

A Proof-Producing Compiler for Blockchain Applications

Jeremy Avigad, Carnegie Mellon

Lior Goldberg, StarkWare Industries

David Levit, StarkWare Industries

Yoav Seginer, independent

Alon Titelman, StarkWare Industries

July 28, 2023

STARKs and formal verification

StarkWare has developed means of “running” decentralized applications (dapps) on blockchain more efficiently.

- They use this to run a cryptocurrency exchange.
- They have a platform for developers to run their applications.

Both use a programming language, Cairo, that they have developed.

We have been using Lean to verify their methods and code.

Blockchain

The magic:

- A ledger in the sky.
- The ledger grows, but nothing is ever deleted.
- Users can own resources, like bitcoin, and transfer them.

Application: banking without government or institutional control (or oversight).

Under the hood:

- Decentralized maintenance.
- Proof of work or proof of stake.
- Clever incentives to maintain and extend the blockchain.
- Cryptography.

Smart contracts

The magic:

- One can put a computer program on the ledger that executes when some conditions are met.

Applications: contracts, auctions, exchanges, trading NFTs, selling concert tickets, voting, etc., again without government or institutional control.

Under the hood:

- A programming language.
- Blockchain.

Smart contracts

Limitations:

- It is expensive (everyone maintaining the blockchain has to execute the code).
- It is slow. (For example, the number of transactions that Visa performs in a second dwarf what can be done on blockchain.)

Solution:

- Design a suitable programming language.
- Write programs in such a way that successful completion guarantees the result (of the exchange, auction, etc.) is correct.
- Use a cryptographic protocol to publish a short (probabilistic) proofs that programs run to completion.

Cairo

I am a powerful prover, and you are a resource-limited verifier.

- We agree on a program in a programming language, Cairo 0, such that successful termination guarantees my claim.
- A compiler translates it to assembly code and then machine code for the Cairo CPU.
- The claim that there is an assignment to memory, extending the program and input data, such that the CPU runs to completion is encoded as the existence of solutions to a parametric family of polynomials.
- The Cairo runner publishes to blockchain short cryptographic certificates that guarantee the existence of the solutions.

Cairo

Should you trust it?

- You have to believe the Cairo program does what it is supposed to.
- You have to believe that the translation to machine code is correct.
- You have to believe that the polynomial encoding is correct.
- You have to believe the cryptographic protocol.

Cairo verification

Our approach:

- (CPP '22) We proved the correctness of the polynomial encoding.
- (ITP '23) We provide means of proving that CPU execution of explicit machine code meets high-level specifications.
- The result is an end-to-end formal proof: if these explicit polynomials have a solution, then that high-level claim holds.
- We trust the cryptographic protocol and its implementation.

We have verified substantial parts of the Cairo 0 library, including elliptic curve signature validation and the implementation of a dictionary data structure.

Cairo verification

Novelties:

1. The fact that the programming language is used to prove things introduces some quirks (e.g. memory is read only).
2. The cryptographic foundation introduces some quirks (e.g. all values are elements of a large finite field).
3. From the high-level specification down to the table of polynomials, our proofs are verified entirely in Lean.
4. We harvest just enough information from the compiler to construct, automatically, long source-code proofs in Lean.
5. We provide flexible means to prove our own specifications from autogenerated ones.
6. The compiler developers barely even noticed that we were there.

Where to find stuff

The Cairo 0 compiler is here:

<https://github.com/starkware-libs/cairo-lang>.

Our public repository for the verification is here:

<https://github.com/starkware-libs/formal-proofs>.

There are a [paper](#) and a [talk](#) on the verification of the reduction to the AIR (algebraic intermediate representation).

The current work is described in [this ITP paper](#).

Note: StarkWare is now developing a successor language, [Cairo 1](#), and our verification efforts have shifted to that.

The Cairo CPU

The CPU state consists of three registers: a program counter, an allocation pointer, and a frame pointer.

An instruction consists of 15 one-bit flags and three 16-bit bitvectors.

