Improving Performance of Provable Computations Using Rust

How we reimplemented the Cairo VM using Rust

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LambdaClass

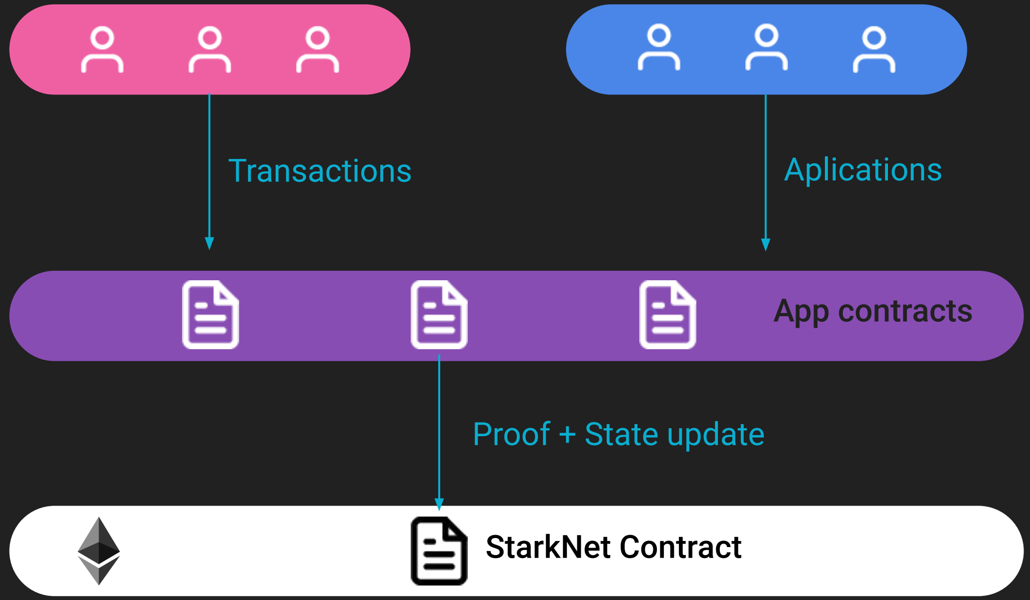
Who are we?

LAMBDA

Context

What is **StarkNet**?

StarkNet is a ZK-Rollup



What is **StarkNet**?

Cost of verification ~ log(n)

What is **StarkNet**?

Cost of verification ~ log(n)

n → infinity => Tsx fee → 0

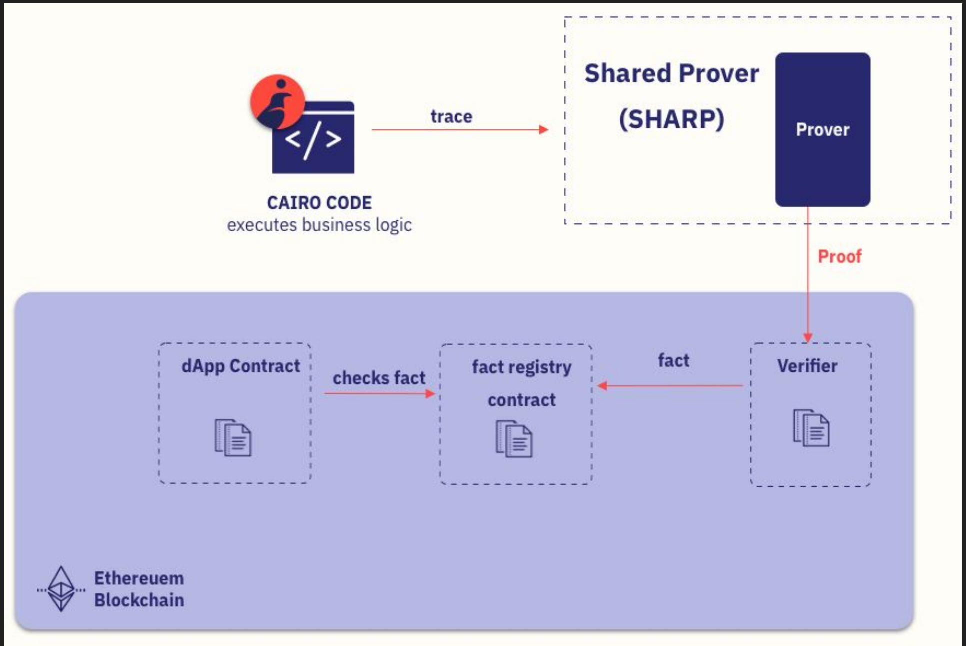
What is a **STARK**?

