Linking Types: Secure compilation of multi-language programs

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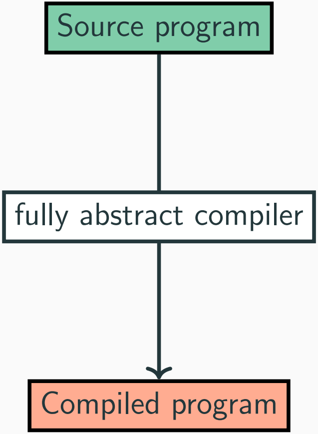
Fully abstract compilers



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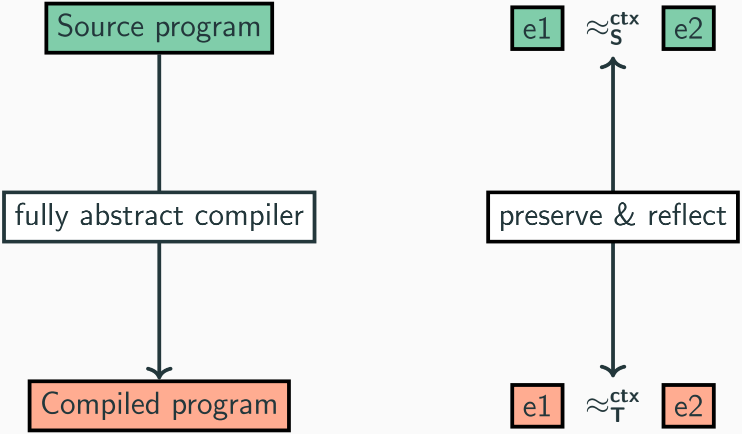
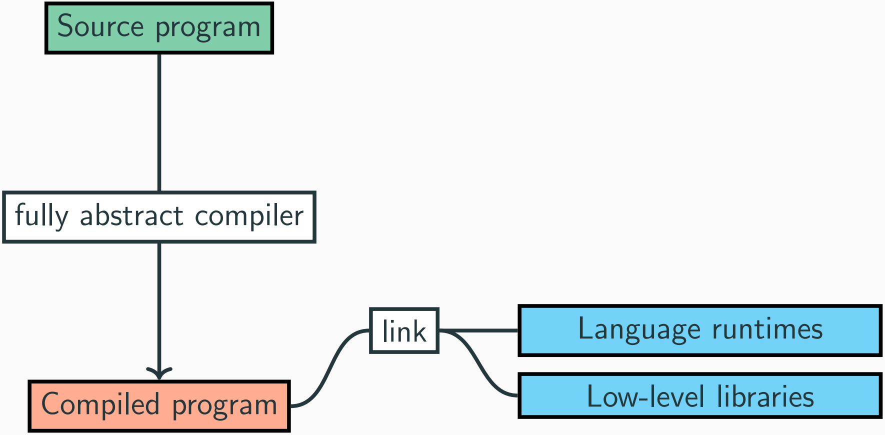


Fully abstract compilers in the real world



How do we implement fully abstract compilers for multi-language programs?

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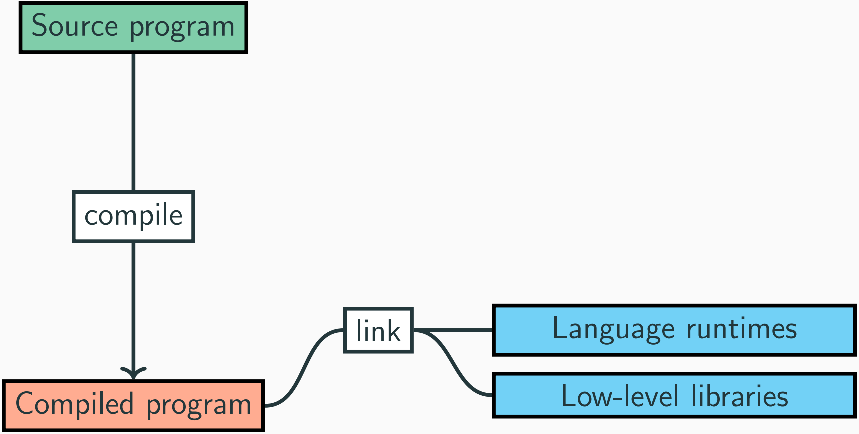

