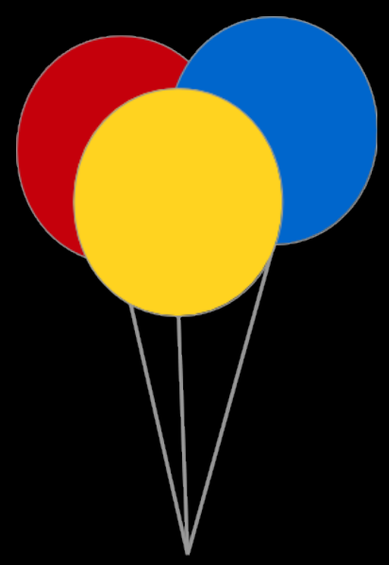

Balloon Hashing

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
11:35
WED, SEPTEMBER 17
THU 7:00 AM
YouTube
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Play Store


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WED, SEPTEMBER 17
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Play Store


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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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dave	0xfb791a9a	0x1dbd71f3

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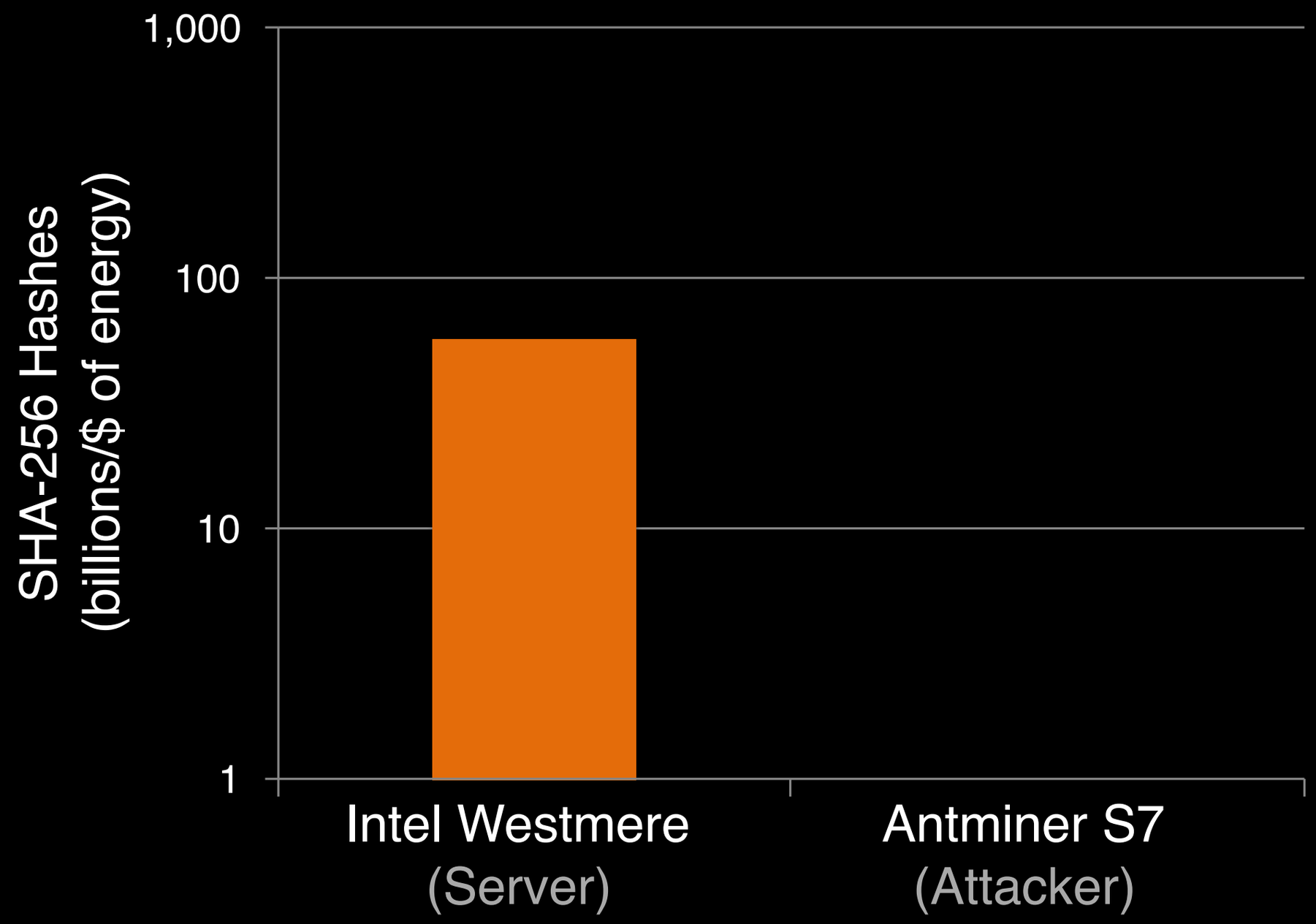
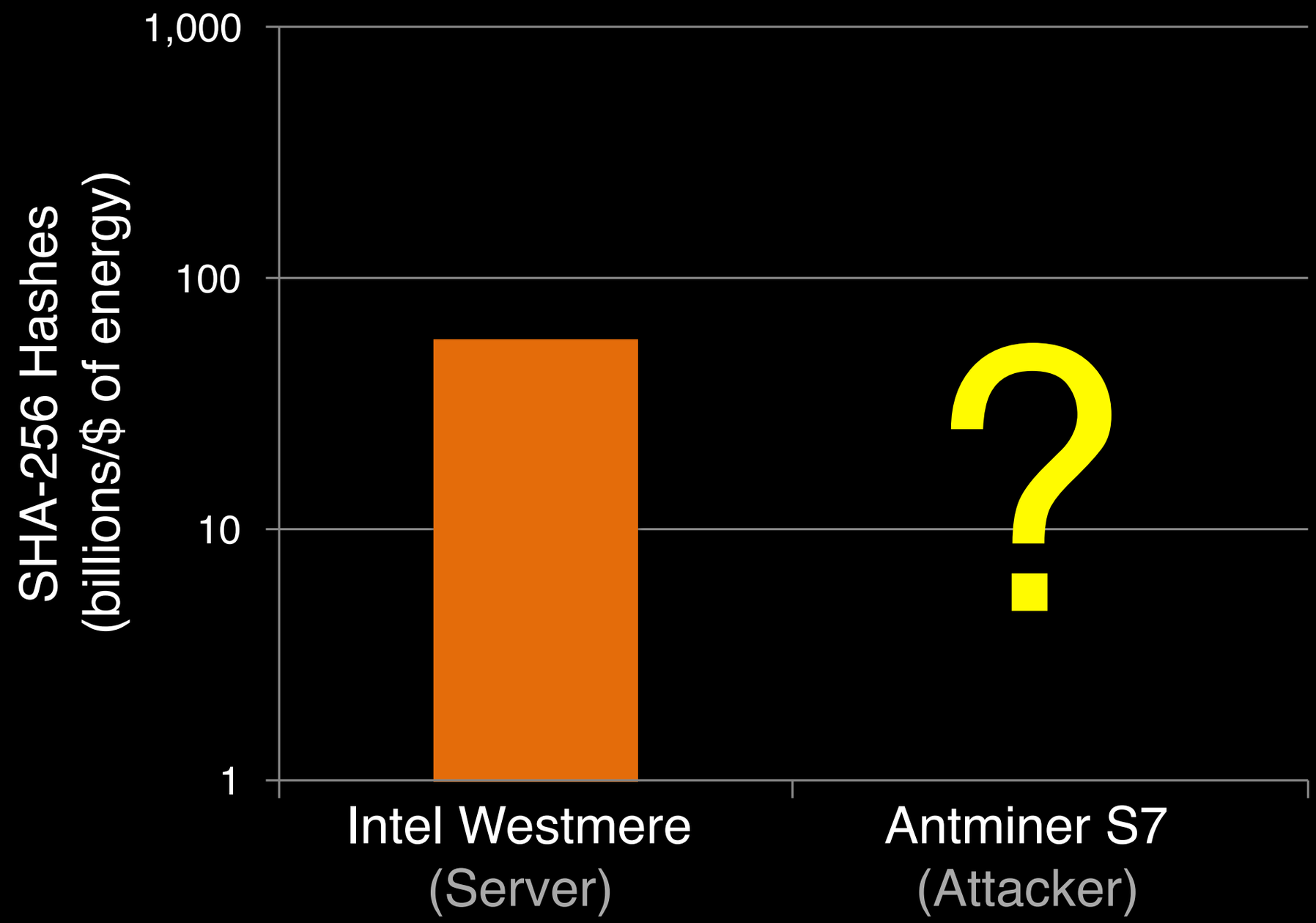
By this metric, conventional hash functions (e.g., SHA-256) are far from optimal!


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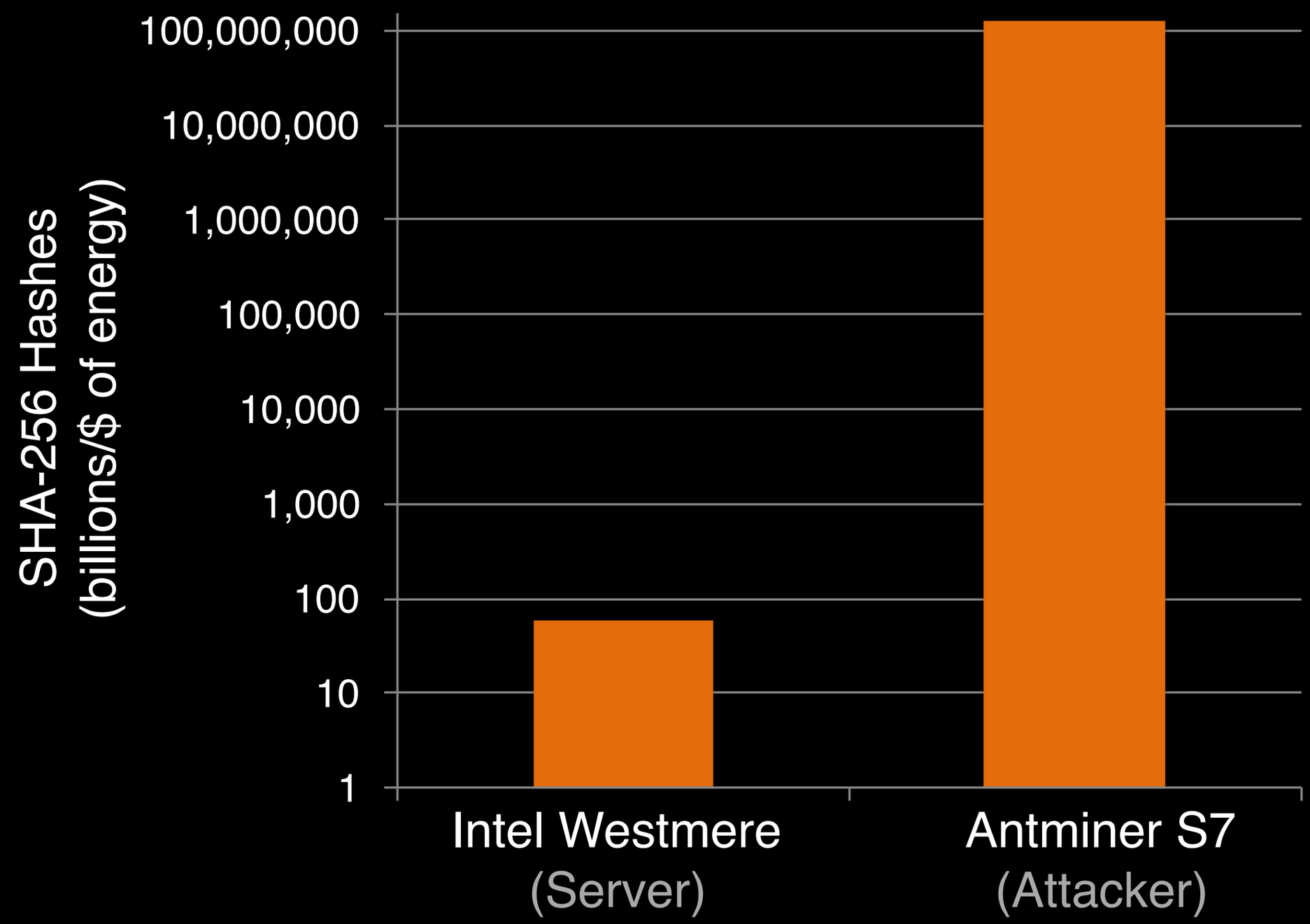
(Attacker)


