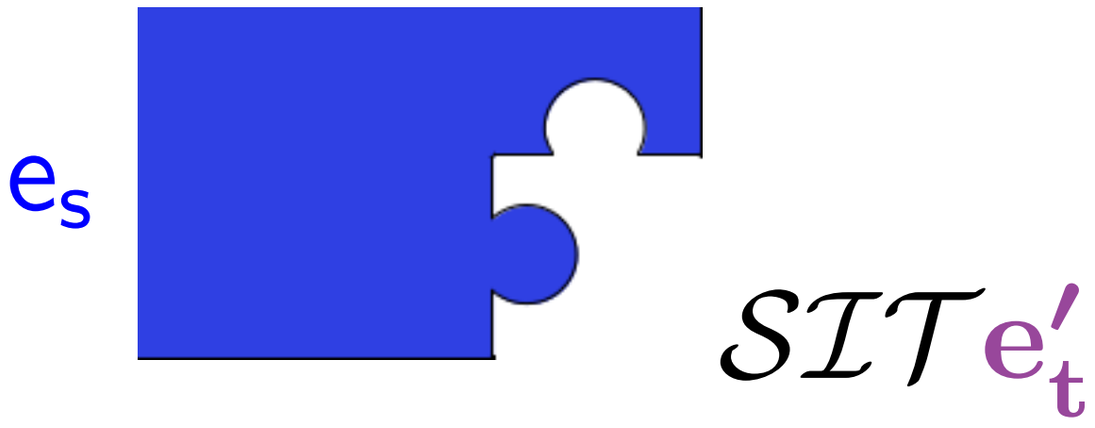
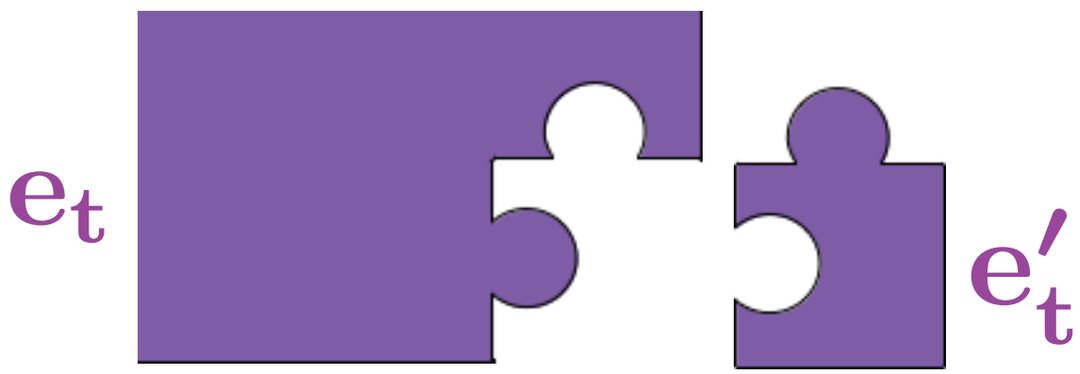