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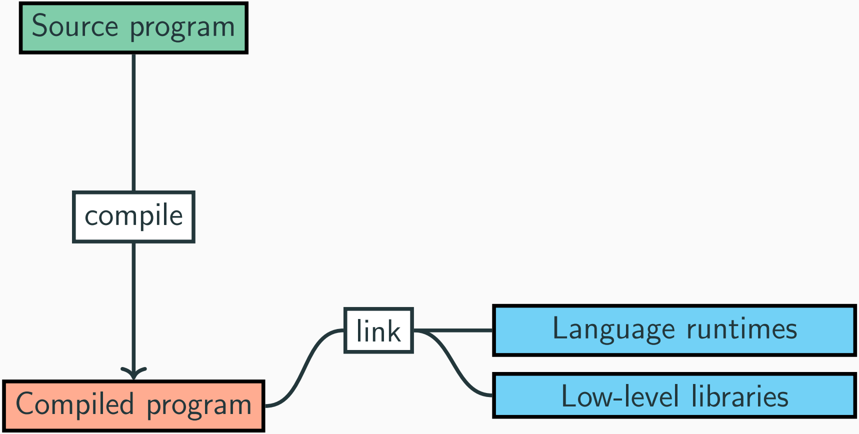

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- first-class control

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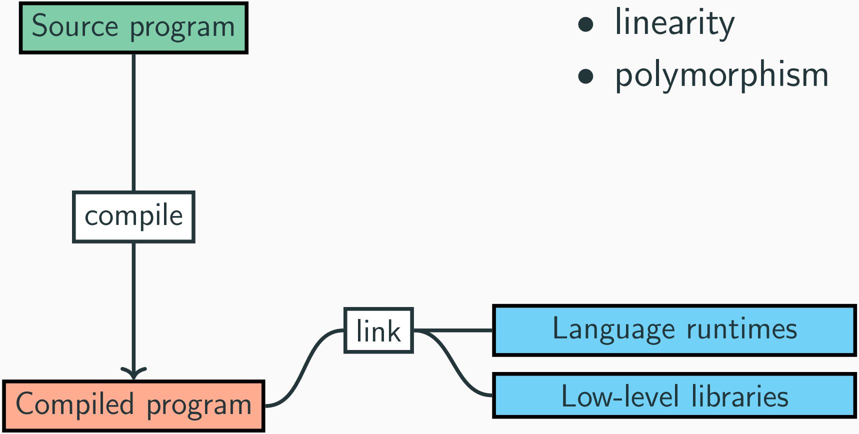

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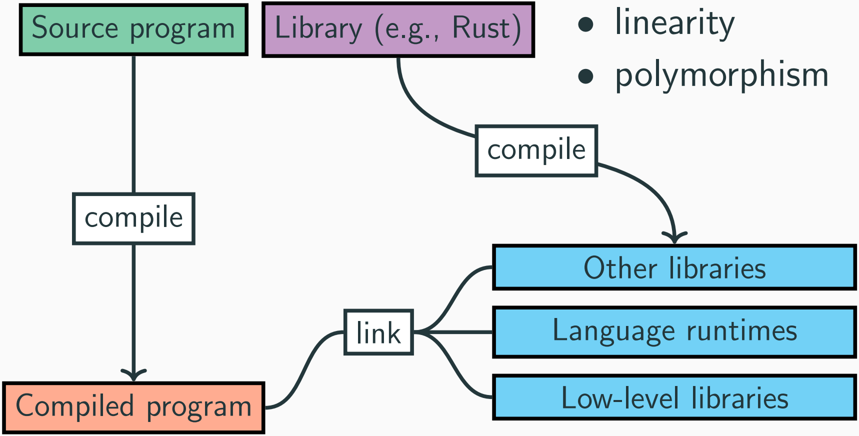

- linearity
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Without a full accounting for linking, full abstraction—and secure compilation—is doomed.

