Towards verified compilation of CakeML into WebAssembly

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How this project came about...

- Previously: Bachelor's in Software Engineering at TU Wien
- Currently: European Master's Program in Computational Logic
    - TU Dresden, Germany, EU
    - Free University of Bolzano, Italy, EU
    - TU Wien, Austria, EU
- My project work is sponsored in part by EMCL and by Data61, and I am supervised by Michael Norrish.

Agenda

Prelude

Motivation

Software systems have “bugs”
that lead to injury and death!

- Generally, when bugs mean human casualties or significant financial loss.
- Critical infrastructure from power plants to TLS implementations (Microsoft Research, *F**).
- Airplanes, weapon systems.
- And yes, sometimes even operating systems (Data 61, seL4 Linux).

The question that programmers repeatedly ask themselves ...

Does my code do what it should?

- Is it free of security vulnerabilities (that I can describe)?
- Is it deadlock-free, e.g. will it remain responsive to some degree in any scenario?
- Does it implement what was specified?
- Will all components that want to access a resource eventually access it?

Formal Verification vs. Testing

Unit testing? Each unit test covers **one** trace through the implementation. However, there are **infinitely many** possible traves. Therefore, unit testing is gravely limited.

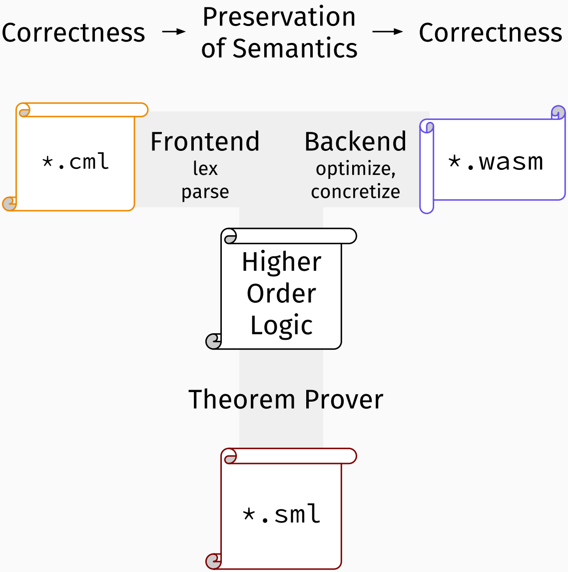
Other testing approaches? Might cover complex scenarios, but can always only check for specific cases. Same problem.

You get formal proof, not a just green box in your test report! Makes possible new tools and answering new questions.

Business?

Mostly static analysis tools. Not many synthesis tools have been published.

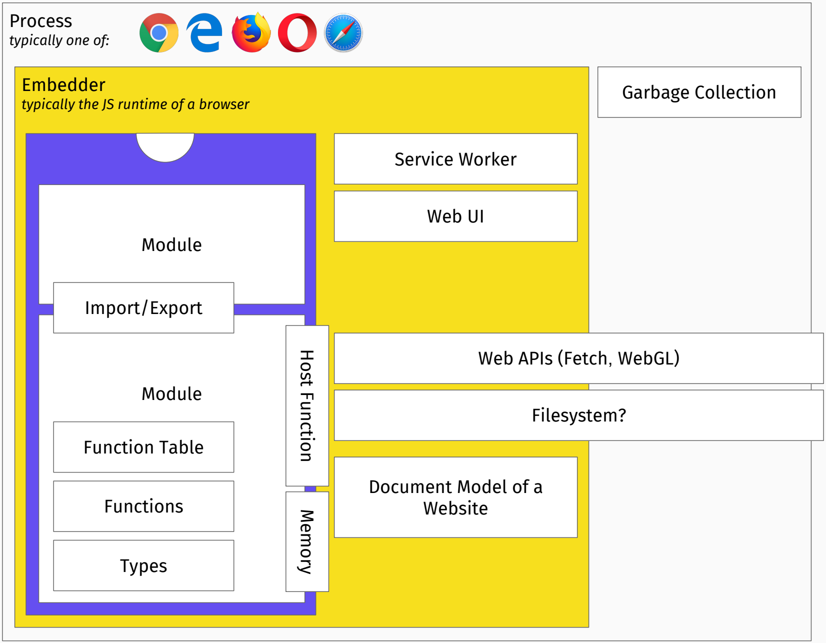
- DiffBlue Ltd. (17M GPB investment by Goldman Sachs and Oxford Sciences Innovation in 2017)
- Infer (static analyzer by Facebook, Inc.)
- Galois, Inc. (bootstrapped, founded dotcom times)
- Automated Reasoning Group at Amazon, Software Analysis Team at Google, Microsoft Research teams
- Chip manufacturers (ARM, Intel, Apple, Google, …)
- Verified compilers are slowly moving from research to product stages.


