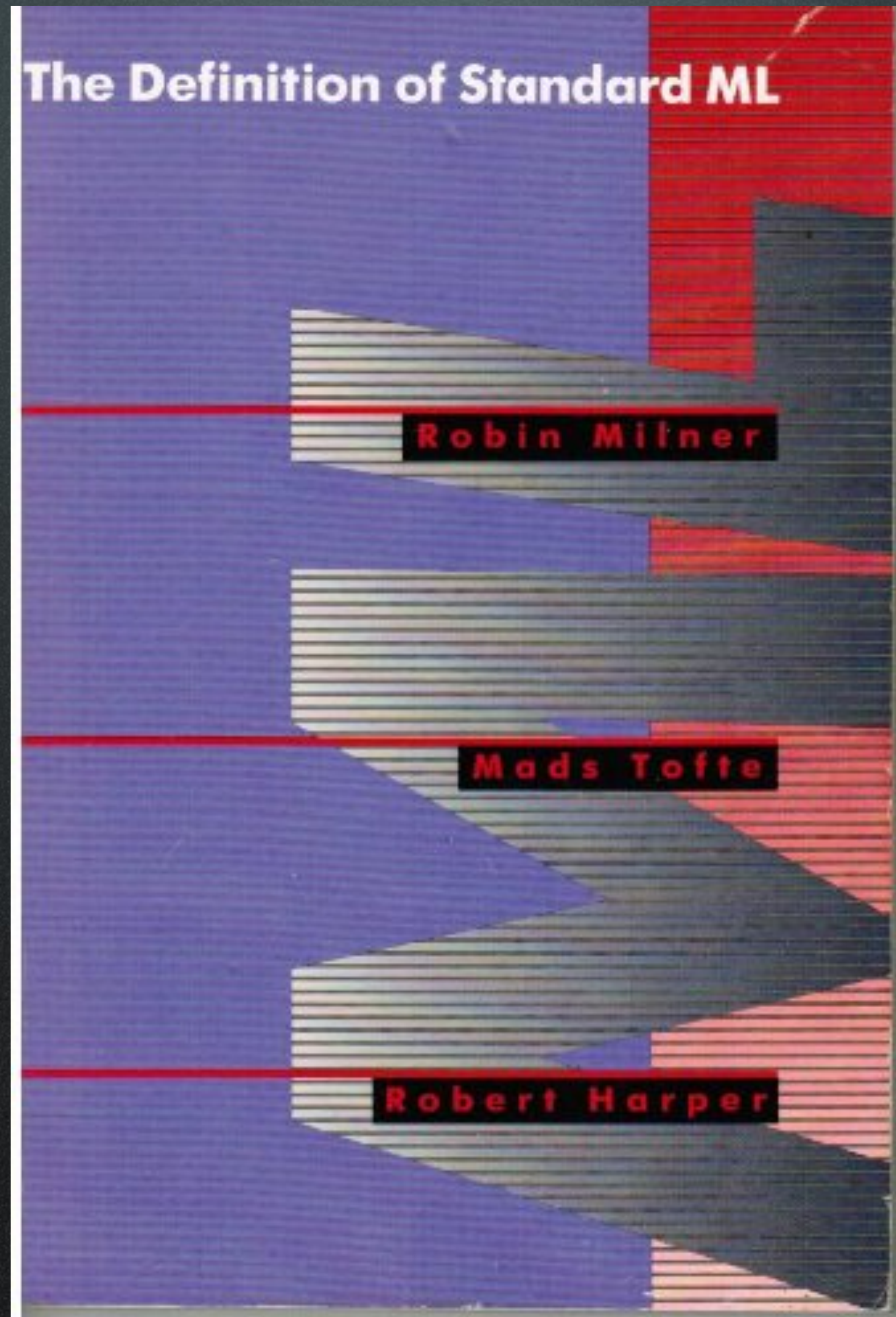
Language formalisation goes mainstream

Verified Software Workshop 2019

Andreas Rossberg
Dfinity


The Definition of Standard ML
Robin Milner
Mads Tofte
Robert Harper

Language formalisation goes mainstream

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WebAssembly
Language formalisation goes mainstream

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WebAssembly

Wasm

~~WASM~~

Wasm

a virtual instruction set architecture

that is fully sandboxed

and freely embeddable anywhere

a low-level virtual machine

open standard (W3C, github)

Goals & Constraints

Semantics

Language-independent

Platform-independent

Hardware-independent

Fast to execute

Safe to execute

Deterministic

Easy to reason about

Representation

Compact

Easy to generate

Fast to decode

Fast to validate

Fast to compile

Streamable

Parallelisable

modular & sandboxed

binaries are modules

function from explicit imports to exports

encapsulated, no access to internals

sandboxed, no ambient capabilities

type system

simple, linear-time type system

type-safe and memory-safe

no undefined behaviour

custom loader could implement extensions

formal semantics

from the get-go!

textbook techniques

meta-mission: raise the bar
for real-world language specs

static semantics

typing, a.k.a. validation

inference rules

$\Gamma \vdash e^* : t_1^* \rightarrow t_2^*$

stack machine

(**i32.const** 42)	: ε → i32
(**local.get** $x)	: ε → Γ($x)
(**i32.add**)	: i32 i32 → i32