Full abstraction: by example

e.g. a pure language λ linking with a counter library

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$$\mathtt{C}^{\mathtt{counter}}[\lambda \mathtt{c}.\, \mathtt{c}()] \Downarrow 1 \qquad \mathtt{C}^{\mathtt{counter}}[\lambda \mathtt{c}.\, \mathtt{c}(); \mathtt{c}()] \Downarrow 2$$

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$$\mathsf{c}' : \mathtt{unit} \to \mathtt{int} \quad \neq \quad \mathsf{c} : \mathtt{unit} \to \mathtt{int}$$

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e.g. a pure language λ linking with a counter library

$$\lambda c.\, c() \not\approx^{ctx}_{\lambda^?} \lambda c.\, c(); c() : (\mathtt{unit} \rightarrow \mathtt{int}) \rightarrow \mathtt{int}$$

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$$C^{\mathtt{counter}}[\lambda c.\, c()] \Downarrow 1 \qquad C^{\mathtt{counter}}[\lambda c.\, c(); c()] \Downarrow 2$$

$$c' : \mathtt{unit} \rightarrow \mathtt{int} \quad \neq \quad c : \mathtt{unit} \rightarrow \mathtt{int}$$

Writing a type which corresponds to behavior **inexpressible** in your language is the essence of **linking types**.

Linking types: in more detail

Two source languages: λ and $\lambda^{\texttt{ref}}$.

$$
\begin{array}{lcl}
\tau & ::= & \texttt{unit} \mid \texttt{int} \mid \tau \rightarrow \tau \\
\texttt{e} & ::= & () \mid \texttt{n} \mid \texttt{x} \mid \lambda \texttt{x} : \tau . \texttt{e} \\
 & & \mid \texttt{e}\,\texttt{e} \mid \texttt{e} + \texttt{e} \mid \texttt{e} * \texttt{e} \\
\texttt{v} & ::= & () \mid \texttt{n} \mid \lambda \texttt{x} : \tau . \texttt{e}
\end{array}
\qquad
\begin{array}{lcl}
\tau & ::= & \ldots \mid \texttt{ref}\,\tau \\
\texttt{e} & ::= & \ldots \mid \texttt{ref}\,\texttt{e} \mid \texttt{e} := \texttt{e} \mid !\texttt{e} \\
\texttt{v} & ::= & \ldots \mid \ell
\end{array}
$$

Compiled to a shared, typed, target (not shown).

Linking types: extended language λ^κ

Extend λ to λ^κ:

$$
\begin{aligned}
\tau &::= \texttt{unit} \mid \texttt{int} \mid \texttt{ref}\,\tau \mid \tau \to \mathrm{R}^{\epsilon}\,\tau \\
\texttt{e} &::= () \mid \texttt{n} \mid \texttt{x} \mid \lambda\texttt{x} : \tau.\,\texttt{e} \mid \texttt{e}\,\texttt{e} \mid \texttt{e} + \texttt{e} \\
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Extend λ **types** to λ^κ:

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\end{aligned}$$

- $\mathtt{R}^{\circ}\,\tau$ is a pure computation.
- $\mathtt{R}^{\bullet}\,\tau$ may allocate, read, or write references.

Linking types: extended language λ^κ

Extend λ **terms** to λ^κ:

$$
\begin{aligned}
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&\quad \mid \texttt{e} * \texttt{e} \mid \textbf{ref e} \mid \textbf{e} := \textbf{e} \mid !\textbf{e} \\
\texttt{v} &::= () \mid \texttt{n} \mid \lambda \texttt{x} : \tau.\,\texttt{e} \mid \ell \\
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\end{aligned}
$$

- Add *representative* terms for new behavior.
- Programmers use these to *reason* about inhabitants of type $\texttt{R}^{\bullet}\,\tau$.

