

>> Zero to RandomX.js:

>> Bringing Webmining Back From The Grave

Thursday, November 6th | K15 Old main G32 | 2 PM - 4 PM

2. About me

- Liam, l-m, github.com/l1mey112 (GH)
 - <https://l-m.dev/>, l-m at l-m.dev
 - ~~Highschool student~~ University Student
 - Adv Mathematics/Computer Science @ UNSW
-
- Compilers, **Systems Programming**, WebAssembly, Linux



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 - (new!) Interactive Theorem Proving w/ [Lean](#)



3. This Talk?

// **TODO:** (1.RX) Introduce RandomX.

// **TODO:** (2.JS) Introduce RandomX.js

// **TODO:** (3.FP) Cover the semifloat impl. in RandomX.js

>> (1.RX) RandomX

5. (1.RX) ASICs



6. (1.RX) RandomX

RandomX is a proof-of-work algorithm that is optimized for general-purpose CPUs. It has stood the test of time as an **ASIC resistant** hash function.

Defn. *Application-Specific-Integrated-Circuit* – ASIC are specialised circuits.

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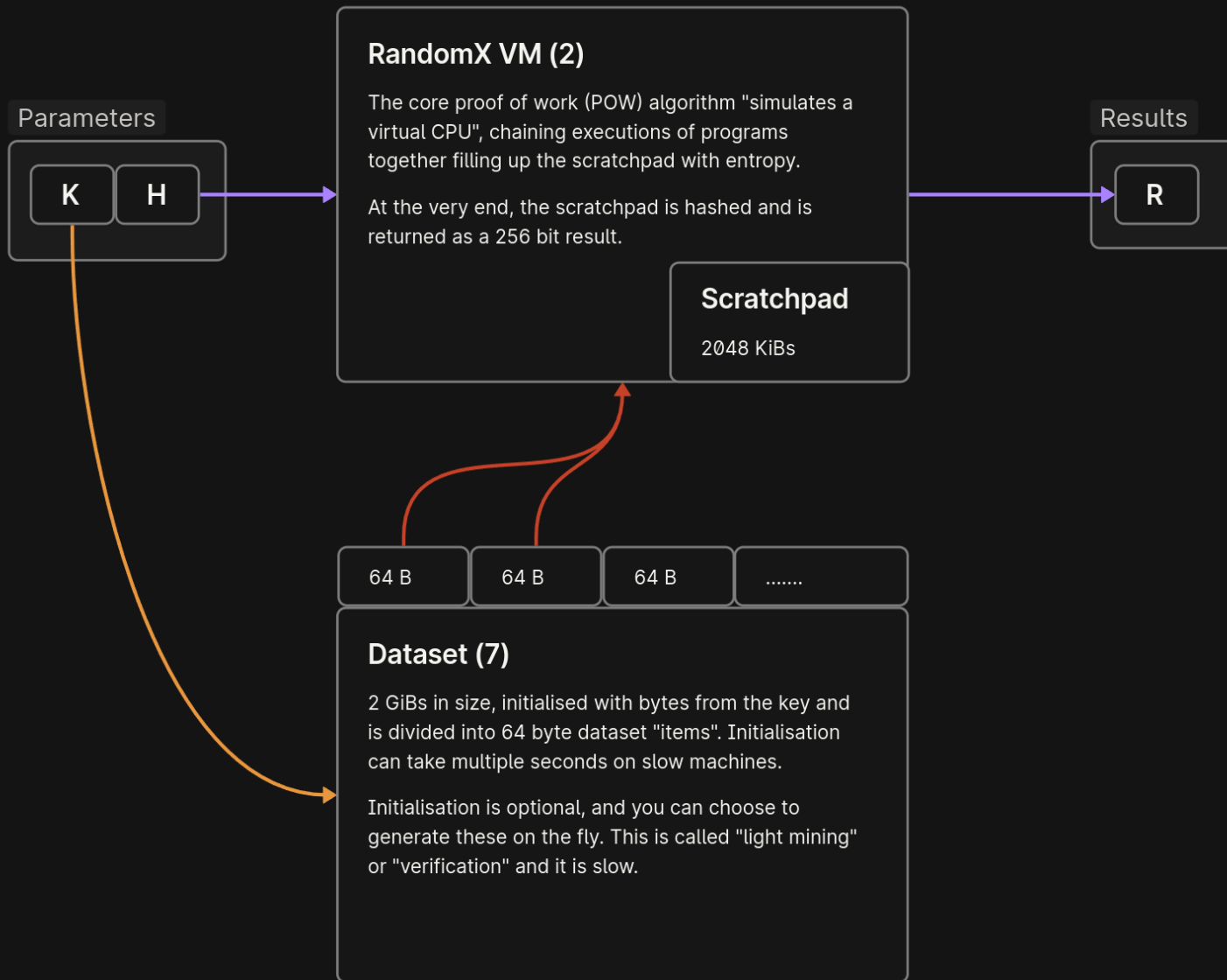
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(Goal: Promote egalitarian mining!)

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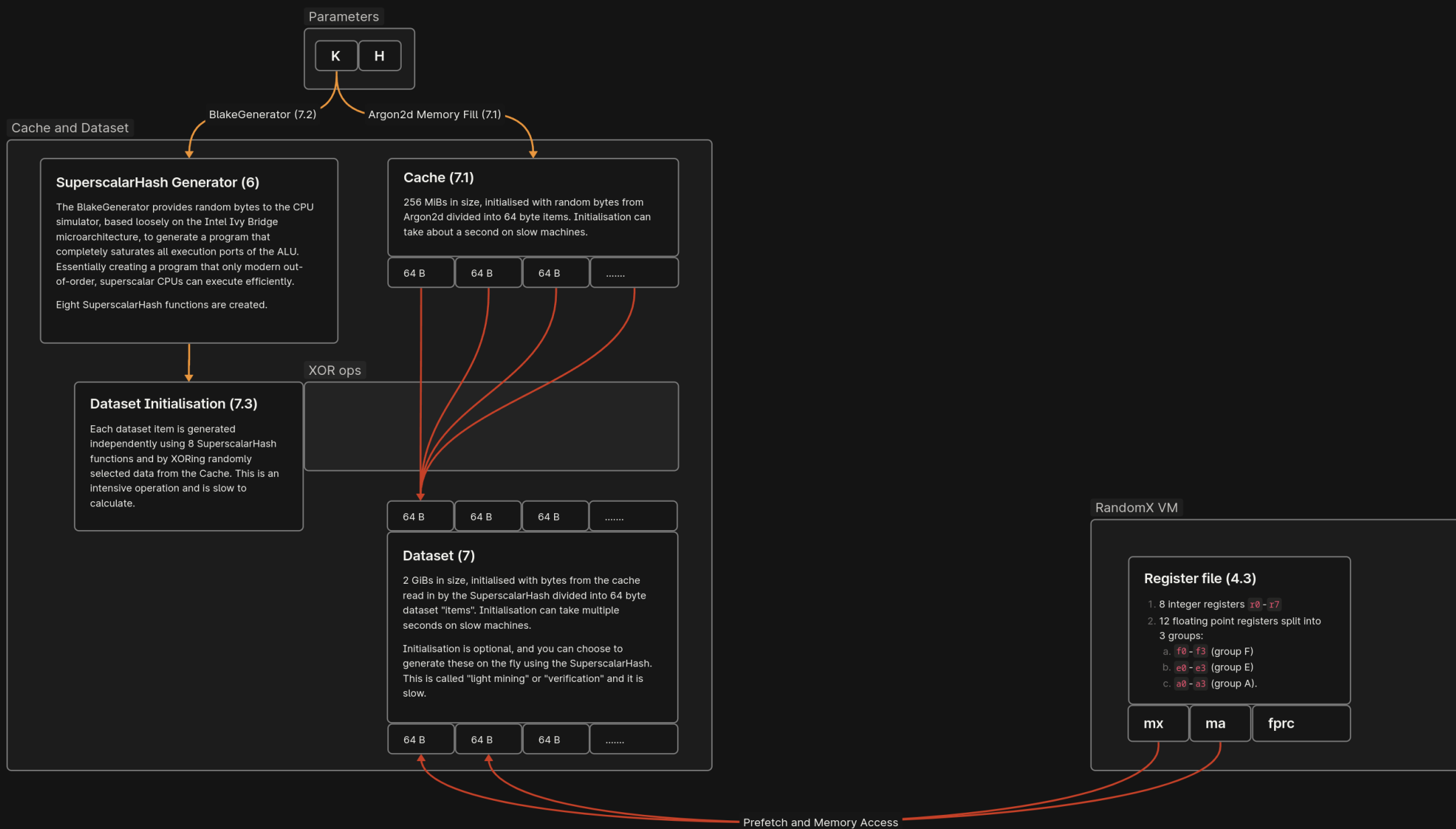
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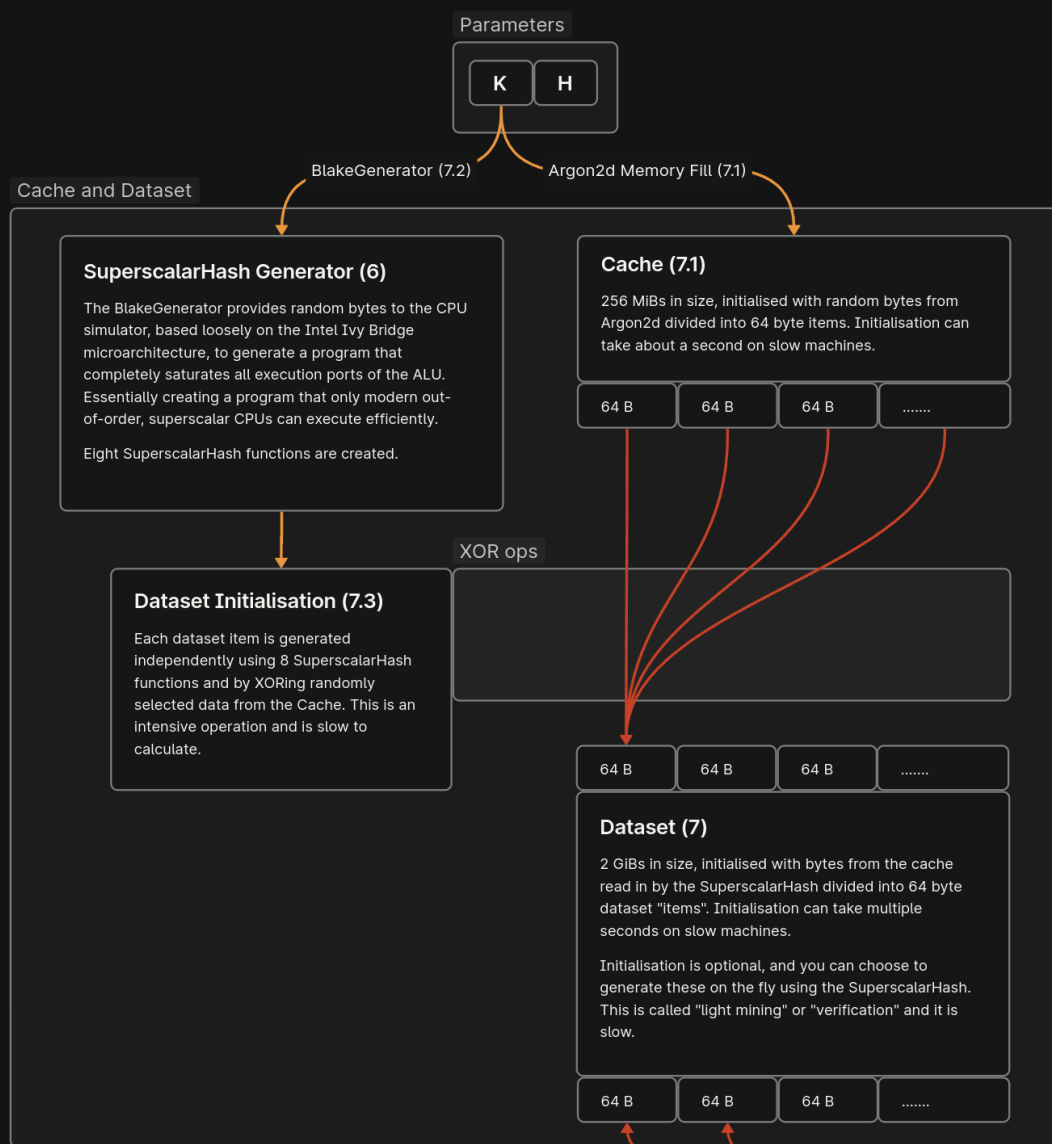
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-