SHA-256 Hashes
(billions/$ of energy)
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Intel Westmere
(Server)
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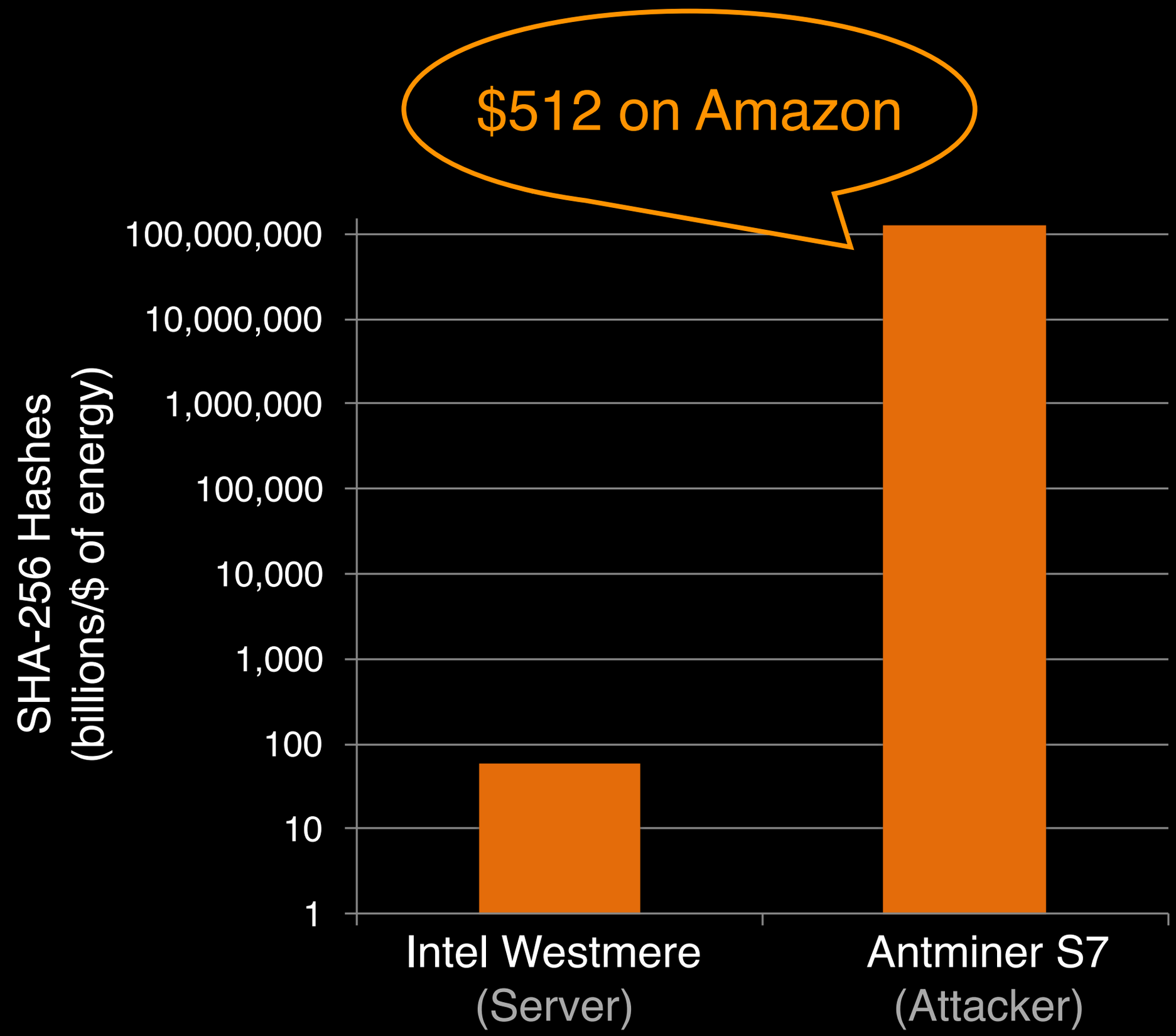
$512 on Amazon
SHA-256 Hashes
(billions/$ of energy)
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Intel Westmere
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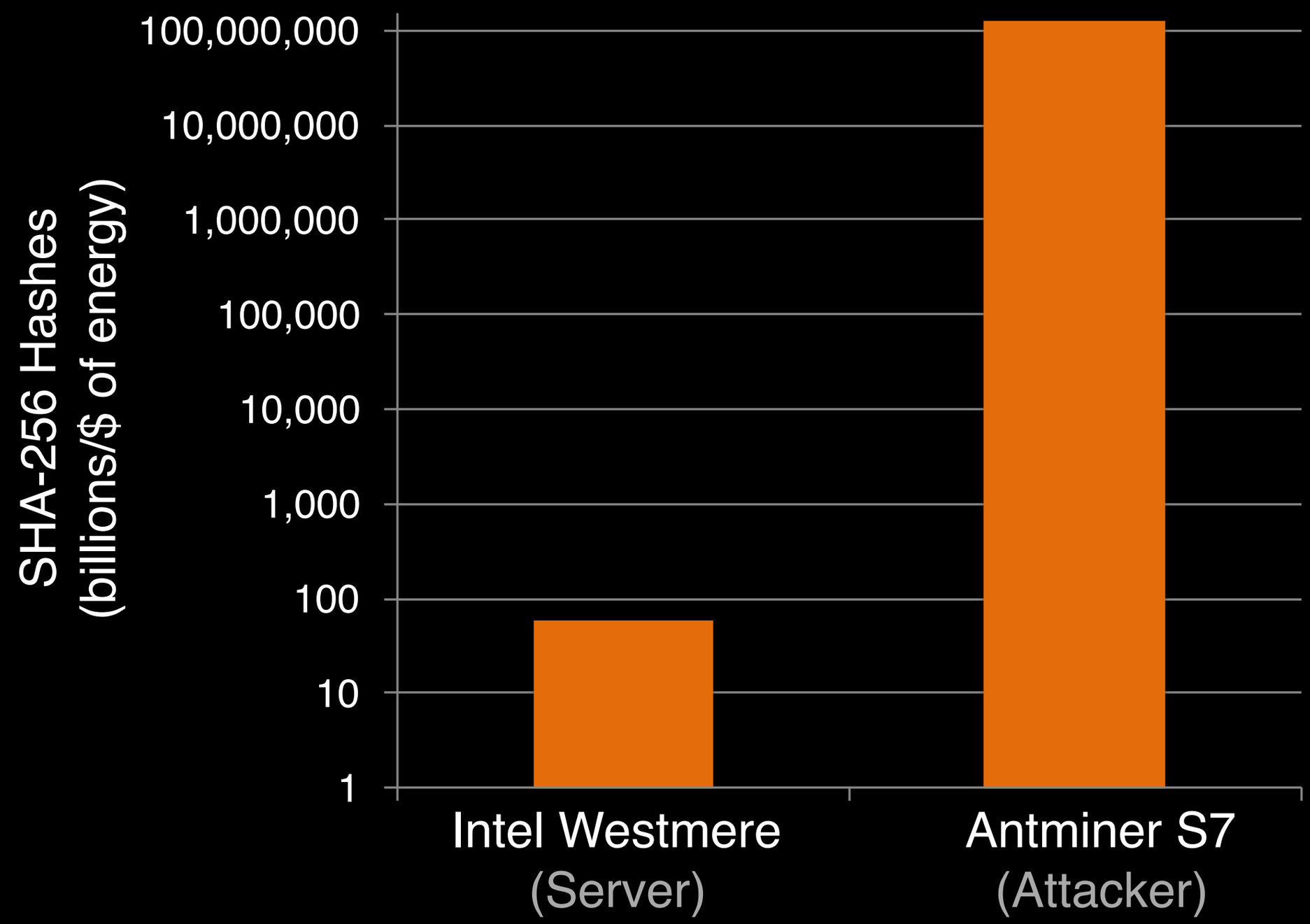
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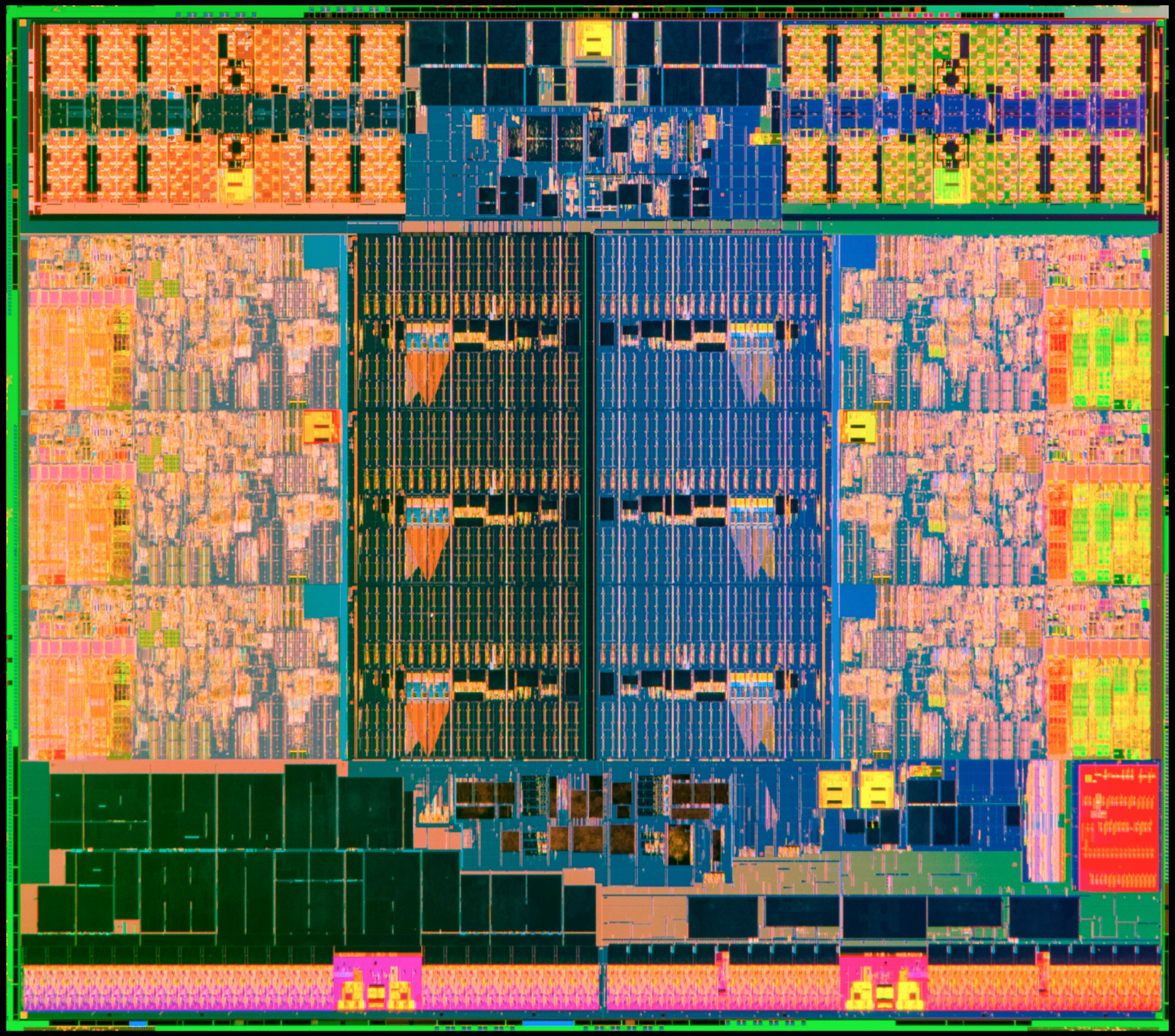
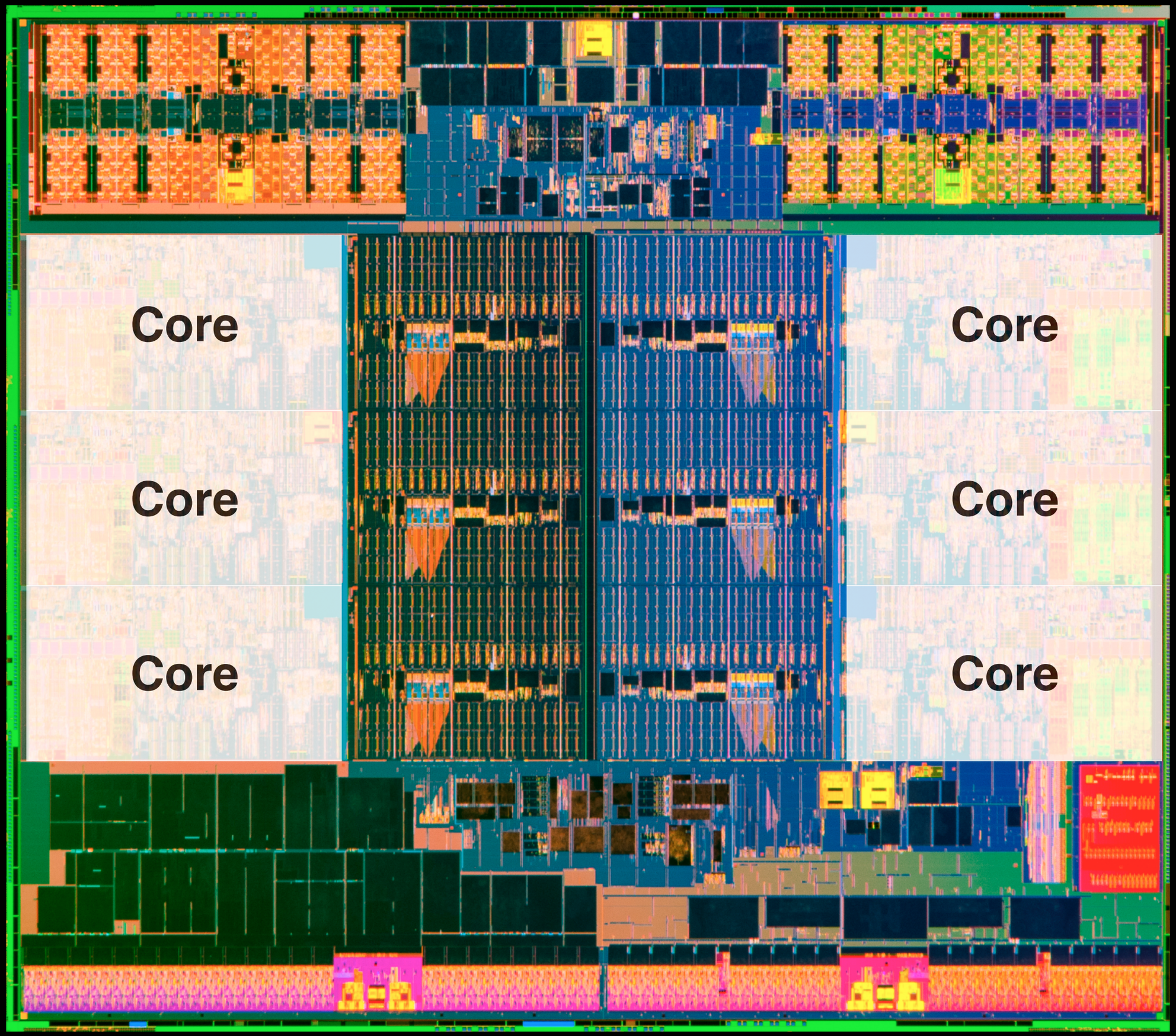