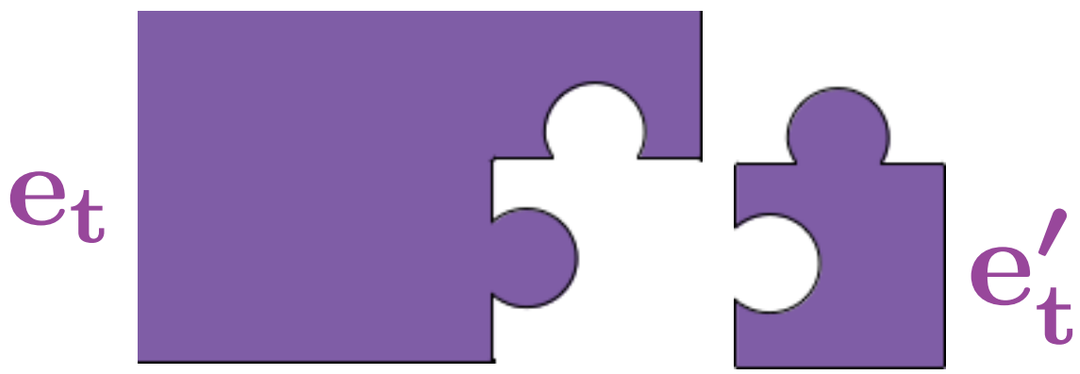


Multi-Lang. Approach: Linking ✓

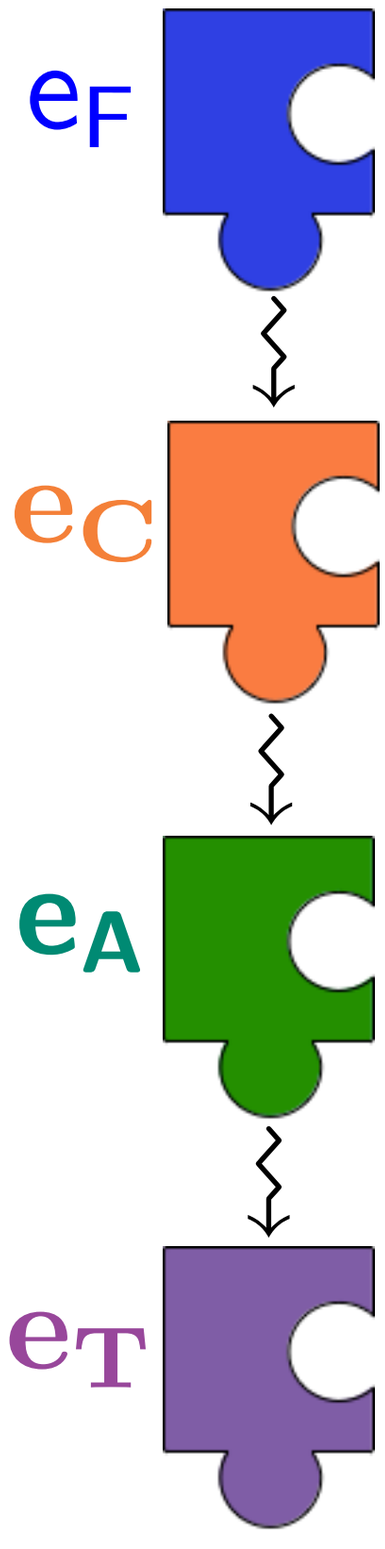
$$\mathcal{SIT}\,\mathbf{e'_t}$$

$$\mathcal{TIS}(\mathsf{e_s}\ (\mathcal{SIT}\,\mathbf{e'_t}))$$

$$\approx^{ctx}\ \mathbf{e_t}\ \mathbf{e'_t}$$



Compiler Correctness: F to TAL

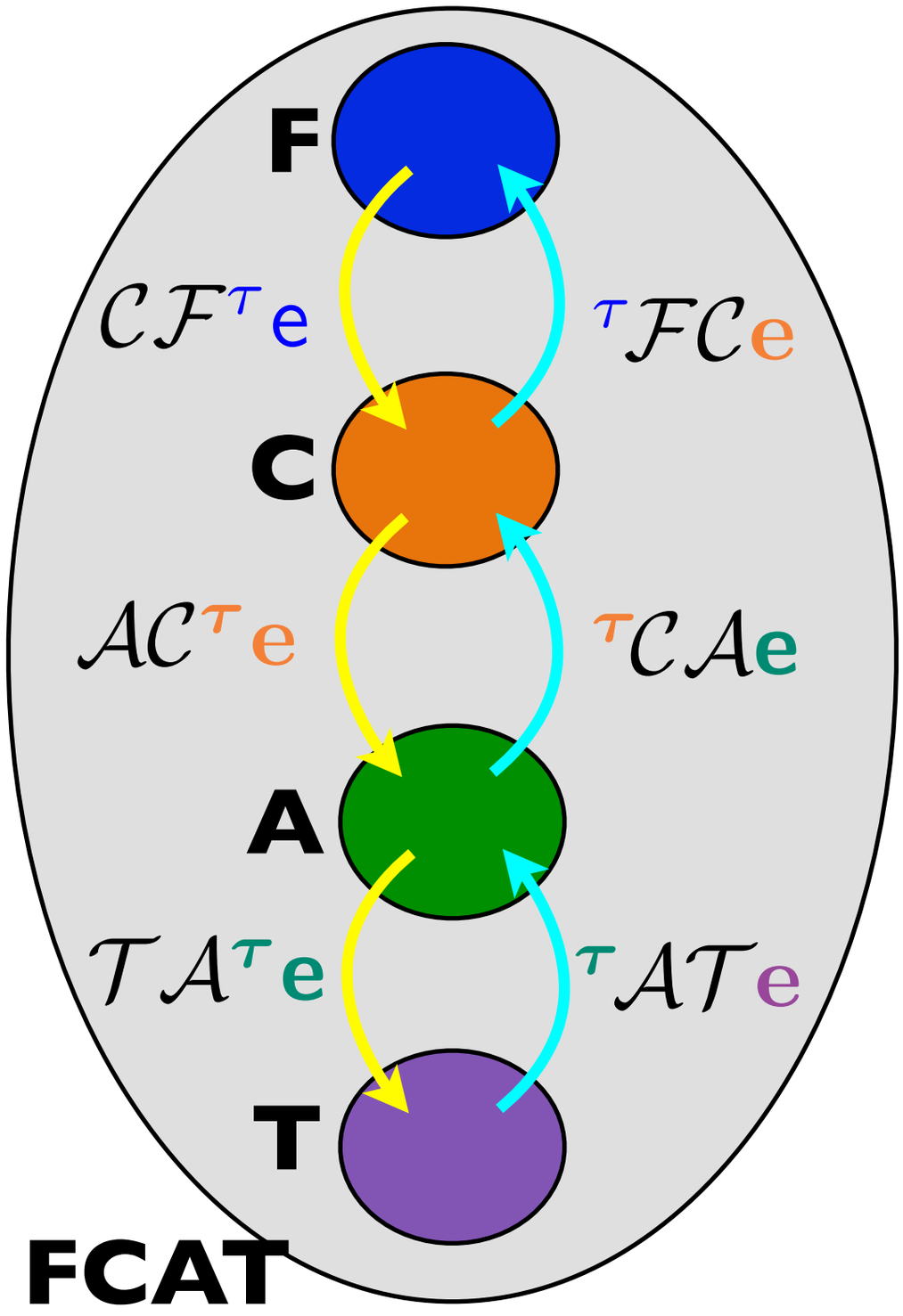


Closure Conversion τ^{C}

Allocation $\tau^{\mathcal{A}}$

Code Generation $\tau^{\mathcal{T}}$

Combined language **FCAT**



[Perconti-Ahmed'14]
[Patterson et al.'17]

- Boundaries mediate between

  $\tau \,\&\, \tau^{\mathcal{C}}$ $\tau \,\&\, \tau^{\mathcal{A}}$ $\tau \,\&\, \tau^{\mathcal{T}}$

- Operational semantics

  $\mathcal{C}\mathcal{F}^{\tau}\,\mathsf{e} \longmapsto^{*} \mathcal{C}\mathcal{F}^{\tau}\,\mathsf{v} \longmapsto \mathsf{v}$

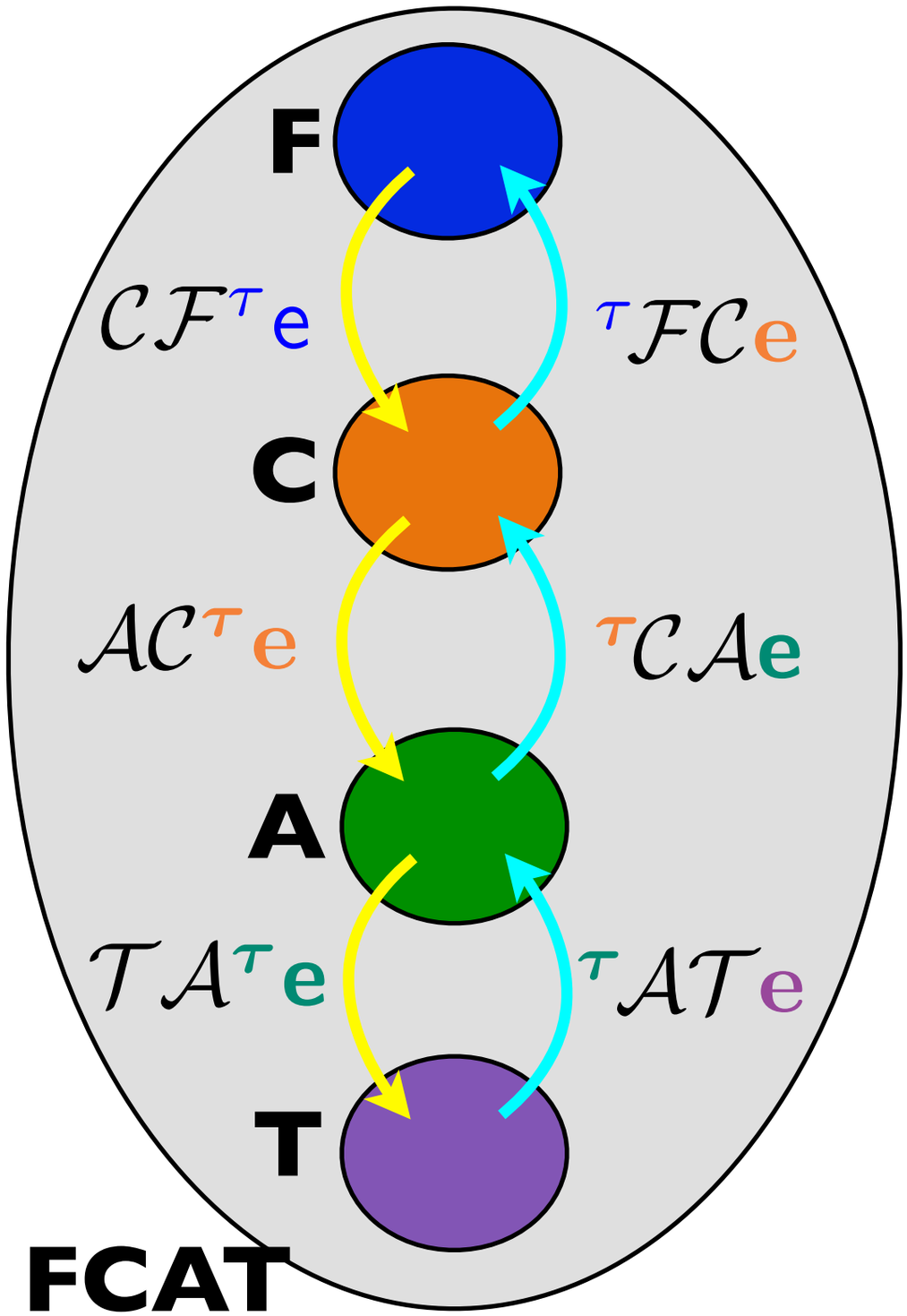
  ${}^{\tau}\mathcal{F}\mathcal{C}\,\mathsf{e} \longmapsto^{*} {}^{\tau}\mathcal{F}\mathcal{C}\,\mathsf{v} \longmapsto \mathsf{v}$

- Boundary cancellation

  ${}^{\tau}\mathcal{F}\mathcal{C}\mathcal{C}\mathcal{F}^{\tau}\,\mathsf{e} \approx^{ctx} \mathsf{e} : \tau$

  $\mathcal{C}\mathcal{F}^{\tau}\,{}^{\tau}\mathcal{F}\mathcal{C}\,\mathsf{e} \approx^{ctx} \mathsf{e} : \tau^{\mathcal{C}}$