Scalable Transparent Argument of Knowledge

- STARKS are a specific type of Zero Knowledge Proofs
- ZKP allow us to prove the veracity of a statement without revealing any information beyond the fact that the statement is true

What is **Cairo**?

- Programming language for writing provable programs.
- Running a program produces a trace.
- The trace can be sent to a **prover** to generate a STARK proof.

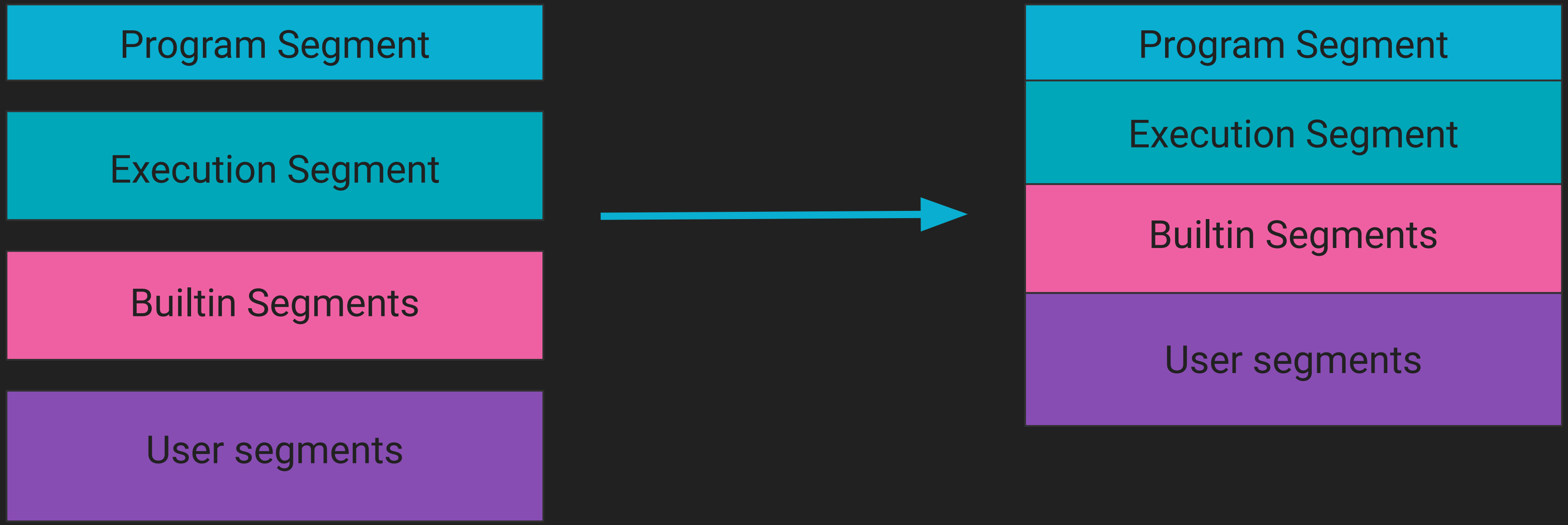


Cairo VM

Cairo VM


Source code
Cairo Compiler
Compiled Program
Cairo VM
Trace
JSON
JSON

Characteristics of Cairo VM Architecture: **Memory Model**



Relocation Process: Computing each Segment Size

Size

0	0:0 74168662805676031 0:1 2 0:2 5189976364521848832 0:3 4 0:4 2345108766317314046
1	1:0 2:0 1:1 3:0 1.2 4
2	
3	

Relocation Process: Calculating each Segment Base

Prev Segment Base + Prev Segment Size = Segment Base

0	0:0 0:1 0:2 0:3 0:4	7416866280567603 1 2 5189976364521848832 4 2345108766317314046	1
1	1:0 1:1 1.2	2:0 3:0 4	1 + 5 = 6
2			6 + 3 = 9
3			9 + 0 = 9