Correctness
Preservation of Semantics
Correctness
*.cml
Frontend
lex
parse
Backend
optimize,
concretize
*.wasm
Higher Order Logic
Theorem Prover
*.sml

Introduction

WA

WEBASSEMBLY


Process
typically one of:
Embedder
typically the JS runtime of a browser
Garbage Collection
Service Worker
Web UI
Module
Import/Export
Module
Function Table
Functions
Types
Host Function
Memory
Web APIs (Fetch, WebGL)
Filesystem?
Document Model of a Website

What is WebAssembly?...

- A portable code format and instruction set architecture
- Sandboxed, embedded by design
- Open Standard, steered by a World Wide Web Consortium working group
- Actually supported by all major browser vendors
- Supersedes PNaCl (*portable native client*, Google), asm.js (simple subset of JS, Mozilla)
- Within 10% of native code performance in the browser
- Opens up browsers for other languages than JS

Design Goals

Semantics	Representation
Language independent	Compact
Platform independent	Easy to generate
Hardware independent	Fast to decode
Fast to execute	Fast to validate
Safe to execute	Fast to compile
Deterministic	Streamable
Easy to reason about	Parallelisable

Taken from presentation “Neither Web nor Assembly” by Andreas Rossberg (spec author).

Concrete Syntax by Example

S-Expression:

```
(module
  (func $add
    (param i32 i32)
    (result i32)
    (i32.add         ;; 3
      (get_local 0)  ;; 1
      (get_local 1)  ;; 2
    )
  )
  (export "add" (func $add))
)
```

```
00 6100 6d73 0001 0000 0701 6001 7f02 017f
10 037f 0102 0700 010a 6106 6464 7754 006f
20 0a00 0109 0007 0020 0120 0b6a 1900 6e04
30 6d61 0165 0109 0600 6461 5464 6f77 0702
40 0001 0002 0100 0000
```

Preferred by browsers, for bandwidth!

Concrete Syntax by Example

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00 6100 6d73 0001 0000 0701 6001 7f02 017f
10 037f 0102 0700 010a 6106 6464 7754 006f
20 0a00 0109 0007 0020 0120 0b6a 1900 6e04
30 6d61 0165 0109 0600 6461 5464 6f77 0702
40 0001 0002 0100 0000
```

Preferred by browsers, for bandwidth!

Postfix notation:

```
(module
  (func $fac
    (param f64) (result f64)
    (get_local 0)
    (f64.const 1)
    f64.lt
    if (result f64)
      f64.const 1
    else
      get_local 0
      get_local 0
      f64.const 1
      f64.sub
      call $fac
      f64.mul
    end
  )
)
```

Abstract Syntax

- Instructions

  Numeric Constants, unary and binary operations, binary relations, conversions.

  Variables `get_local`, `set_local`, `get_global`, `set_global`

  Memory `load`, `store`, `size`, `grow`

  Control Flow `if`, `loop`, `block`, `call`. All of them have some notion of a return type.

  ... and a few others.

- Declarations for tables, memories, exports, imports, ...

Semantics

- Statically as a type system ("embarassingly simple")
- Dynamically as a nondeterministic, relational small-step reduction, and types extending the static setting.
- Combining these two, soundness provides:
  - Type Safety (locals, globals, instruction/function args)
  - Memory Safety (locals, globals, tables, memory)
  - No undefined behaviour (evaluation rules cover all cases and are mutually consistent)
  - Encapsulation (scope of locals, module components according to imports/exports)

$$
\begin{array}{lrcl}
\text{(value types)} & t & ::= & \mathsf{i32} \mid \mathsf{i64} \mid \mathsf{f32} \mid \mathsf{f64} \\
\text{(packed types)} & tp & ::= & \mathsf{i8} \mid \mathsf{i16} \mid \mathsf{i32} \\
\text{(function types)} & tf & ::= & t^* \rightarrow t^* \\
\text{(global types)} & tg & ::= & \mathsf{mut}^? \; t
\end{array}
$$

$$
\begin{array}{rcl}
unop_{\mathsf{i}N} & ::= & \mathbf{clz} \mid \mathbf{ctz} \mid \mathbf{popcnt} \\
unop_{\mathsf{f}N} & ::= & \mathbf{neg} \mid \mathbf{abs} \mid \mathbf{ceil} \mid \mathbf{floor} \mid \mathbf{trunc} \mid \mathbf{nearest} \mid \mathbf{sqrt} \\
binop_{\mathsf{i}N} & ::= & \mathbf{add} \mid \mathbf{sub} \mid \mathbf{mul} \mid \mathbf{div}\_sx \mid \mathbf{rem}\_sx \mid \\
 & & \mathbf{and} \mid \mathbf{or} \mid \mathbf{xor} \mid \mathbf{shl} \mid \mathbf{shr}\_sx \mid \mathbf{rotl} \mid \mathbf{rotr} \\
binop_{\mathsf{f}N} & ::= & \mathbf{add} \mid \mathbf{sub} \mid \mathbf{mul} \mid \mathbf{div} \mid \mathbf{min} \mid \mathbf{max} \mid \mathbf{copysign} \\
testop_{\mathsf{i}N} & ::= & \mathbf{eqz} \\
relop_{\mathsf{i}N} & ::= & \mathbf{eq} \mid \mathbf{ne} \mid \mathbf{lt}\_sx \mid \mathbf{gt}\_sx \mid \mathbf{le}\_sx \mid \mathbf{ge}\_sx \\
relop_{\mathsf{f}N} & ::= & \mathbf{eq} \mid \mathbf{ne} \mid \mathbf{lt} \mid \mathbf{gt} \mid \mathbf{le} \mid \mathbf{ge} \\
cvtop & ::= & \mathbf{convert} \mid \mathbf{reinterpret} \\
sx & ::= & \mathbf{s} \mid \mathbf{u}
\end{array}
$$

$$
\begin{array}{lrcl}
\text{(instructions)} & e & ::= & \mathbf{unreachable} \mid \mathbf{nop} \mid \mathbf{drop} \mid \mathbf{select} \mid \\
 & & & \mathbf{block}\; tf\; e^*\; \mathbf{end} \mid \mathbf{loop}\; tf\; e^*\; \mathbf{end} \mid \mathbf{if}\; tf\; e^*\; \mathbf{else}\; e^*\; \mathbf{end} \mid \\
 & & & \mathbf{br}\; i \mid \mathbf{br\_if}\; i \mid \mathbf{br\_table}\; i^+ \mid \mathbf{return} \mid \mathbf{call}\; i \mid \mathbf{call\_indirect}\; tf \mid \\
 & & & \mathbf{get\_local}\; i \mid \mathbf{set\_local}\; i \mid \mathbf{tee\_local}\; i \mid \mathbf{get\_global}\; i \mid \\