Challenges

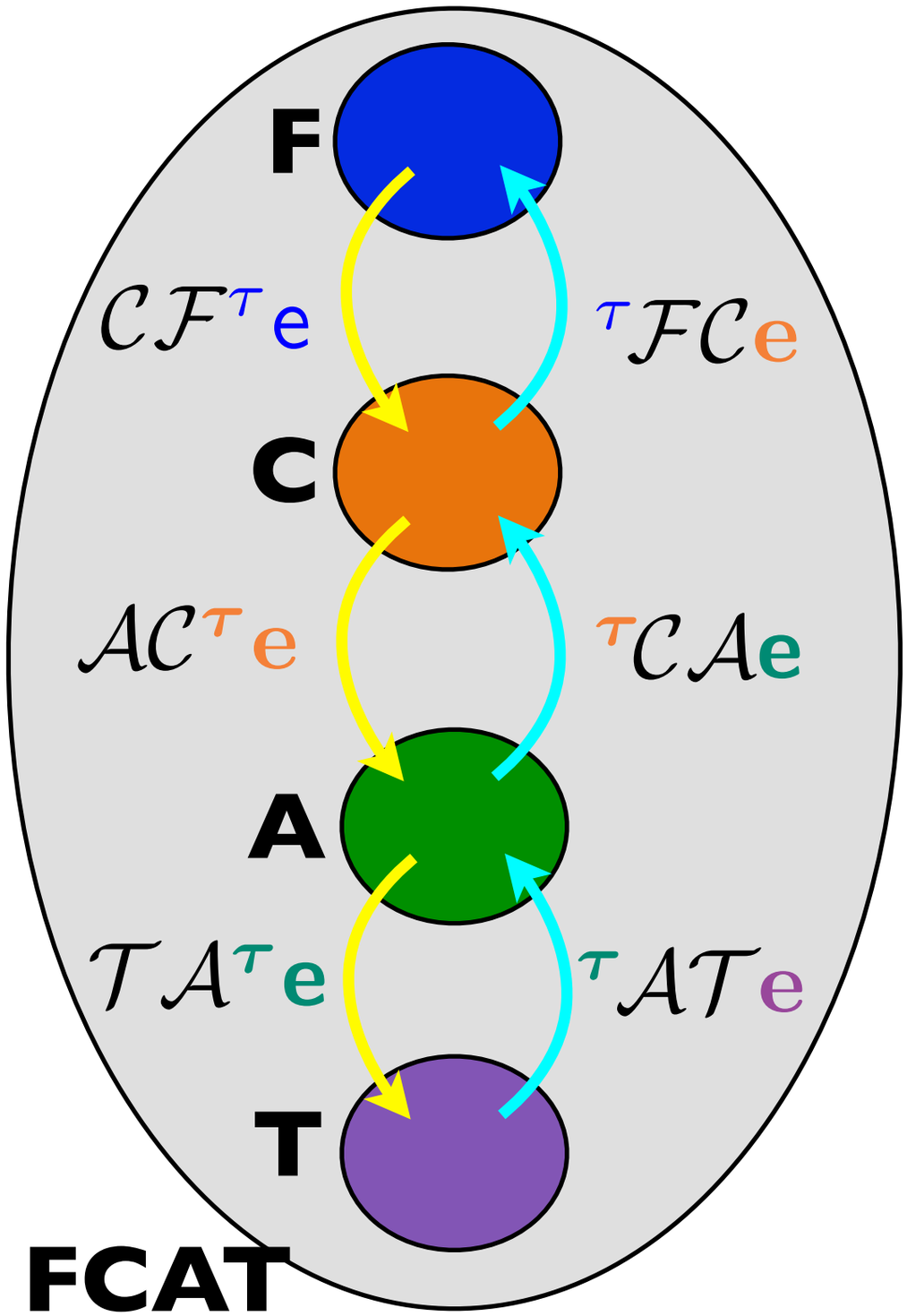


F+C: Interoperability semantics with type abstraction in both languages

C+A: Interoperability when compiler pass allocates code & tuples on heap

A+T: What is e? What is v? How to define contextual equiv. for TAL *components*? How to define logical relation?

Challenges



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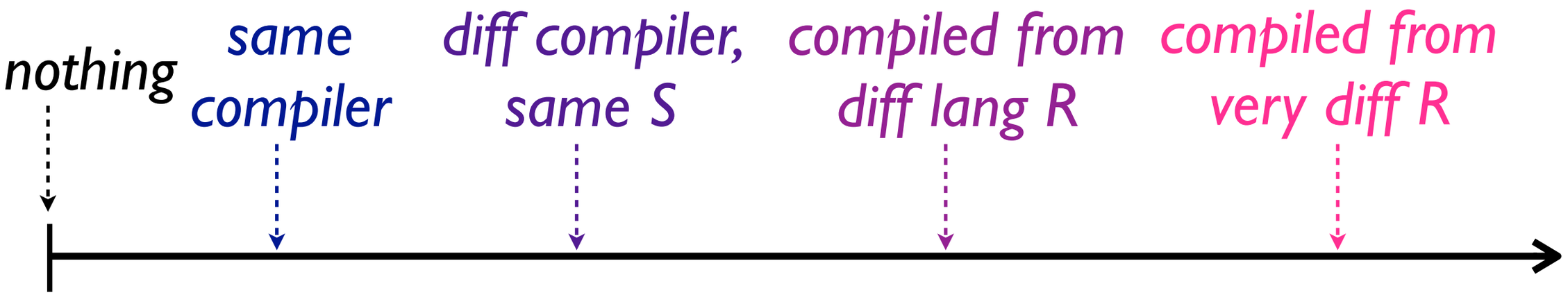
Central Challenge: interoperability between high-level (direct-style) language & assembly (continuation style)

FunTAL: Reasonably Mixing a Functional Language with Assembly *[Patterson et al. PLDI'17]*

CompCompCert vs. Multi-language

Transitivity:	
- structured simulations	- all passes use multi-lang $\approx^{ctx}$
Check okay-to-link-with:	
- satisfies CompCert memory model	- satisfies expected type (translation of source type)
Contexts:	
- semantic representation	- syntactic representation
Requires uniform memory model across compiler IRs?	
- yes	- no

What we can link with



CompCert

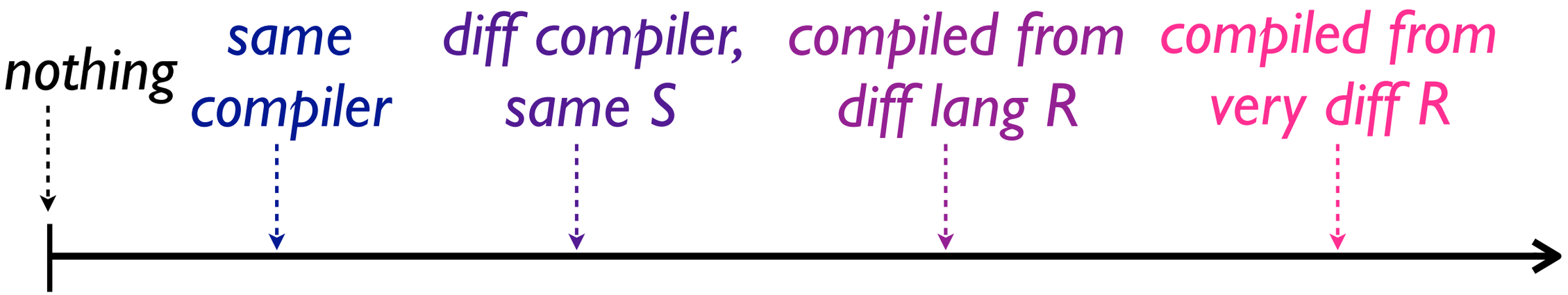
SepCompCert
Kang et al.'16

Pilsner
Neis et al.'15

Compositional CompCert
Stewart et al.'15

Allows linking with behavior inexpressible in S → *Multi-language ST*
Perconti-Ahmed'14

Proving Transitivity



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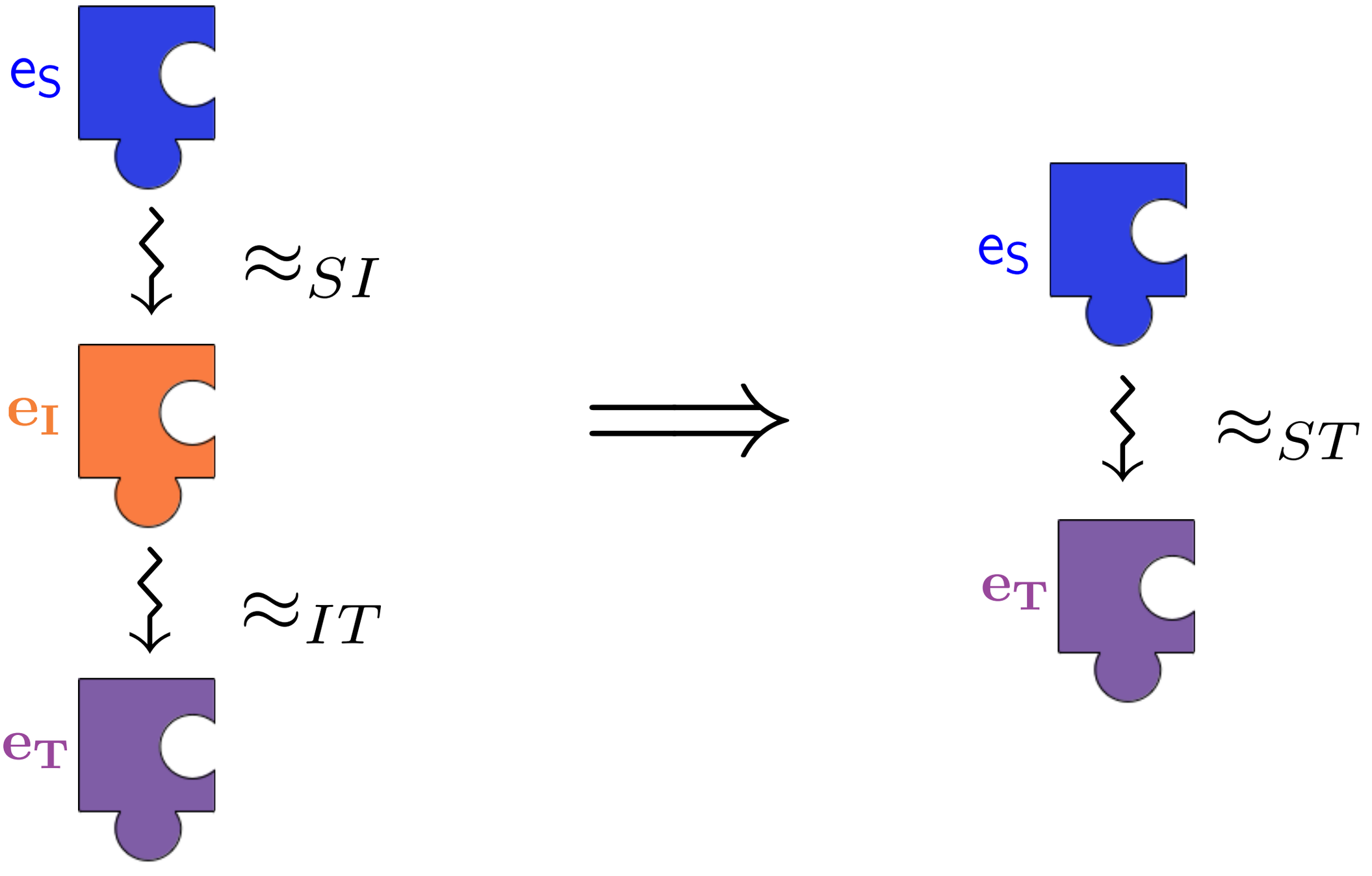
Multi-language ST
Perconti-Ahmed'14

