Formal Methods and the WebAssembly Specification

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SREPLS'11

REMS

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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Fellow of Wolfson college

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)

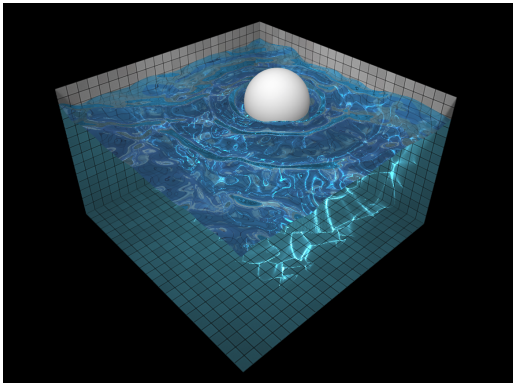
Teaching

- 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

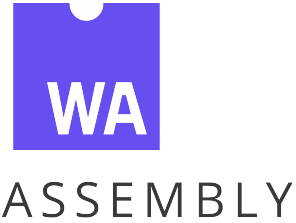
- We want richer web apps - 3D rendering, physics, 60fps.
- asm.js exists but is limited by being built on top of JavaScript.
- We're at the limits of JavaScript - need a purpose-built language.



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]



[1] Andreas Rossberg et al. "Bringing the Web Up to Speed with WebAssembly". In: *Communications of the ACM* 61.12 (Nov. 2018), pp. 107–115. ISSN: 0001-0782. DOI: 10.1145/3282510. URL: http://doi.acm.org/10.1145/3282510.

WebAssembly execution

A small-step stack reduction semantics...

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

Type: [i32]

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

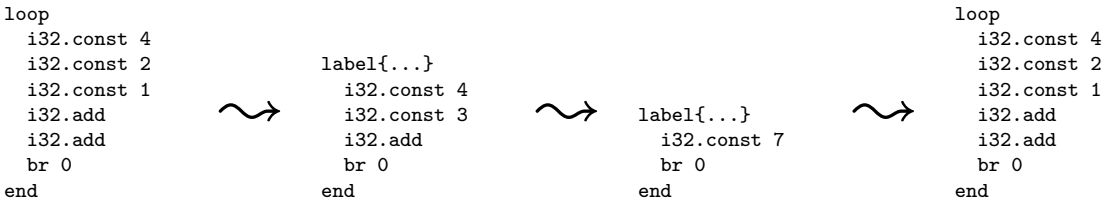
Type: [i32]

```
i32.const 7
```

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).

WebAssembly type system

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

```
i32.const 4
```

Type:
$[] \to [\text{i32}]$

```
i32.add
i32.add
```

Type:
$[\text{i32}, \text{i32}, \text{i32}] \to [\text{i32}]$

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

Type:
$\bot$

WebAssembly type system

Preservation

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

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]

[2] A.K. Wright and M. Felleisen. "A Syntactic Approach to Type Soundness". In: *Information and Computation* 115.1 (1994). ISSN: 0890-5401.

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.

[3] Conrad Watt. "WebAssembly". In: *Archive of Formal Proofs* (Apr. 2018). http://isa-afp.org/entries/WebAssembly.html, Formal proof development. ISSN: 2150-914x.

Mechanisation

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

Mechanisation

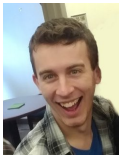
Two categories of errors were found.

