Microsoft

Research Faculty Summit 2018

Systems | Fueling future disruptions

Microsoft

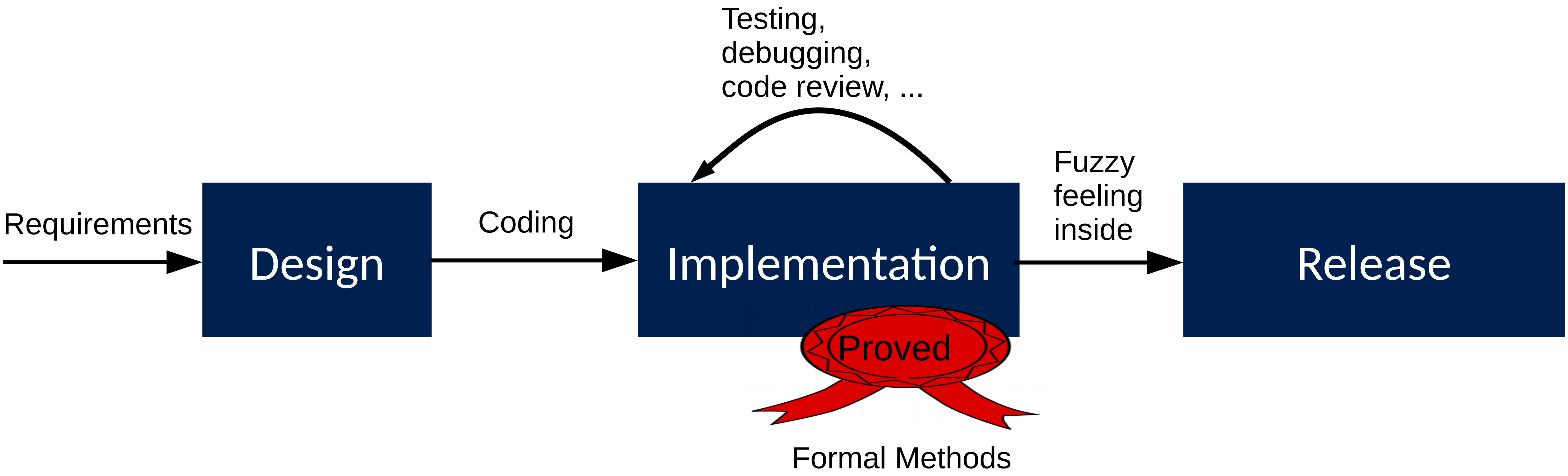
How Formal-Methods Adoption Should Drive Changes to System Designs