Intel Ivy Bridge-E Core i7-4960X
http://kylebennett.com/files/hfpics/IVB-E_%28LCC%29_Die_Wafer_Shot-7837.jpg



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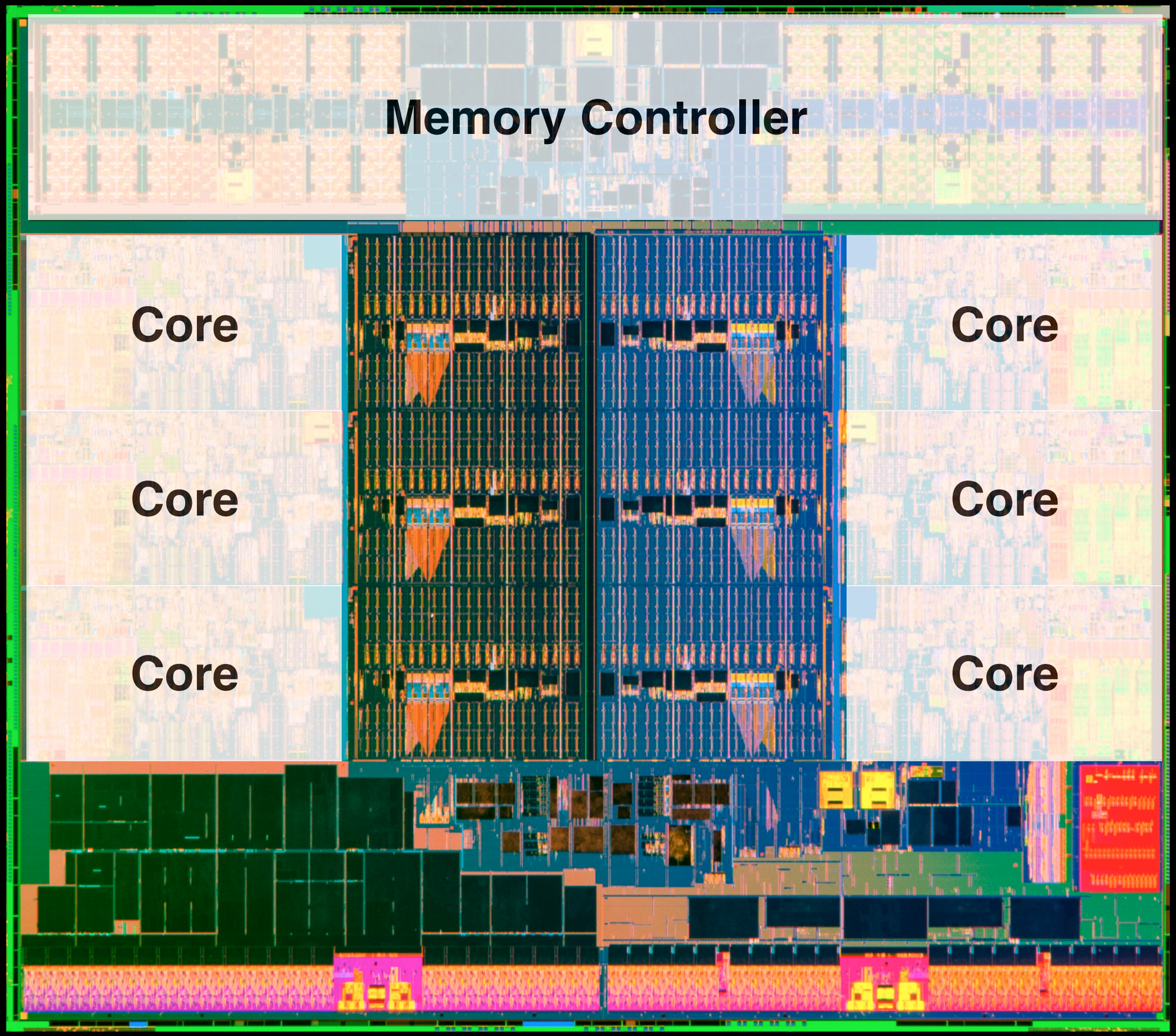

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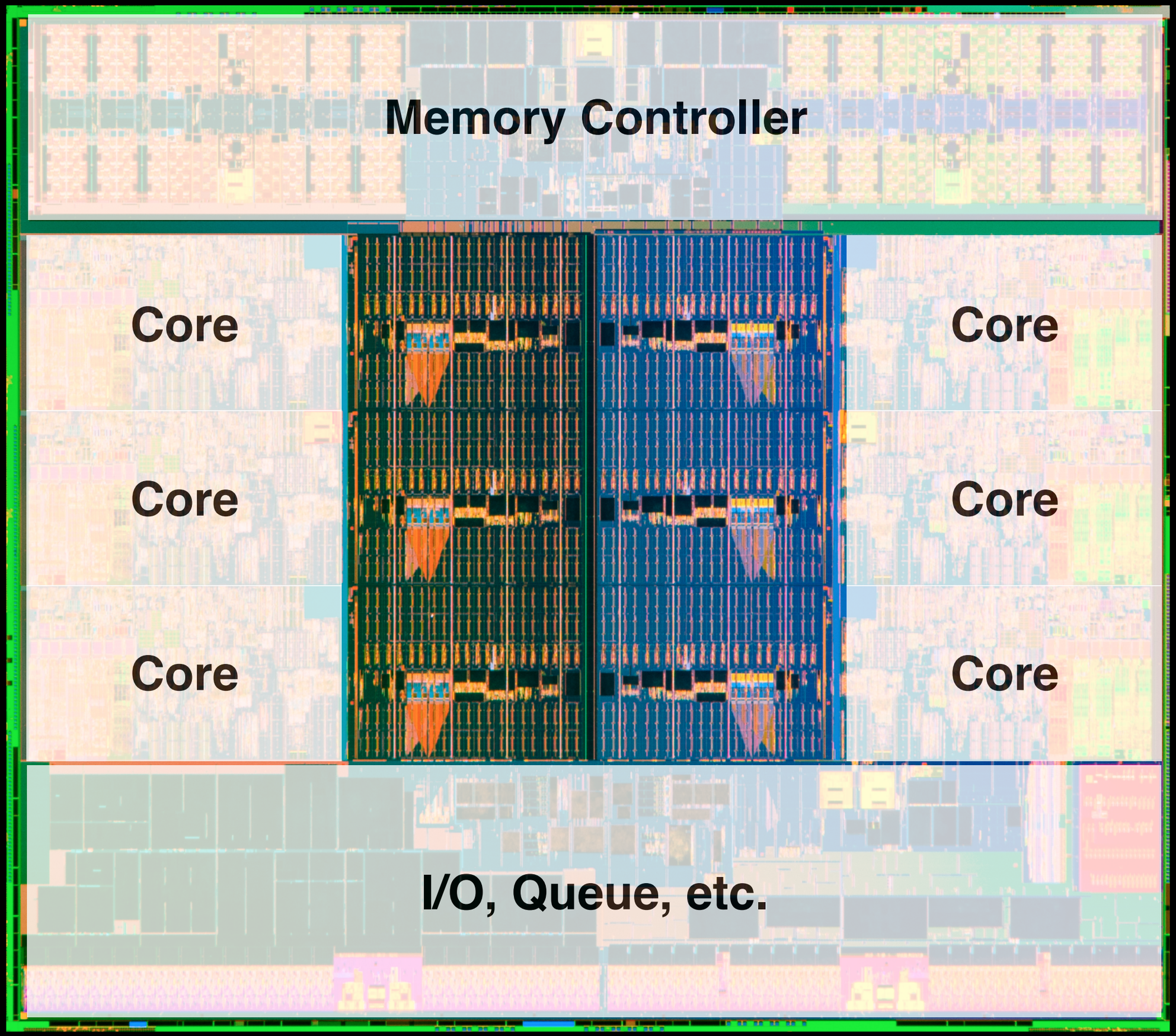

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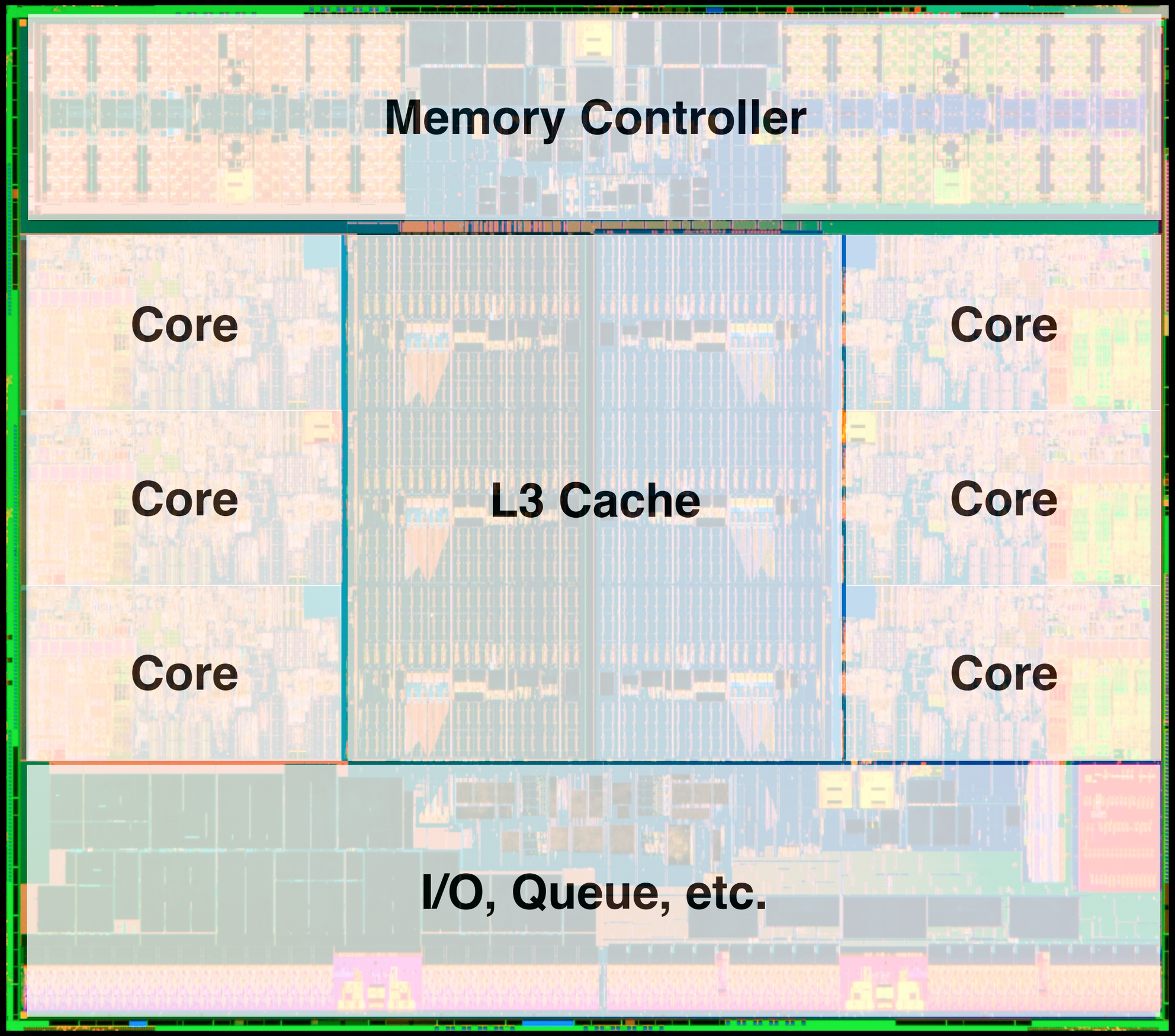

