Formal Methods and the WebAssembly Specification

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SREPLS’11
A brief history of JavaScript

- Prototyped in 10 days, in 1995.
- We’re stuck with it now.
- Every website relies on it (almost).
- Accumulated technical debt weighs heavy on the spec.
The web’s evolution

- We want richer web apps - 3D rendering, physics, 60fps.
- asm.js exists but is limited by being built on top of JavaScript.
- 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

- We want richer web apps - 3D rendering, physics, 60fps.
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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.
- Formally specified! \(^1\)

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WebAssembly execution

A small-step stack reduction semantics...

```
i32.const 4
i32.const 2
i32.const 1
i32.add
i32.add

i32.const 4
i32.const 3
i32.add
i32.add

Type: [ i32 ]
Type: [ i32 ]
Type: [ i32 ]
```
WebAssembly execution

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

Note

**label** is an “administrative” operation. It represents the loop unrolled once, keeping track of the continuation (abbreviated).
All WebAssembly programs must be validated (typed) before execution. WebAssembly instruction types have the form $t^* \rightarrow t^*$

- `i32.const 4`  
  `i32.add`  
  `i32.add`  

  Type: 
  $[] \rightarrow [i32]$  

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

  Type: 
  $[i32, i32, i32] \rightarrow [i32]$  

- `i32.add`  

  Type: 
  $\bot$
WebAssembly type system

Preservation
If a program $P$ is validated with a type $t_s$, any program obtained by reducing $P$ to $P'$ can also be validated with type $t_s$.

Progress
For any validated program $P$ that has not terminated with a result, there exists $P'$ such that $P$ reduces to $P'$

These properties together guarantee syntactic type soundness.\(^2\)

Mechanisation

- An unambiguous formal specification and an unambiguous correctness condition.
- Perfect for mechanisation!
- \(~11,000\) lines of Isabelle/HOL.\(^3\)
- Found several errors in the draft specification.
- Also included:
  - Verified sound and complete type-checking algorithm.
  - Verified sound run-time interpreter.

Two categories of errors were found.

- **Trivial “syntactic” errors:**
  - typos, obviously malformed constraints
  - missing conditions/cases

- **Deeper “semantic” errors:**
  - edge-cases where well-typed programs get stuck
  - sound inter-op with JavaScript/the host environment
Two categories of errors were found.

- **Trivial “syntactic” errors:**
  - often discovered because of Isabelle’s type-checked metatheory
  - don’t need the full power of an interactive theorem prover

- **Deeper “semantic” errors:**
  - discovered during the soundness proof
  - difficult to find by hand/light-weight specification
Mechanisation

CT-Wasm
Secure information flow type system.

John Renner
Natalie Popescu
Sunjay Cauligi
Deian Stefan
UC San Diego

Wasm Logic
A separation logic for WebAssembly.

Petar Maksimović*
Neel Krishnaswami†
Philippa Gardner*
Imperial College London*/Cambridge†
Relaxed memory

- WebAssembly program can read from and write to a linear buffer of raw bytes.
- Adding threads, these buffers can now be shared.
- Need a relaxed memory model.

![Diagram of WebAssembly operations on a linear buffer]
Relaxed memory

- JavaScript also has threads ("web workers") and shared buffers, even a memory model!
- The WebAssembly memory will be exposed to JavaScript as a shared buffer.
Committee: JS/Wasm interop should “just work”.  

So a lot of Wasm consistency behaviour is inherited from JS.
Relaxed memory

- But Wasm has additional feature - memory growth.
- Now, the size of the memory needs to become part of the axiomatic model.

```
x = buff[i]
Atomics.store(buff,i,v)
```
- Implementers don’t want to guarantee SC bounds-checking behaviour.

- Updates to memory size can create “data” races.

\[
\begin{array}{cccc}
\text{load } x & \text{load } y & \text{grow 2}
\end{array}
\]
Relaxed memory

- We said Wasm follows JS.
- What if the JS model is wrong? Ideally, we fix it.
- JS standards body has been very welcoming.
- Shu-yu Guo (Bloomberg LP) has been a great point of contact.
Relaxed memory

- Several JS memory model problems discovered.
  - Missing synchronization for wait/wake ops.\(^4\)
  - SC-DRF violation.\(^5\)
  - ARMv8 lda/stl not supported (Stephen Dolan, Cambridge).\(^6\)

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Conclusion

- WebAssembly’s formal specification hasn’t saved it from errors, but at least we can find them more easily.

- Building PL research on top of the WebAssembly semantics works excellently.

- WebAssembly would be widely used even if it was badly designed. It’s deserving of research attention!
Thanks for listening!