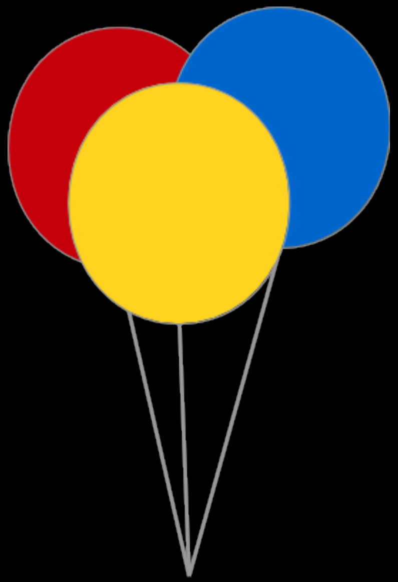

Balloon Hashing

A Memory-Hard Function with Provable Protection Against Sequential Attacks

Dan Boneh, Stanford
*Henry Corrigan-Gibbs, Stanford
Stuart Schechter, Microsoft Research

Balloon Hashing

A new password hashing function that:

1. Is <u>proven</u> memory-hard (in the sequential setting)
2. Uses a password-independent data access pattern
3. Matches the performance of the best heuristically secure memory-hard functions

11:35
Google
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THU 7:00 AM
YouTube
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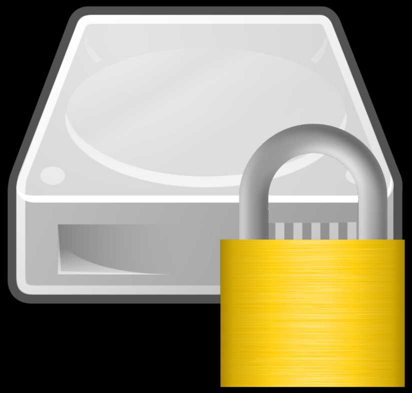

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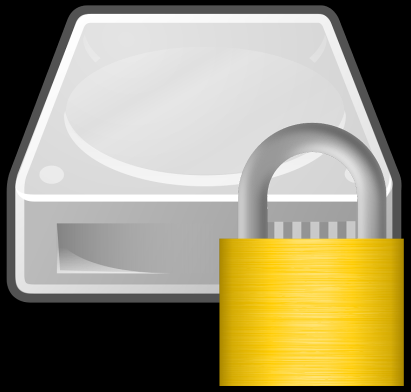

PDF
Adobe

$

The Attacker's Job

User	Salt	H(passwd, salt)
alice	0x65ff0162	0x526642d8
bob	0x37ceb328	0x5a325ad2
carol	0xec967ec1	0xf4441a71
dave	0xfb791a9a	0x1dbd71f3

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For each row,
attacker wants to make
2^{30} guesses

Overall Goal

A good password hashing function makes the attacker’s job as difficult as possible.

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If the authentication server can compute…

X hashes per **$ of energy**

then an attacker *with custom hardware* should only be able to compute…

(1+ε)X hashes per **$ of energy**

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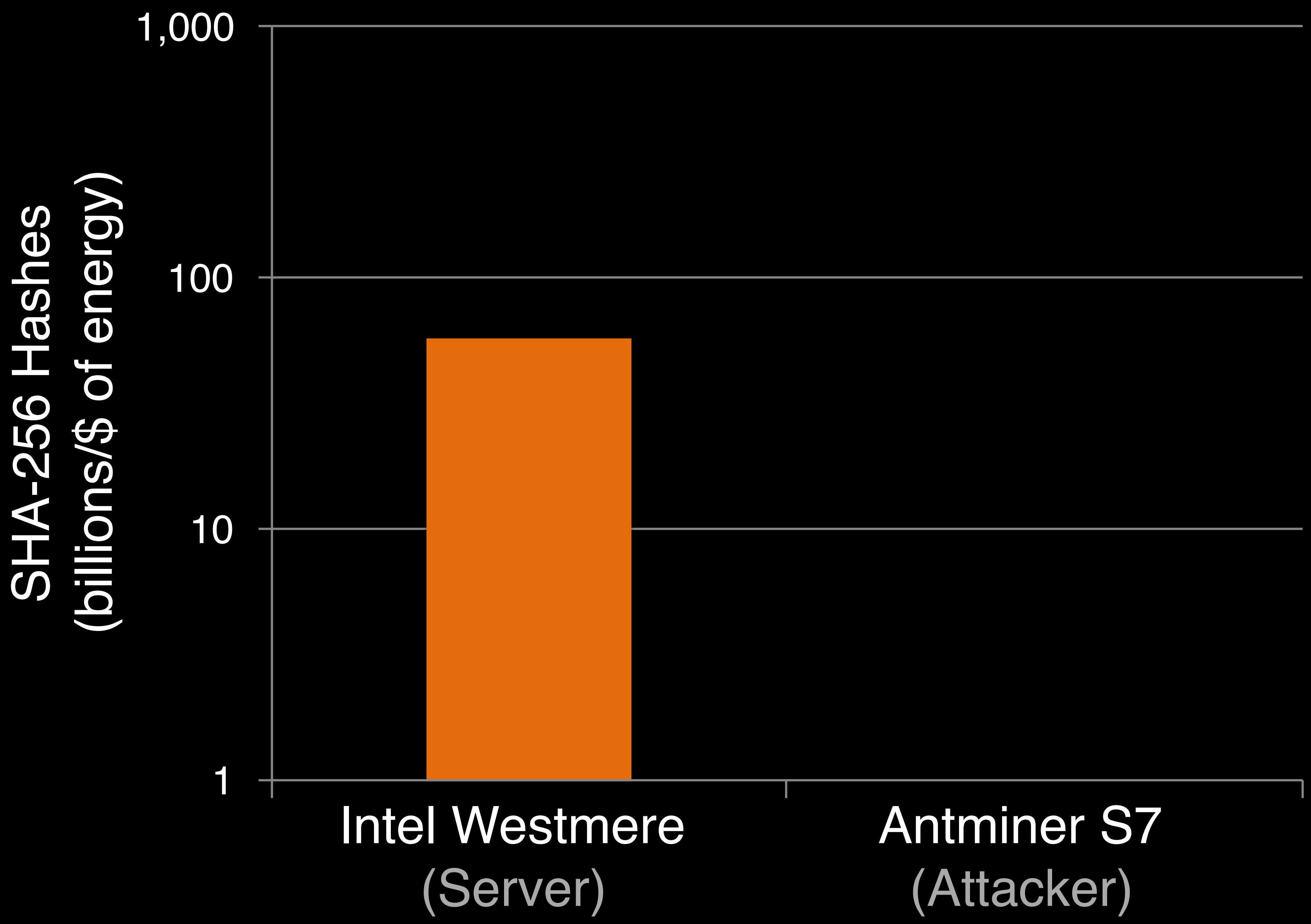
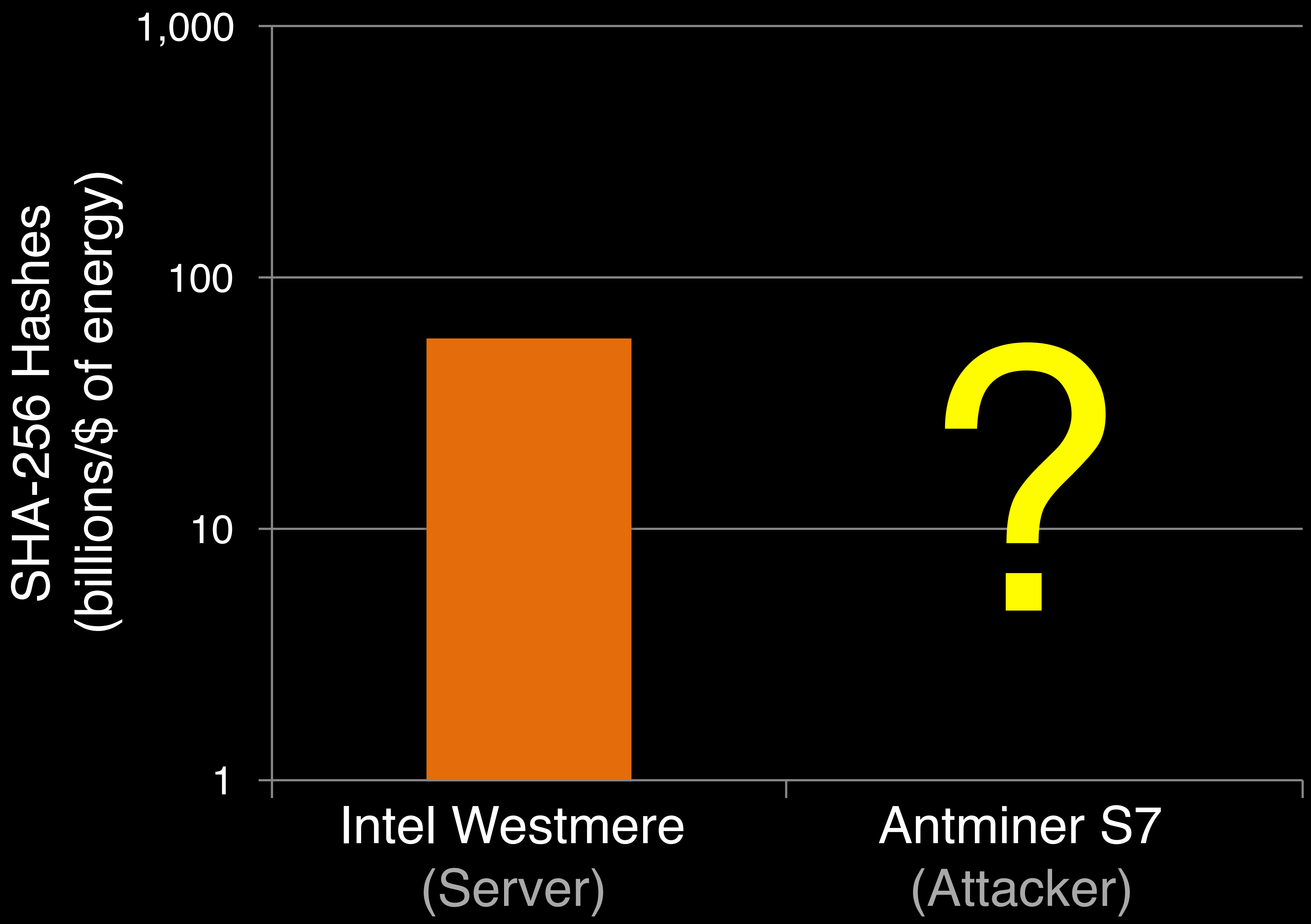
By this metric, conventional hash functions (e.g., SHA-256) are far from optimal!


SHA-256 Hashes
(billions/$ of energy)
1,000
100
10
1
Intel Westmere
(Server)
Antminer S7
(Attacker)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(billions/$ of energy)
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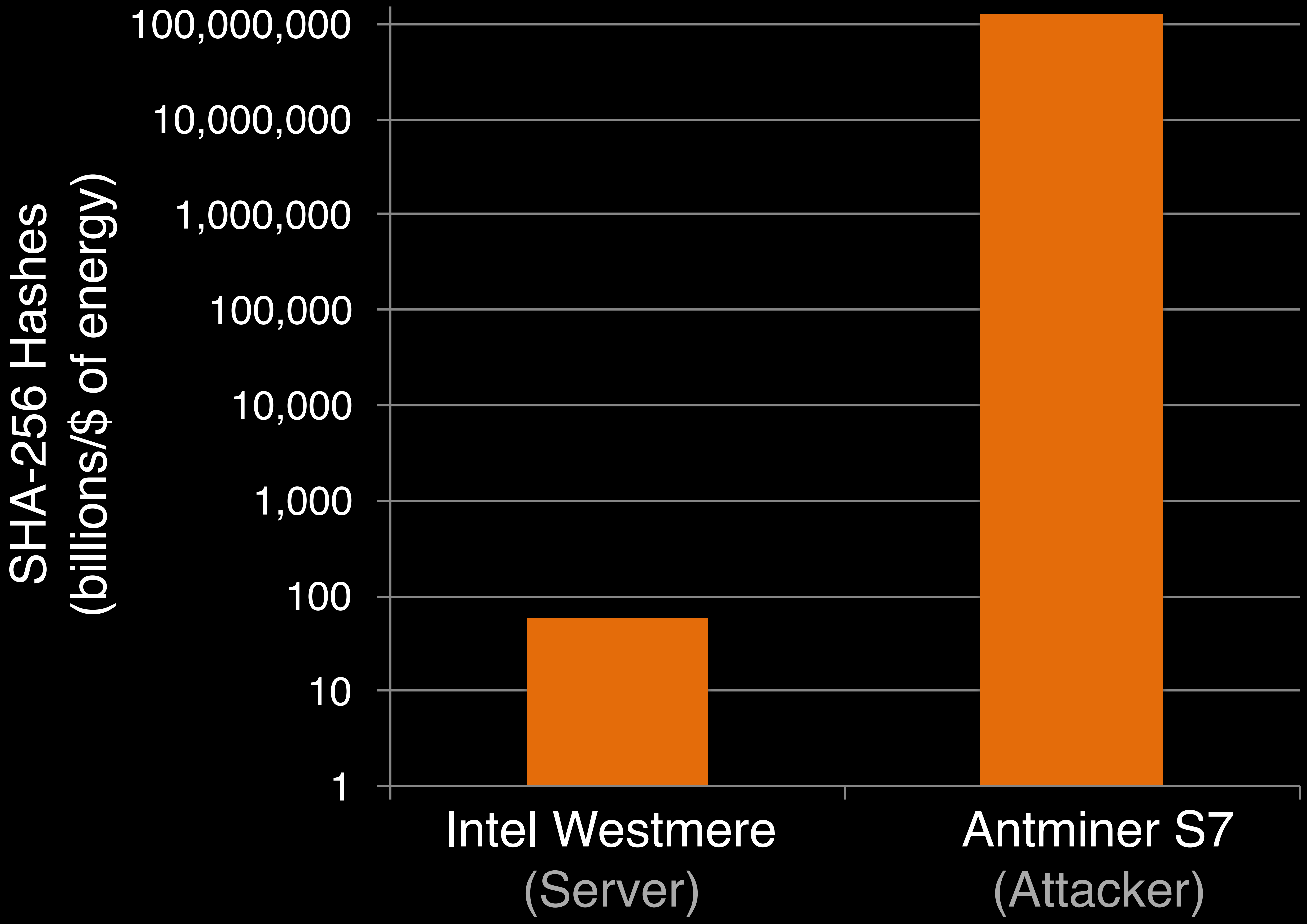
SHA-256 Hashes
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Intel Westmere
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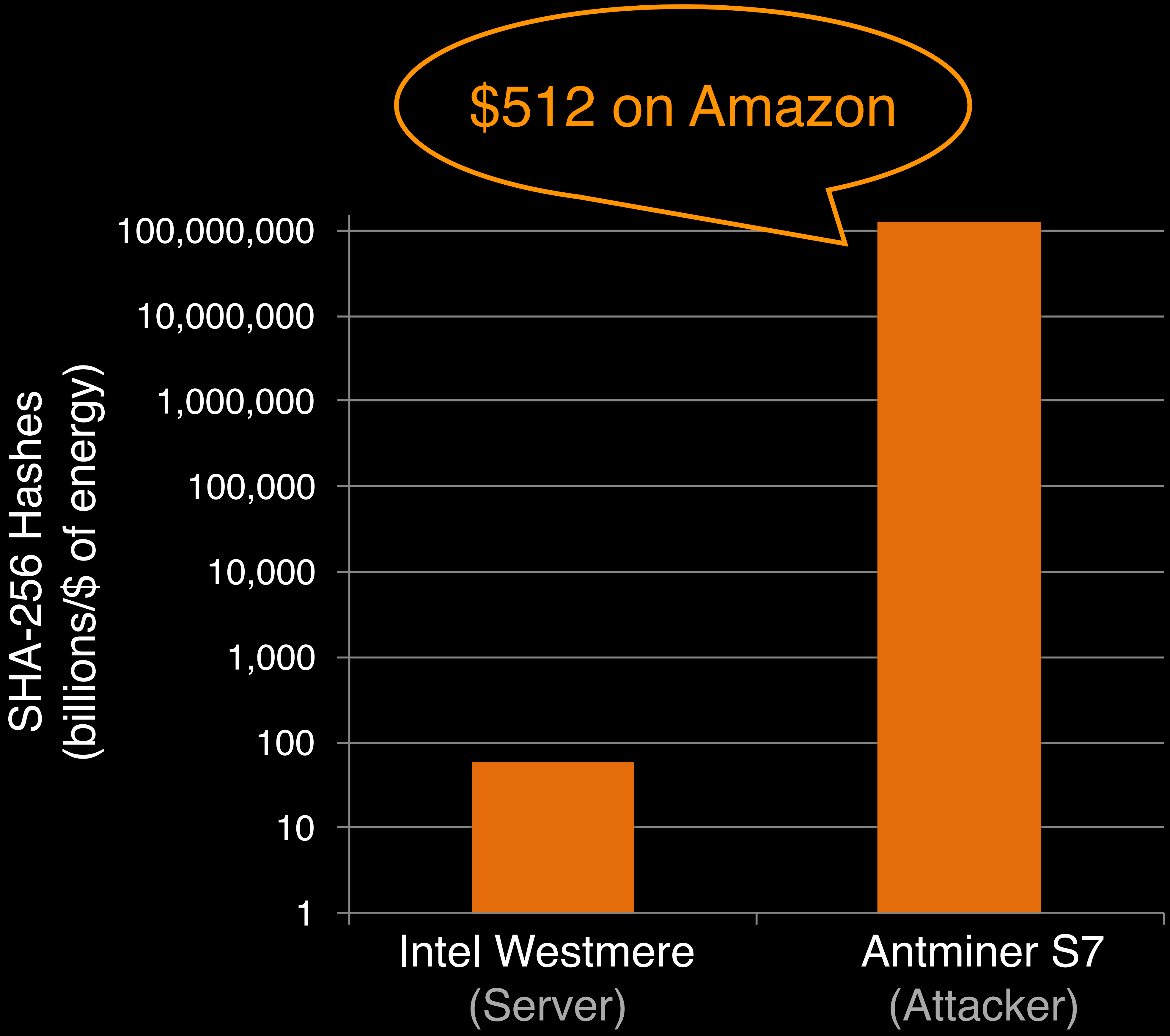
$512 on Amazon
SHA-256 Hashes
(billions/$ of energy)
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Intel Westmere
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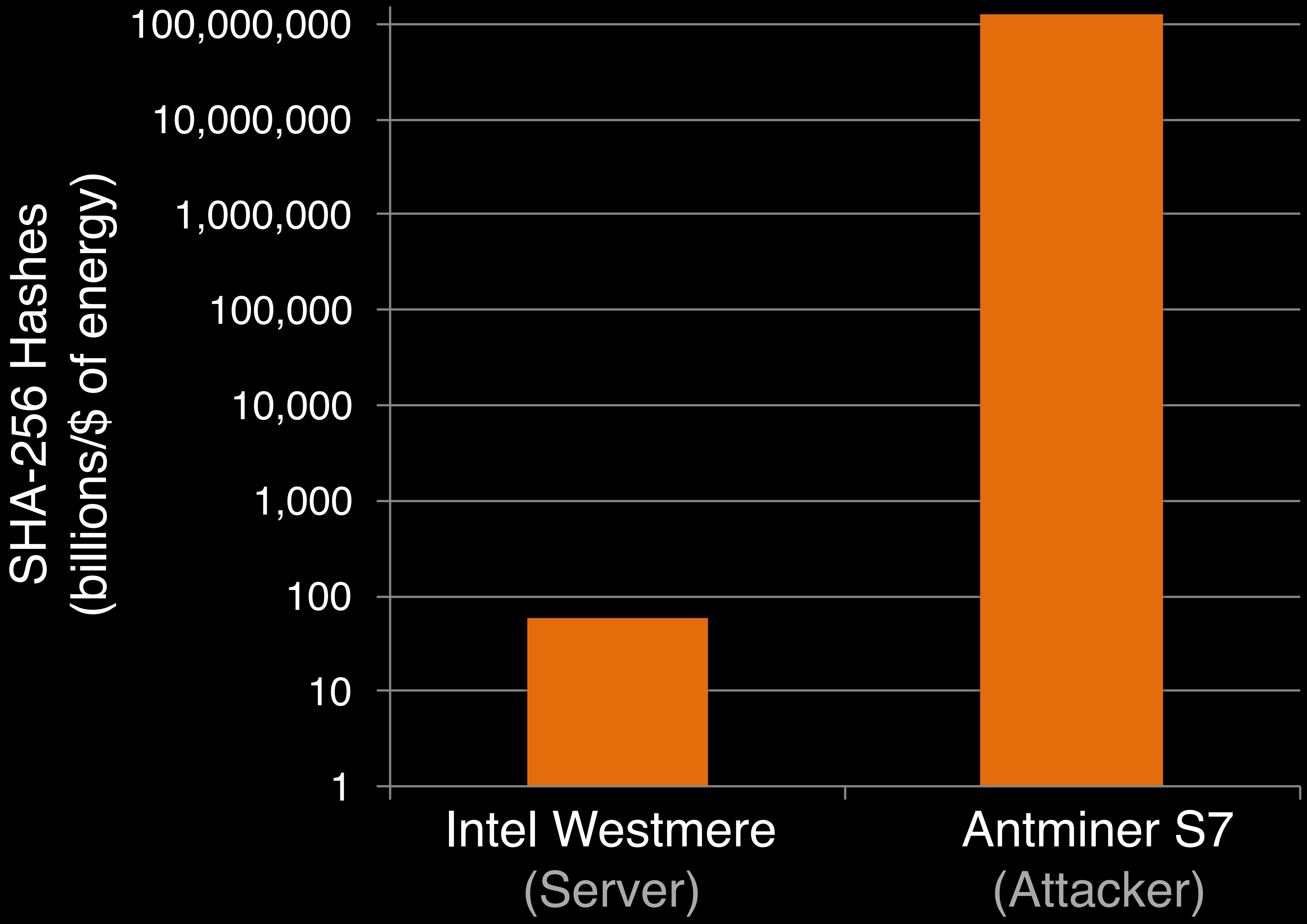
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(billions/$ of energy)
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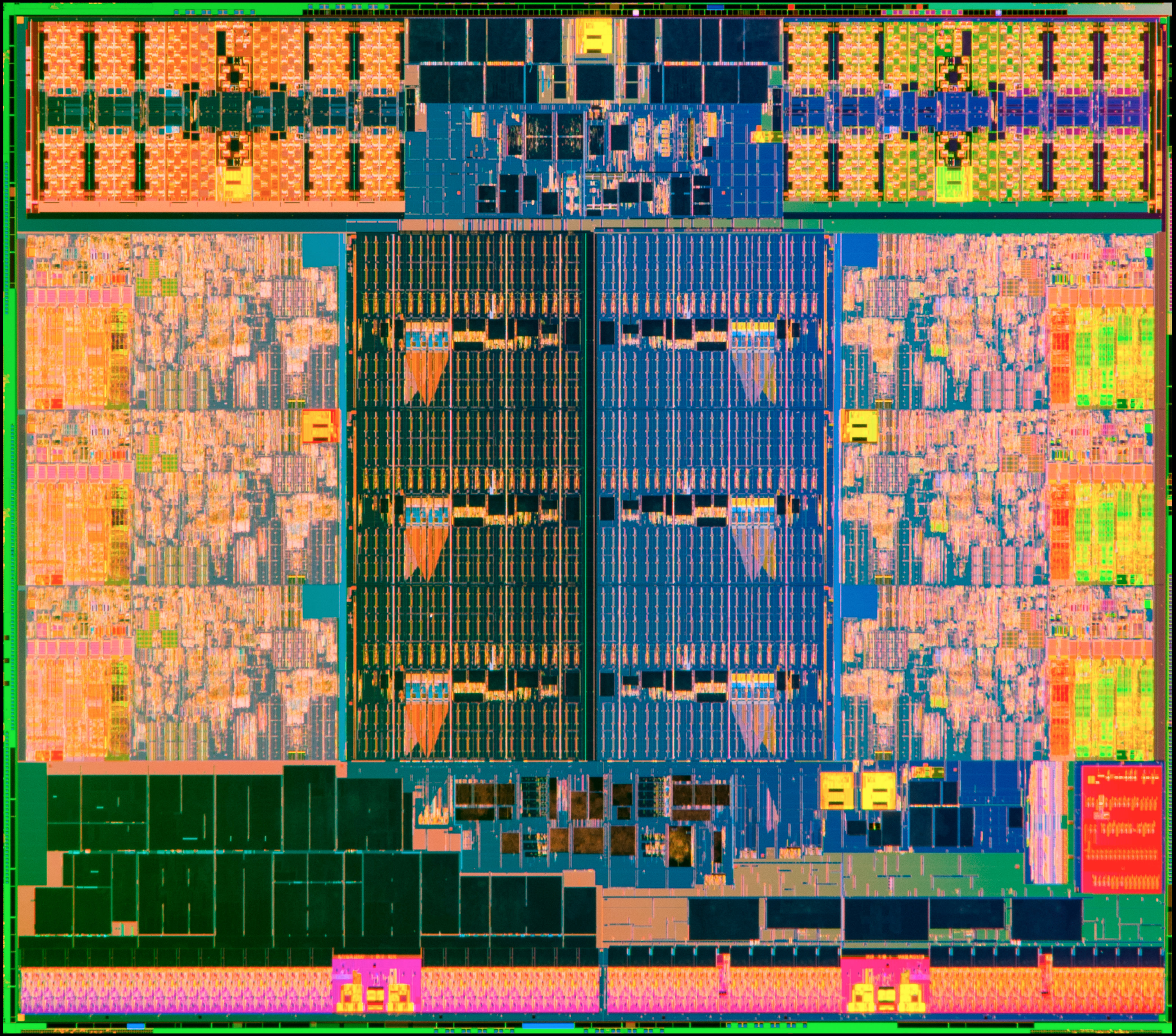
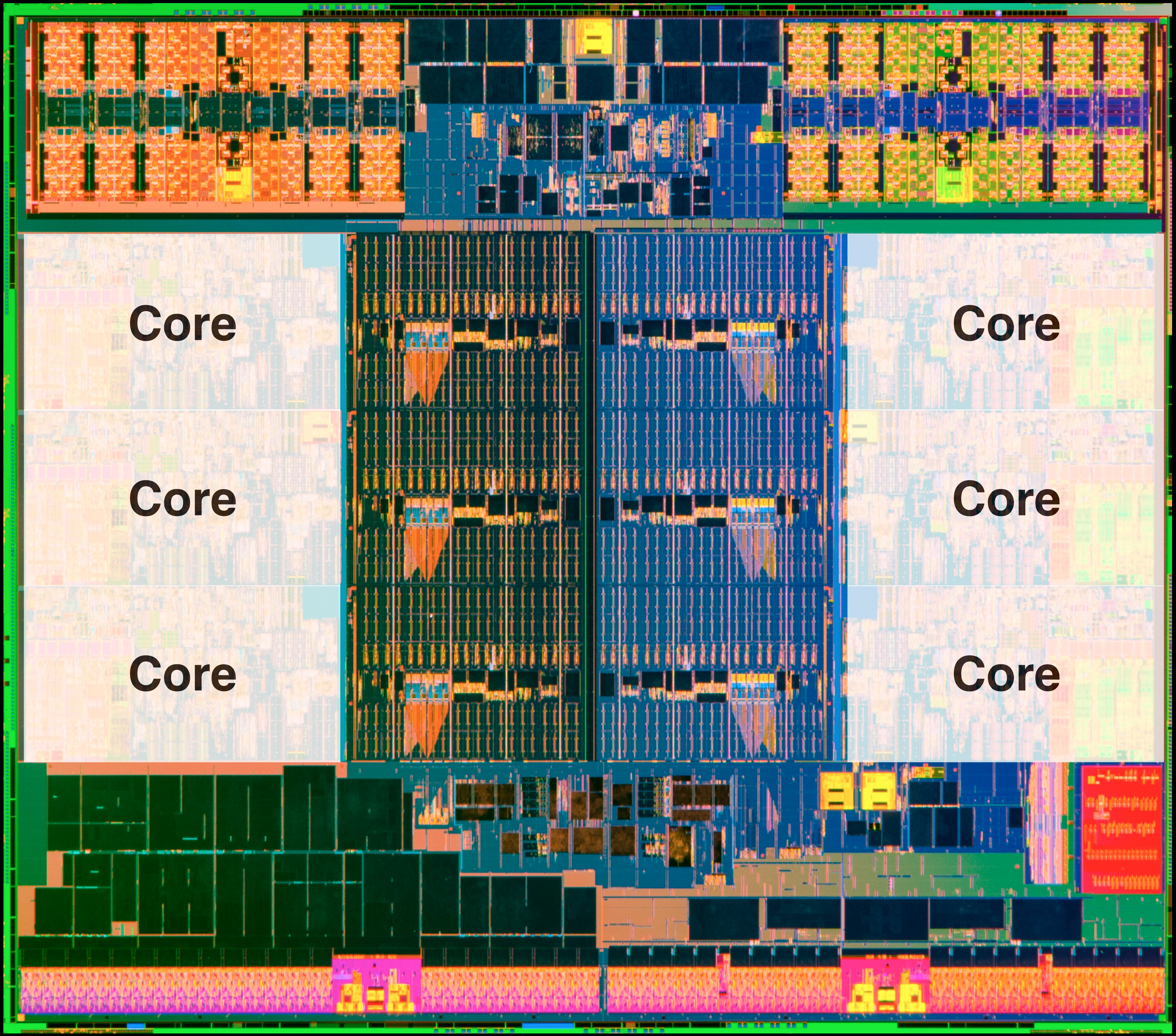


Intel Ivy Bridge-E Core i7-4960X
http://kylebennett.com/files/hfpics/IVB-E_%28LCC%29_Die_Wafer_Shot-7837.jpg



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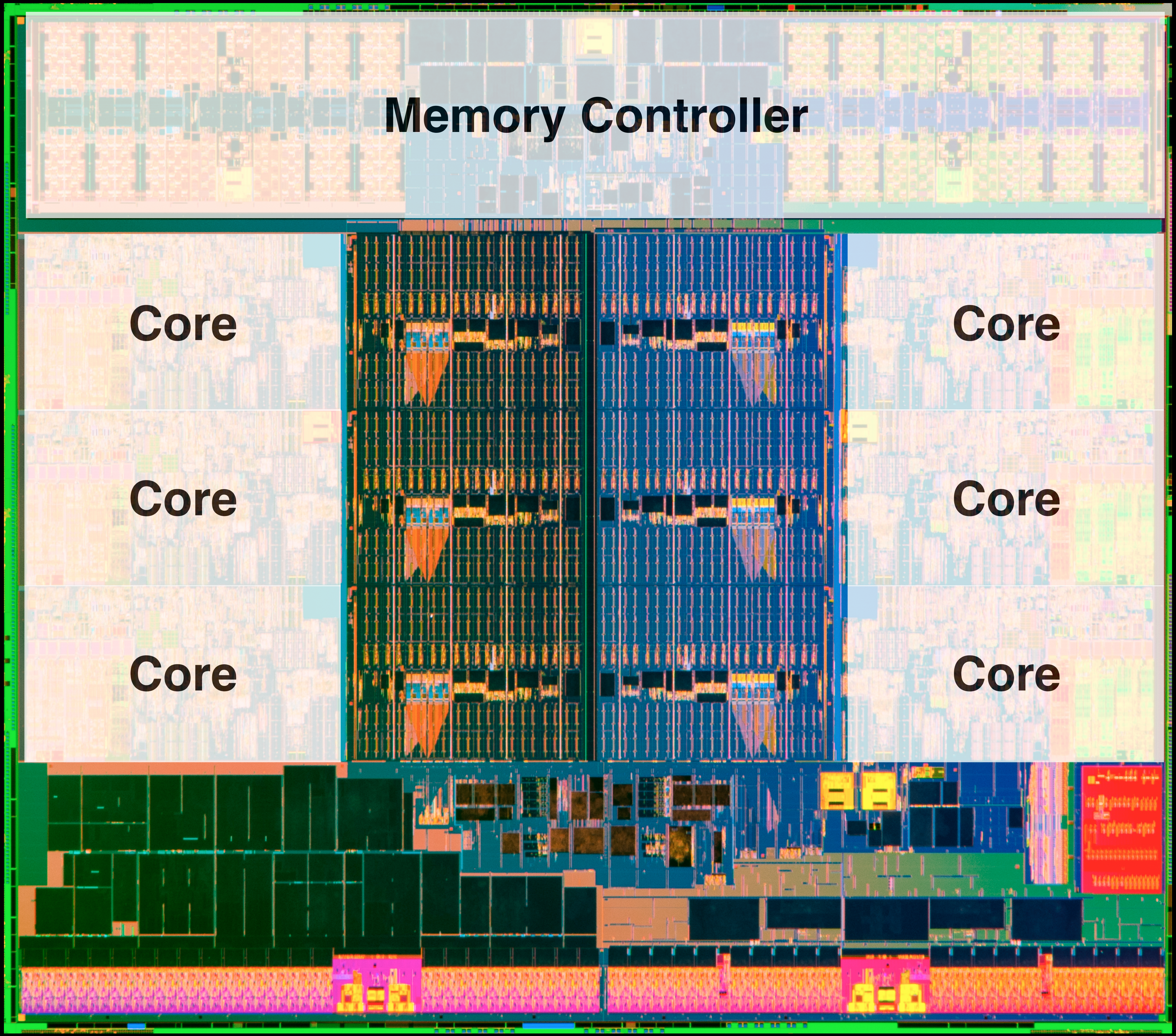