Instructions:

- Assert two things are equal (e.g. $[ap + 3] = [fp - 5] + 3$).
- Jump.
- Conditional jump.
- Call.
- Return.

Memory consists of values in a large finite field. Arithmetic operations are $+$ and $*$.

Semantics

We have a formal specification of the execution semantics.

```
def ensures (mem : F → F) (σ : register_state F)
  (P : ℕ → register_state F → Prop) : Prop :=
  ∀ n : ℕ, ∀ exec : fin (n+1) → register_state F,
  is_halting_trace mem exec → exec 0 = σ →
  ∃ i : fin (n + 1), ∃ κ ≤ i, P κ (exec i)
```

“Given memory mem and starting state σ , if execution runs to completion, then at some point P holds.”

Modulo the algebraic encoding, the cryptographic certificate verifies that the execution runs to completion.

For technical reasons, we sometimes need to know that some value is less than the length of the execution.

Modeling the assembly language in Lean

The compiler emits assembly code as well as the machine translations:

```
...
[ap] = [fp + (-4)]; ap++
[ap] = [fp + (-3)]; ap++
call rel -11
ret
```

We can also get it to emit hackish Lean notation that approximates the assembly syntax:

```
def starkware.cairo.common.math.code_assert_nn_le : list F := [
  ...
  'assert_eq['dst[ap] === 'res['op1[fp+ -4]];ap++].to_nat,
  'assert_eq['dst[ap] === 'res['op1[fp+ -3]];ap++].to_nat,
  'call_rel['op1[imm]].to_nat, -11,
  'ret[].to_nat ]
```

Modeling the assembly language in Lean

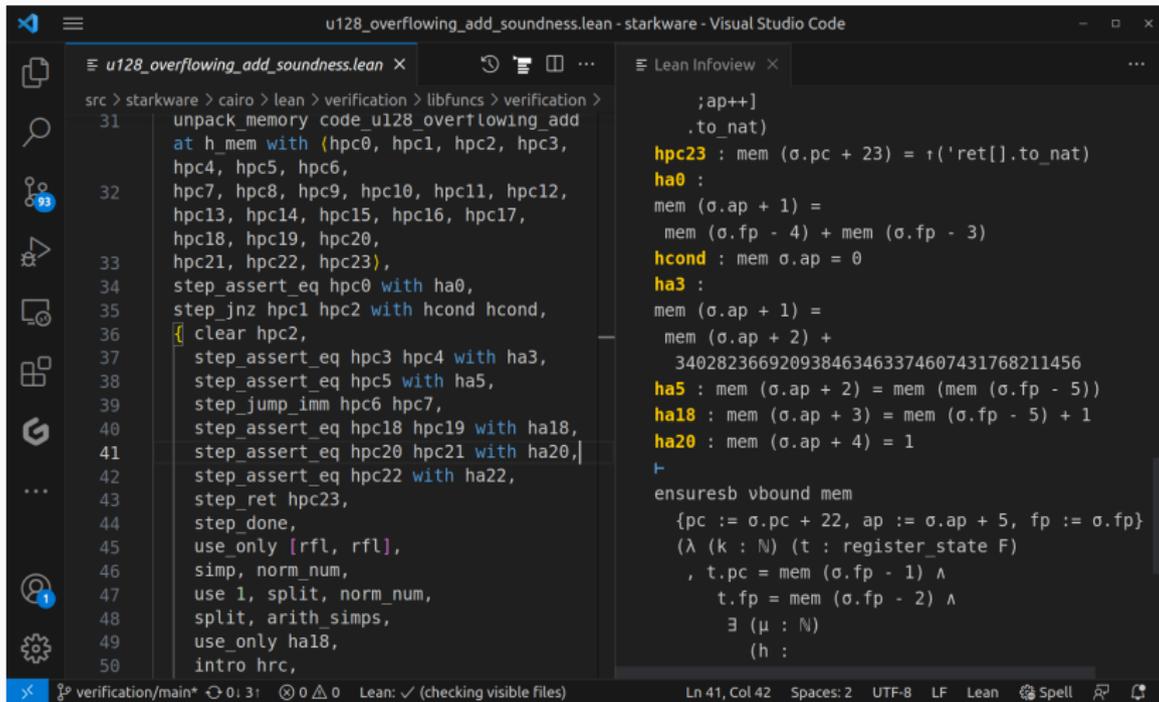
The Lean notation represents Lean definitions of machine code instructions.