Adam Chlipala

Associate Professor, MIT CSAIL

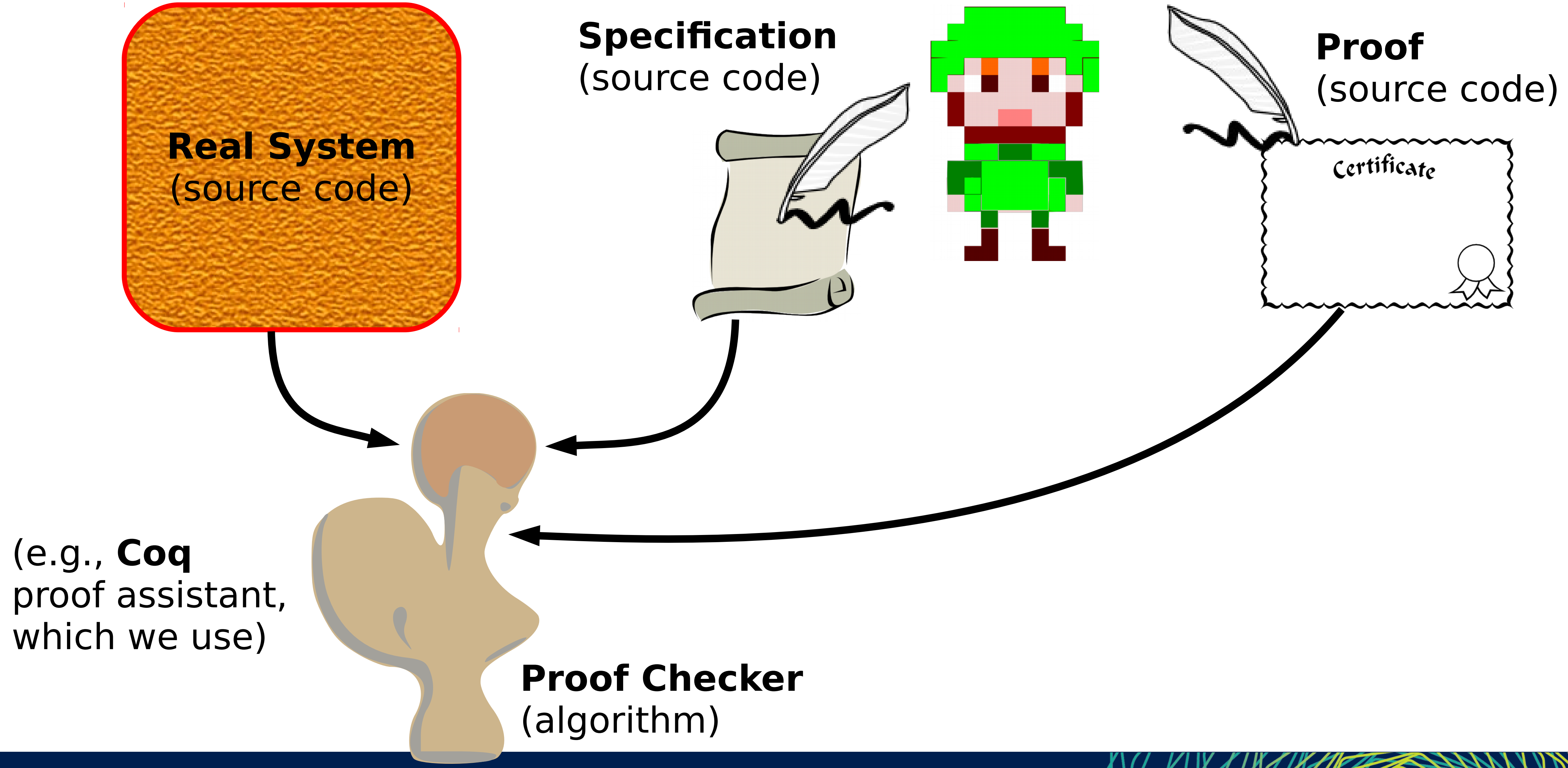
CSAIL

System Development Processes

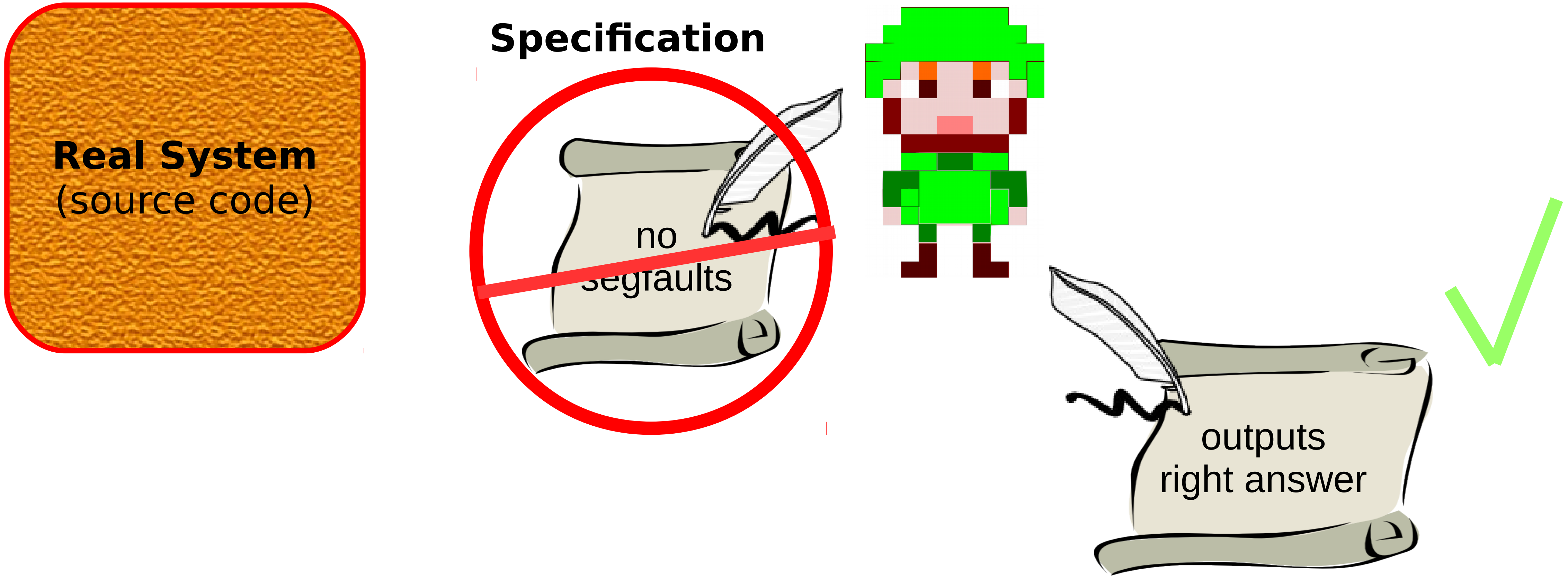


“**Mechanized**, **end-to-end** proofs of **functional correctness**”