Transitivity requires effort / engineering

Vertical Compositionality

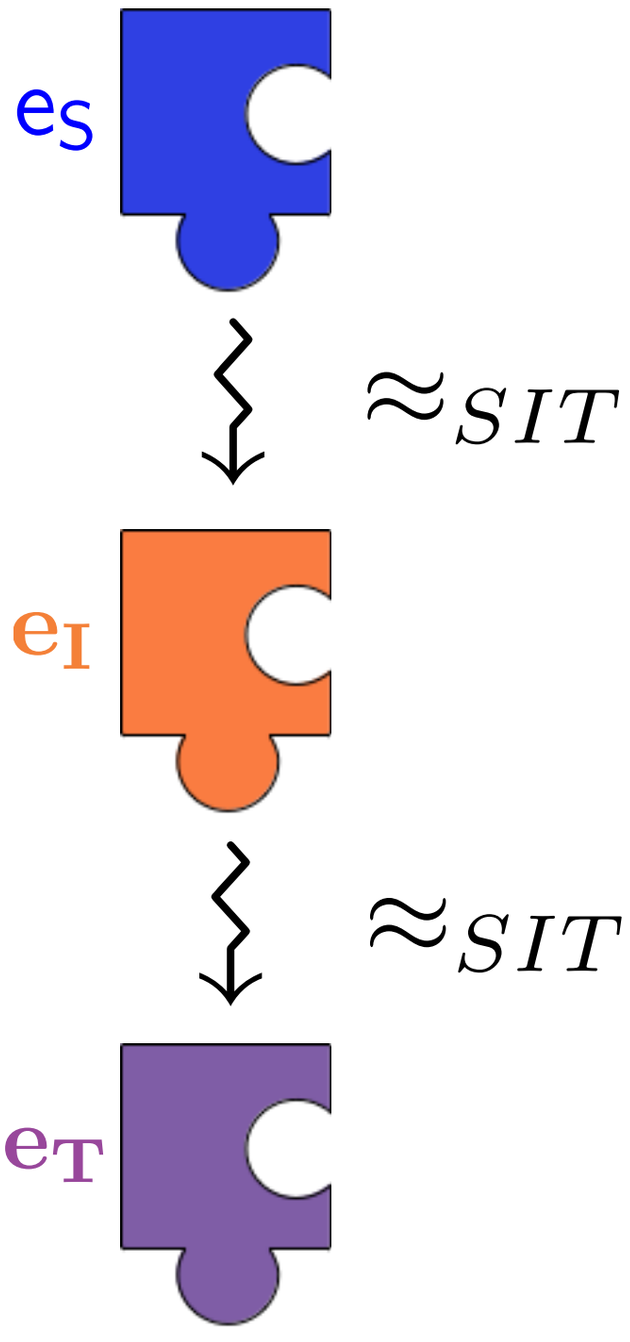
Transitivity

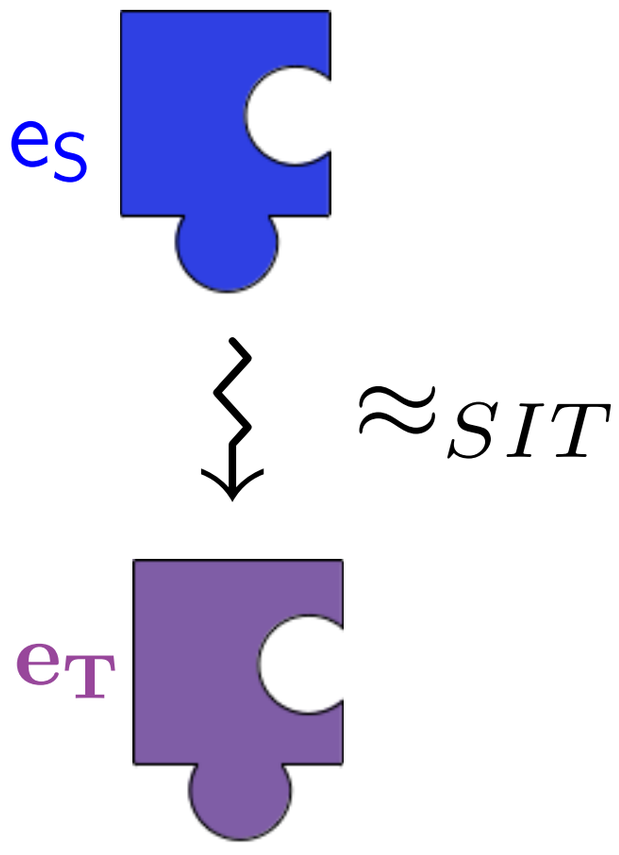
Vertical Compositionality



Transitivity

CompCompCert & Multi-lang





Horizontal Compositionality

Source-Independent Linking

Vertical Compositionality

Transitivity

Horizontal Compositionality

Pilsner
Neis et al.'15

Source-Independent Linking

Compositional CompCert
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Multi-language ST
Perconti-Ahmed'14

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To Understand if Theorem is Correct…

Pilsner
Neis et al.'15

- source-target PILS

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To Understand if Theorem is Correct…

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Perconti-Ahmed'14

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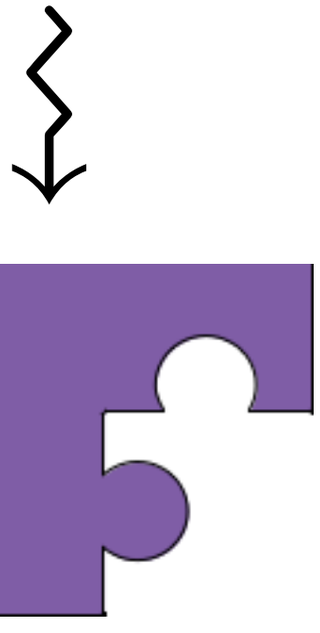
Is there a generic CCC theorem?

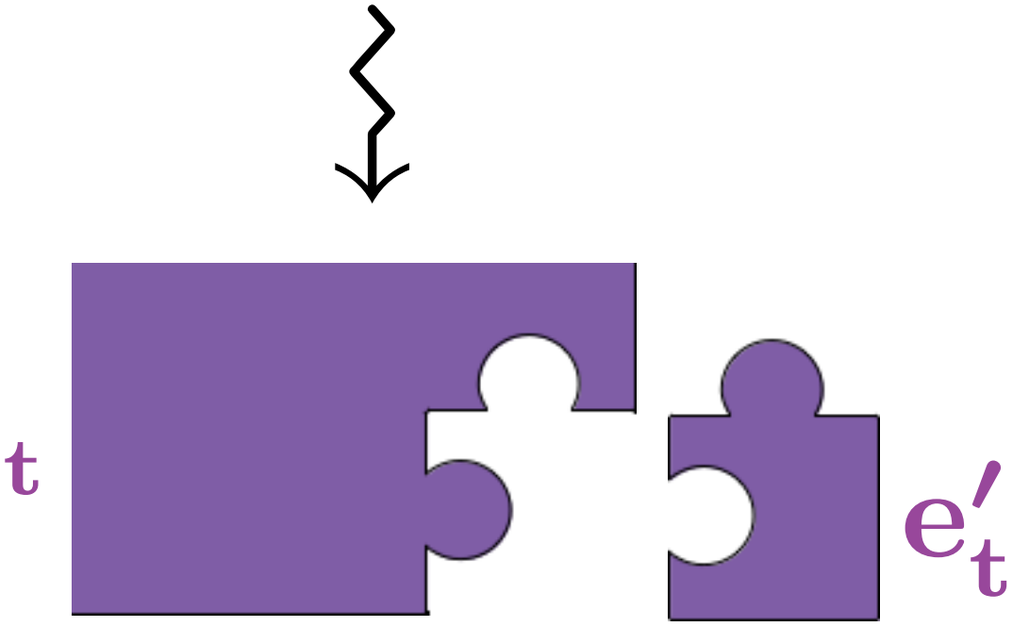
Generic CCC Theorem?



$e_S \approx e_T$

expressed how?

Generic CCC Theorem?



