An Adjoint Separation Logic for the Wasm Call Stack

Work in Progress!

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June 11, 2025 @ Dagstuhl 25241

Context: Formally Specifying ABIs

Application Binary Interface (ABI)

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

– Swift

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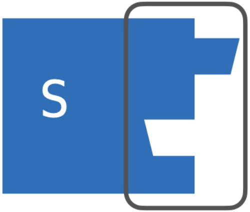

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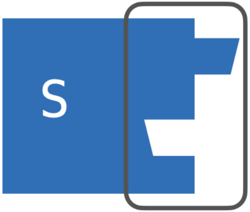

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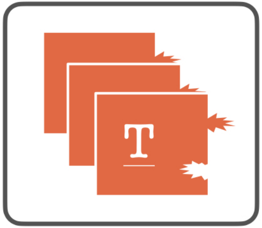

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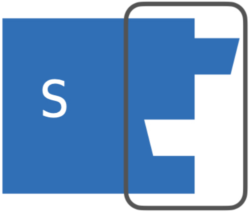

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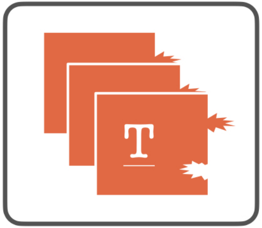
$\underline{e}$ is **ABI compliant** with τ if

$$\underline{e} \in \llbracket \tau \rrbracket$$



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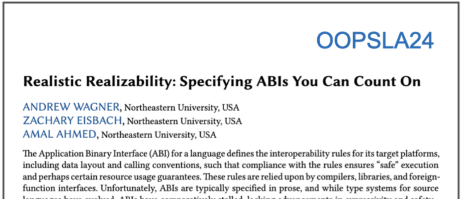

OOPSLA24

Realistic Realizability: Specifying ABIs You Can Count On

ANDREW WAGNER, Northeastern University, USA
ZACHARY EISBACH, Northeastern University, USA
AMAL AHMED, Northeastern University, USA

The Application Binary Interface (ABI) for a language defines the interoperability rules for its target platforms, including data layout and calling conventions, such that compliance with the rules ensures "safe" execution and perhaps certain resource usage guarantees. These rules are relied upon by compilers, libraries, and foreign-function interfaces. Unfortunately, ABIs are typically specified in prose, and while type systems for source

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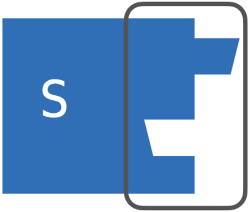

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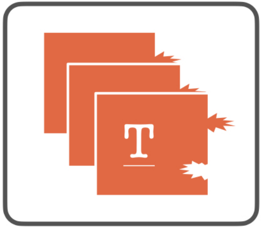

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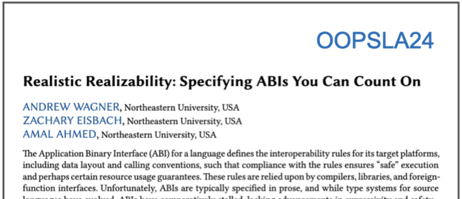
Target-level separation logic predicate



