Adventures in Mechanising and Verifying WebAssembly

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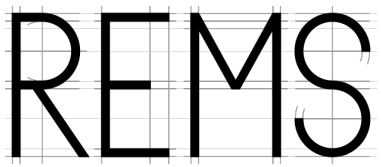
Formal Methods Meets JavaScript, VeTSS



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.

Peter Sewell

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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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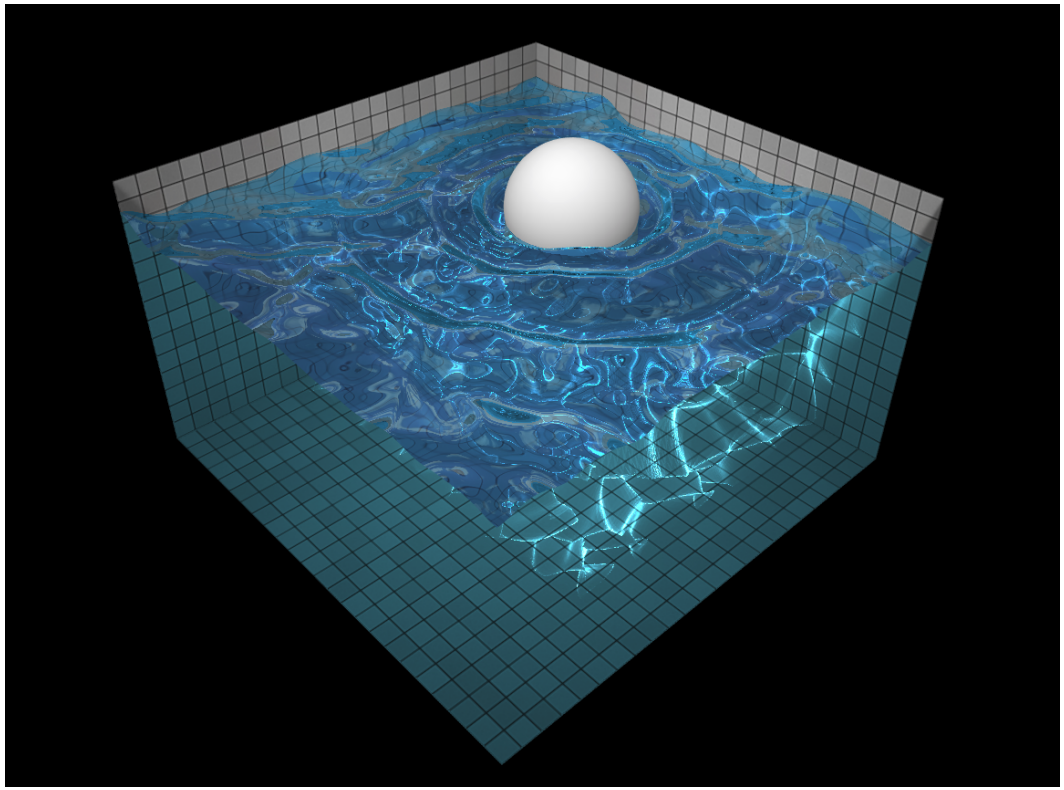


https://github.com/evanw/webgl-water

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
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 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 7
  br 0
end
```

```
loop
  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
```

Type:
[] $\rightarrow$ [i32]

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

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

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

Type:
$\bot$

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'

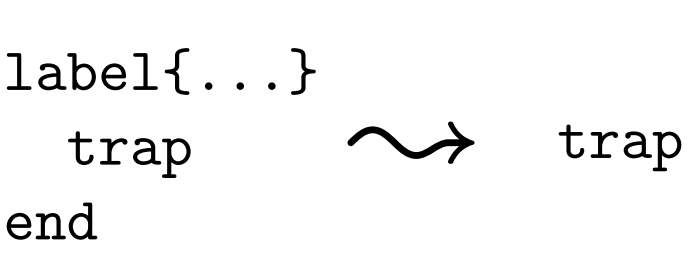
Initial mechanisation and soundness proof

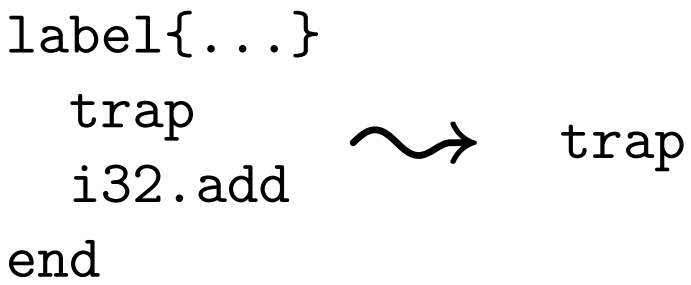
- Initially based on an accepted draft of the WASM group's PLDI paper[1] combined with the draft specification.