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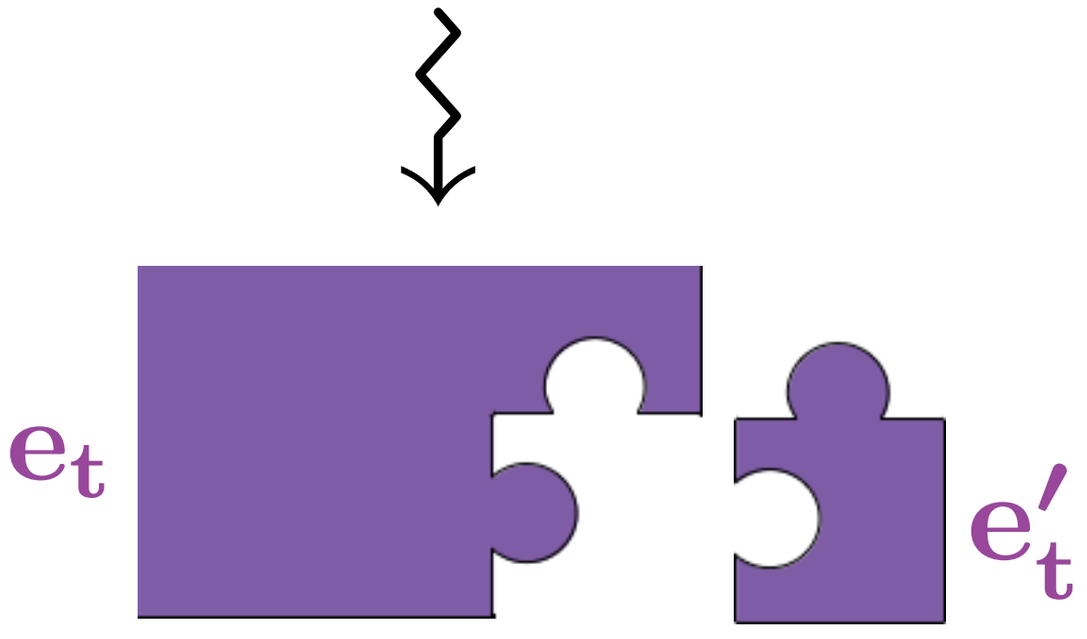
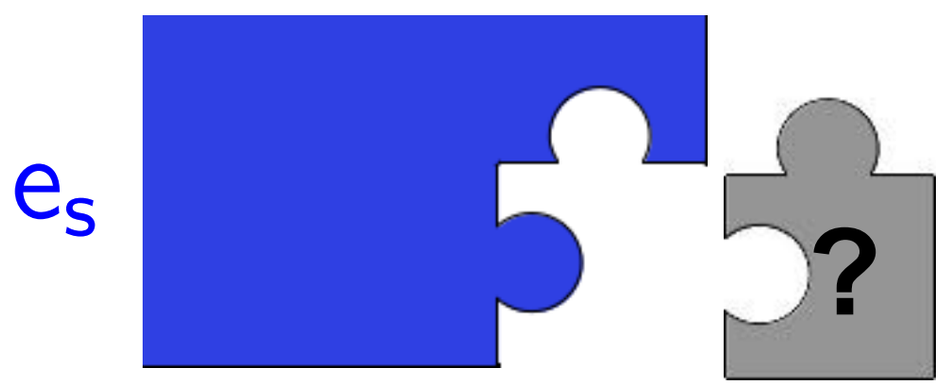


$\in \mathcal{L}$ ⟵ *linking set*

Generic CCC Theorem?



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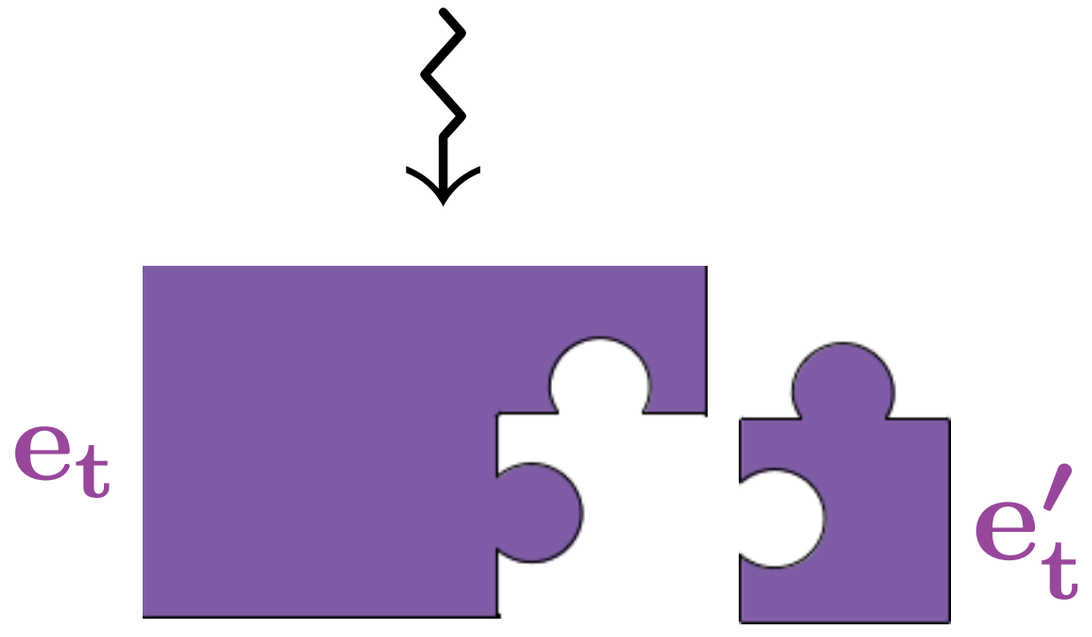

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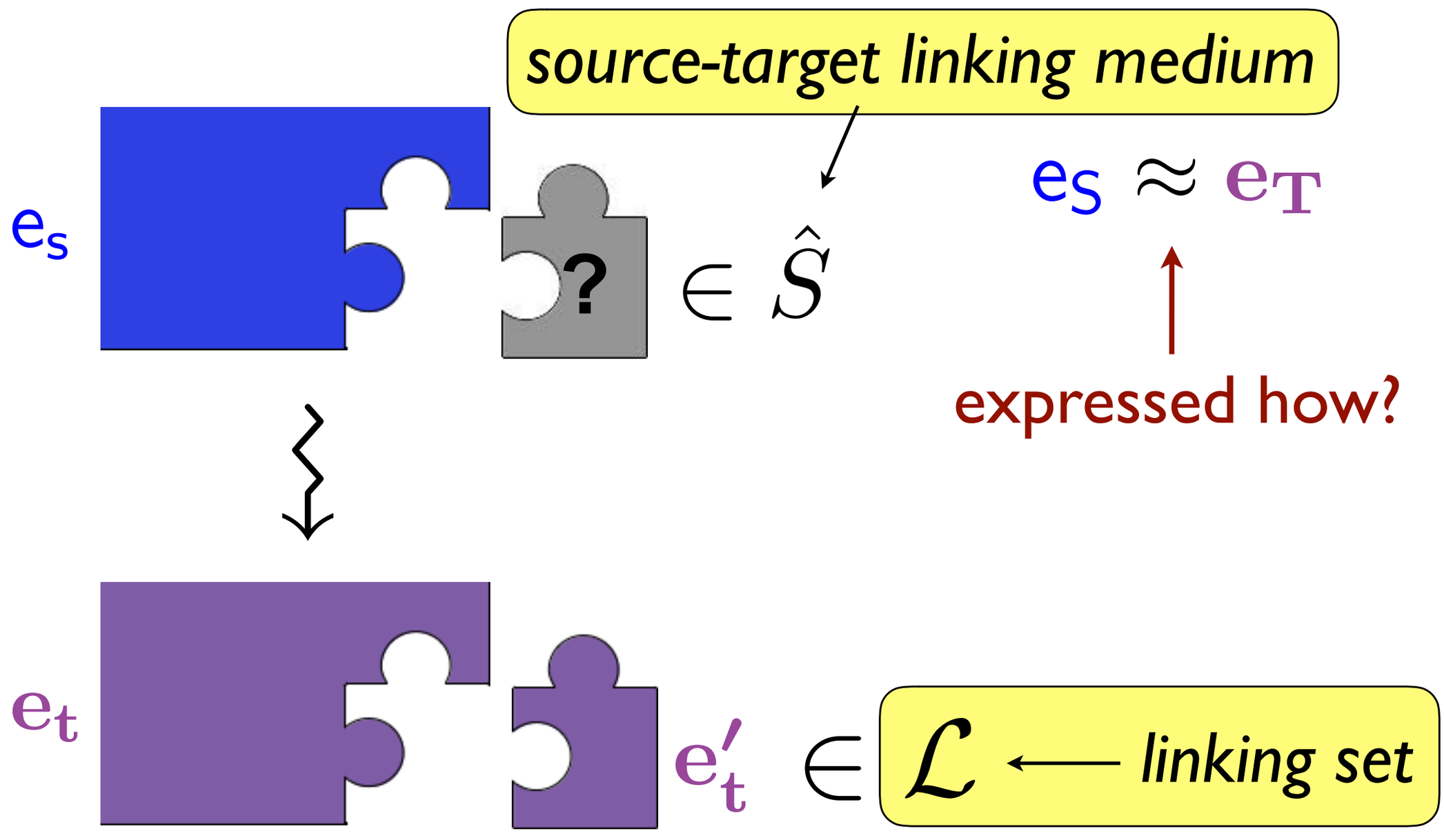