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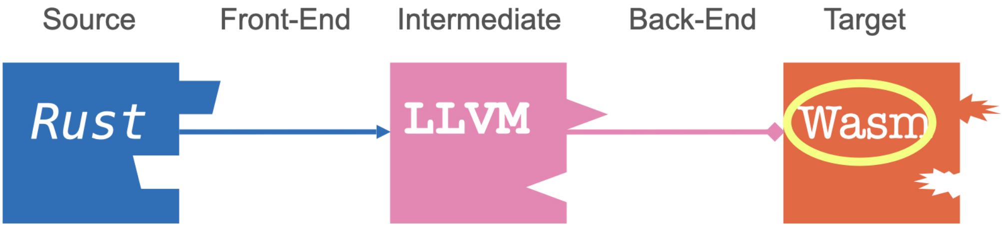
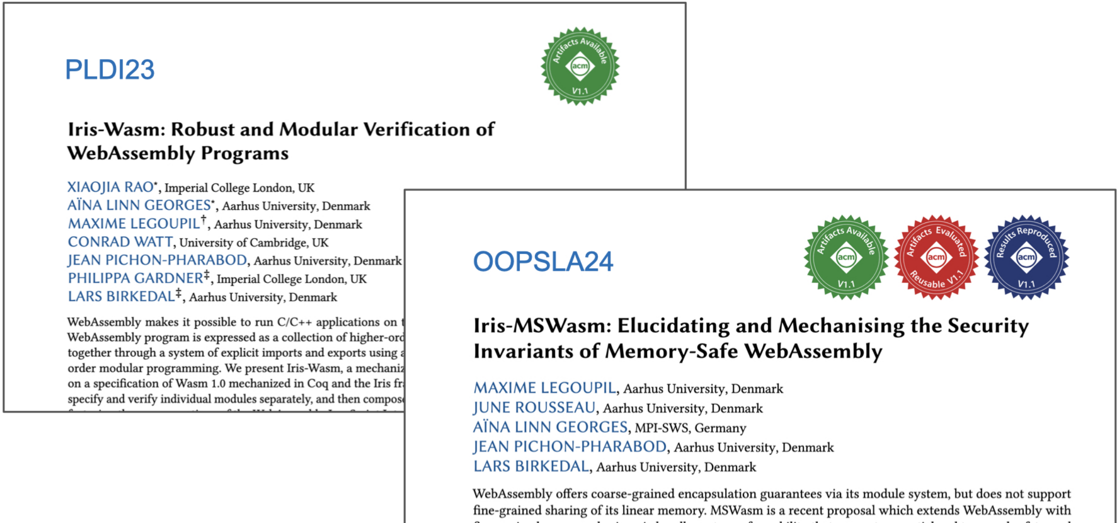


$$\Gamma \vdash e : T \cdots\cdots\blacktriangleright \{[\![\Gamma]\!]\}\ e\ \{[\![T]\!]\} \cdots\cdots\blacklozenge \{[\![\Gamma]\!]\}\ e\ \{[\![T]\!]\}$$

We need:

1. A `semantics` for borrowing
2. To support *independent updates* to the `front-end` and `back-end`
3. A separation logic for Wasm

State of the Art: IrisWasm



PLDI23

Iris-Wasm: Robust and Modular Verification of WebAssembly Programs

XIAOJIA RAO*, Imperial College London, UK
AÏNA LINN GEORGES*, Aarhus University, Denmark
MAXIME LEGOUPIL†, Aarhus University, Denmark
CONRAD WATT, University of Cambridge, UK
JEAN PICHON-PHARABOD, Aarhus University, Denmark
PHILIPPA GARDNER‡, Imperial College London, UK
LARS BIRKEDAL‡, Aarhus University, Denmark

WebAssembly makes it possible to run C/C++ applications on t
WebAssembly program is expressed as a collection of higher-ord
together through a system of explicit imports and exports using a
order modular programming. We present Iris-Wasm, a mechaniz
on a specification of Wasm 1.0 mechanized in Coq and the Iris fr
specify and verify individual modules separately, and then compose

OOPSLA24

Iris-MSWasm: Elucidating and Mechanising the Security Invariants of Memory-Safe WebAssembly

MAXIME LEGOUPIL, Aarhus University, Denmark
JUNE ROUSSEAU, Aarhus University, Denmark
AÏNA LINN GEORGES, MPI-SWS, Germany
JEAN PICHON-PHARABOD, Aarhus University, Denmark
LARS BIRKEDAL, Aarhus University, Denmark

