CTWASM

WebAssembly, Formal Methods, and Secure Cryptography

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Extended from slides by John Renner

The web has evolved

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Peter Sewell

Professor of Computer Science, Computer Laboratory, University of Cambridge
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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

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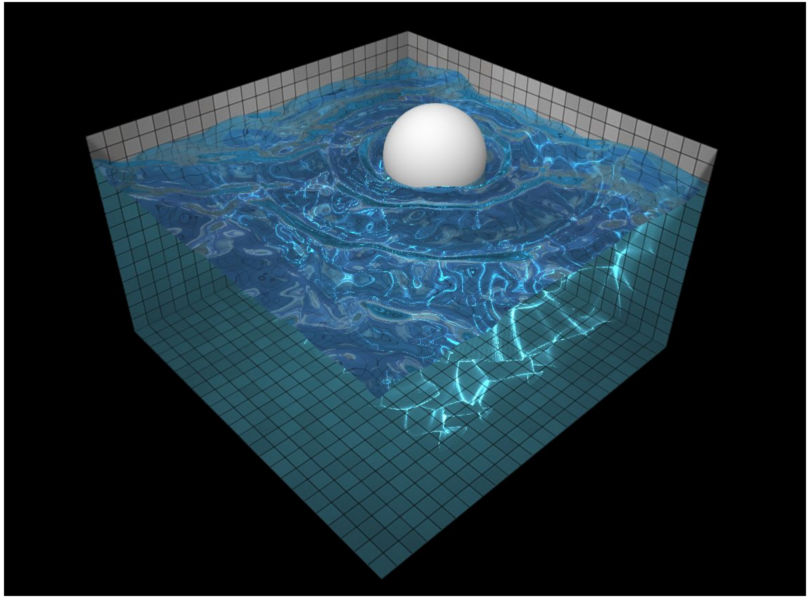

https://github.com/evanw/webgl-water

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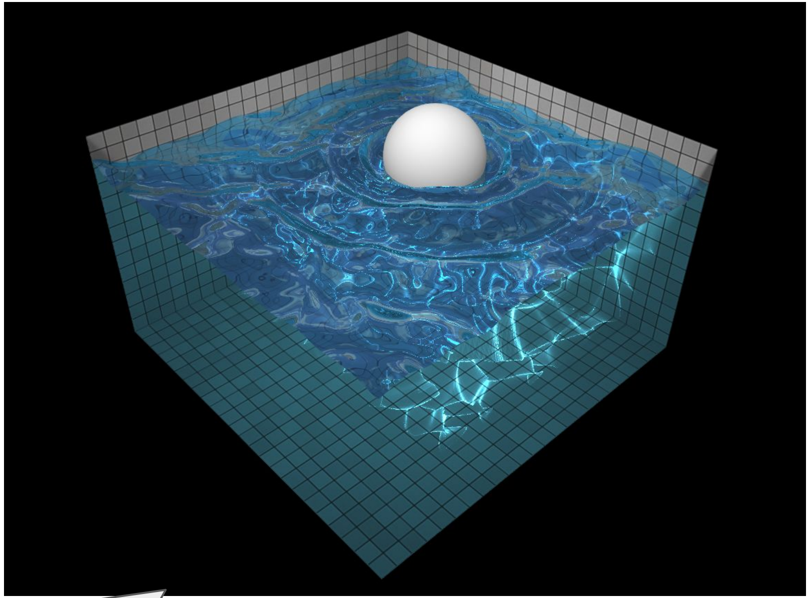

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The web has evolved

- We want richer web apps -
  3D rendering, physics, 60 FPS.
- 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.

The web has evolved

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

  Bringing the web up to speed with WebAssembly [Haas et al. 2017]

What does WebAssembly look like?

```
(module
  (func $add (param i32 i32) (result i32)
    (local.get 0)
    (local.get 1)
    (i32.add)
    (return))
  (export "add_ints" (func $add))
```

What does WebAssembly look like?

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    (return))
  (export "add_ints" (func $add)))
```

WebAssembly execution, formally

$$F; e^* \hookrightarrow F'; e'^*$$

$$t \triangleq \texttt{i32} \mid \texttt{i64} \mid \texttt{f32} \mid \texttt{f64}$$

$$\begin{aligned} e \triangleq\ & t.\texttt{const}\ n \mid t.\texttt{add} \mid t.\texttt{load} \mid t.\texttt{store} \\ & \mid \texttt{local.get}\ n \mid \texttt{local.set}\ n \mid \ldots \end{aligned}$$

Addition

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

↪