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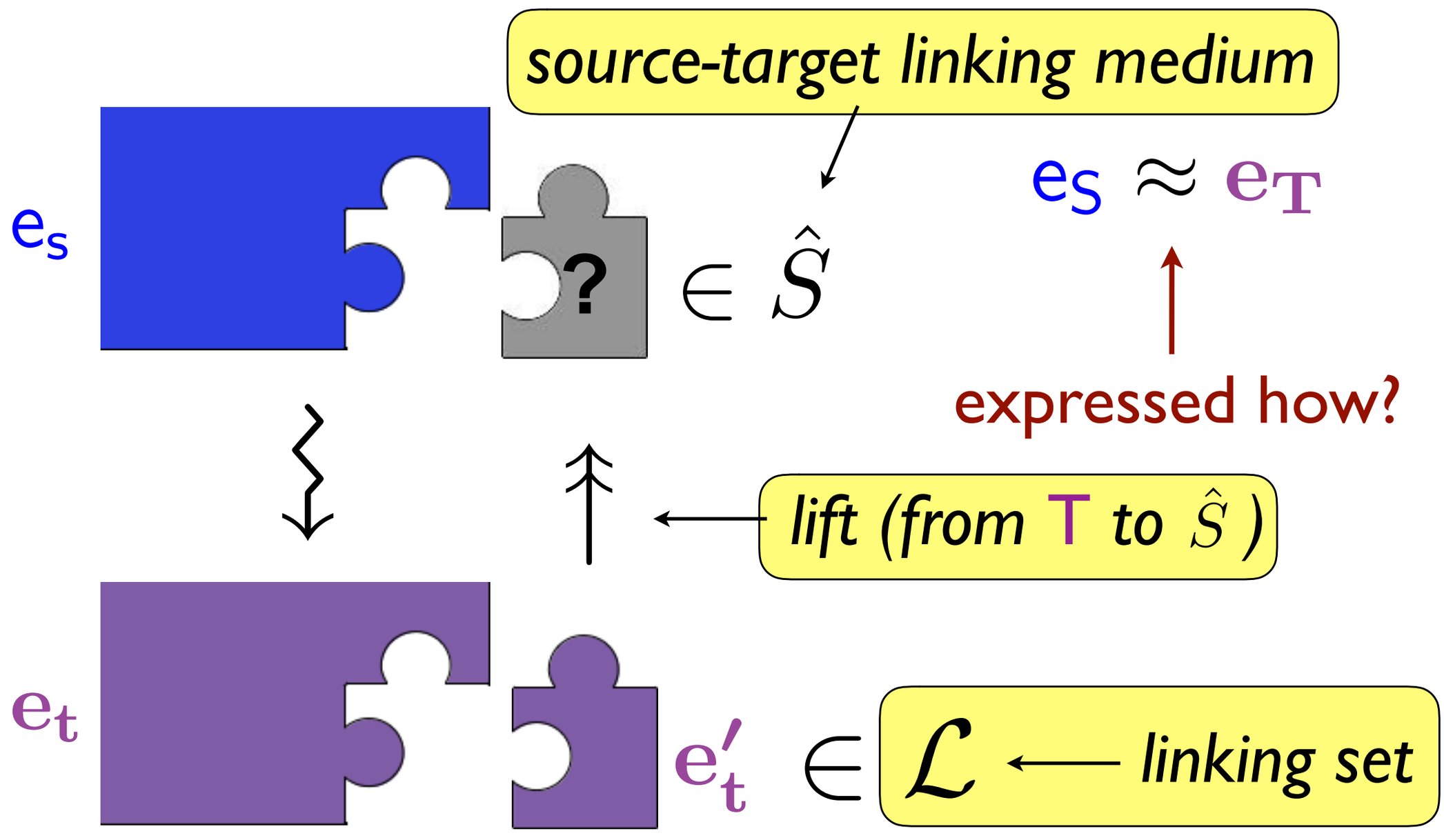
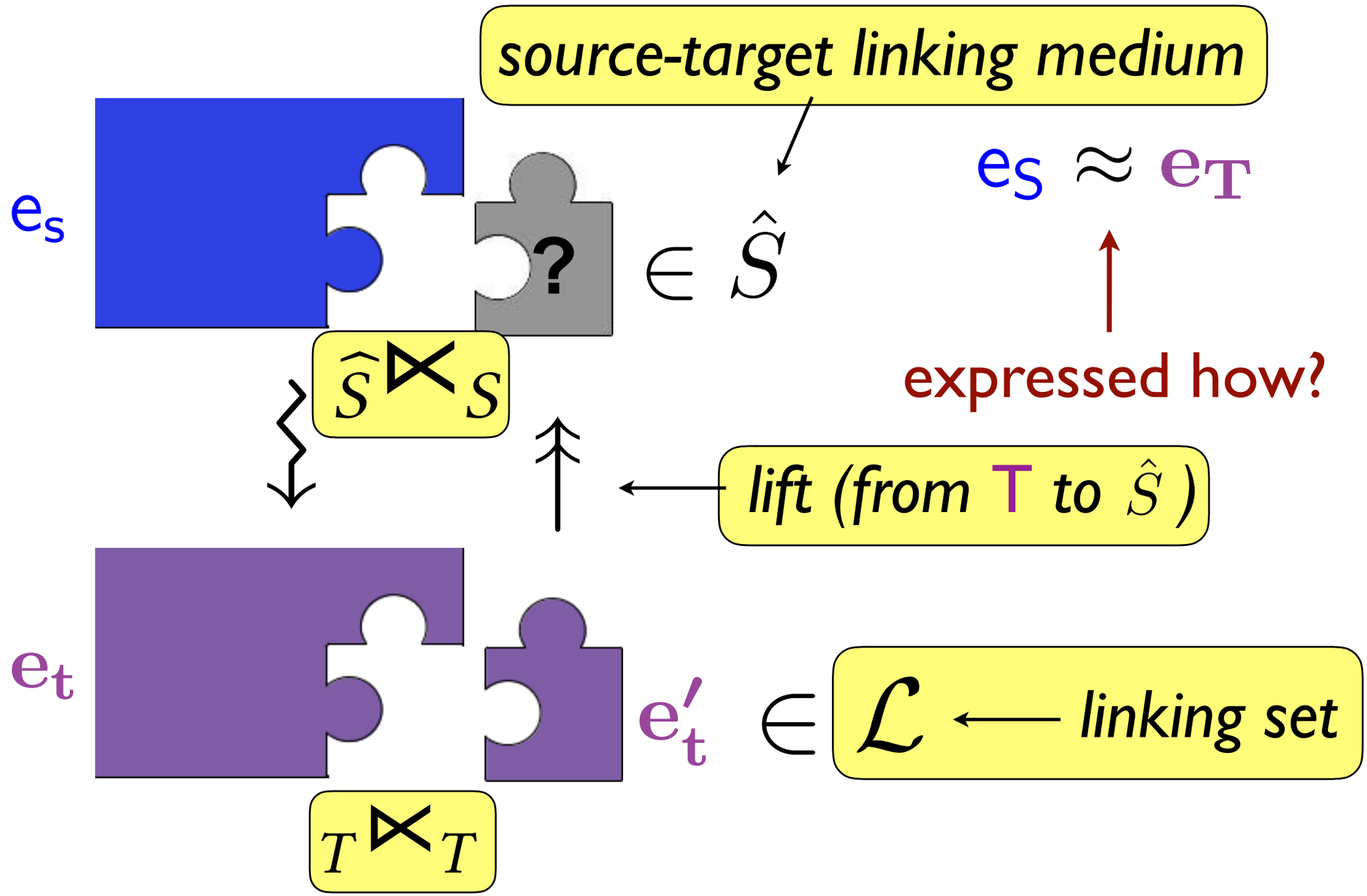
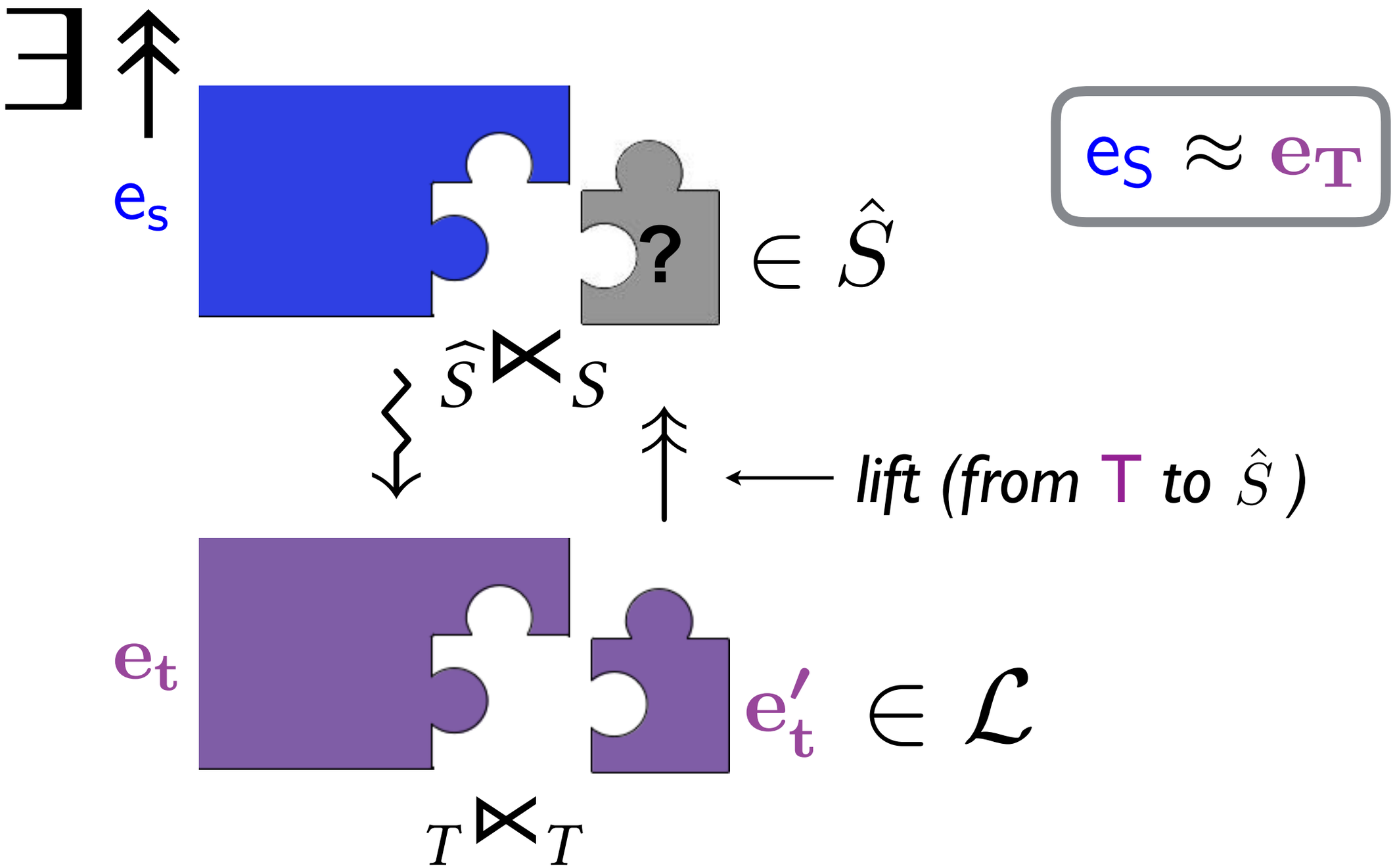