WebAssembly offers coarse-grained encapsulation guarantees via its module system, but does not support fine-grained sharing of its linear memory. MSWasm is a recent proposal which extends WebAssembly with

IrisWasm: Sample wp Rules

`wp_binop`

$$\frac{[\![t.\mathit{binop}]\!](c_1, c_2) = c \ast \triangleright \Phi(\mathbf{immV}\ [t.\mathbf{const}\ c]) \ast \xhookrightarrow{\text{FR}} F}{\text{wp}\ [t.\mathbf{const}\ c_1; t.\mathbf{const}\ c_2; t.\mathbf{binop}\ \mathit{binop}]\ \left\{w, \Phi(w) \ast \xhookrightarrow{\text{FR}} F\right\}}$$

`wp_call`

$$\frac{(F.\text{inst}.\text{funcs}[i] = \mathit{addri}) \ast \xhookrightarrow{\text{FR}} F \ast \triangleright\left(\xhookrightarrow{\text{FR}} F \mathrel{-\!\!\ast} \text{wp}\ [\mathbf{invoke}\ \mathit{addri}]\ \{w, \Phi(w)\}\right)}{\text{wp}\ [\mathbf{call}\ i]\ \{w, \Phi(w)\}}$$

`wp_invoke_native`

$$\frac{\begin{array}{c}|\mathit{vs}| = |\mathit{ts}_1| \ast \mathit{cl} = \{(\mathit{inst}; \mathit{ts}); \mathit{es}\}^{\text{NativeCl}}_{(\mathit{ts}_1 \to \mathit{ts}_2)} \ast F' = \{\text{locs} := \mathit{vs} +\!\!+\ \mathbf{zeros}(\mathit{ts}); \text{inst} := \mathit{inst}\} \ast \\ i \xmapsto{\text{wf}} \mathit{cl} \ast \xhookrightarrow{\text{FR}} F \ast \triangleright \left[\begin{array}{c}(i \xmapsto{\text{wf}} \mathit{cl} \ast \xhookrightarrow{\text{FR}} F) \mathrel{-\!\!\ast} \\ \text{wp}\ \left[\mathbf{local}_{|\mathit{ts}_2|}\{F'\}\ (\mathbf{block}\ ([] \to \mathit{ts}_2)\ \mathit{es})\ \mathbf{end}\right]\ \{w, \Phi(w)\}\end{array}\right]\end{array}}{\text{wp}\ (\mathit{vs} +\!\!+\ \mathbf{invoke}\ i)\ \{w, \Phi(w)\}}$$

`wp_local_bind`

$$\frac{\xhookrightarrow{\text{FR}} F \ast \left(\xhookrightarrow{\text{FR}} F_1 \mathrel{-\!\!\ast} \text{wp}\ \mathit{es} \left\{w, \exists F_1', \xhookrightarrow{\text{FR}} F_1' \ast \left(\xhookrightarrow{\text{FR}} F \mathrel{-\!\!\ast} \text{wp}\ [\mathbf{local}_n\{F_1'\}\ w\ \mathbf{end}]\ \{w', \Phi(w')\}\right)\right\}\right)}{\text{wp}\ [\mathbf{local}_n\{F_1\}\ \mathit{es}\ \mathbf{end}]\ \{w', \Phi(w')\}}$$

What do all of these rules have in common?

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Explicit threading of the monolithic "frame resource" $\xhookrightarrow{\textsc{Fr}} F$

Context Splitting

$$\Gamma \vdash \mathsf{e} : \mathsf{T}$$

$$\rightsquigarrow$$

$$\{\llbracket \Gamma \rrbracket\}\ \mathsf{e}^{*}\ \{\llbracket \mathsf{T} \rrbracket\}$$

Context Splitting

$$\begin{tikzcd}
\Gamma \vdash e : T \arrow[d, rightsquigarrow] & (\Gamma = \overline{x : T_x}) \\
\{F \star \cdots\}\ e^*\ \{[\![T]\!]\} & (F = \overline{\$x \mapsto v_x})
\end{tikzcd}$$