Each increases die area for an ASIC!





Pre-initialisation.

- The key K is passed to the SSH generator, which generates 8 "superscalar" hash functions.
- K is also used to fill 256 MiBs of static memory.

RandomX VM

Register file (4.3)

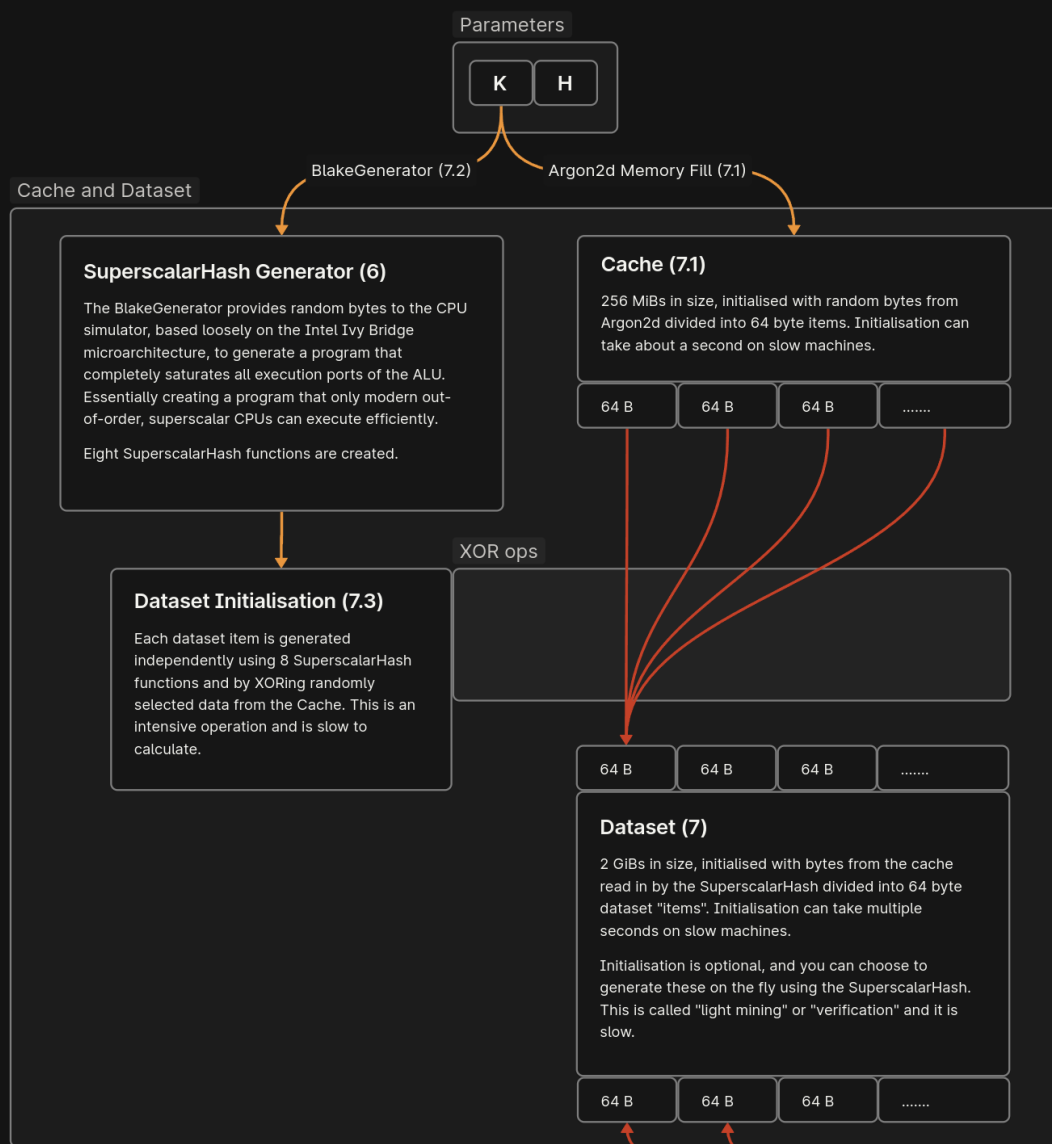
1. 8 Integer registers $r0 - r7$
2. 12 floating point registers split into 3 groups:
 - a. $f0 - f3$ (group F)
 - b. $e0 - e3$ (group E)
 - c. $a0 - a3$ (group A).

mx

ma

fprc

Prefetch and Memory Access



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Dataset-initialisation.

- Each 64-byte Dataset item is generated by executing each of those 8 functions, and XORing data from the cache.
- Cache $\Rightarrow$ Dataset.