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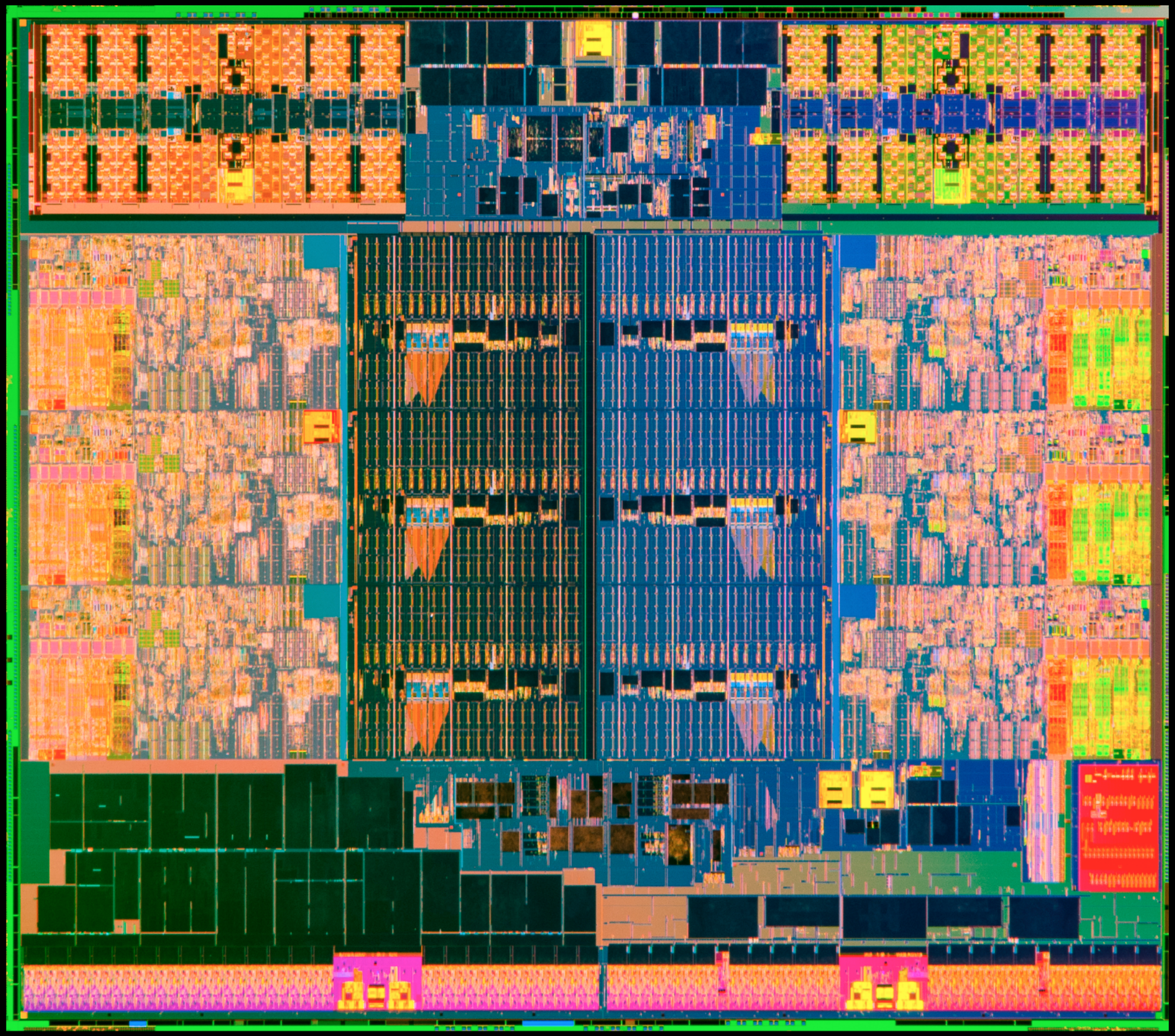

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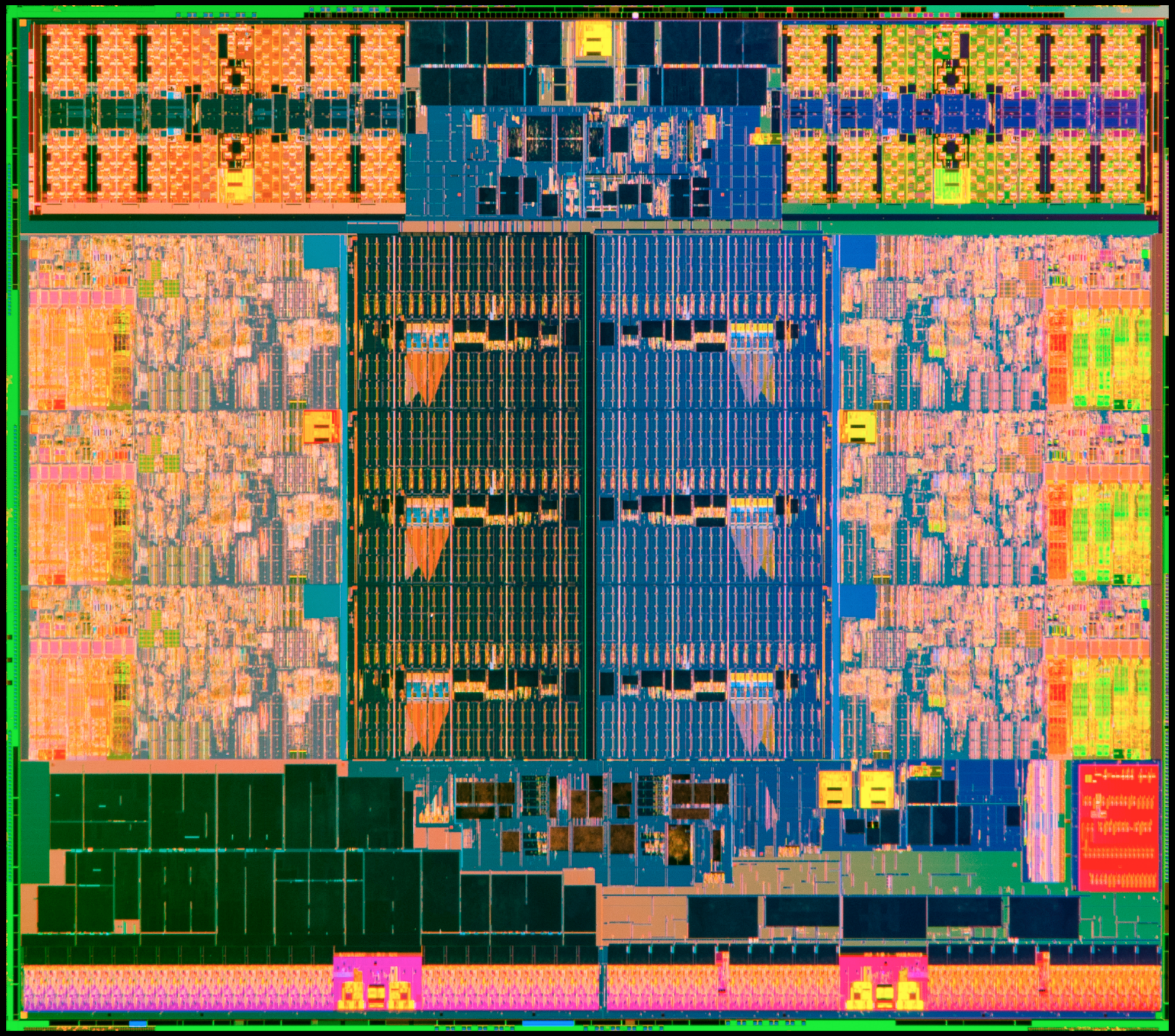

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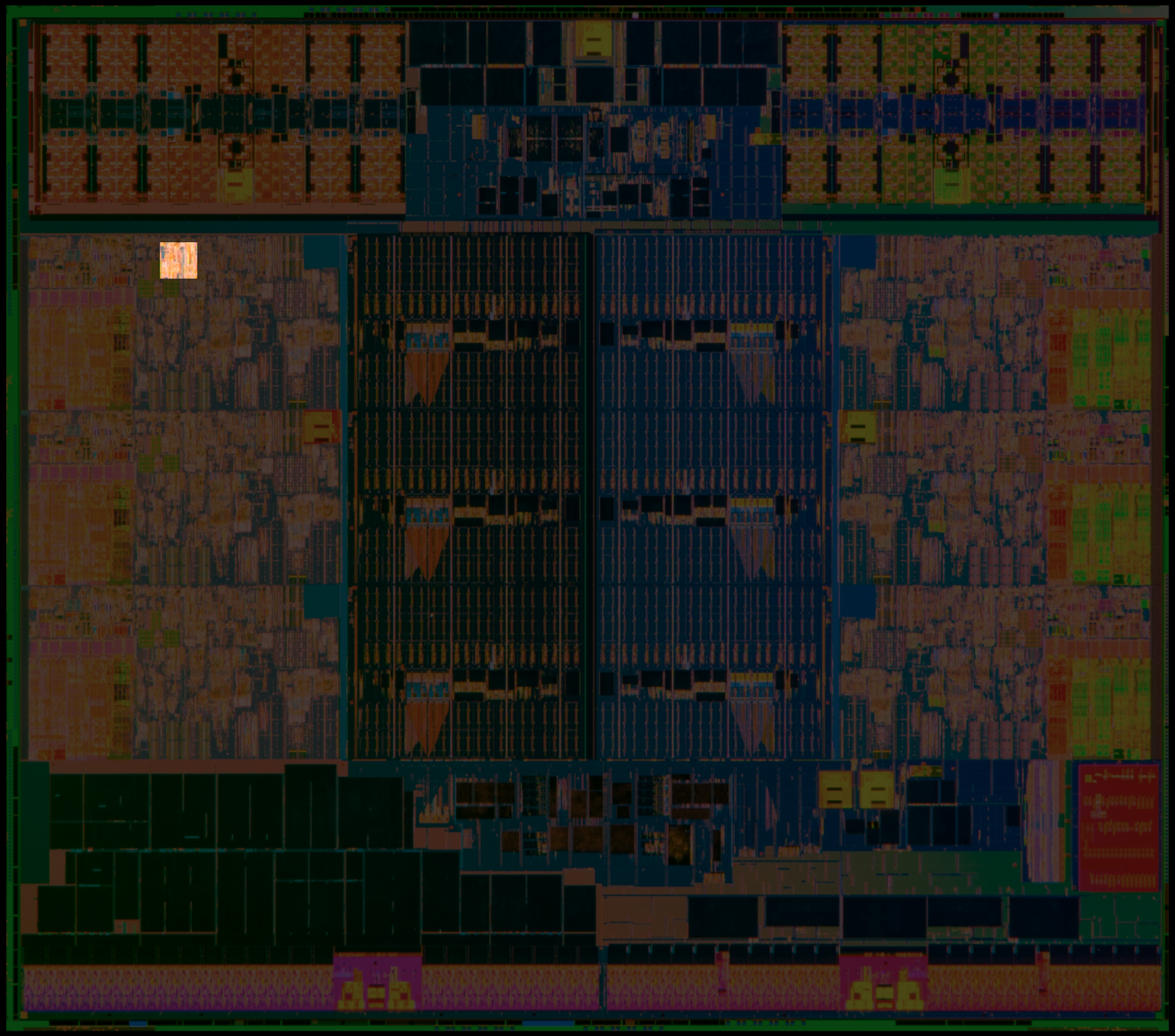