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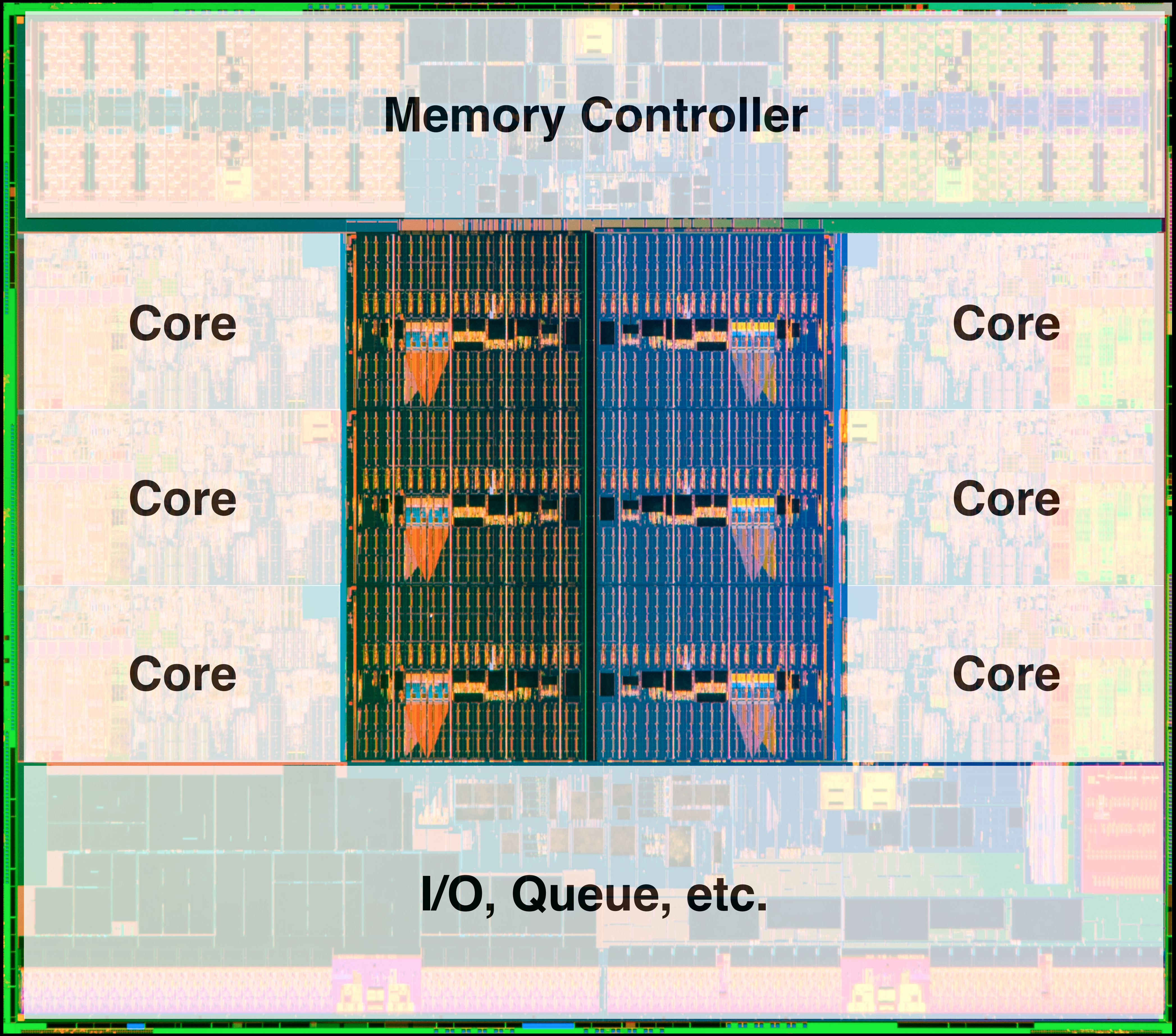

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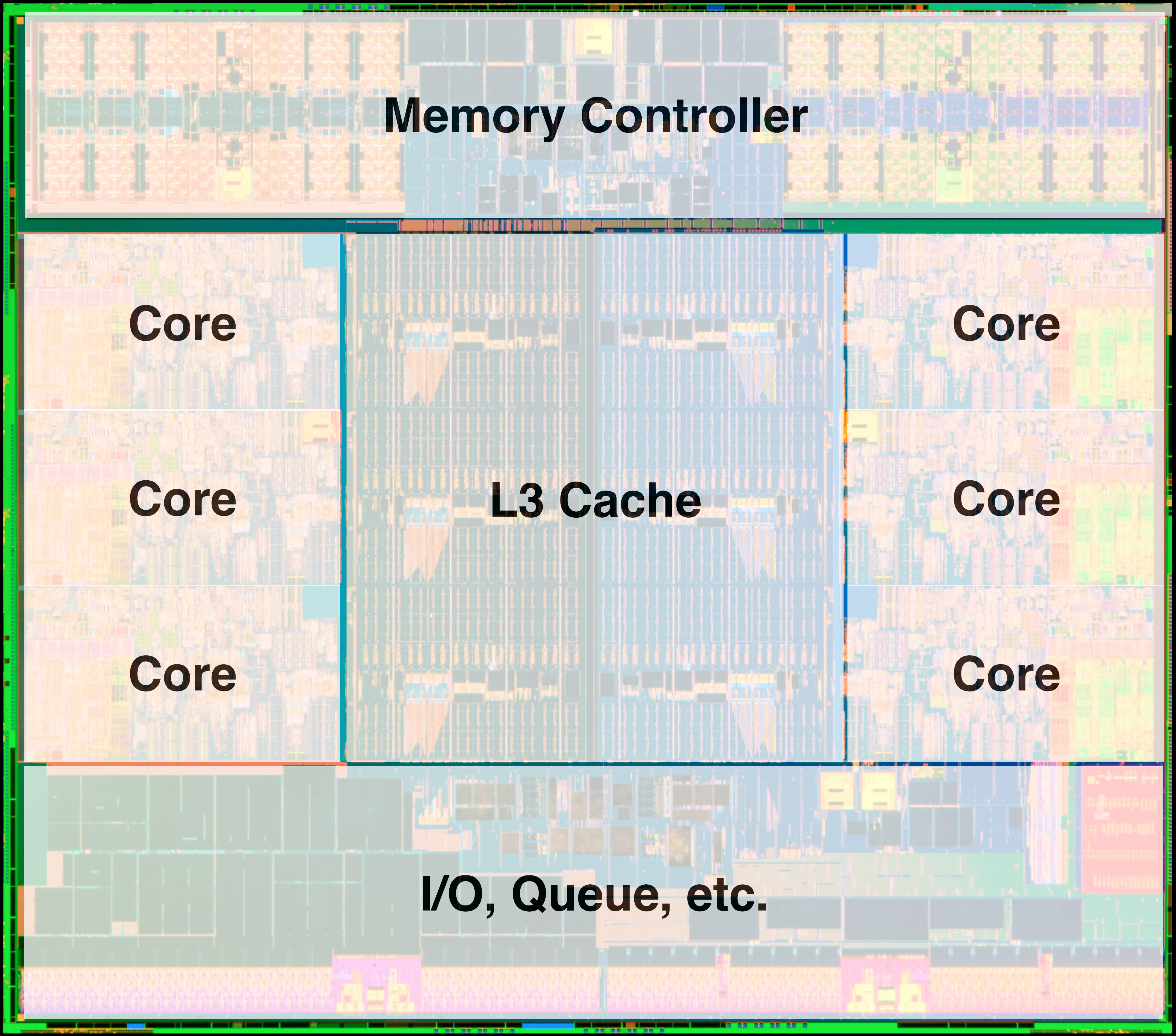

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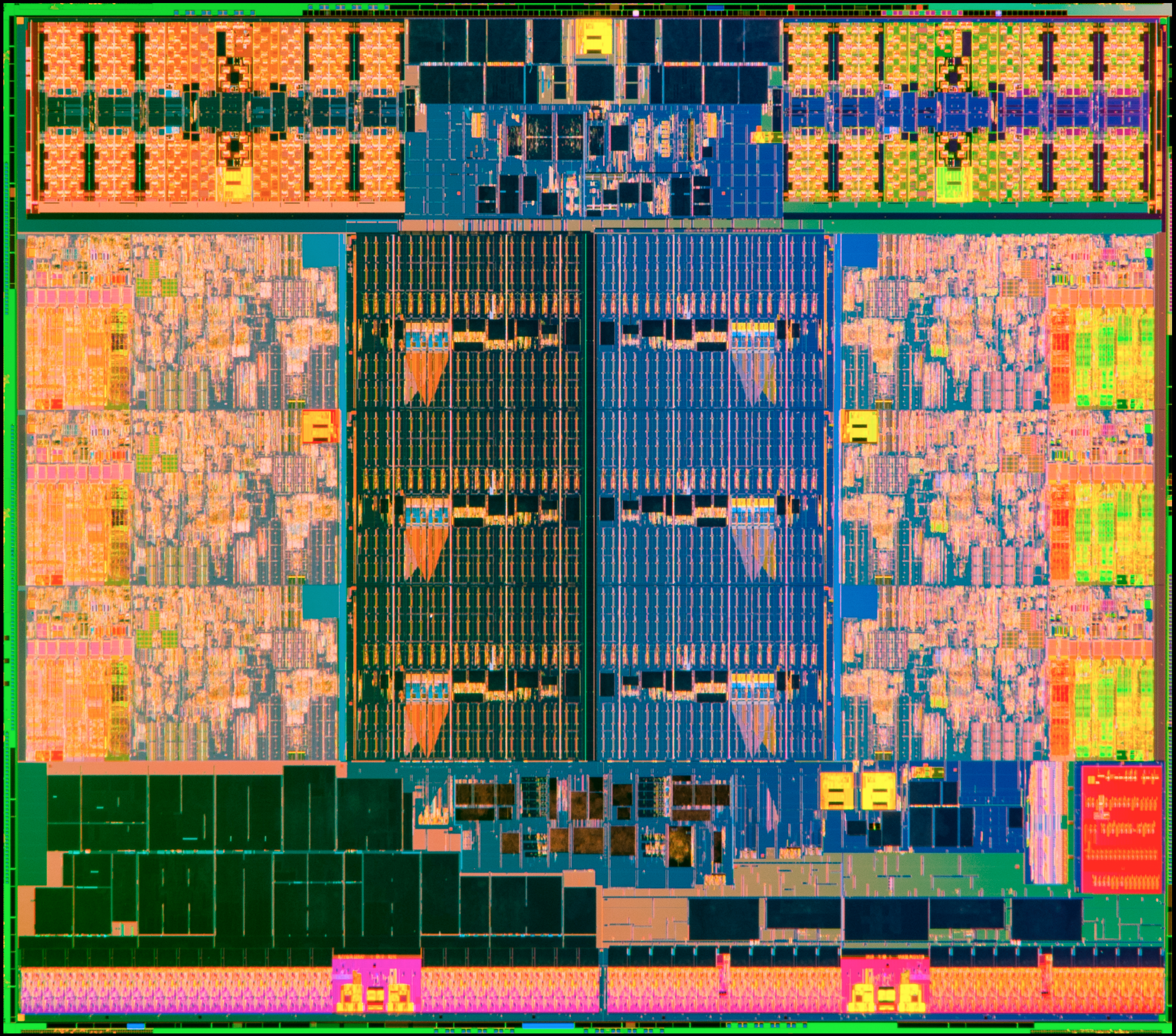

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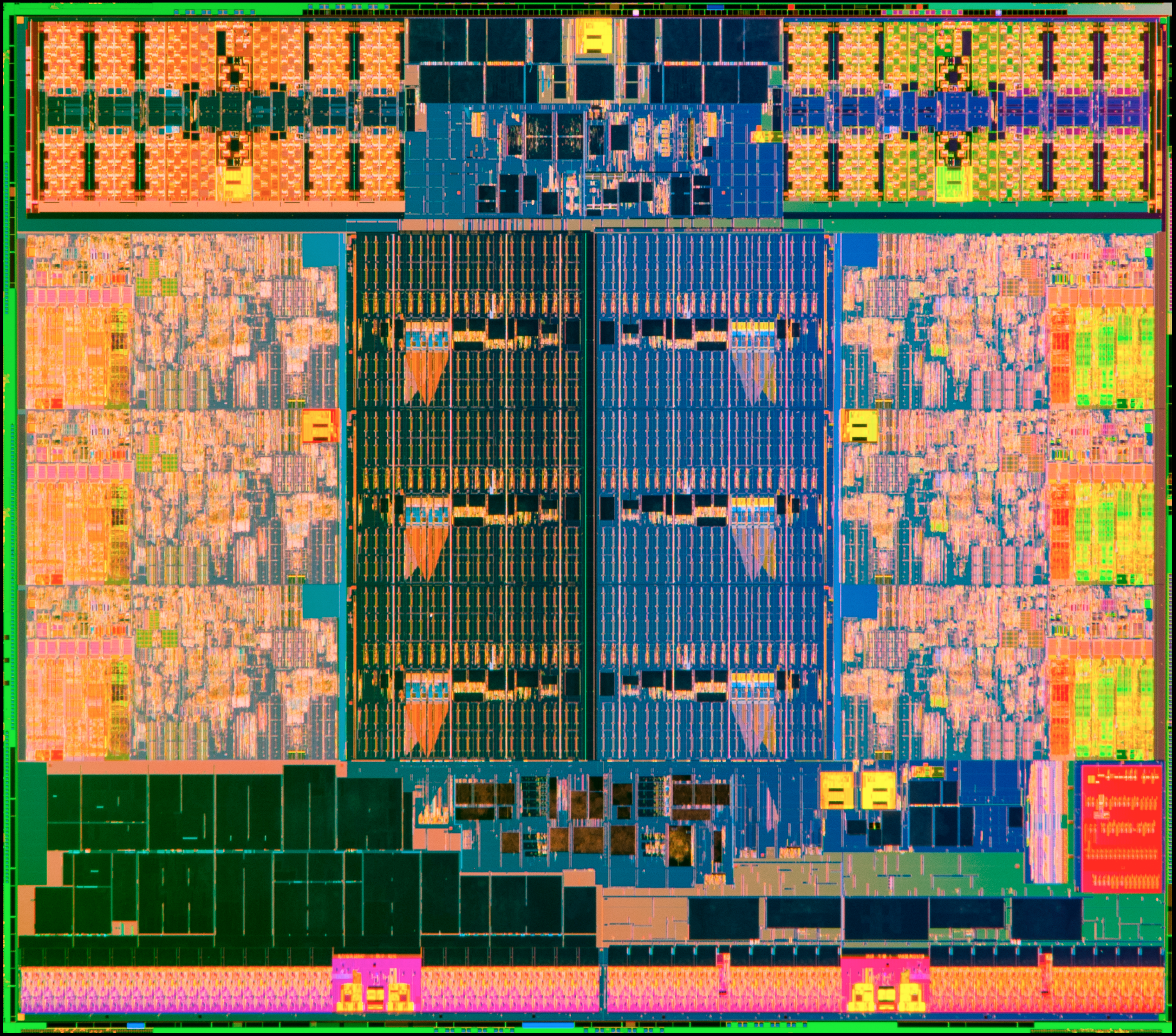

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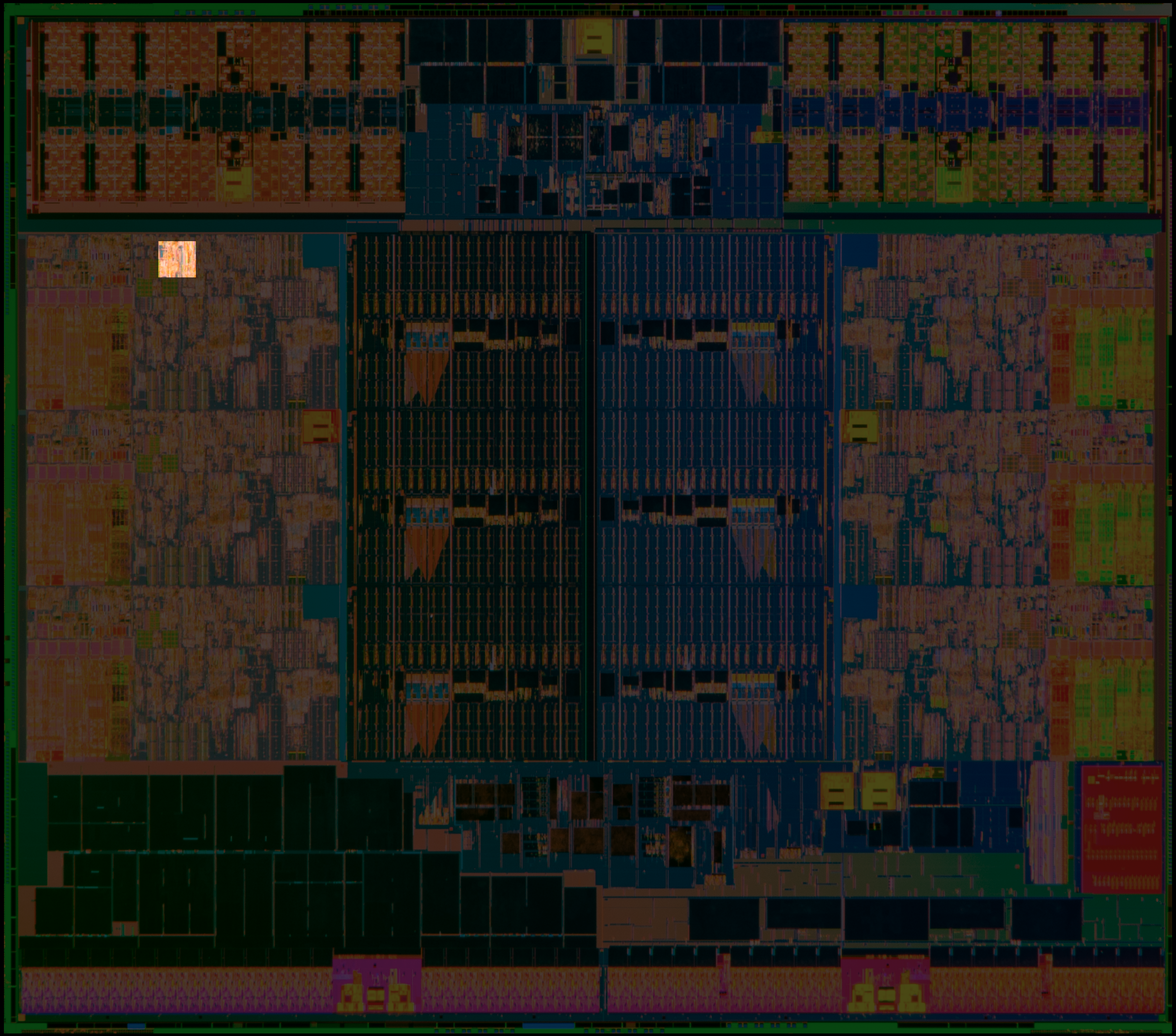

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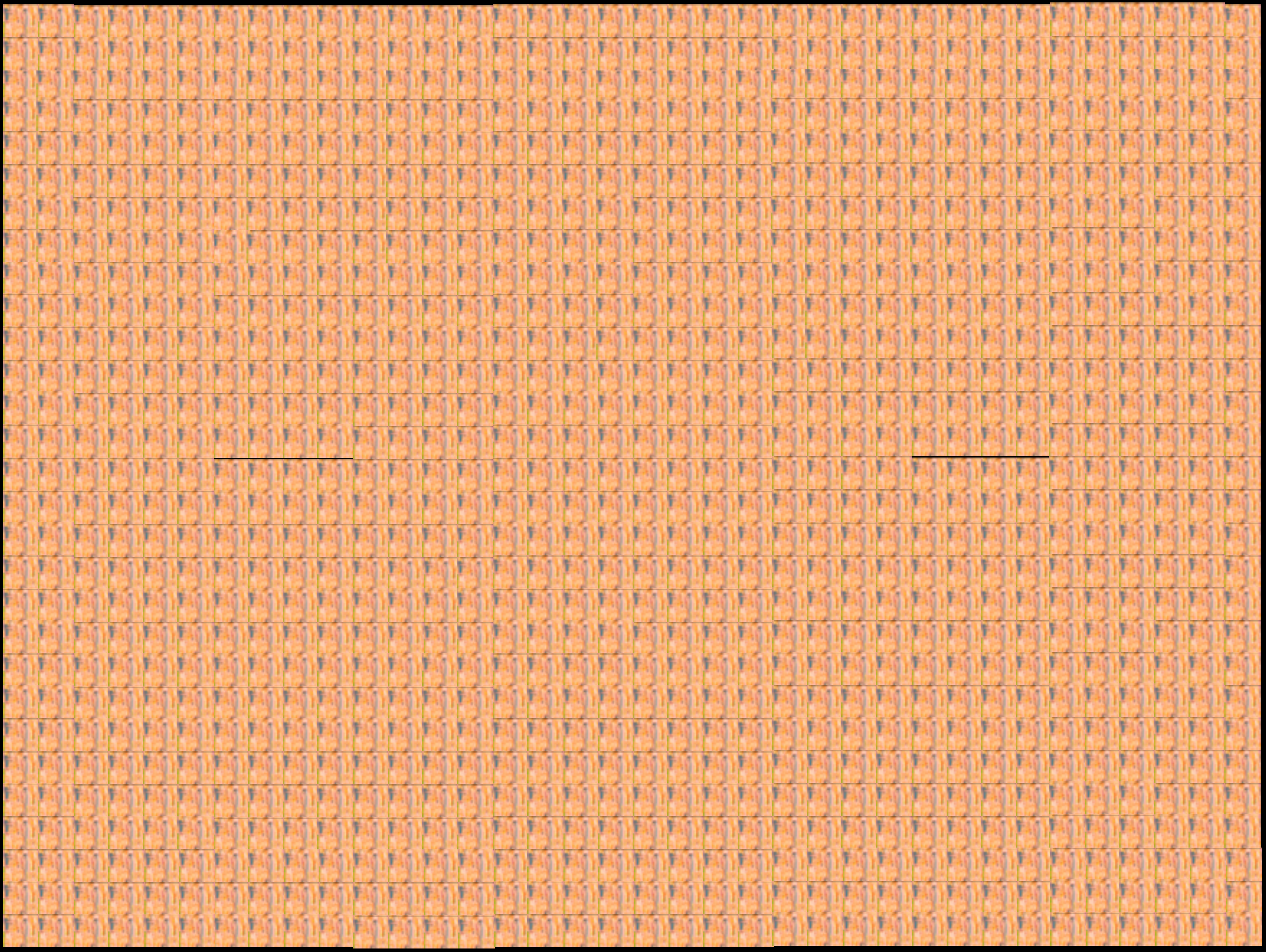
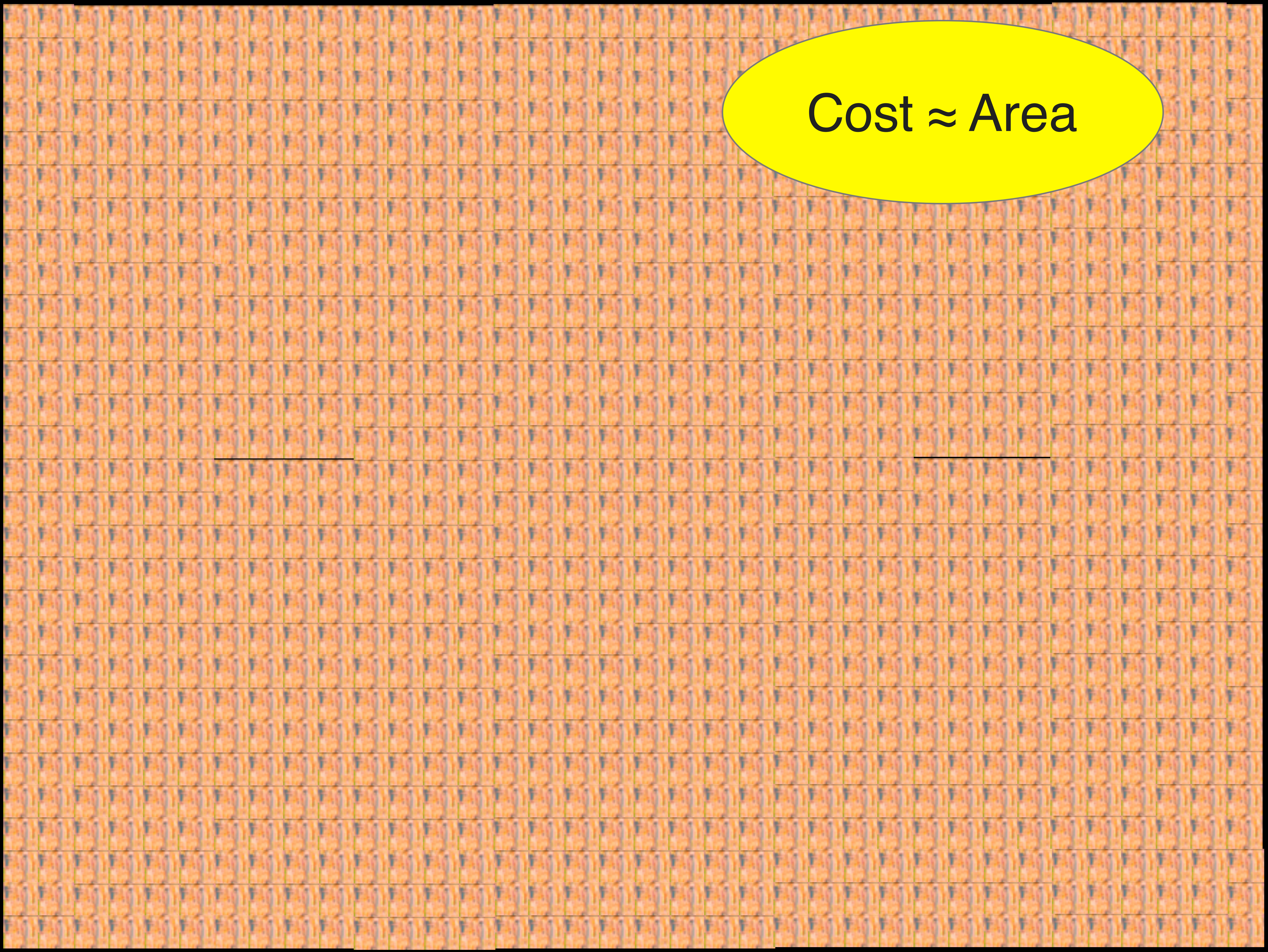
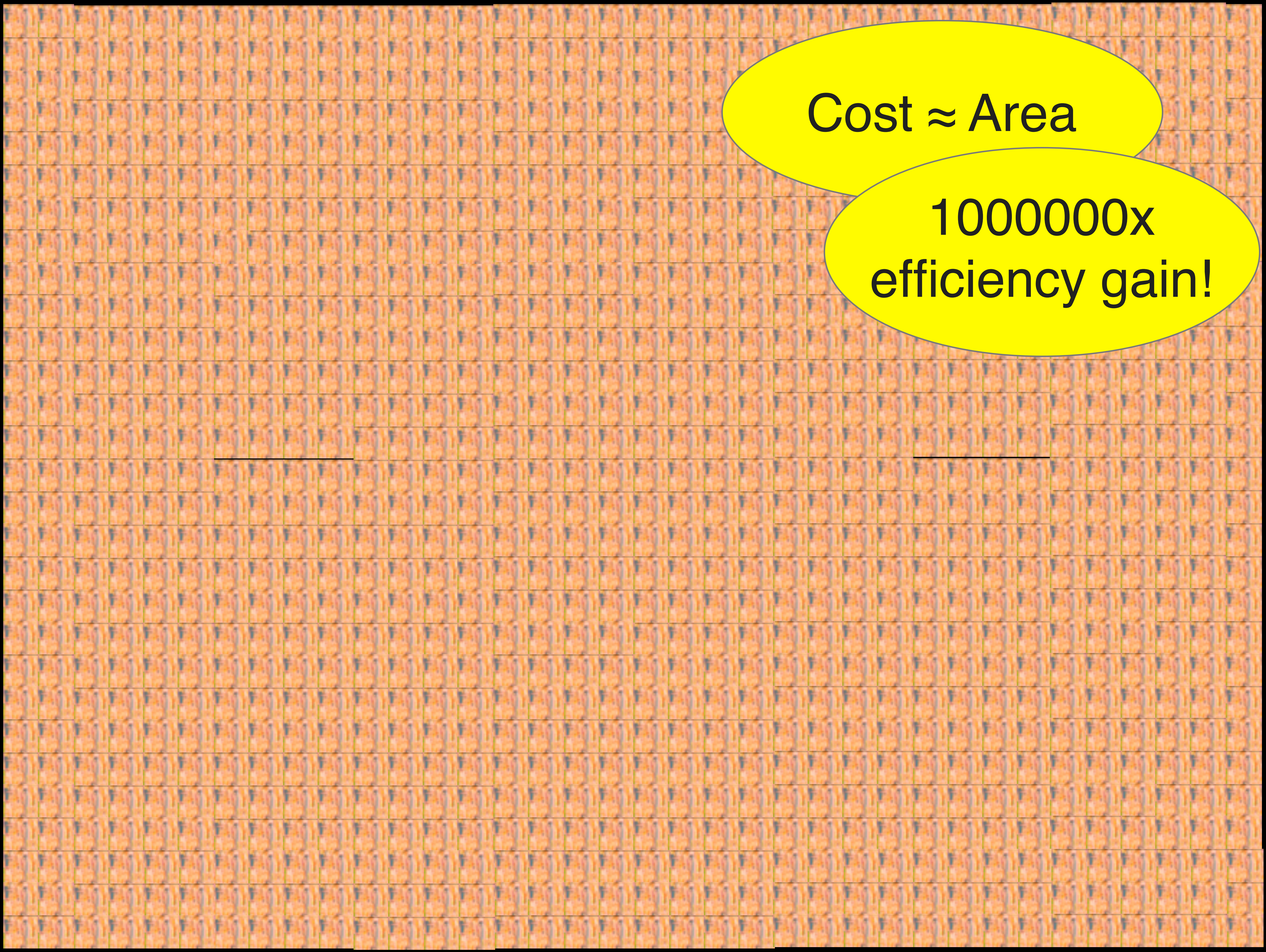


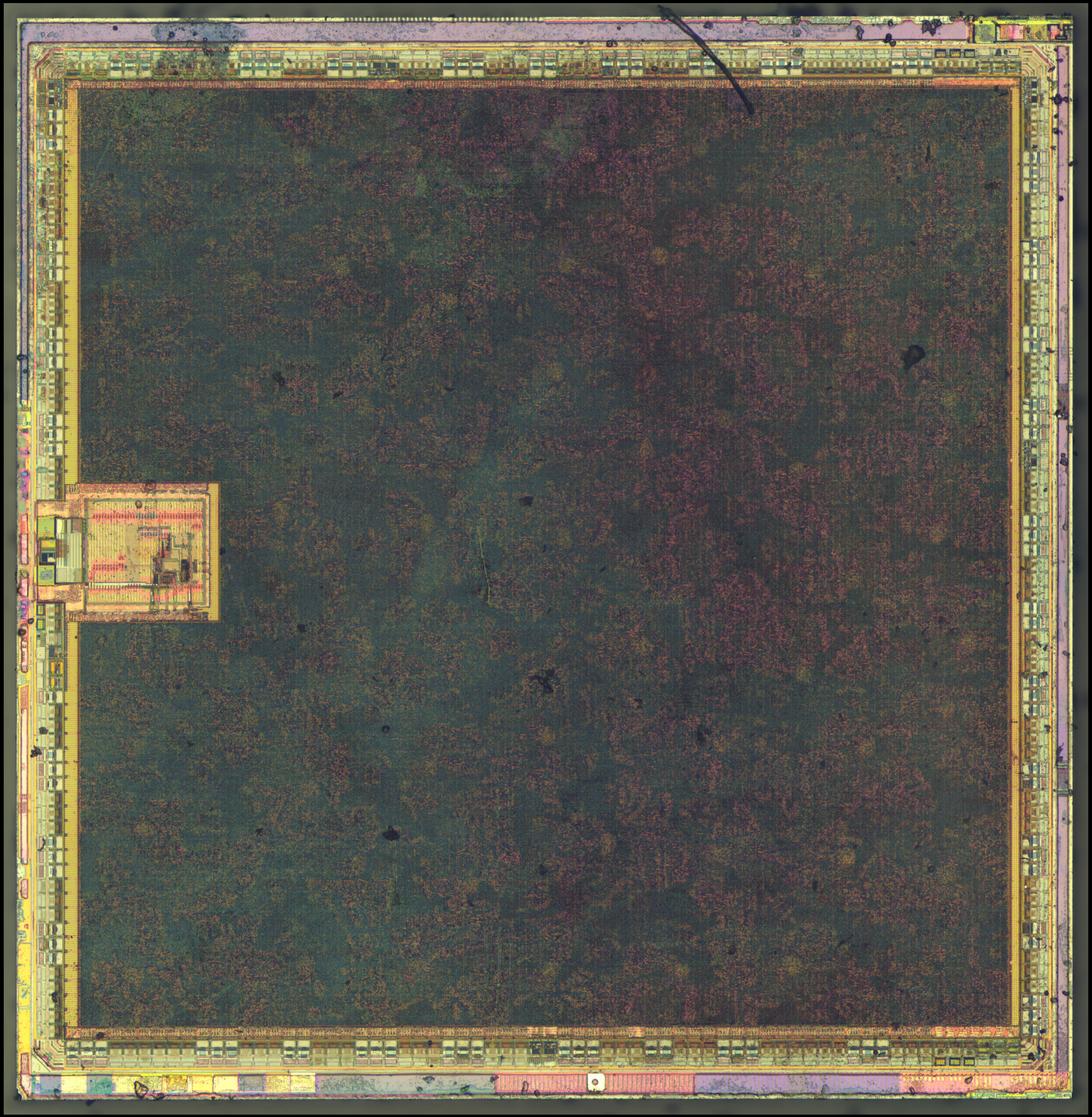


Cost ≈ Area



Cost ≈ Area

1000000x
efficiency gain!