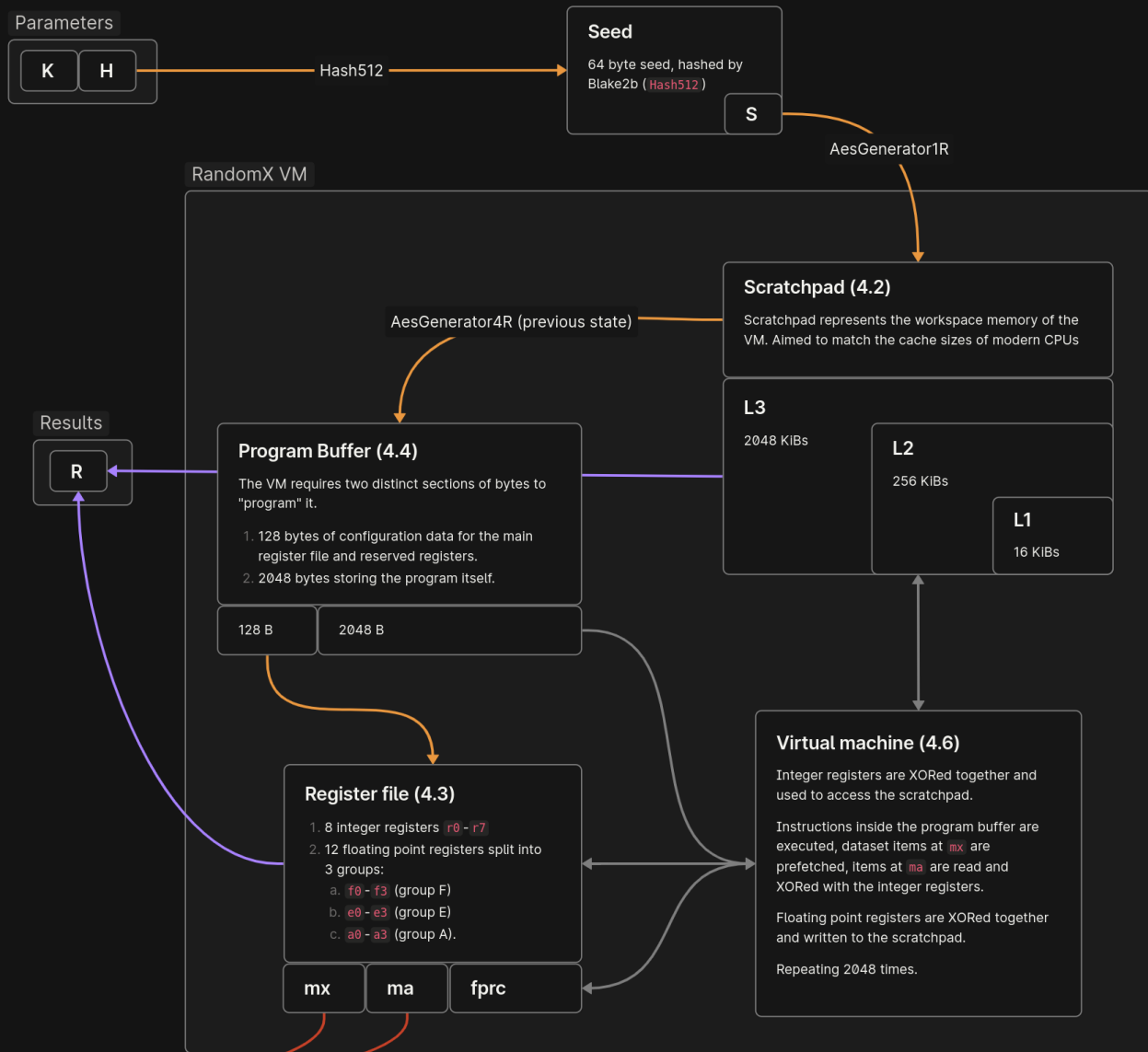
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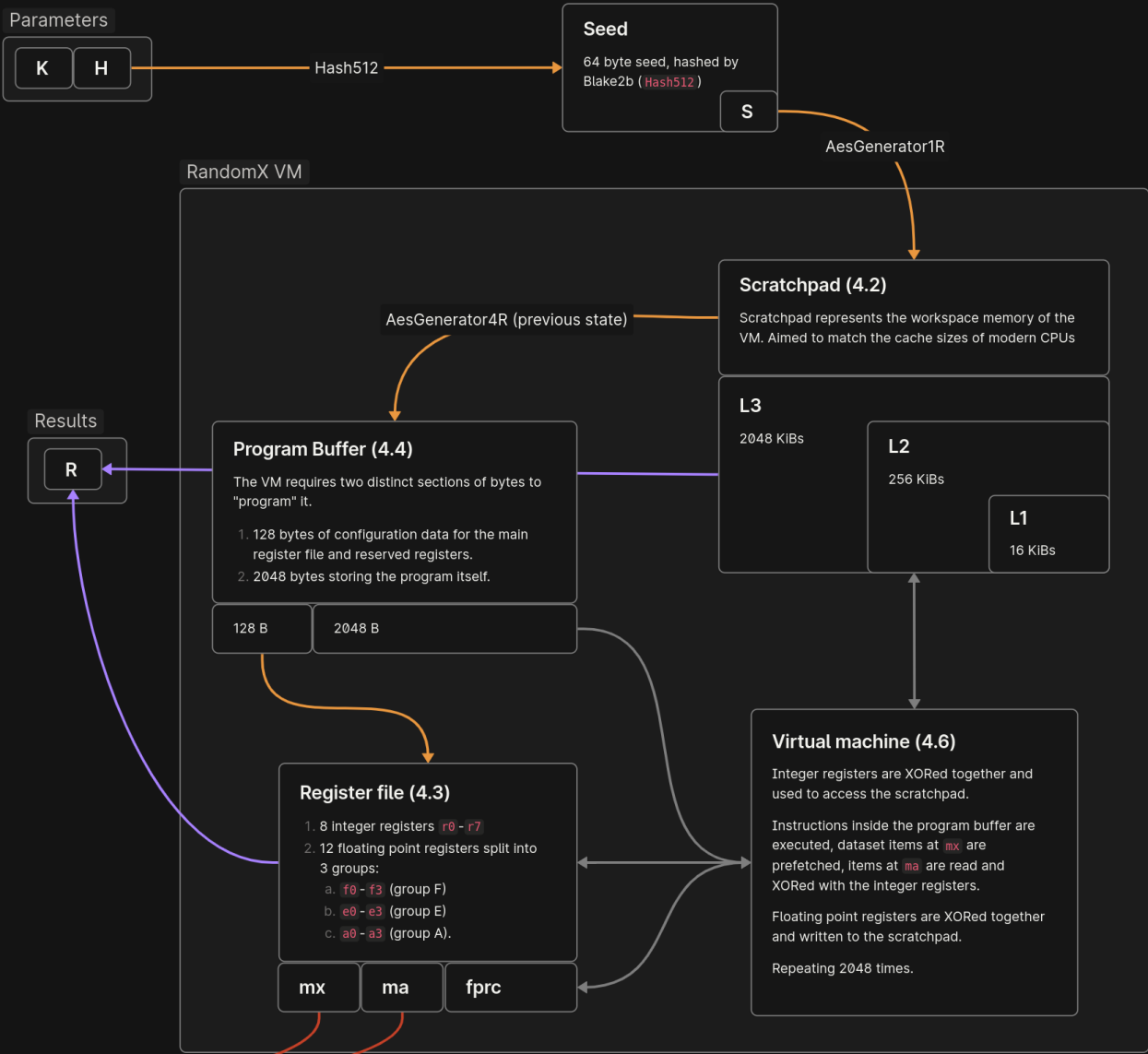
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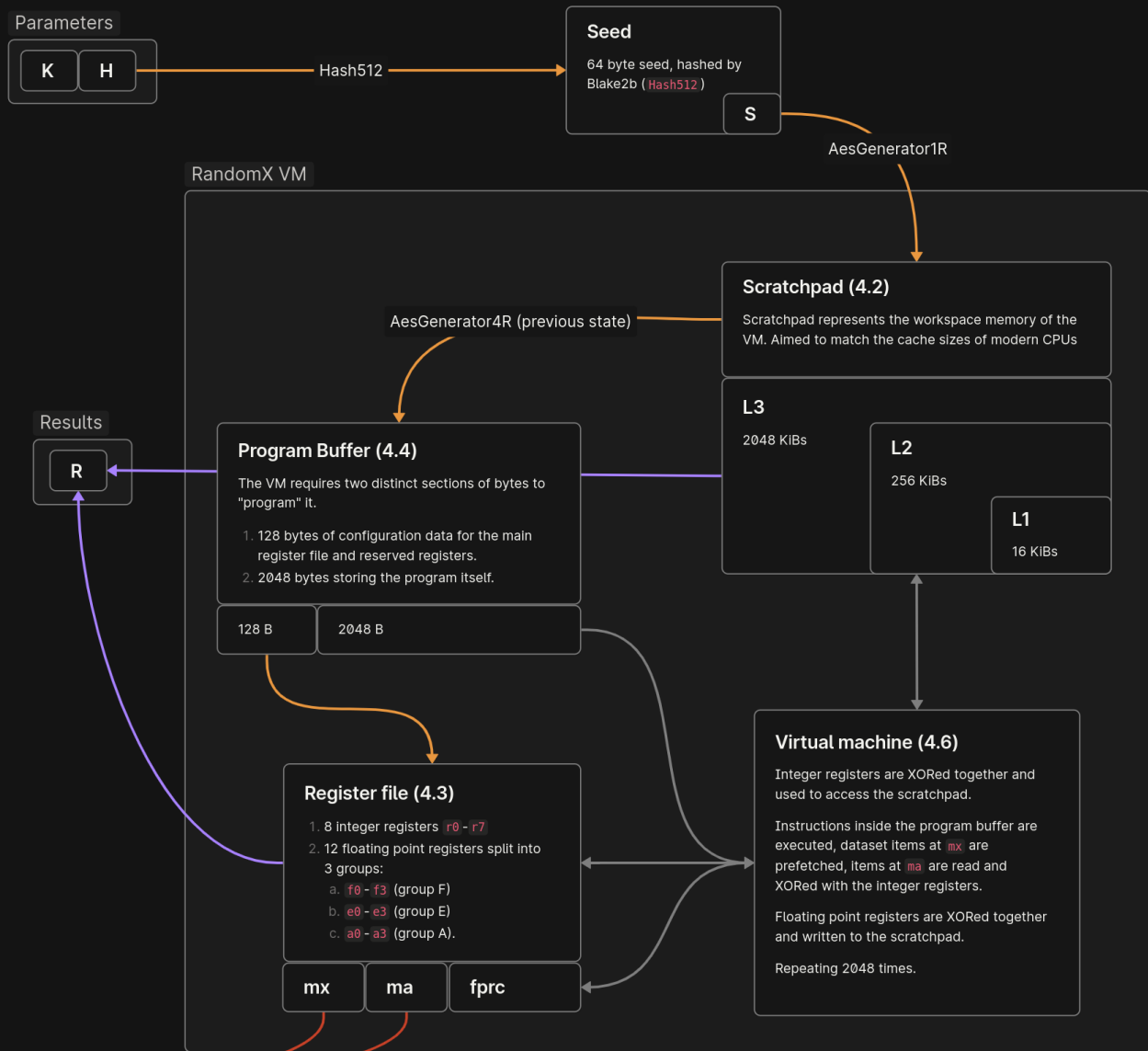


Algorithm.