Relocation Process: Relocating each Address

Segment Base + Offset = Relocated Address

	0:0	7416866280567603 1
0	0:1	2
	0:2	5189976364521848832
	0:3	4
	0:4	2345108766317314046
1	1:0	2:0
	1:1	3:0
	1.2	4
2		
3		

1	1 + 0 = 1 1 + 1 = 2 1 + 2 = 3 1 + 3 = 4 1 + 4 = 5
6	6 + 0 = 6 9 + 0 = 9 6 + 1 = 7 9 + 0 = 9 6 + 2 = 8 4
9	
9	

Relocation Process: Relocating each Address

Segment Base + Offset = Relocated Address

0	0:0 74168662805676031 0:1 2 0:2 5189976364521848832 0:3 4 0:4 2345108766317314046
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2	
3	

1	1 + 0 = 1 1 + 1 = 2 1 + 2 = 3 1 + 3 = 4 1 + 4 = 5
6	6 + 0 = 6 9 + 0 = 9 6 + 1 = 7 9 + 0 = 9 6 + 2 = 8 4
9	
9	

Relocation Process: Relocating each Address

Segment Base + Offset = Relocated Address

0	0:0	74168662805676031
	0:1	2
	0:2	5189976364521848832
	0:3	4
	0:4	2345108766317314046
1	1:0	2:0
	1:1	3:0
	1.2	4
2		
3		

1	1	74168662805676031
	2	2
	3	5189976364521848832
	4	4
	5	2345108766317314046
6	6	9
	7	9
	8	4
9		
9		

Characteristics of Cairo VM Architecture: **Registers**

Program Segment

Execution Segment

Builtin Segments

User segments

Characteristics of Cairo VM Architecture: **Registers**

PC

Program Segment

"0x40780017fff7fff",

"0x1",

"0x208b7fff7fff7ffe",

"0x400380007ffc7ffd",

"0x480680017fff8000",

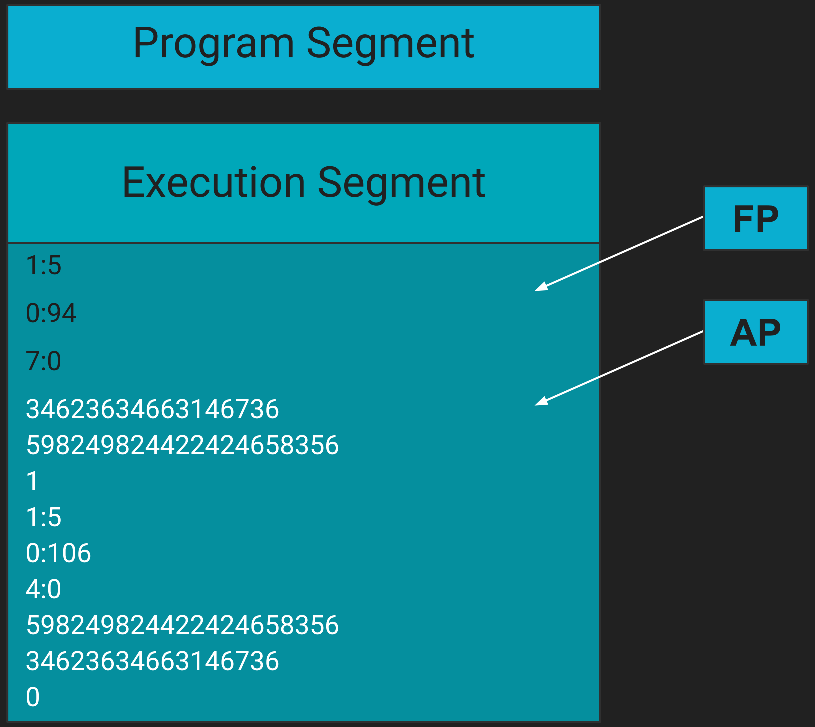
"0xff00ff00ff00ff00ff00ff00ff00ff",

"0x400280017ffc7fff",

"0x480680017fff8000"