 & & & \mathbf{set\_global}\; i \mid t.\mathbf{load}\; (tp\_sx)^?\; a\; o \mid t.\mathbf{store}\; tp^?\; a\; o \mid \\
 & & & \mathbf{current\_memory} \mid \mathbf{grow\_memory} \mid t.\mathbf{const}\; c \mid \\
 & & & t.unop_t \mid t.binop_t \mid t.testop_t \mid t.relop_t \mid t.cvtop\; t\_sx^?
\end{array}
$$

$$
\begin{array}{lrcl}
\text{(functions)} & f & ::= & ex^*\; \mathbf{func}\; tf\; \mathbf{local}\; t^*\; e^* \mid ex^*\; \mathbf{func}\; tf\; im \\
\text{(globals)} & glob & ::= & ex^*\; \mathbf{global}\; tg\; e^* \mid ex^*\; \mathbf{global}\; tg\; im \\
\text{(tables)} & tab & ::= & ex^*\; \mathbf{table}\; n\; i^* \mid ex^*\; \mathbf{table}\; n\; im \\
\text{(memories)} & mem & ::= & ex^*\; \mathbf{memory}\; n \mid ex^*\; \mathbf{memory}\; n\; im \\
\text{(imports)} & im & ::= & \mathbf{import}\; \text{“}name\text{”}\; \text{“}name\text{”} \\
\text{(exports)} & ex & ::= & \mathbf{export}\; \text{“}name\text{”} \\
\text{(modules)} & m & ::= & \mathbf{module}\; f^*\; glob^*\; tab^?\; mem^?
\end{array}
$$

Figure 1. WebAssembly abstract syntax

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

Reduction

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

$$
\begin{array}{rcll}
L^0[\mathbf{trap}] & \hookrightarrow & \mathbf{trap} & \text{if } L^0 \neq [\_] \\[4pt]
(t.\mathbf{const}\ c)\ t.\mathit{unop} & \hookrightarrow & t.\mathbf{const}\ \mathit{unop}_t(c) & \\
(t.\mathbf{const}\ c_1)\ (t.\mathbf{const}\ c_2)\ t.\mathit{binop} & \hookrightarrow & t.\mathbf{const}\ c & \text{if } c = \mathit{binop}_t(c_1, c_2) \\
(t.\mathbf{const}\ c_1)\ (t.\mathbf{const}\ c_2)\ t.\mathit{binop} & \hookrightarrow & \mathbf{trap} & \text{otherwise} \\
(t.\mathbf{const}\ c)\ t.\mathit{testop} & \hookrightarrow & \mathbf{i32.const}\ \mathit{testop}_t(c) & \\
(t.\mathbf{const}\ c_1)\ (t.\mathbf{const}\ c_2)\ t.\mathit{relop} & \hookrightarrow & \mathbf{i32.const}\ \mathit{relop}_t(c_1, c_2) & \\[4pt]
(t_1.\mathbf{const}\ c)\ t_2.\mathbf{convert}\ t_1\_\mathit{sx}^? & \hookrightarrow & t_2.\mathbf{const}\ c' & \text{if } c' = \mathrm{cvt}^{\mathit{sx}^?}_{t_1,t_2}(c) \\
(t_1.\mathbf{const}\ c)\ t_2.\mathbf{convert}\ t_1\_\mathit{sx}^? & \hookrightarrow & \mathbf{trap} & \text{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)) & \\[4pt]
\mathbf{unreachable} & \hookrightarrow & \mathbf{trap} & \\
\mathbf{nop} & \hookrightarrow & \epsilon & \\
v\ \mathbf{drop} & \hookrightarrow & \epsilon & \\
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 & \\[4pt]
v^n\ \mathbf{block}\ (t_1^n \to t_2^m)\ e^*\ \mathbf{end} & \hookrightarrow & \mathbf{label}_m\{\epsilon\}\ v^n\ e^*\ \mathbf{end} & \\
v^n\ \mathbf{loop}\ (t_1^n \to t_2^m)\ e^*\ \mathbf{end} & \hookrightarrow & \mathbf{label}_n\{\mathbf{loop}\ (t_1^n \to t_2^m)\ e^*\ \mathbf{end}\}\ v^n\ e^*\ \mathbf{end} & \\
(\mathbf{i32.const}\ 0)\ \mathbf{if}\ \mathit{tf}\ e_1^*\ \mathbf{else}\ e_2^*\ \mathbf{end} & \hookrightarrow & \mathbf{block}\ \mathit{tf}\ e_2^*\ \mathbf{end} & \\
(\mathbf{i32.const}\ k+1)\ \mathbf{if}\ \mathit{tf}\ e_1^*\ \mathbf{else}\ e_2^*\ \mathbf{end} & \hookrightarrow & \mathbf{block}\ \mathit{tf}\ e_1^*\ \mathbf{end} & \\[4pt]