Context Splitting

$$\otimes\mathrm{I}\;\frac{\Gamma_1 \vdash e_1 : T_1 \qquad \Gamma_2 \vdash e_2 : T_2}{\Gamma_1, \Gamma_2 \vdash (e_1, e_2) : T_1 \otimes T_2}$$

$$\rightsquigarrow$$

$$\{F_1 \star F_2 \star \cdots\}\; e_1^*; e_2^*\; \{[\![T_1]\!] \star [\![T_2]\!]\}$$

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WP-PLUS

$$\frac{\Phi(\mathsf{i32.const}\,(n_1 + n_2))}{\mathsf{wp}\ \ (\mathsf{i32.const}\, n_1; \mathsf{i32.const}\, n_2; \mathsf{i32.add})\ \{\Phi\}}$$

WP-LOC-GET

$$\frac{\$x \xrightarrow{\mathsf{loc}} v \star \Phi(v)}{\mathsf{wp}\ \ (\mathsf{local.get}\, \$x)\ \{\Phi\}}$$

WP-LOC-SET

$$\frac{\$x \xrightarrow{\mathsf{loc}} v' \star (\$x \xrightarrow{\mathsf{loc}} v \mathrel{-\!\!\star} \Phi(\epsilon))}{\mathsf{wp}\ \ (v; \mathsf{local.get}\, \$x)\ \{\Phi\}}$$

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WP-FRAME-BIND†

$$\frac{F \mathrel{-\!\!\star} \textsf{wp}\ (e^*)\ \{v^n.\ \Phi(v^n)\}}{\textsf{wp}\ (\textsf{frame}_n\,F\,e^*)\ \{\Phi\}}$$

Problem 1: Popped Frames Not Encapsulated

$$\frac{}{\mathsf{wp}\ \left(\mathsf{frame}_0\,(\mathsf{locals}\,(\$x\ 42))\,\epsilon\right)\ \{\$x \xmapsto{\mathsf{loc}} 42\}}$$

Local $\$x$ should not be returnable from the frame. This *should* be false.

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Binding under a frame moves the postcondition under a pop:

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$$\frac{}{\$x \overset{\mathsf{loc}}{\longmapsto} 42 \vdash \mathsf{wp}\ \ (\mathsf{frame}_1\,(\mathsf{locals})\,\mathsf{local.get}\,\$x)\ \{v.\ v = \mathsf{i32.const}\,42\}}$$

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Adjoint Logic

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They form an adjunction:

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Example: Suspending and Resuming Frames

$\$x \xmapsto{\mathsf{loc}} 20 \vdash \mathsf{wp}\ ((\mathsf{frame}_1\ (\mathsf{locals})\ \mathsf{i32.const}\, 25)\, ; \mathsf{local.get}\, \$x ; \mathsf{i32.add})\ \{v.\ v = 45\}$

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$$\text{(WP-CTX-BIND)}\ \frac{\$x \overset{\text{loc}}{\longmapsto} 20 \vdash \text{wp}\ (\text{frame}_1\ (\text{locals})\ \text{i32.const}\ 25)\ \{v'.\ \text{wp}\ (v'; \text{local.get}\ \$x; \text{i32.add})\ \{v.v = 45\}\}}{\$x \overset{\text{loc}}{\longmapsto} 20 \vdash \text{wp}\ ((\text{frame}_1\ (\text{locals})\ \text{i32.const}\ 25)\ ; \text{local.get}\ \$x; \text{i32.add})\ \{v.\ v = 45\}}$$