“Avalon”
http://zeptobars.ru/en/read/avalon-bitcoin-mining-unit-rig

Memory-Hardness

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Memory-hard functions use a large amount of working space during their computation
→ Attacker must keep caches on chip
→ Decreases the advantage of special-purpose HW
[Reinhold 1999], [Dwork, Goldberg, Naor 2003], [Abadi et al. 2005], [Percival 2009]

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Typical technique:

1. **Fill** – fill buffer with pseudo-random bytes
2. **Mix** – read and write pseudo-random blocks in buffer
3. **Extract** – extract function output from buffer contents

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Without memory-hardness

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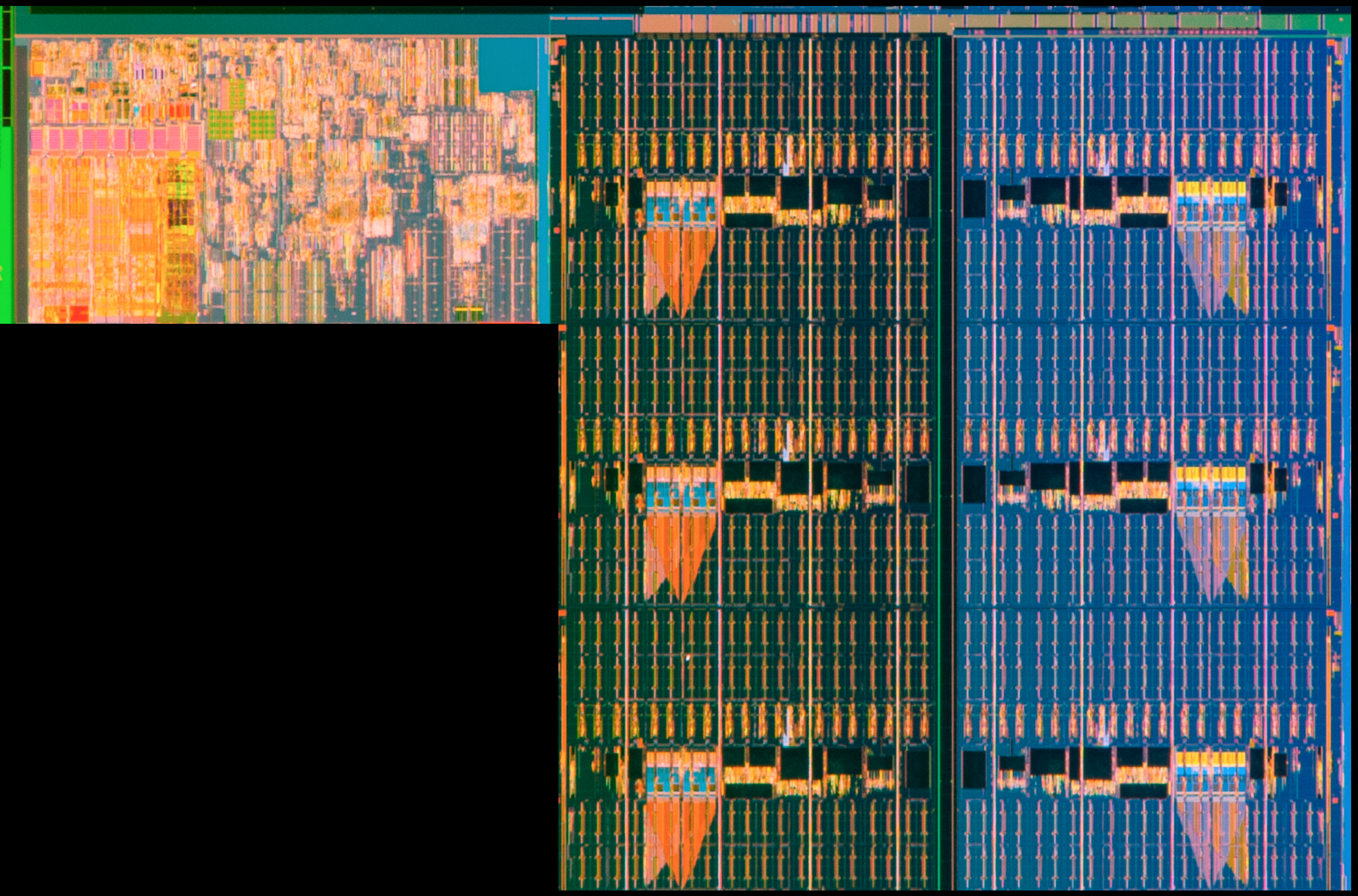

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Plan

I. Background on password hashing

II. Goals

III. The Balloon algorithm

IV. Discussion

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Goal 1: Memory-Hardness

Random oracles: [Bellare & Rogaway 1993]

Memory-hard functions: [Abadi et al. 2005] [Percival 2009]

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Informally, a memory-hard function, with hardness parameter N, requires space *S* and time *T* to compute, where

$$S \cdot T \in \Omega(N^2)$$

in the random-oracle model.

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Informally, a memory-hard function, with hardness parameter N, requires space S and time T to compute, where

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in the random-oracle model.

Intuition: any adversary who tries to save space will pay a large penalty in computation time.

Random oracles: [Bellare & Rogaway 1993]
Memory-hard functions: [Abadi et al. 2005] [Percival 2009]

Goal 2: Side-Channel Resistance

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- The memory access pattern should not leak information about the password being hashed
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Goal 3: Real-World Practical

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Goal 3: Real-World Practical

- The hash should be able to support hundreds of logins per second while filling L2 cache (or more)

Existing Schemes

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bcrypt, PBKDF2 [Provos & Mazières 1999], [Kaliski 2000]

Not memory hard

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Parallel-secure schemes [Alwen & Serbinenko 2015] [Alwen, Blocki, Pietrzak 2016]

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Argon2i and Catena [Biryukov et al. 2015] [Forler et al. 2015]

Lack formal security analysis

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We demonstrate a practical attack against Argon2i

Argon2i and Catena [Biryukov et al. 2015] [Forler et al. 2015]

Lack formal security analysis

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```
Balloon(password, salt, N = space_cost, R = num_rounds):
    $\delta \leftarrow 3$                  // A security parameter.
    var $B_1, \dots, B_N$            // A buffer of N blocks.

    // Step 1: Fill Buffer
    $B_1 \leftarrow$ Hash(password, salt)
    for i = 2, …, N:
        $B_i \leftarrow$ Hash($B_{i-1}$)

    // Step 2: Mix Buffer
    for r = 1, …, R:
        for i = 1,…, N:
            // Chosen pseudorandomly from salt
            $(v_1, \dots, v_\delta) \leftarrow$ Hash( salt, r, i ) $\in Z_N^\delta$
            $B_i \leftarrow$ Hash($B_{(i-1 \bmod N)}, B_i, B_{v_1}, \dots, B_{v_\delta}$)

    // Step 3: Extract
    return $B_N$
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A conventional hash function (e.g., SHA-256)

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Balloon Hashing Algorithm

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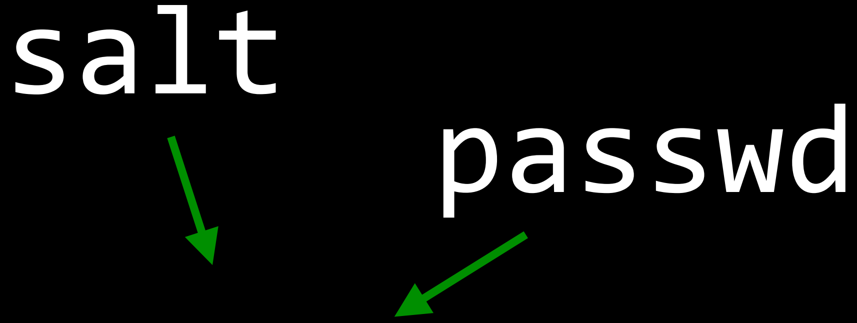
```
salt
         passwd
```

Balloon Hashing Algorithm



salt

passwd

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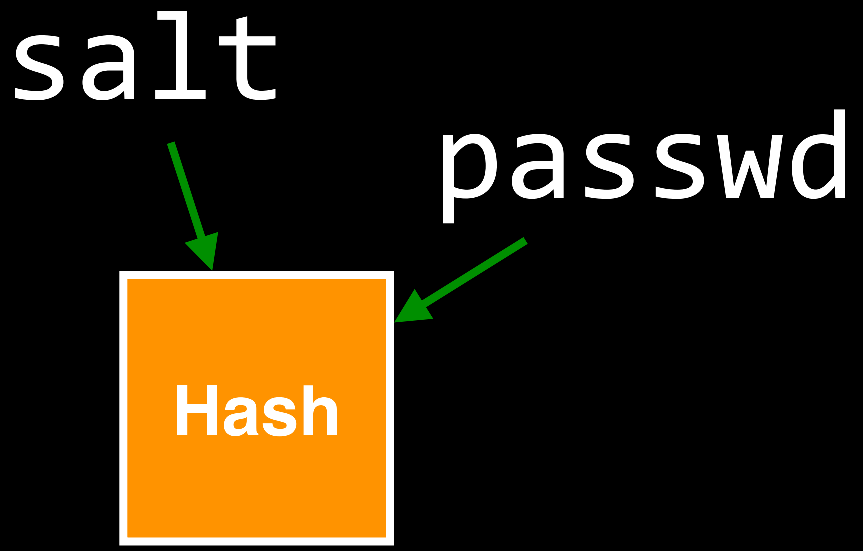

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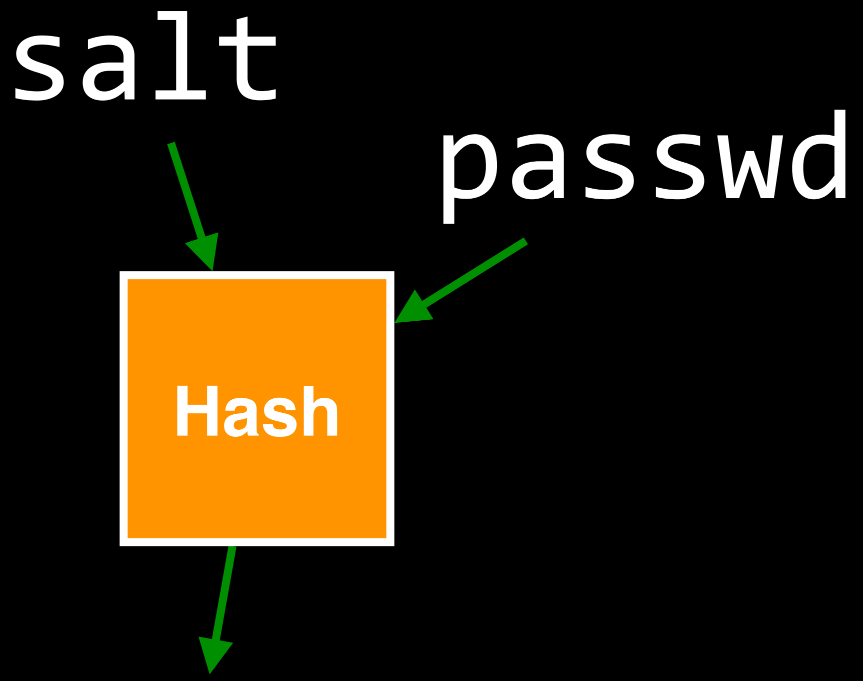

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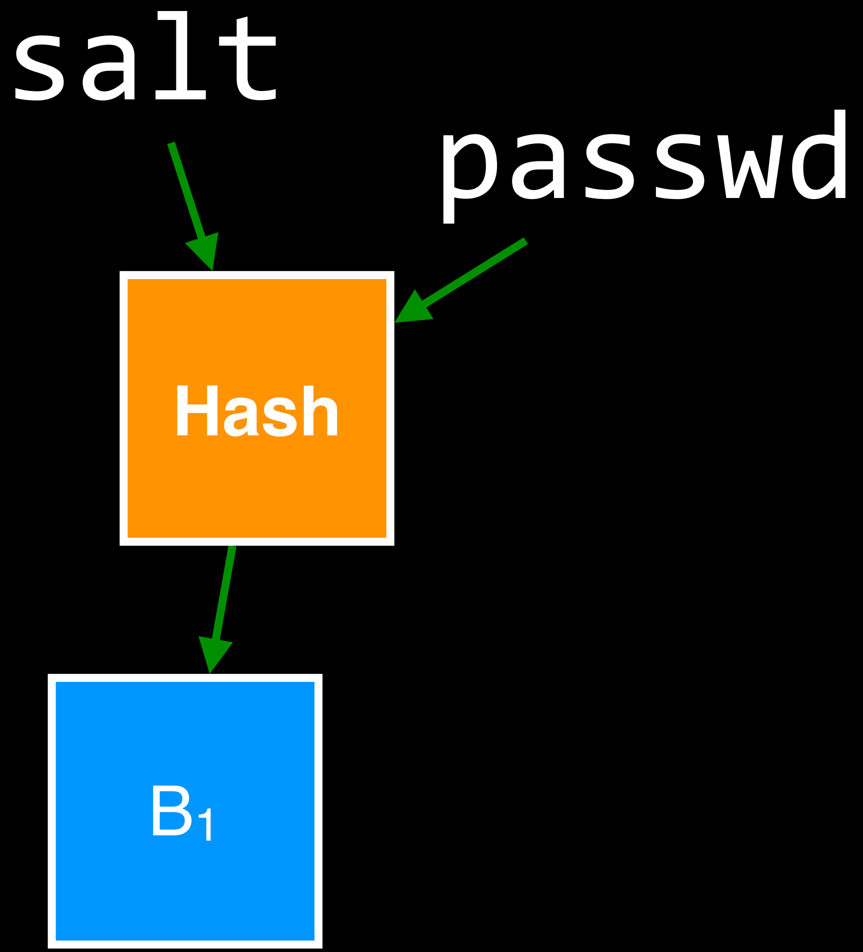

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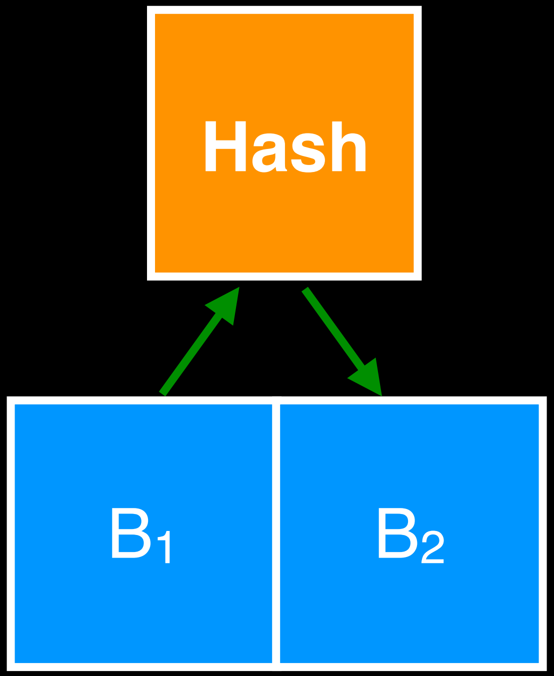

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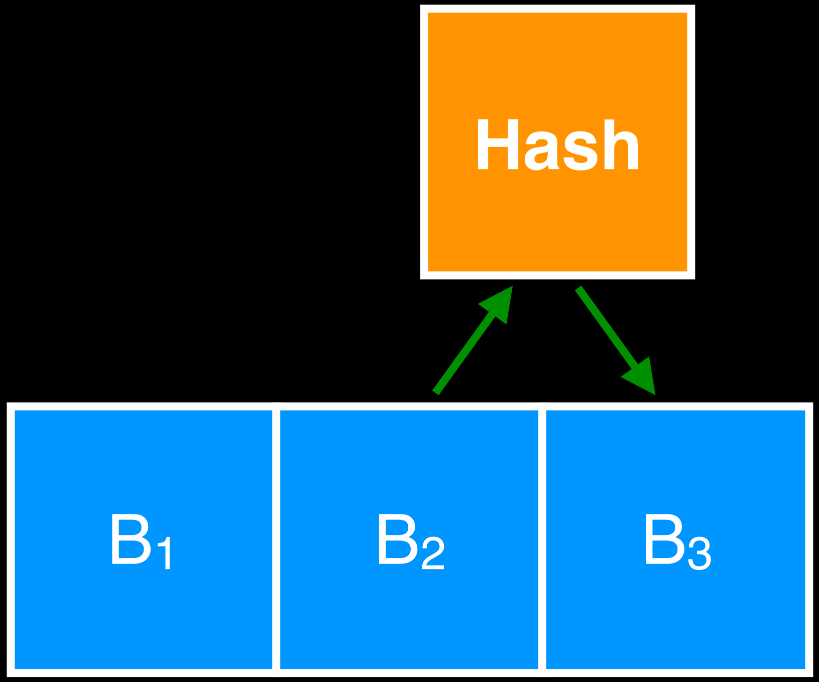

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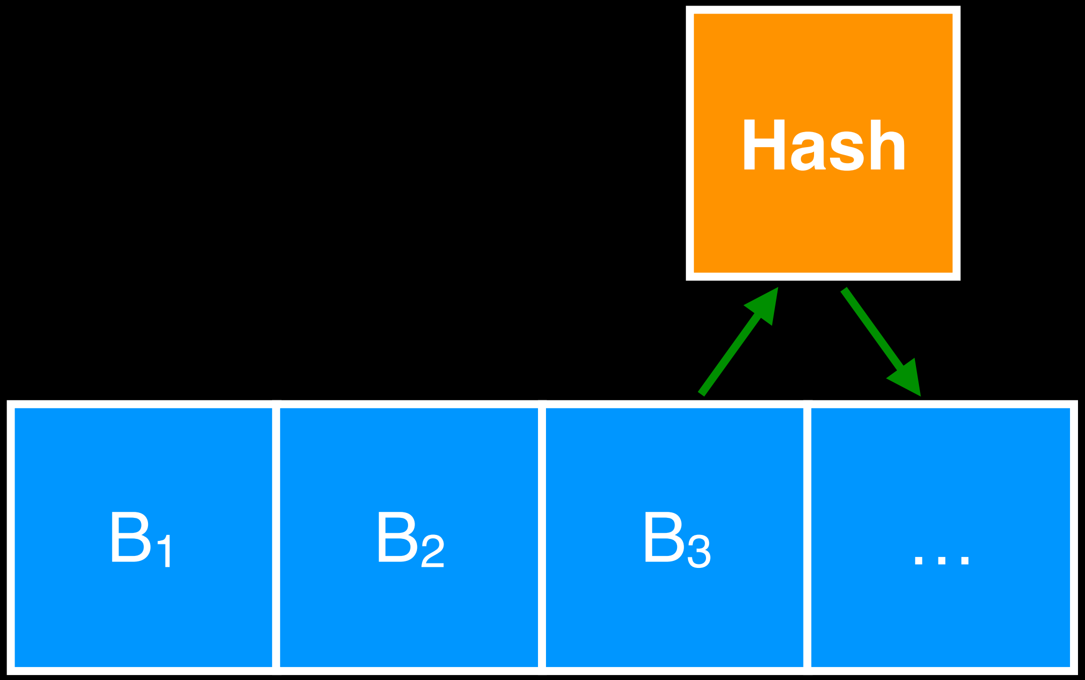

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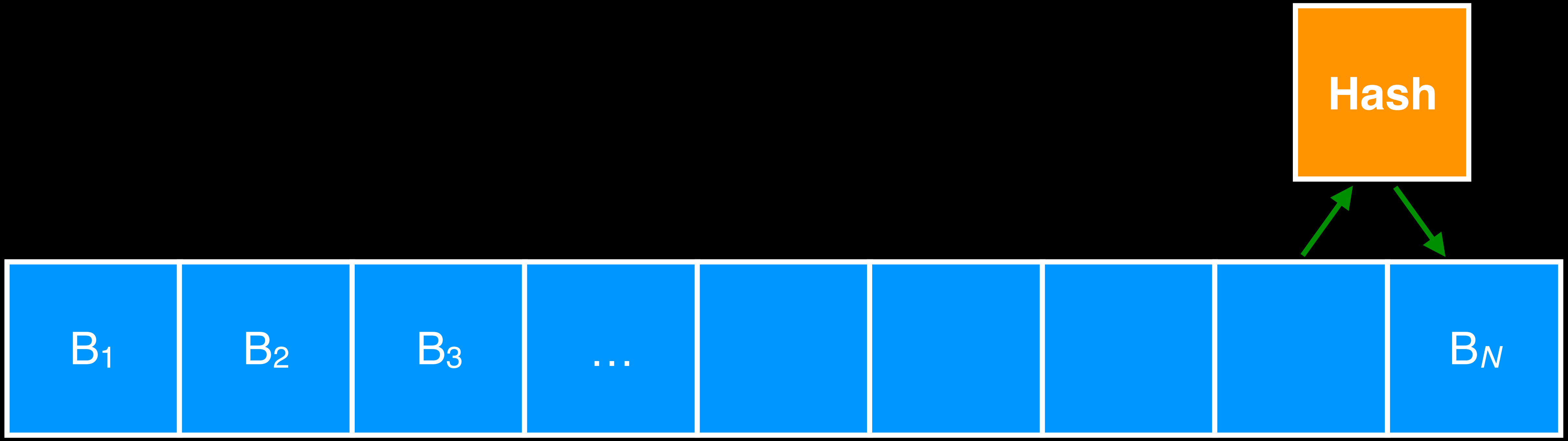

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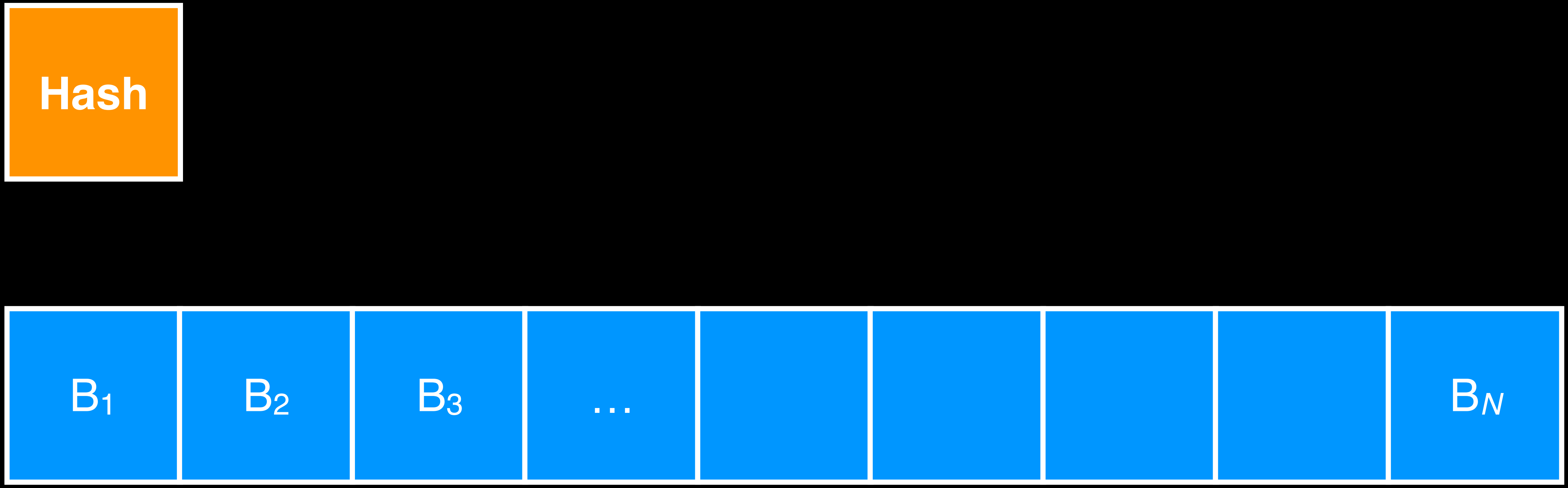
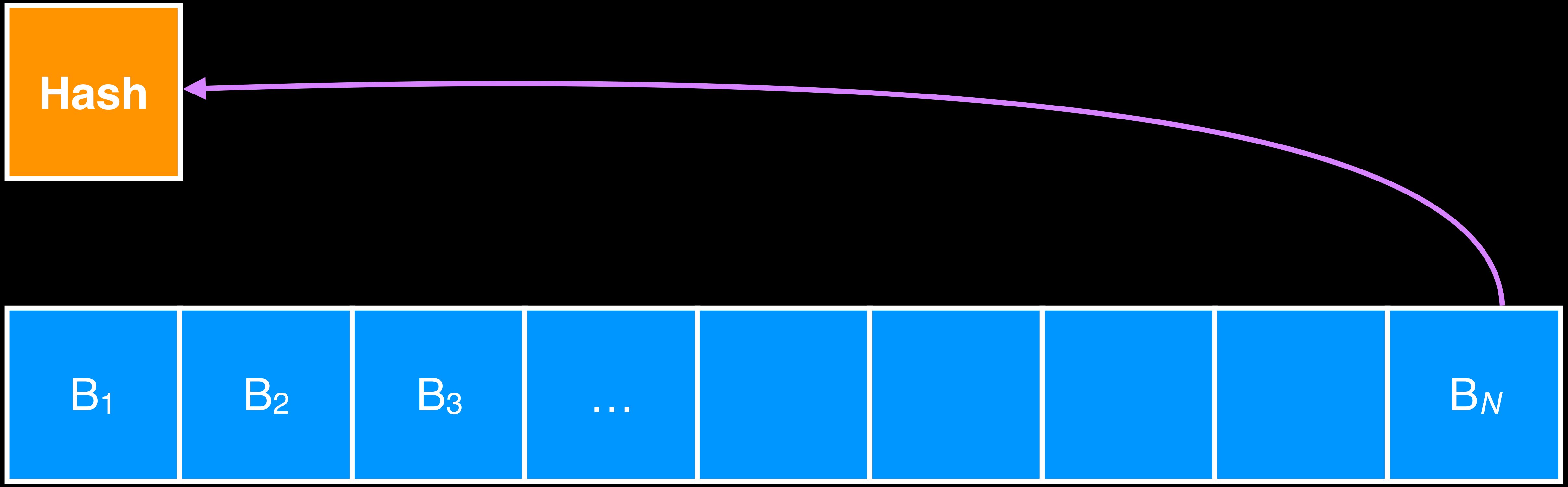


Hash

B_1 B_2 B_3 … B_N

Balloon Hashing Algorithm



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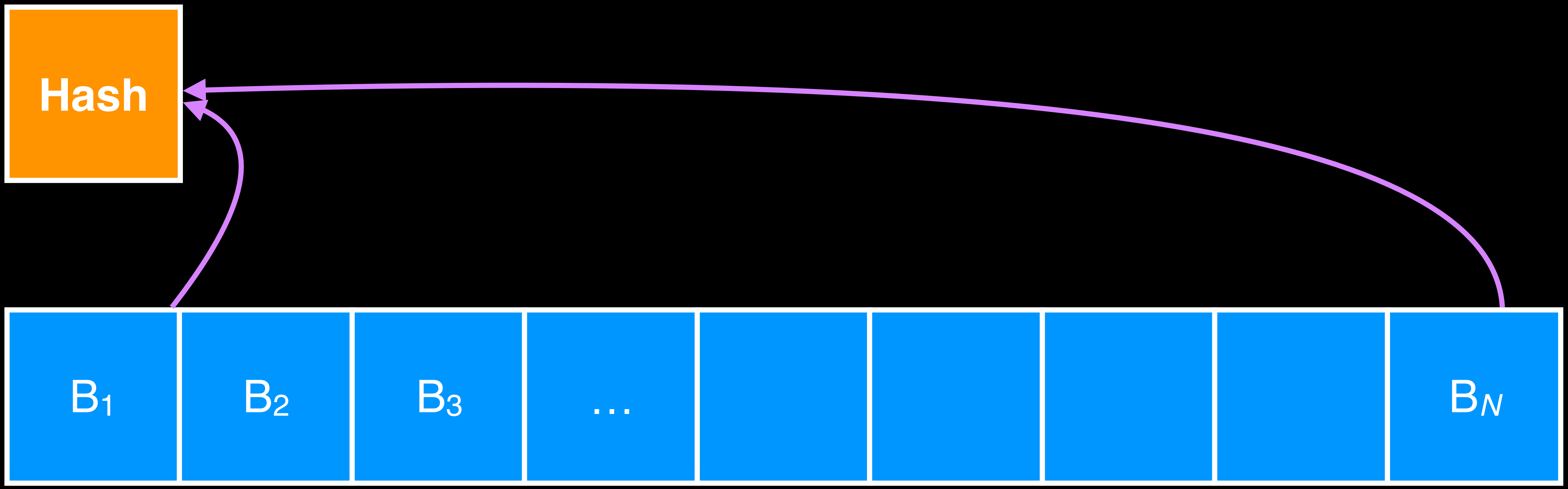

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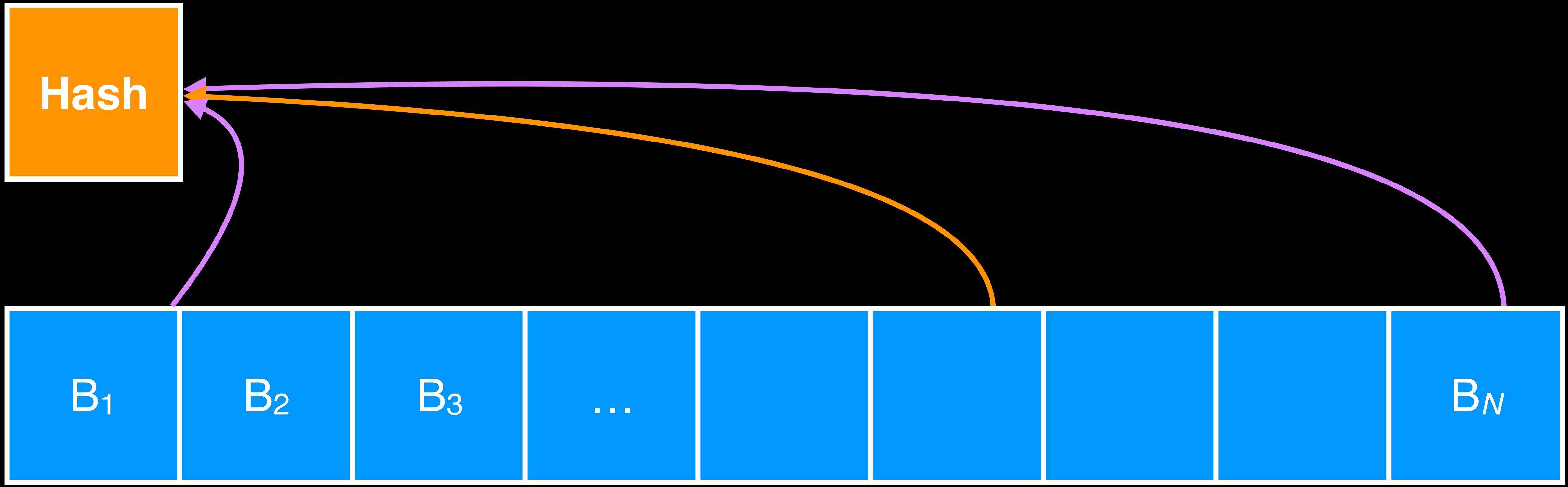