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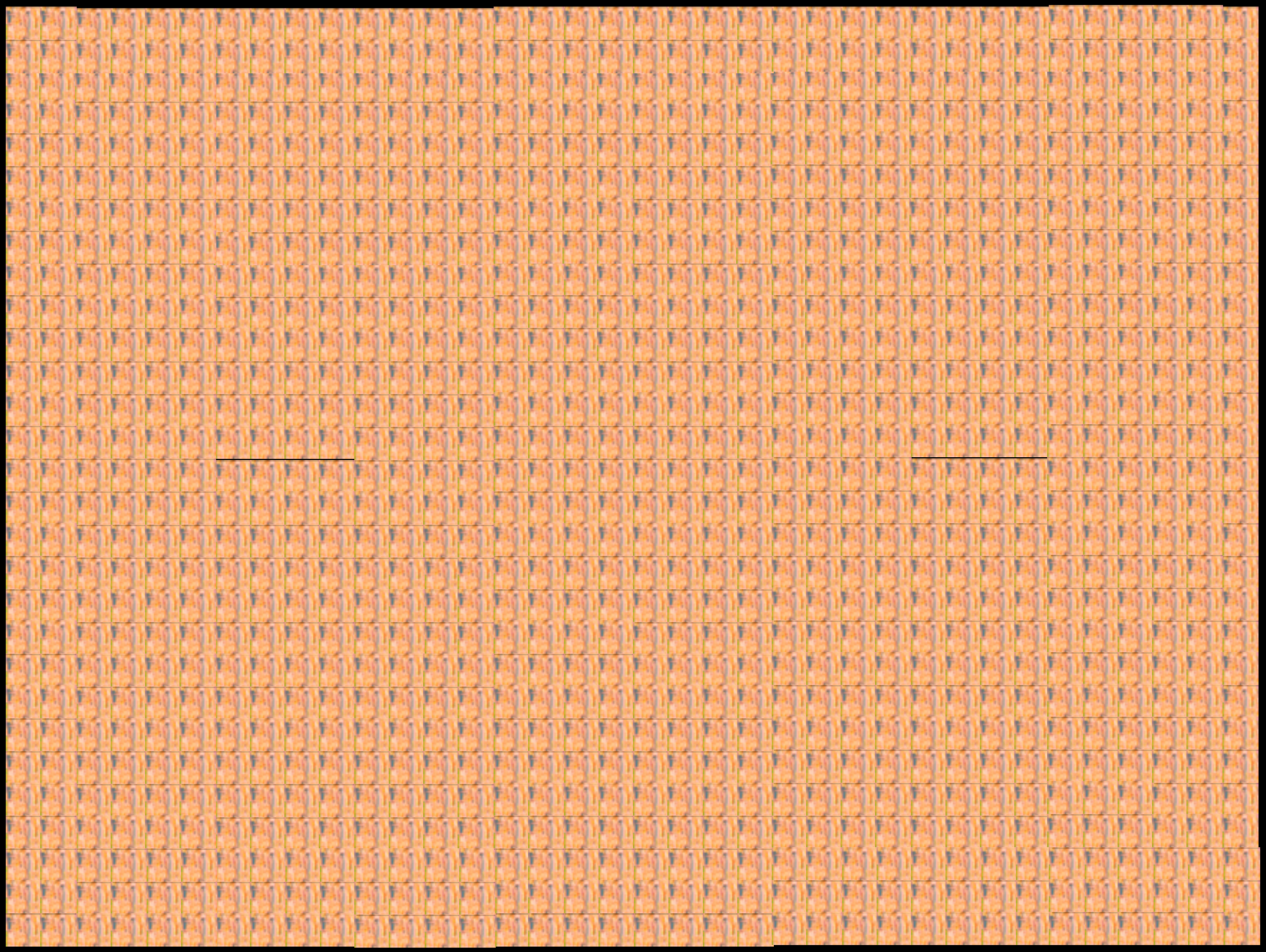
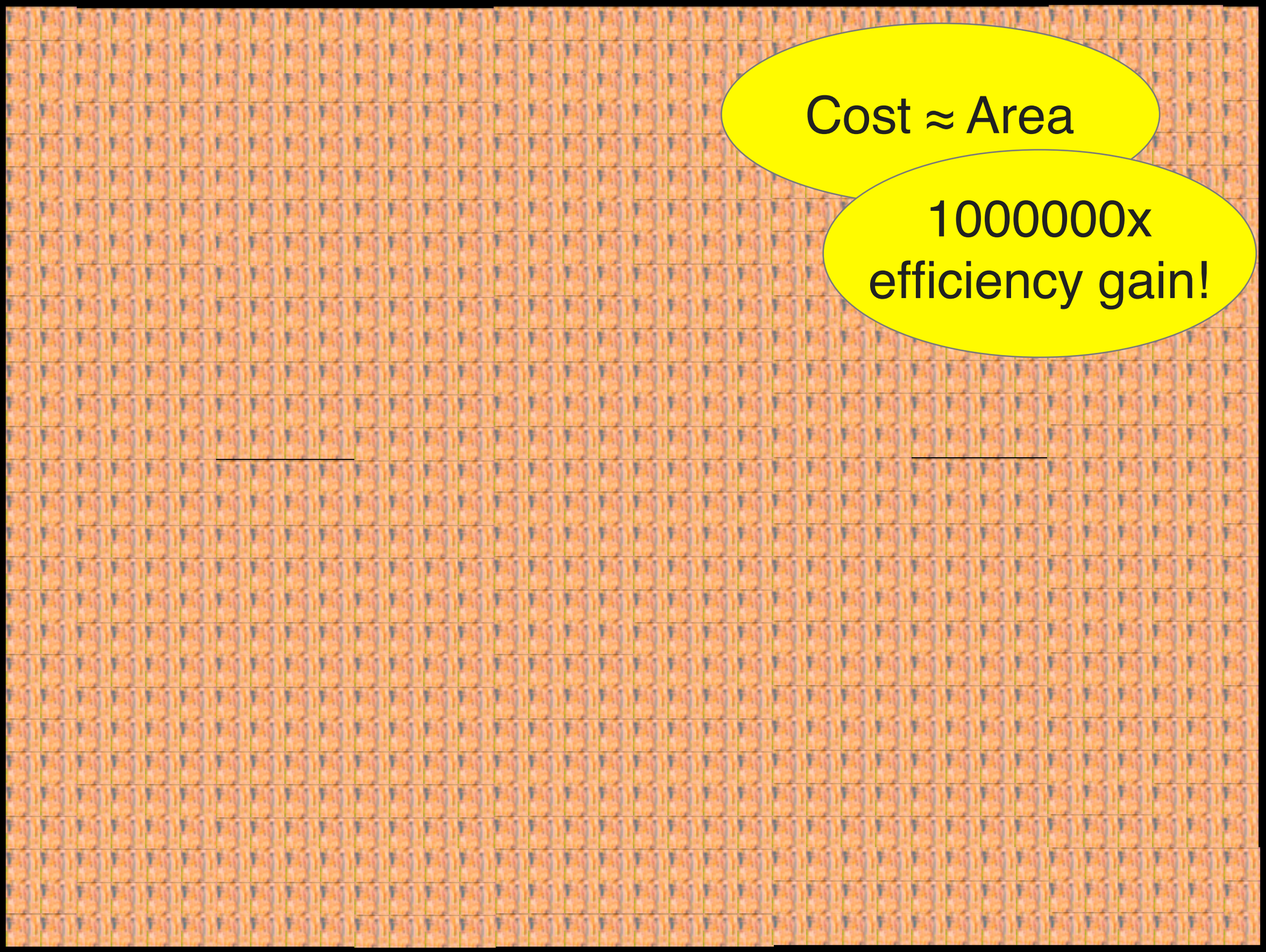
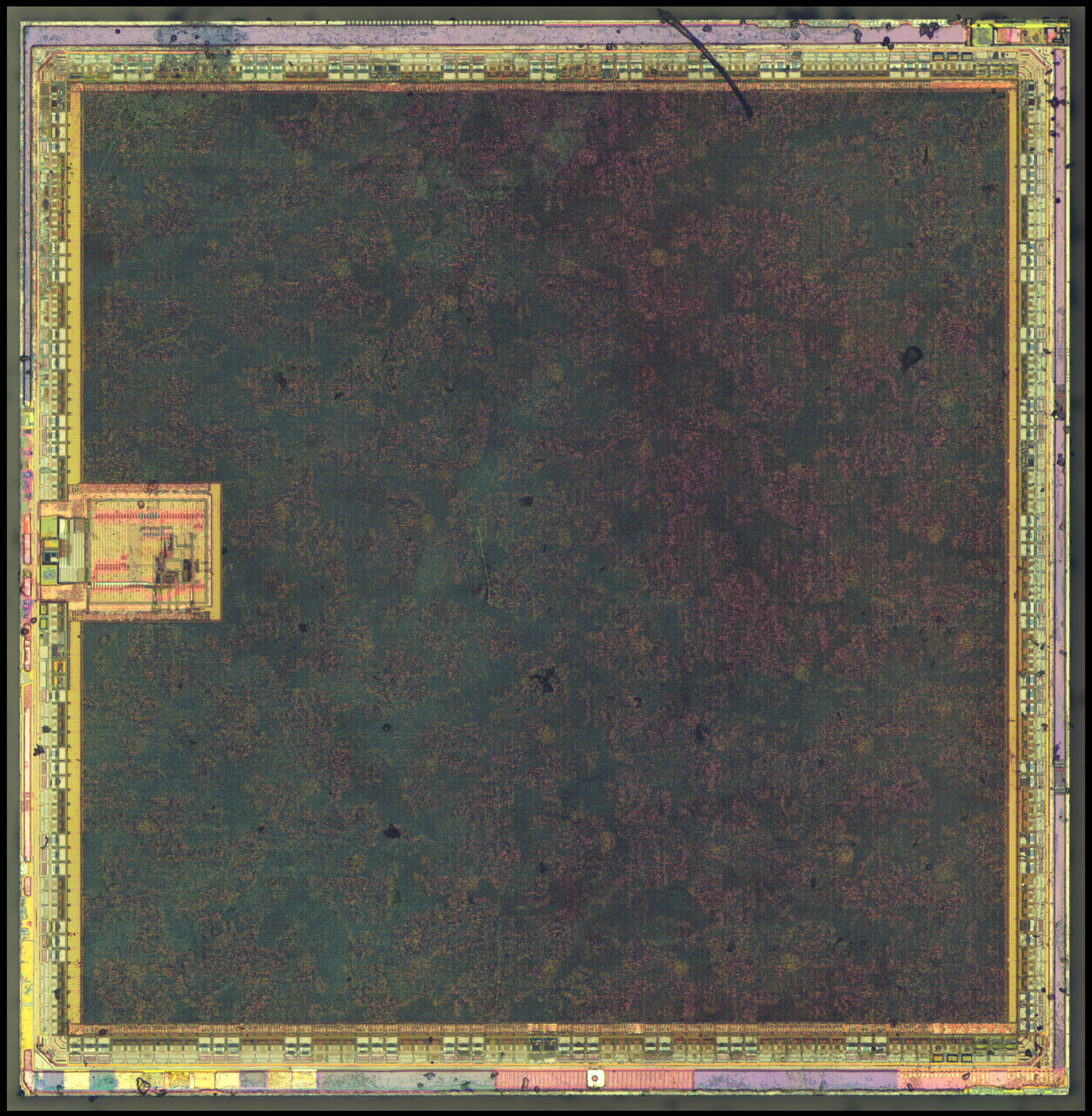



Cost ≈ Area


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

Intel Ivy Bridge-E Core i7-4960X
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Without memory-hardness

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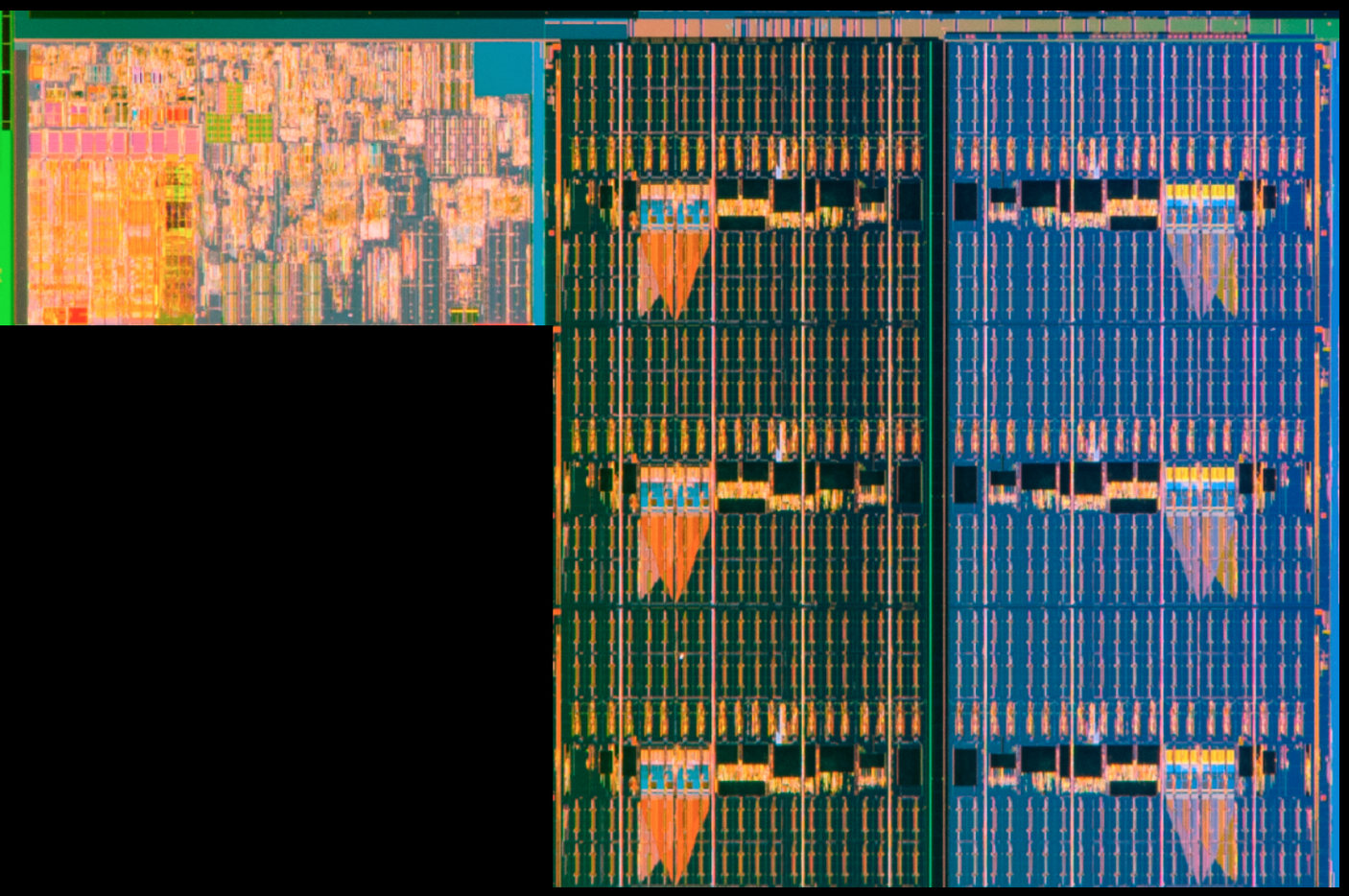
Without
memory-hardness



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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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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
  [Tsunoo *et al.* 2003] [Bernstein 2005] [Bonneau & Mironov 2006] […]

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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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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]

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2. Uses a password-independent data access pattern
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```
Balloon(password, salt, N = space_cost, R = num_rounds):
    δ ← 3                    // A security parameter.
    var B_1, …, B_N          // A buffer of N blocks.