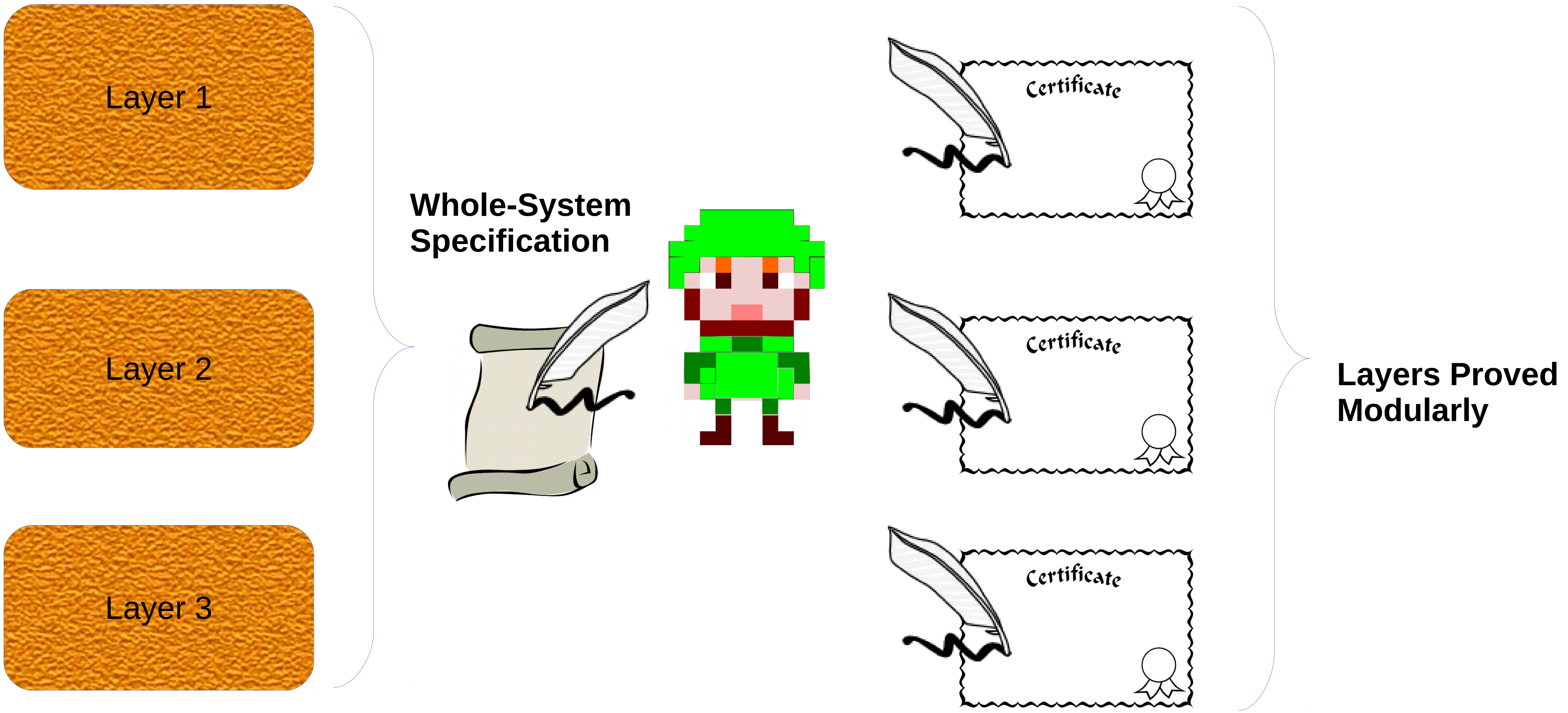
Mechanized proofs



Proofs of **Functional Correctness**



End-to-End Proofs



The Big Tradeoff

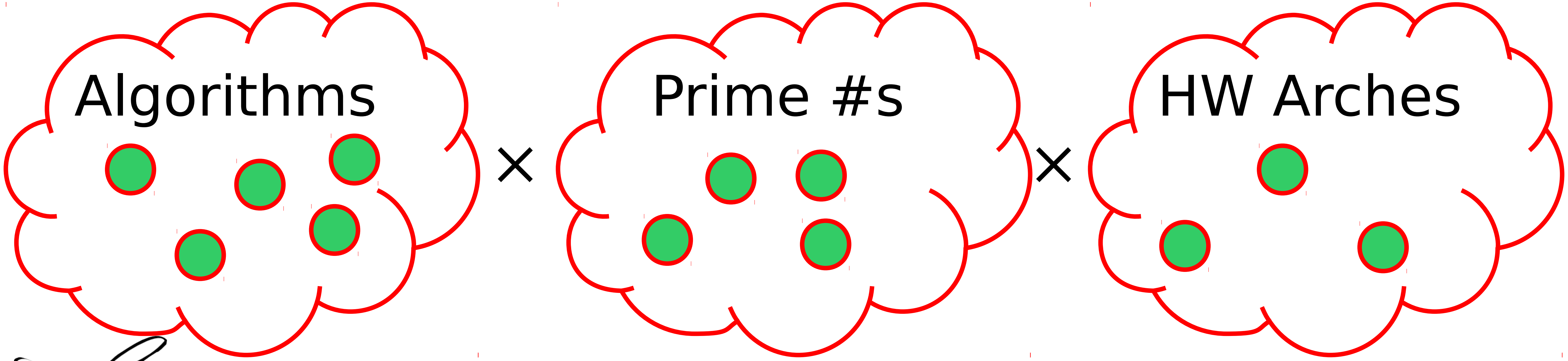
Performance vs. Maintainability

Is it *fundamental* that systems hackers need to spend their time writing intricate, bug-prone, low-level code?

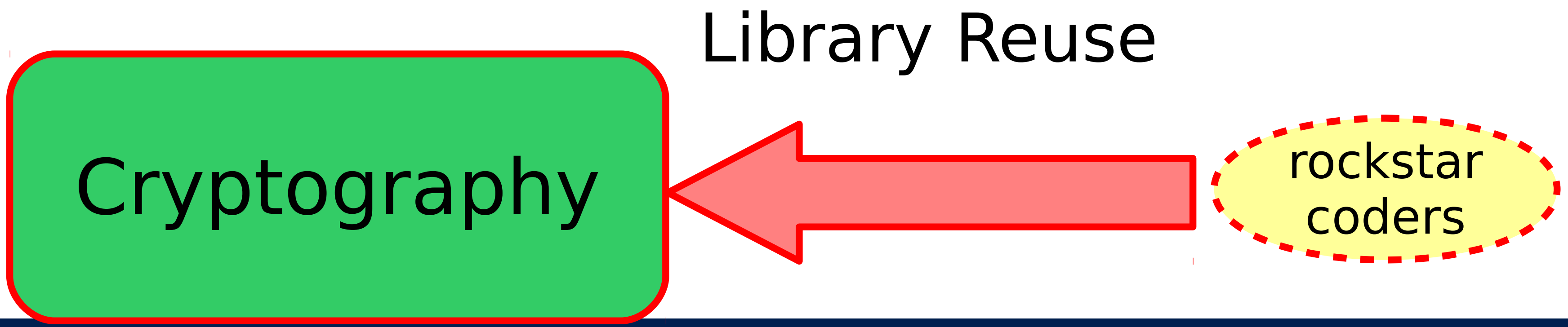
Crypto is Hard (Adam Langley's Curve25519 C code)

```
d0 = r0 * 2;
d1 = r1 * 2;
d2 = r2 * 2 * 19;
d419 = r4 * 19;
d4 = d419 * 2;

t[0] = ((uint128_t) r0) * r0 + ((uint128_t) d4) * r1 + (((uint128_t) d2) * (r3     ));
t[1] = ((uint128_t) d0) * r1 + ((uint128_t) d4) * r2 + (((uint128_t) r3) * (r3 * 19));
t[2] = ((uint128_t) d0) * r2 + ((uint128_t) r1) * r1 + (((uint128_t) d4) * (r3     ));
t[3] = ((uint128_t) d0) * r3 + ((uint128_t) d1) * r2 + (((uint128_t) r4) * (d419   ));
t[4] = ((uint128_t) d0) * r4 + ((uint128_t) d1) * r3 + (((uint128_t) r2) * (r2     ));

r0 = (limb)t[0] & 0x7ffffffffffff; c = (limb)(t[0] >> 51);
t[1] += c;      r1 = (limb)t[1] & 0x7ffffffffffff; c = (limb)(t[1] >> 51);
t[2] += c;      r2 = (limb)t[2] & 0x7ffffffffffff; c = (limb)(t[2] >> 51);
t[3] += c;      r3 = (limb)t[3] & 0x7ffffffffffff; c = (limb)(t[3] >> 51);
t[4] += c;      r4 = (limb)t[4] & 0x7ffffffffffff; c = (limb)(t[4] >> 51);
r0 +=   c * 19; c = r0 >> 51; r0 = r0 & 0x7ffffffffffff;
r1 +=   c;      c = r1 >> 51; r1 = r1 & 0x7ffffffffffff;
r2 +=   c;
```

But the experts know how to do all this, right?