\mathbf{label}_n\{e^*\}\ v^*\ \mathbf{end} & \hookrightarrow & v^* & \\
\mathbf{label}_n\{e^*\}\ \mathbf{trap}\ \mathbf{end} & \hookrightarrow & \mathbf{trap} & \\
\mathbf{label}_n\{e^*\}\ L^j[v^n\ (\mathbf{br}\ j)]\ \mathbf{end} & \hookrightarrow & v^n\ e^* & \\
(\mathbf{i32.const}\ 0)\ (\mathbf{br\_if}\ j) & \hookrightarrow & \epsilon & \\
(\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 & \\[4pt]
s; \mathbf{call}\ j & \hookrightarrow_i & \mathbf{call}\ s_{\mathsf{func}}(i, j) & \\
s; (\mathbf{i32.const}\ j)\ \mathbf{call\_indirect}\ \mathit{tf} & \hookrightarrow_i & \mathbf{call}\ s_{\mathsf{tab}}(i, j) & \text{if } s_{\mathsf{tab}}(i,j)_{\mathsf{code}} = (\mathbf{func}\ \mathit{tf}\ \mathbf{local}\ t^*\ e^*) \\
s; (\mathbf{i32.const}\ j)\ \mathbf{call\_indirect}\ \mathit{tf} & \hookrightarrow_i & \mathbf{trap} & \text{otherwise} \\
v^n\ (\mathbf{call}\ \mathit{cl}) & \hookrightarrow & \mathbf{local}_m\{\mathit{cl}_{\mathsf{inst}}; v^n\ (t.\mathbf{const}\ 0)^k\}\ \mathbf{block}\ (\epsilon \to t_2^m)\ e^*\ \mathbf{end}\ \mathbf{end}\ \dots & \\
\mathbf{local}_n\{i; v_l^*\}\ v^n\ \mathbf{end} & \hookrightarrow & v^n & \mid\ \dots \text{if } \mathit{cl}_{\mathsf{code}} = (\mathbf{func}\ (t_1^n \to t_2^m)\ \mathbf{local}\ t^k\ e^*) \\
\mathbf{local}_n\{i; v_l^*\}\ \mathbf{trap}\ \mathbf{end} & \hookrightarrow & \mathbf{trap} & \\
\mathbf{local}_n\{i; v_l^*\}\ L^k[v^n\ \mathbf{return}]\ \mathbf{end} & \hookrightarrow & v^n & \\[4pt]
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 & \text{if } s' = s \text{ with } \mathsf{glob}(i,j) = v \\[4pt]
s; (\mathbf{i32.const}\ k)\ (t.\mathbf{load}\ a\ o) & \hookrightarrow_i & t.\mathbf{const}\ \mathrm{const}_t(b^*) & \text{if } s_{\mathsf{mem}}(i, k+o, |t|) = b^* \\
s; (\mathbf{i32.const}\ k)\ (t.\mathbf{load}\ \mathit{tp\_sx}\ a\ o) & \hookrightarrow_i & t.\mathbf{const}\ \mathrm{const}_t^{\mathit{sx}}(b^*) & \text{if } s_{\mathsf{mem}}(i, k+o, |\mathit{tp}|) = b^* \\
s; (\mathbf{i32.const}\ k)\ (t.\mathbf{load}\ \mathit{tp\_sx}^?\ a\ o) & \hookrightarrow_i & \mathbf{trap} & \text{otherwise} \\
s; (\mathbf{i32.const}\ k)\ (t.\mathbf{const}\ c)\ (t.\mathbf{store}\ a\ o) & \hookrightarrow_i & s'; \epsilon & \text{if } s' = s \text{ with } \mathsf{mem}(i, k+o, |t|) = \mathrm{bits}_t^{|t|}(c) \\
s; (\mathbf{i32.const}\ k)\ (t.\mathbf{const}\ c)\ (t.\mathbf{store}\ \mathit{tp}\ a\ o) & \hookrightarrow_i & s'; \epsilon & \text{if } s' = s \text{ with } \mathsf{mem}(i, k+o, |\mathit{tp}|) = \mathrm{bits}_t^{|\mathit{tp}|}(c) \\
s; (\mathbf{i32.const}\ k)\ (t.\mathbf{const}\ c)\ (t.\mathbf{store}\ \mathit{tp}^?\ a\ o) & \hookrightarrow_i & \mathbf{trap} & \text{otherwise} \\
s; \mathbf{current\_memory}] & \hookrightarrow_i & \mathbf{i32.const}\ |s_{\mathsf{mem}}(i, *)|/64\,\mathrm{Ki} & \\
s; (\mathbf{i32.const}\ k)\ \mathbf{grow\_memory} & \hookrightarrow_i & s'; \mathbf{i32.const}\ |s_{\mathsf{mem}}(i, *)|/64\,\mathrm{Ki} & \text{if } s' = s \text{ with } \mathsf{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) &
\end{array}
$$

Figure 2. Small-step reduction rules

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

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

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