```
(i32.const 4)
(i32.const 3)
(i32.add)
```

↪

```
(i32.const 7)
```

Load

$$F;\ \begin{array}{l}(\texttt{i32.const}\ k)\\ (t.\texttt{load})\end{array} \hookrightarrow F;\ (t.\texttt{const}\ v)$$

if

$$\begin{array}{l}F = \{\\ \quad \dots\\ \quad \text{memory} = mem\\ \}\end{array}$$

and

$$v = \text{load}(mem,\ k,\ t)$$

Store

$$F;\ \begin{array}{l}(\texttt{i32.const}\ k)\\(t\texttt{.const}\ v)\\(t\texttt{.store})\end{array} \hookrightarrow F';\ .$$

if

$$F = \{ \begin{array}{l} \dots \\ \text{memory} = \mathit{mem} \end{array} \}$$

and

$$F' = \{ \begin{array}{l} \dots \\ \text{memory} = \\ \quad \text{store}(\mathit{mem}, k, v) \end{array} \}$$

Get local

$$F;\ (\mathtt{local.get}\ k) \hookrightarrow F;\ (t\mathtt{.const}\ v)$$

if

$$F = \{$$

$$\quad \ldots$$

$$\quad \mathrm{local}[k] = (\ v :: t\ )$$

$$\}$$

Set local

$$F;\ \begin{matrix}(t.\mathtt{const}\ v)\\(\mathtt{local.set}\ k)\end{matrix} \hookrightarrow F';\ .$$

if

$$F = \{\ \begin{matrix}\ldots\\ \mathrm{local}[k] = \ldots\end{matrix}\ \}$$

and

$$F' = \{\ \begin{matrix}\ldots\\ \mathrm{local}[k] = (\ v :: t\ )\end{matrix}\ \}$$

Structured control flow

- WebAssembly has no “goto” operation
- Instead, directly encode control flow constructs
- Only structured control flow is allowed

$$\begin{aligned} e \triangleq \ldots\ & \mathtt{block}\ \mathit{tf}\ e^*\ \mathtt{end} \\ \mid\ & \mathtt{loop}\ \mathit{tf}\ e^*\ \mathtt{end} \\ \mid\ & \mathtt{if}\ \mathit{tf}\ e^*\ \mathtt{else}\ e^*\ \mathtt{end} \end{aligned}$$

Type system

All WebAssembly programs must be validated (type checked) before execution.

$$tf \triangleq (t^* \rightarrow t^*)$$

`(i32.const 4)`

Type:

$([] \rightarrow [\mathtt{i32}])$

Type system

All WebAssembly programs must be validated (type checked) before execution.

$tf \triangleq (t^* \to t^*)$

```
(i32.const 4)
```

Type:

([] → [i32])

```
(i32.add)
(i32.add)
```

Type:

([i32,i32,i32] → [i32])

Type system

All WebAssembly programs must be validated (type checked) before execution.

$tf \triangleq (t^* \to t^*)$

```
(i32.const 4)
```

Type:

([] → [i32])

```
(i32.add)
(i32.add)
```

Type:

([i32, i32, i32] → [i32])

```
(f64.const 2)
(i32.const 1)
(i32.add)
```

Ill-typed

Type soundness

- Preservation
    - If a program (F; e*) is validated with a type ([] → [t*]), any program obtained by reducing (F; e*) to (F'; e'*) can also be validated with type ([] → [t*]).

- Progress
    - For any validated program (F; e*) that has not terminated with a result, there exists (F'; e'*) such that (F; e*) reduces to (F'; e'*).

A Syntactic Approach to Type Soundness [Wright and Felleisen. 1994]

Mechanisation

- An unambiguous formal specification and correctness condition.

- Perfect for mechanisation!

- ~11,000 lines of Isabelle/HOL definitions and proofs.

Mechanisation

- Found several errors in the draft specification.
- With fixes, proof complete!
- Also included: verified interpreter and type-checker

Mechanisation

Two categories of error were found.

- Trivial “syntactic” errors
    - typos
    - missing cases

- Deeper “semantic” errors
    - Edge-cases where formal rules get stuck
    - Sound interop with JavaScript/host

Mechanisation

Two categories of error were found.

- Trivial “syntactic” errors
  - simply copying definitions down
  - don’t need a full prover

- Deeper “semantic” errors
  - Discovered during soundness proof
  - Hard to find by hand

CTWASM

Writing crypto code is hard

Functional correctness is not enough

`enc(m,prv1)` 25ns

`enc(m,prv2)` 20ns

Timing discrepancies leak information about inputs

Remote Timing Attacks are Practical [Brumley et al. 2003]

Remote Timing Attacks are Still Practical [Brumley et al. 2011]

Hey, You, Get Off of My Cloud [Ristenpart et al. 2009]

Lucky Thirteen [Farden et al. 2013]

Lucky Thirteen Strikes Back [Irazoqui et al. 2015]

JavaScript Runtime

code.js

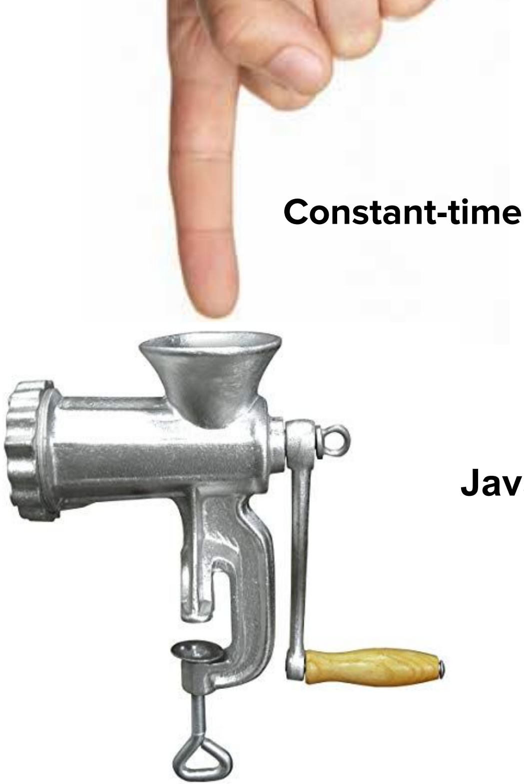
JavaScript Runtime

`code.js`

Fast machine code

```
10101001  11111111  10001101  10000100
00000011  10101001  11001000  10001101
10001000  00000011  10101001  00000000
10001101  10000110  00000011  10001101
10001010  00000011  10001101  10001011
```

JavaScript Runtime



Constant-time code

Fast machine code