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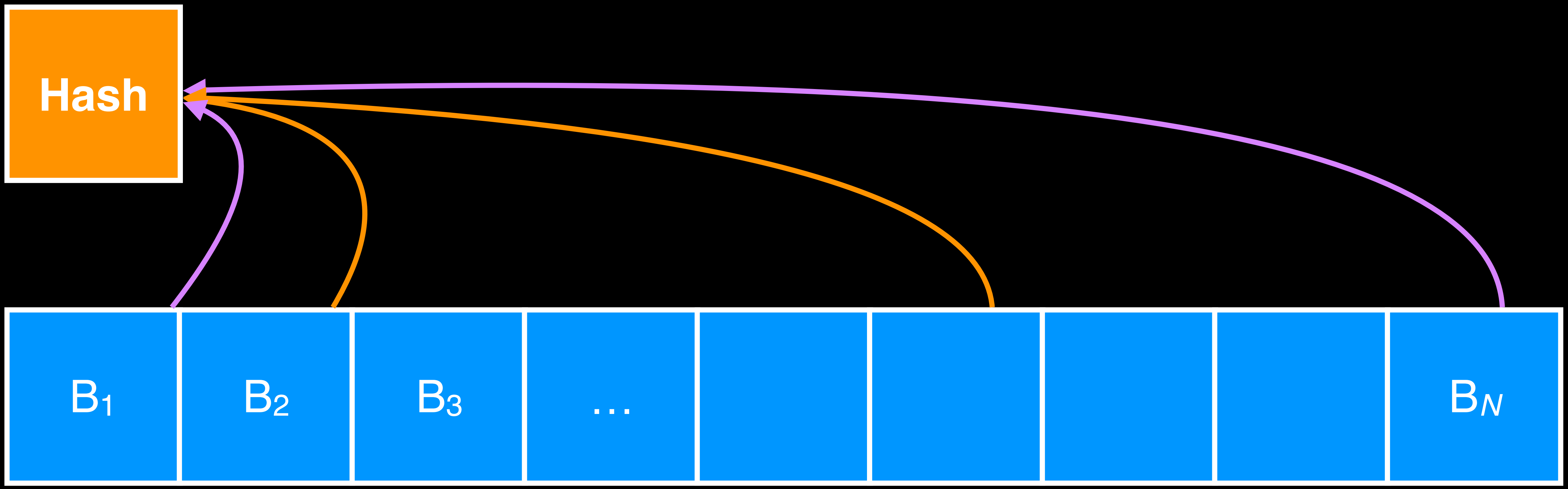

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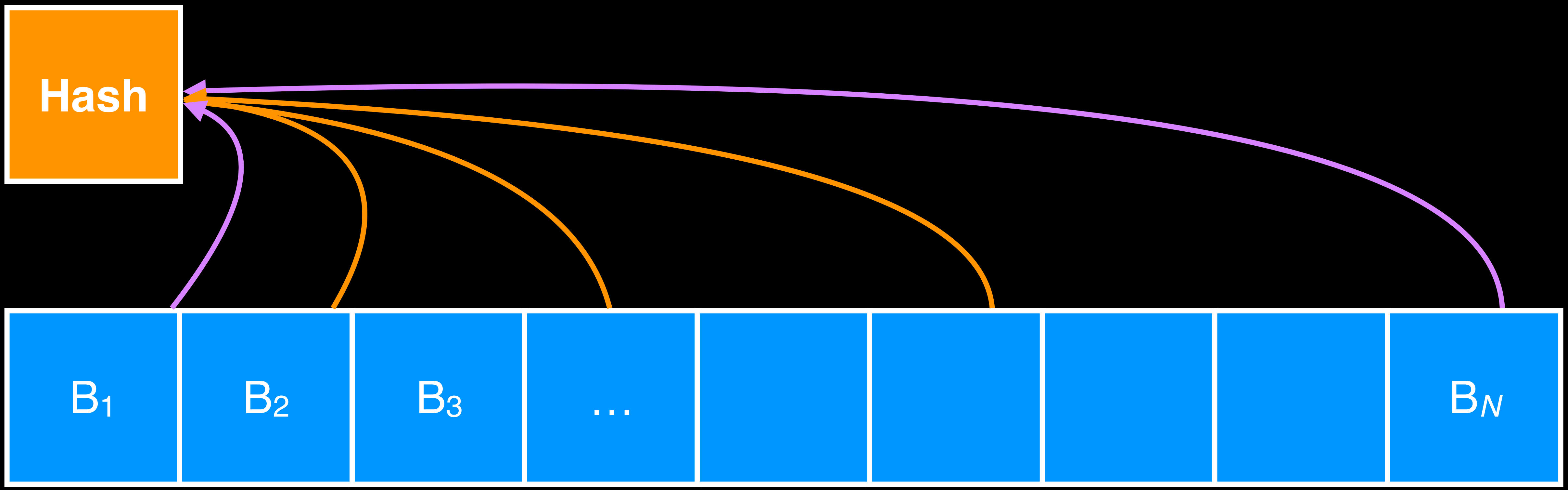

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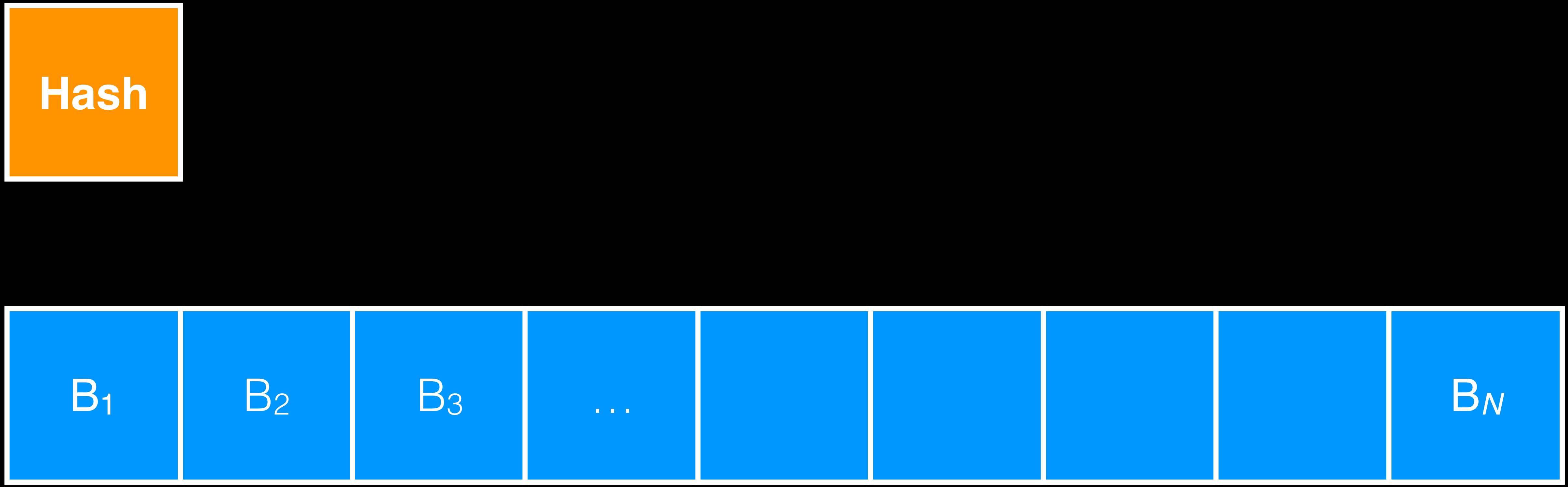

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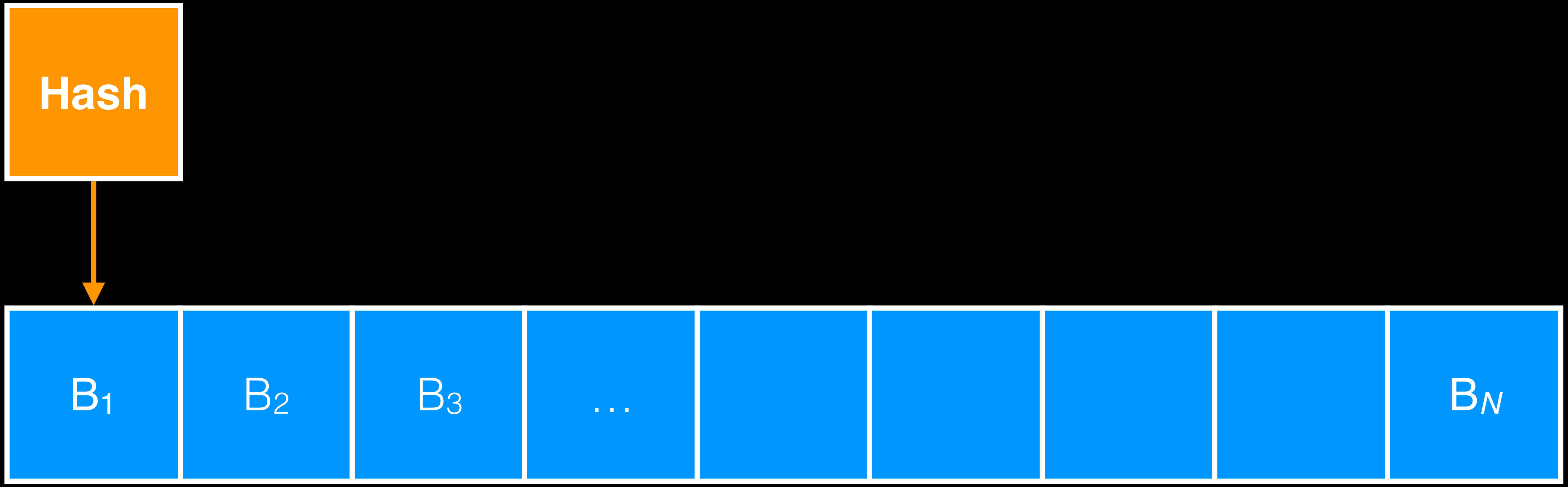

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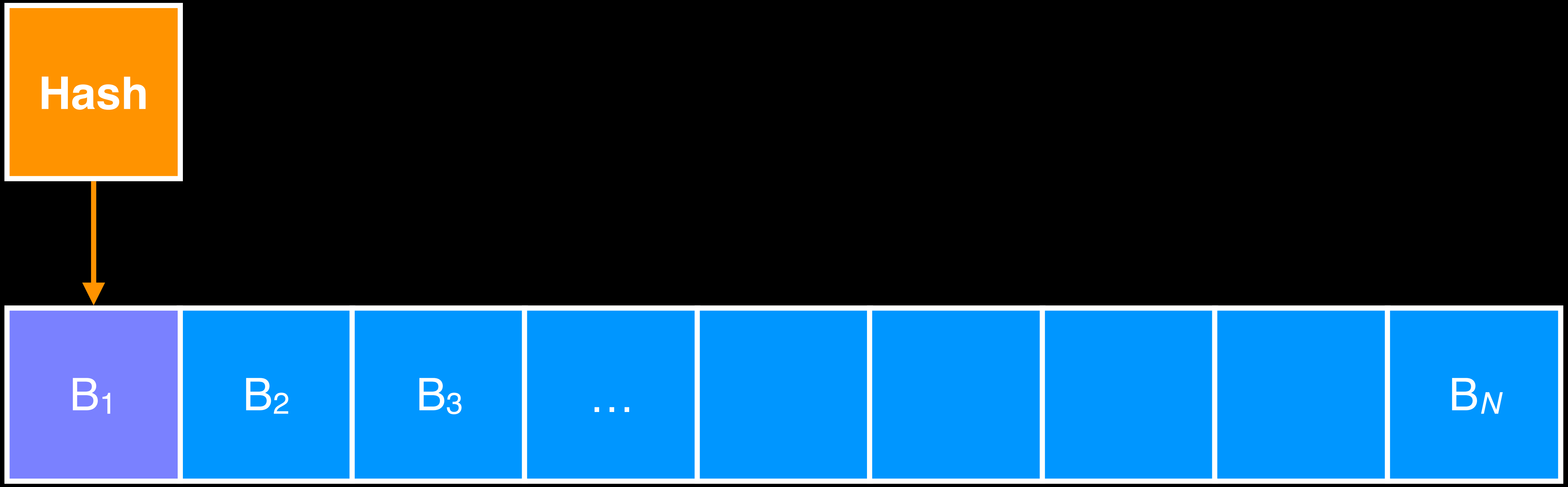

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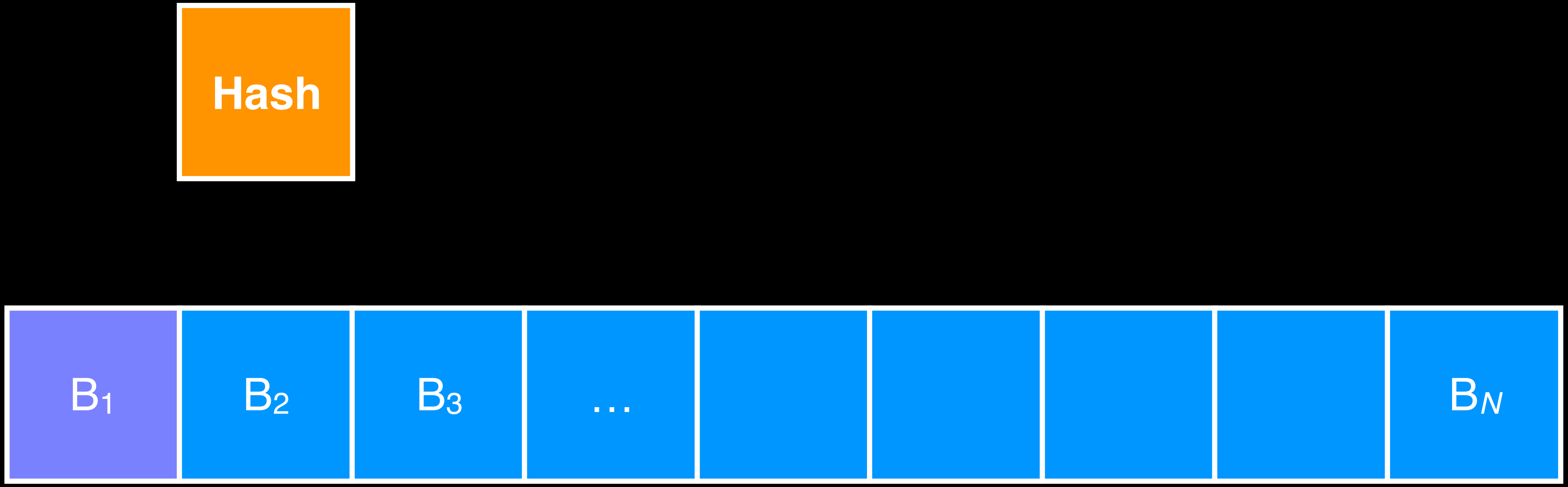

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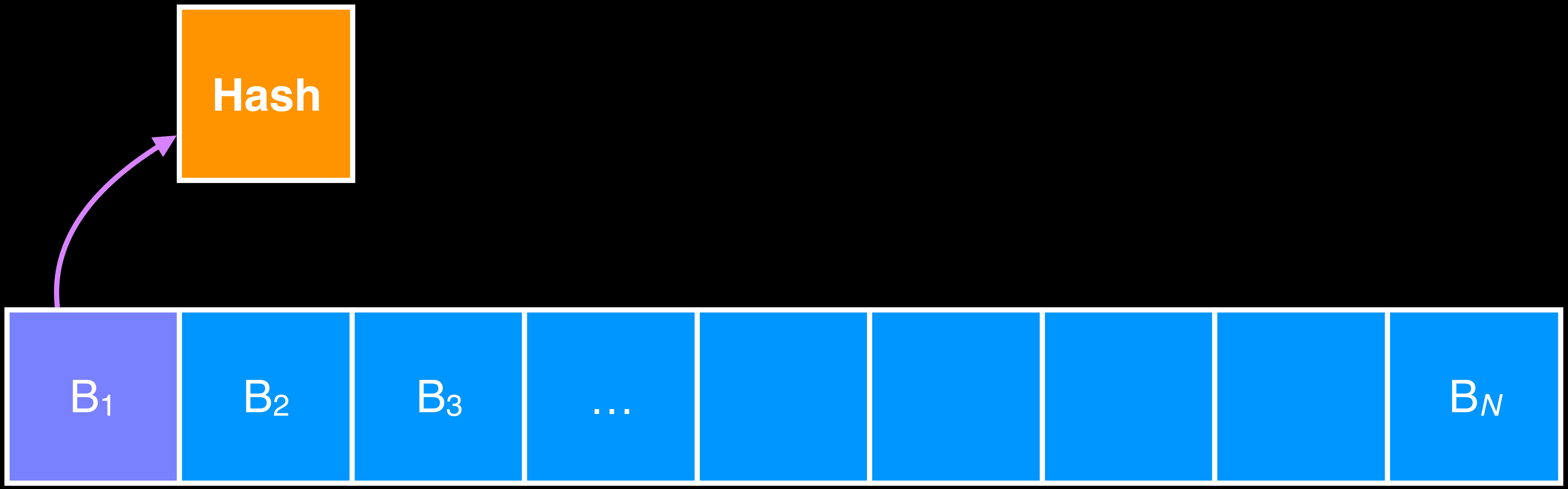

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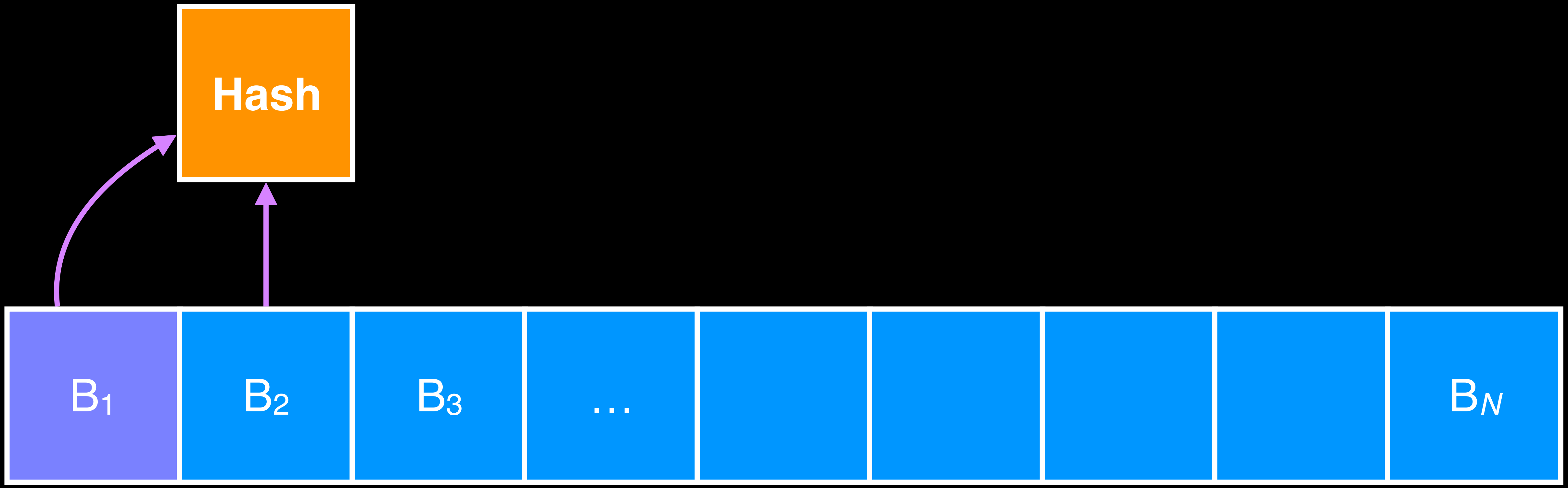

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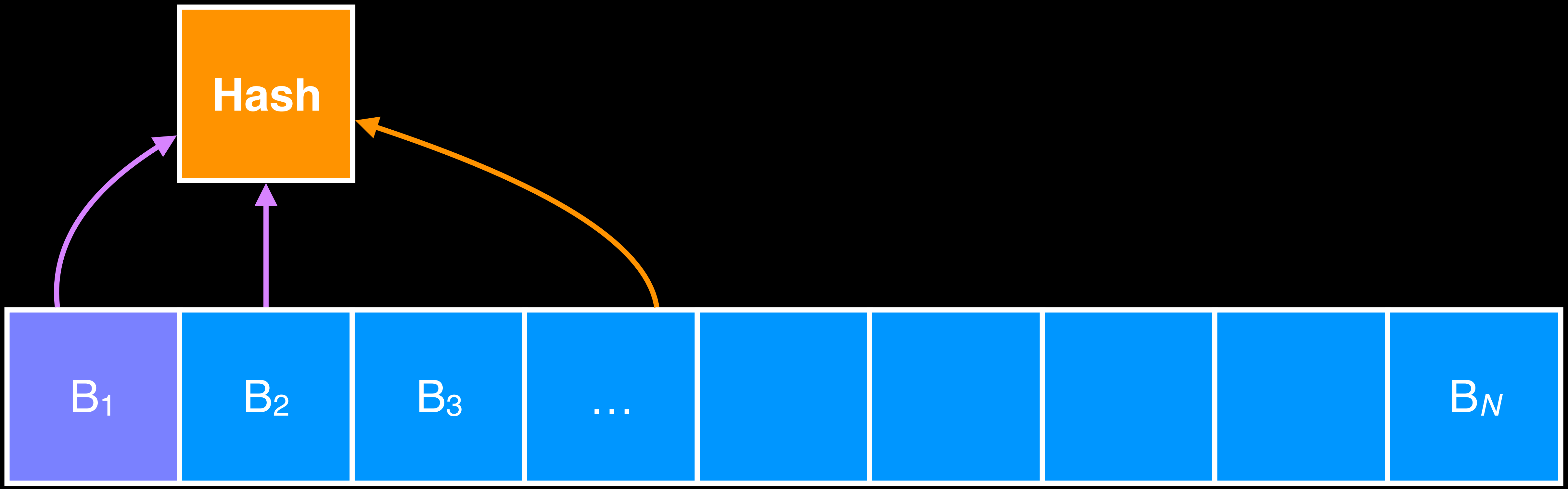

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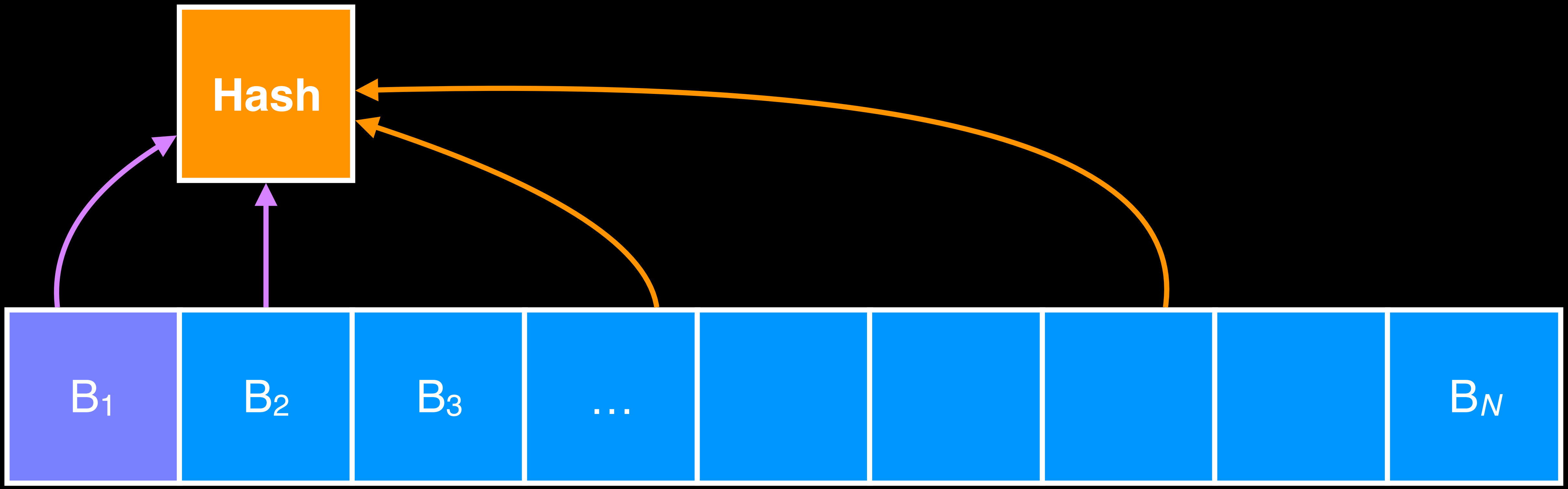

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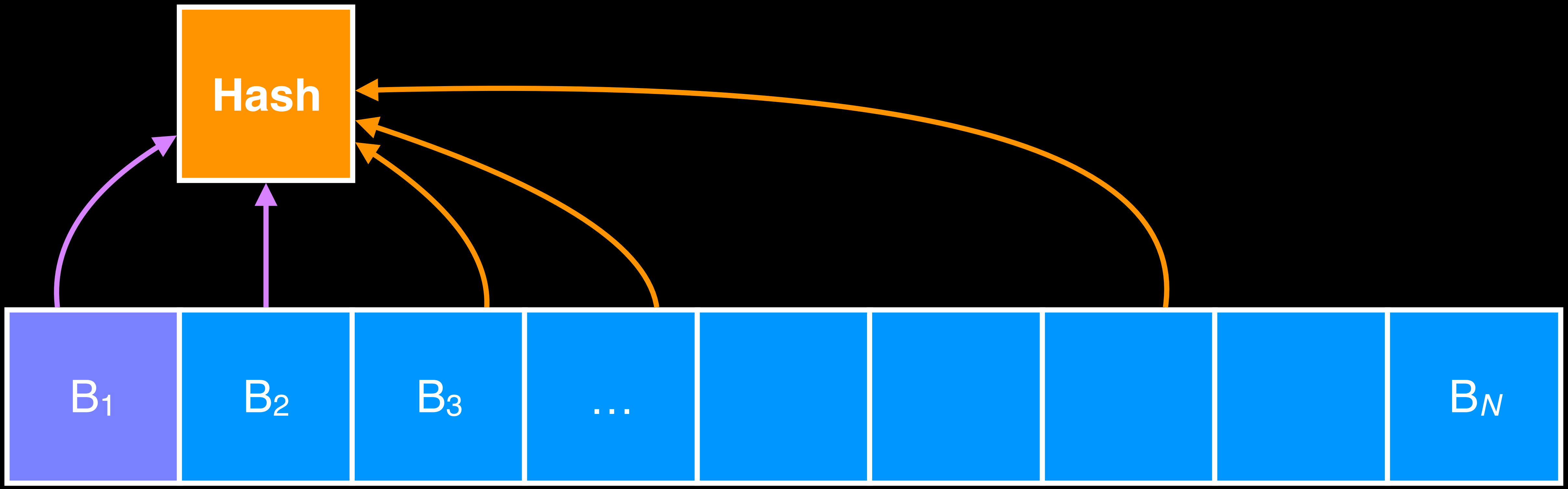

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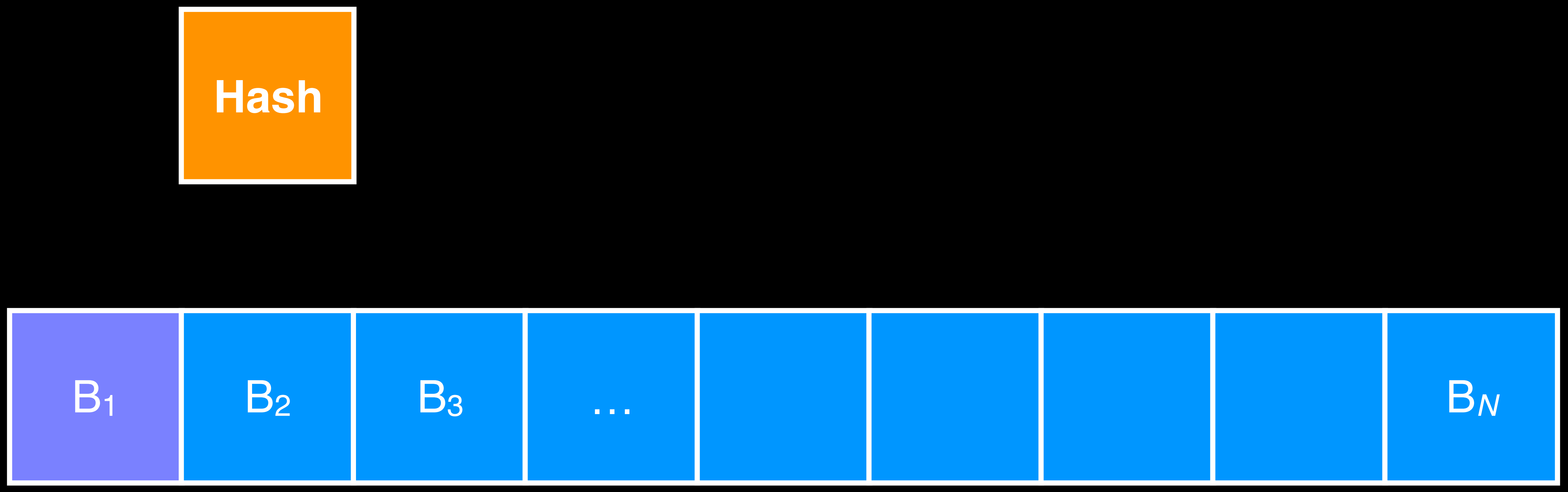

Hash

B_1 B_2 B_3 … B_N

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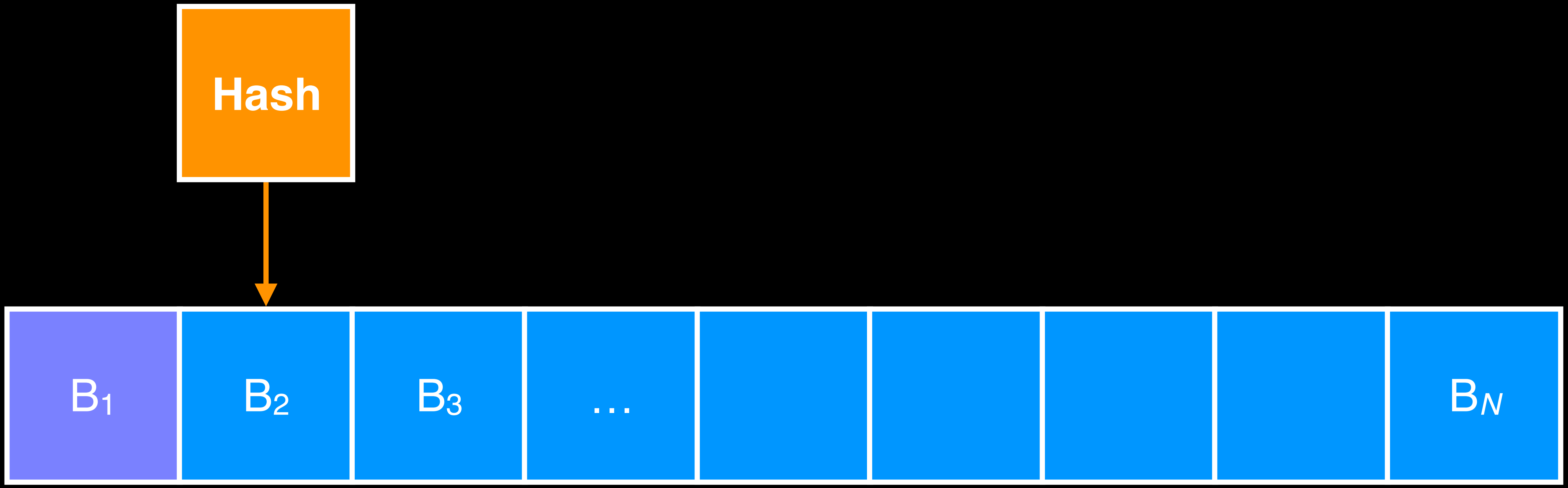

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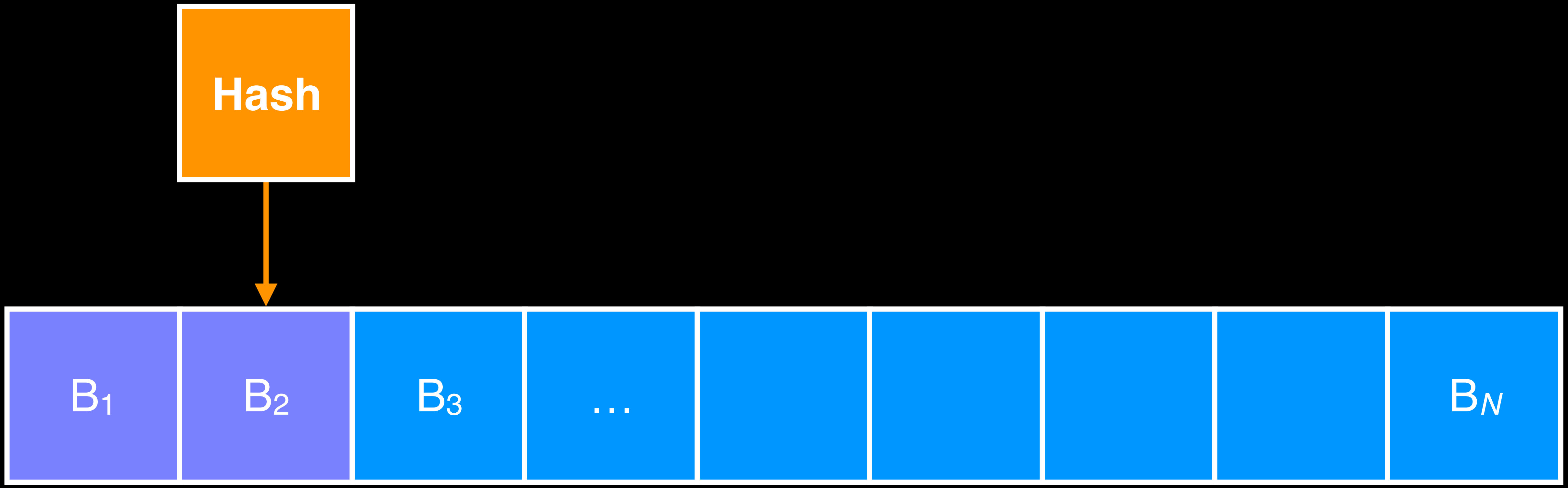