} : ε → i32

$$\frac{}{\Gamma \vdash t.\mathbf{const}\ c : \varepsilon \rightarrow t}$$

$$\frac{}{\Gamma \vdash t.\mathbf{add} : t\ t \rightarrow t}$$

$$\frac{\Gamma(\$x) = t}{\Gamma \vdash \mathbf{local.get}\ \$x : \varepsilon \rightarrow t}$$

$$\frac{\Gamma \vdash e_0 : t_1{*} \rightarrow t_3{*} \qquad \Gamma \vdash e{*} : t_3{*} \rightarrow t_2{*}}{\Gamma \vdash e_0\ e{*} : t_1{*} \rightarrow t_2{*}}$$

$$\frac{\Gamma \vdash e{*} : t_1{*} \rightarrow t_2{*}}{\Gamma \vdash e{*} : t_0{*}\ t_1{*} \rightarrow t_0{*}\ t_2{*}}$$

structured control flow

$\$l : t_2{}^*$

(**block** $\$l\ (t_1{}^* \to t_2{}^*)$

…

(**br** $\$l$) $: t_2{}^* \to \bot$

…

end)

$\$l : t_1{}^*$

(**loop** $\$l\ (t_1{}^* \to t_2{}^*)$

…

(**br** $\$l$) $: t_1{}^* \to \bot$

…

end)

$$\frac{\Gamma, \$l : t_2^* \vdash e^* : t_1^* \rightarrow t_2^*}{\Gamma \vdash \textbf{block}\ \$l\ e^*\ \textbf{end} : t_1^* \rightarrow t_2^*}$$

$$\frac{\Gamma(\$l) = t^*}{\Gamma \vdash \textbf{br}\ \$l : t^* \rightarrow \bot}$$

$$\frac{\Gamma, \$l : t_1^* \vdash e^* : t_1^* \rightarrow t_2^*}{\Gamma \vdash \textbf{loop}\ \$l\ e^*\ \textbf{end} : t_1^* \rightarrow t_2^*}$$

$$\frac{\Gamma, \$l : t_2^* \vdash e^* : t_1^* \rightarrow t_2^*}{\Gamma \vdash \textbf{block}\ \$l\ e^*\ \textbf{end} : t_1^* \rightarrow t_2^*}$$

$$\frac{\Gamma(\$l) = t^*}{\Gamma \vdash \textbf{br}\ \$l : t^* \rightarrow \bot}$$

$$\frac{\Gamma, \$l : t_1^* \vdash e^* : t_1^* \rightarrow t_2^*}{\Gamma \vdash \textbf{loop}\ \$l\ e^*\ \textbf{end} : t_1^* \rightarrow t_2^*}$$

$$\frac{\Gamma, \$l : t_2^* \vdash e^* : t_1^* \to t_2^*}{\Gamma \vdash \textbf{block}\ \$l\ e^*\ \textbf{end} : t_1^* \to t_2^*}$$

$$\frac{\Gamma(\$l) = t^*}{\Gamma \vdash \textbf{br}\ \$l : t_1^*\ t^* \to t_2^*}$$

$$\frac{\Gamma, \$l : t_1^* \vdash e^* : t_1^* \to t_2^*}{\Gamma \vdash \textbf{loop}\ \$l\ e^*\ \textbf{end} : t_1^* \to t_2^*}$$

dynamic semantics

structured operational semantics

small-step reduction rules

$s; e^* \longmapsto^* s'; e'^*$

$$(\text{t.}\textbf{const}\ c_1)\ (\text{t.}\textbf{const}\ c_2)\ \text{t.}\textbf{add} \quad \longmapsto \quad (\text{t.}\textbf{const}\ c_1{+}c_2)$$

(values)	$v ::= (\text{t.}\textbf{const}\ c)$
(eval contexts)	$E ::= v^*\ [\,]\ e^* \mid (\textbf{label}\{e^*\}\ E\ \textbf{end})$

$$(\textbf{block}\ e^*\ \textbf{end}) \longmapsto (\textbf{label}\{\varepsilon\}\ e^*\ \textbf{end})$$

$$(\textbf{loop}\ e^*\ \textbf{end}) \longmapsto (\textbf{label}\{\textbf{loop}\ e^*\ \textbf{end}\}\ e^*\ \textbf{end})$$

$$(\textbf{label}\{e^*\}\ v^*\ \textbf{end}) \longmapsto v^*$$

$$(\textbf{label}\{e^*\}\ L^n[v^*\ (\textbf{br}\ n)]\ \textbf{end}) \longmapsto v^*\ e^*$$

$$\text{(label contexts)}\quad L^0 ::= v^*\ [\,]\ e^*$$

$$L^{n+1} ::= v^*\ (\textbf{label}\{e^*\}\ L^n\ \textbf{end})\ e^*$$

$$\frac{s.\mathrm{mem}[i..i+|t|-1] = \mathrm{bytes}_t(c)}{s;\ (\mathbf{i32.const}\ i)\ t.\mathbf{load} \quad \longmapsto \quad s;\ (t.\mathbf{const}\ c)}$$

$$\frac{s' = s\ \mathrm{with}\ \mathrm{mem}[i..i+|t|-1] = \mathrm{bytes}_t(c)}{s;\ (\mathbf{i32.const}\ i)\ (t.\mathbf{const}\ c)\ t.\mathbf{store} \quad \longmapsto \quad s';\ \varepsilon}$$

soundness

If $\vdash e^* : \varepsilon \rightarrow t^*$ and $\vdash s$,

then $s; e^* \longmapsto^* s'; v^*$

and $\vdash v^* : \varepsilon \rightarrow t^*$ and $\vdash s'$.