```
10101001  11111111  10001101  10000100
00000011  10101001  11001000  10001101
10001000  00000011  10101001  00000000
10001101  10000110  00000011  10001101
10001010  00000011  10001101  10001011
```

JavaScript Runtime

Signal

crypto-js

JavaScript library of crypto standards.

444,906

Existing JS Crypto Solutions

Platform Crypto (WebCrypto, node.js crypto)

- **Missing modern algorithms (Poly1305)**
- **Unreliable support**

Native C Modules

- **Doesn’t work in browsers**

So what can we do?

WA

WEBASSEMBLY

Statically Typed

Low-level

Portable

WebAssembly is not enough

Doesn’t stop you from writing leaky code

Runtime can still introduce vulnerabilities

Solution:
Make Secrecy Explicit

Secret Types

`s32`
`s64`

All other types are public:
`i32, i64, f32, f64`

Turn vulnerabilities into type errors

Inform the runtime

Key Insights

Observe “best-practice” cryptography code

https://cryptocoding.net/index.php/Coding_rules

Restrictions are course-grained - simple type system!

Prevent Explicit Leaks

Prevent Implicit Leaks

Prevent Leaks via Timing

Direct leakage as type errors

```
(local $pub i32)
(local $sec s32)

(local.set $pub (get_local $sec))
```

Preventing explicit leaks

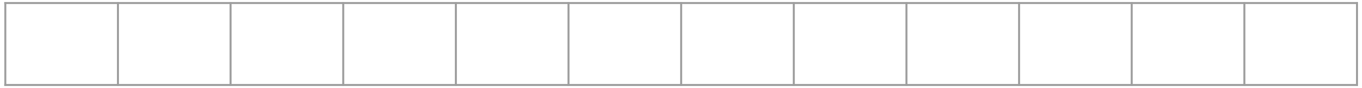
```
(local $pub i32)
(local $sec s32)