We can evaluate them and compare them to the values output by the compiler.

So we are really proving things about the Cairo machine code.

We then wrote tactics that enable us to step through the machine code.

Modeling the assembly language in Lean



The image shows a screenshot of the Visual Studio Code editor. The main window displays a Lean file named `u128_overflowing_add_soundness.lean`. The code in the editor is as follows:

```
src > starkware > cairo > lean > verification > libfuncs > verification >
31  unpack_memory_code u128_overflowing_add
    at h_mem with (hpc0, hpc1, hpc2, hpc3,
32  hpc4, hpc5, hpc6,
    hpc7, hpc8, hpc9, hpc10, hpc11, hpc12,
    hpc13, hpc14, hpc15, hpc16, hpc17,
33  hpc18, hpc19, hpc20,
    hpc21, hpc22, hpc23),
34  step_assert_eq hpc0 with ha0,
35  step_jnz hpc1 hpc2 with hcond hcond,
36  { clear hpc2,
37    step_assert_eq hpc3 hpc4 with ha3,
38    step_assert_eq hpc5 with ha5,
39    step_jump_imm hpc6 hpc7,
40    step_assert_eq hpc18 hpc19 with ha18,
41    step_assert_eq hpc20 hpc21 with ha20,|
42    step_assert_eq hpc22 with ha22,
43    step_ret hpc23,
44    step_done,
45    use only [rfl, rfl],
46    simp, norm_num,
47    use 1, split, norm_num,
48    split, arith_simps,
49    use only ha18,
50    intro hrc,
```

The right-hand pane shows the Lean Infotview, displaying the current proof state:

```
;ap++]
.to_nat)
hpc23 : mem (σ.pc + 23) = ↑('ret[] .to_nat)
ha0 :
mem (σ.ap + 1) =
  mem (σ.fp - 4) + mem (σ.fp - 3)
hcond : mem σ.ap = 0
ha3 :
mem (σ.ap + 1) =
  mem (σ.ap + 2) +
  340282366920938463374607431768211456
ha5 : mem (σ.ap + 2) = mem (mem (σ.fp - 5))
ha18 : mem (σ.ap + 3) = mem (σ.fp - 5) + 1
ha20 : mem (σ.ap + 4) = 1
⊢
ensuresb vbound mem
{pc := σ.pc + 22, ap := σ.ap + 5, fp := σ.fp}
(λ (k : ℕ) (t : register_state F)
, t.pc = mem (σ.fp - 1) ∧
  t.fp = mem (σ.fp - 2) ∧
  ∃ (μ : ℕ)
  (h :
```

The status bar at the bottom indicates the current position is Ln 41, Col 42, with 2 spaces, UTF-8 encoding, and LF line endings. The Lean compiler is currently checking visible files.

Cairo

Cairo 0 code looks like this:

```
func assert_nn{range_check_ptr}(a) {  
    a = [range_check_ptr];  
    let range_check_ptr = range_check_ptr + 1;  
    return (); }
```

```
func assert_le{range_check_ptr}(a, b) {  
    assert_nn(b - a);  
    return (); }
```

```
func assert_nn_le{range_check_ptr}(a, b) {  
    assert_nn(a);  
    assert_le(a, b);  
    return (); }
```

There are also conditionals, structures, recursive calls, ...

Verifying Cairo

We want to write specifications about the high-level Cairo functions, and verify that the machine code meets the specifications.

Steps:

- Write a Python tool that extracts a (naive) high-level specification of each Cairo function, and *proves* that the compiled code satisfies the naive specification.
- For each particular program, show (iteratively) that the naive specifications imply our own specifications.