$$
\begin{array}{lrcl}
\text{(value types)} & t & ::= & \mathsf{i32} \mid \mathsf{i64} \mid \mathsf{f32} \mid \mathsf{f64} \\
\text{(packed types)} & pt & ::= & \mathsf{i8} \mid \mathsf{i16} \mid \mathsf{i32} \\
\text{(function types)} & ft & ::= & t^* \rightarrow t^* \\
\\
 & unop & ::= & \textbf{neg} \mid \textbf{abs} \mid \ldots \\
 & binop & ::= & \textbf{add} \mid \textbf{sub} \mid \textbf{mul} \mid \textbf{div\_s} \mid \textbf{div\_u} \mid \ldots \\
 & relop & ::= & \textbf{eq} \mid \textbf{ne} \mid \textbf{lt} \mid \textbf{gt} \mid \ldots \\
 & cvtop & ::= & \textbf{convert}/t \mid \textbf{reinterpret}/t \\
\\
\text{(instructions)} & e & ::= & t.\textbf{const}\ c \mid t.unop \mid t.binop \mid t.relop \mid t.cvtop \mid \\
 & & & \textbf{unreachable} \mid \textbf{nop} \mid \textbf{drop} \mid \textbf{select} \mid \\
 & & & \textbf{block}\ ft\ e^*\ \textbf{end} \mid \textbf{loop}\ ft\ e^*\ \textbf{end} \mid \textbf{if}\ ft\ e^*\ \textbf{else}\ e^*\ \textbf{end} \mid \\
 & & & \textbf{br}\ i \mid \textbf{br\_if}\ i \mid \textbf{br\_table}\ i^*\ i \mid \\
 & & & \textbf{call}\ i \mid \textbf{call\_indirect}\ ft \mid \textbf{return} \mid \\
 & & & \textbf{get\_local}\ i \mid \textbf{set\_local}\ i \mid \textbf{tee\_local}\ i \mid \\
 & & & \textbf{get\_global}\ i \mid \textbf{set\_global}\ i \mid \\
 & & & t.\textbf{load}\ pt^?\ n \mid t.\textbf{store}\ pt^?\ n \mid \textbf{current\_mem} \mid \textbf{grow\_mem} \\
\\
\text{(functions)} & func & ::= & \textbf{func}\ ft\ (\textbf{local}\ t)^*\ e^* \\
\text{(globals)} & glob & ::= & \textbf{global}\ \textbf{mut}^?\ t\ e^* \\
\text{(tables)} & tab & ::= & \textbf{table}\ n\ i^* \\
\text{(memories)} & mem & ::= & \textbf{memory}\ n \\
\text{(modules)} & m & ::= & \textbf{module}\ import^*\ func^*\ glob^*\ tab^?\ mem^?\ export^*
\end{array}
$$

(store)	s	$::=$	$\{\mathsf{inst}\ inst^*,\ \mathsf{tab}\ tabinst^*,\ \mathsf{mem}\ meminst^*\}$	
(instances)	$inst$	$::=$	$\{\mathsf{func}\ cl^*,\ \mathsf{glob}\ v^*,\ \mathsf{tab}\ i^?,\ \mathsf{mem}\ i^?\}$	
	$tabinst$	$::=$	cl^*	
	$meminst$	$::=$	b^*	
(closures)	cl	$::=$	$\{\mathsf{inst}\ i,\ \mathsf{code}\ f\}$	(where f is not an import and has all exports ex^* erased)
(values)	v	$::=$	$t.\mathbf{const}\ c$	
(administrative operators)	e	$::=$	$\dots \mid \mathbf{trap} \mid \mathbf{call}\ cl \mid \mathbf{label}\{t^*;e^*\}\ e^*\ \mathbf{end} \mid \mathbf{local}\{i;v^*\}\ e^*\ \mathbf{end}$	
(local contexts)	L^0	$::=$	$v^*\ [\_]\ e^*$	
	L^{k+1}	$::=$	$v^*\ \mathbf{label}\{t^*;e^*\}\ L^k\ \mathbf{end}\ e^*$	

Reduction $\dfrac{s;v^*;e^* \hookrightarrow_i s';v'^*;e'^*}{s;v^*;L^k[e^*] \hookrightarrow_i s';v'^*;L^k[e'^*]}$ $\dfrac{s;v^*;e^* \hookrightarrow_i s';v'^*;e'^*}{s;v_0^*;\mathbf{local}\{i;v^*\}\ e^*\ \mathbf{end} \hookrightarrow_j s';v_0^*;\mathbf{local}\{i;v'^*\}\ e'^*\ \mathbf{end}}$ $\boxed{s;v^*;e^* \hookrightarrow_i s;v^*;e^*}$