(local.set $pub (get_local $sec))
```

```
Error: type mismatch in set_local,
       expected i32 but got s32
```

What about memory?

`(memory 1)`



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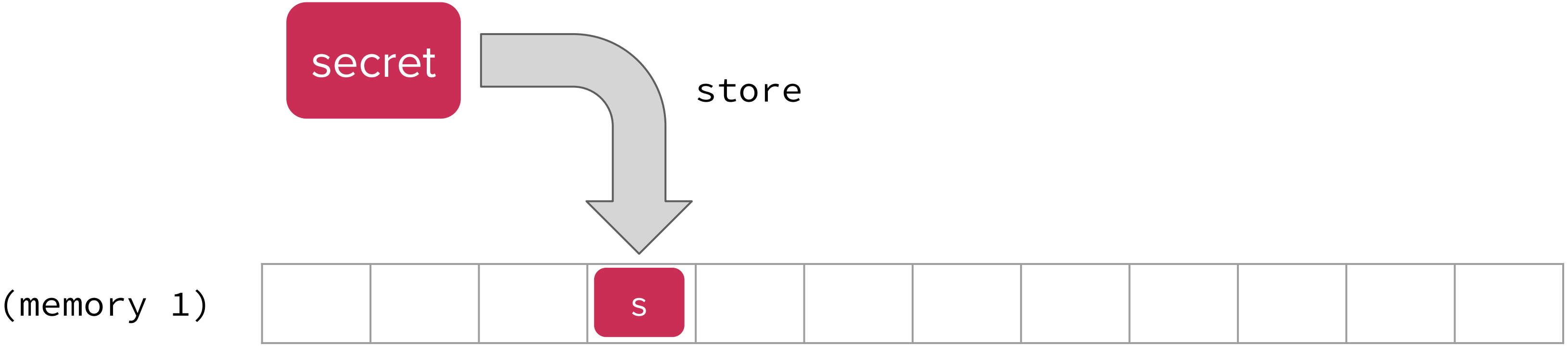

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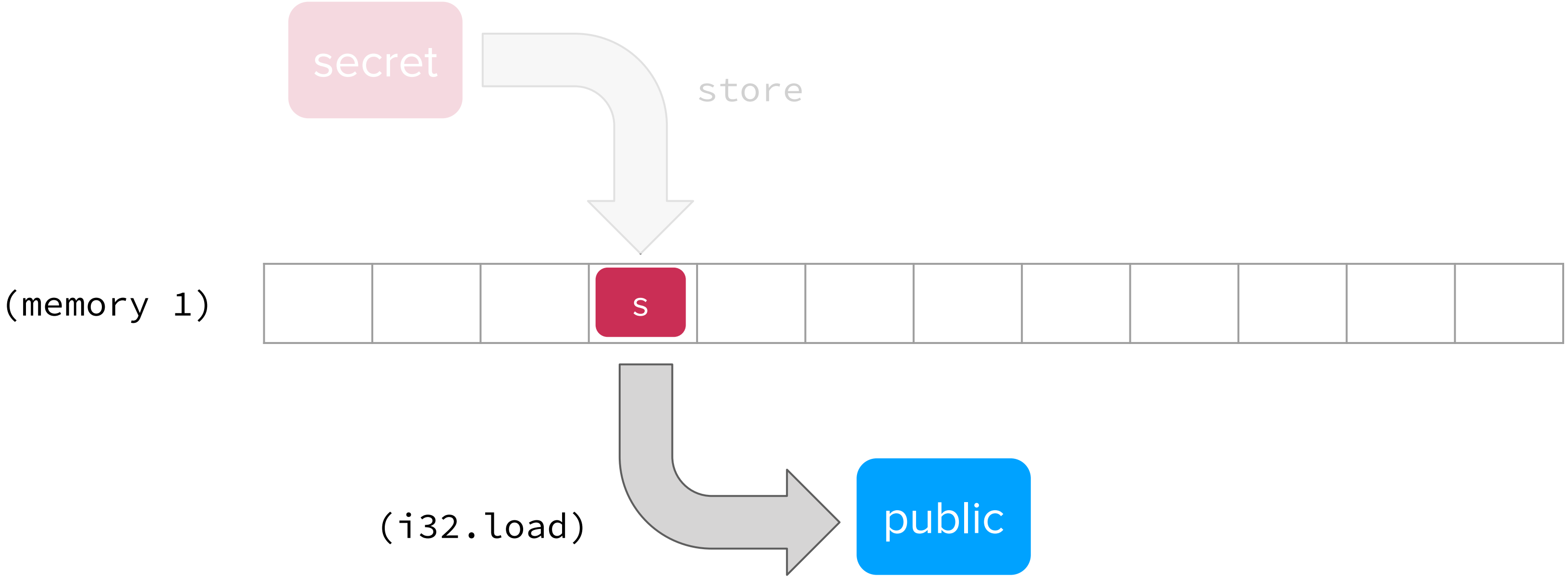

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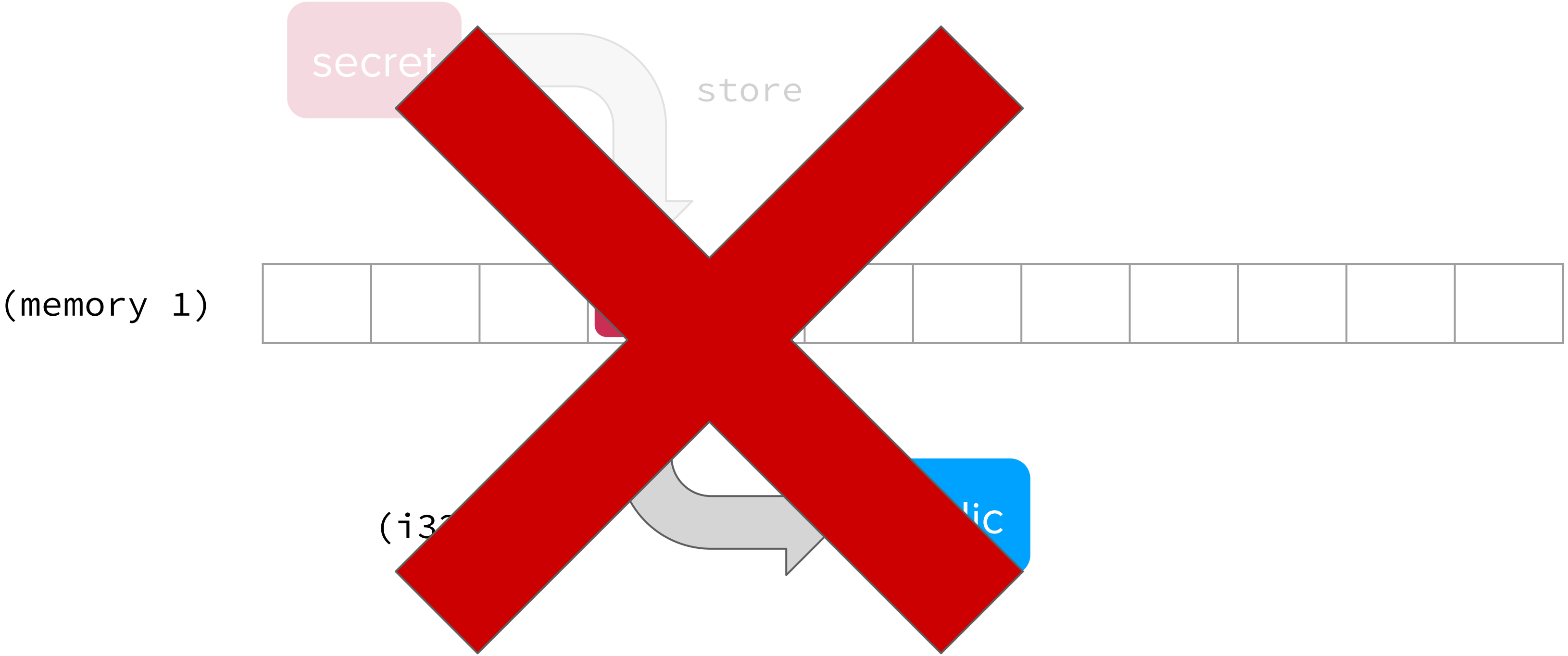


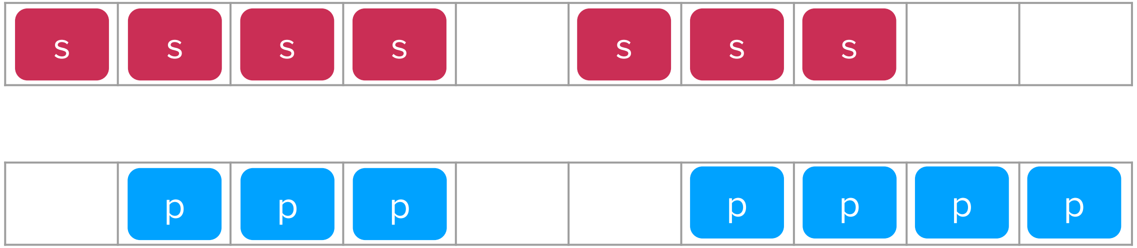
Secret Memory

```
(memory secret 1)
```

Secret opcodes

```
s32.load
s32.store
...
```

Secret Memory



`(memory secret 1)`	s	s	s	s		s	s	s		
`(memory 1)`		p	p	p			p	p	p	p

Prevent Explicit Leaks

Prevent Implicit Leaks

Prevent Leaks via Timing

Preventing leaks via control flow

```
(if (local.get $sec)

(then

    (local.get $pub ...))