Linking types: using them

Consider the following λ programs

$$\texttt{program 1} \quad \lambda \texttt{f} : \texttt{int} \rightarrow \texttt{int}.\, \texttt{f}\ 0$$
$$\texttt{program 2} \quad \lambda \texttt{f} : \texttt{int} \rightarrow \texttt{int}.\, \texttt{f}\ 0;\ \texttt{f}\ 0$$

In λ^{κ}, by "default" $\texttt{f}$ has type: $\texttt{int} \rightarrow \texttt{R}^{\circ}\, \texttt{int}$

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In λ^{κ}, by "default" $\texttt{f}$ has type: $\texttt{int} \rightarrow \texttt{R}^{\circ}\, \texttt{int}$

But a programmer can annotate:

$$\begin{array}{ll} \texttt{program 1} & \lambda \texttt{f} : \texttt{int} \rightarrow \texttt{R}^{\bullet}\, \texttt{int}.\, \texttt{f}\, 0 \\ \texttt{program 2} & \lambda \texttt{f} : \texttt{int} \rightarrow \texttt{R}^{\bullet}\, \texttt{int}.\, \texttt{f}\, 0;\ \texttt{f}\, 0 \end{array}$$

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$$\forall \mathtt{e}_1, \mathtt{e}_2.\ \mathtt{e}_1 \approx^{ctx}_{\lambda} \mathtt{e}_2 : \tau \implies \mathtt{e}_1 \approx^{ctx}_{\lambda^\kappa} \mathtt{e}_2 : \kappa^+(\tau).$$

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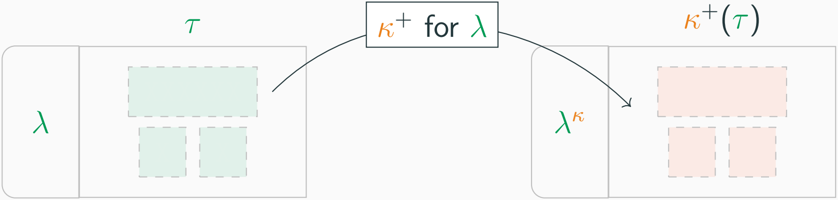

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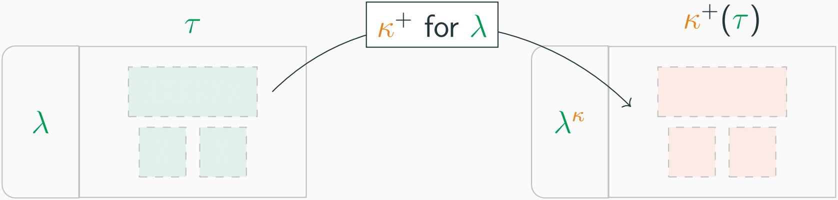
$$\begin{aligned} \kappa^+(\mathtt{unit}) &= \mathtt{unit} \\ \kappa^+(\mathtt{int}) &= \mathtt{int} \\ \kappa^+(\tau_1 \to \tau_2) &= \kappa^+(\tau_1) \to \mathtt{R}^\circ\, \kappa^+(\tau_2) \end{aligned}$$



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e.g.,

$$\lambda(\mathtt{r} : \mathtt{ref}\, \mathtt{int})(\mathtt{f} : \mathtt{ref}\, \mathtt{int} \to \mathtt{R}^{\bullet}\, \mathtt{int}).\, \mathtt{f}\, \mathtt{r}$$

$$\stackrel{\kappa^-}{\Longrightarrow} \lambda(\mathtt{r} : \mathtt{int})(\mathtt{f} : \mathtt{int} \to \mathtt{int}).\, \mathtt{f}\, \mathtt{r}$$

More about equivalences

$\texttt{program}\,\texttt{A} - \lambda\texttt{f} : \texttt{int} \to \texttt{int}.\, \texttt{1}$

$\texttt{program}\,\texttt{B} - \lambda\texttt{f} : \texttt{int} \to \texttt{int}.\, \texttt{f}\,\texttt{0};\ \texttt{1}$

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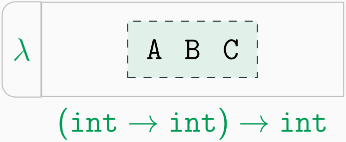