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

    // Step 2: Mix Buffer
    for r = 1, …, R:
        for i = 1,…, N:
            // Chosen pseudorandomly from salt
            (v_1, …, v_δ) ← Hash( salt, r, i ) ∈ Z_N^δ
            B_i ← Hash(B_{(i-1 mod N)}, B_i, B_{v_1}, …, B_{v_δ})

    // 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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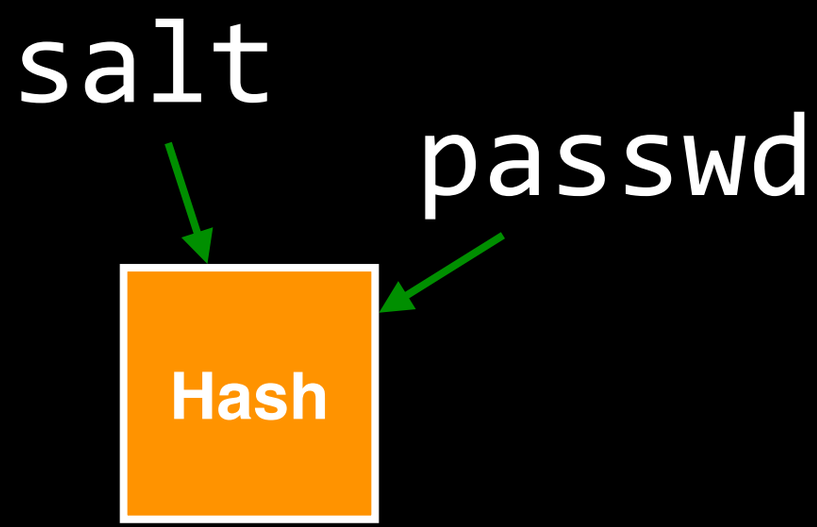
```
salt
      passwd
```

Balloon Hashing Algorithm

salt

passwd

Balloon Hashing Algorithm



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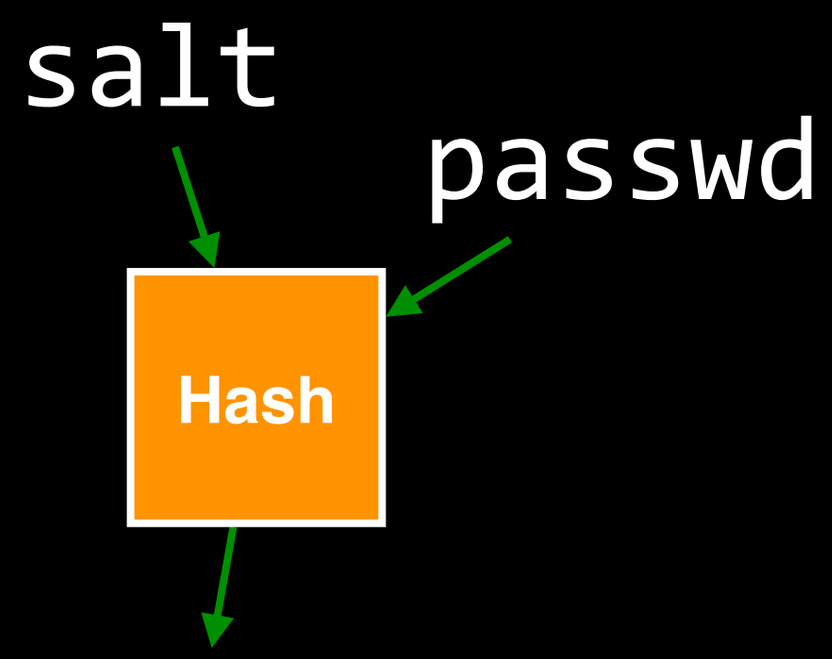

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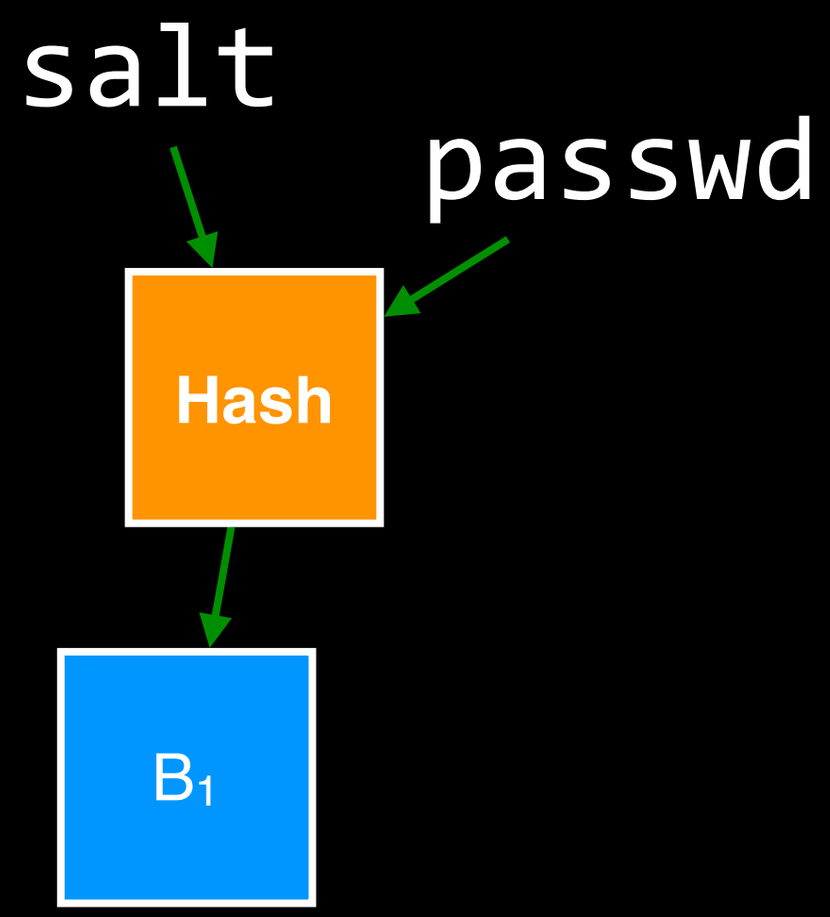

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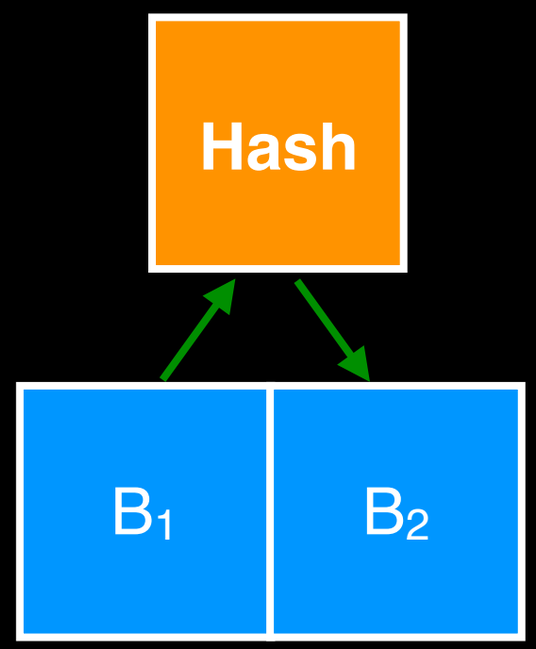

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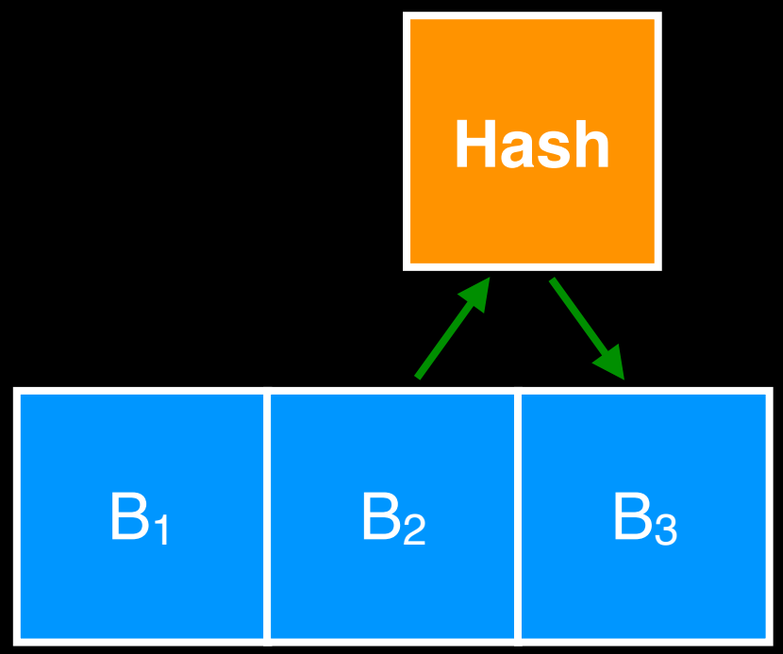

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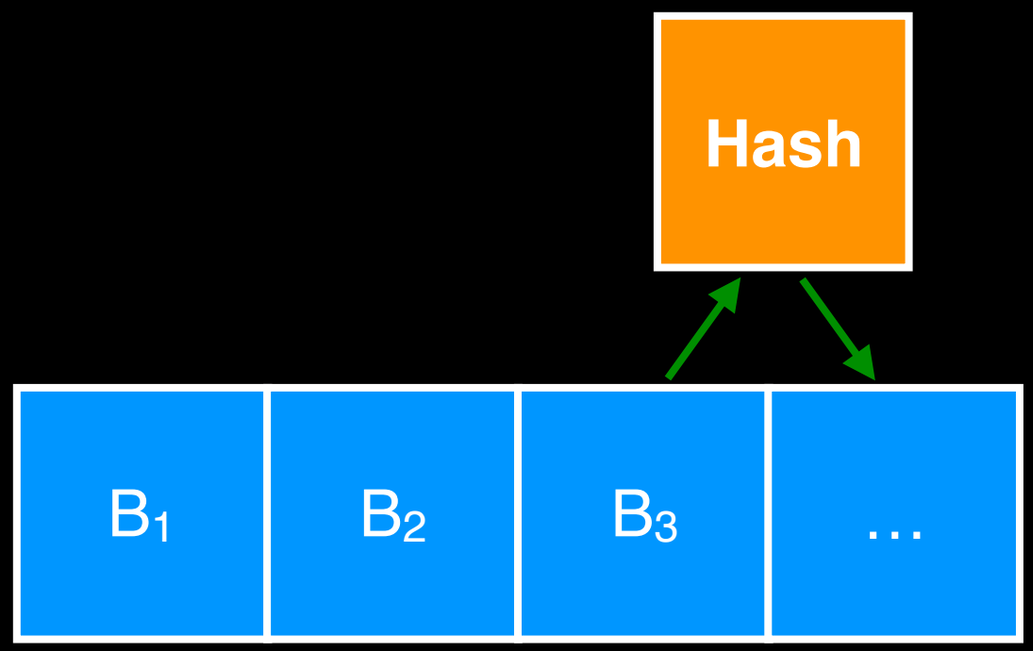