We have used this method to verify parts of the Cairo library, including a validation procedure for cryptographic signatures.

Verifying Cairo

Notes:

- Memory is read only; the CPU makes assertions about the contents of memory.
- Programs are used to *prove* claims to a skeptical verifier. To prove $f(x) = y$, write a program that computes $f(x)$, compares it to y , and fails if they don't agree.
- Memory locations contain elements of a field, but there are cryptographic primitives that allow us to say that x is the cast of an integer in $[0, 2^{128})$.
- In this phase, we only cared about *soundness*. Termination and memory management are free.

Verifying Cairo

```
// Given a scalar, an integer m in the range [0, 250), and a point on
// the elliptic curve, point, verifies that  $0 \leq \text{scalar} < 2 \cdot m$  and
// returns  $(2 \cdot m \cdot \text{point}, \text{scalar} \cdot \text{point})$ .
func ec_mul_inner{range_check_ptr}(point: EcPoint, scalar: felt,
                                   m: felt) -> (pow2: EcPoint, res: EcPoint)
{
    if (m == 0) {
        scalar = 0;
        let ZERO_POINT = EcPoint(BigInt3(0, 0, 0), BigInt3(0, 0, 0));
        return (pow2=point, res=ZERO_POINT);
    }

    alloc_locals;
    let (double_point: EcPoint) = ec_double(point);
    %{ memory[ap] = (ids.scalar % PRIME) % 2 %}
    jmp odd if [ap] != 0, ap++;
    return ec_mul_inner(point=double_point, scalar=scalar / 2, m=m - 1);

    ...
}
```

Verifying Cairo

-- Do not change this definition.

```
def auto_spec_ec_mul_inner (mem : F → F) (κ : ℕ)
  (range_check_ptr : F) (point : EcPoint mem)
  (scalar m ρ_range_check_ptr : F)
  (ρ_pow2 ρ_res : EcPoint mem) : Prop :=
  ((m = 0 ∧
    scalar = 0 ∧
    ∃ ZERO_POINT : EcPoint mem, ZERO_POINT = {
      x := { d0 := 0, d1 := 0, d2 := 0 },
      y := { d0 := 0, d1 := 0, d2 := 0 }
    } ∧
    16 ≤ κ ∧
    ρ_range_check_ptr = range_check_ptr ∧
    ρ_pow2 = point ∧
    ρ_res = ZERO_POINT) ∨
  (m ≠ 0 ∧
    ∃ (κ₁ : ℕ) (range_check_ptr₁ : F) (double_point : EcPoint mem),
    spec_ec_double mem κ₁ range_check_ptr point range_check_ptr₁
    double_point ∧
    ∃ anon_cond : F,
    ((anon_cond = 0 ∧ ...))))
```

Verifying Cairo

```
-- You may change anything in this definition except the name and
-- arguments.
def spec_ec_mul_inner (mem : F → F) (κ : ℕ) (range_check_ptr : F)
  (point : EcPoint mem) (scalar m ρ_range_check_ptr : F)
  (ρ_pow2 ρ_res : EcPoint mem) : Prop :=
  ∀ (secpF : Type) [hsecp : secp_field secpF],
  point.x ≠ ⟨0, 0, 0⟩ →
  ∀ hpt : BddECPointData secpF point,
  ∃ nn : ℕ,
  m = ↑nn ∧
  nn < ring_char F ∧
  (nn ≤ SECP_LOG2_BOUND →
    ∃ scalarn : ℕ,
    scalar = ↑scalarn ∧
    scalarn < 2^nn ∧
    ∃ hpow2 : BddECPointData secpF ρ_pow2,
    ρ_pow2.x ≠ ⟨0, 0, 0⟩ ∧
    hpow2.toECPoint = 2^nn · hpt.toECPoint ∧
    ∃ hres : BddECPointData secpF ρ_res,
    hres.toECPoint = scalarn · hpt.toECPoint)
```