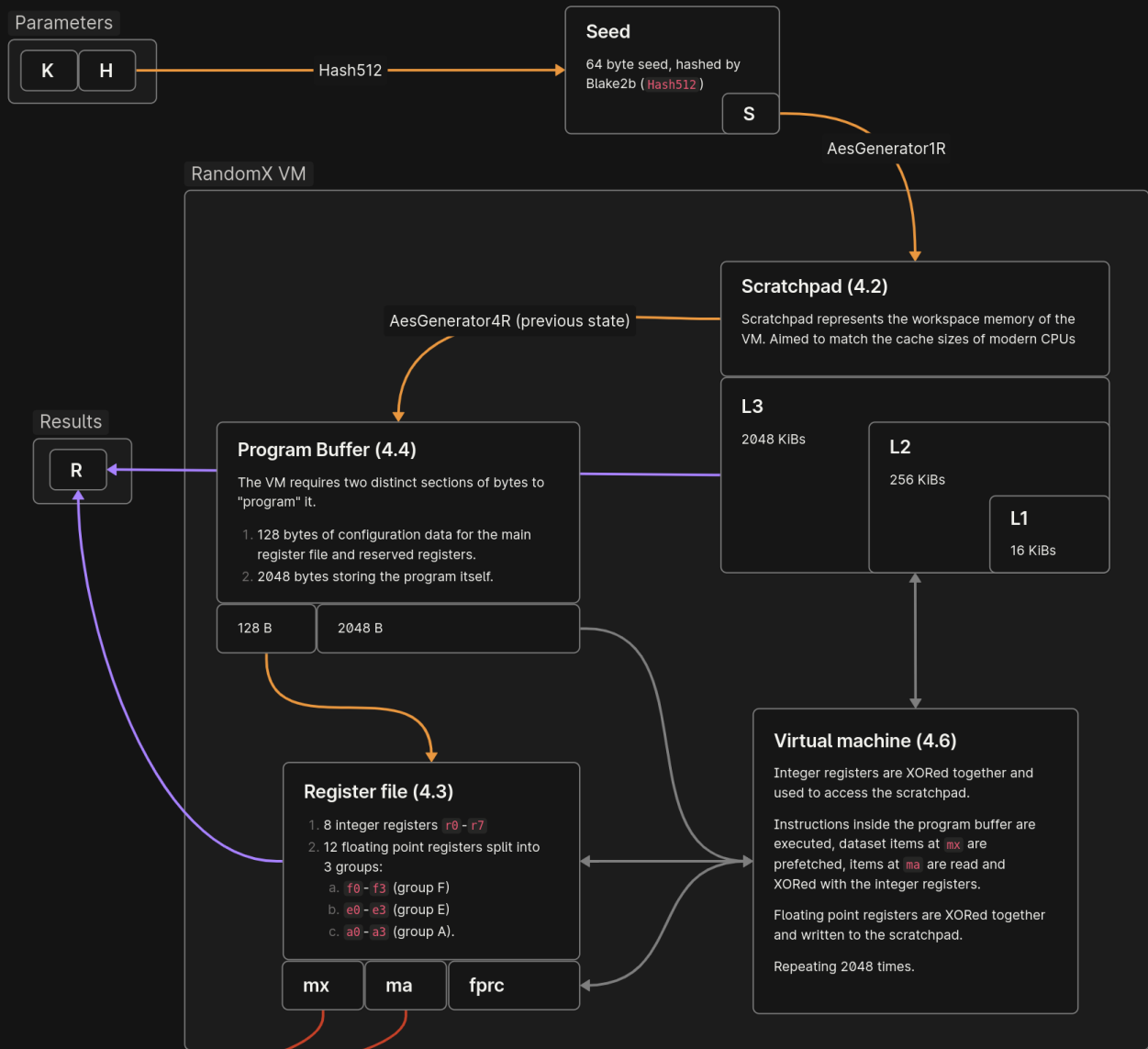
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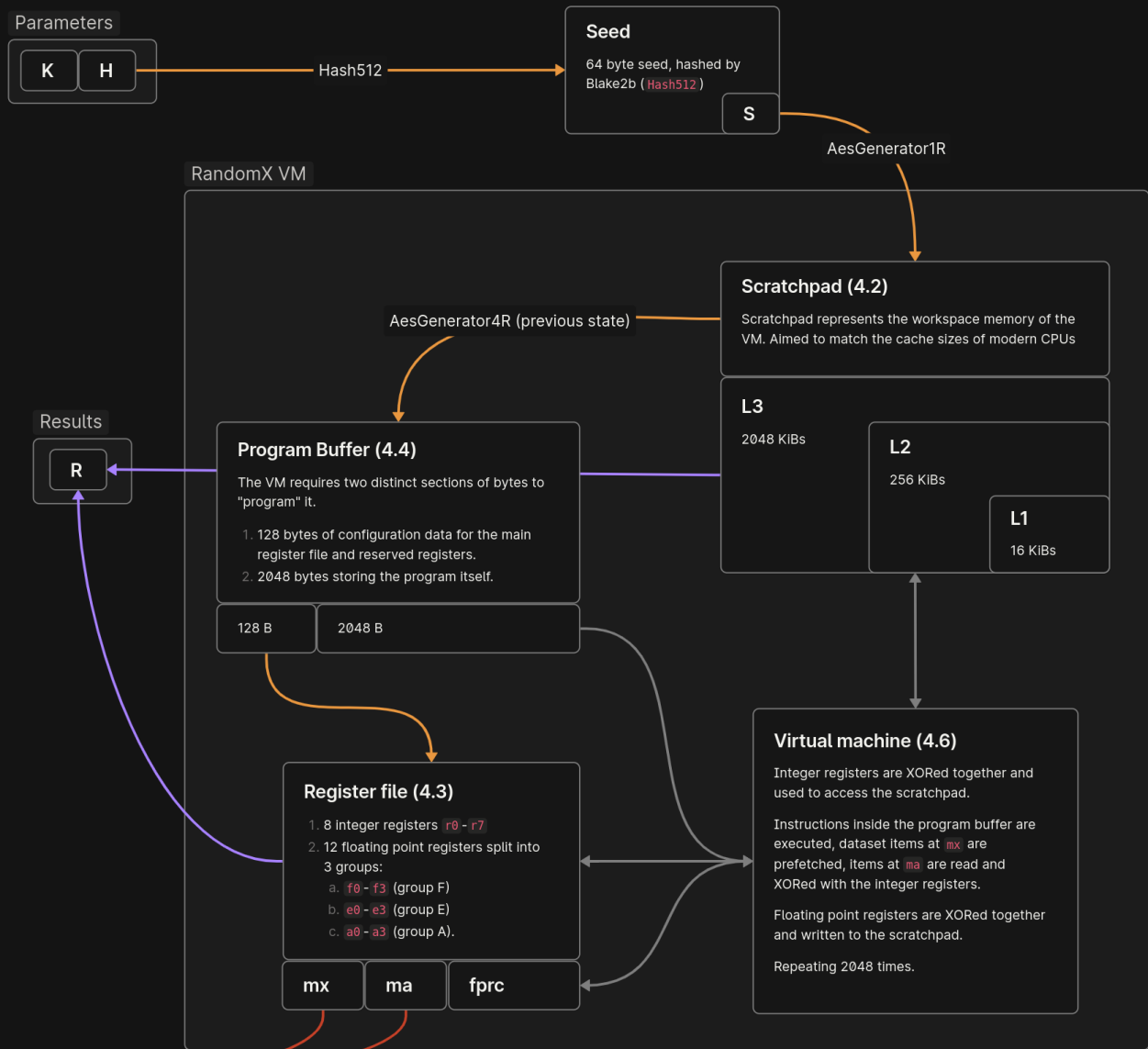
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(VM is programmed from contents)
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(chained VM execution)



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7. Scratchpad fingerprint is calculated. (AesHash1R)
8. Final result R is the hash of scratchpad fingerprint + register file. (Blake2b)



11. (1.RX) Instructions + Registers

```
(64-bit integers)
(pairs of doubles)
(misc)
```

[illegible]

11. (1.RX) Instructions + Registers

Instructions (integer).

- IADD, ISUB, IMUL, IMULH, ISMULH, INEG
- IXOR, IROL, ISWAP_R
- IMUL_RCP (division by imm32)

Instructions (FP).

(IEEE754) FADD, FSUB, FMUL, FDIV, FSQRT

- FSWAP_R: (dst0, dst1) = (dst1, dst0)
- FSCAL_R: (XOR by 0x80F0000000000000)

(most instructions have *_R, *_M variants)

(64-bit integers)

(pairs of doubles)

(misc)

r0	r1	r2	r3	r4	r5	r6	r7				
f0	f1	f2	f3	e0	e1	e2	e3	a0	a1	a2	a3
ma	mx	fprc									

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- **IEEE754** makes a *tradeoff*. Define $\mathbb{R}$ as set of *doubles* without NaN. Then $|\mathbb{R}| < 2^{64}$.

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```
bool chk(double x, double y, double z) {  
    // 99% this is false  
    return (x + y) + z == x + (y + z);  
}
```

$$\circ(\circ(x + y) + z) \neq \circ(x + \circ(y + z))$$

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FP *feels random*, is portable/well defined?

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FP is perfectly specified, with $+$, $-$, $\times$, $\div$, $\sqrt{x}$ **correctly rounded**. (IEEE754)

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- P/L defn. as $x + y := \mathbf{RN}(x + y)$, $\text{sqrt}(x) := \mathbf{RN}(\sqrt{x})$, etc.
- Anything else? Sorry. $\sin(x)$, $\exp(x)$ behave differently on other platforms.

fprc		
0	roundTiesToEven	$\mathbf{RN} : \mathbb{R}^\infty \rightarrow \mathbb{R}$
1	roundTowardNegative	$\mathbf{RD} : \mathbb{R}^\infty \rightarrow \mathbb{R}$
2	roundTowardPositive	$\mathbf{RU} : \mathbb{R}^\infty \rightarrow \mathbb{R}$
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Define $\circ : \mathbb{R}^\infty \rightarrow \mathbb{R}$ to be a function that rounds according to a (global) fprc.

- $\text{fadd}(x, y) = \circ(x + y)$, $\text{fsqrt}(x) = \circ(\sqrt{x})$, etc.

```
o(x) {
  case fprc = 0: RN(x)
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  case fprc = 2: RU(x)
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Caveat. All P/L give you **RN** only.
(foreshadowing)

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14. (1.RX) IEEE754 in P/L

Assumed $\text{add}(x, y) = \mathbf{RN}(x + y)$ in all P/L.

```
// in C
double add(double x, double y) {
    return x + y                // RN(x + y)
}
```

```
// in JavaScript
function add(x, y) {
    return x + y                // RN(x + y)
}
```

```
// in Rust
pub fn add(x: f64, y: f64) -> f64 {
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Opt-in to avoid UB.