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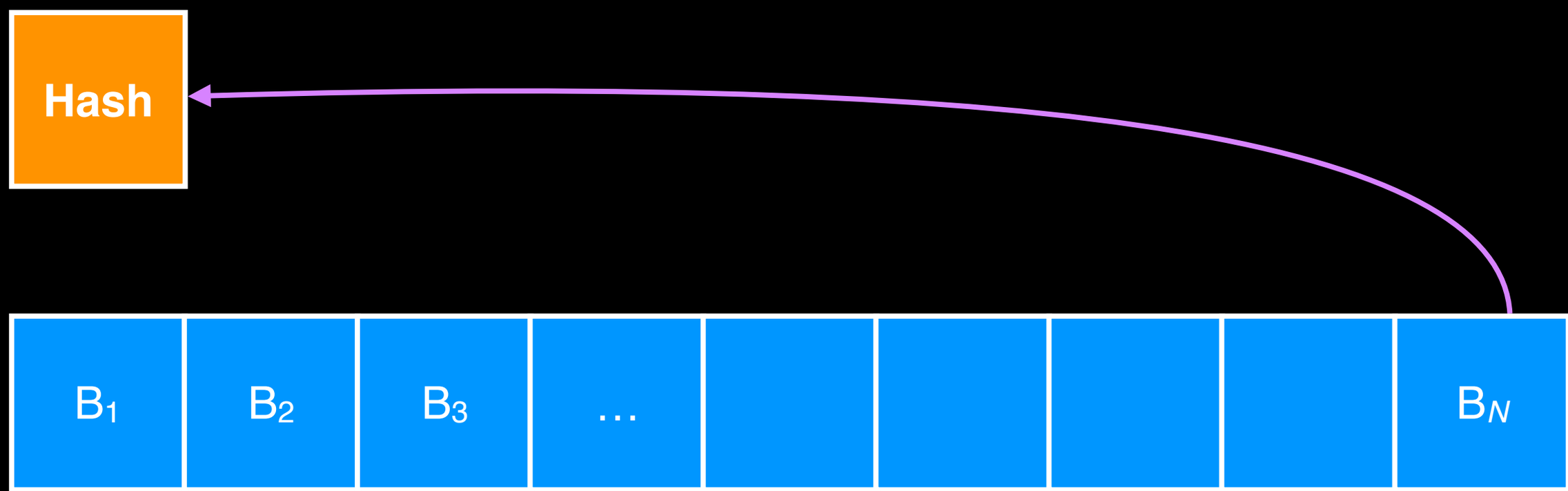

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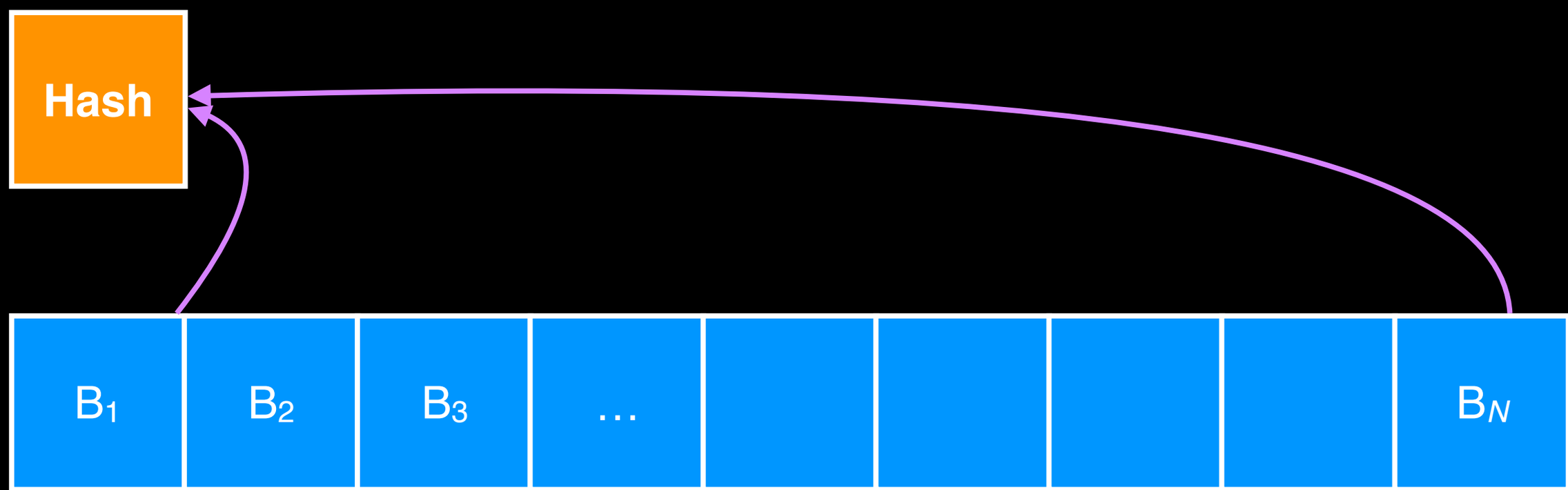

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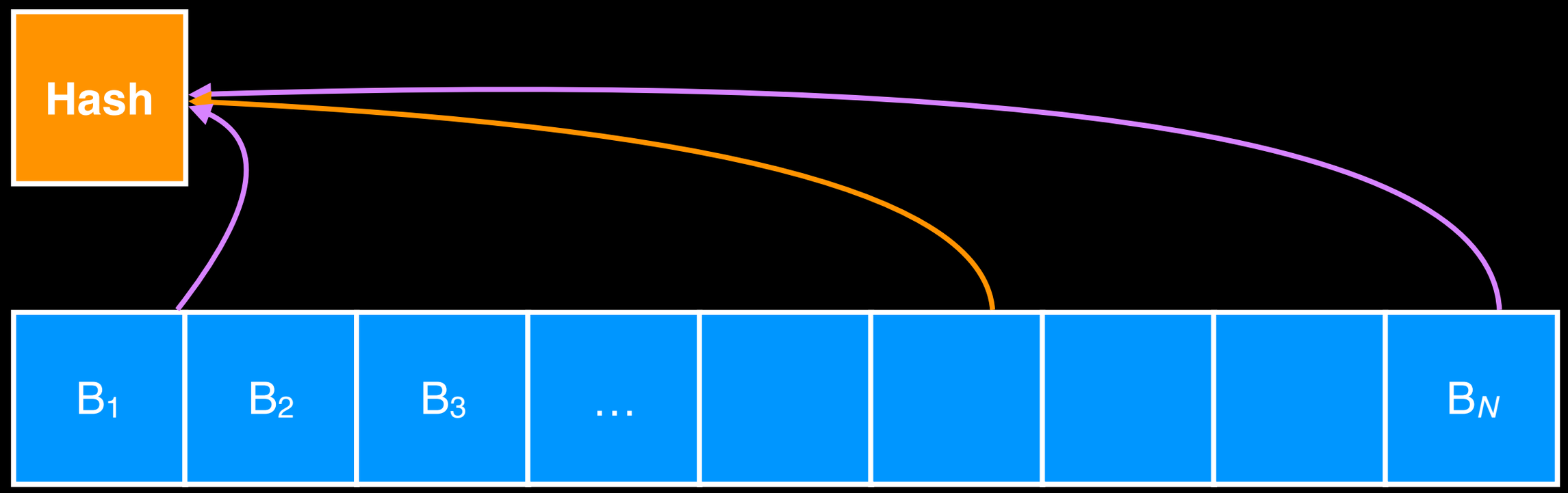

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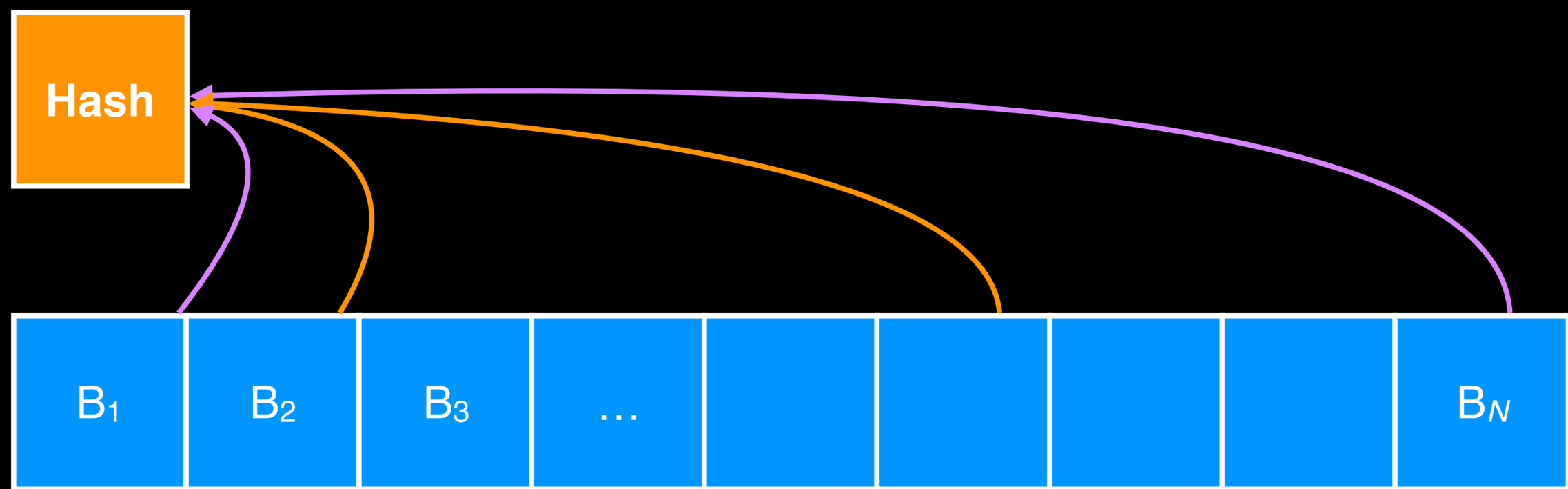

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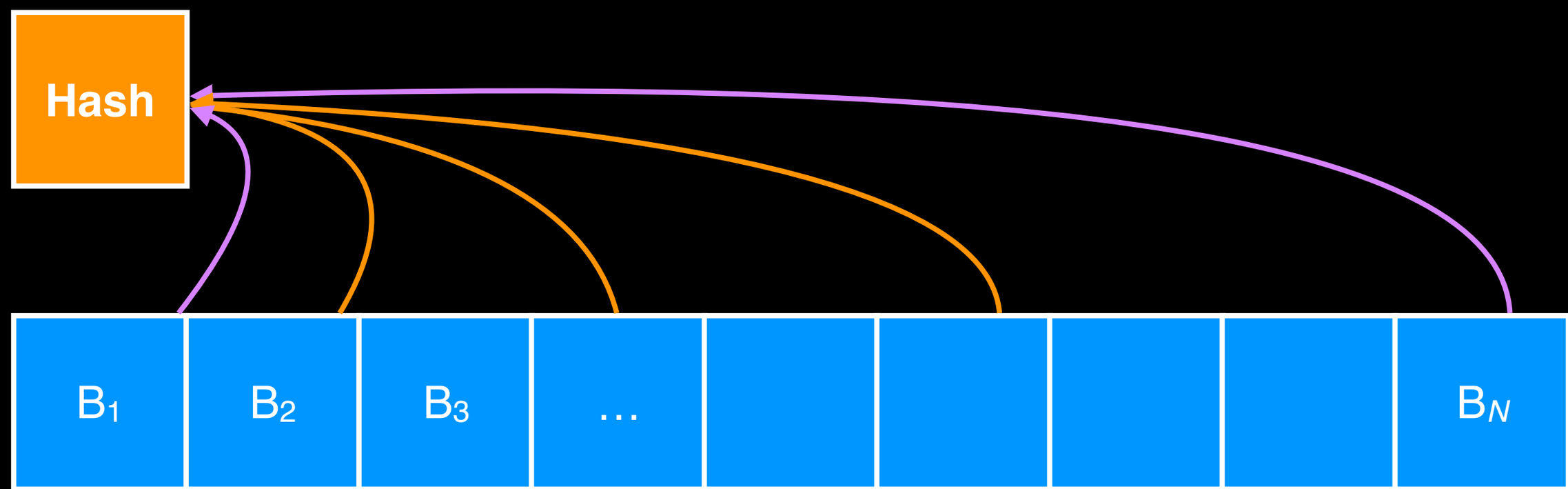

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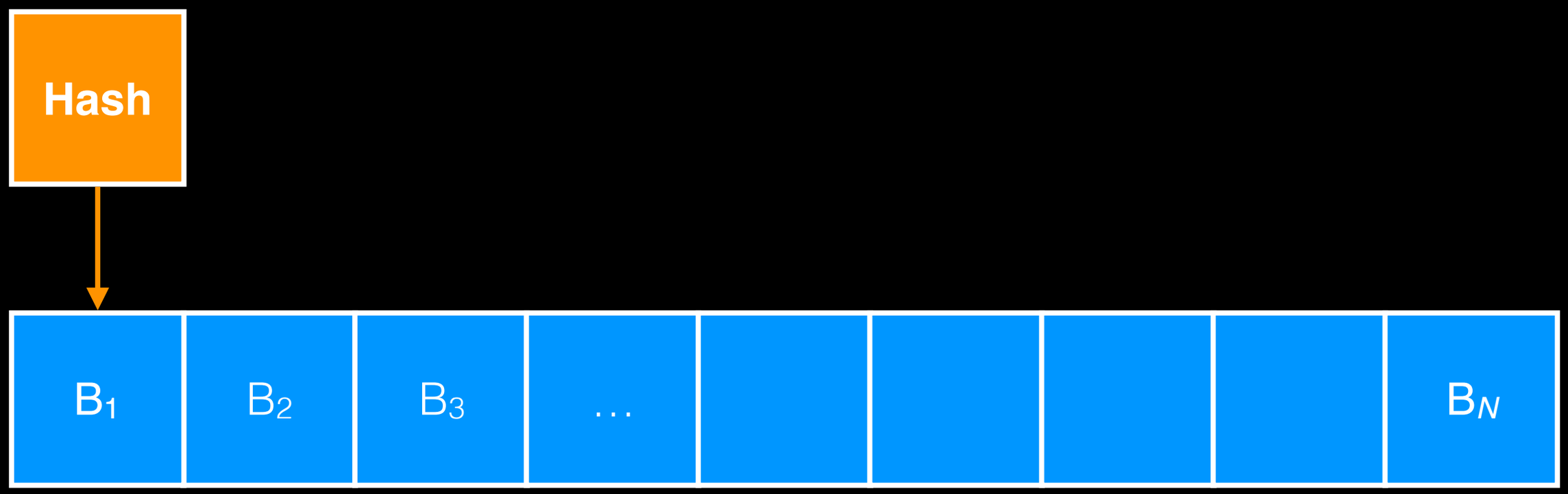