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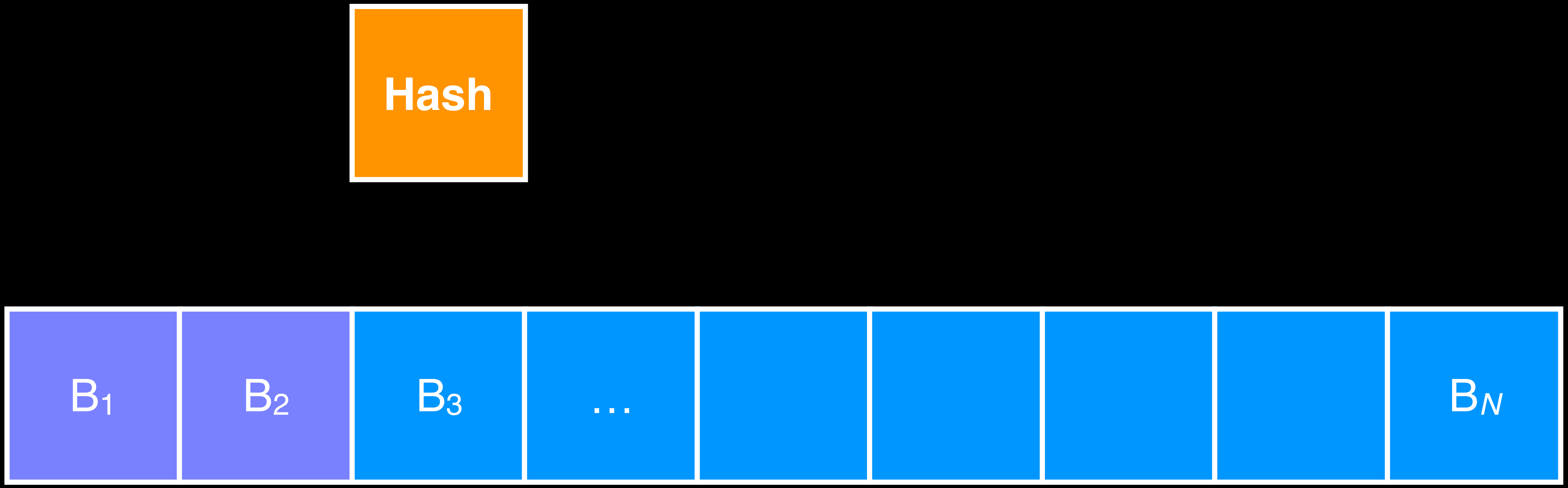

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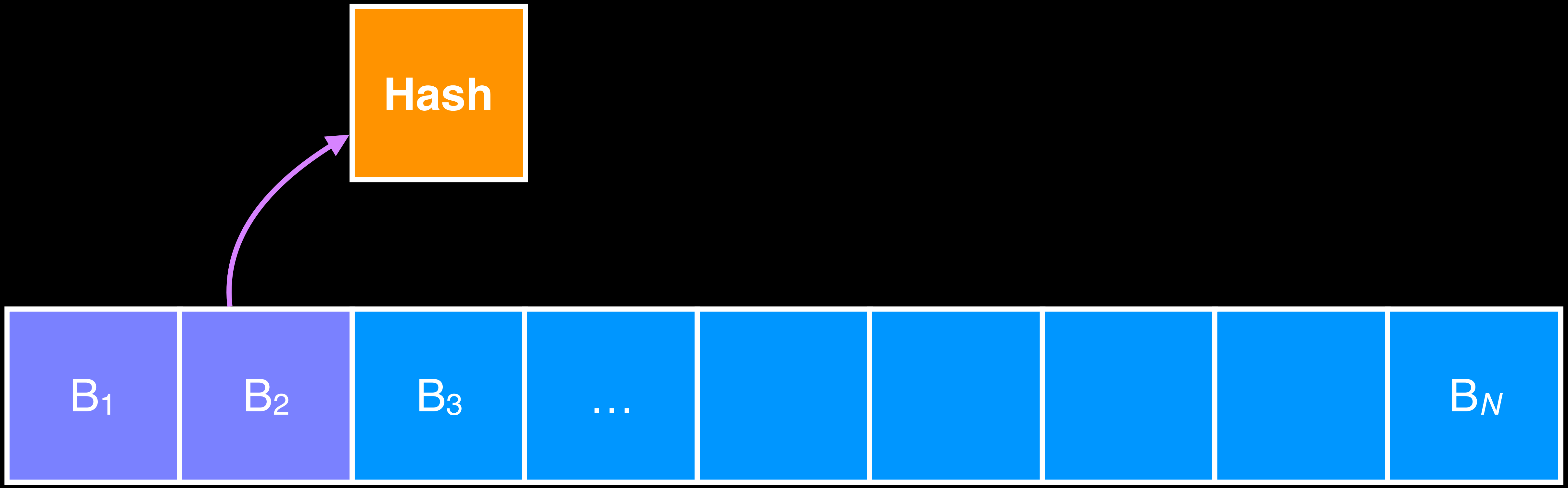

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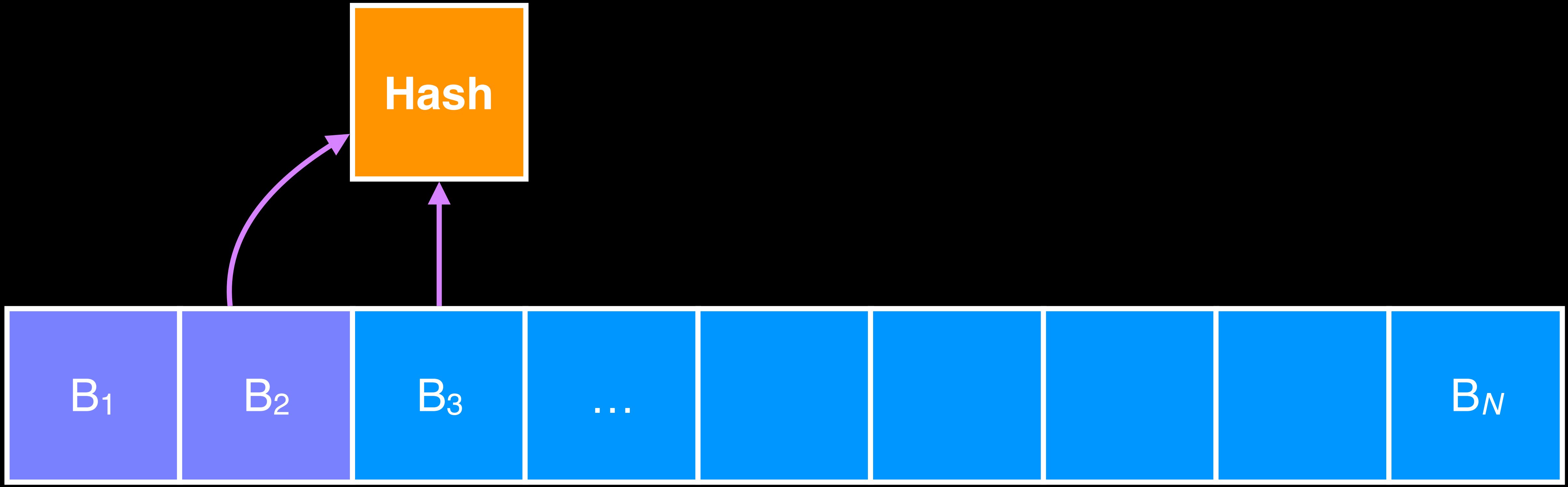

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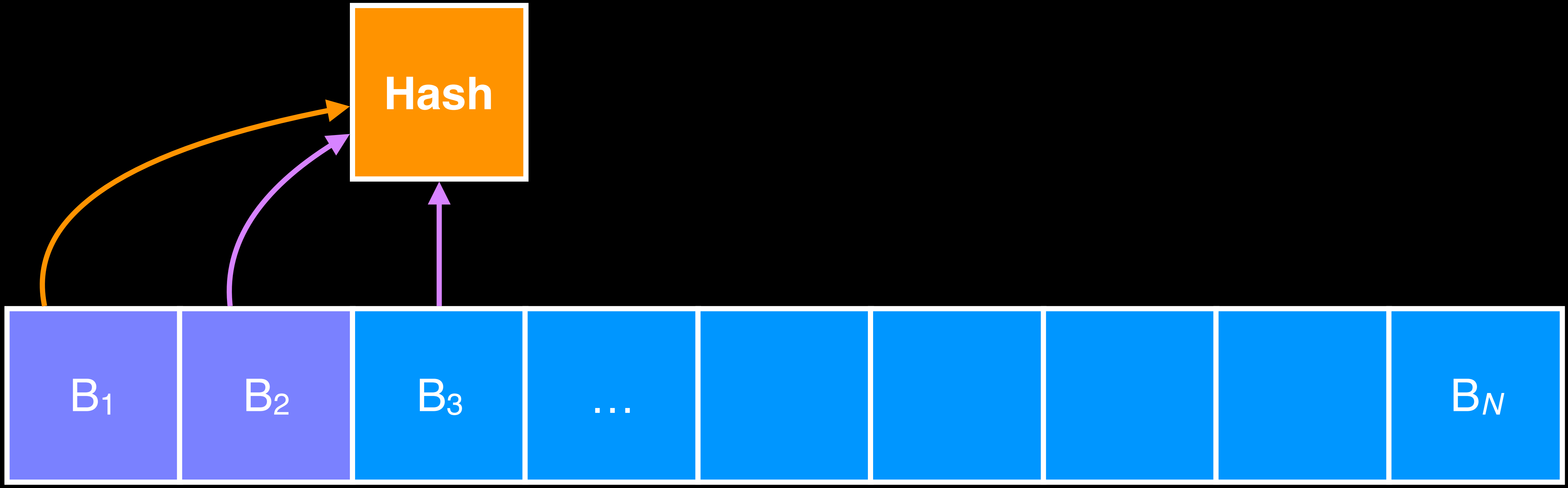

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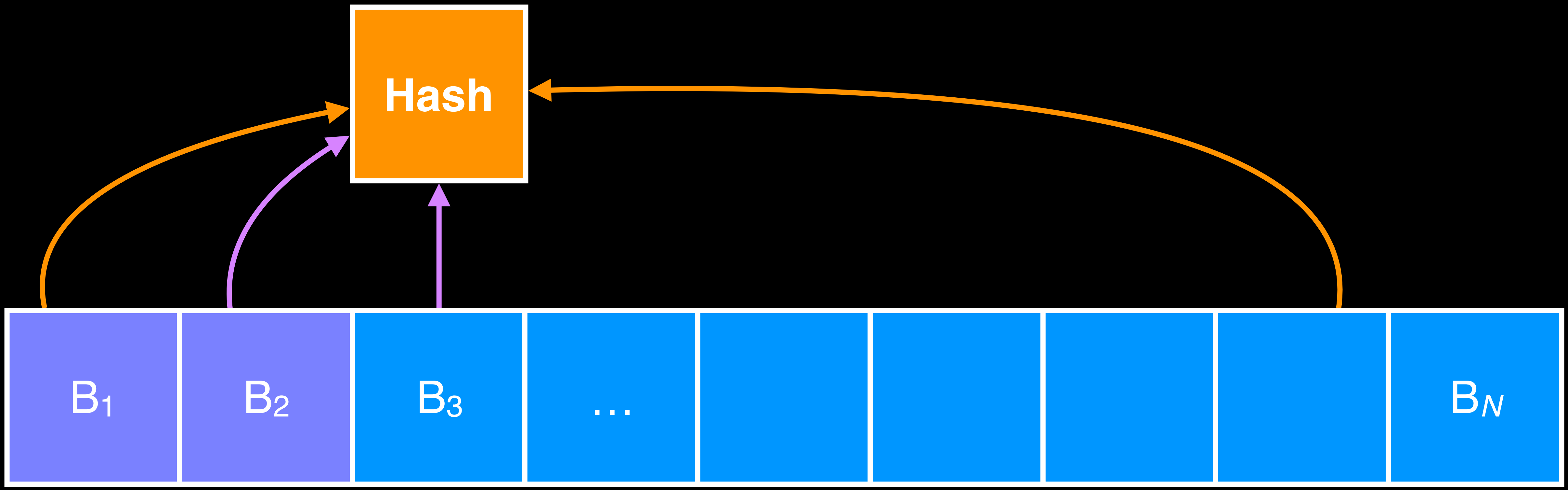

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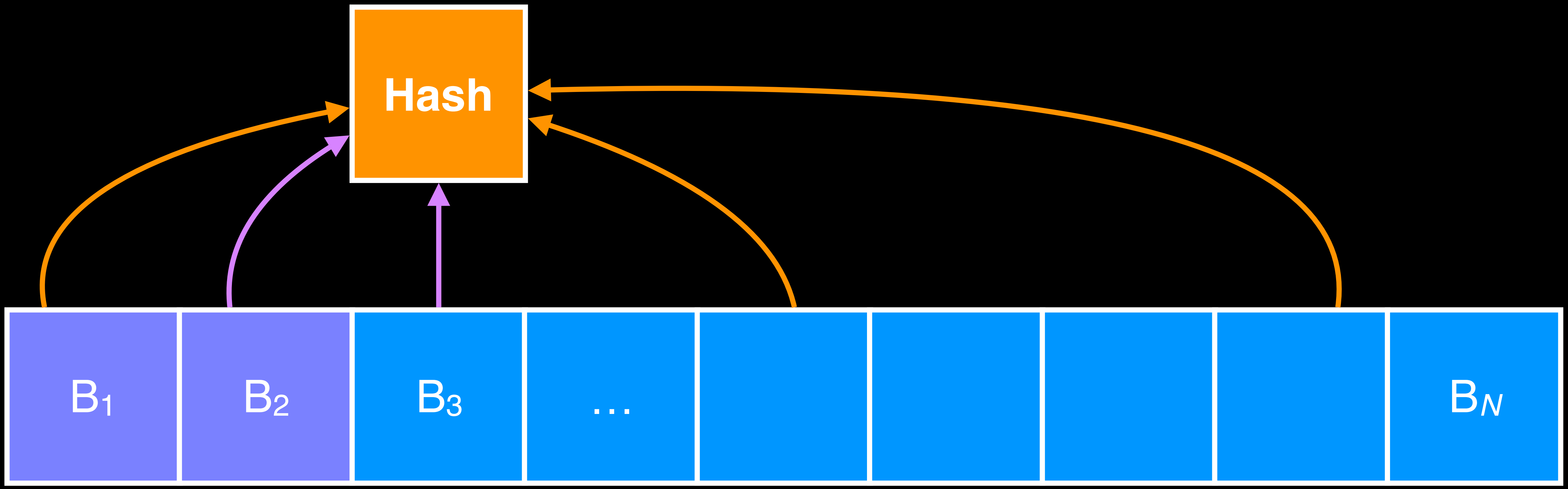

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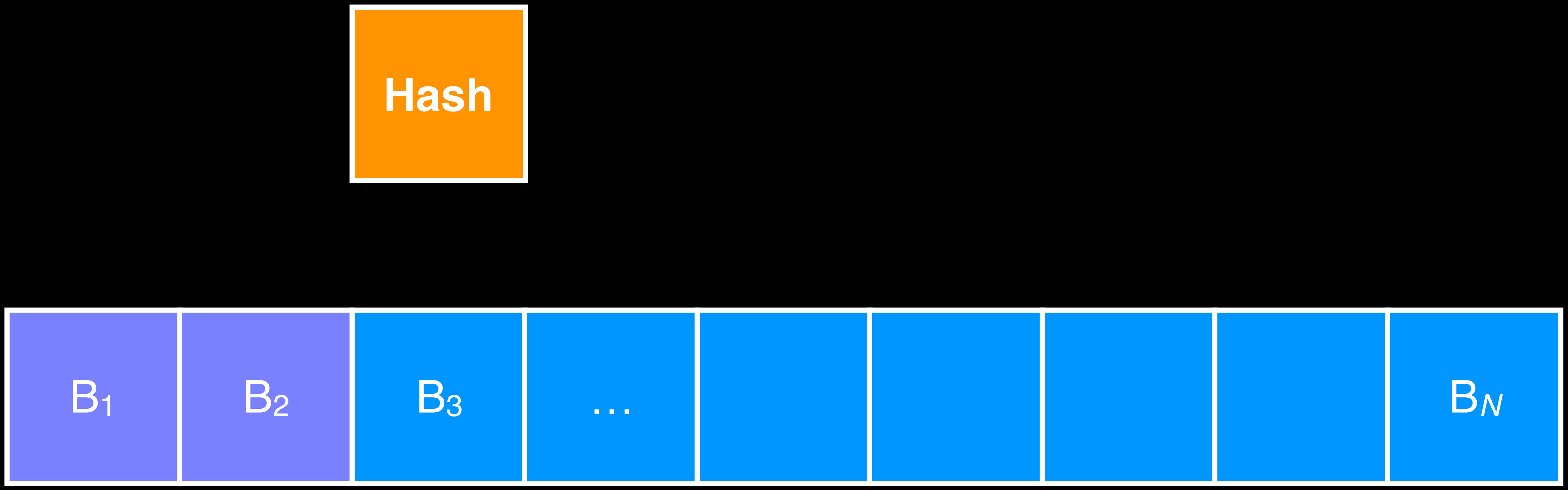

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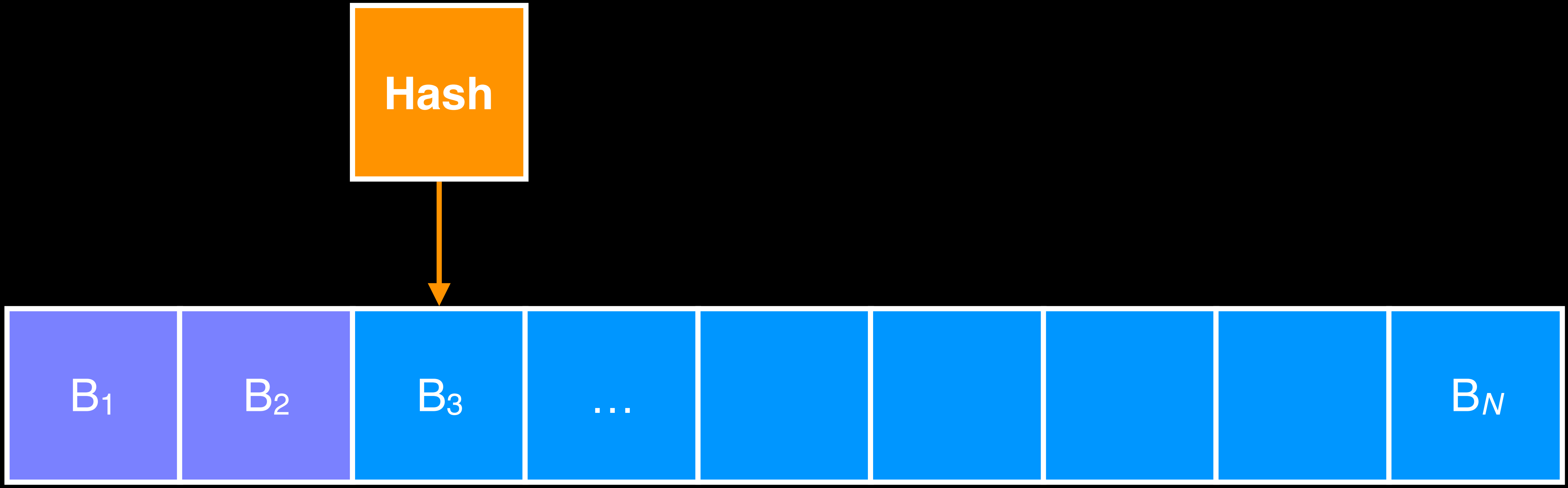

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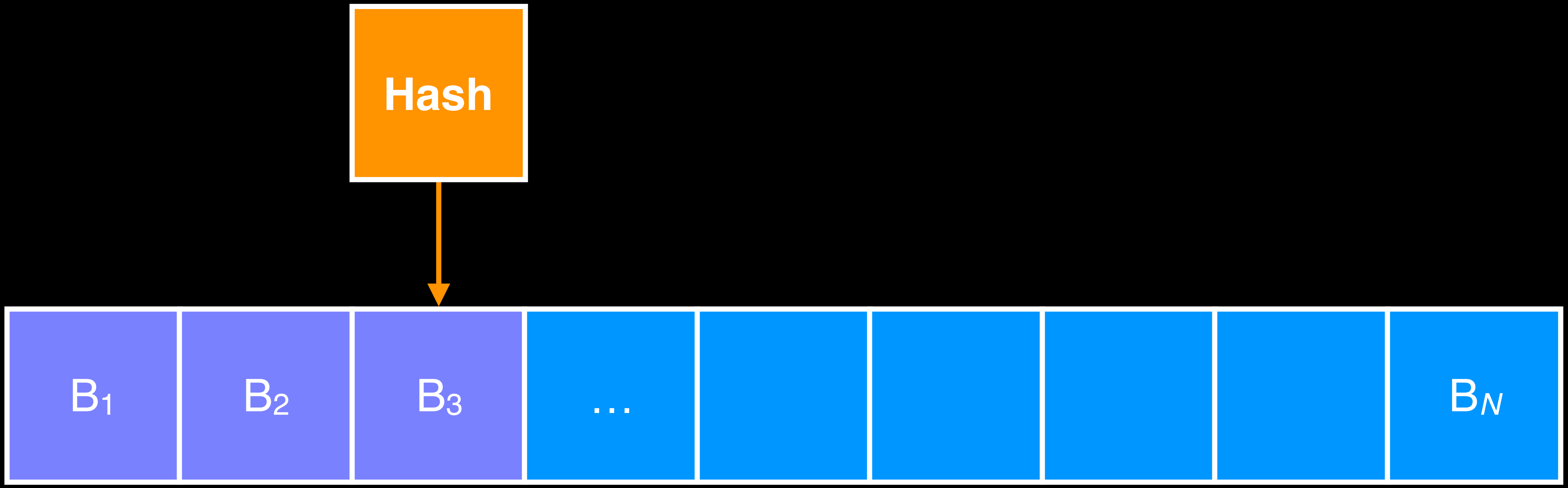

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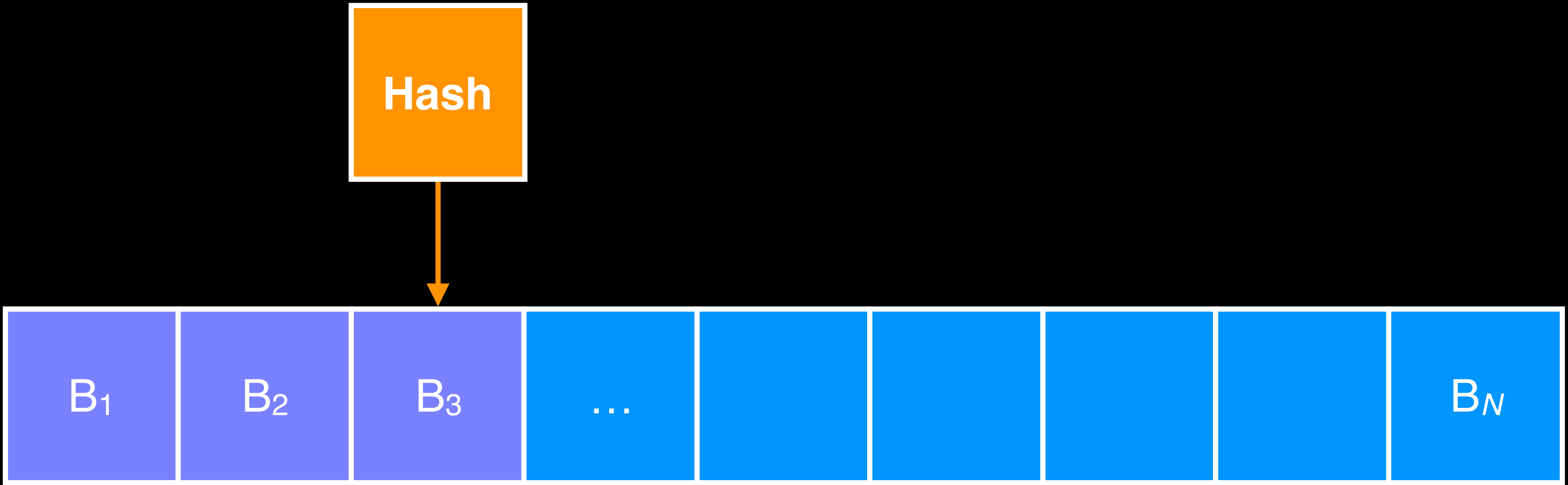

A “mode of operation” for a cryptographic hash function

Balloon Hashing

A password hashing function that:

1. Is proven memory-hard (in the sequential setting)

2. Uses a password-independent data access pattern

3. Matches the performance of the best heuristically secure memory-hard functions

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Proving Memory-Hardness

Theorem [informal]:
Computing the N-block R-round Balloon function w.h.p., when δ=7, with space **S ≤ N/8** requires time **T** such that

$$\mathbf{S} \cdot \mathbf{T} \geq (2^R - 1) / 8 \cdot \mathbf{N^2} \,.$$

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Saving a factor of 8 in space causes a slowdown **exponential** in # rounds

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When R=20, using 8× less space requires using **60,000×** more time

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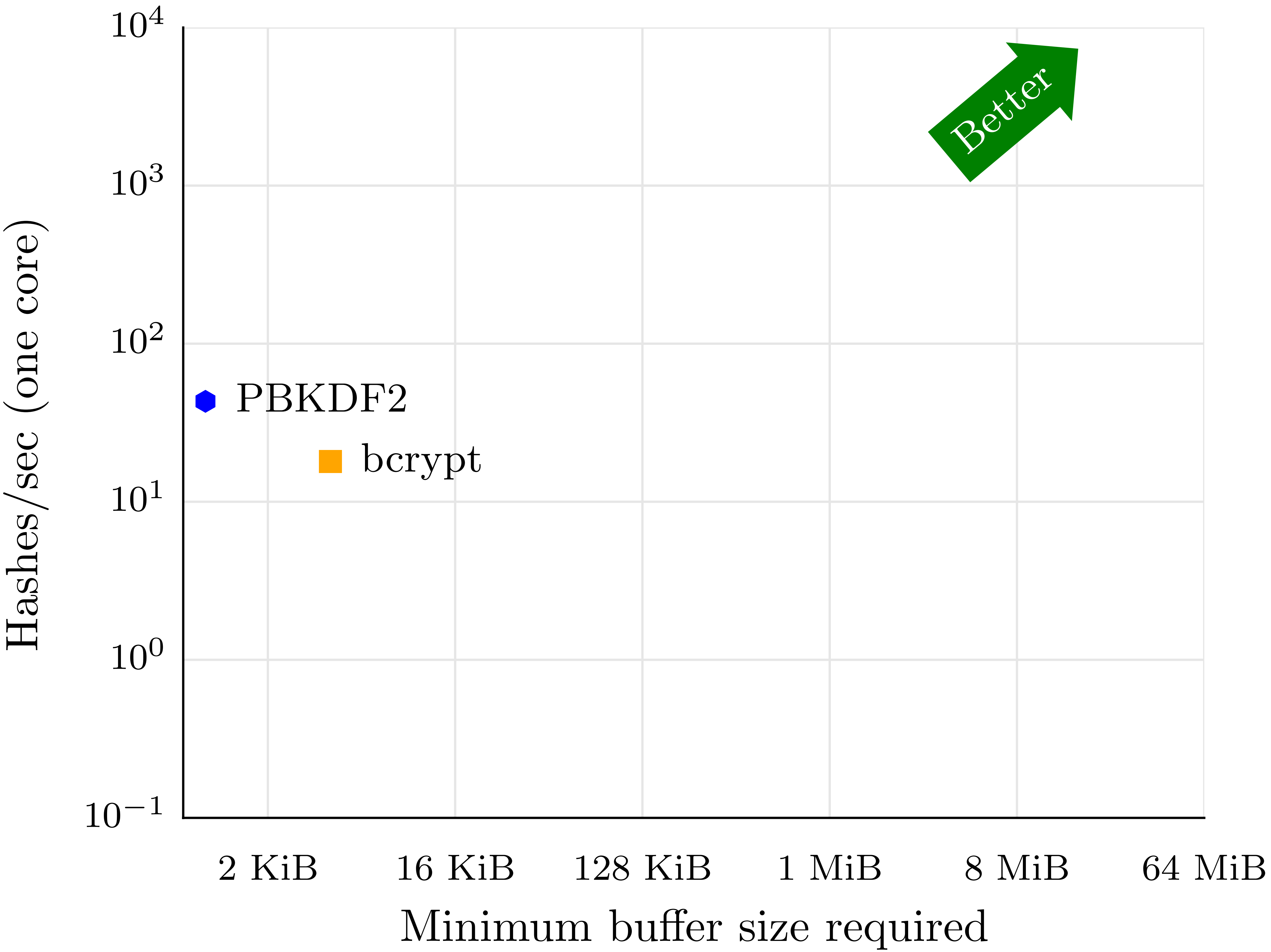
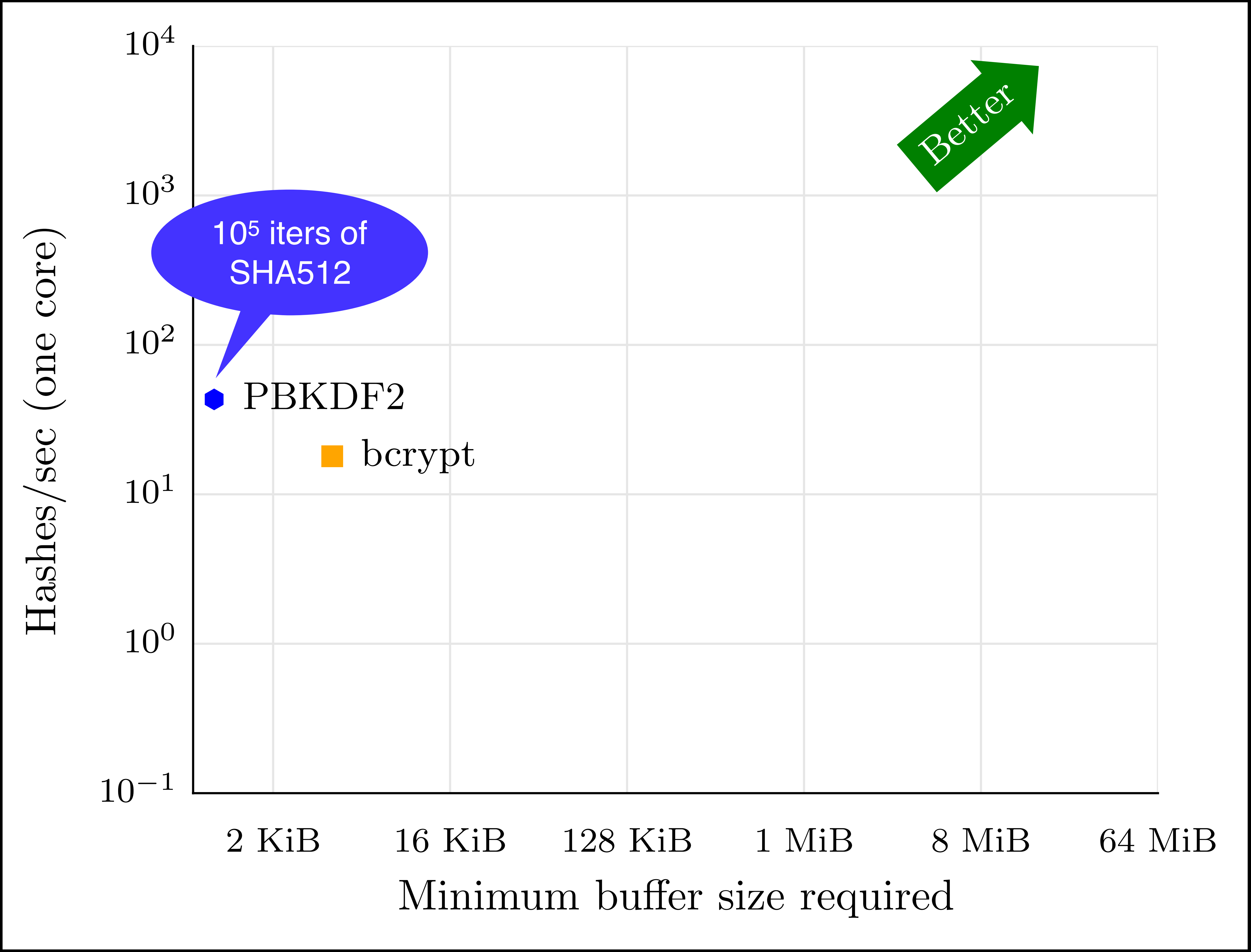
The proof works by inspecting the Balloon computation's data-dependency graph.

We draw heavily on prior work on pebbling arguments

[Paterson & Hewitt 1970] [Paul & Tarjan 1978] [Dwork, Naor, Wee 2005] [Dziembowski, Kazana, Wichs 2011] [Alwen & Serbinenko 2015]



Using Balloon (δ=3). Both algorithms take four passes over memory.