```
#include <fenv.h>
```

```
double add(double x, double y) {
    #pragma STDC FENV_ACCESS ON

    return x + y; // ○(x + y)
}
```

```
-----
add(double, double):
    ; xmm0 = ○(xmm0 + xmm1)
    addsd    xmm0, xmm1
    ret
```

15. (1.RX) Conclusion

RandomX uses random code execution (hence the name) together with several memory-hard techniques to minimize the efficiency advantage of specialized hardware.

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Does RandomX facilitate botnets/malware mining or web mining?

[...]

Web mining is infeasible due to the large memory requirement and the lack of directed rounding support for floating point operations in both Javascript and WebAssembly.

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(Stuck with **RN** !!)

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(Stuck with **RN** !!)



witchofthewind • 5y ago

JavaScript miners are possible, but would be way too slow and inefficient to be practical.



1



Reply



tevador • 5y ago • Edited 5y ago

You'd need to emulate floating point. I estimate ~~≈1 hash per minute~~
30 H/min on a decent CPU in javascript.



4



Reply



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RandomX.js is an implementation of the ubiquitous Monero POW algorithm RandomX in JavaScript.

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~5 years later (2024):

- JavaScript has WebAssembly now, with SIMD and shared memory.
- JavaScript has threads (web workers).
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No native AES instruction, no **RD**, **RU**, **RZ**, and

- **shouldn't** have 2 GiB dataset, so only light mining.

(compute dataset items on fly, expensive...)

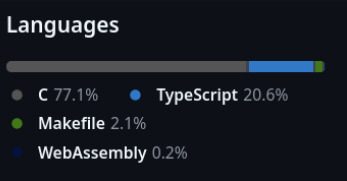


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- Complete rewrite of core RandomX (C++) in C, 5000 lines.
 - 500 lines of host glue TypeScript. (to execute JIT VM)
 - Same tests as RX, and 200k LOC test suite for FP impl.
- (Most readable RandomX impl. in existence)



```

  v jit
    v stubs
      C mulh.c
      C mulh.h
      C semifloat.c
      C semifloat.h
      C inst.h
      C jit_ssh.c
      C jit_vm_decoder.c
      C jit_vm_inst.c
      C jit_vm.c
      C jit_vm.h
      C jit.c
      C jit.h
      C ssh_internal.h
      C ssh.c
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      C wasm_jit.c
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```

RandomX WASM JIT - VM implementation	Dataset/Crypto	FP+mul	VM
2600 lines	1200 lines	400	300

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-
- No interpreter, RX code generated in WASM and executed by JS.
 - Rewritten cryptography to use WASM SIMD.
 - Performant directed rounding, **semifloat**. (!!)
 - Support for shared memory/threads.

(i.e. share the 256 MiB cache)

Languages



```

  j
  stubs
    mulh.c
    mulh.h
    semifloat.c
    semifloat.h
    inst.h
    jit_ssh.c
    jit_vm_decoder.c
    jit_vm_inst.c
    jit_vm.c
    jit_vm.h
    jit.c
    jit.h
    ssh_internal.h
    ssh.c
    ssh.h
    wasm_jit.c
    wasm_jit.h
```

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21. (2.JS) Performance?

```
node examples/randomx.js
```

```
# machine id: AMD Ryzen 7 3800X 8-Core Processor [rx/0+relaxed-simd+!fma] Node.js/v22.9.0 (linux x64)
```

```
# cache construction time 535.8 ms
```

```
# average hashrate: 22.0 H/s
```

```
node examples/randomx_threaded.js
```

```
# machine id: AMD Ryzen 7 3800X 8-Core Processor [rx/0+relaxed-simd+!fma] Node.js/v22.9.0 (linux x64)
```

```
# initialising thread 0..15
```

```
# average hashrate: 208.0 H/s
```

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```

```
# machine id: AMD Ryzen 7 3800X 8-Core Processor [rx/0+relaxed-simd+!fma] Node.js/v22.9.0 (linux x64)
```

```
# cache construction time 535.8 ms
```

```
# average hashrate: 22.0 H/s
```

```
node examples/randomx_threaded.js
```

```
# machine id: AMD Ryzen 7 3800X 8-Core Processor [rx/0+relaxed-simd+!fma] Node.js/v22.9.0 (linux x64)
```

```
# initialising thread 0..15
```

```
# average hashrate: 208.0 H/s
```

On the same machine (with light mining), I got 100 H/s per thread.

21. (2.JS) Performance?

```
node examples/randomx.js
```

```
# machine id: AMD Ryzen 7 3800X 8-Core Processor [rx/0+relaxed-simd+!fma] Node.js/v22.9.0 (linux x64)
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```

```
# initialising thread 0..15
```

```
# average hashrate: 208.0 H/s
```

On the same machine (with light mining), I got 100 H/s per thread.

5x slower is pretty good!

22. (2.JS) Motivation

- During VM, a branch table (`call_indirect`) selects correct FP op w/ rounding, so FADD_R has *fadd_0* RN, *fadd_1* RD, *fadd_2* RU, *fadd_3* RZ.

```
case FADD_R:
    // dst = dst + src
    WASM_U8_THUNK({
        0x20, F(inst->dst), // local.get $dest
        0x20, A(inst->src), // local.get $src
        0x23, $fprc,        // global.get $fprc
        0x11, 3, 0,         // call_indirect table 0
        0x21, F(inst->dst), // local.set $dest
    });
    break;
```

```
WASM_SECTION(WASM_SECTION_ELEMENT, {
    WASM_U8_THUNK({
        5, // elems = vec(5)

        // elem 0: fadd
        0x02,
        0, // table index = 0
        0x41, 0, 0x0b, // offset = i32.const 0
        0x00, // funcref
        4, // elements = vec(4)
        FIDX(3), FIDX(4), FIDX(5), FIDX(6), // fprc_0..fprc_3
        // fadd_0, fadd_1, fadd_2, fadd_3
        //
        // setup fsub_0-3, fmul_0-3, fdiv_0-3, fsqrt_0-3, ...
```

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        0x21, F(inst->dst), // local.set $dest
    });
    break;

v128_t fadd_0(v128_t a, v128_t b) {
    return wasm_f64x2_add(a, b); // RN(a + b)
}
```