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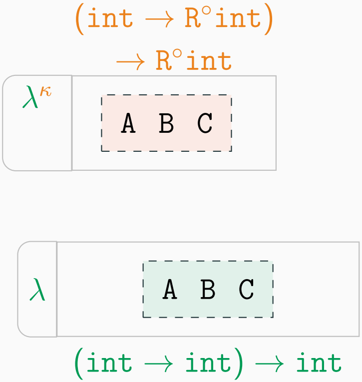

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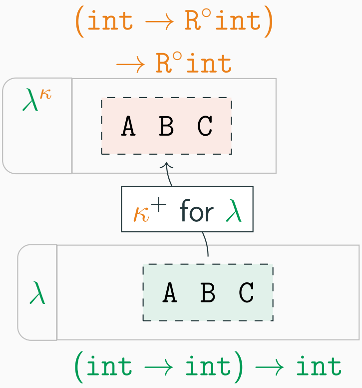

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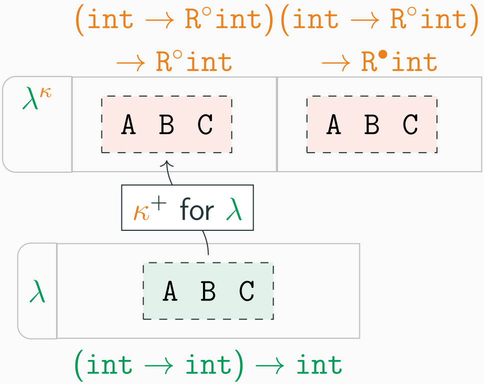

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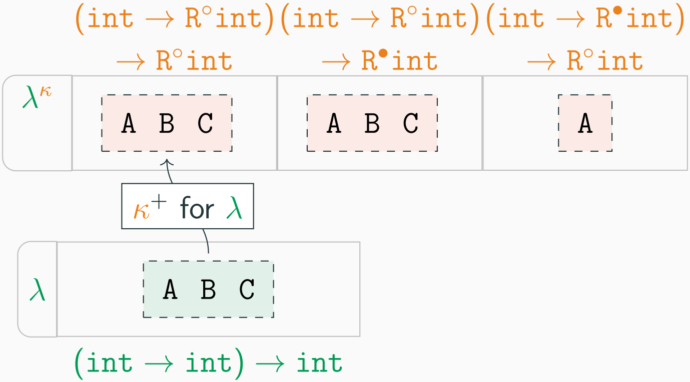

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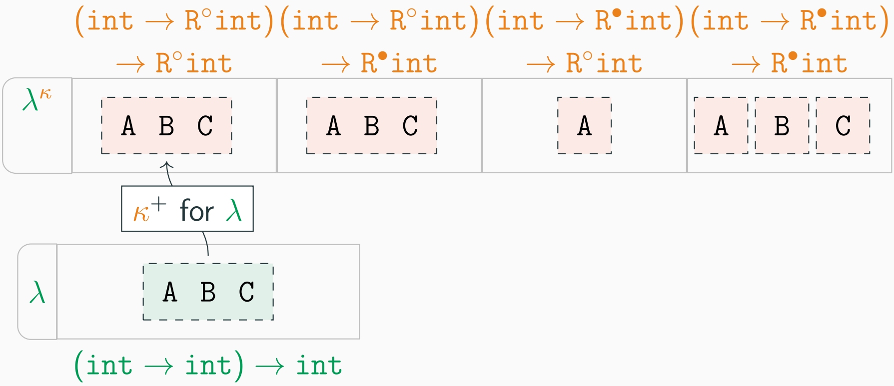