(else

    (local.get $pub ...)))
```

Leaks:

- Indirect flow
- Timing (Conditional jump)

Preventing implicit leaks

```
(if (local.get $sec)
(then
    (local.get $pub ...))
(else
    (local.get $pub ...)))
```

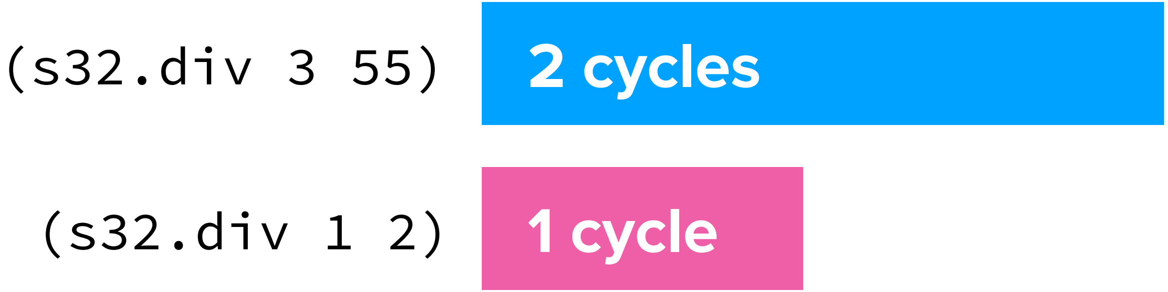
```
TypeError
‘if’ requires i32
     found    s32
```

Prevent Explicit Leaks

Prevent Implicit Leaks

Prevent Leaks via Timing

Certain instructions are leaky



`(s32.div 3 55)` **2 cycles**

`(s32.div 1 2)` **1 cycle**

Some operations are constant-time:
`add, xor, sub, mul, …`

Others are not:
`div, rem`

Floating point arithmetic

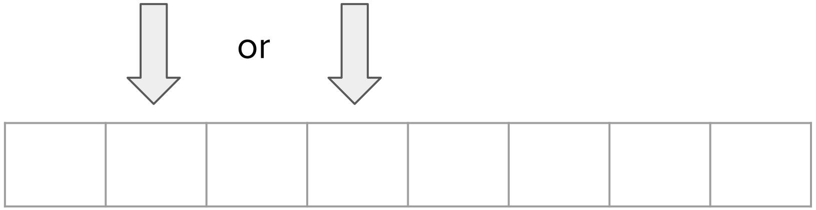
Preventing cache timing attacks

All memory operations both mutate and leak cache state

Cache state must be independent of secrets

Disallow secrets as memory indices

`(s32.load (get_local $sec))`



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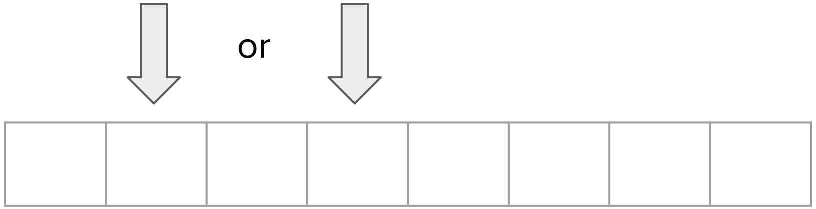


```
TypeError
's32.load' requires i32
           found    s32
```

Too safe for our own good

secret

encrypt (secret)

encrypt (secret) → public

encrypt (secret) → public

```
i32.declassify :: s32 → i32
```

Limiting `declassify` to trusted code

New Function Type

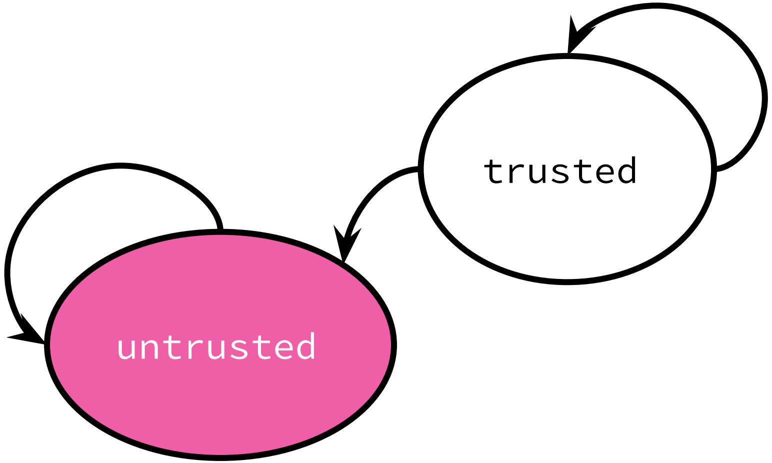
`(func untrusted ...)`

Can't `declassify`

Can only call other `untrusted` functions

Most crypto code is `untrusted`

Untrusted functions can’t `declassify`



Secure linking with untrusted