Verifying Cairo

-- Do not change the statement of this theorem. You may change the proof.

```
theorem sound_ec_mul_inner
  {mem : F → F} (κ : ℕ)
  (range_check_ptr : F) (point : EcPoint mem)
  (scalar m ρ_range_check_ptr : F) (ρ_pow2 ρ_res : EcPoint mem)
  (h_auto : auto_spec_ec_mul_inner mem κ range_check_ptr point
    scalar m ρ_range_check_ptr ρ_pow2 ρ_res) :
  spec_ec_mul_inner mem κ range_check_ptr point scalar m
  ρ_range_check_ptr ρ_pow2 ρ_res :=
begin
  intros secpF _ ptxnez hpt,
  rcases h_auto with ⟨neq, scalareq, _, rfl, _, _, ret1eq, ret2eq⟩ |
  ⟨nnz, _, _, double_pt, hdouble_pt, _, heven_or_odd⟩,
  { use 0, split,
    { rw [neq, nat.cast_zero] }, split,
    { rw PRIME.char_eq, apply PRIME_pos },
    intro _,
    use 0, split,
    ... }
  ...
end
```

Verifying Cairo

Summary:

- Our tool generates Lean descriptions of the machine code, which the user never has to see.
- It also generates naive specifications.
- Users write their own specifications, and prove their that they are implied by the naive ones.
- Later autogenerated specifications refer to the user specifications.
- Our tool automatically uses the user's theorems in end-to-end correctness proofs that the user never has to see.

Verifying Cairo

```
theorem auto_sound_ec_mul_inner
-- arguments
(range_check_ptr : F) (point : EcPoint F) (scalar m : F)
-- code is in memory at  $\sigma.pc$ 
(h_mem : mem_at mem code_ec_mul_inner  $\sigma.pc$ )
-- all dependencies are in memory
(h_mem_0 : mem_at mem code_nondet_bigint3 ( $\sigma.pc - 407$ ))
...
(h_mem_9 : mem_at mem code_fast_ec_add ( $\sigma.pc - 143$ ))
-- input arguments on the stack
(hin_range_check_ptr : range_check_ptr = mem ( $\sigma.fp - 11$ ))
(hin_point : point = cast_EcPoint mem ( $\sigma.fp - 10$ ))
(hin_scalar : scalar = mem ( $\sigma.fp - 4$ ))
(hin_m : m = mem ( $\sigma.fp - 3$ ))
-- conclusion
: ensures_ret mem  $\sigma$  ( $\lambda \kappa \tau, \exists \mu \leq \kappa,$ 
  rc_ensures mem (rc_bound F)  $\mu$  (mem ( $\sigma.fp - 11$ )) (mem $  $\tau.ap - 13$ )
    (spec_ec_mul_inner mem range_check_ptr point scalar m
      (mem ( $\tau.ap - 13$ )) (cast_EcPoint mem ( $\tau.ap - 12$ ))
      (cast_EcPoint mem ( $\tau.ap - 6$ )))) := ...
```

Verifying Cairo

Additional notes:

- We do a control flow analysis, divide code into blocks, and handle regular graphs appropriately.
- We handle recursive calls appropriately.
- We handle a lot of range-check plumbing automatically.
- Our tool regenerates the specification files gracefully, without overwriting the parts the user has written.

Observations

We carried out everything in a single proof system:

- low-level semantics
- algebraic encodings
- integer and field arithmetic
- definitions and properties of elliptic curves.

Also notable: rather than verifying the compiler, we make it proof-producing.

- We don't have to handle every language feature.
- We can build capability incrementally.
- We required minimal interactions with compiler developers.
- It was o.k. that the compiler kept changing.

Observations

Automatically generating source code for an interactive theorem prover sounds weird, but it worked out surprisingly well.

As developers, we could:

- Work out small examples or additions by hand, and then write code to do what we just did.
- Debug failures by hand, and then do the same.

As users, the workflow was also convenient. We could focus on proving specifications from manageable Hoare-style descriptions.

Conclusions

- Blockchain verification is a good market for verification.
- It's possible to do fun and interesting projects in an industrial setting.
- Our approach worked.