Execution Segment

Characteristics of Cairo VM Architecture: **Registers**



Main execution loop: **Step**

Trace Generation

```
TraceEntry {
  pc: Relocatable {
    segment_index: 0,
    offset: 0
    },
  ap: Relocatable {
    segment_index: 1,
    offset: 2
    },
  fp: Relocatable {
    segment_index: 1,
    offset: 2
  }
}
```

→

```
TraceEntry {
  ap: 4,
  fp: 4,
  pc: 1
}
```

Features of Cairo: **Builtins**

- Low level optimizations
- Integrated into the core loop of the VM
- Allow otherwise expensive computations to be performed

Main execution loop: **Step with Builtins**

Main execution loop: **Step with Builtins**

```
fn deduce_memory_cell(
  &mut self,
  addr: &Relocatable,
  memory: &Memory,
) -> Result<MaybeRelocatable> {
  let x = memory[addr -1]
  let y = memory[addr - 2]
  return pedersen_hash(x,y)
}
```

Deduce Operands

Pedersen Example

```
func hash2{hash_ptr: HashBuiltin*}(x, y) -> (result: felt) {
    hash_ptr.x = x;
    hash_ptr.y = y;
    let result = hash_ptr.result;
    let hash_ptr = hash_ptr + HashBuiltin.SIZE;
    return (result=result);
}
```

Features of Cairo: **Hints**

- Python code embedded into a Cairo program
- Can access and modify the VM's state
- Can also interact with each other through **execution scopes**

```
// Allocates a new memory segment.
func alloc() -> (ptr: felt*) {
    %{ memory[ap] = segments.add() %}
    ap += 1;
    return (ptr=cast([ap - 1], felt*));
}
```

Features of Cairo: **Hints**

Execution Scopes:

- Stack of dictionaries which hold variables created inside hints.
- Hints can pop and push scopes (enter & exit).
- Multiple hints can access the same scope

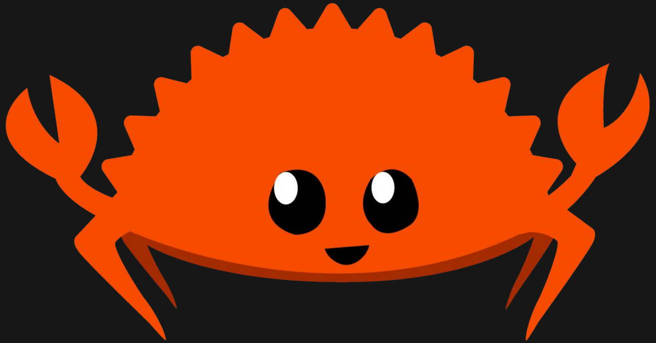
```
// Copies len field elements from src to dst.
func memcpy(dst: felt*, src: felt*, len) {
    struct LoopFrame {
        dst: felt*,
        src: felt*,
    }

    if (len == 0) {
        return ();
    }

    %{ vm_enter_scope({'n': ids.len}) %}
    tempvar frame = LoopFrame(dst=dst, src=src);

    loop:
    let frame = [cast(ap - LoopFrame.SIZE, LoopFrame*)];
    assert [frame.dst] = [frame.src];

    let continue_copying = [ap];
    // Reserve space for continue_copying.
    let next_frame = cast(ap + 1, LoopFrame*);
    next_frame.dst = frame.dst + 1, ap++;
    next_frame.src = frame.src + 1, ap++;
    %{
        n -= 1
        ids.continue_copying = 1 if n > 0 else 0
    %}
    static_assert next_frame + LoopFrame.SIZE == ap + 1;
    jmp loop if continue_copying != 0, ap++;
    // Assert that the loop executed len times.
    len = cast(next_frame.src, felt) - cast(src, felt);

    %{ vm_exit_scope() %}
    return ();
}
```

Section 2

Hints in Cairo-rs

Why Rust?