Labor-intensive adaptation, with each combination taking *at least* several days for an expert.



And by the way, sometimes there are serious bugs.

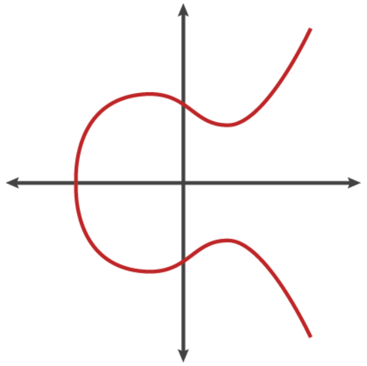
Correct-by-Construction Cryptography

Abstract security property

"Knowledge of the secret key is needed to produce a signature in polynomial time."

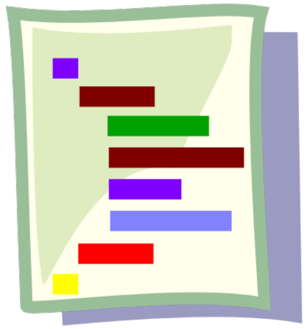
protocol verification

Mathematical algorithm



$$y^2 = x^3 - x + 1$$

Low-level code

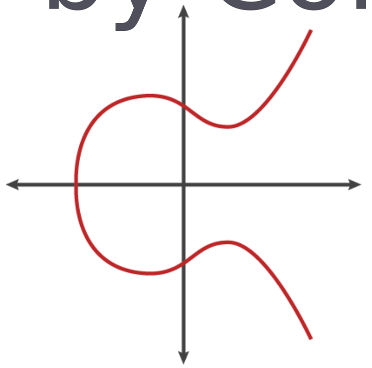


specialized assembly code

implementation synthesis

Correct-by-Construction Cryptography

Mathematical algorithm

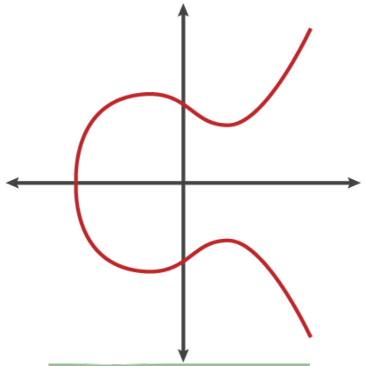


point = (x, y)

Proved abstraction relation

classic verification
of functional programs

Optimized point format

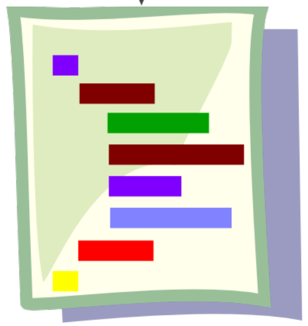


point = (x, y, z, t)

Proved abstraction relation

classic verification
of functional programs

High-level modular arithmetic

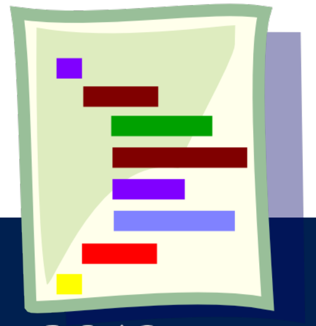


$x = x_0, x_1, \ldots, x_n$
(mathematical integers)

compile-time code
specialization

compiler verification

Low-level code



specialized low-level code
(assumes fixed set of integer sizes)

Fiat Cryptography

(logo shared with other parts of deepspec project)

Joint work with Andres Erbsen, Jade Philipoom, Jason Gross, and Robert Sloan

Implementation of Multiplication?

Just compute all the cross terms.

E.g., [(a, x), (b, y)] × [(c, u), (d, v)]
→ [(ac, xu), (ad, xv), (bc, yu), (bd, yv)]

```
Definition mul (p q:list (Z*Z)) : list (Z*Z) :=
  flat_map (fun t =>
    map (fun t' =>
      (fst t * fst t', (snd t * snd t')%RT))
  q) p.
Lemma eval_mul p q :
  eval (mul p q) = eval p * eval q.
```

Putting It All Together

Convert from fixed base system to simpler custom form at start of execution.

