Adventures in Mechanising and Verifying WebAssembly

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Formal Methods Meets JavaScript, VeTSS
The web’s evolution

- We want richer web apps - 3D rendering, physics, 60fps.
- Asm.js exists but is too slow and janky.
- We’re at the limits of JavaScript - need a purpose-built language.

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Here are my contact details, a photo, short bio, and CV

PhD students, RAs, and Co-authors Meetings Funding Papers (by date) Papers (by topic)

Teaching

- The 2017-18 Part 1B Semantics of Programming Languages course
- The 2017-18 Multicore Semantics and Programming (R204) ACS MPhil module
- ...previous teaching

http://www.cl.cam.ac.uk/~pes20/
The web’s evolution

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https://github.com/evanw/webgl-water
What is WebAssembly?

- A web-friendly bytecode.
- Runs on any browser.
- “Near-native” performance.
- Targetted by LLVM.
WebAssembly is weird

A stack reduction semantics...

$$\begin{align*}
i32\text{.const } 4 & \quad \text{Type: } [ \text{i32} ] \\
i32\text{.const } 2 & \quad \text{Type: } [ \text{i32} ] \\
i32\text{.const } 1 & \quad \text{Type: } [ \text{i32} ] \\
i32\text{.add} & \quad \sim \quad i32\text{.const } 4 & \quad \text{Type: } [ \text{i32} ] \\
i32\text{.add} & \quad \sim \quad i32\text{.const } 3 & \quad \sim \quad i32\text{.add} & \quad i32\text{.const } 7 & \quad \text{Type: } [ \text{i32} ]
\end{align*}$$
WebAssembly is weird

...but allows only **structured control flow**.

```
loop
  i32.const 4
  i32.const 2
  i32.const 1
  i32.add
  i32.add
  br 0
end
```

```
label{...}
  i32.const 4
  i32.const 3
  i32.add
  br 0
end
```

```
label{...}
  i32.const 4
  i32.const 2
  i32.const 1
  i32.add
  i32.add
  br 0
end
```

**Note**

*label* is an “administrative” operation. It represents the loop unrolled once, keeping track of the continuation (abbreviated).
The WebAssembly type system

- All WebAssembly programs must be validated (typed) before execution.
- WebAssembly instruction types have the form $t^* \rightarrow t^*$

```
i32.const 4  i32.add  f32.const 0
  i32.add
i32.add

Type:       Type:       Type:
[ ] \rightarrow [i32] [i32, i32, i32] \rightarrow [i32] ⊥
```
The WebAssembly type system

Preservation
If a program P is validated with a type $ts$, the program obtained by running P one step to P' can also be validated with type $ts$.

Progress
For any validated program P that is not a list of constant values or a bare trap result, there exists P' such that P reduces to P'.
Initial mechanisation and soundness proof

- Initially based on an accepted draft of the WASM group’s PLDI paper\(^1\) combined with the draft specification.
- Definitions and proofs in Isabelle.
- Type soundness properties: preservation and progress.
- Progress property as stated in the draft had a trivial counterexample.

Problems found - administrative instructions

- Exceptions did not properly propagate through administrative instructions.
- Malformed, irreducible nestings of administrative instructions containing a `return` opcode could be well-typed.
- Our suggested fixes were incorporated into the specification.

```
label{...}  label{...}  label{...}
  trap  ~->  trap  trap  ~->  trap
  end  i32.add  end
```
Problems found

- Various trivial mistakes in the constraints of casting instructions.
- Big one - host function interface was unsound.²
- After these changes, managed to get a fully mechanised proof of soundness! (∼5000 LOC)

Directly animating the mechanised specification was infeasible.

For the reduction relation - exception propagation is non-deterministic (but confluent), and the specification leans heavily on recursively defined evaluation contexts.

For the typing judgement - there is a weakening rule with no upper bound, and the rules for typing dead code(!) involve a high degree of polymorphism - not syntax-directed.

Some of these problems are solvable by re-formulating the mechanisation, but wanted eyeball-closeness with the official specification.
The flow of trust

- Normative specification
- Mechanised specification
- Proven properties
- Conformance tests
The flow of trust

- Normative specification
- Mechanised executable specification
- Proven properties
- Extracted implementation (+untrusted interface)
- Conformance tests
The flow of trust

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The flow of trust

- Normative specification
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The flow of trust

Normative specification → Mechanised specification → Verified implementation

Proven properties

Extracted implementation (+untrusted interface)

Conformance tests

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Solution

- A separate reference interpreter, and typechecker.
- Proof of correctness between the inductive rules of the model, and the executable definitions of the interpreter and typechecker.
- Attempted fuzzing using interpreter as a test oracle - only found crash bugs in industry tools unfortunately.
The threads proposal!

We’ve already seen that specifying interop between JS and WebAssembly isn’t trivial, but this is on another level.

Need a compatible axiomatic weak memory model.

But more complicated than JS: WASM memory can change size, but (until now) SharedArrayBuffers cannot.
Next steps

- Already finding bugs in the JS memory model.\(^3\)

  ```javascript
  Atomics.wait(tA, 0, 0) || Atomics.store(tA, 0, 1)
  var x = Atomics.load(tA, 0) || Atomics.wake(tA, 0, 1)
  ```

- Full formal spec for WebAssembly threading is being drafted.

- Mechanisation? Not impossible, but meaningful proofs could be a lot of work.

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\(^3\) **Conrad Watt.** *Normative: Strengthen Atomics.wait/wake synchronization to the level of other Atomics operations.*  Mar. 2018. URL: https://github.com/tc39/ecma262/pull/1127.
Future work

- Continue looking at SharedArrayBuffer, WASM threads.
- Verifying ct-wasm (watch this space!).
- Model module instantiation.
- Look at Ethereum’s EVM2.0 (?)