- Definitions and proofs in Isabelle.
- Type soundness properties: preservation and progress.
- Progress property as stated in the draft had a trivial counterexample.

[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.





Problems found

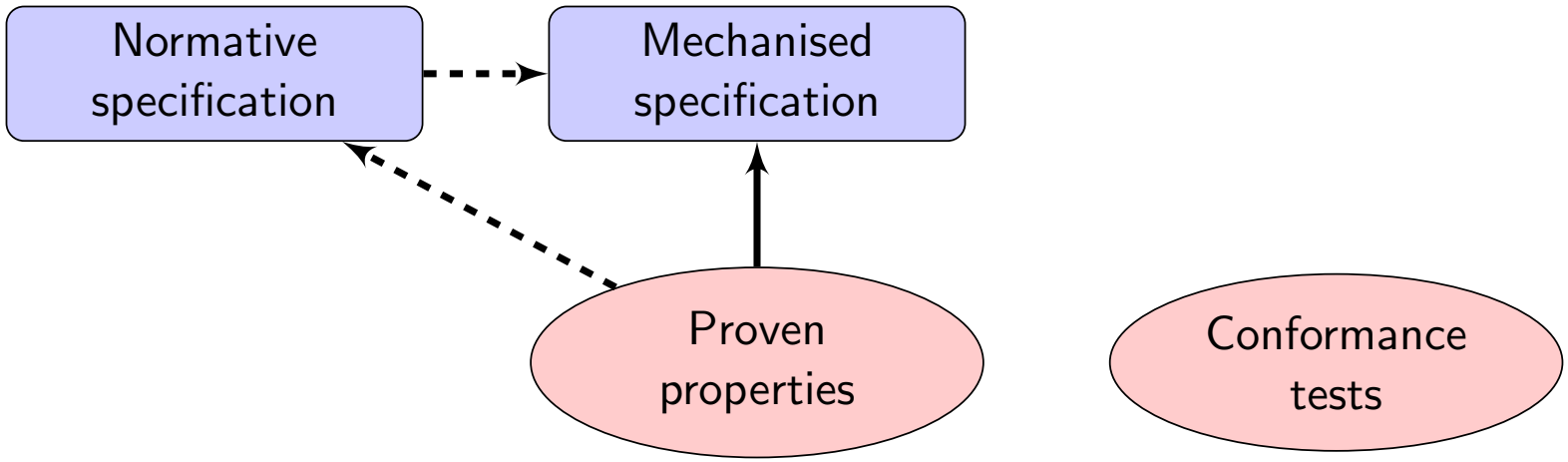
- Various trivial mistakes in the constraints of casting instructions.