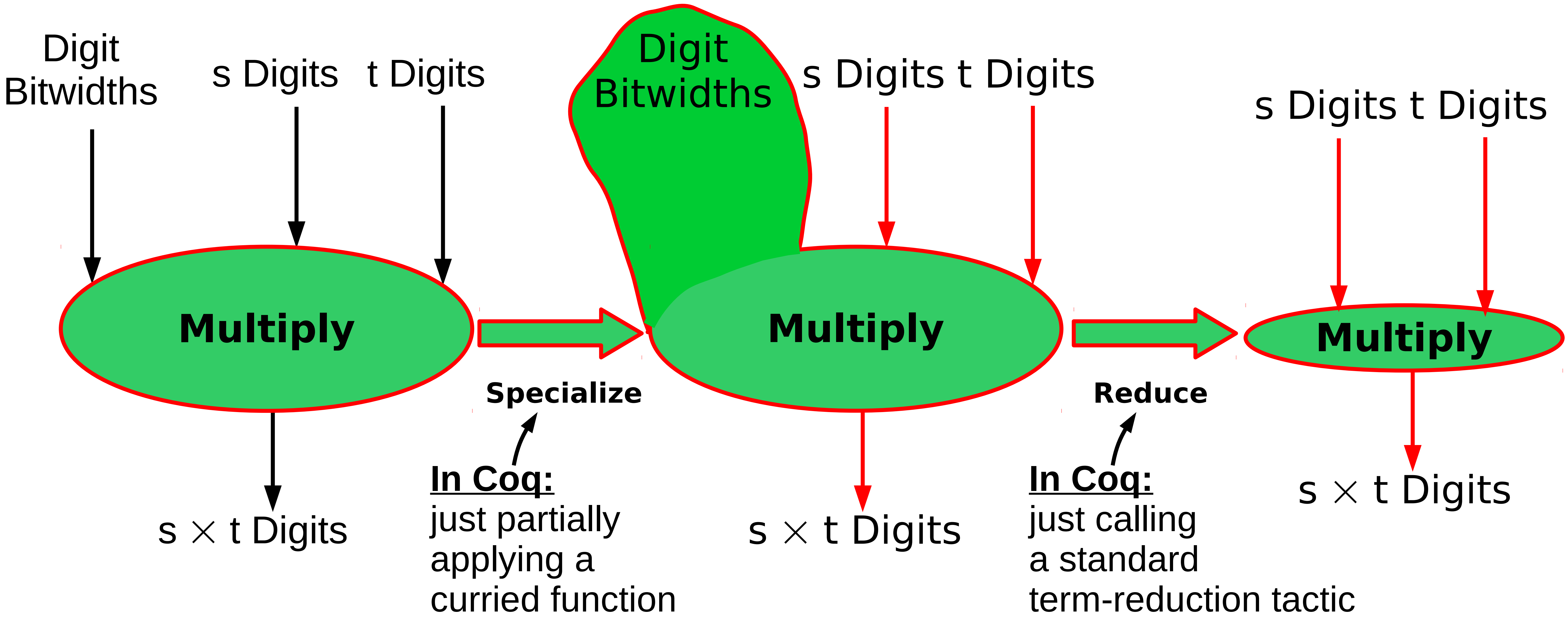
```
Definition mulmod {n} (a b:tuple Z n) : tuple Z n
  := let a_a := to_associational a in
     let b_a := to_associational b in
     let ab_a := Associational.mul a_a b_a in
     let abm_a := Associational.reduce s c ab_a in
     from_associational n abm_a.
```

Compute in custom form.

Convert back at end.