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$$\dfrac{\dfrac{\dfrac{\downarrow(\$x \overset{\text{loc}}{\longmapsto} 20) \vdash \text{wp }(\text{i32.const}\,25)\ \{v'.\ \downarrow\text{wp }(v';\text{local.get}\,\$x;\text{i32.add})\ \{v.\ v = 45\}\}}{\$x \overset{\text{loc}}{\longmapsto} 20 \vdash \uparrow\text{wp }(\text{i32.const}\,25)\ \{v'.\ \downarrow\text{wp }(v';\text{local.get}\,\$x;\text{i32.add})\ \{v.\ v = 45\}\}}\,(\updownarrow\text{-ADJ})}{\$x \overset{\text{loc}}{\longmapsto} 20 \vdash \text{wp }(\text{frame}_1\ (\text{locals})\ \text{i32.const}\,25)\ \{v'.\ \text{wp }(v';\text{local.get}\,\$x;\text{i32.add})\ \{v.v = 45\}\}}\,(\text{WP-FRAME-BIND})}{\$x \overset{\text{loc}}{\longmapsto} 20 \vdash \text{wp }((\text{frame}_1\ (\text{locals})\ \text{i32.const}\,25)\,;\text{local.get}\,\$x;\text{i32.add})\ \{v.\ v = 45\}}\,(\text{WP-CTX-BIND})$$

Example: Suspending and Resuming Frames

$$\downarrow(\$x \xmapsto{\mathsf{loc}} 20) \vdash \downarrow \mathsf{wp}\ (\mathsf{i32.const}\ 25; \mathsf{local.get}\ \$x; \mathsf{i32.add})\ \{v.\ v = 45\}$$

(WP-VAL)

$$\downarrow(\$x \xmapsto{\mathsf{loc}} 20) \vdash \mathsf{wp}\ (\mathsf{i32.const}\ 25)\ \{v'.\ \downarrow \mathsf{wp}\ (v'; \mathsf{local.get}\ \$x; \mathsf{i32.add})\ \{v.\ v = 45\}\}$$

($\updownarrow$ -ADJ)

$$\$x \xmapsto{\mathsf{loc}} 20 \vdash \uparrow \mathsf{wp}\ (\mathsf{i32.const}\ 25)\ \{v'.\ \downarrow \mathsf{wp}\ (v'; \mathsf{local.get}\ \$x; \mathsf{i32.add})\ \{v.\ v = 45\}\}$$

(WP-FRAME-BIND)

$$\$x \xmapsto{\mathsf{loc}} 20 \vdash \mathsf{wp}\ (\mathsf{frame}_1\ (\mathsf{locals})\ \mathsf{i32.const}\ 25)\ \{v'.\ \mathsf{wp}\ (v'; \mathsf{local.get}\ \$x; \mathsf{i32.add})\ \{v.v = 45\}\}$$

(WP-CTX-BIND)

$$\$x \xmapsto{\mathsf{loc}} 20 \vdash \mathsf{wp}\ ((\mathsf{frame}_1\ (\mathsf{locals})\ \mathsf{i32.const}\ 25)\ ; \mathsf{local.get}\ \$x; \mathsf{i32.add})\ \{v.\ v = 45\}$$

Example: Suspending and Resuming Frames

$$\$x \overset{\mathsf{loc}}{\longmapsto} 20 \vdash \mathsf{wp}\ (\mathsf{i32.const}\ 25; \mathsf{local.get}\ \$x; \mathsf{i32.add})\ \{v.\ v = 45\}$$

(↓ -Mono)

$$\downarrow (\$x \overset{\mathsf{loc}}{\longmapsto} 20) \vdash {\downarrow} \mathsf{wp}\ (\mathsf{i32.const}\ 25; \mathsf{local.get}\ \$x; \mathsf{i32.add})\ \{v.\ v = 45\}$$

(WP-VAL)

$$\downarrow (\$x \overset{\mathsf{loc}}{\longmapsto} 20) \vdash \mathsf{wp}\ (\mathsf{i32.const}\ 25)\ \{v'.\ {\downarrow} \mathsf{wp}\ (v'; \mathsf{local.get}\ \$x; \mathsf{i32.add})\ \{v.\ v = 45\}\}$$