$(t.\mathbf{const}\ c)\ t.unop$	$\hookrightarrow$	$t.\mathbf{const}\ unop_t(c)$	
$(t.\mathbf{const}\ c_1)\ (t.\mathbf{const}\ c_2)\ t.binop$	$\hookrightarrow$	$t.\mathbf{const}\ c$	if $c = binop_t(c_1,c_2)$
$(t.\mathbf{const}\ c_1)\ (t.\mathbf{const}\ c_2)\ t.binop$	$\hookrightarrow$	$\mathbf{trap}$	otherwise
$(t.\mathbf{const}\ c)\ t.testop$	$\hookrightarrow$	$\mathbf{i32.const}\ testop_t(c)$	
$(t.\mathbf{const}\ c_1)\ (t.\mathbf{const}\ c_2)\ t.relop$	$\hookrightarrow$	$\mathbf{i32.const}\ relop_t(c_1,c_2)$	
$(t_1.\mathbf{const}\ c)\ t_2.\mathbf{convert}\ t_1\_sx^?$	$\hookrightarrow$	$t_2.\mathbf{const}\ c'$	if $c' = \mathrm{cvt}^{sx^?}_{t_1,t_2}(c)$
$(t_1.\mathbf{const}\ c)\ t_2.\mathbf{convert}\ t_1\_sx^?$	$\hookrightarrow$	$\mathbf{trap}$	otherwise
$(t_1.\mathbf{const}\ c)\ t_2.\mathbf{reinterpret}\ t_1$	$\hookrightarrow$	$t_2.\mathbf{const}\ \mathrm{const}_{t_2}(\mathrm{bits}_{t_1}(c))$	
$\mathbf{unreachable}$	$\hookrightarrow$	$\mathbf{trap}$	
$\mathbf{nop}$	$\hookrightarrow$	ϵ	
$v\ \mathbf{drop}$	$\hookrightarrow$	ϵ	
$v_1\ v_2\ (\mathbf{i32.const}\ 0)\ \mathbf{select}$	$\hookrightarrow$	v_2	
$v_1\ v_2\ (\mathbf{i32.const}\ k+1)\ \mathbf{select}$	$\hookrightarrow$	v_1	
$v^n\ \mathbf{block}\ (t_1^n \to t_2^m)\ e^*\ \mathbf{end}$	$\hookrightarrow$	$\mathbf{label}\{t_2^m;\epsilon\}\ v^n\ e^*\ \mathbf{end}$	
$v^n\ \mathbf{loop}\ (t_1^n \to t_2^m)\ e^*\ \mathbf{end}$	$\hookrightarrow$	$\mathbf{label}\{t_1^n;\mathbf{loop}\ (t_1^n \to t_2^m)\ e^*\ \mathbf{end}\}\ v^n\ e^*\ \mathbf{end}$	
$(\mathbf{i32.const}\ 0)\ \mathbf{if}\ tf\ e_1^*\ \mathbf{else}\ e_2^*\ \mathbf{end}$	$\hookrightarrow$	$\mathbf{block}\ tf\ e_2^*\ \mathbf{end}$	
$(\mathbf{i32.const}\ k+1)\ \mathbf{if}\ tf\ e_1^*\ \mathbf{else}\ e_2^*\ \mathbf{end}$	$\hookrightarrow$	$\mathbf{block}\ tf\ e_1^*\ \mathbf{end}$	
$\mathbf{label}\{t^*;e^*\}\ v^*\ \mathbf{end}$	$\hookrightarrow$	v^*	
$\mathbf{label}\{t^*;e^*\}\ \mathbf{trap}\ \mathbf{end}$	$\hookrightarrow$	$\mathbf{trap}$	
$\mathbf{label}\{t^n;e^*\}\ L^j[v^n\ (\mathbf{br}\ j)]\ \mathbf{end}$	$\hookrightarrow$	$v^n\ e^*$	
$(\mathbf{i32.const}\ 0)\ (\mathbf{br\_if}\ j)$	$\hookrightarrow$	ϵ	
$(\mathbf{i32.const}\ k+1)\ (\mathbf{br\_if}\ j)$	$\hookrightarrow$	$\mathbf{br}\ j$	
$(\mathbf{i32.const}\ k)\ (\mathbf{br\_table}\ j_1^k\ j\ j_2^*)$	$\hookrightarrow$	$\mathbf{br}\ j$	
$(\mathbf{i32.const}\ k+n)\ (\mathbf{br\_table}\ j_1^k\ j)$	$\hookrightarrow$	$\mathbf{br}\ j$	
$s;\mathbf{call}\ j$	$\hookrightarrow_i$	$\mathbf{call}\ s_{\mathsf{func}}(i,j)$	
$s;(\mathbf{i32.const}\ j)\ \mathbf{call\_indirect}\ tf$	$\hookrightarrow_i$	$\mathbf{call}\ s_{\mathsf{tab}}(i,j)$	if $s_{\mathsf{tab}}(i,j)_{\mathsf{code}} = (\mathbf{func}\ tf\ \mathbf{local}\ t^*\ e^*)$
$s;(\mathbf{i32.const}\ j)\ \mathbf{call\_indirect}\ tf$	$\hookrightarrow_i$	$\mathbf{trap}$	otherwise
$v^n\ (\mathbf{call}\ cl)$	$\hookrightarrow$	$\mathbf{local}\{cl_{\mathsf{inst}};v^n\ (t.\mathbf{const}\ 0)^k\}\ \mathbf{block}\ (\epsilon \to t_2^m)\ e^*\ \mathbf{end}\ \mathbf{end}$ ...	
$\mathbf{local}\{i;v_l^*\}\ v^*\ \mathbf{end}$	$\hookrightarrow$	v^*	$\mid$ ... if $cl_{\mathsf{code}} = (\mathbf{func}\ (t_1^n \to t_2^m)\ \mathbf{local}\ t^k\ e^*)$
$\mathbf{local}\{i;v_l^*\}\ \mathbf{trap}\ \mathbf{end}$	$\hookrightarrow$	$\mathbf{trap}$	
$\mathbf{local}\{i;v_l^*\}\ L^{k+1}[\mathbf{return}]\ \mathbf{end}$	$\hookrightarrow$	$\mathbf{local}\{i;v_l^*\}\ L^{k+1}[\mathbf{br}\ k]\ \mathbf{end}$	
$v_1^j\ v\ v_2^k;\mathbf{get\_local}\ j$	$\hookrightarrow$	v	
$v_1^j\ v\ v_2^k;v'\ (\mathbf{set\_local}\ j)$	$\hookrightarrow$	$v_1^j\ v'\ v_2^k;\epsilon$	
$v\ (\mathbf{tee\_local}\ j)$	$\hookrightarrow$	$v\ v\ (\mathbf{set\_local}\ j)$	
$s;\mathbf{get\_global}\ j$	$\hookrightarrow_i$	$s_{\mathsf{glob}}(i,j)$	
$s;v\ (\mathbf{set\_global}\ j)$	$\hookrightarrow_i$	$s';\epsilon$	if $s' = s$ with $\mathrm{glob}(i,j) = v$
$s;(\mathbf{i32.const}\ k)\ (t.\mathbf{load}\ a\ o)$	$\hookrightarrow_i$	$t.\mathbf{const}\ \mathrm{const}_t(b^*)$	if $s_{\mathsf{mem}}(i,k+o,\lvert t\rvert) = b^*$
$s;(\mathbf{i32.const}\ k)\ (t.\mathbf{load}\ tp\_sx\ a\ o)$	$\hookrightarrow_i$	$t.\mathbf{const}\ \mathrm{const}_t^{sx}(b^*)$	if $s_{\mathsf{mem}}(i,k+o,\lvert tp\rvert) = b^*$
$s;(\mathbf{i32.const}\ k)\ (t.\mathbf{load}\ tp\_sx^?\ a\ o)$	$\hookrightarrow_i$	$\mathbf{trap}$	otherwise
$s;(\mathbf{i32.const}\ k)\ (t.\mathbf{const}\ c)\ (t.\mathbf{store}\ a\ o)$	$\hookrightarrow_i$	$s';\epsilon$	if $s' = s$ with $\mathrm{mem}(i,k+o,\lvert t\rvert) = \mathrm{bits}_t^{\lvert t\rvert}(c)$
$s;(\mathbf{i32.const}\ k)\ (t.\mathbf{const}\ c)\ (t.\mathbf{store}\ tp\ a\ o)$	$\hookrightarrow_i$	$s';\epsilon$	if $s' = s$ with $\mathrm{mem}(i,k+o,\lvert tp\rvert) = \mathrm{bits}_t^{\lvert tp\rvert}(c)$
$s;(\mathbf{i32.const}\ k)\ (t.\mathbf{const}\ c)\ (t.\mathbf{store}\ tp^?\ a\ o)$	$\hookrightarrow_i$	$\mathbf{trap}$	otherwise
$s;\mathbf{current\_memory}]$	$\hookrightarrow_i$	$\mathbf{i32.const}\ \lvert s_{\mathsf{mem}}(i,*)\rvert/64\,\mathrm{Ki}$	
$s;(\mathbf{i32.const}\ k)\ \mathbf{grow\_memory}$	$\hookrightarrow_i$	$s';\mathbf{i32.const}\ \lvert s_{\mathsf{mem}}(i,*)\rvert/64\,\mathrm{Ki}$	if $s' = s$ with $\mathrm{mem}(i,*) = s_{\mathsf{mem}}(i,*)\ (0)^{k\cdot 64\,\mathrm{Ki}}$
$s;(\mathbf{i32.const}\ k)\ \mathbf{grow\_memory}$	$\hookrightarrow_i$	$\mathbf{i32.const}\ (-1)$	