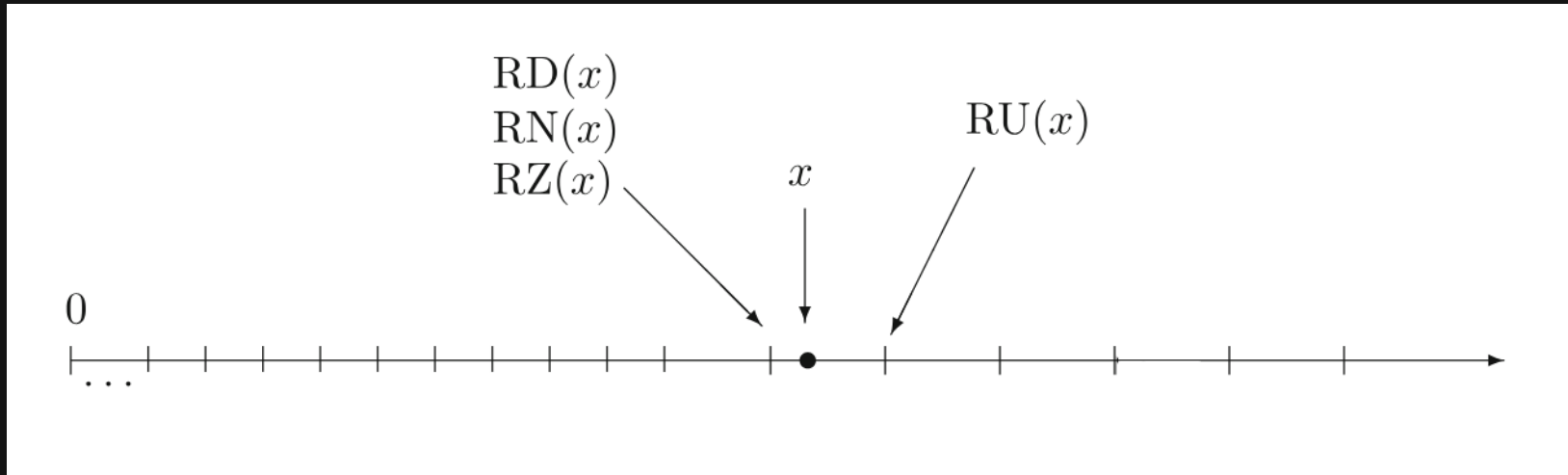
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        4, // elements = vec(4)
        FIDX(3), FIDX(4), FIDX(5), FIDX(6), // fprc_0..fprc_3
        // fadd_0, fadd_1, fadd_2, fadd_3
        //
        // setup fsub_0-3, fmul_0-3, fdiv_0-3, fsqrt_0-3, ...
    })
});
```

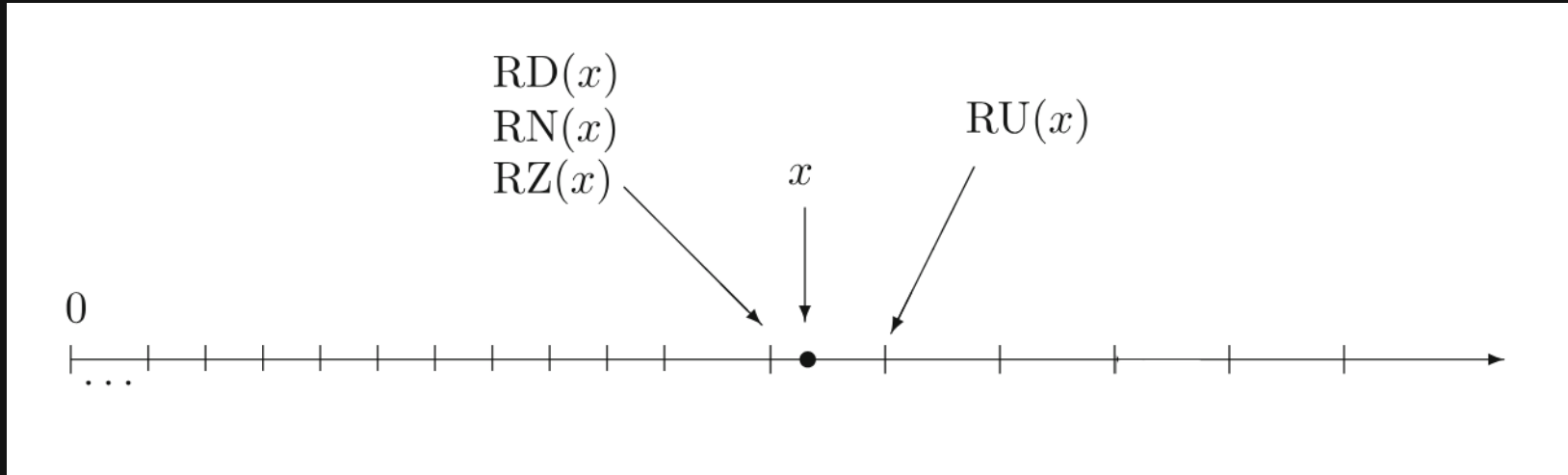
Goal. How do we actually implement *fadd_1*, *fadd_2*, etc?

>> (3.FP) Semifloat

24. (3.FP) How does rounding actually work?

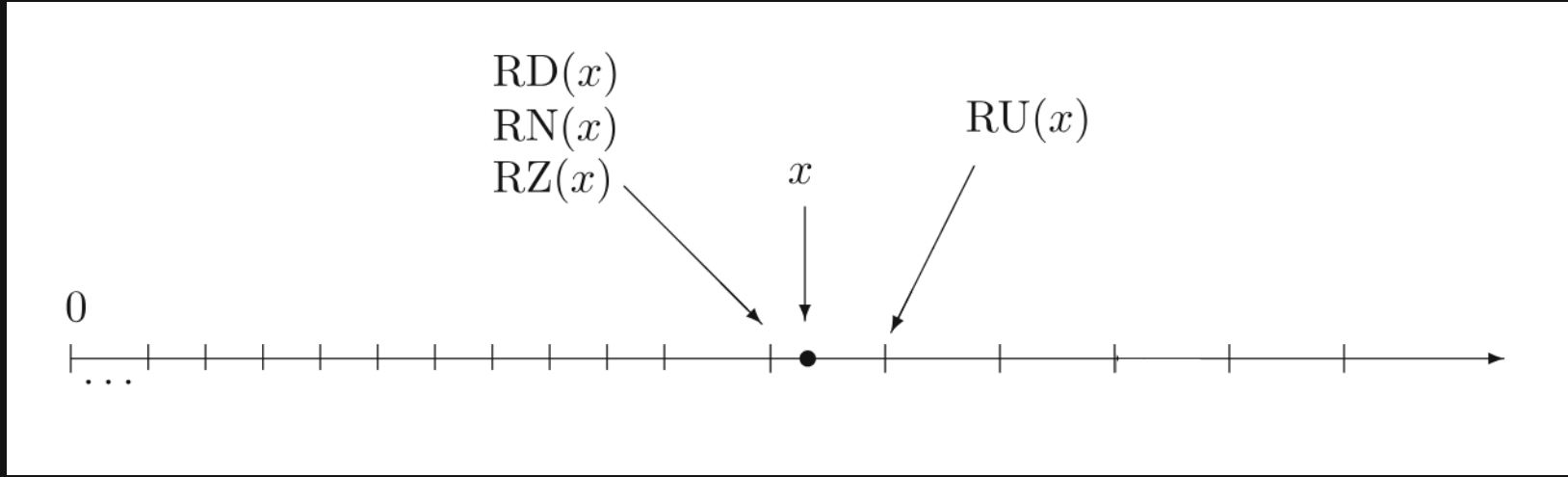


24. (3.FP) How does rounding actually work?



- **RN** returns the closest FP to x (with conditions to break ties)
- **RD** returns largest FP $\leq x$ (round toward $-\infty$)
- **RU** returns smallest FP $\geq x$ (round toward $+\infty$)

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Then, we define

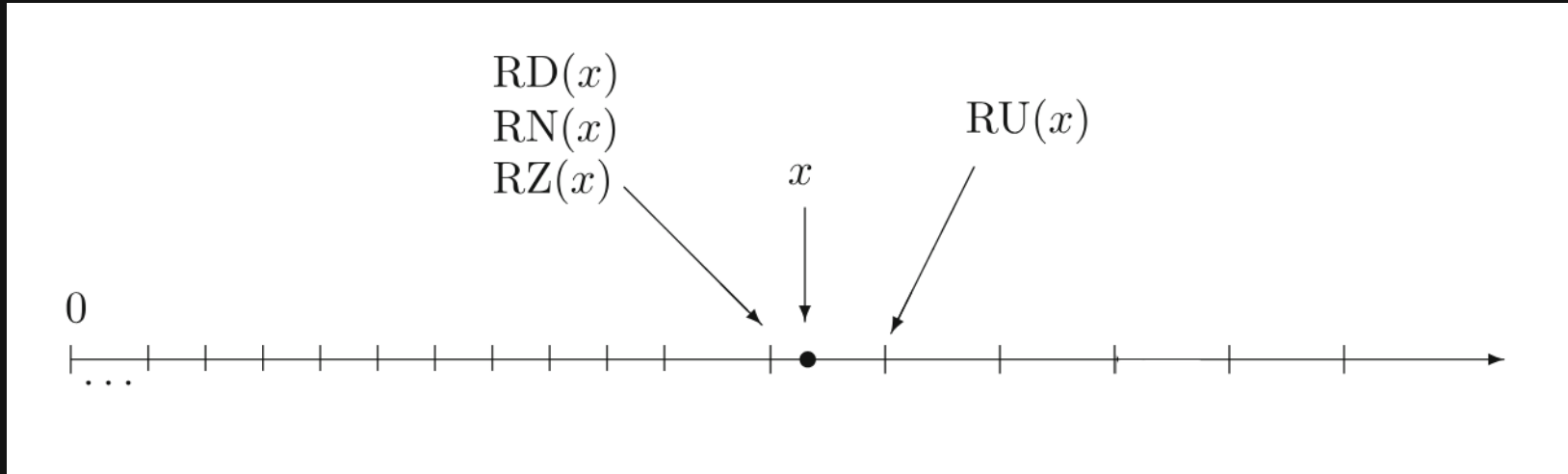
$$\mathbf{RZ}(x) = \begin{cases} \mathbf{RD}(x) & x > 0, \\ \mathbf{RU}(x) & x < 0, \\ 0 & \text{otherwise.} \end{cases}$$

25. (3.FP) How does rounding actually work?

Defn. *Unit in the last-place (ULP)* is the gap between two FP numbers nearest to x . (Kahan)

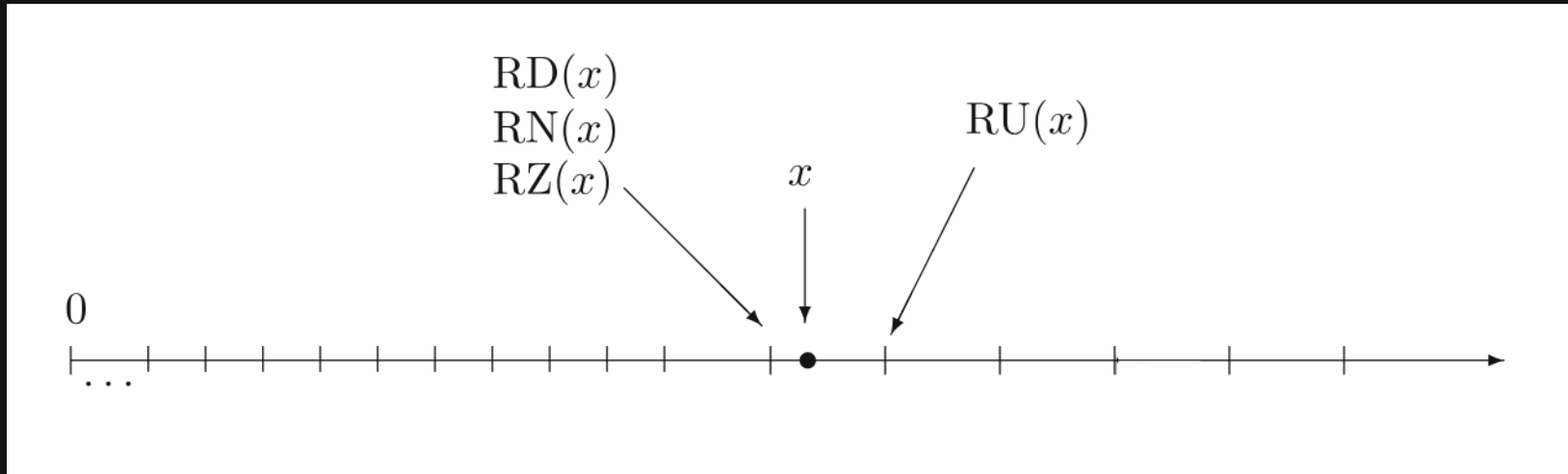
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Each FP number (tick) is at most one ULP away! (can we use this?)

Note. All ways to round either go up a tick, or go down a tick, nothing else.

26. (3.FP) Measuring error

Take some $x \in \mathbb{R}$, then $x = o(x) + \varepsilon$.

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Imagine $\mathbf{RN}^* : \mathbb{R} \rightarrow (\mathbb{R} \times \mathbb{R})$,

$$(X, \varepsilon) = \mathbf{RN}^*(x) \implies X + \varepsilon = x$$

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Upshot. If we find ε , even just the $\pm$, we can detect when rounding happens and correct it!

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$$(X, \varepsilon) = \mathbf{RN}^*(x) \implies X + \varepsilon = x$$

($\mathbf{RN}^*$ doesn't exist in general)

```
// impl. fprc = 1, so RD (round down)
fadd_1(x, y) {
    sum, ε = RN*(x + y)

    if ε < 0 {
        // sum rounded up
        return sum - ulp
    } else {
        // sum rounded down or exact
        return sum
    }
}
```

27. (3.FP) TwoSum (error free transform)

```
// RN*(x + y)
TwoSum(x, y) {
    s  = RN(a + b)
    a' = RN(s - b)
    b' = RN(s - a')
    δa = RN(a - a')
    δb = RN(b - b')
    ε  = RN(δa + δb)
    return (s, ε)
}
```

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    return (s, ε)
}

fadd_1(x, y) {
    sum, ε = TwoSum(x, y)

    if ε < 0 {
        return sum - ulp
    } else {
        return sum
    }
}
```

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    ε  = RN(δa + δb)
    return (s, ε)
}

fadd_1(x, y) {
    sum, ε = TwoSum(x, y)

    if ε < 0 {
        return sum - ulp
    } else {
        return sum
    }
}
```

```
#include <math.h> // for nextafter()

double sum_residue(double a, double b, double c) {
    double delta_a = a - (c - b);
    double delta_b = b - (c - a);
    double res = delta_a + delta_b;
    return res;
}

// return RD(a + b)
double fadd_1(double a, double b) {
    double c = a + b;
    double res = sum_residue(a, b, c);
    if (res < 0) {
        // c - ulp
        return nextafter(c, -INFINITY);
    } else {
        return c;
    }
}
```

28. (3.FP) FP implementations

- FP impl. by hardware is often called **hardfloat**.

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What is this thing called?

- In vein of these similar defn. FP emulations in terms of **RN** will be called **semifloat**.

28. (3.FP) FP implementations

- FP impl. by hardware is often called **hardfloat**.
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(Motv. CPU only supports integer operations, emulate FP in software.)

What is this thing called?

- In vein of these similar defn. FP emulations in terms of **RN** will be called **semifloat**. (Is semifloat any faster than softfloat?)