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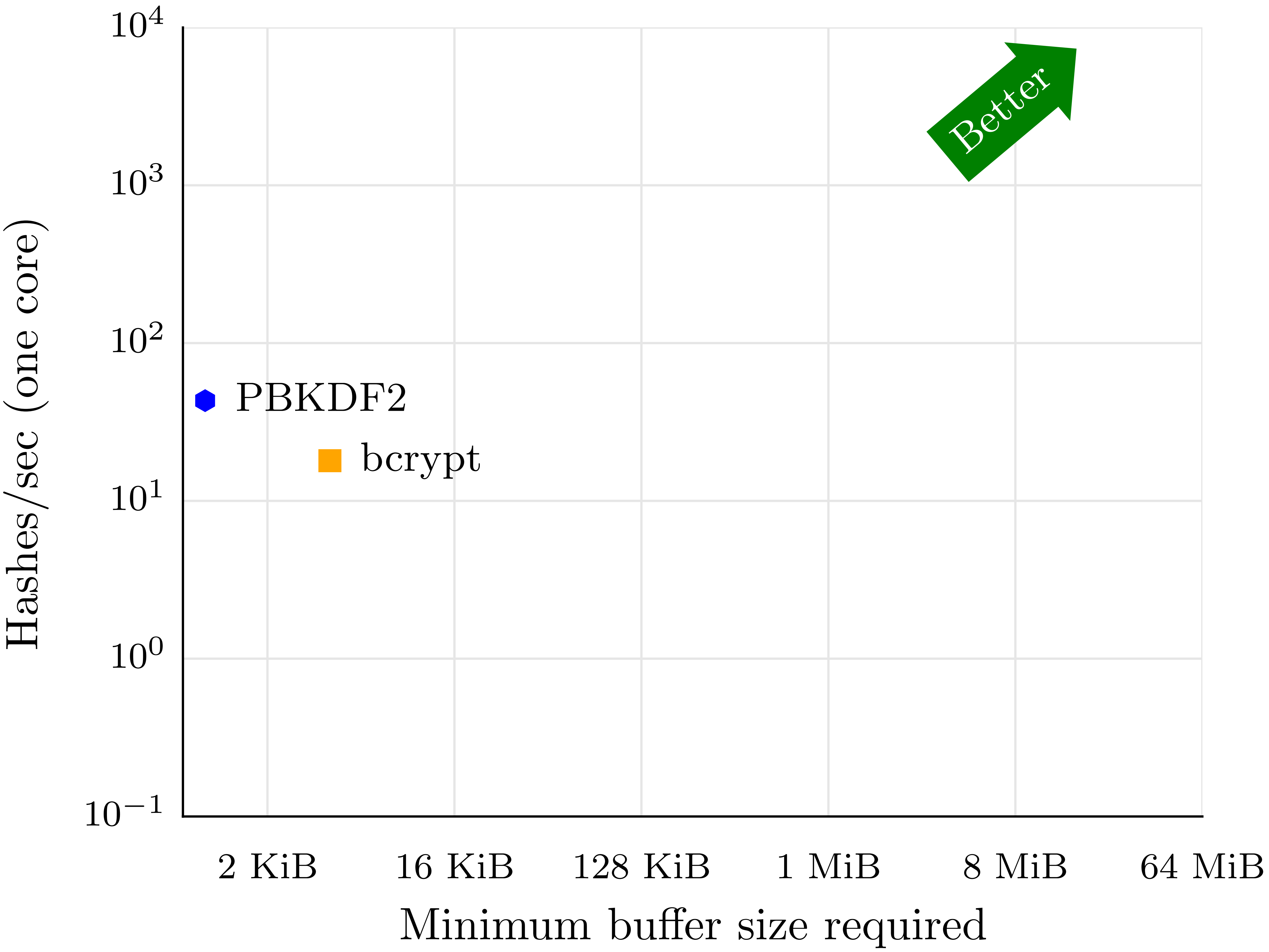

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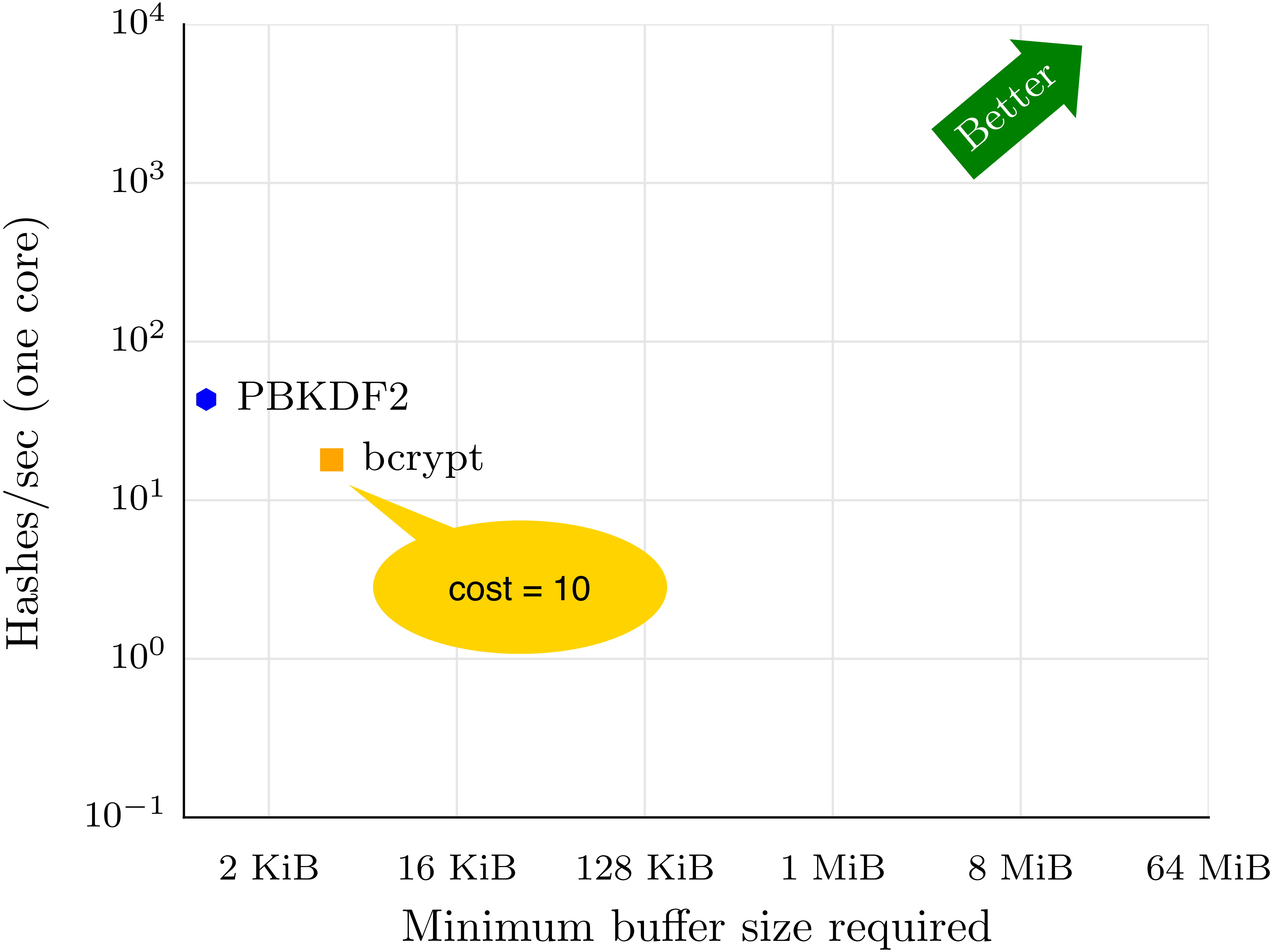

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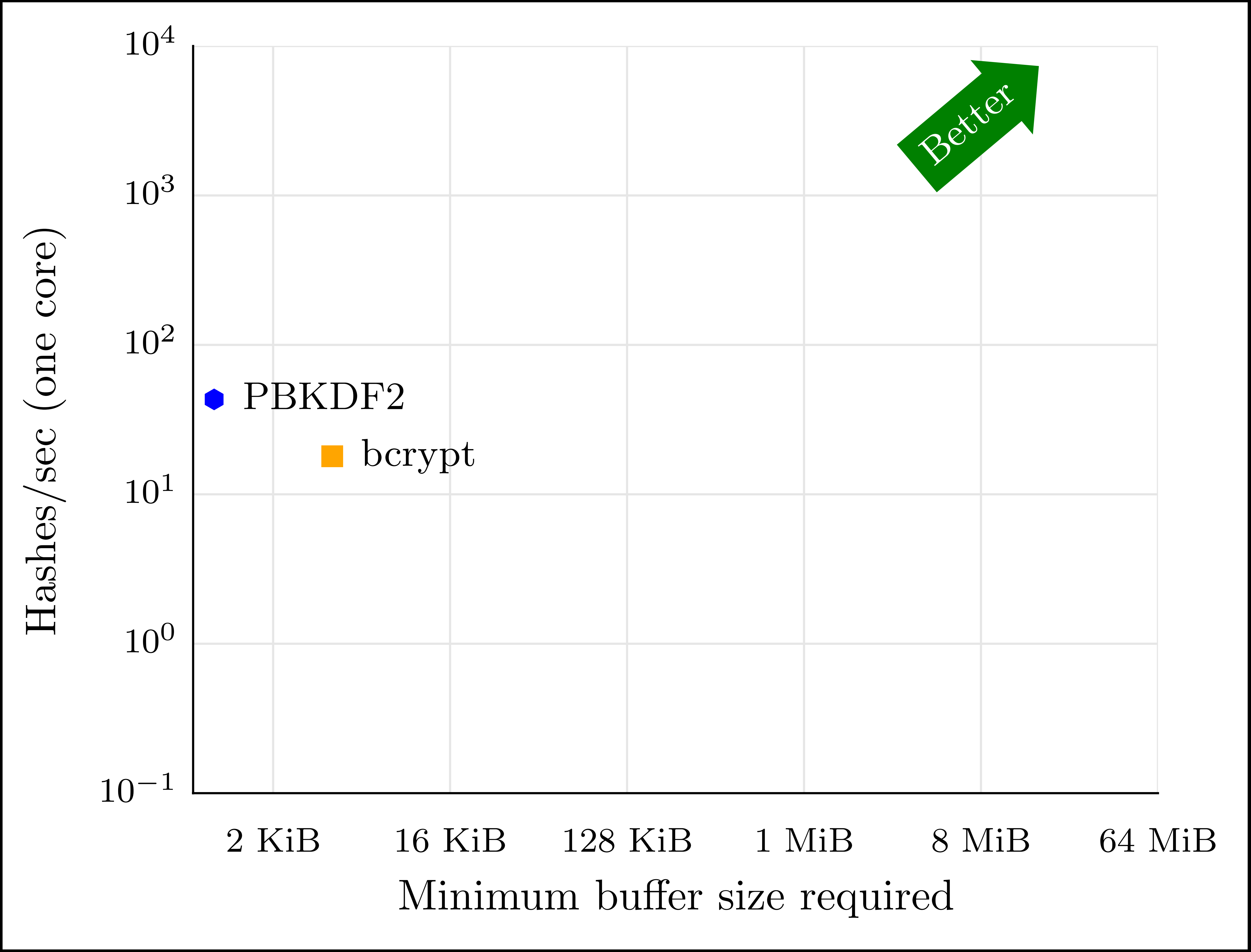

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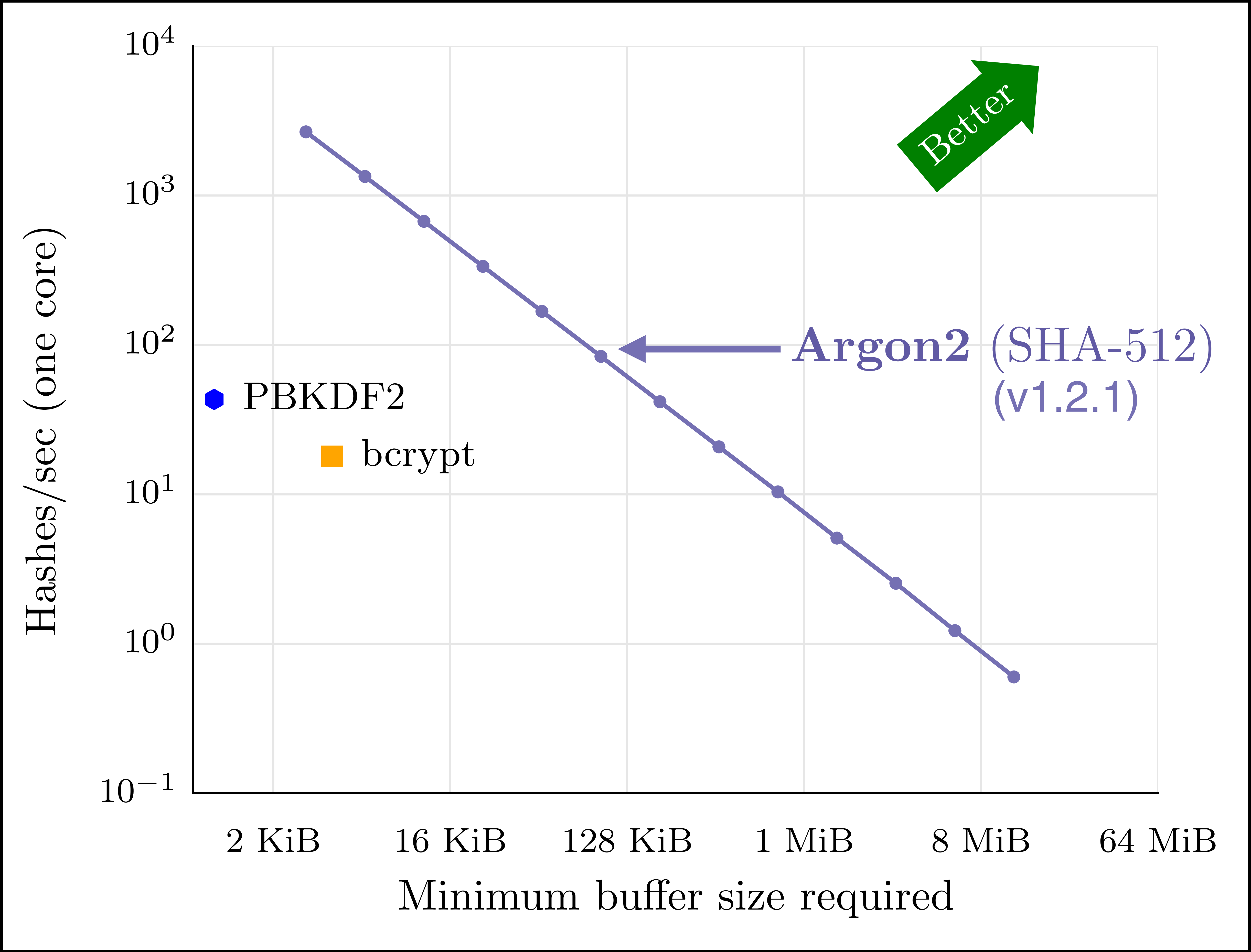

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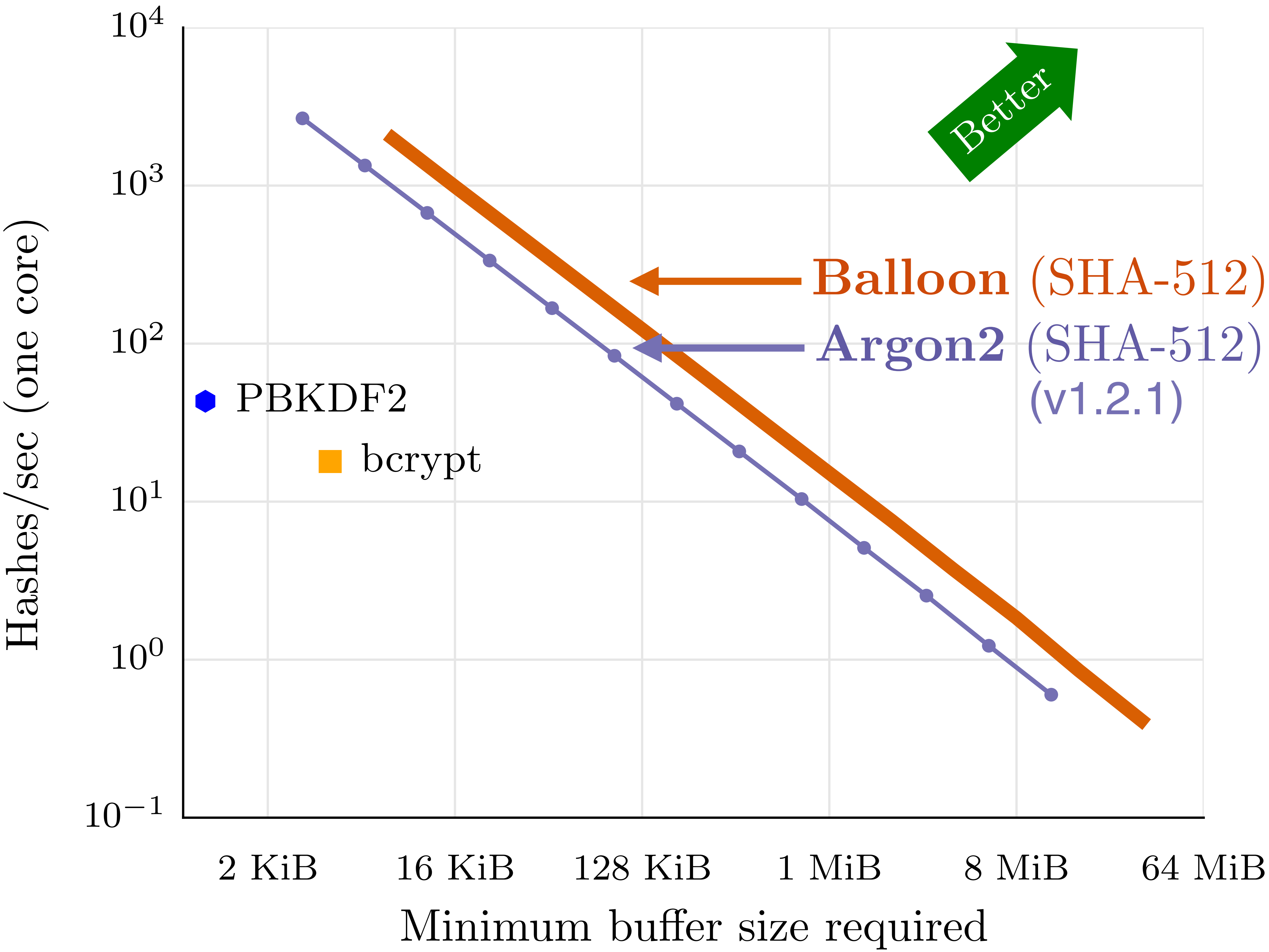

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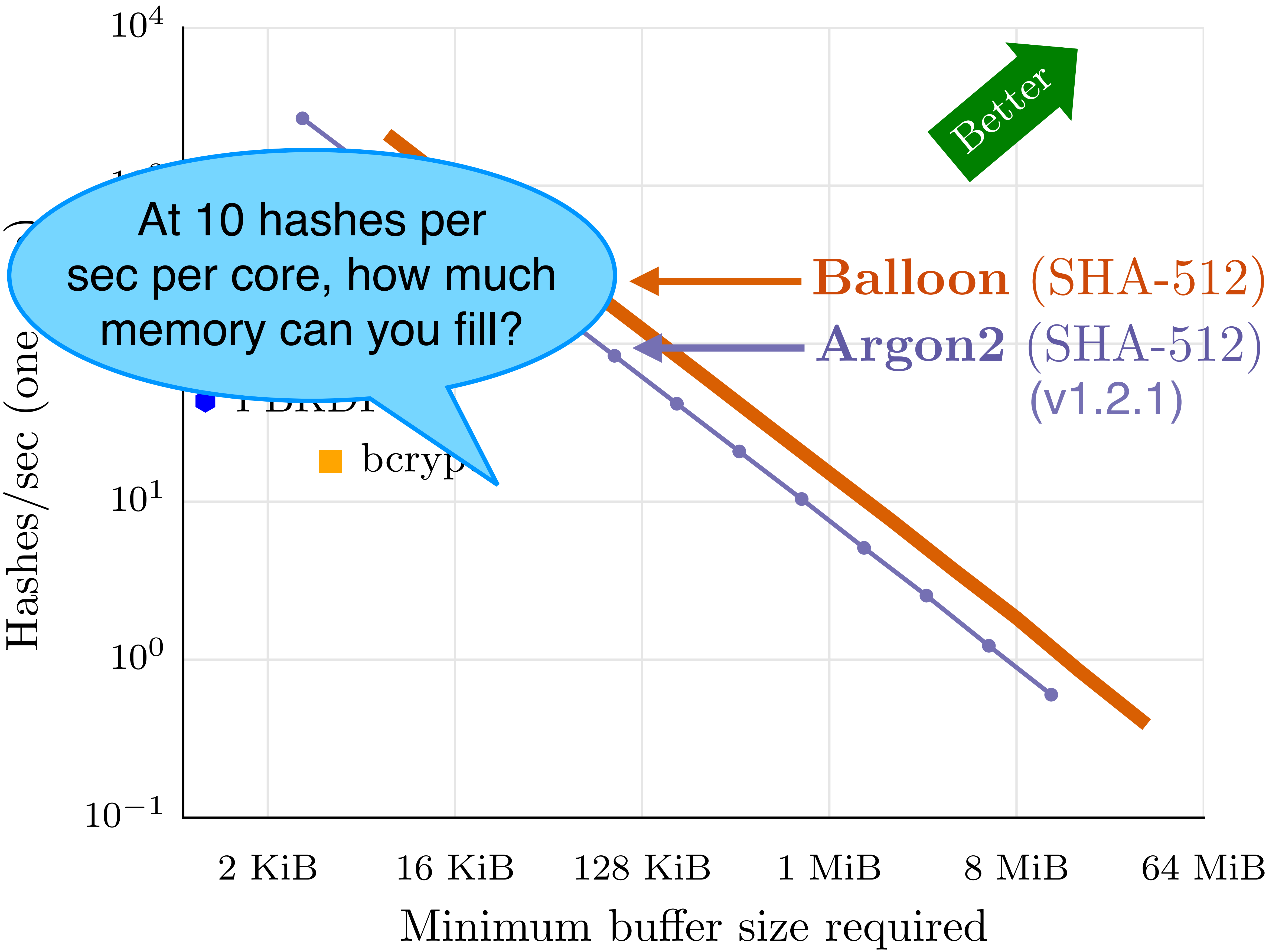

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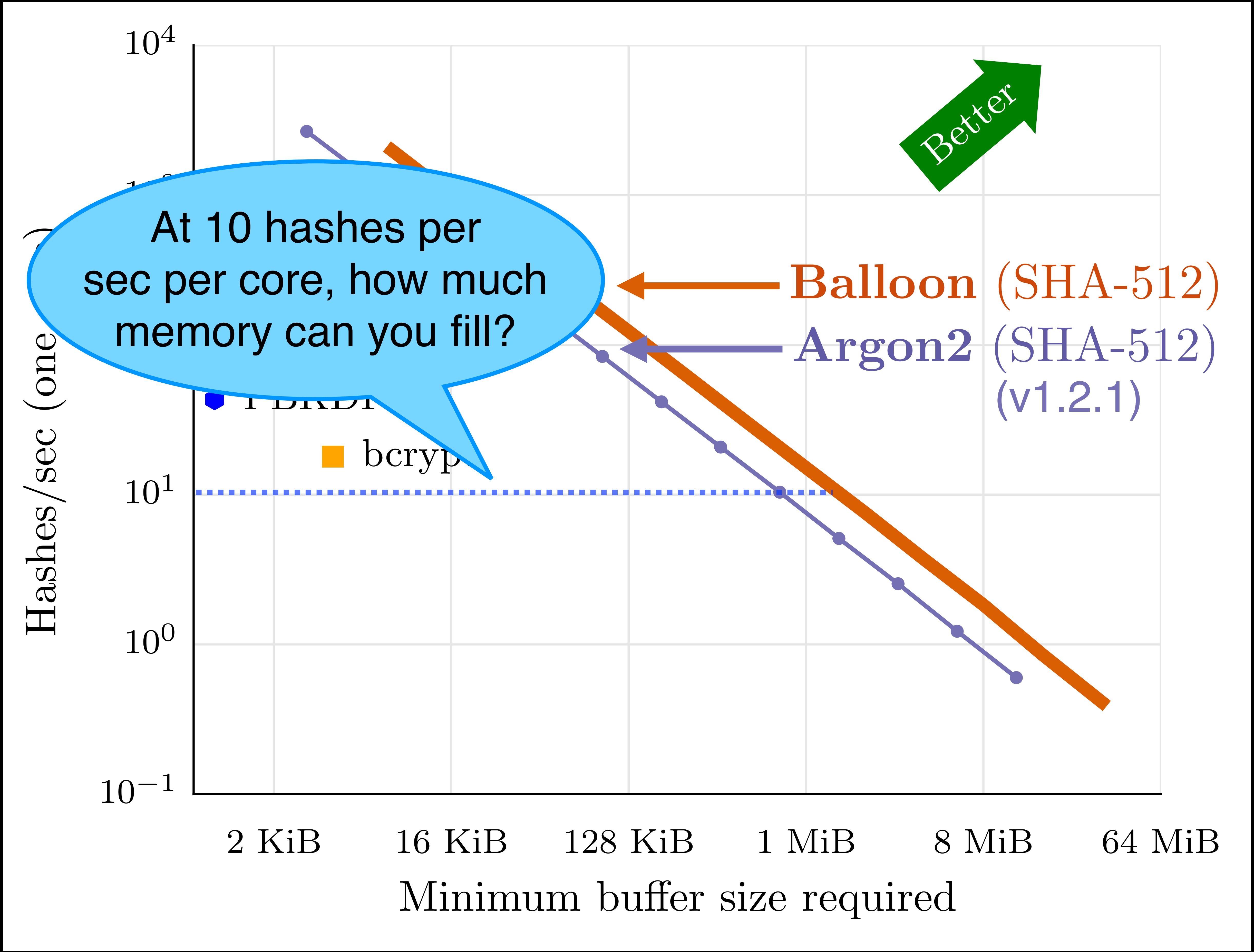

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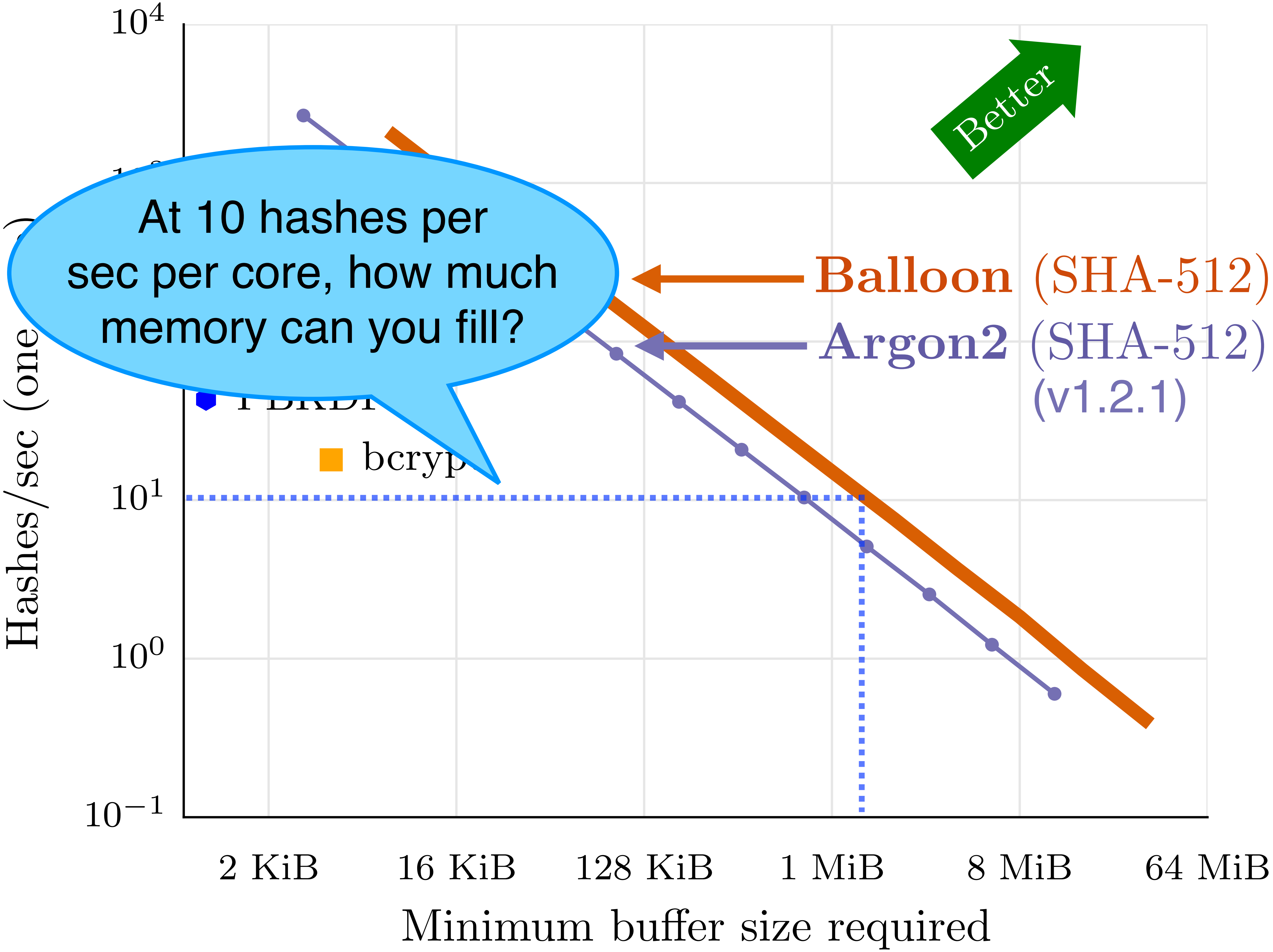

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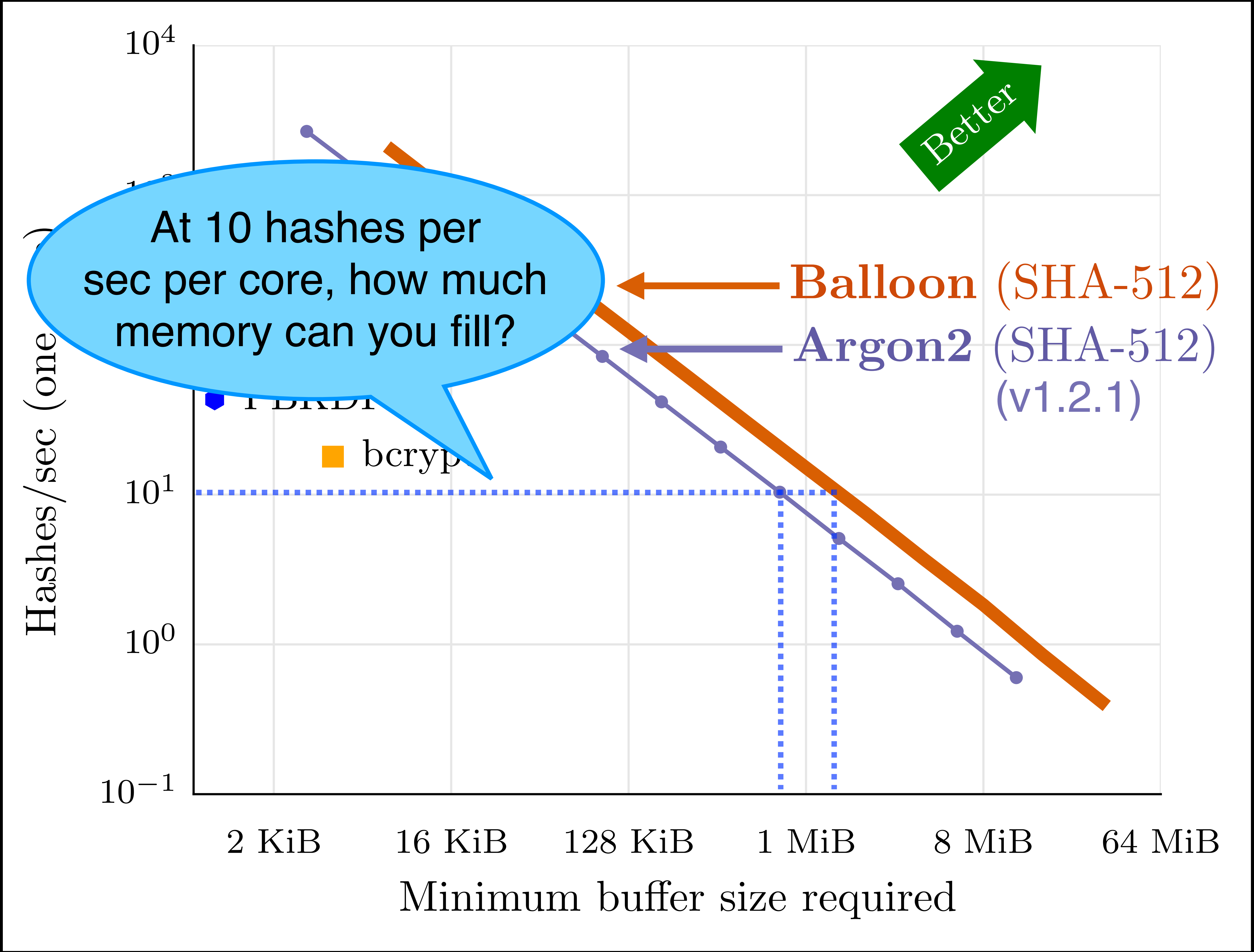