Generic CCC Theorem?



Generic CCC Theorem



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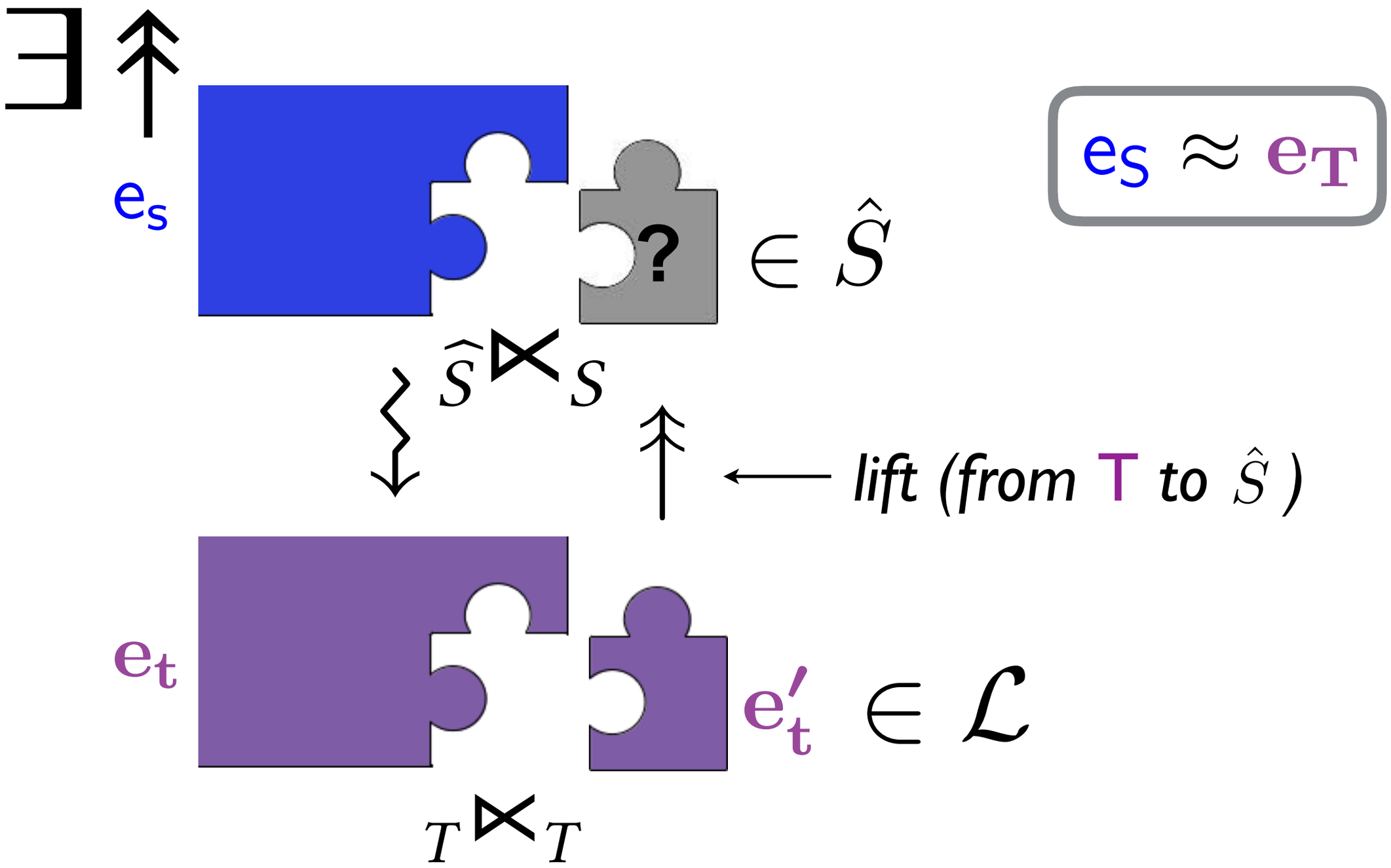


…and "lift" is inverse of "compile" on compiler output

Generic CCC Theorem

$$\exists \twoheaduparrow.\ \forall e_S, e_T.\ e_S \rightsquigarrow e_T \implies$$

$$\forall (e'_T, \varphi) \in \mathcal{L}.\ ok_{\ltimes}(e'_T, e_T) \implies$$

$$e'_T\ {}_T\ltimes_T\ e_T \implies {}_T\sqsubset_{\widehat{S}}\ \twoheaduparrow(e'_T, \varphi)\ \widehat{S}\ltimes_S\ e_S$$

…and "lift" is inverse of "compile" on compiler output

$$\forall (e'_T, \varphi) \in \mathcal{L}.\ \forall e_S, e_T.\ e_S \rightsquigarrow e_T \implies$$

$$e'_T\ {}_T\sqsubseteq_T\ e_T \implies \twoheaduparrow(e'_T, \varphi)\ \widehat{S}\sqsubseteq_S\ e_S$$

CCC Properties

Implies whole-program compiler correctness & correct separate compilation

Can be instantiated with different formalisms…

CCC with Pilsner

$\mathcal{L}$	$\{(e_T, \varphi) \mid \varphi = \text{source component } e_S \;\&\; \text{proof that } e_S \simeq e_T\}$
$\widehat{S}$	unchanged source language S
$\widehat{S}{\ltimes}_S$	unchanged source language linking
$\widehat{S}{\sqsubset}_S$	source language (whole program) observational equivalence
$\twoheaduparrow(\cdot)$	$\twoheaduparrow(e_T, (e_S, \_)) = e_S$

CCC with Multi-language

$\mathcal{L}$ $\{(e_T, \_) \mid$ where e_T is any target component $\}$

$\widehat{S}$ source-target multi-language ST

$\widehat{S}{\ltimes}_S$ $e\ {}_{ST}{\ltimes}_{ST}\ e_S$

$\widehat{S}{\sqsubset}_S$ run $\widehat{S}$ according to multi-lang ST, compare with running S

$\twoheaduparrow(\cdot)$ $\twoheaduparrow(e_T, \_) = \mathcal{ST}(e_T)$

Vertical Compositionality for Free

when $\Uparrow_{ST} = \Uparrow_{SI} \circ \Uparrow_{IT}$

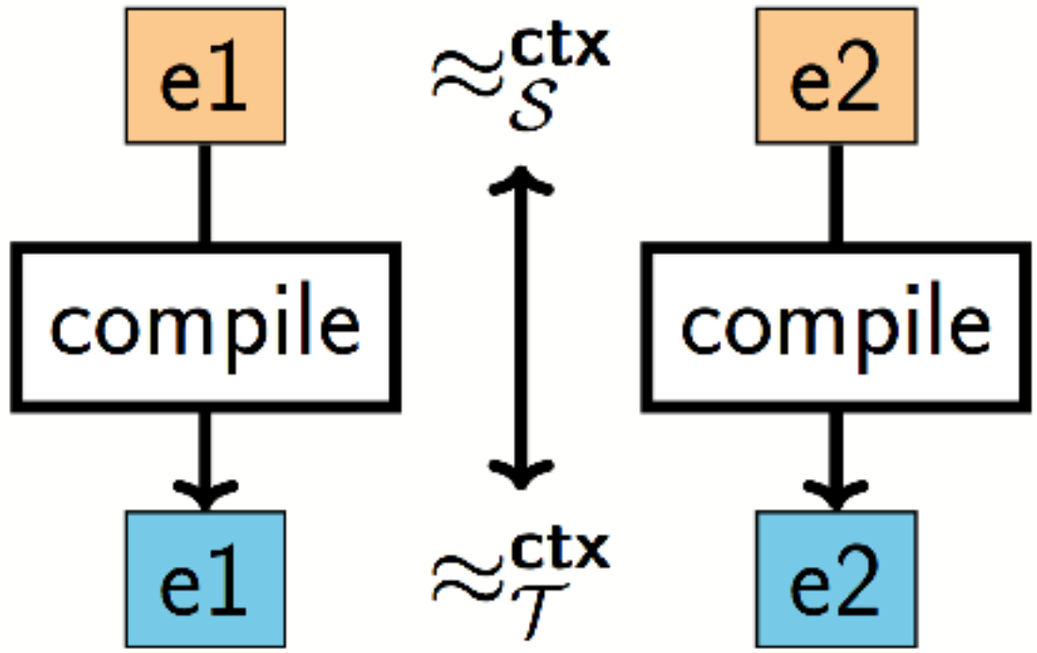
i.e., when lift $\Uparrow$ is a back-translation that maps every $e_T \in \mathcal{L}$ to some e_S

Fully abstract compilers have such back-translations!