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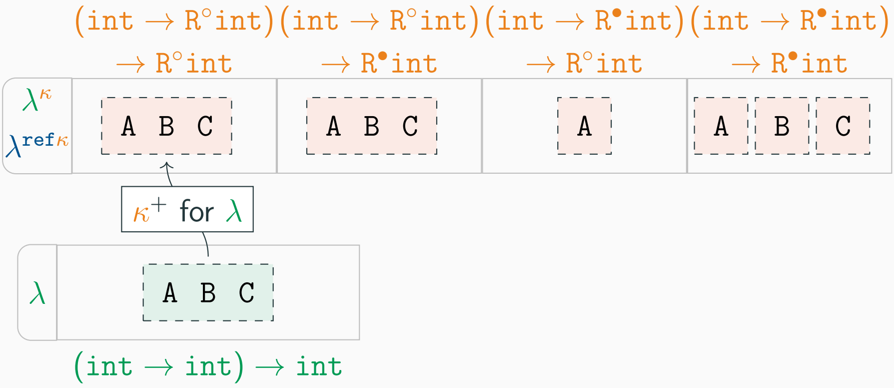

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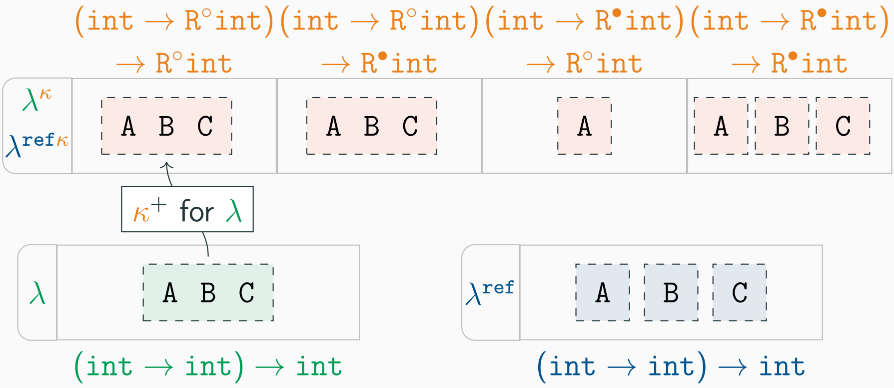

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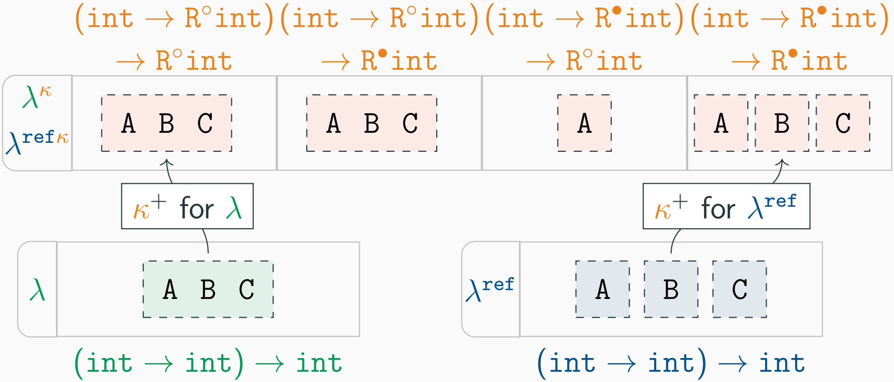

Linking types: back to example

$$\lambda \mathtt{c}\colon \mathtt{unit} \rightarrow \mathtt{int}.\, \mathtt{c}() \approx^{ctx}_{\lambda^{\kappa}} \lambda \mathtt{c}\colon \mathtt{unit} \rightarrow \mathtt{int}.\, \mathtt{c}(); \mathtt{c}()$$

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With **linking types**, the programmer specifies the equivalences she wants, in a language she can understand.