```
(import "crypto_lib" “handle_secret"
   (func untrusted (param s32)))
```

Explicit import types assert trust

Typechecker ensures library can’t leak

Verified in Isabelle

- Build on top of existing mechanisation
- ~5,800 lines of alterations/insertions
- Non-interference, constant-time

Non-Interference

A computation's public outputs
are independent from secret inputs

Non-Interference

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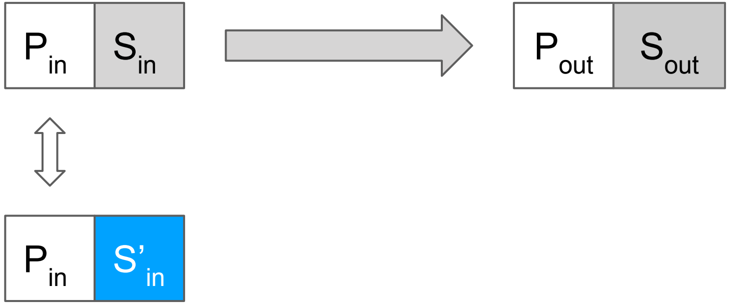


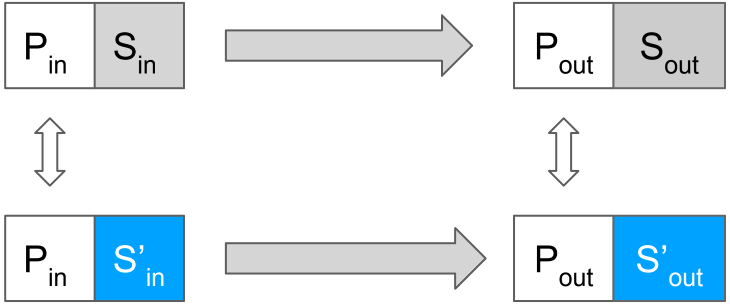
P_{in} S_{in}

P_{out} S_{out}

P_{in} S'_{in}

Non-Interference

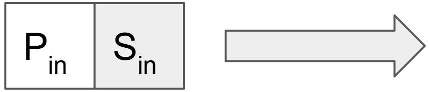
A computation's public outputs
are independent from secret inputs



Constant-Time

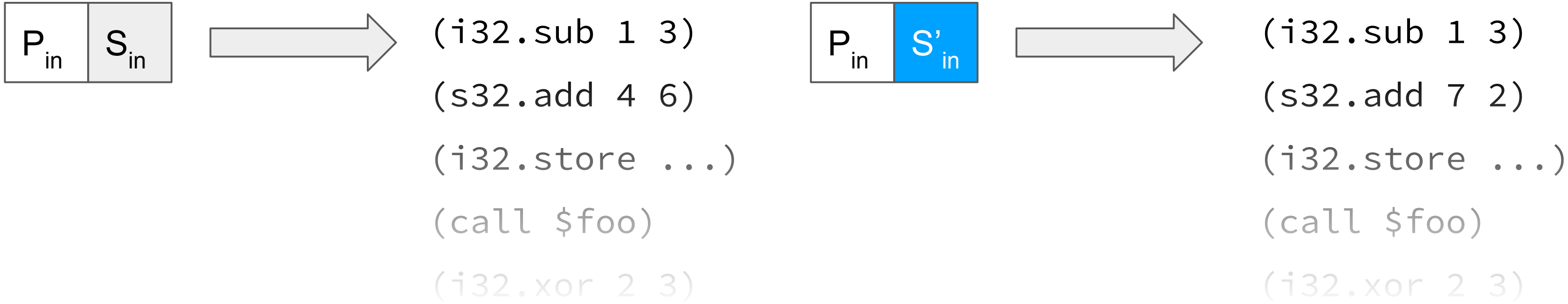
A program’s leakage
is independent from secret inputs

Constant-Time


P_{in} S_{in}

```
(i32.sub 1 3)
(s32.add 4 6)
(i32.store ...)
(call $foo)
(i32.xor 2 3)
```

Constant-Time



P_{in} S_{in}

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(i32.store ...)
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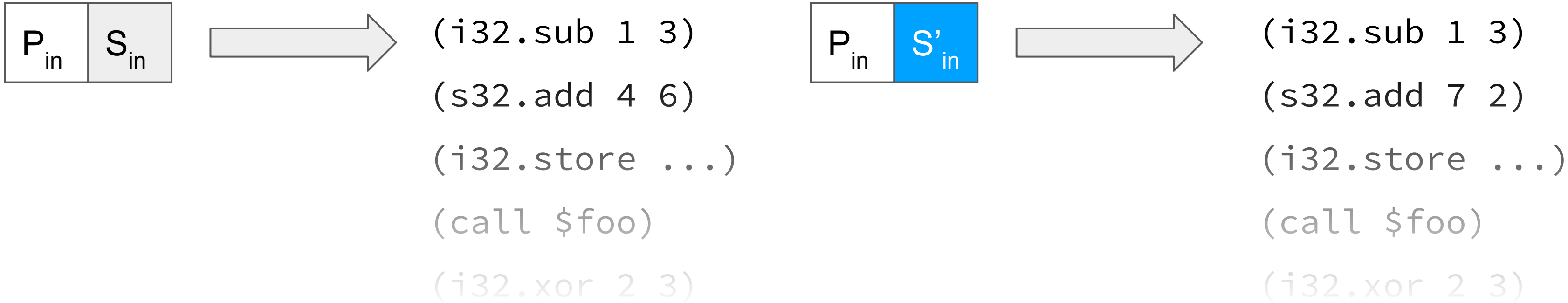
```

P_{in} S'_{in}

```
(i32.sub 1 3)
(s32.add 7 2)
(i32.store ...)
(call $foo)
(i32.xor 2 3)
```