```
#include <fenv.h> // fesetround()

double hard_fadd_1(double a, double b) {
    #pragma STDC FENV_ACCESS ON

    fesetround(FE_DOWNWARD);
    double res = a + b;
    fesetround(FE_TONEAREST);
    return res;
}
```

```
v128_t sum_residue(v128_t a, v128_t b, v128_t c) {
    v128_t delta_a = wasm_f64x2_sub(a, wasm_f64x2_sub(c, b));
    v128_t delta_b = wasm_f64x2_sub(b, wasm_f64x2_sub(c, a));
    v128_t res = wasm_f64x2_add(delta_a, delta_b);
    return res;
}

v128_t semi_fadd_1(v128_t dest, v128_t src) {
    v128_t c = wasm_f64x2_add(dest, src);
    v128_t res = sum_residue(dest, src, c);
    // performs the if (res < 0) nextafter(c, -INFINITY); as SIMD
    return nextafter_1_finite_nzero(res, c);
}
```

29. (3.FP) Softfloat (additive)

```
// github.com/ucb-bar/berkeley-softfloat-3
static float64_t f64_add(float64_t a, float64_t b) {
    // ...

    uA.f = a;
    uiA = uA.ui;
    signA = signF64UI( uiA );
    uB.f = b;
    uiB = uB.ui;
    signB = signF64UI( uiB );
    if ( signA == signB ) {
        return softfloat_addMagsF64( uiA, uiB, signA );
    } else {
        return softfloat_subMagsF64( uiA, uiB, signA );
    }
}
```

github.com/l1mey112/fp-rounding-emulation
(check bench_RD folder)

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```
static float64_t f64_add(float64_t a, float64_t b) {
    // ...

    uA.f = a;
    uiA = uA.ui;
    signA = signF64UI( uiA );
    uB.f = b;
    uiB = uB.ui;
    signB = signF64UI( uiB );
    if ( signA == signB ) {
        return softfloat_addMagsF64( uiA, uiB, signA );
    } else {
        return softfloat_subMagsF64( uiA, uiB, signA );
    }
}
```

github.com/l1mey112/fp-rounding-emulation

(check bench_RD folder)

// performs $|A| + |B|$

```
static float64_t
softfloat_addMagsF64( uint_fast64_t uiA, uint_fast64_t uiB,
    bool signZ )
{
    // ....
    expA = expF64UI( uiA );
    sigA = fracF64UI( uiA );
    expB = expF64UI( uiB );
    sigB = fracF64UI( uiB );
    expDiff = expA - expB;
    if ( ! expDiff ) {
        if ( ! expA ) {
            uiZ = uiA + sigB;
            goto uiZ;
        }
        expZ = expA;
        sigZ = UINT64_C( 0x0020000000000000 ) + sigA + sigB;
        sigZ <=< 9;
    } else {
        sigA <=< 9;
        sigB <=< 9;

        if ( expDiff < 0 ) {
            expZ = expB;
            if ( expA ) {
                sigA += UINT64_C( 0x2000000000000000 );
            }
            sigA = softfloat_shiftRightJam64( sigA, -expDiff );
        } else {
            expZ = expA;
```

29. (3.FP) Softfloat (additive)

```
// github.com/ucb-bar/berkeley-softfloat-3
static float64_t f64_add(float64_t a, float64_t b) {
    // ...

    uA.f = a;
    uiA = uA.ui;
    signA = signF64UI( uiA );
    uB.f = b;
    uiB = uB.ui;
    signB = signF64UI( uiB );
    if ( signA == signB ) {
        return softfloat_addMagsF64( uiA, uiB, signA );
    } else {
        return softfloat_subMagsF64( uiA, uiB, signA );
    }
}
```

github.com/l1mey112/fp-rounding-emulation

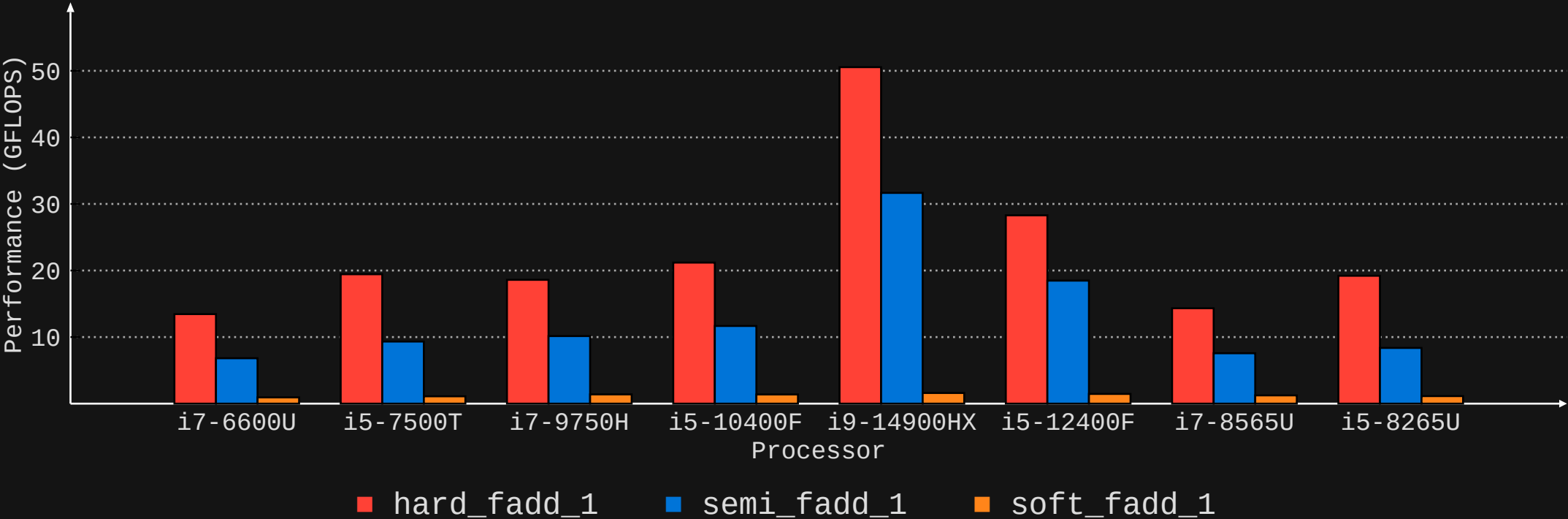
(check bench_RD folder)

```
    } else {
        sigA <= 9;
        sigB <= 9;

        if ( expDiff < 0 ) {
            expZ = expB;
            if ( expA ) {
                sigA += UINT64_C( 0x2000000000000000 );
            }
            sigA = softfloat_shiftRightJam64( sigA, -expDiff );
        } else {
            expZ = expA;
            if ( expB ) {
                sigB += UINT64_C( 0x2000000000000000 );
            }
            sigB = softfloat_shiftRightJam64( sigB, expDiff );
        }
        sigZ = UINT64_C( 0x2000000000000000 ) + sigA + sigB;
        if ( sigZ < UINT64_C( 0x4000000000000000 ) ) {
            --expZ;
            sigZ <= 1;
        }
    }
    // perform rounding here
    return softfloat_roundPackToF64( signZ, expZ, sigZ );
uiZ:
    uZ.ui = uiZ;
    return uZ.f;
}
```

30. (3.FP) Benchmark (additive)

```
$ git clone https://github.com/llmey112/fp-rounding-emulation
$ cd fp-rounding-emulation/bench_RD
$ clang ... && ./bench
# fprc(1):    XX.XX GFLOPS "hard_fadd_1"
# fprc(1):    XX.XX GFLOPS "semi_fadd_1" (x1.88 overhead)
# fprc(1):    X.XX GFLOPS "soft_fadd_1" (x17.56 overhead)
#                                     (average overhead)  ^^^^^^^^^^^^^^^^^^^
```



31. (3.FP) Semifloat (multiplicative)

```
v128_t semi_fmul_1(v128_t dest, v128_t src) {
    v128_t c = wasm_f64x2_mul(dest, src);

    // scale a_scaled, b_scaled, c_scaled to be within [0.5,1) - frexp(3), ldexp(3)
    v128_t expa, expb;
    v128_t a_scaled = frexp_reg_e_nozero_noinf(dest, &expa);
    v128_t b_scaled = frexp_reg_e_nozero_noinf(src, &expb);
    v128_t c_scaled = ldexp_reg_e_nozero_noinf(c, wasm_i64x2_sub(wasm_i64x2_neg(expa), expb)); // -expa - expb
    v128_t res = mul_residue(a_scaled, b_scaled, c_scaled);

    v128_t isinf = wasm_f64x2_eq(c, wasm_f64x2_const(INFINITY, INFINITY));

    // branch hit 0.024882% to 0.003414% of the time, so never
    if (unlikely(wasm_v128_any_true(isinf))) {
        v128_t isfinite_a = wasm_f64x2_ne(dest, wasm_f64x2_const(INFINITY, INFINITY));
        // fin * fin = _inf_; round down to the nearest representable number
        // inf * fin = inf
        //
        // res = isinf ? (isfinite_a ? -1.0 : 1.0) : res
        //           ^^^^   ^^^
        //           rounding down   no rounding
        v128_t res_isinf = wasm_v128_bitselect(wasm_f64x2_const(-1.0, -1.0), wasm_f64x2_const(1.0, 1.0), isfinite_a);
        res = wasm_v128_bitselect(res_isinf, res, isinf);
    }

    return nextafter_1_finite_nozero(res, c);
}
```