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

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

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

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

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

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

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

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

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

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

Typing Modules

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

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

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

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

Figure 3. Typing rules

(store context) $\quad S \quad ::= \quad \{\mathsf{inst}\ C^*,\ \mathsf{tab}\ n^*,\ \mathsf{mem}\ n^*\}$

$$\frac{S = \{\mathsf{inst}\ C^*,\ \mathsf{tab}\ n^*,\ \mathsf{mem}\ m^*\} \qquad (S \vdash inst : C)^* \qquad ((S \vdash cl : tf)^*)^* \qquad (n \leq |cl^*|)^* \qquad (m \leq |b^*|)^*}{\vdash \{\mathsf{inst}\ inst^*,\ \mathsf{tab}\ (cl^*)^*,\ \mathsf{mem}\ (b^*)^*\} : S}$$

$$\frac{S_{\mathsf{inst}}(i) \vdash f : tf}{S \vdash \{\mathsf{inst}\ i,\ \mathsf{code}\ f\} : tf} \qquad \frac{(S \vdash cl : tf)^* \qquad (\vdash v : t)^* \qquad (S_{\mathsf{tab}}(i) = n)^? \qquad (S_{\mathsf{mem}}(j) = m)^?}{S \vdash \{\mathsf{func}\ cl^*,\ \mathsf{glob}\ v^*,\ \mathsf{tab}\ i^?,\ \mathsf{mem}\ j^?\} : \{\mathsf{func}\ tf^*,\ \mathsf{global}\ (\mathsf{mut}^?\ t)^*,\ \mathsf{table}\ n^?,\ \mathsf{memory}\ m^?\}}$$

$$\frac{\vdash s : S \qquad S; \epsilon \vdash_i v^*; e^* : t^*}{\vdash_i s; v^*; e^* : t^*} \qquad \frac{(\vdash v : t_v)^* \qquad S; S_{\mathsf{inst}}(i), \mathsf{local}\ t_v^*, \mathsf{return}\ (t^*)^? \vdash e^* : \epsilon \to t^*}{S; (t^*)^? \vdash_i v^*; e^* : t^*} \qquad \frac{}{\vdash t.\mathbf{const}\ c : t}$$

$$\frac{}{C \vdash \mathbf{trap} : tf} \qquad \frac{C \vdash e_0^* : t_1^n \to t_2^* \qquad C, \mathsf{label}\ (t_1^n) \vdash e^* : \epsilon \to t_2^*}{C \vdash \mathbf{label}_n\{e_0^*\}\ e^*\ \mathbf{end} : \epsilon \to t_2^*} \qquad \frac{S \vdash cl : tf}{S; C \vdash \mathbf{call}\ cl : tf} \qquad \frac{S; (t^n) \vdash_i v^*; e^* : t^n}{S; C \vdash \mathbf{local}_n\{i; v^*\}\ e^*\ \mathbf{end} : \epsilon \to t^n}$$

Figure 4. Store and configuration typing and rules for administrative instructions

Soundness: Key Theorems

Preservation If $\vdash (S, T) : t$ and $(S, T) \hookrightarrow (S', T')$ then $\vdash (S', T') : t$ and $\vdash S \preceq S'$.

Progress If $\vdash (S, T) : t$ then either (S, T) is terminal or there is (S', T') s.t. $(S, T) \hookrightarrow (S', T')$.

Soundness If $\vdash (S, T) : t$ then (S, T) either diverges or takes a finite number of $\hookrightarrow$-steps to reach a terminal configuration (S', T') s.t. $\vdash (S', T') : t$.

Proofs mechanized in Isabelle/HOL in [**?**] based on the definitions on paper in [**?**].

Maturity and Adoption i

- Specification officially (still) a draft, however widely implemented and used.
- Released a minimum viable product early on.