- Big one - host function interface was unsound.[2]
- After these changes, managed to get a fully mechanised proof of soundness! (∼5000 LOC)

[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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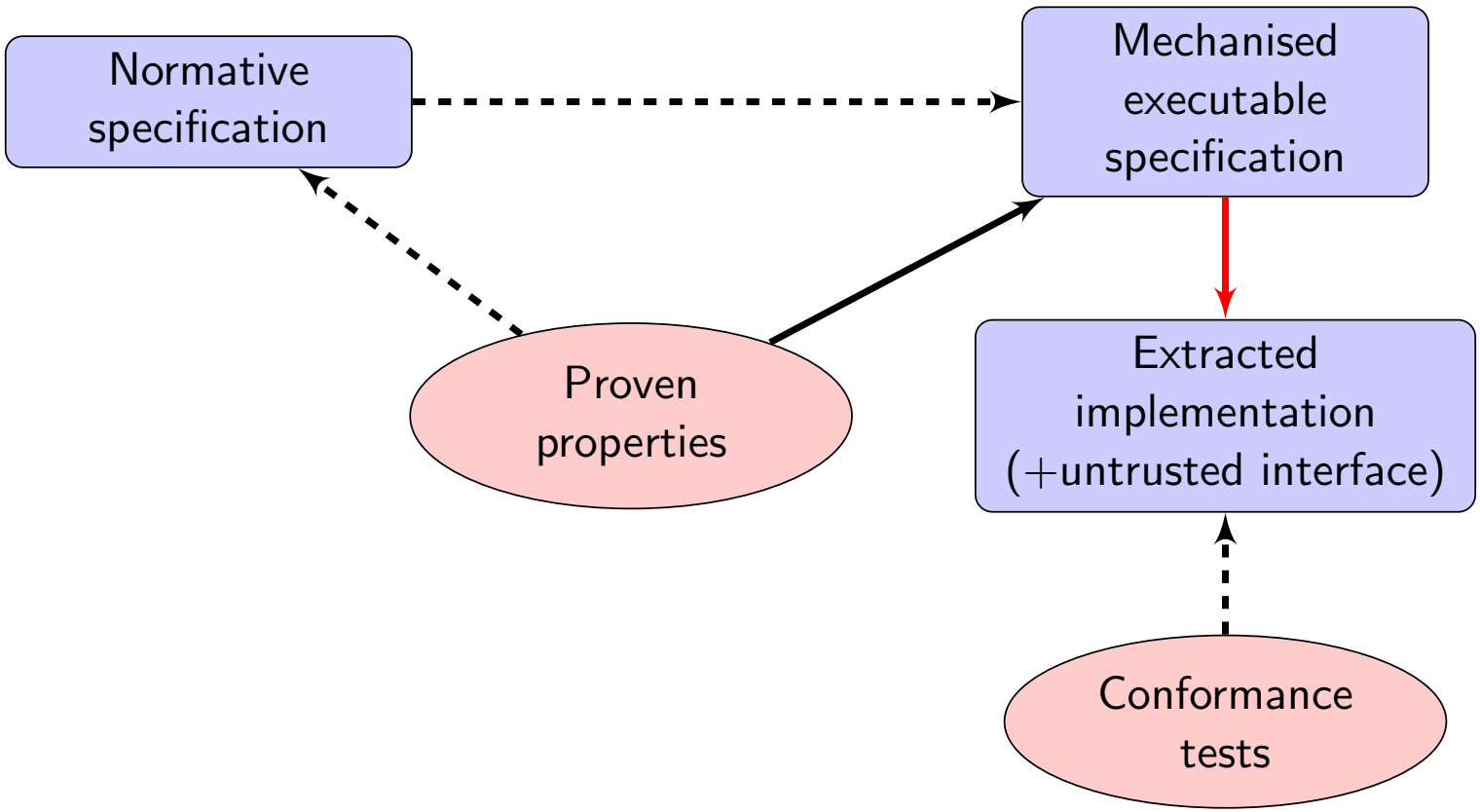

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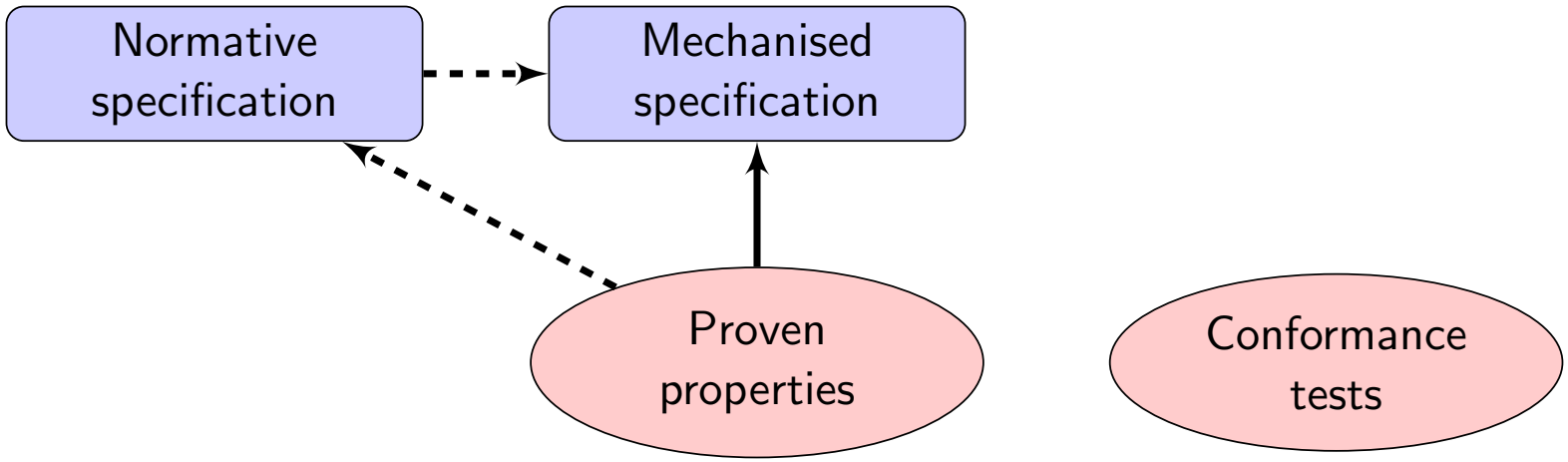

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