Figure 1. Small-step reduction rules

[PLDI 2017]

$$\text{(contexts)}\quad C \quad ::= \quad \{\mathsf{func}\ tf^*,\ \mathsf{global}\ tg^*,\ \mathsf{table}\ n^?,\ \mathsf{memory}\ n^?,\ \mathsf{local}\ t^*,\ \mathsf{label}\ (t^*)^*\}$$

Typing Instructions $\quad \boxed{C \vdash e^* : tf}$

$$\frac{}{C \vdash t.\mathbf{const}\ c : \epsilon \to t} \qquad \frac{}{C \vdash t.unop : t \to t} \qquad \frac{}{C \vdash t.binop : t\ t \to t} \qquad \frac{}{C \vdash t.testop : t \to \mathsf{i32}} \qquad \frac{}{C \vdash t.relop : t\ t \to \mathsf{i32}}$$

$$\frac{t_1 \neq t_2 \qquad sx^? = \epsilon \Leftrightarrow (t_1 = \mathsf{i}n \wedge t_2 = \mathsf{i}n' \wedge |t_1| < |t_2|) \vee (t_1 = \mathsf{f}n \wedge t_2 = \mathsf{f}n')}{C \vdash t_1.\mathbf{convert}\ t_2\_sx^? : t_2 \to t_1} \qquad \frac{t_1 \neq t_2 \qquad |t_1| = |t_2|}{C \vdash t_1.\mathbf{reinterpret}\ t_2 : t_2 \to t_1}$$