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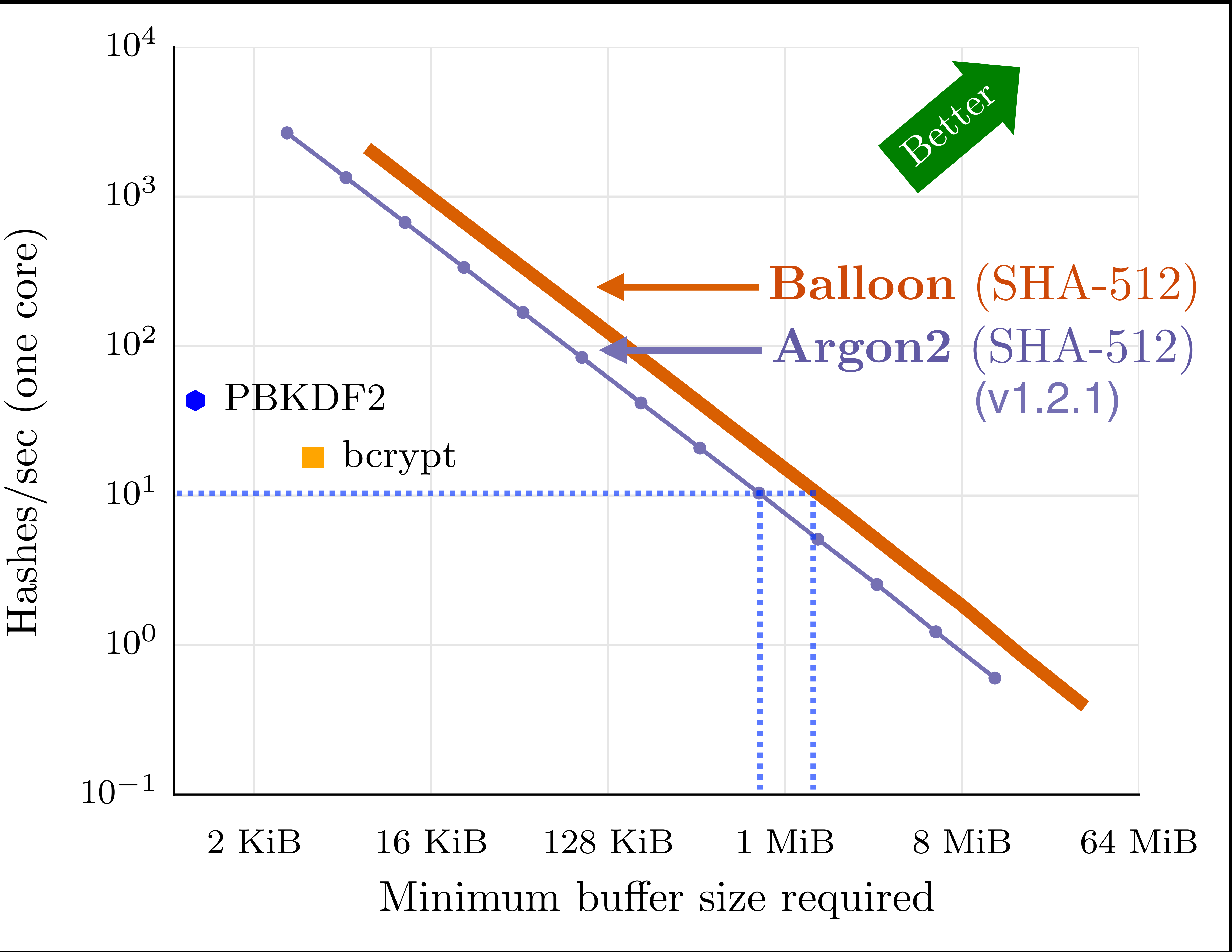

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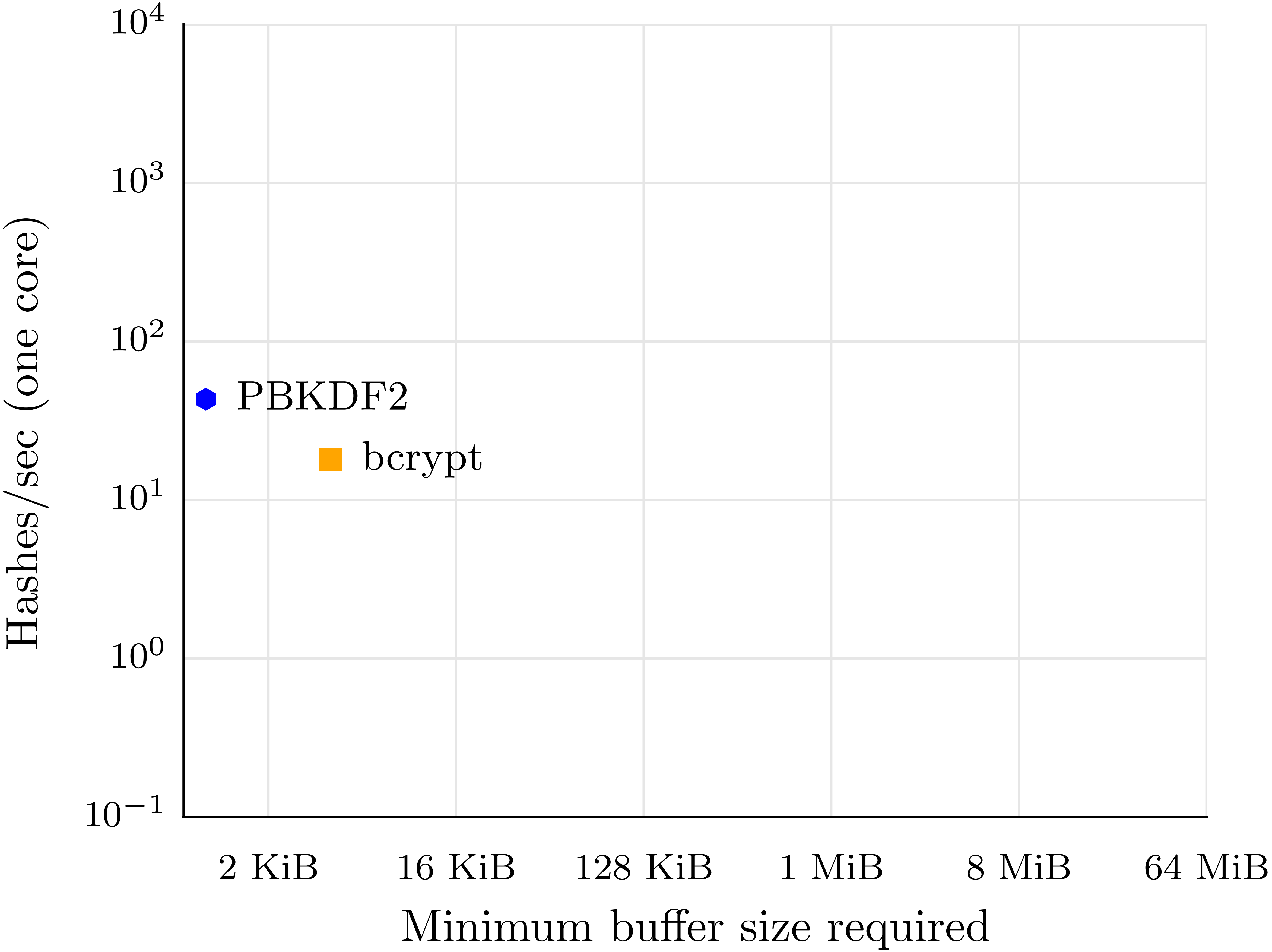

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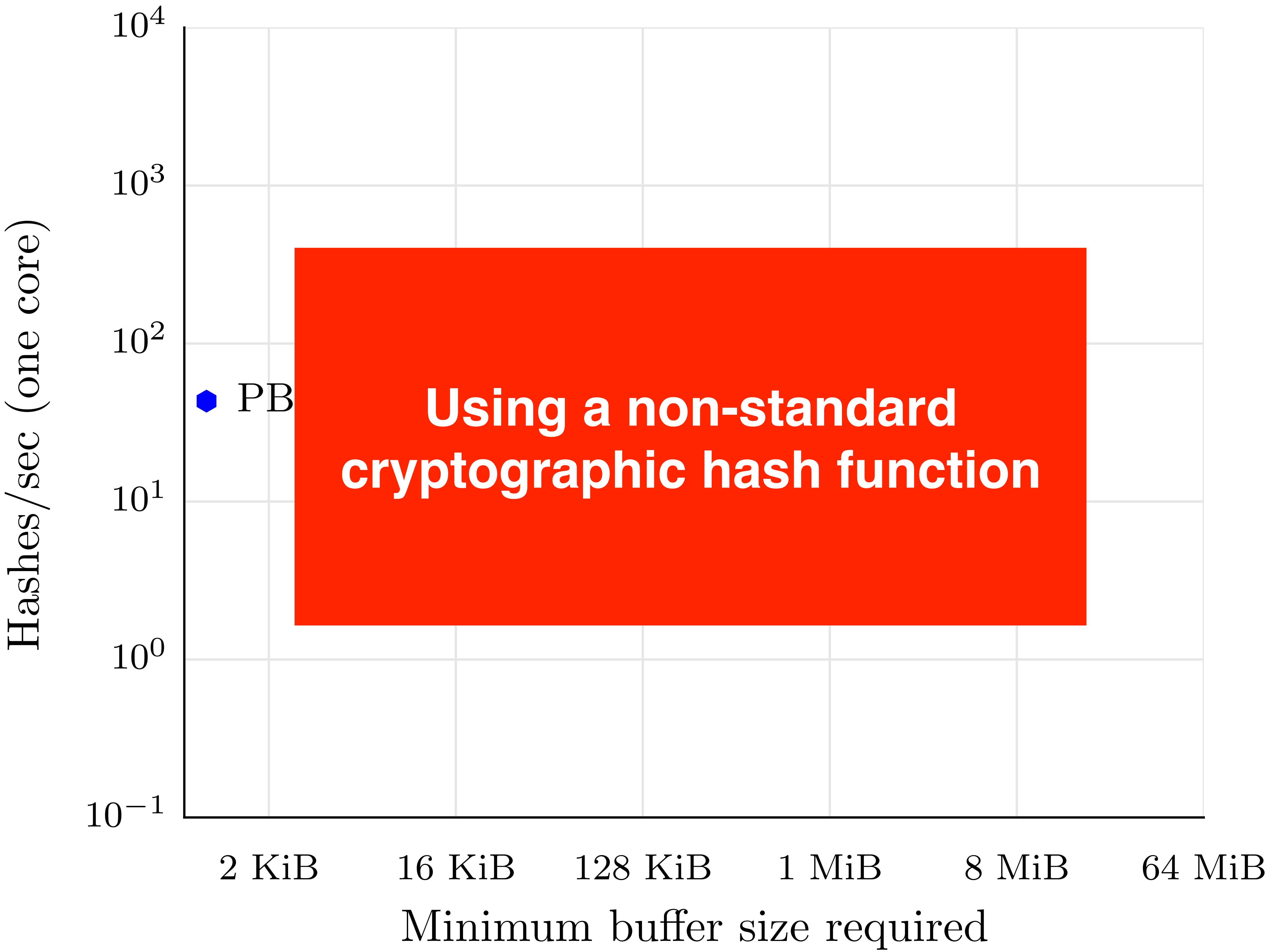

Using a non-standard cryptographic hash function

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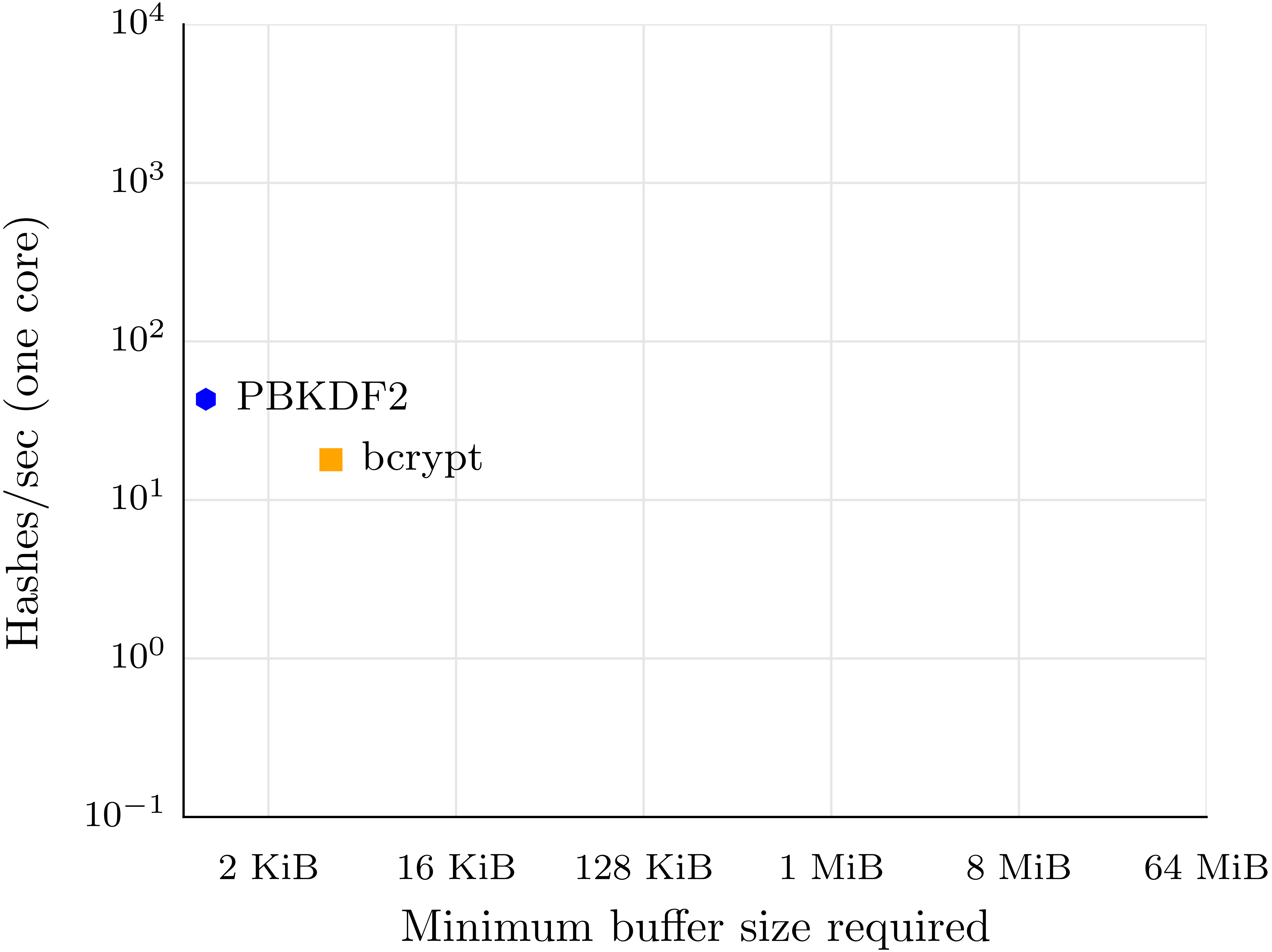

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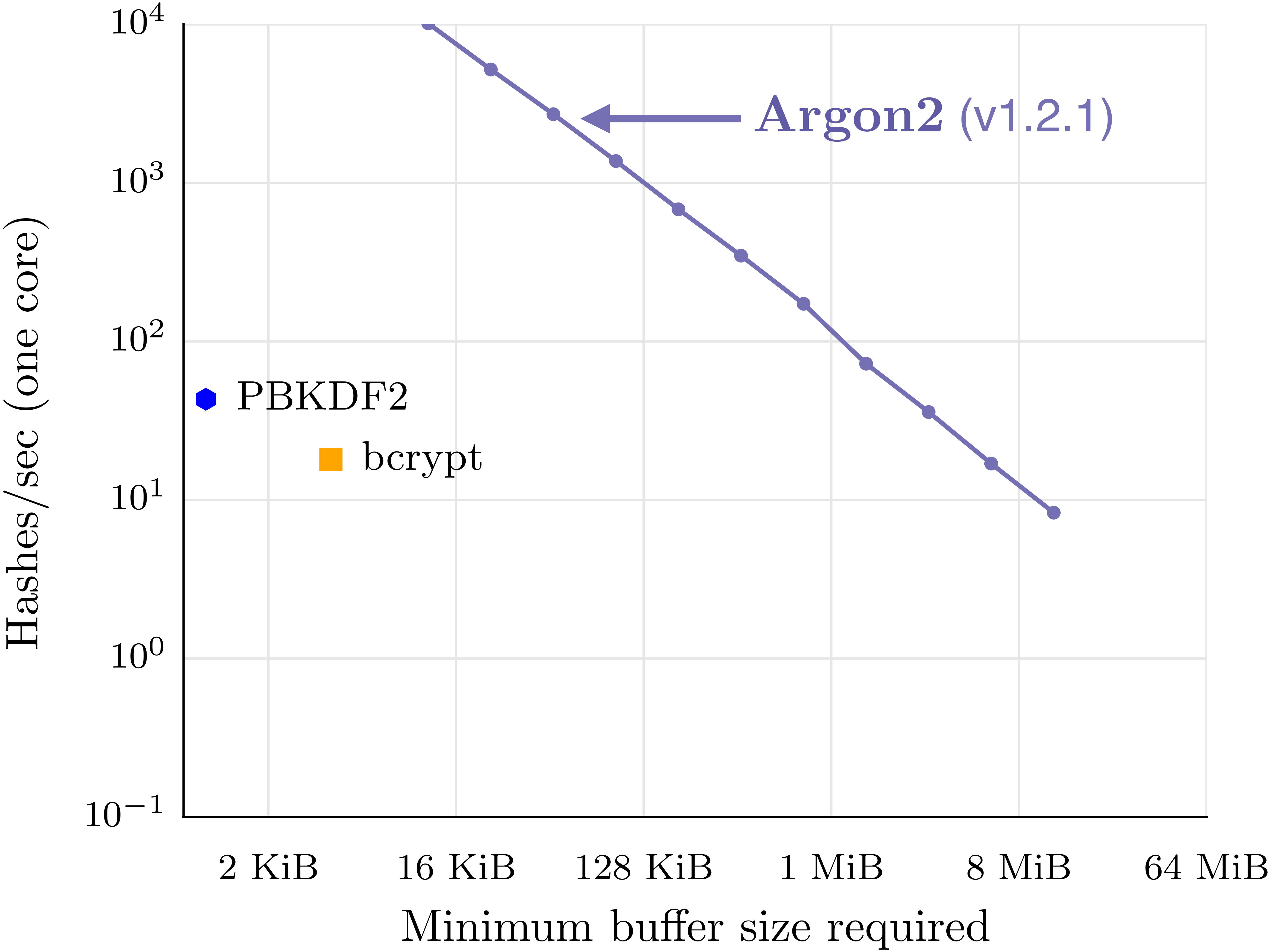

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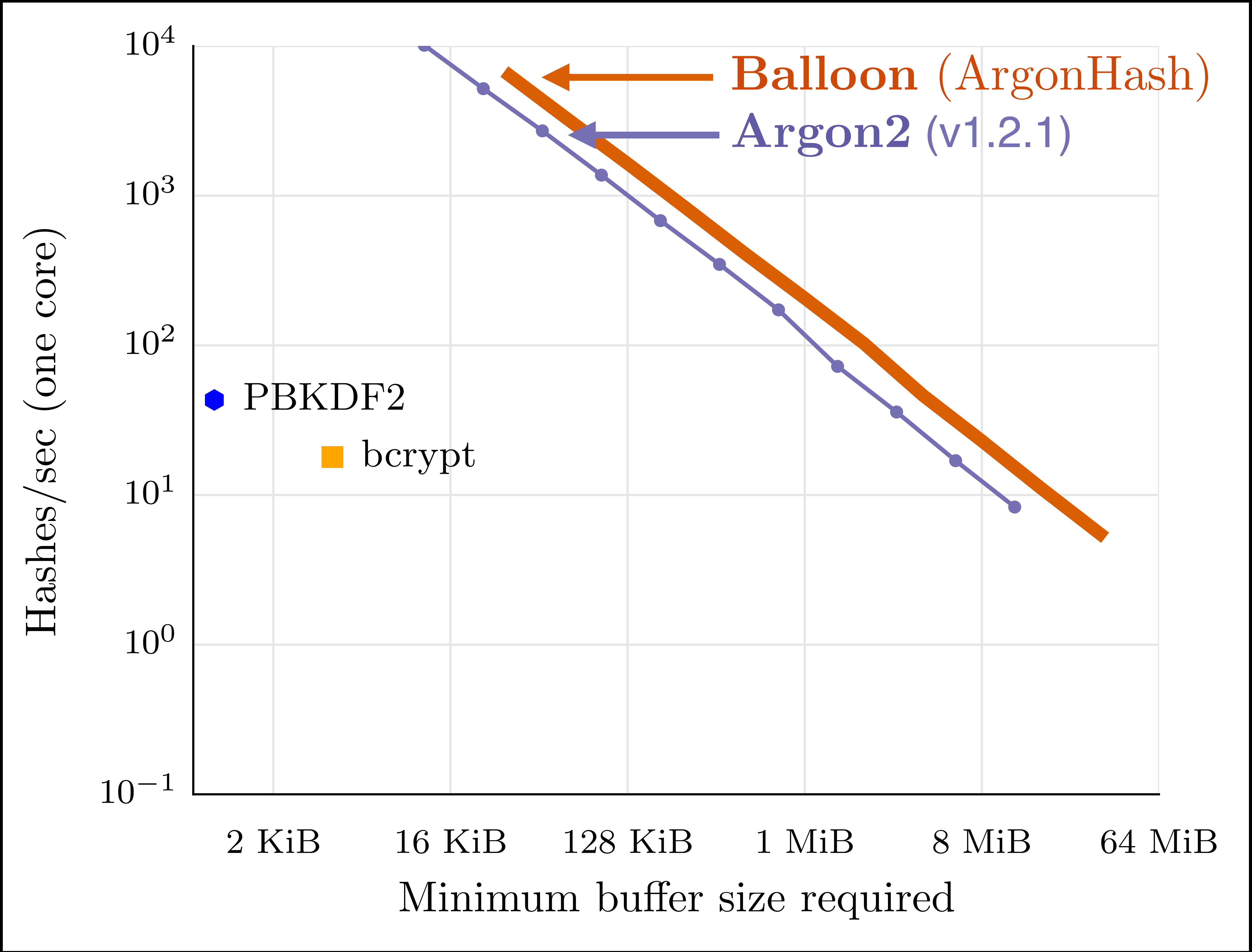

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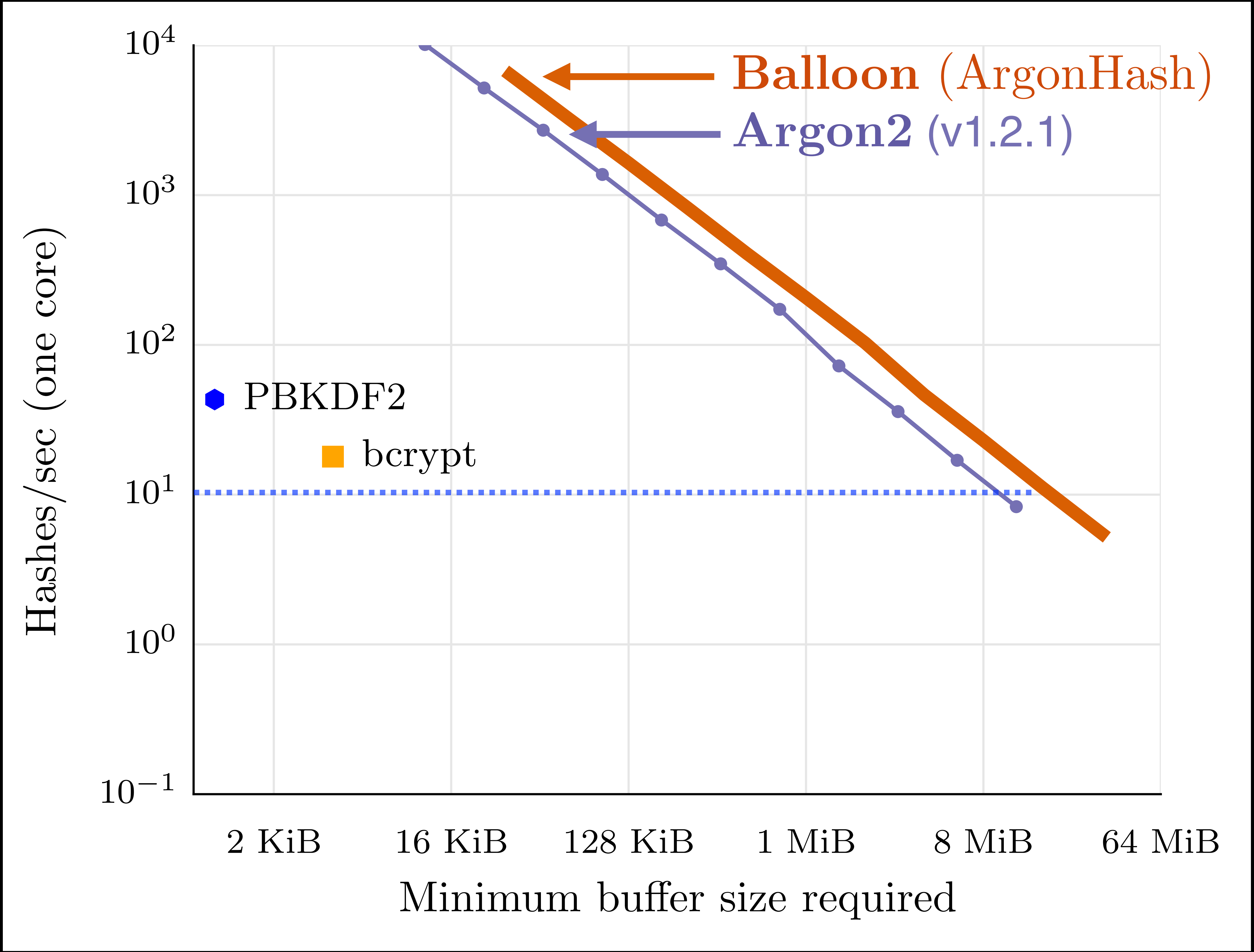

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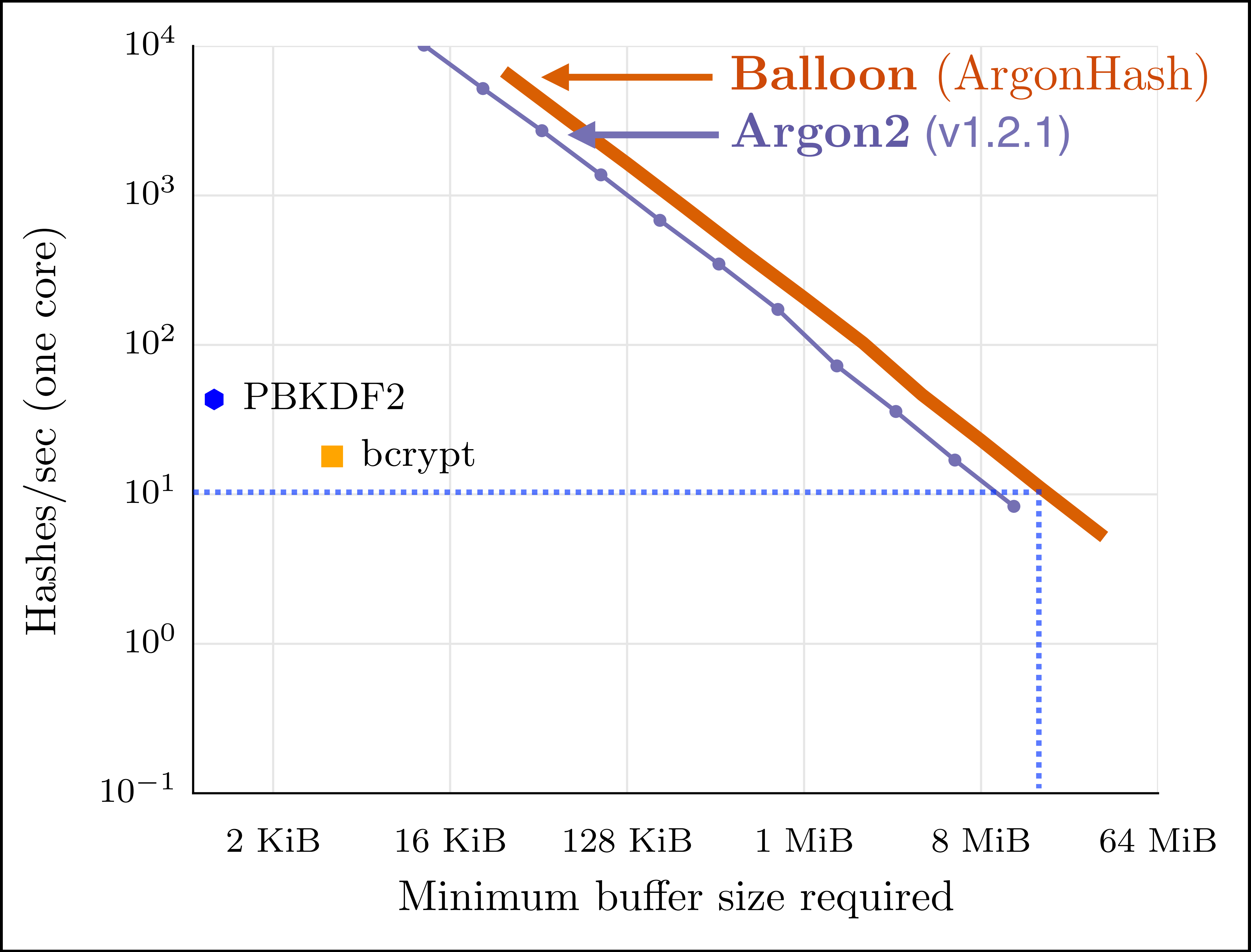

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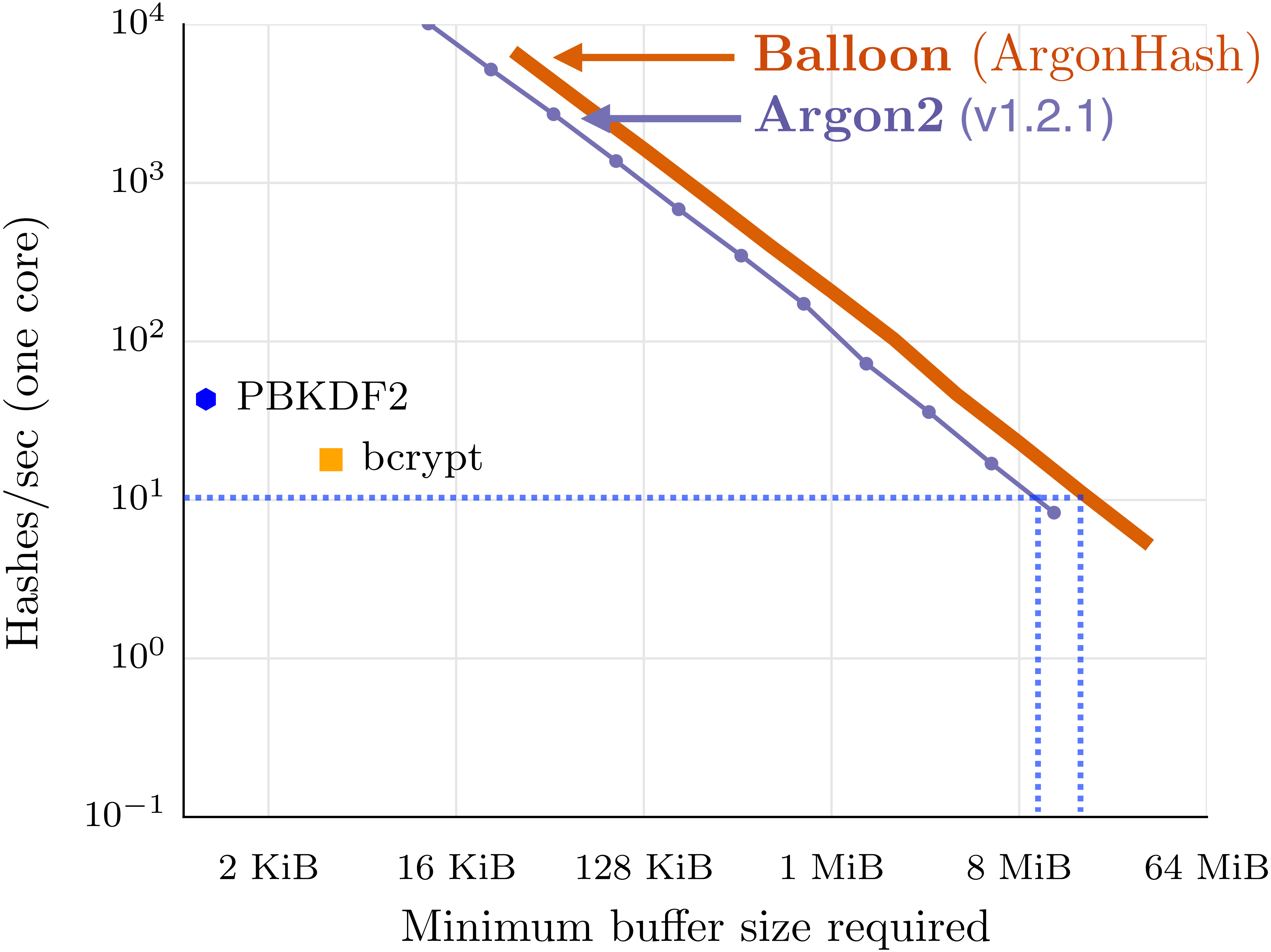

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II. Goals

III. The Balloon algorithm

IV. Discussion

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→ Not yet clear whether these attacks are of practical concern.