32. (3.FP) Semifloat (multiplicative)

```
static inline v128_t upper_half(v128_t x) {
    v128_t secator = wasm_f64x2_const(134217729.0, 134217729.0);
    v128_t p = wasm_f64x2_mul(x, secator);
    return wasm_f64x2_add(p, wasm_f64x2_sub(x, p));
}

static inline v128_t mul_residue(v128_t a, v128_t b, v128_t c) {
    v128_t aup = upper_half(a);
    v128_t alo = wasm_f64x2_sub(a, aup);
    v128_t bup = upper_half(b);
    v128_t blo = wasm_f64x2_sub(b, bup);

    v128_t high = wasm_f64x2_mul(aup, bup);
    v128_t mid = wasm_f64x2_add(wasm_f64x2_mul(aup, blo), wasm_f64x2_mul(alo, bup));
    v128_t low = wasm_f64x2_mul(alo, blo);
    v128_t ab = wasm_f64x2_add(high, mid);
    v128_t resab = wasm_f64x2_add(wasm_f64x2_sub(high, ab), mid);
    resab = wasm_f64x2_add(resab, low);

    v128_t fma = wasm_f64x2_sub(ab, c); // a*b - c ----- we want a * b - RN(a * b) = res
    return wasm_f64x2_add(resab, fma);
}
```

33. (3.FP) Semifloat FMA? (multiplicative)

Let $c = \mathbf{RN}(a \times b)$, assume $\varepsilon \in \mathbb{R}$. Going back to what we know,

$$a \times b = \mathbf{RN}(a \times b) + \varepsilon$$

$$a \times b = c + \varepsilon.$$

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$$a \times b = c + \varepsilon.$$

Solving for ε ,

$$a \times b - c = \varepsilon,$$

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$$a \times b = c + \varepsilon.$$

Solving for ε ,

$$a \times b - c = \varepsilon,$$

apply $\mathbf{RN}$ on both sides,

$$\begin{aligned}\mathbf{RN}(a \times b - c) &= \mathbf{RN}(\varepsilon) \\ &= \varepsilon,\end{aligned}$$

33. (3.FP) Semifloat FMA? (multiplicative)

Let $c = \mathbf{RN}(a \times b)$, assume $\varepsilon \in \mathbb{R}$. Going back to what we know,

$$a \times b = \mathbf{RN}(a \times b) + \varepsilon$$

$$a \times b = c + \varepsilon.$$

Solving for ε ,

$$a \times b - c = \varepsilon,$$

apply $\mathbf{RN}$ on both sides,

$$\begin{aligned} \mathbf{RN}(a \times b - c) &= \mathbf{RN}(\varepsilon) \\ &= \varepsilon, \end{aligned}$$

as ε is already a floating point number.

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$$a \times b - c = \varepsilon,$$

apply $\mathbf{RN}$ on both sides,

$$\begin{aligned}\mathbf{RN}(a \times b - c) &= \mathbf{RN}(\varepsilon) \\ &= \varepsilon,\end{aligned}$$

as ε is already a floating point number.

Goal. Is there a way to do $a \times b - c$ in one rounding?

34. (3.FP) Semifloat FMA (multiplicative)

IEEE754-2008 specifies $+$, $-$, $\times$, $\div$, $\sqrt{x}$, $\text{fma}(a, b, c)$ correctly rounded. (?? fma)

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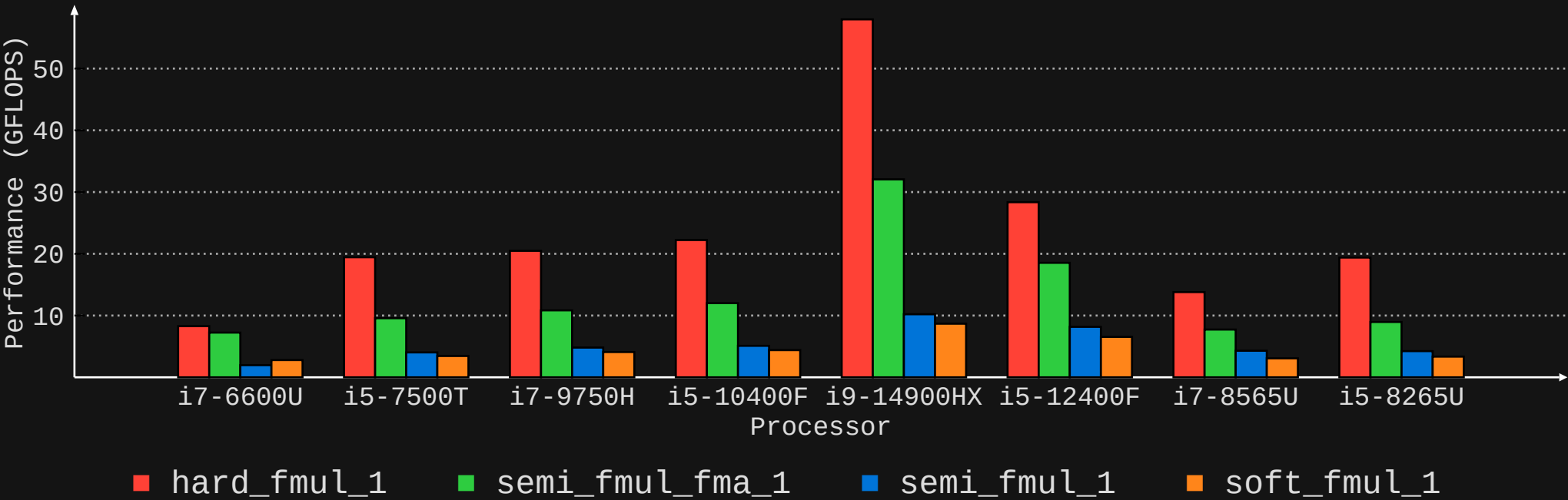
(Not a double round! So $\text{fma}(a, b, c) \neq \circ(\circ(a \times b) + c).$)

```
v128_t mul_residue_fma(v128_t a, v128_t b, v128_t c) {
    // return fma(a, b, -c)
    return wasm_f64x2_relaxed_madd(wasm_f64x2_neg(c), b, a); // RN(a*b - c)
}

v128_t semi_fmul_fma_1(v128_t dest, v128_t src) {
    v128_t c = wasm_f64x2_mul(dest, src);
    v128_t res = mul_residue_fma(dest, src, c);
    return nextafter_1_finite_nozero(res, c);
}
```

35. (3.FP) Benchmark (multiplicative)

```
$ git clone https://github.com/llmeyer112/fp-rounding-emulation
$ cd fp-rounding-emulation/bench_RD
$ clang ... && ./bench
# fprc(1):      XX.XX GFLOPS "hard_fm mul_1"
# fprc(1):      XX.XX GFLOPS "semi_fm mul_fma_1" (x1.78 overhead)
# fprc(1):      X.XX GFLOPS "semi_fm mul_1"      (x4.33 overhead)
# fprc(1):      X.XX GFLOPS "soft_fm mul_1"      (x5.00 overhead)
#                                     ^^^^^^^^^^^^^^^^^^^
```



36. (3.FP) Softfloat (multiplicative)

```
float64_t f64_mul( float64_t a, float64_t b )
{
    union ui64_f64 uA, uB, uZ;
    uA.f = a; uB.f = b;
    uint64_t uiA = uA.ui;          uint64_t uiB = uB.ui;
    int16_t expA  = expF64UI( uiA ); uint64_t sigA  = fracF64UI( uiA );
    int16_t expB  = expF64UI( uiB ); uint64_t sigB  = fracF64UI( uiB );

    if ( expA == 0x7FF ) {
        goto infArg;
    }
    int16_t expZ = expA + expB - 0x3FF;
    sigA = (sigA | UINT64_C( 0x0010000000000000 ))<<10;
    sigB = (sigB | UINT64_C( 0x0010000000000000 ))<<11;

    // perform 64 bit multiply -> returning 128 bit result
    struct uint128 sig128Z = softfloat_mul64To128( sigA, sigB );
    uint64_t sigZ = sig128Z.v64 | (sig128Z.v0 != 0);
    if ( sigZ < UINT64_C( 0x4000000000000000 ) ) {
        --expZ;
        sigZ <= 1;
    }
    // perform rounding, you've seen this before with f64_add
    return softfloat_roundPackToF64( 0 /* signZ */, expZ, sigZ );
infArg:
    uZ.ui = packToF64UI( 0 /* signZ */, 0x7FF, 0 );
    return uZ.f;
}
```

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    uA.f = a; uB.f = b;
    uint64_t uiA = uA.ui;      uint64_t uiB = uB.ui;
    int16_t expA = expF64UI( uiA ); uint64_t sigA = fracF64UI( uiA );
    int16_t expB = expF64UI( uiB ); uint64_t sigB = fracF64UI( uiB );

    if ( expA == 0x7FF ) {
        goto infArg;
    }
    int16_t expZ = expA + expB - 0x3FF;
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infArg:
    uZ.ui = packToF64UI( 0 /* signZ */, 0x7FF, 0 );
    return uZ.f;
}
```

Take two FP numbers, a and b .
Then,

$$a = m \times 2^e,$$

$$b = n \times 2^u.$$

Multiplying,

$$a \times b = (m \times n) \times 2^{e+u},$$

which is much, much easier to
do in software.

(compared to FP addition.)

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- RandomX “forces” nontrivial FP rounding on you to maximise die space on an ASIC.

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 - This speeds up emulation of addition considerably, multiplication, a little.
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- The bane of slow software implementations is unpredictable branches.
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This allows RandomX.js to be fast!

>> Finishing Up

39. Q&A - The End + Reference material

Thank you everyone! It's Q&A time.

Slides cut to make time. Easy program problem, memory-hardness, scratchpad, longer exposition on the ASIC problem, relaxed SIMD caveats, RandomX FP assumptions.

Error Free Transforms (EFTs)

- Muller, J.-M. et al. (2018) Handbook of Floating-Point Arithmetic.
 - Arnold, J. (2012) "Floating-Point Arithmetic."
<https://indico.cern.ch/event/166141/sessions/125684/attachments/201414/282782/Arnold-FPWorkshop-Print.pdf>
 - (My question on SO) <https://stackoverflow.com/questions/78776730>
-

RandomX

- (docs) <https://github.com/tevador/RandomX/blob/master/doc/docs.md>
 - (specs) <https://github.com/tevador/RandomX/blob/master/doc/specs.md>
-

RandomX.js

- (perf tracking) <https://github.com/l1mey112/randomx.js/issues/1>