Constant-Time



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(i32.sub 1 3)
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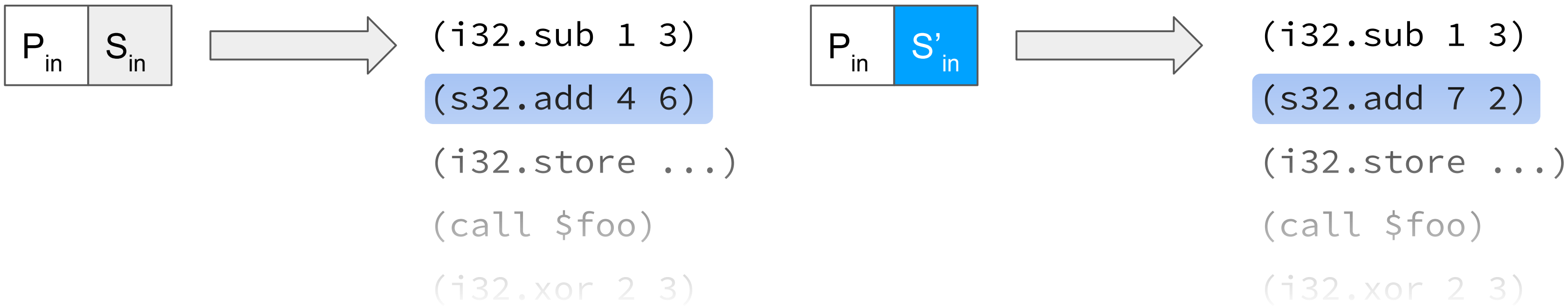
Recall: No branching on secrets

Program traces only differ on secret values

Constant-Time



P_{in} S_{in}

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P_{in} S'_{in}

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(i32.sub 1 3)
(s32.add 7 2)
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```

Recall: No branching on secrets

Program traces only differ on secret values

Constant-time Proof

P_{in} S_{in}

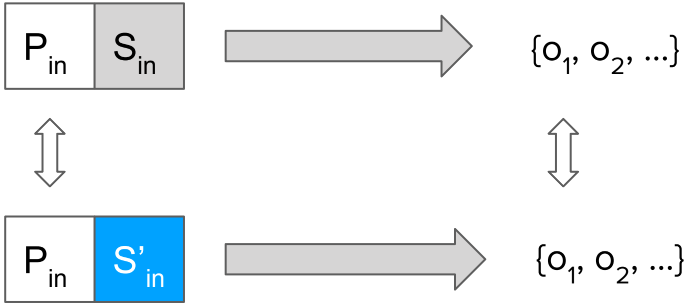
$\{o_1, o_2, \ldots\}$

Constant-time Proof

Observations:

- Branch conditions
- Memory access patterns
- Non-CT operands

Constant-time Proof



Observations:

- Branch conditions
- Memory access patterns
- Non-CT operands

Does it work in practice?

Implementations

Reference Interpreter	**V8**
Written in OCaml	Written in C++
Extended test suite	Production-quality runtime
Verified typechecker	Empirically checked

Evaluation

Performance & Security

TEA

SHA-256

Salsa20

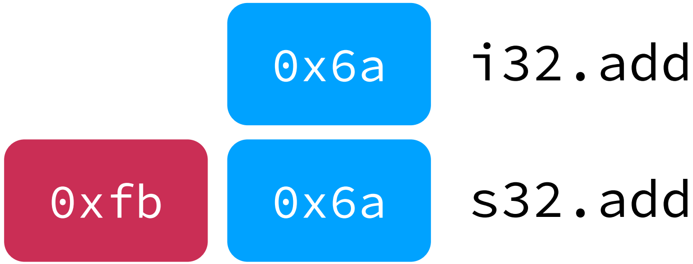
TweetNaCl

Evaluation

Performance & Security

- TEA
- SHA-256
- Salsa20
- **TweetNaCl**
    - X25519, Poly1305, XSalsa20
    - SHA-512, Ed25519

Binary size overhead



~15% overhead in practice

0% overhead for vanilla Wasm code

Performance overhead

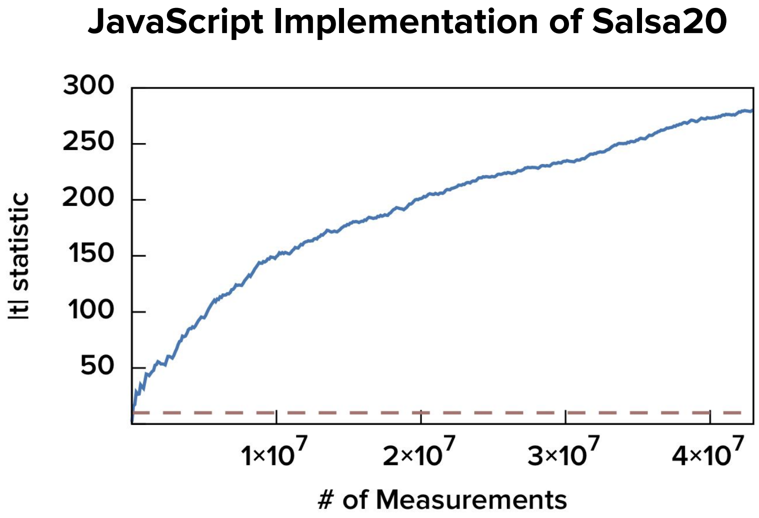
Runtime: < 1 %

Typechecking (Wasm): 14%

Typechecking (CT-Wasm): 20%

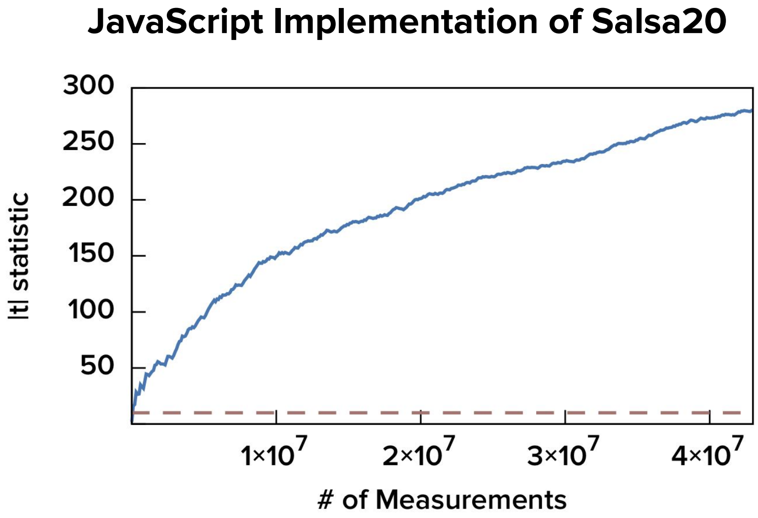
In practice: submillisecond validation of TweetNaCl