- Formal specification, reference interpreter (OCaml) maintained by spec authors.
- Many embedders in/compilers from various languages available (just search GitHub).
- Early Adopters: Gamers! Run all the flash minigames with WebAssembly.
- But now, it is possible to compile game engines from C/C++ to the web!
- “Native performance on the web.”
- Leveraging legacy codebases, i.e. PSPDFKit’s PDF handling library.
- Standalone VM using LLVM IR and JIT

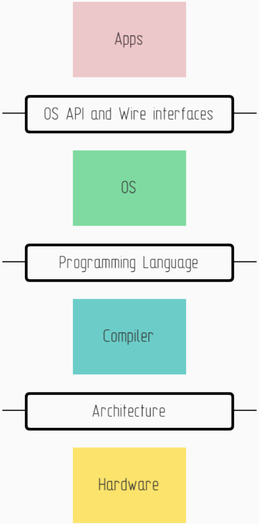
Future

- Multiple memories, 64bit addressable memory, multiple return values
- Garbage collection (reference types, `call_ref`, `{struct|array|i31ref}.new`, more typing)
- Concurrency through threads (atomic operations, mutexes)
- Exception handling (`try`/`catch`)
- Tail Calls
- SIMD

CAKEML

REMS

Rigorous Engineering of Mainstream Systems



Task 4a: System APIs and Protocols

TLS: nqsbTLS
TCP: Huginn-TCP
POSIX filesystem test oracle: SibylFS
POSIX filesystem logic

Task 3: Systems Programming Languages

Sequential C (de facto/ISO/CHERI): Cerberus
Concurrent C: C/C++11 and new models
C runtime typechecking: libcrunch
ELF linking: linksem
Verified ML implementation: CakeML
JavaScript

Task 2: Architectural Multiprocessor Semantics

Sail ISA models: ARM, Power, MIPS, CHERI
L3 ISA models: ARM, MIPS, x86, CHERI, RISC-V
ARM and Power Concurrency
CHERI ISA

"Task 1: Semantic tools" and
"Task 4b: Concurrency Reasoning" not shown.

A verified Implementation of ML i

- ...as a compiler in Higher Order Logic.
- First verified compiler of a functional programming language (POPL'14).
- Developed by team of 16+25 with many publications, please see website!

A verified Implementation of ML ii

- CakeML is a substantial subset of Standard ML.
- Two frontends:
    1. Translate from HOL to CakeML abstract syntax
    2. Parse CakeML concrete syntax
- Optimizing backend which targets x86, ARM, RISC-V, MIPS. Working on targeting WebAssembly.
- Can bootstrap inside HOL, i.e. compile itself via frontend 1.
- Allows calls to a foreign function interface

Ecosystem

Proof-producing synthesis / *Verified compiler backend*

HOL functions → **CakeML AST** → **CakeML AST** → **machine code**

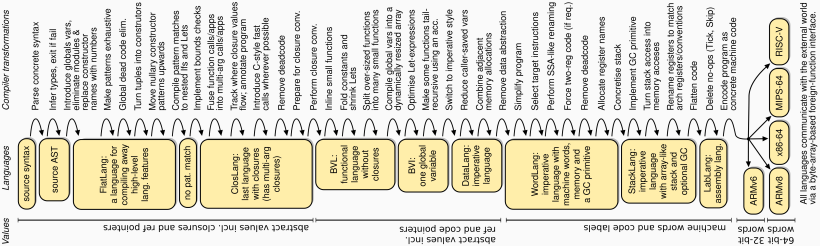
Verified parsing / *Verified type inference*

ASCII → **CakeML AST** → **CakeML AST** → **typeable yes/no**

Proof-producing verification-condition generation

CakeML AST → **Characteristic Formula** **i.e. a ‘verification condition’**

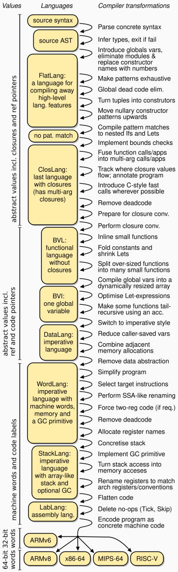
Compiler Architecture



Translating CakeML to WebAssembly

Which intermediate language to compile from?

Looking for a language that matches WebAssembly's features:

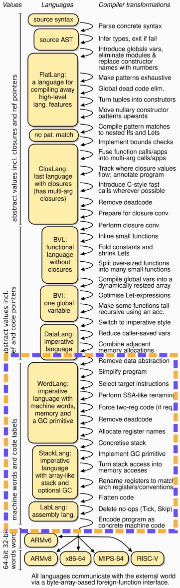


All languages communicate with the external world via a byte-array-based foreign-function interface.

Which intermediate language to compile from?

Looking for a language that matches WebAssembly's features:

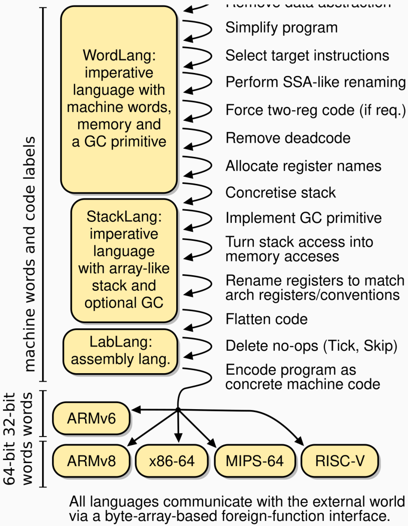
1. Operates on words



Which intermediate language to compile from?

Looking for a language that matches WebAssembly's features:

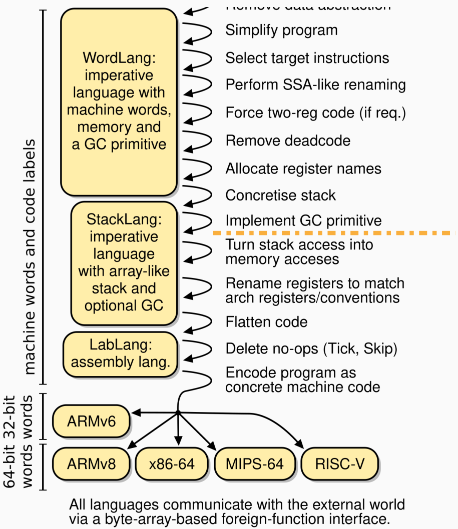
1. Operates on words



Which intermediate language to compile from?