Linking types: next steps

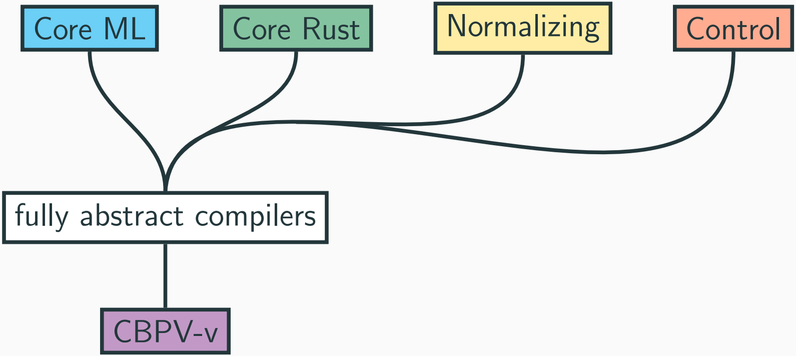
Core ML

Core Rust

Normalizing

Control

Linking types: next steps



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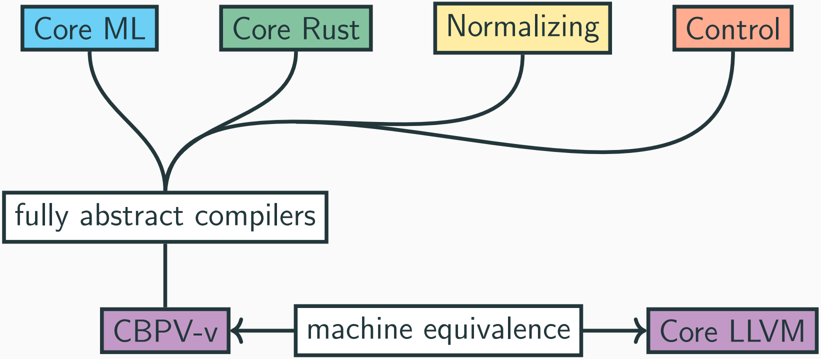
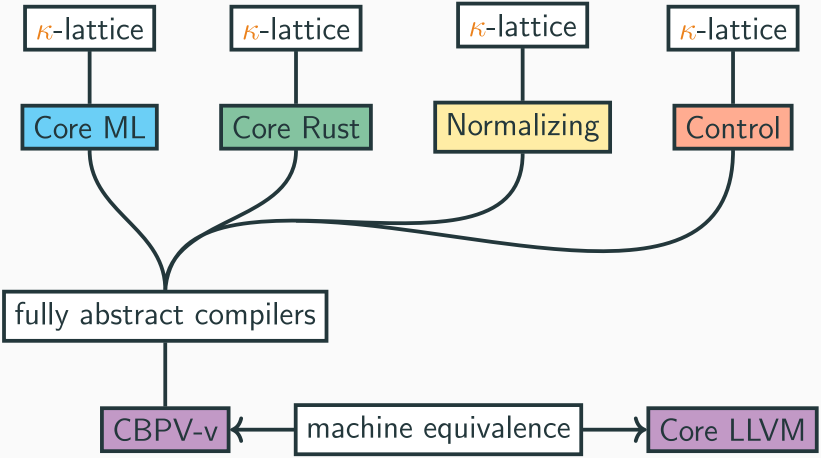


Linking types: next steps



Linking types make realizing fully abstract compilation possible in multi-language systems

Learn more:
https://dbp.io/pubs/2017/linking-types-snapl-submission.pdf

Linking types make realizing fully abstract compilation possible in multi-language systems (which are the only systems that really exist).

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Linking types: extra content

Backwards Compatibility

- Annotations are optional for programmers.
- To change target, only need to fully abstractly compile old target to the new.

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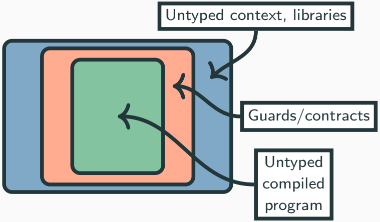
Developer Tooling

- With typed target, type translations can guide if two components can be linked together.
- Type translate to target, attempt reverse type translation to other language. Enables *cross-language type errors*.

Full abstraction: different approaches

Dynamic enforcement

- Devriese *et al.*, POPL16
- Patrignani *et al.*, TOPLAS15
- Patrignani, 2015 Dissertation
- *etc.*



Typed target languages

- New *et al.*, ICFP16
- Ahmed, Blume, ICFP11
- *etc.*