Research
Faculty Summit 2018
Systems | Fueling future disruptions

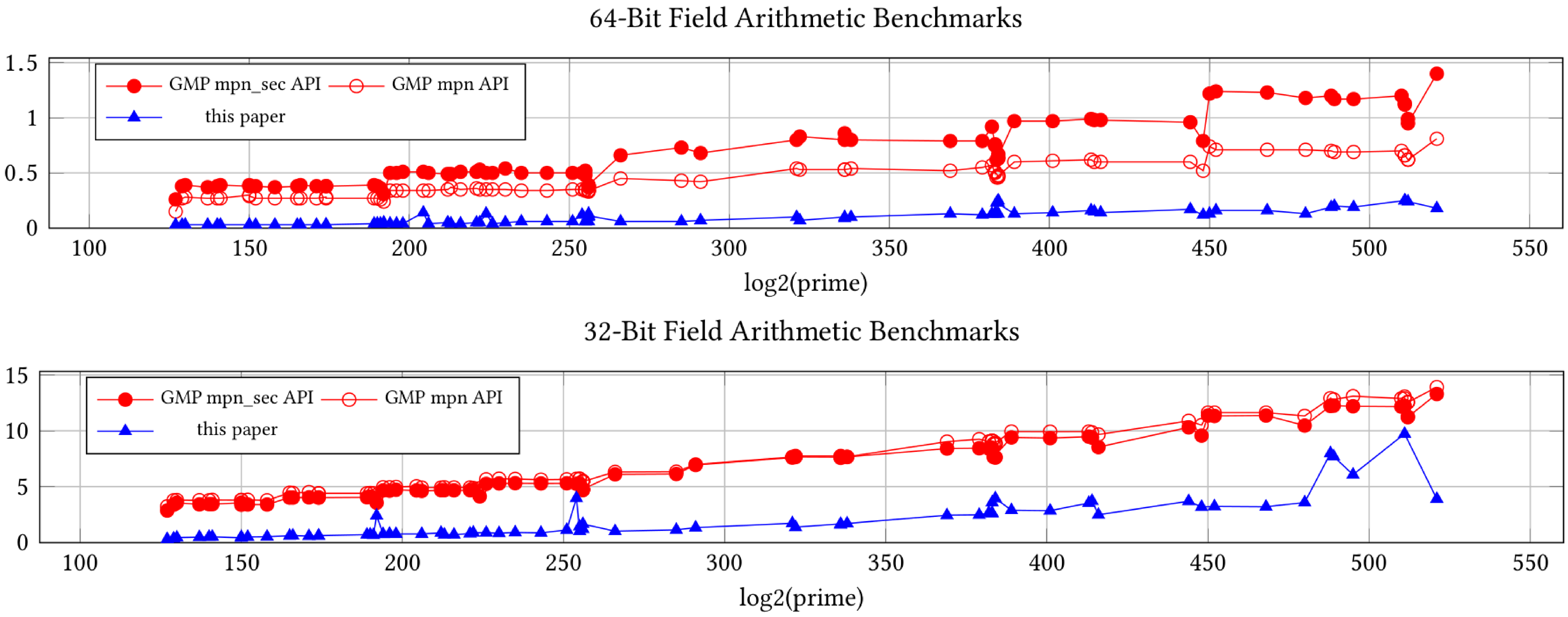
Time for Some Partial Evaluation

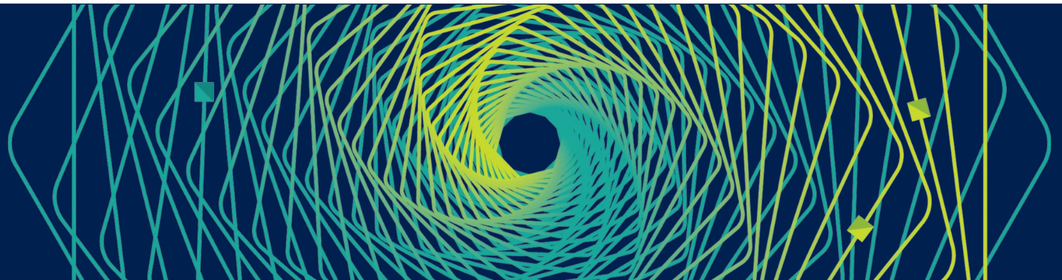


Performance on Curve25519

Implementation	CPU cycles
`amd64-64`, asm	151586
this work B, 64-bit	152195
`sandy2x`, asm	154313
`hacl-star`, 64-bit	154982
`donna64`, 64-bit C	168502
this work A, 64-bit	174637
this work, 32-bit	310585
`donna32`, 32-bit C	529812

Performance on Many Curves





And We're in Chrome Now!