Looking for a language that matches WebAssembly's features:

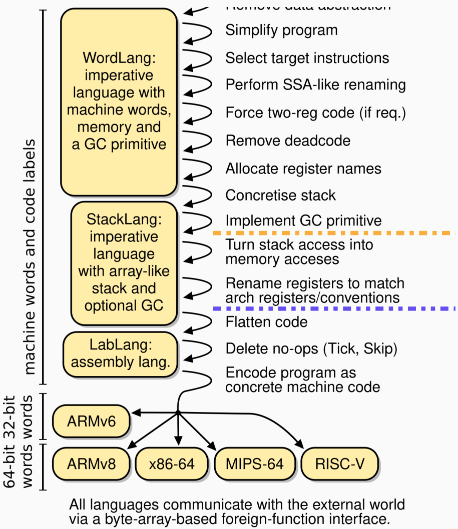
1. Operates on words
2. Manages memory



Which intermediate language to compile from?

Looking for a language that matches WebAssembly's features:

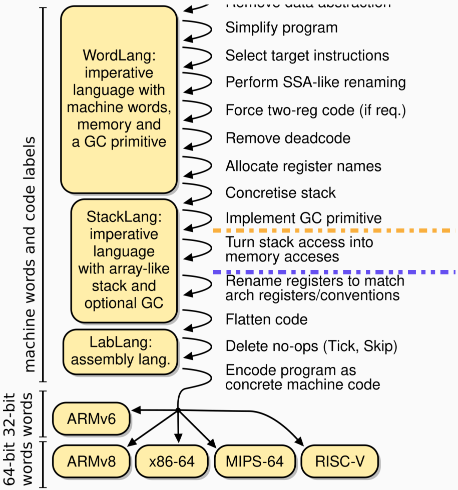
1. Operates on words
2. Manages memory
3. Local control flow



Which intermediate language to compile from?

Looking for a language that matches WebAssembly's features:

1. Operates on words
2. ■ Manages memory
3. ■ Local control flow
4. ■ No register usage conventions

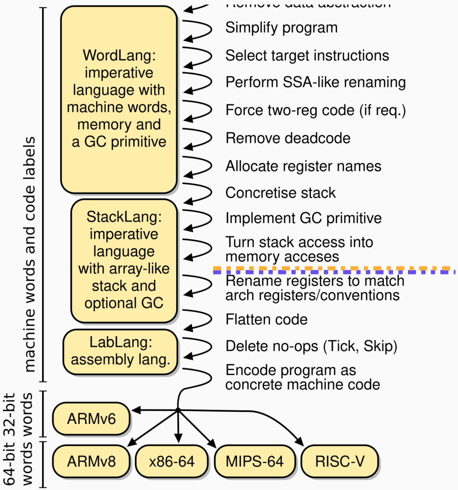


All languages communicate with the external world via a byte-array-based foreign-function interface.

Which intermediate language to compile from?

Looking for a language that matches WebAssembly's features:

1. Operates on words
2. ■ Manages memory
3. ■ Local control flow
4. ■ No register usage conventions
5. ■ Implicit stack?



All languages communicate with the external world via a byte-array-based foreign-function interface.

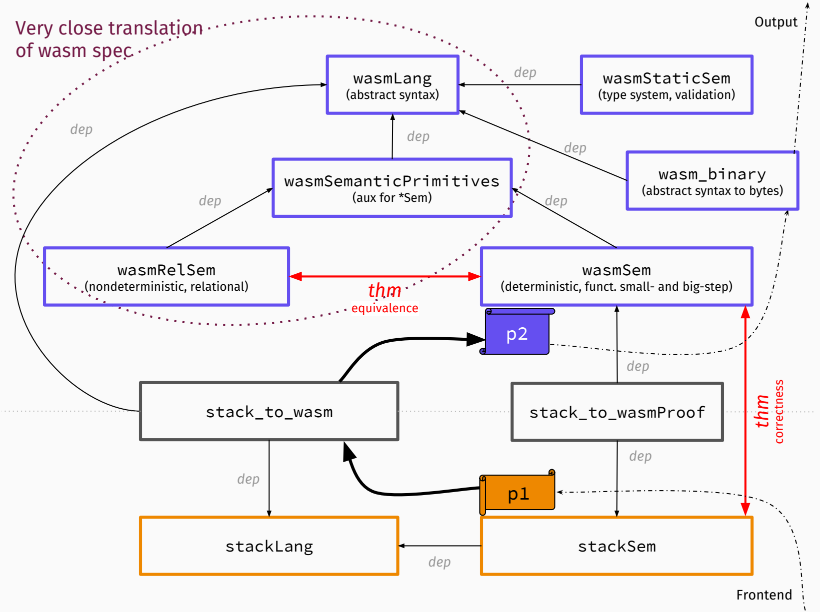
Challenges $\approx$ mismatch(StackLang, WebAssembly)

What I need to "compile away":

- No exception handling.
- No tail recursive calls in WebAssembly!
    1. Cannot use `call`/`return` without risk of stack overflows.
    2. Hence, emulate jumps in WebAsssembly!
    3. Jumps emulated by `br_table` which with local control flow.
    4. Cannot use `if`, `loop`, `block`, `br`.

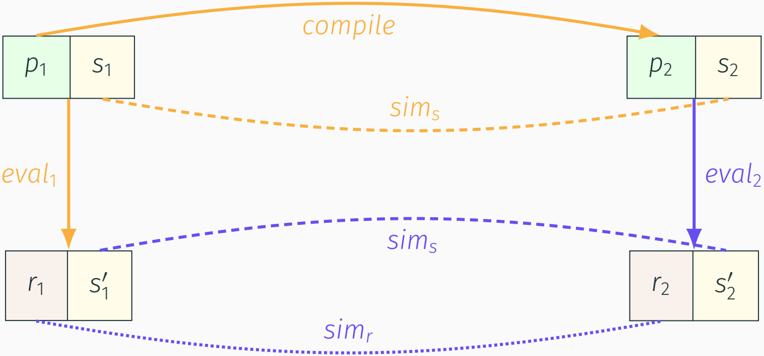
Also: Provide a functional big-step semantics.

Implementation



Verification

Compiler Correctness Theorem



$$(\forall \ \ldots) \ \ eval_1 \, p_1 \, s_1 = (r_1, s_1') \wedge sim_s \, s_1 \, s_2 \wedge compile \, p_1 = p_2 \wedge r_1 \neq Error$$

$$\longrightarrow$$

$$(\exists \, r_2 \, s_2') \ \ eval_2 \, p_2 \, s_2 = (r_2, s_2') \wedge sim_s \, s_1' \, s_2' \wedge sim_r \, r_1 \, r_2$$

Progress and Outlook

Progress

- Mechanized static and dynamic semantics
- Mechanized most of the initialization semantics
- Specified an alternative dynamic semantics in functional big-step style
- Prototyped translation
- Prepared the CakeML compiler architecture for integrating the new target
- Proved some lemmas, mostly about the relation between the two semantics
- Thought about and formulated some …conjectures …
- Prototyped a runtime to execute generated code in browser

TODO

- Prove that all compiler output is valid WebAssembly
- Prove compiler correctness

Recap

Questions, please!

Or mail to **`lorenz@leutgeb.xyz`**!

References i

A. Haas, A. Rossberg, D. L. Schuff, B. L. Titzer, M. Holman, D. Gohman, L. Wagner, A. Zakai, and J. F. Bastien.
Bringing the web up to speed with webassembly.
In A. Cohen and M. T. Vechev, editors, *Proceedings of the 38th ACM SIGPLAN Conference on Programming Language Design and Implementation, PLDI 2017, Barcelona, Spain, June 18-23, 2017*, pages 185–200. ACM, 2017.

C. Watt.
Mechanising and verifying the webassembly specification.
In J. Andronick and A. P. Felty, editors, *Proceedings of the 7th ACM SIGPLAN International Conference on Certified Programs and Proofs, CPP 2018, Los Angeles, CA, USA, January 8-9, 2018*, pages 53–65. ACM, 2018.