Statistical analysis with dudect



Dude, is my code constant time? [Reparaz et al. 2017]

Statistical analysis with dudect

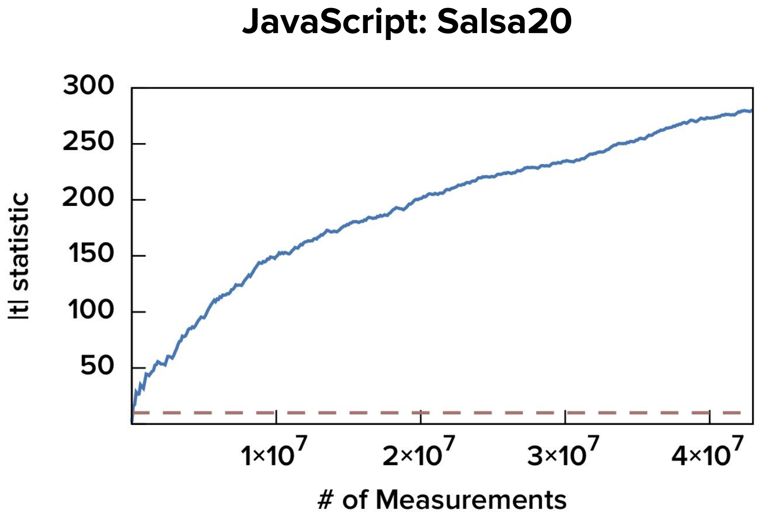


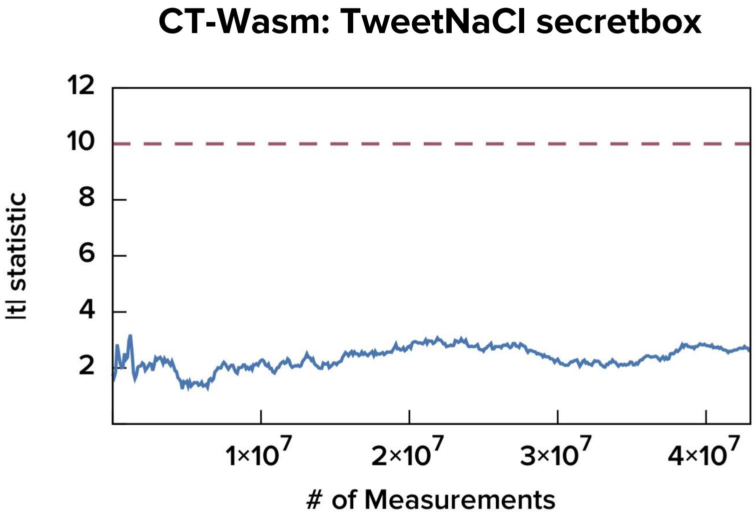
Why?

- Algorithm encodes sequences of 32-bit numbers
- V8 boxes >31-bit numbers
- Not obvious!

Dude, is my code constant time? [Reparaz et al. 2017]

Statistical analysis with dudect





Dude, is my code constant time? [Reparaz et al. 2017]

But can I use CT-Wasm today?

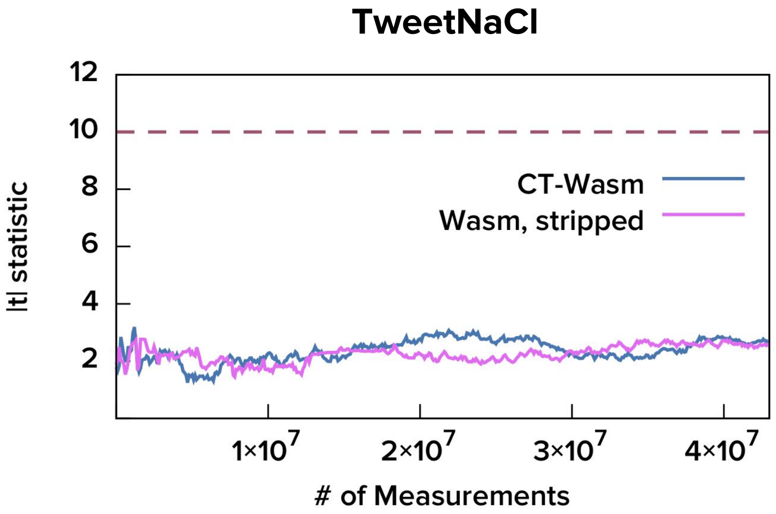
`ct2wasm`

Convert typechecked CT-Wasm to standard Wasm

Guarantees of constant-time structure

Best effort safety from runtime

`select` transform



Going Forward

Verified Compilation

CT-Wasm as a crypto IR

Label Inference

WA

CTWASM

Type system for secure crypto

Formally verified in Isabelle

Performant implementation in V8

Usable today through `ct2wasm`