via the BoringSSL library

for Curve25519 & P256

Coming soon, pending internship success: P384

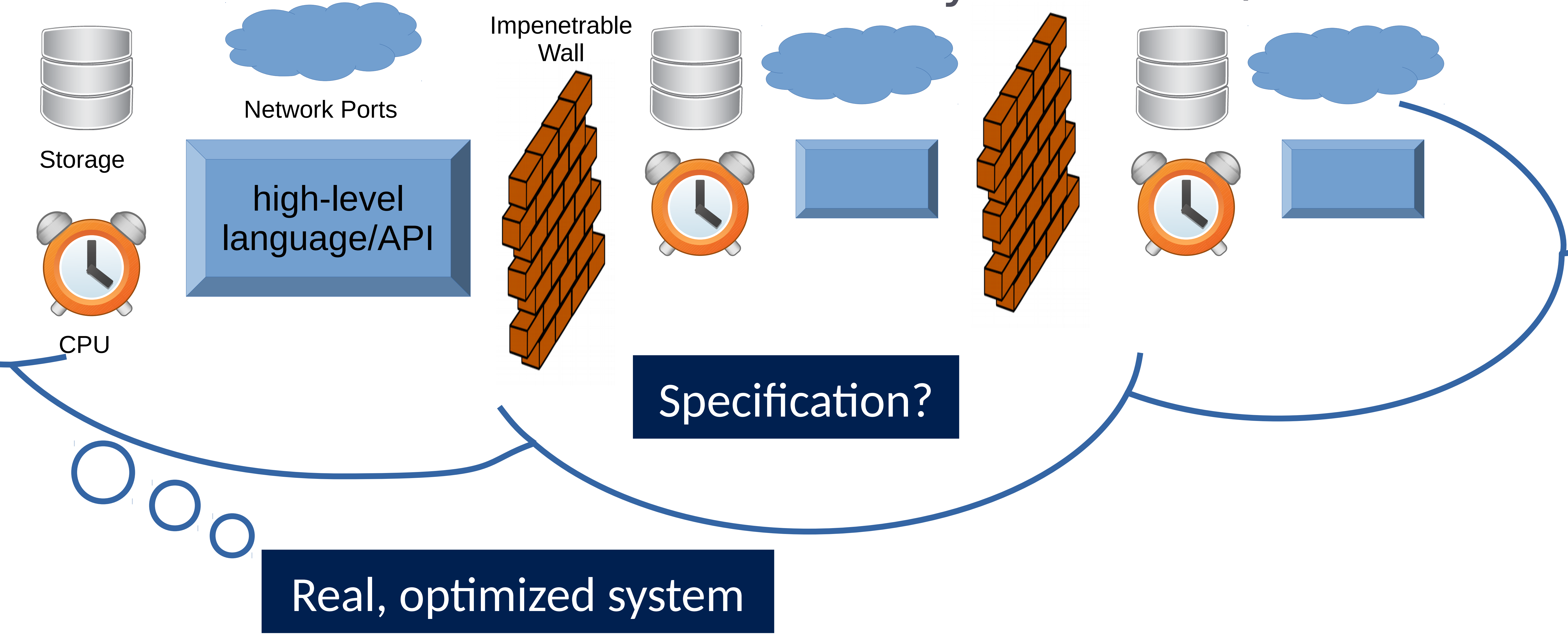
The Big Tradeoff

Performance vs. Maintainability

Is it *fundamental* that systems hackers need to spend their time writing intricate, ~~bug-prone~~, ~~low-level~~ code?

Is it *fundamental* that abstractions bring runtime performance costs?

A General Schema for Goals of Systems SW/HW?



Going All-In with Compile-Time Verification

- **Goal: platform for efficient execution of functional programs, written in high-level notation so simple that auditing catches bugs well**
- **Proof-Carrying Code:** no code (SW or HW) allowed on the system, in any digital component, without *proof of functional correctness.*
- **End-to-End Proofs:** all proofs connected together in a proved way, for a small TCB consisting of proof checker, plus semantics of hardware description language (~1000 lines?) and applications and system API (~1000 lines?).
- **No Runtime Enforcement of Isolation** (it's all in the proofs.)

Simplifying the Runtime Story

Functional code (spec)

C-like code

Machine code

Processors

Memory System

Uses **object capabilities** and other patterns

Compiler analysis **infers object lifetimes**

No type system! Expose memory directly.
Fixed type systems are vestigial w/ program proof.

Compiler computes **worst-case running time**,

Thanks to proved characterizations of functions,
knows which handlers need which objects.
Moves objects into CPU caches preemptively,
providing a clean **transactions** view to SW.
No more **weak memory**!

In Summary....

- Surprisingly many hard systems challenges go away when we commit to requiring functional-correctness proofs of *all* installed SW.
- That kind of regime is more practical than folks would assume if they've held onto 20th-century perspectives!
- Fun question to leave you with: for various important domains, what would be the dollar cost of rewriting all platform software (& maybe digital hardware, too), with functional-correctness proofs?
  - [Conjecture: it's a small fraction of venture-capital investment in tech startups each year.]

Thank you!

Microsoft

© Copyright Microsoft Corporation. All rights reserved.