(↕ -Adj)

$$\$x \overset{\mathsf{loc}}{\longmapsto} 20 \vdash {\uparrow} \mathsf{wp}\ (\mathsf{i32.const}\ 25)\ \{v'.\ {\downarrow} \mathsf{wp}\ (v'; \mathsf{local.get}\ \$x; \mathsf{i32.add})\ \{v.\ v = 45\}\}$$

(WP-FRAME-BIND)

$$\$x \overset{\mathsf{loc}}{\longmapsto} 20 \vdash \mathsf{wp}\ (\mathsf{frame}_1\ (\mathsf{locals})\ \mathsf{i32.const}\ 25)\ \{v'.\ \mathsf{wp}\ (v'; \mathsf{local.get}\ \$x; \mathsf{i32.add})\ \{v.v = 45\}\}$$

(WP-CTX-BIND)

$$\$x \overset{\mathsf{loc}}{\longmapsto} 20 \vdash \mathsf{wp}\ ((\mathsf{frame}_1\ (\mathsf{locals})\ \mathsf{i32.const}\ 25)\ ; \mathsf{local.get}\ \$x; \mathsf{i32.add})\ \{v.\ v = 45\}$$

Example: Suspending and Resuming Frames

(WP-CTX-BIND, WP-LOCAL-GET, WP-BINOP, WP-VAL)

$$\$x \overset{\text{loc}}{\longmapsto} 20 \vdash \text{wp}\ (\text{i32.const}\, 25; \text{local.get}\, \$x; \text{i32.add})\ \{v.\ v = 45\}$$

(↓ -Mono)

$$\downarrow (\$x \overset{\text{loc}}{\longmapsto} 20) \vdash \downarrow \text{wp}\ (\text{i32.const}\, 25; \text{local.get}\, \$x; \text{i32.add})\ \{v.\ v = 45\}$$

(WP-VAL)

$$\downarrow (\$x \overset{\text{loc}}{\longmapsto} 20) \vdash \text{wp}\ (\text{i32.const}\, 25)\ \{v'.\ \downarrow \text{wp}\ (v'; \text{local.get}\, \$x; \text{i32.add})\ \{v.\ v = 45\}\}$$

(↕ -Adj)

$$\$x \overset{\text{loc}}{\longmapsto} 20 \vdash \uparrow \text{wp}\ (\text{i32.const}\, 25)\ \{v'.\ \downarrow \text{wp}\ (v'; \text{local.get}\, \$x; \text{i32.add})\ \{v.\ v = 45\}\}$$

(WP-FRAME-BIND)

$$\$x \overset{\text{loc}}{\longmapsto} 20 \vdash \text{wp}\ (\text{frame}_1\ (\text{locals})\ \text{i32.const}\, 25)\ \{v'.\ \text{wp}\ (v'; \text{local.get}\, \$x; \text{i32.add})\ \{v.v = 45\}\}$$

(WP-CTX-BIND)

$$\$x \overset{\text{loc}}{\longmapsto} 20 \vdash \text{wp}\ ((\text{frame}_1\ (\text{locals})\ \text{i32.const}\, 25)\, ; \text{local.get}\, \$x; \text{i32.add})\ \{v.\ v = 45\}$$

Other Stacks

Other Stacks

A shadow stack

WP-SPUSH

$$\frac{\uparrow^{s} \Phi(\epsilon)}{\mathsf{wp}\ (\$\mathsf{spush})\ \{\Phi\}}$$

WP-SPOP

$$\frac{\downarrow_{s} \Phi(\epsilon)}{\mathsf{wp}\ (\$\mathsf{spop})\ \{\Phi\}}$$