- Performance
- Memory Safety
- Great Community



Hints in Cairo-rs:
How we began implementing hints in Rust

```rust
fn execute_hint(
    vm: &mut VM,
    exec_scopes &mut ExecutionScopes
    hint_data: HintProcessorData,
){
    match hint_data.code {
        ADD_SEGMENT => add_segment(vm),
        IS_NN => is_nn(vm, &hint_data),
        IS_LE_FELT => is_le_felt(vm, &hint_data),
        ASSERT_LE_FELT => assert_le_felt(vm, &hint_data),
        ASSERT_250_BITS => assert_250_bit(vm, &hint_data),
        IS_POSITIVE => is_positive(vm, &hint_data),
```

Hints in Cairo-rs:
How we began implementing hints in Rust

“memory[ap] = segments.add()”

```rust
pub fn add_segment(vm: &mut VirtualMachine) {
    vm.memory.insert(vm.ap, vm.segments.add())
}
```

Hints in Cairo-rs:
How we began implementing hints in Rust

Pros

- Easy to integrate as no new tools were needed
- Better performance

Cons

- Need to watch out and modify our implementation if hints change
- Not extensible, as any new hints need to be implemented separately

Hints in Cairo-rs:
How we began integrating python hints with PyO3

Why PyO3?

- Provides **Rust bindings** for Python
- Allows sharing the VM state with a python context
- Allows python to modify the VM state
- Allow us to define a strict interface through ***pyclasses*** & ***pymethods***

Python Hints:
Modifying VM Memory through Hints

```rust
#[pyclass(unsendable)]
pub struct PyMemory {
    vm: Rc<RefCell<VirtualMachine>>,
}

#[pymethods]
impl PyMemory {
    #[getter]
    pub fn __getitem__(&self, key: &PyRelocatable, py: Python) -> PyResult<PyObject> {
        self.vm.memory.get(key).to_object(py))),
    }

    #[setter]
    pub fn __setitem__(&self, key: &PyRelocatable, value: PyMaybeRelocatable) -> PyResult<()> {
      self.vm.memory.insert(&key, value)
    }
}
```

Python Hints:
Modifying Cairo Variables through Hints

```
#[pyclass(unsendable)]
pub struct PyIds {
    vm: Rc<RefCell<VirtualMachine>>,
    references: HashMap<String, HintReference>,
    ap_tracking: ApTracking,
}

#[pymethods]
impl PyIds {

    pub fn __getattr__(&self, name: String, py: Python) -> PyResult<PyObject> {
        let hint_ref = self.references.get(&name);
        get_value_from_reference(&self.vm, hint_ref, &self.ap_tracking)?.to_object(py))
    }

    pub fn __setattr__(&self, name: String, val: PyMaybeRelocatable) -> PyResult<()> {
        let hint_ref = self.references.get(&name);
        let var_addr = compute_addr_from_reference(hint_ref, &self.vm, &self.ap_tracking);
        self.vm.memory.insert(&var_addr, &val)
    }
}
```

