# 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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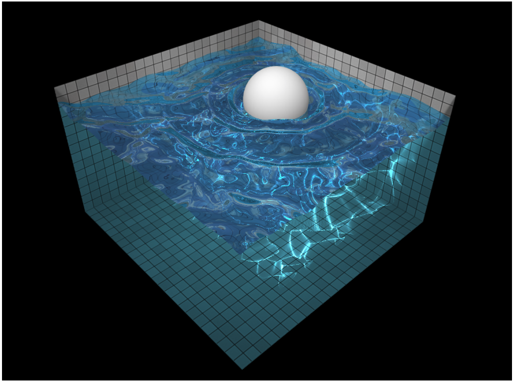


https://github.com/evanw/webgl-water

# What is WebAssembly?

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

# WebAssembly is weird

A stack reduction semantics...

| | | | | |
|---|---|---|---|---|
| `i32.const 4`<br>`i32.const 2`<br>`i32.const 1`<br>`i32.add`<br>`i32.add` | $\rightsquigarrow$ | `i32.const 4`<br>`i32.const 3`<br>`i32.add` | $\rightsquigarrow$ | `i32.const 7` |
| Type: [ i32 ] | | Type: [ i32 ] | | Type: [ i32 ] |

# WebAssembly is weird

...but allows only structured control flow.

```
loop                                                                            loop
  i32.const 4                                                                     i32.const 4
  i32.const 2        label{...}                                                   i32.const 2
  i32.const 1          i32.const 4                                                i32.const 1
  i32.add      ⤳       i32.const 3    ⤳    label{...}                 ⤳          i32.add
  i32.add              i32.add                i32.const 7                         i32.add
  br 0                 br 0                   br 0                                br 0
end                  end                    end                                 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`<br>`i32.add` | `f32.const 0`<br>`i32.const 4`<br>`i32.add` |
| Type:<br>$[] \rightarrow [i32]$ | Type:<br>$[i32, i32, i32] \rightarrow [i32]$ | Type:<br>$\perp$ |

# 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.

[1] Andreas Haas et al. "Bringing the Web Up to Speed with WebAssembly". In: *Proceedings of the 38th ACM SIGPLAN Conference on Programming Language Design and Implementation*. PLDI 2017. New York, NY, USA: ACM, 2017, pp. 185–200.

# 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{...}
  trap        ⤳   trap
end
```

```
label{...}
  trap
  i32.add     ⤳   trap
end
```

# Problems found

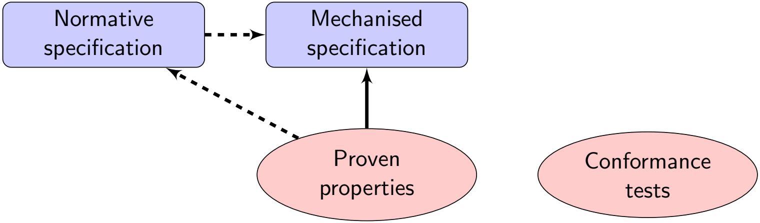
- Various trivial mistakes in the constraints of casting instructions.
- Big one - host function interface was unsound.[2]
- After these changes, managed to get a fully mechanised proof of soundness! ($\sim$5000 LOC)

[2] Andreas Rossberg. *[spec] Fix and clean up invariants for host functions*. Sept. 2017. URL: https://github.com/WebAssembly/spec/pull/563.

# Verified reference interpreter

- 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



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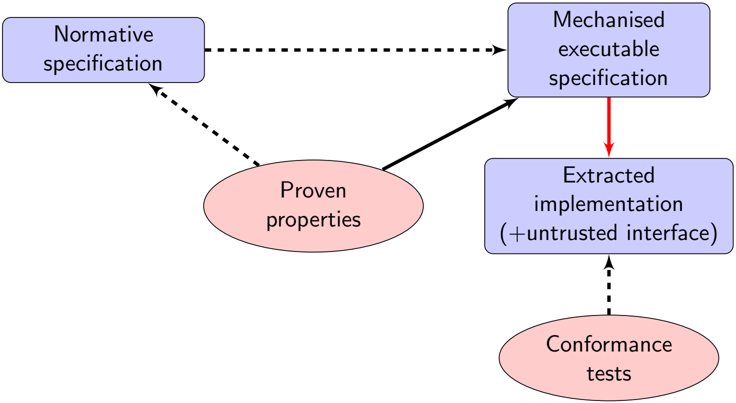

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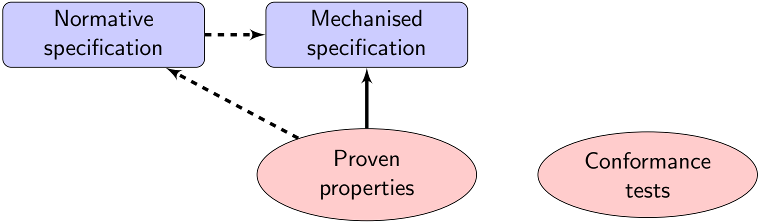

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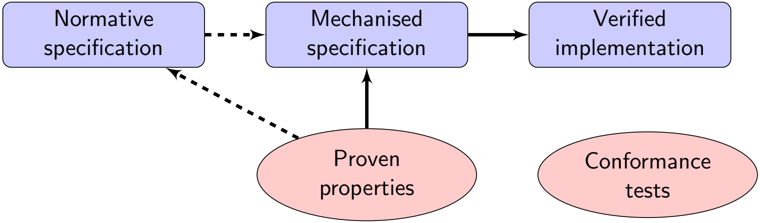

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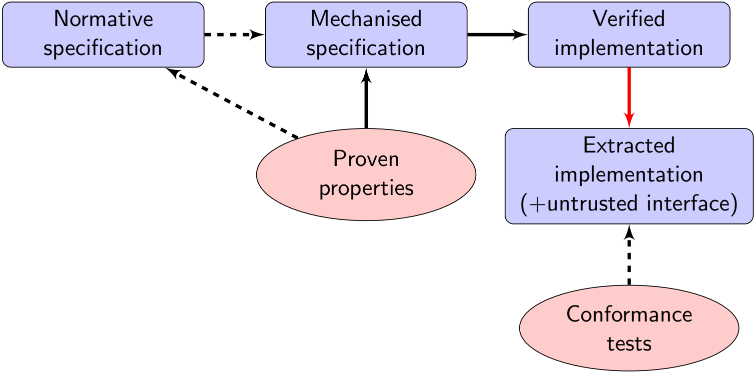

# Solution

- 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.

# Next steps

- 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]

```
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.

[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 (?)