- 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*

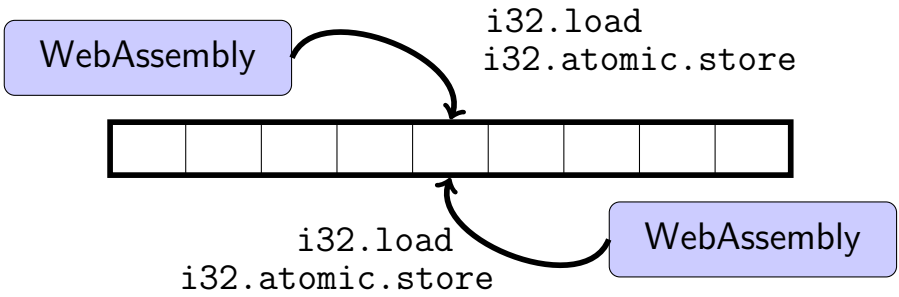
Neel Krishnaswami†

Philippa Gardner*

Imperial College London*/Cambridge†

Relaxed memory

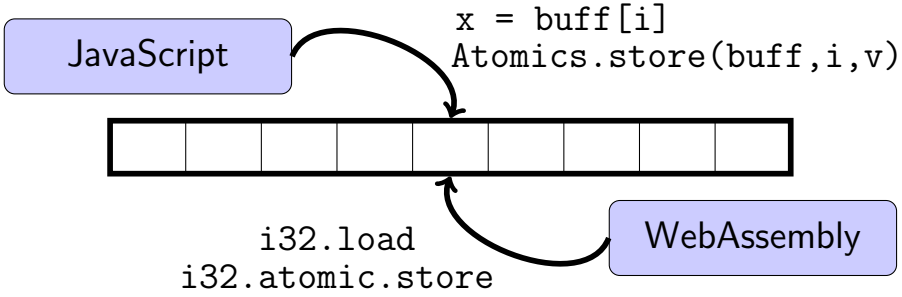
- WebAssembly program can read from and write to a linear buffer of raw bytes.
- Adding threads, these buffers can now be shared.
- Need a relaxed memory model.



Relaxed memory

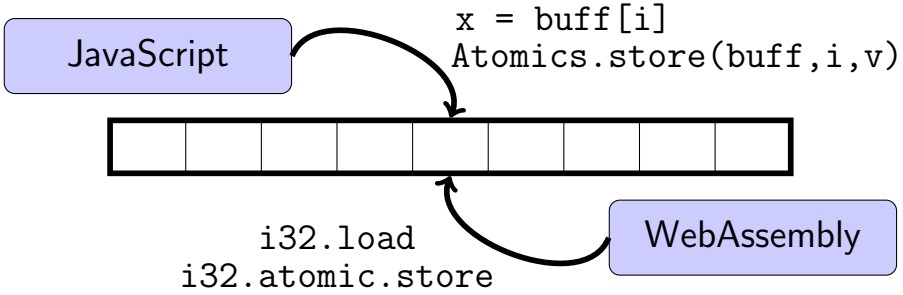
- JavaScript also has threads ("web workers") and shared buffers, even a memory model!

- The WebAssembly memory will be exposed to JavaScript as a shared buffer.



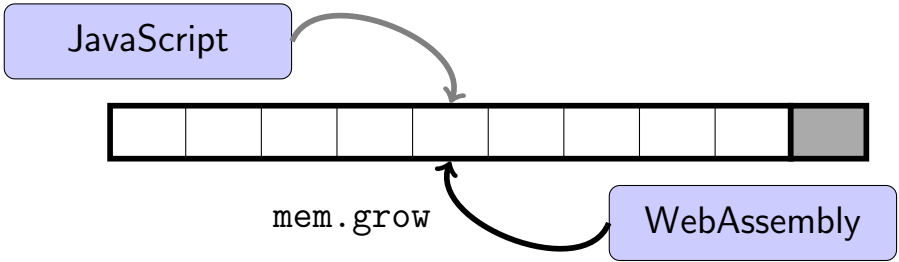
Relaxed memory

- Committee: JS/Wasm interop should "just work".
- So a lot of Wasm consistency behaviour is inherited from JS.



Relaxed memory

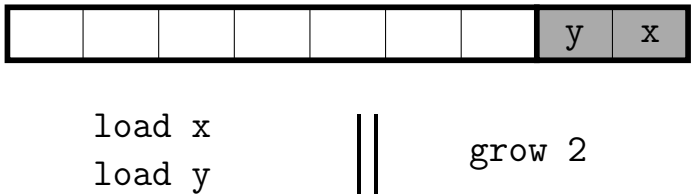
- But Wasm has additional feature - memory growth.
- Now, the size of the memory needs to become part of the axiomatic model.



Relaxed memory

- Implementers don't want to guarantee SC bounds-checking behaviour.

- Updates to memory size can create "data" races.



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]

[4] 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.

[5] Shu-yu Guo. *Normative: Fix memory model so DRF-SC holds*. Nov. 2018. URL: https://github.com/tc39/ecma262/pull/1362.

[6] Shu-yu Guo. *Memory Model Support for ARMv8 LDA/STL*. Jan. 2019. URL: https://docs.google.com/presentation/d/1qif7z-Y8C-nvJM20UNJQzAKJgLN4wmXS_5NN2Wgipb4/edit?usp=sharing.

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!

WEBASSEMBLY