WP-SALLOC

$$\frac{\forall n', b^{n}.\ n' \xmapsto{\mathsf{stk}} b^{n} \mathrel{-\!\!\star} \Phi(\mathsf{i32.const}\, n')}{\mathsf{wp}\ (\$\mathsf{salloc}\, n)\ \{\Phi\}}$$

Other Stacks

A shadow stack

$$\textsc{wp-spush}\ \frac{\uparrow^{s} \Phi(\epsilon)}{\mathsf{wp}\ (\$\mathsf{spush})\ \{\Phi\}} \qquad \textsc{wp-spop}\ \frac{\downarrow_{s} \Phi(\epsilon)}{\mathsf{wp}\ (\$\mathsf{spop})\ \{\Phi\}} \qquad \textsc{wp-salloc}\ \frac{\forall n', b^{n}.\ n' \xmapsto{\mathsf{stk}} b^{n} \mathrel{-\!\!\star} \Phi(\mathsf{i32.const}\, n')}{\mathsf{wp}\ (\$\mathsf{salloc}\, n)\ \{\Phi\}}$$

The operand stack?

$$\mathsf{top}(20) \star \downarrow_{o} \mathsf{top}(25) \star \downarrow_{o} \downarrow_{o} \mathsf{top}(10) \approx \mathsf{i32.const}\ 10; v; \mathsf{i32.const}\ 25; \mathsf{i32.const}\ 20$$

Other Stacks

A shadow stack

WP-SPUSH

$$\frac{\uparrow^{s} \Phi(\epsilon)}{\mathsf{wp}\ (\$\mathsf{spush})\ \{\Phi\}}$$

WP-SPOP

$$\frac{\downarrow_{s} \Phi(\epsilon)}{\mathsf{wp}\ (\$\mathsf{spop})\ \{\Phi\}}$$

WP-SALLOC

$$\frac{\forall n', b^{n}.\ n' \xmapsto{\mathsf{stk}} b^{n} \mathrel{-\!\!\star} \Phi(\mathsf{i32.const}\, n')}{\mathsf{wp}\ (\$\mathsf{salloc}\, n)\ \{\Phi\}}$$

The operand stack?

$$\mathsf{top}(20) \star {\downarrow_o} \mathsf{top}(25) \star {\downarrow_o} {\downarrow_o} \mathsf{top}(10) \approx \mathsf{i32.const}\ 10; v; \mathsf{i32.const}\ 25; \mathsf{i32.const}\ 20$$

Stack switching?

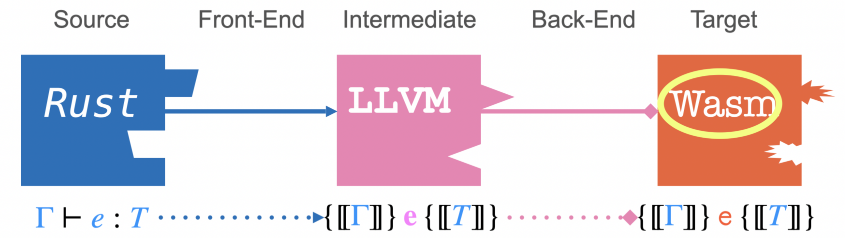
Summary

WP-FRAME-BIND

$$\frac{\uparrow (F \mathrel{-\!\!\star} \mathsf{wp}\ (e^*)\ \{v^n.\ \downarrow \Phi(v^n)\})}{\mathsf{wp}\ (\mathsf{frame}_n\ F\ e^*)\ \{\Phi\}}$$

$\updownarrow$-ADJ

$$\begin{array}{c} \downarrow P \vdash Q \\ \hline\hline P \vdash \uparrow Q \end{array}$$



Source

Front-End

Intermediate

Back-End

Target

Rust

LLVM

Wasm

$\Gamma \vdash e : T$

$\{[\![\Gamma]\!]\}\ e\ \{[\![T]\!]\}$

$\{[\![\Gamma]\!]\}\ e\ \{[\![T]\!]\}$