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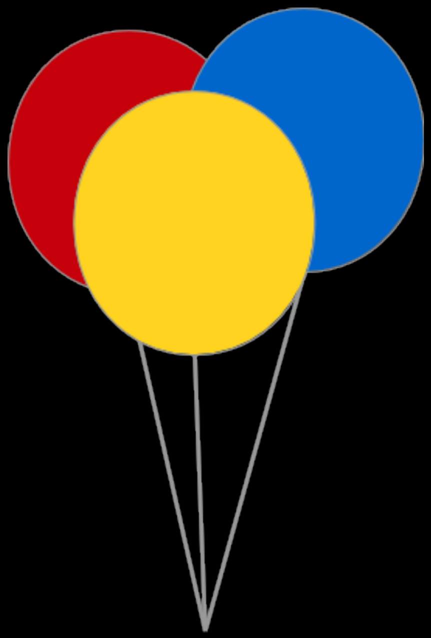
→ Balloon has stronger proven security properties than Argon2i.
(In practice…)

Conclusion



Henry Corrigan-Gibbs
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https://eprint.iacr.org/2016/027
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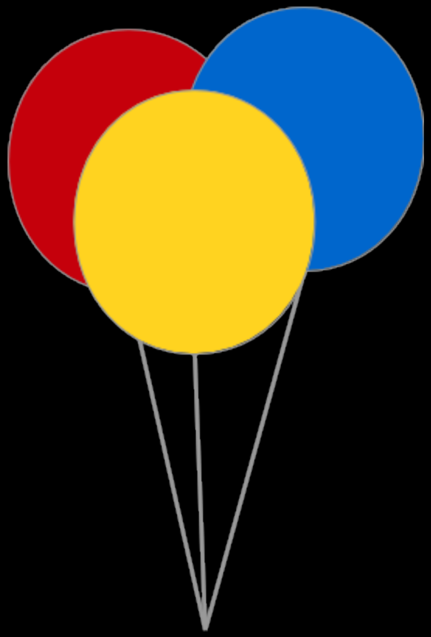
Conclusion



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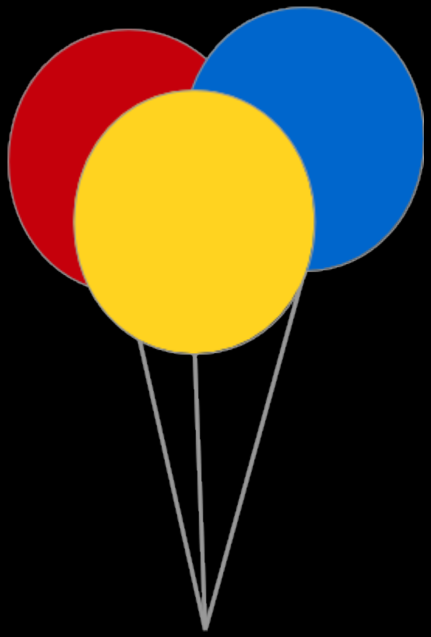

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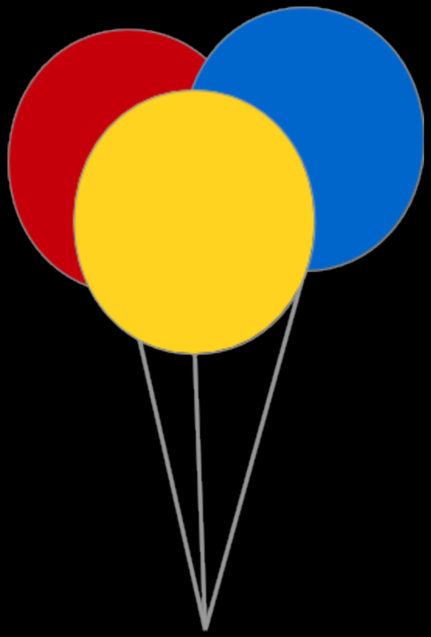

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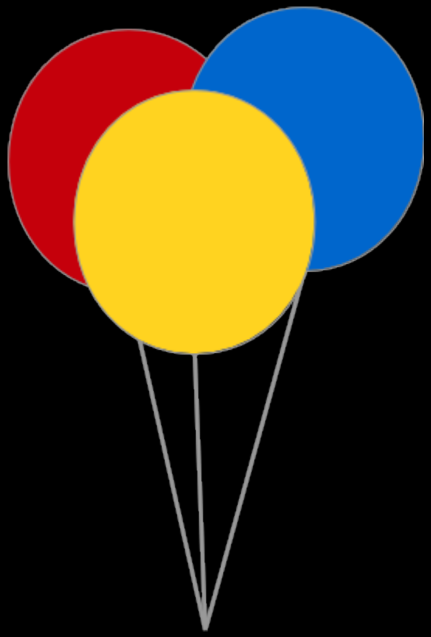

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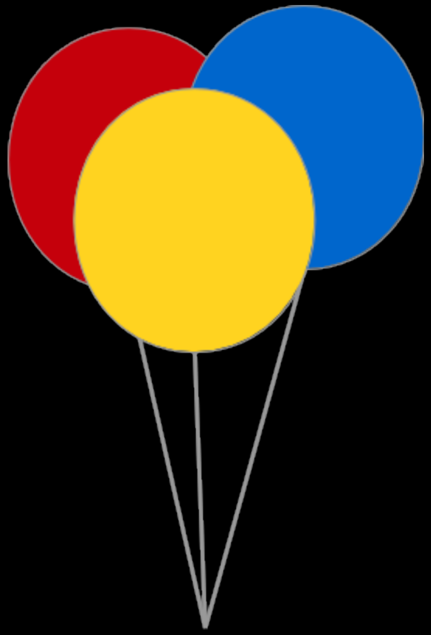

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```
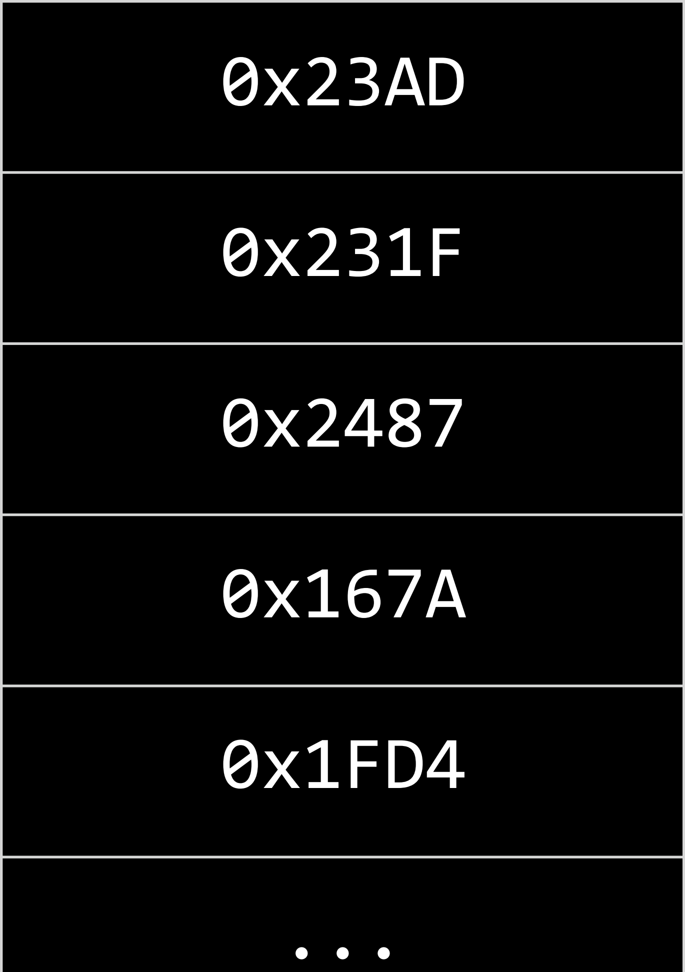

Attacking scrypt

An attacker who learns the memory access pattern of `scrypt(passwd)` can run a dictionary attack in *very little space*

`scrypt(passwd)`



```
0x23AD
0x231F
0x2487
0x167A
0x1FD4
...
```

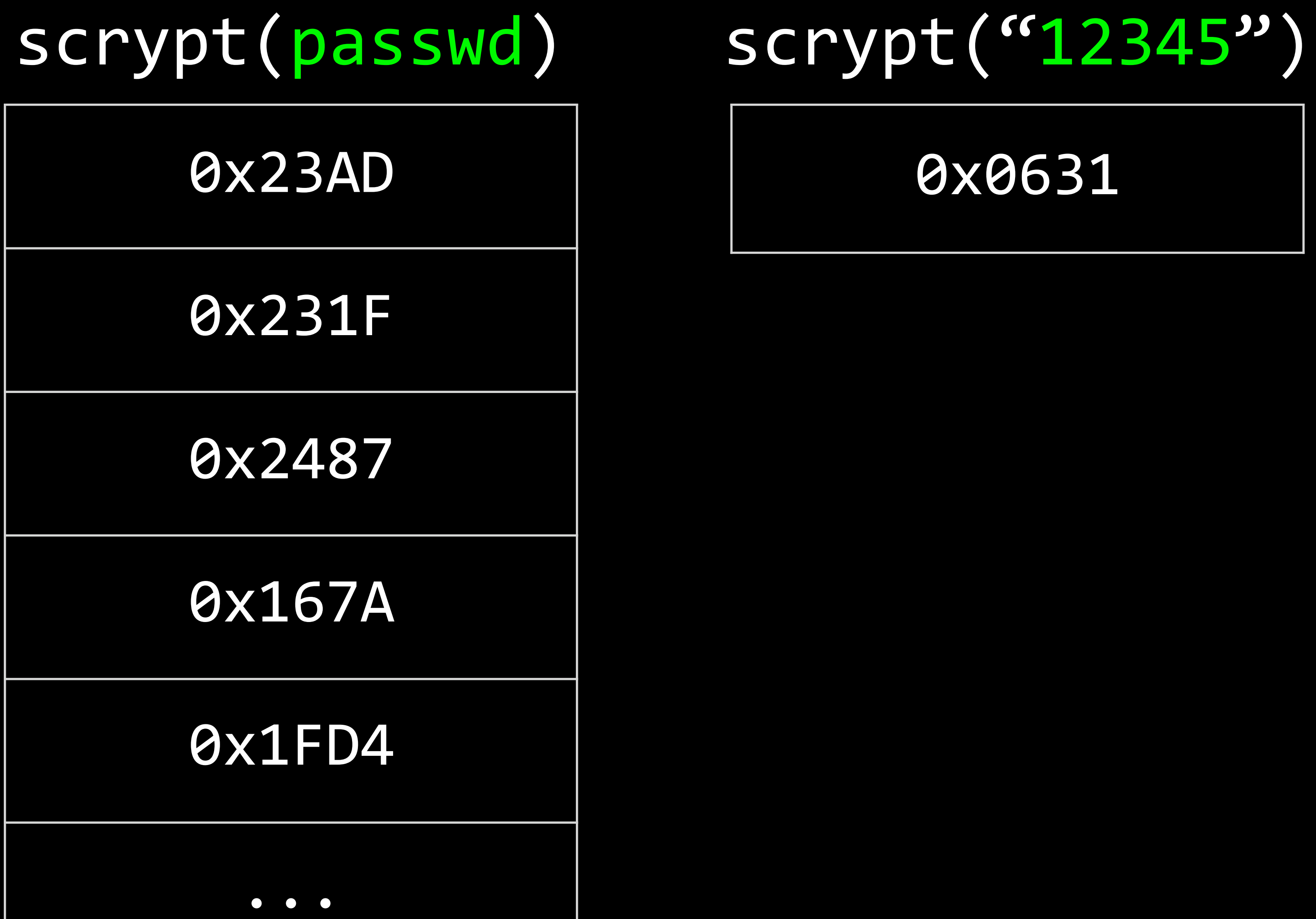
Attacking scrypt

An attacker who learns the memory access pattern of `scrypt(passwd)` can run a dictionary attack in *very little space*

`scrypt(passwd)`	`scrypt(“12345”)`
0x23AD	
0x231F	
0x2487	
0x167A	
0x1FD4	
...	

Attacking scrypt

An attacker who learns the memory access pattern of `scrypt(passwd)` can run a dictionary attack in *very little space*



`scrypt(passwd)`

`0x23AD`

`0x231F`

`0x2487`

`0x167A`

`0x1FD4`

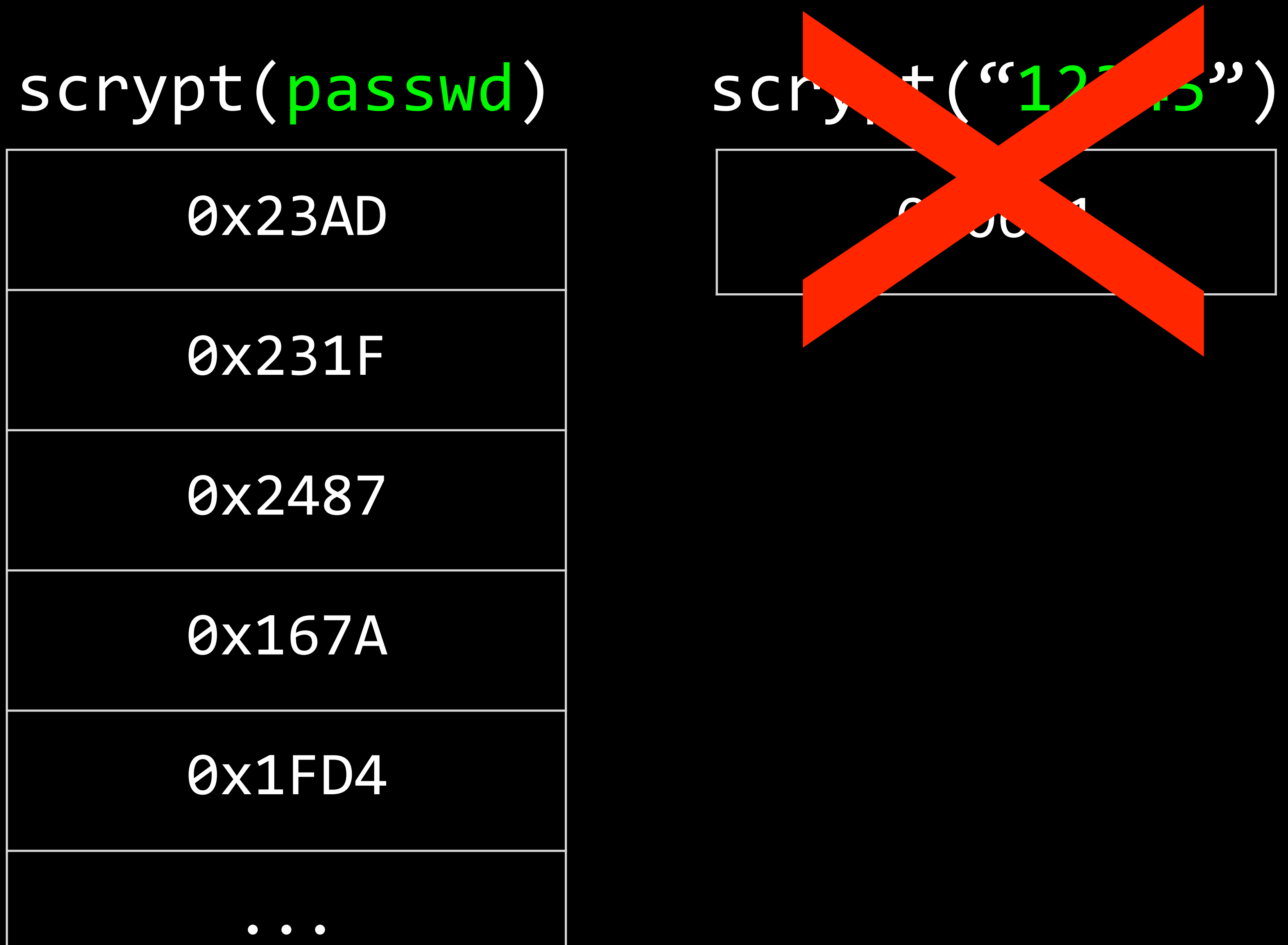
`...`

`scrypt(“12345”)`

`0x0631`

Attacking scrypt

An attacker who learns the memory access pattern of `scrypt(passwd)` can run a dictionary attack in *very little space*



scrypt(passwd)

0x23AD

0x231F

0x2487

0x167A

0x1FD4

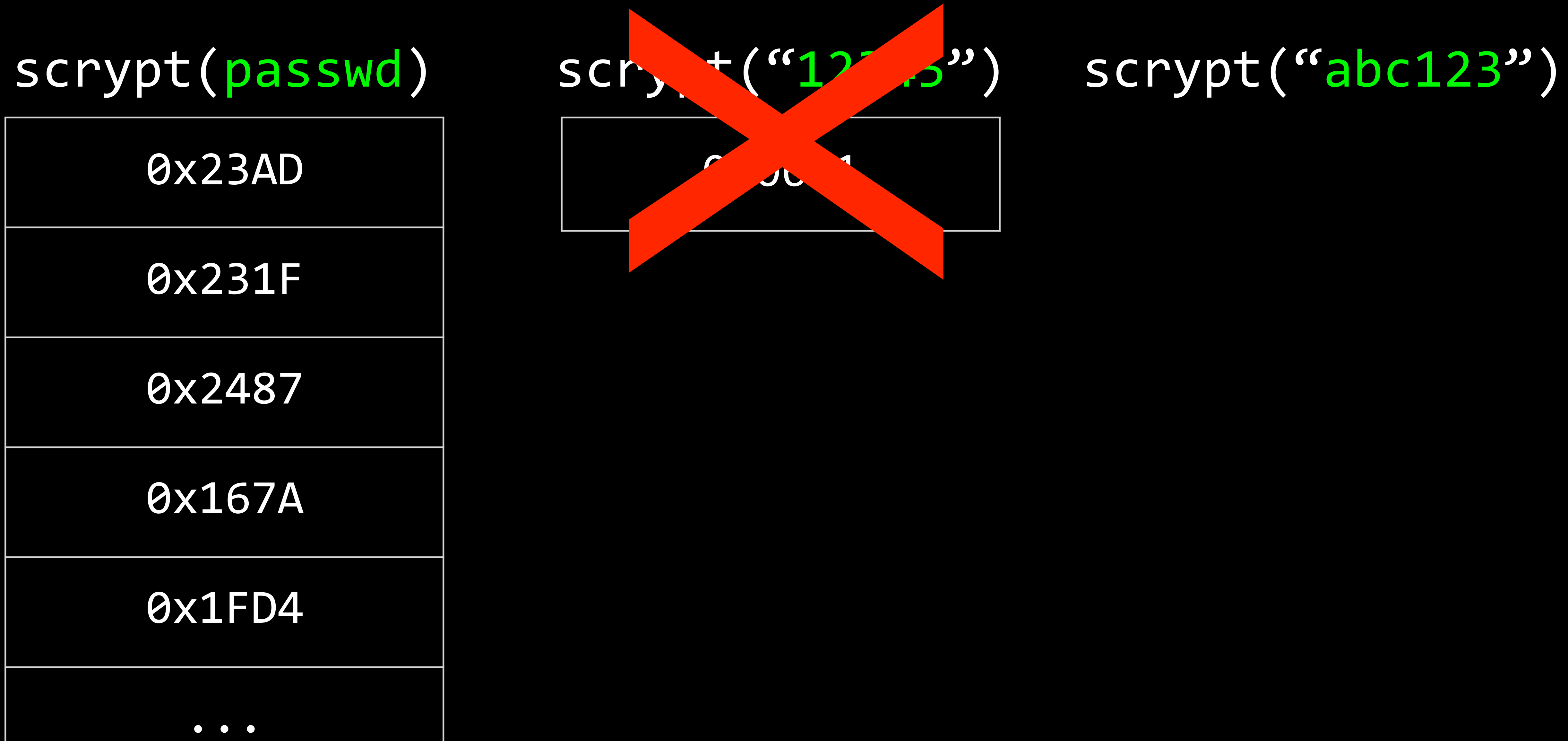
...

scrypt(“12345”)

0x0001

Attacking scrypt

An attacker who learns the memory access pattern of `scrypt(passwd)` can run a dictionary attack in *very little space*



`scrypt(passwd)`

```
0x23AD
0x231F
0x2487
0x167A
0x1FD4
...
```

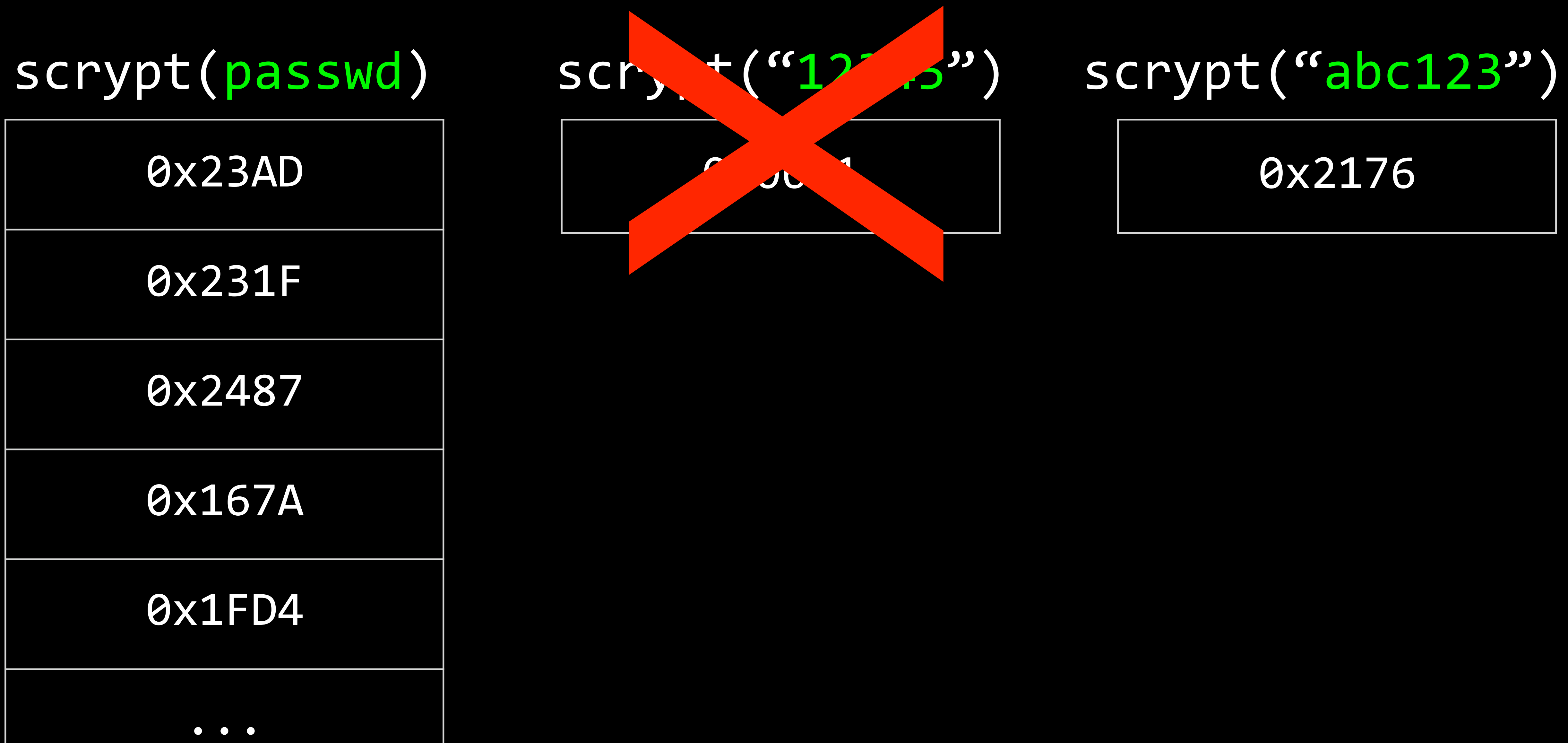
~~`scrypt("12345")`~~

~~`0x00[illegible]1`~~

`scrypt("abc123")`

Attacking scrypt

An attacker who learns the memory access pattern of `scrypt(passwd)` can run a dictionary attack in *very little space*



```
scrypt(passwd)
0x23AD
0x231F
0x2487
0x167A
0x1FD4
...
```

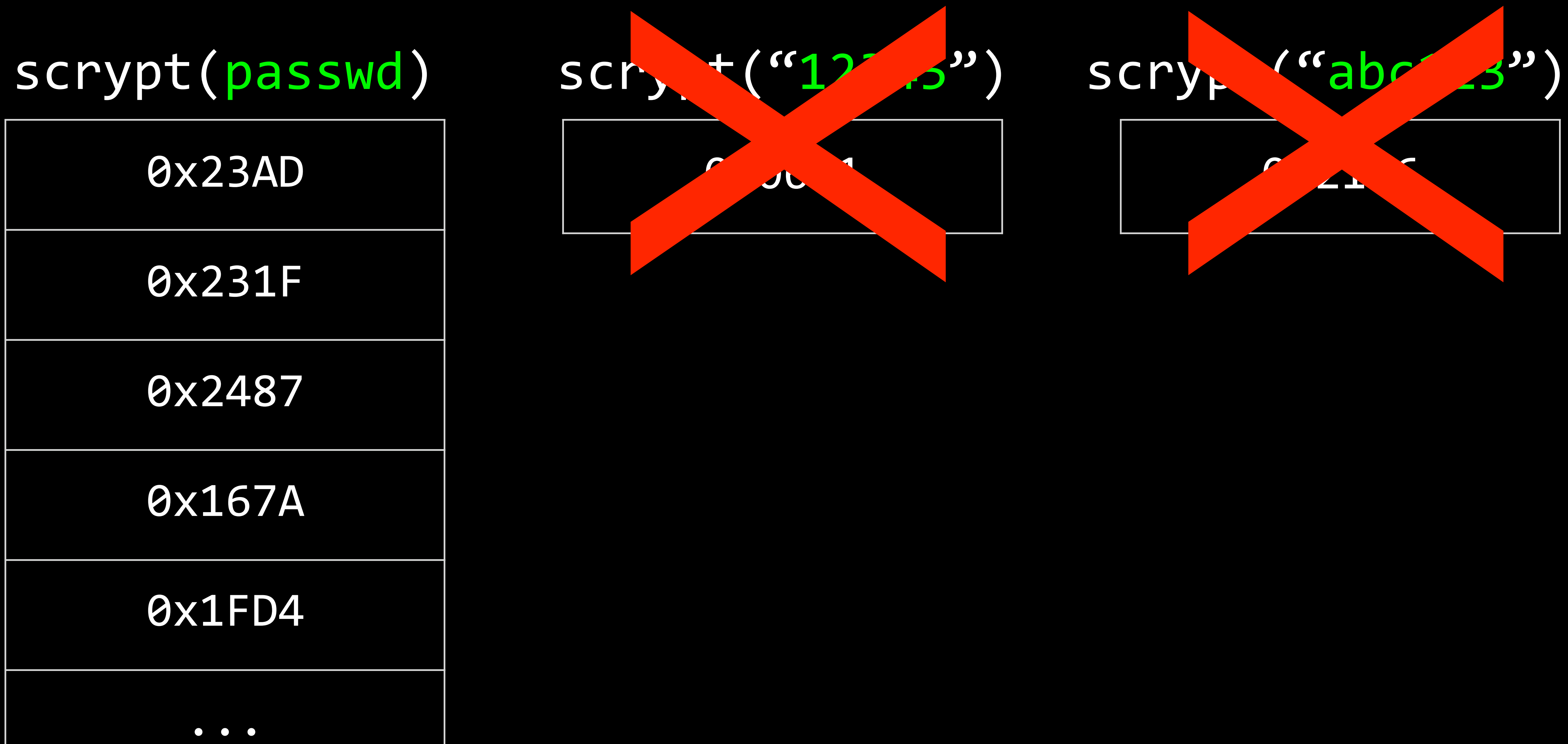
~~scrypt(“12345”)~~

[illegible]

```
scrypt(“abc123”)
0x2176
```

Attacking scrypt

An attacker who learns the memory access pattern of `scrypt(passwd)` can run a dictionary attack in *very little space*



scrypt(passwd)

0x23AD

0x231F

0x2487

0x167A

0x1FD4

...

~~scrypt(“12345”)~~

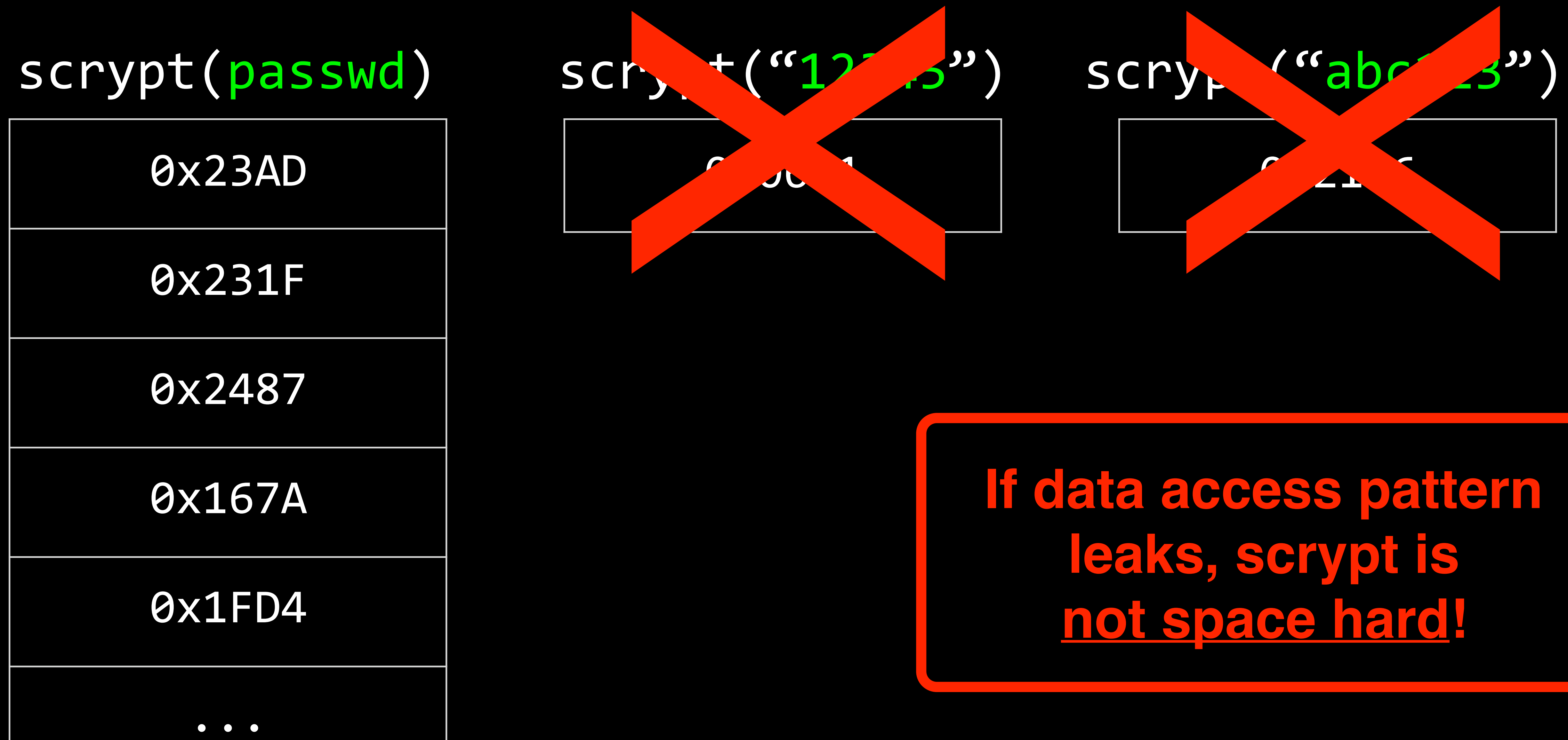
~~0x00[illegible]1~~

~~scrypt(“abc123”)~~

~~0x21[illegible]C~~

Attacking scrypt

An attacker who learns the memory access pattern of `scrypt(passwd)` can run a dictionary attack in *very little space*



`scrypt(passwd)`

```
0x23AD
0x231F
0x2487
0x167A
0x1FD4
...
```

~~scrypt(“12345”)~~

~~[illegible]~~

~~scrypt(“abc123”)~~

~~[illegible]~~

If data access pattern leaks, scrypt is <u>not space hard</u>!