$$\frac{}{C \vdash \mathbf{unreachable} : t_1^* \to t_2^*} \qquad \frac{}{C \vdash \mathbf{nop} : \epsilon \to \epsilon} \qquad \frac{}{C \vdash \mathbf{drop} : t \to \epsilon} \qquad \frac{}{C \vdash \mathbf{select} : t\ t\ \mathsf{i32} \to t}$$

$$\frac{tf = t_1^n \to t_2^m \qquad C, \mathsf{label}\ (t_2^m) \vdash e^* : tf}{C \vdash \mathbf{block}\ tf\ e^*\ \mathbf{end} : tf} \qquad \frac{tf = t_1^n \to t_2^m \qquad C, \mathsf{label}\ (t_1^n) \vdash e^* : tf}{C \vdash \mathbf{loop}\ tf\ e^*\ \mathbf{end} : tf}$$

$$\frac{tf = t_1^n \to t_2^m \qquad C, \mathsf{label}\ (t_2^m) \vdash e_1^* : tf \qquad C, \mathsf{label}\ (t_2^m) \vdash e_2^* : tf}{C \vdash \mathbf{if}\ tf\ e_1^*\ \mathbf{else}\ e_2^*\ \mathbf{end} : t_1^n\ \mathsf{i32} \to t_2^m}$$

$$\frac{C_{\mathsf{label}}(i) = t^*}{C \vdash \mathbf{br}\ i : t_1^*\ t^* \to t_2^*} \qquad \frac{C_{\mathsf{label}}(i) = t^*}{C \vdash \mathbf{br\_if}\ i : t^*\ \mathsf{i32} \to t^*} \qquad \frac{(C_{\mathsf{label}}(i) = t^*)^+}{C \vdash \mathbf{br\_table}\ i^+ : t_1^*\ t^*\ \mathsf{i32} \to t_2^*}$$

$$\frac{C_{\mathsf{label}}(|C_{\mathsf{label}}| - 1) = t^*}{C \vdash \mathbf{return} : t_1^*\ t^* \to t_2^*} \qquad \frac{C_{\mathsf{func}}(i) = tf}{C \vdash \mathbf{call}\ i : tf} \qquad \frac{tf = t_1^* \to t_2^* \qquad C_{\mathsf{table}} = n}{C \vdash \mathbf{call\_indirect}\ tf : t_1^*\ \mathsf{i32} \to t_2^*}$$

$$\frac{C_{\mathsf{local}}(i) = t}{C \vdash \mathbf{get\_local}\ i : \epsilon \to t} \qquad \frac{C_{\mathsf{local}}(i) = t}{C \vdash \mathbf{set\_local}\ i : t \to \epsilon} \qquad \frac{C_{\mathsf{local}}(i) = t}{C \vdash \mathbf{tee\_local}\ i : t \to t} \qquad \frac{C_{\mathsf{global}}(i) = \mathsf{mut}^?\ t}{C \vdash \mathbf{get\_global}\ i : \epsilon \to t} \qquad \frac{C_{\mathsf{global}}(i) = \mathsf{mut}\ t}{C \vdash \mathbf{set\_global}\ i : t \to \epsilon}$$

$$\frac{C_{\mathsf{memory}} = n \qquad 2^a \leq (|tp| <)^? |t| \qquad (tp\_sz)^? = \epsilon \vee t = \mathsf{i}m}{C \vdash t.\mathbf{load}\ (tp\_sz)^?\ a\ o : \mathsf{i32} \to t} \qquad \frac{C_{\mathsf{memory}} = n \qquad 2^a \leq (|tp| <)^? |t| \qquad tp^? = \epsilon \vee t = \mathsf{i}m}{C \vdash t.\mathbf{store}\ tp^?\ a\ o : \mathsf{i32}\ t \to \epsilon}$$

$$\frac{C_{\mathsf{memory}} = n}{C \vdash \mathbf{current\_memory} : \epsilon \to \mathsf{i32}} \qquad \frac{C_{\mathsf{memory}} = n}{C \vdash \mathbf{grow\_memory} : \mathsf{i32} \to \mathsf{i32}}$$

$$\frac{}{C \vdash \epsilon : \epsilon \to \epsilon} \qquad \frac{C \vdash e_1^* : t_1^* \to t_2^* \qquad C \vdash e_2 : t_2^* \to t_3^*}{C \vdash e_1^*\ e_2 : t_1^* \to t_3^*} \qquad \frac{C \vdash e^* : t_1^* \to t_2^*}{C \vdash e^* : t^*\ t_1^* \to t^*\ t_2^*}$$