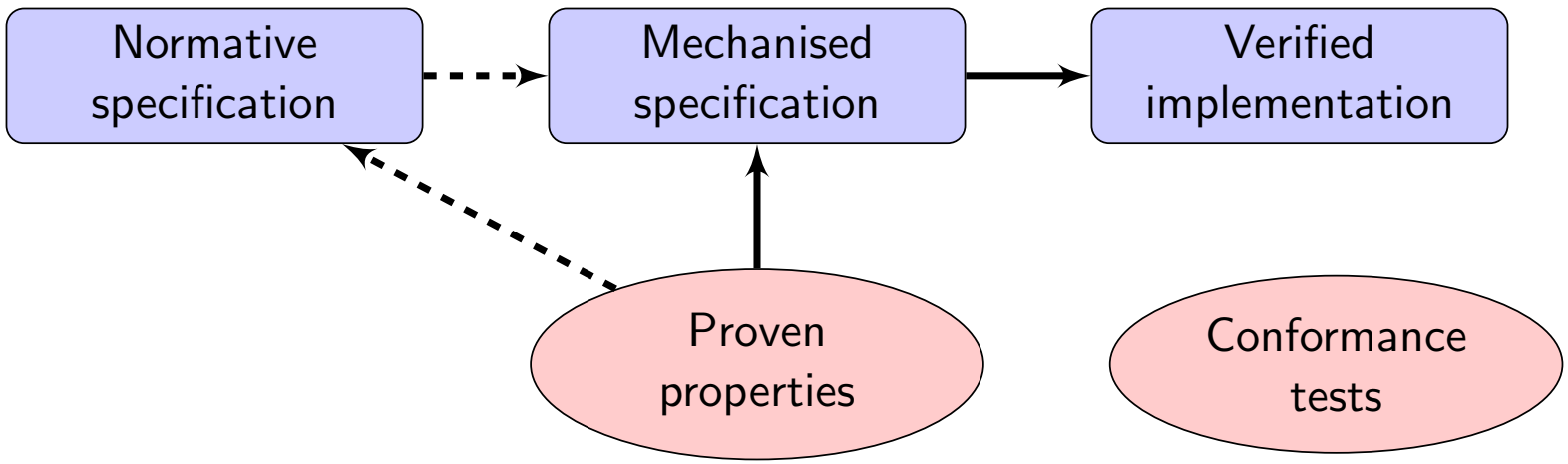

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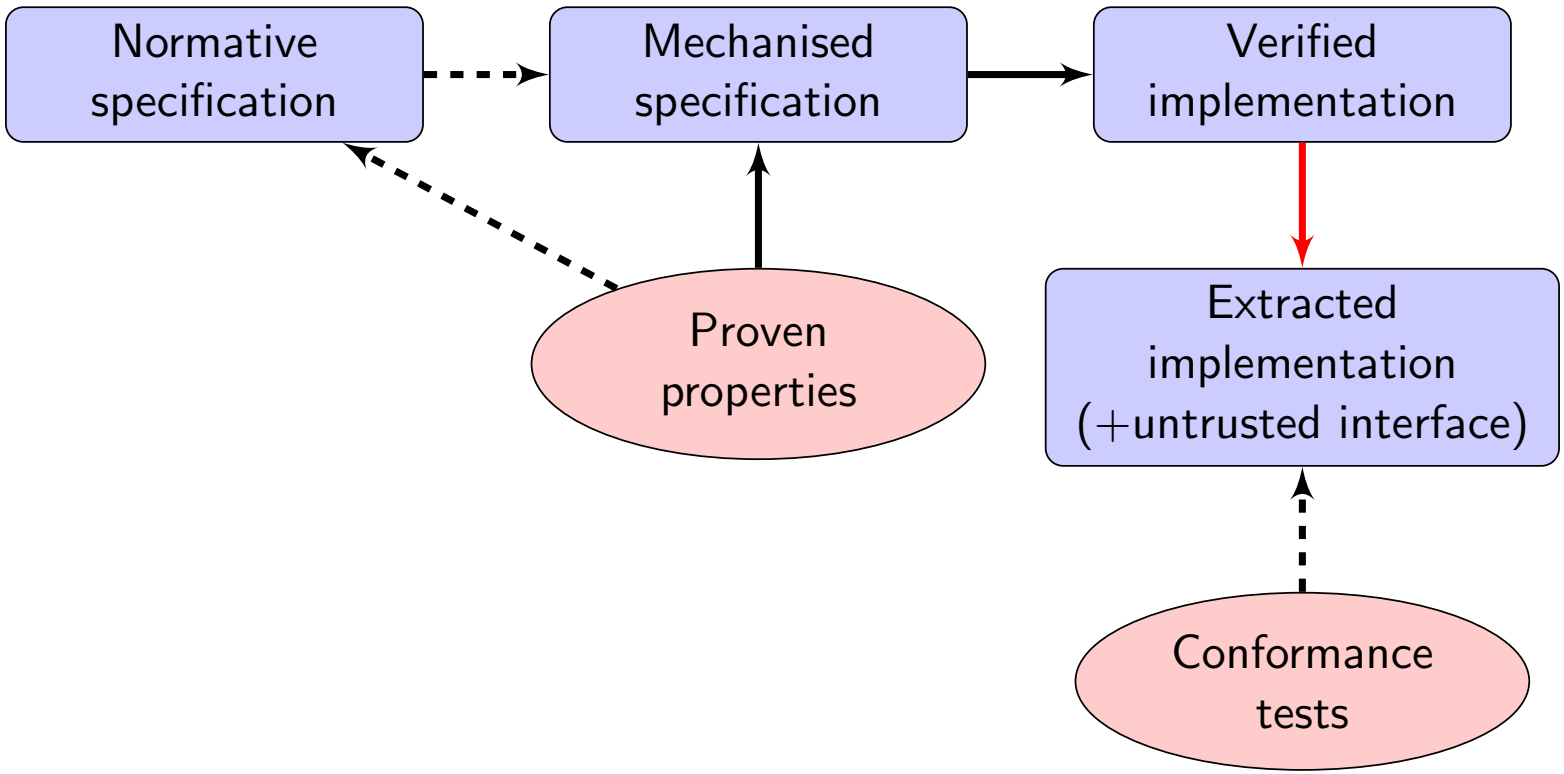

Solution

- 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 (?)