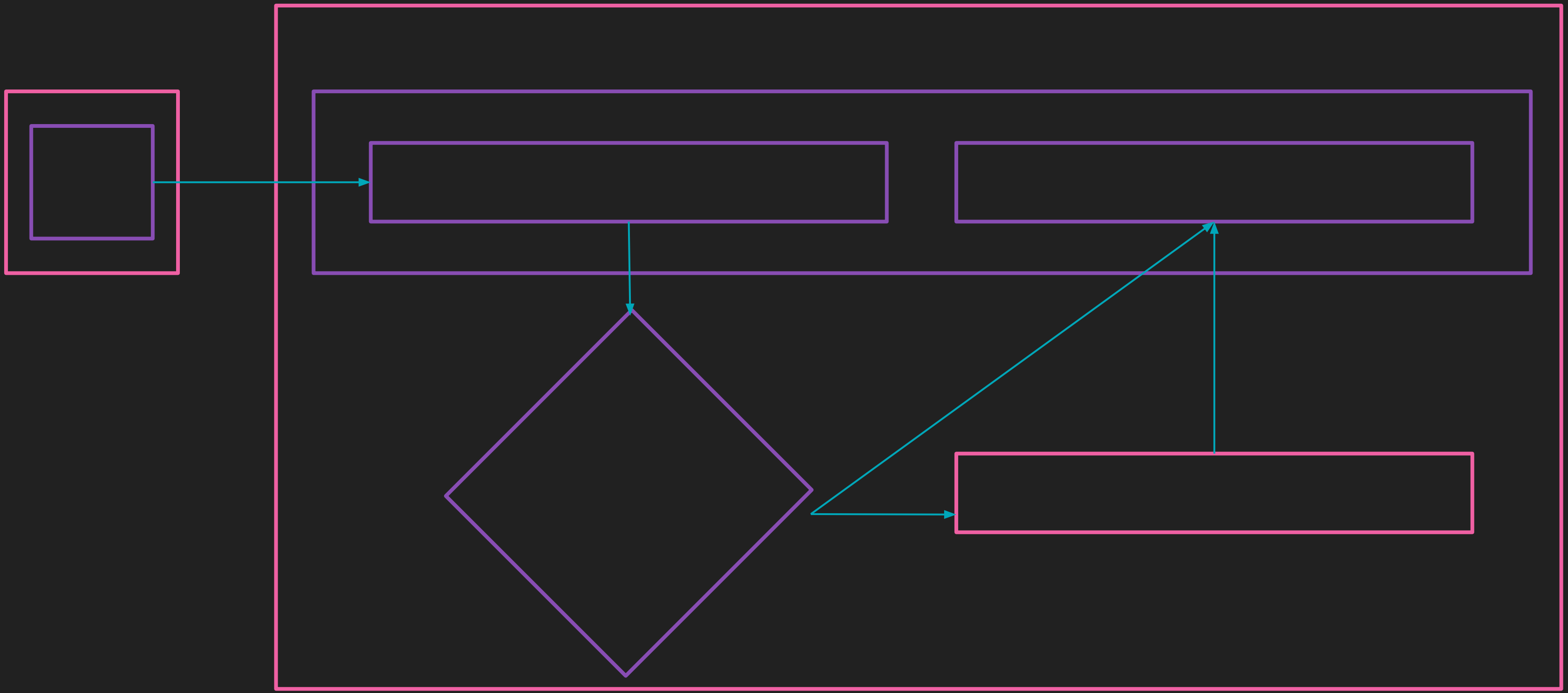
Python Hints FFI:
Interaction between hints through scopes

```rust
fn get_scope_locals(
    exec_scopes: &ExecutionScopes,
    py: Python,
) -> PyDict {
    let locals = PyDict::new(py);
    for (name, elem) in exec_scopes.get_local_variables() {
        if let Some(pyobj) = elem.downcast_ref::<PyObject>() {
            locals.set_item(name, pyobj);
        }
    }

    locals
}

fn update_scope_locals(
    exec_scopes: &mut ExecutionScopes,
    locals: &PyDict,
    py: Python,
) {
    for (name, elem) in locals {
        exec_scopes.assign_or_update_variable(&name, any_box!(elem.to_object(py)));
    }
}
```

Python Hints:
Executing a Hint

```rust
pub(crate) fn execute_hint(
        &self,
        hint_data: &HintProcessorData,
        exec_scopes: &mut ExecutionScopes,
    ){
        Python::with_gil(|py| {
            let locals = get_scope_locals(exec_scopes, py)?;
            let globals = PyDict::new(py);

            globals.set_item("memory", PyMemory::new(&self));
            globals.set_item("segments", PySegmentManager::new(&self));
            globals.set_item("ap", PyRelocatable::from(self.vm.ap));
            globals.set_item("fp", PyRelocatable::from(self.vm.fp));
            globals.set_item("ids", PyIds::new(&self, &hint_data.ids_data, &hint_data.ap_tracking)));

            py.run(&hint_data.code, Some(globals), Some(locals))
            update_scope_locals(exec_scopes, locals, py);

        });
    }
```

cairo-rs-py



Benchmarks

Linear Search

VM	Mean [s]	Min [s]	Max [s]	Relative
Cairo VM (CPython)	11.6 ± 0.2	11.1	11.9	105 ± 3
Cairo VM (PyPy)	3.51 ± 0.09	3.33	3.66	31.9 ± 1.1
Cairo-rs (Rust)	0.11 ± 0.01	0.11	0.12	1.0

Common Lib Math Functions

VM	Mean [s]	Min [s]	Max [s]	Relative
Cairo VM (CPython)	63.7 ± 1.0	61.3	65.8	130 ± 2
Cairo VM (PyPy)	12.1 ± 0.3	11.6	12.9	24.7 ± 0.7
Cairo-rs (Rust)	0.49 ± 0.01	0.49	0.50	1.0

Thank you!

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