Typing Modules

$$\frac{tf = t_1^* \to t_2^* \qquad C, \mathsf{local}\ t_1^*\ t^*, \mathsf{label}\ (t_2^*) \vdash e^* : \epsilon \to t_2^*}{C \vdash ex^*\ \mathbf{func}\ tf\ \mathbf{local}\ t^*\ e^* : ex^*\ tf} \qquad \frac{tg = \mathsf{mut}^?\ t \qquad C \vdash e^* : \epsilon \to t \qquad ex^* = \epsilon \vee tg = t}{C \vdash ex^*\ \mathbf{global}\ tg\ e^* : ex^*\ tg}$$

$$\frac{(C_{\mathsf{func}}(i) = tf)^n}{C \vdash ex^*\ \mathbf{table}\ n\ i^n : ex^*\ n} \qquad \frac{}{C \vdash ex^*\ \mathbf{memory}\ n : ex^*\ n}$$

$$\frac{}{C \vdash ex^*\ \mathbf{func}\ tf\ im : ex^*\ tf} \qquad \frac{tg = t}{C \vdash ex^*\ \mathbf{global}\ tg\ im : ex^*\ tg} \qquad \frac{}{C \vdash ex^*\ \mathbf{table}\ n\ im : ex^*\ n} \qquad \frac{}{C \vdash ex^*\ \mathbf{memory}\ n\ im : ex^*\ n}$$

$$\frac{\begin{array}{c}(C \vdash f : ex_{\mathrm{f}}^*\ tf)^* \qquad (C_i \vdash glob_i : ex_{\mathrm{g}}^*\ tg_i)_i^* \qquad (C \vdash tab : ex_{\mathrm{t}}^*\ n)^? \qquad (C \vdash mem : ex_{\mathrm{m}}^*\ n)^? \\ (C_i = \{\mathsf{global}\ tg^{i-1}\})_i^* \qquad C = \{\mathsf{func}\ tf^*, \mathsf{global}\ tg^*, \mathsf{table}\ n^?, \mathsf{memory}\ n^?\} \qquad ex_{\mathrm{f}}^{**}\ ex_{\mathrm{g}}^{**}\ ex_{\mathrm{t}}^{*?}\ ex_{\mathrm{m}}^{*?}\ \text{distinct}\end{array}}{\vdash \mathbf{module}\ f^*\ glob^*\ tab^?\ mem^?}$$

Figure 1. Typing rules

[PLDI 2017]

mechanisation

OCaml [myself]

Isabelle [Conrad Watt, Cambridge]

Coq (ongoing) [Dave Swasey, MPI]

K (ongoing) [Everett Hildenbrandt, Illinois]

standard

structured around formalisation

adding prose rendering for the uninitiated

webassembly.github.io/spec/

proposal process

must include spec text

must include formalisation!