Bonus of vertical comp: can verify different passes using different formalisms to instantiate CCC

Fully Abstract Compilers

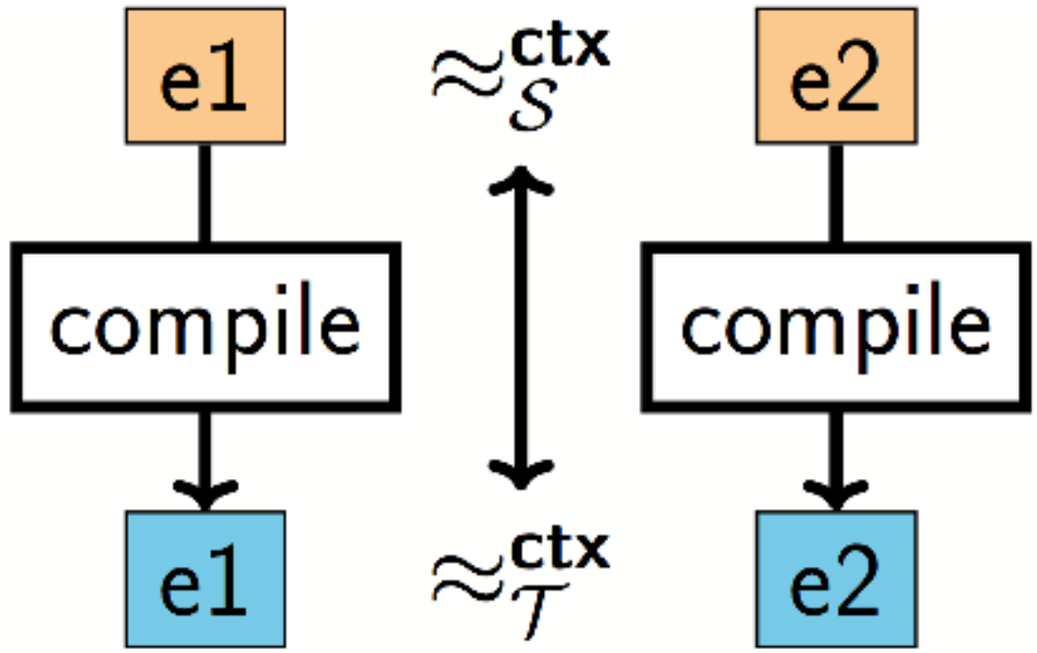
preserve equivalence



- ensure a compiled component does not interact with any target behavior that is inexpressible in S
- Do we want to link with behavior inexpressible in S? Or do we want fully abstract compilers?

Fully Abstract Compilers

preserve equivalence



- ensure a compiled component does not interact with any target behavior that is inexpressible in S
- Do we want to link with behavior inexpressible in S? Or do we want fully abstract compilers?

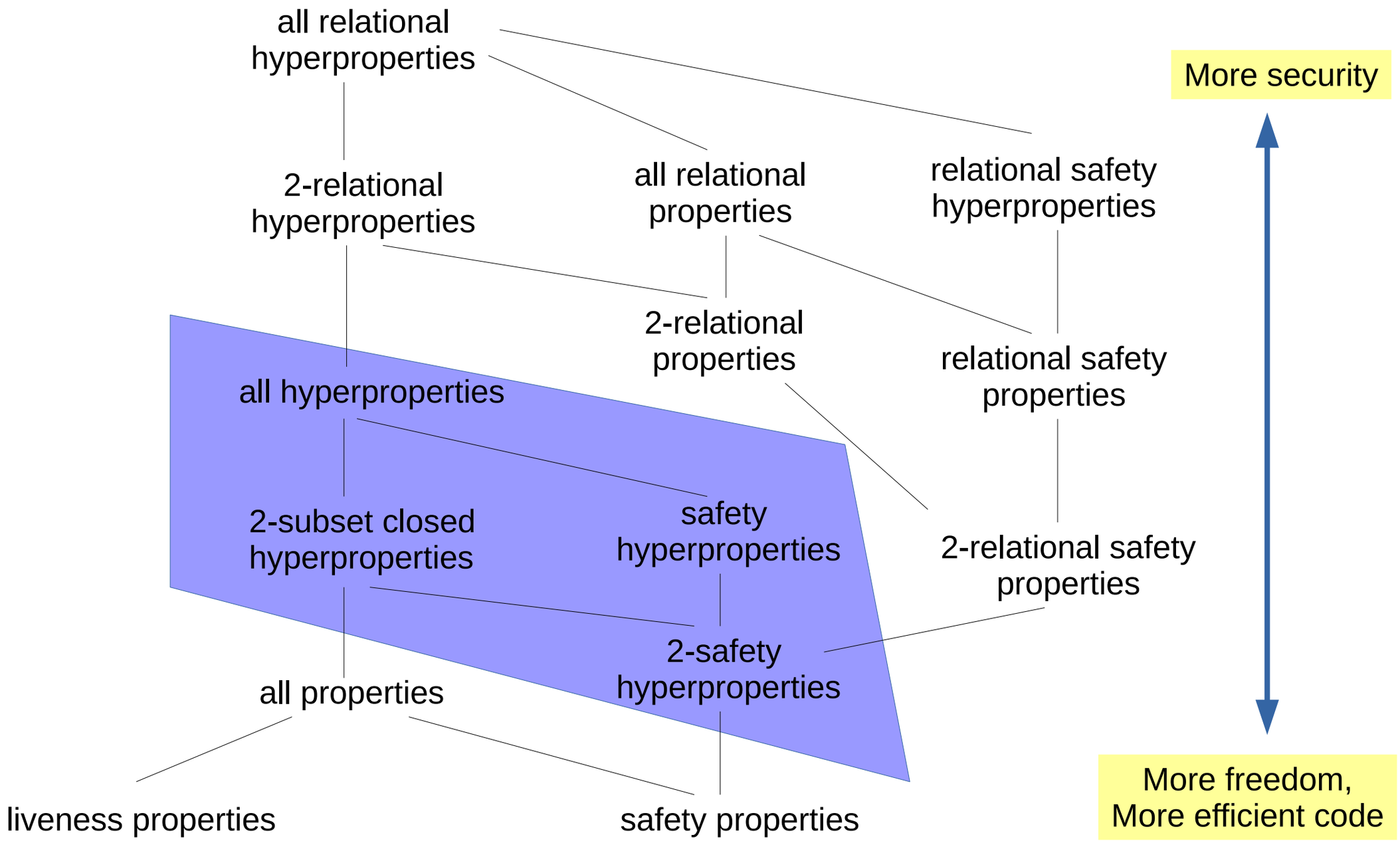
We want both!

Conclusion

- Common attacker model: low-level contexts that compiled code is linked with
- Compositional Compiler Correctness
  - allows linking with low-level code of arbitrary provenance
  - but source-independent linking and vertical compositionality are at odds

Relation to Deepak's talk...

A compiler is secure for X if it robustly preserves all X, where X is:



Relation to Deepak's talk...

Vertical compositionally needs back-translation that can only depend on A', or on A' and P, but not on traces t.

- Compiler security for all relational hyperproperties

  $\forall A'.\ \exists A.\ \forall P.\ \mathrm{Tr}(A' \,\|\, (P\downarrow)) = \mathrm{Tr}(A \,\|\, P)$

- Compiler security for all hyperproperties

  $\forall A'\ P.\ \exists A.\ \mathrm{Tr}(A' \,\|\, (P\downarrow)) = \mathrm{Tr}(A \,\|\, P)$

Relation to Deepak's talk...

Vertically compositional compiler correctness needs back-translation that can *only* depend on A', or on A' and P, but *NOT* on traces t.

Hence, *NOT* compatible with:

- Compiler security for safety

$$\forall A'\ P\ t.\ (t \in \mathrm{Fin}(A' \parallel (P\downarrow))) \Rightarrow \exists A.\ t \in \mathrm{Fin}(A \parallel P)$$

Vertically compositional compiler correctness seems unachievable for certain secure compilers -- those that wrap compiled code with fewer dynamic checks in an effort to attain "weaker but more efficient" secure compilation.