must include OCaml reference interpreter

must include comprehensive test suite

must be implemented in 2 production engines

road map

v1 (shipped): support low-level languages

v2 (next+ year): support high-level languages

v3 (maybe...): support “dynamic” languages

future features

tail calls

references

threads

vector instructions

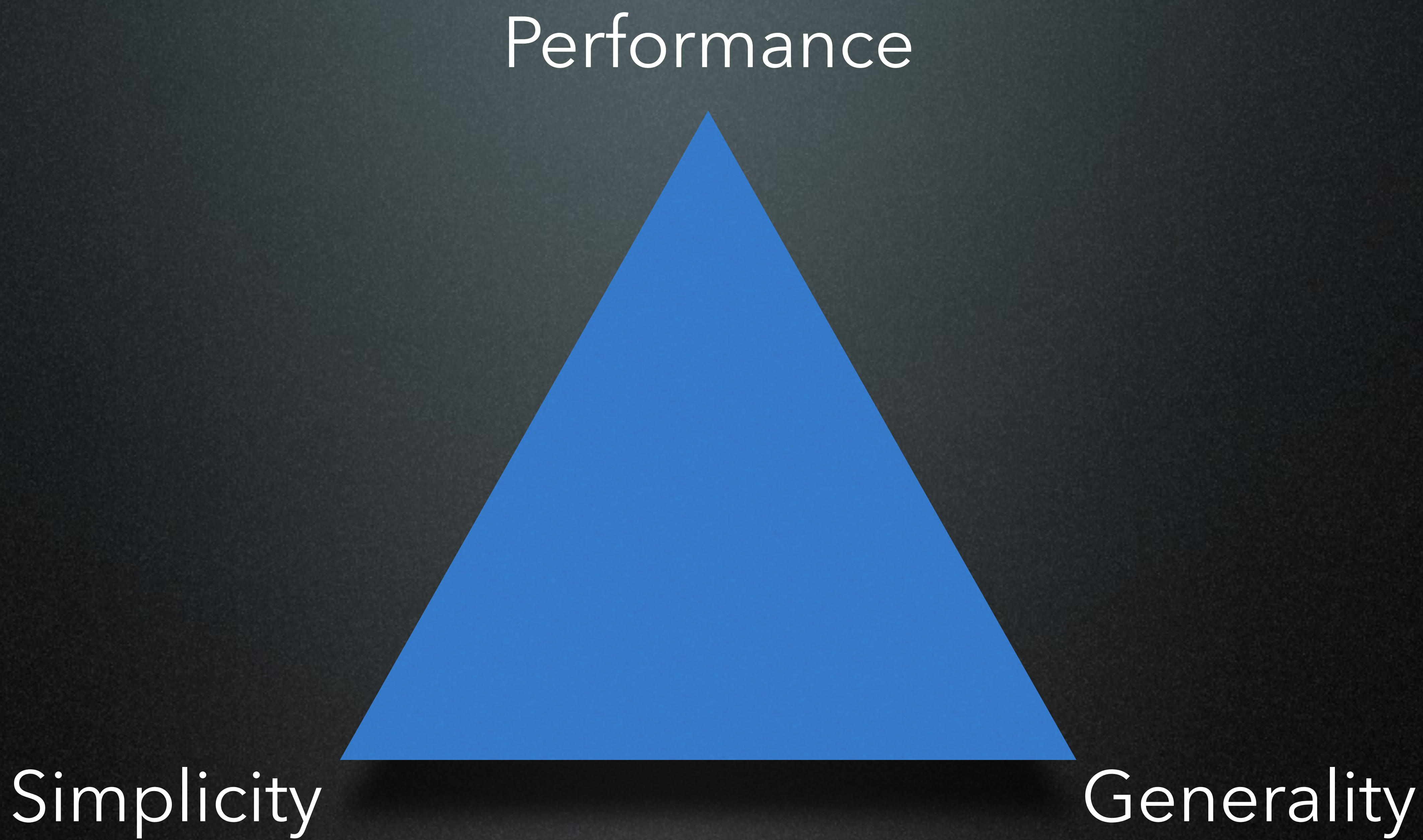
exception handling

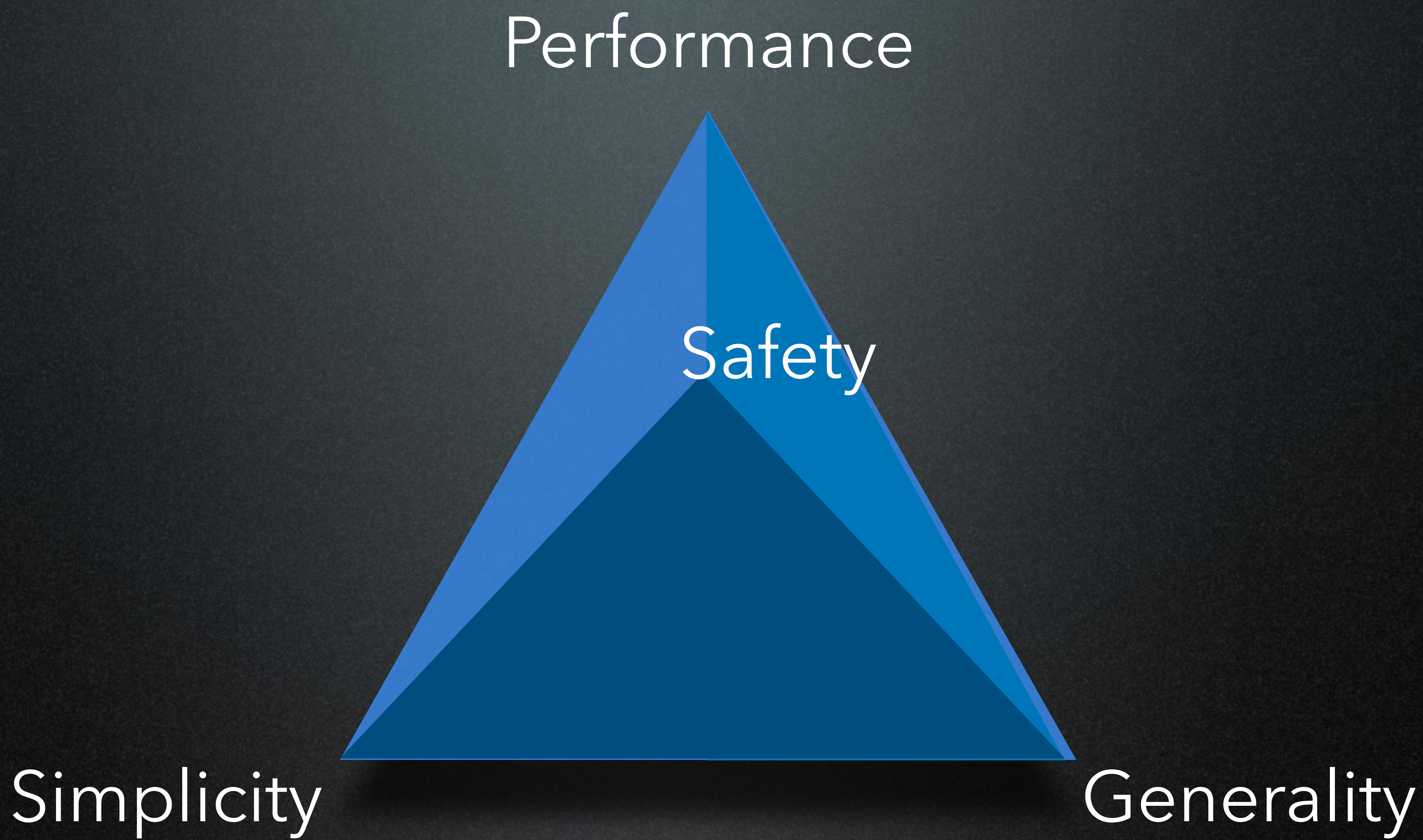
coroutines / effect handlers

garbage collection

…

https://github.com/WebAssembly/proposals


Performance
Simplicity
Generality


Performance
Safety
Simplicity
Generality

inside job

backing from key players

patience & stubbornness

adjust to audience

stay realistic

bus factor

Summary

Formal rigour and machine verification in the mainstream

Led to a clean and simple design

Progress is slow and brittle

But there is hope