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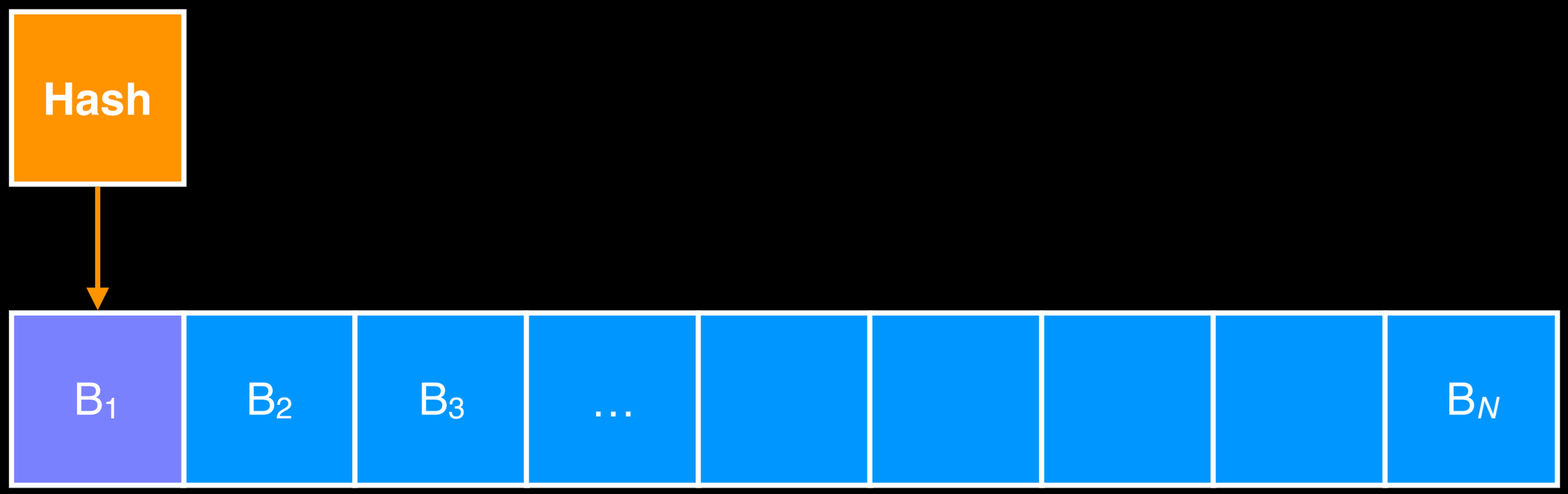
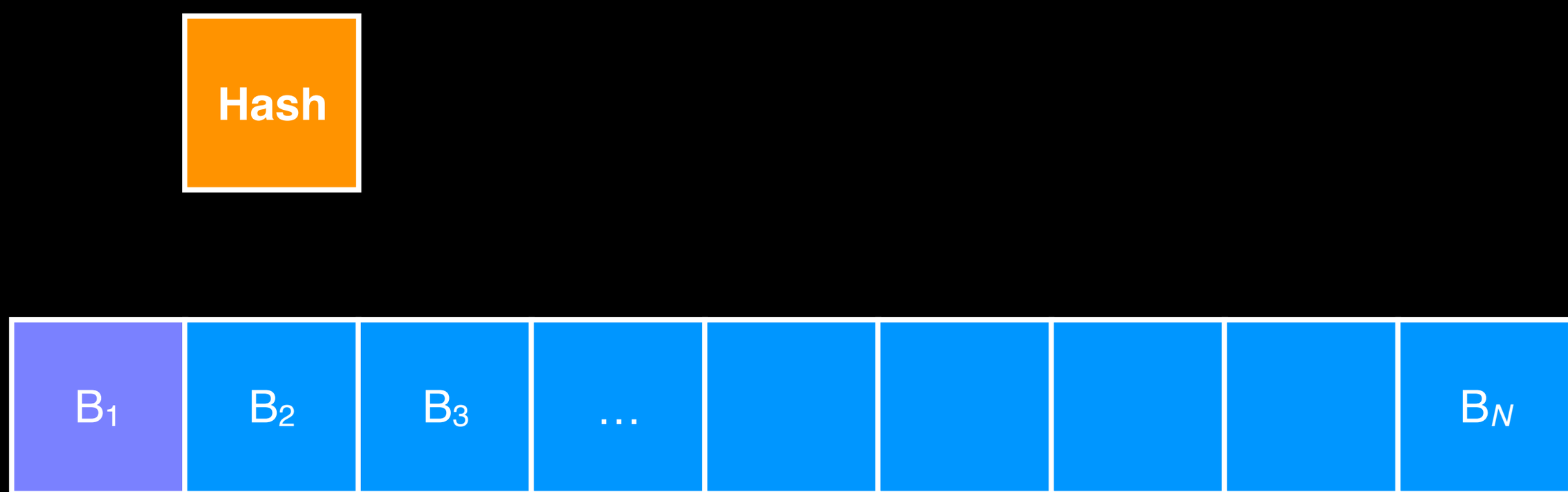


Balloon Hashing Algorithm



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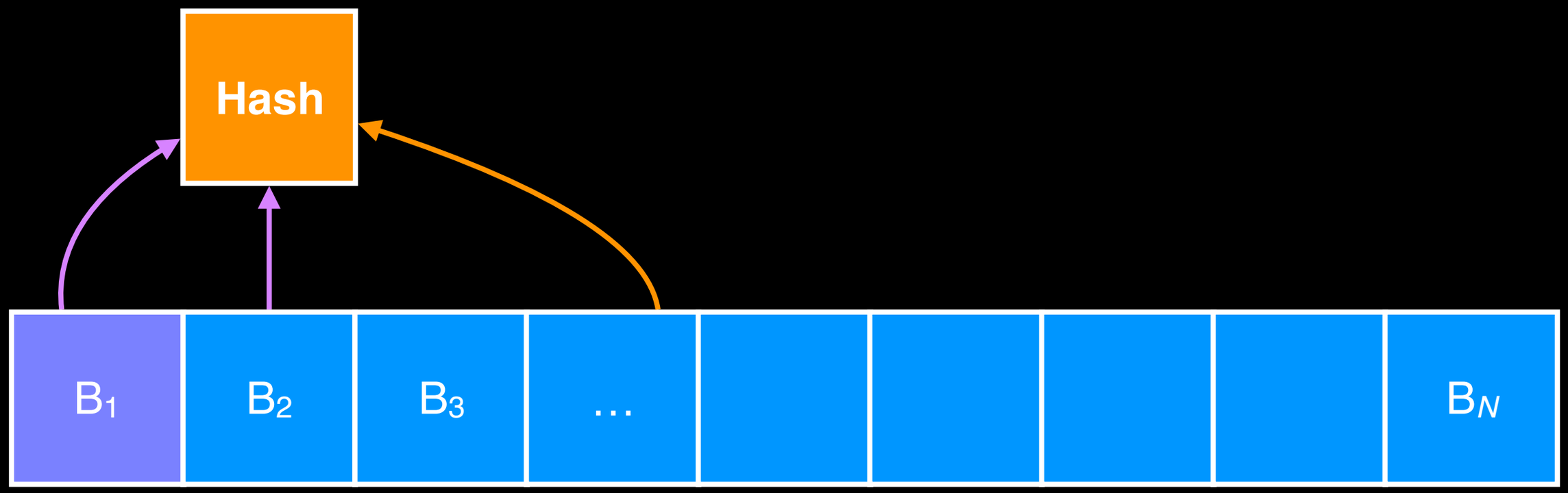

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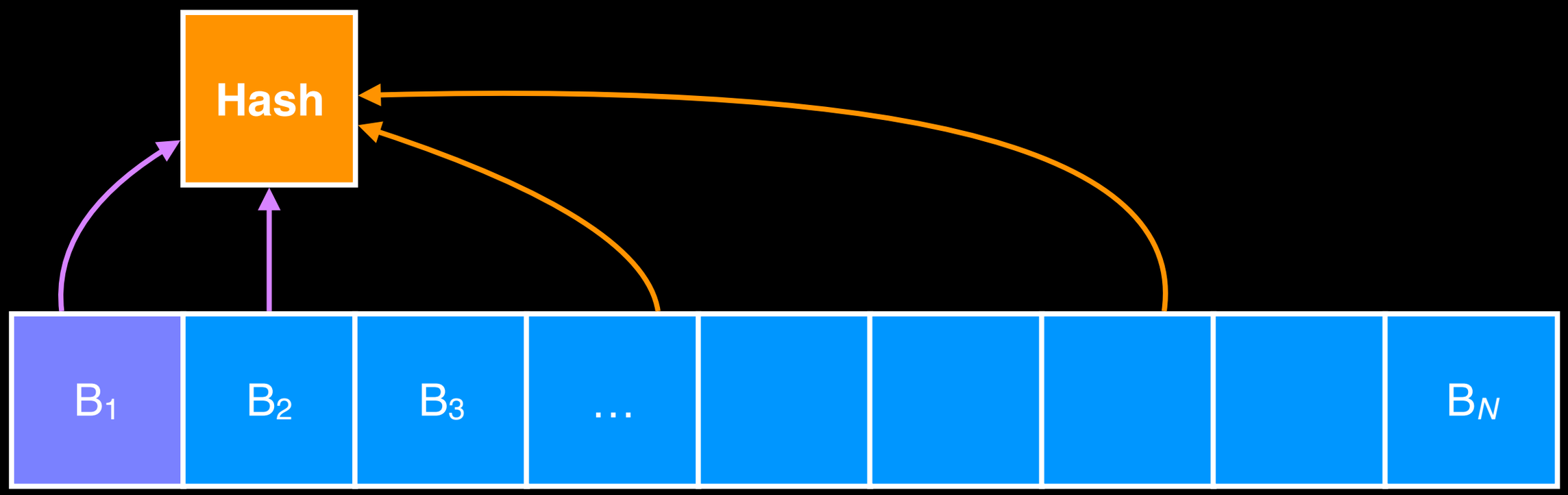

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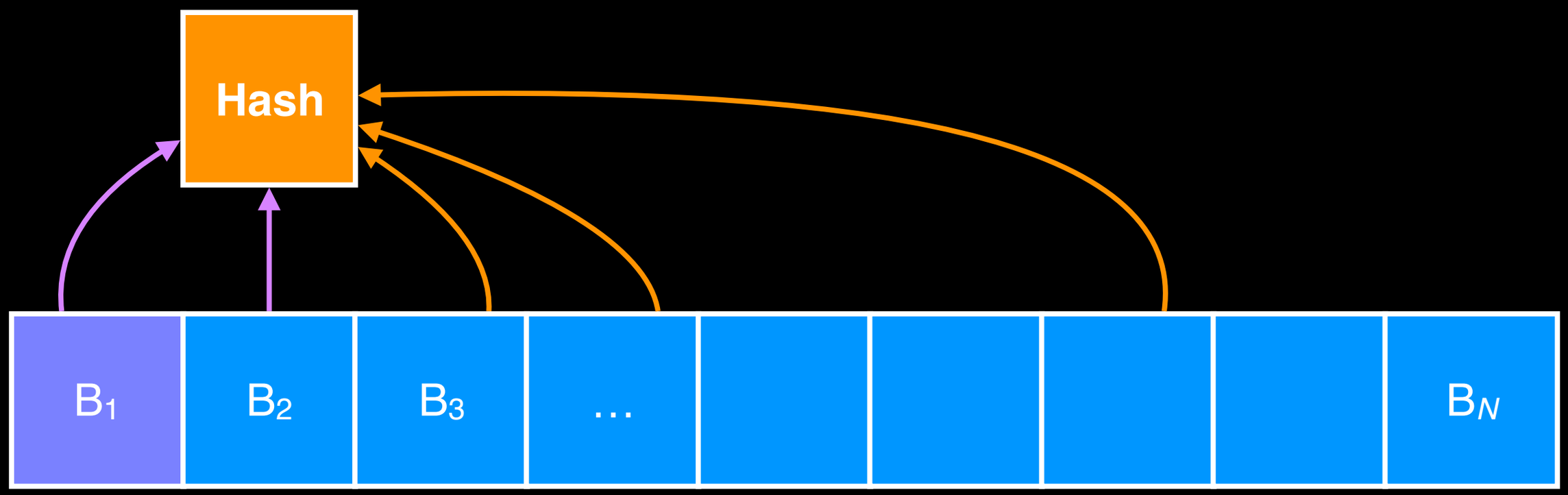

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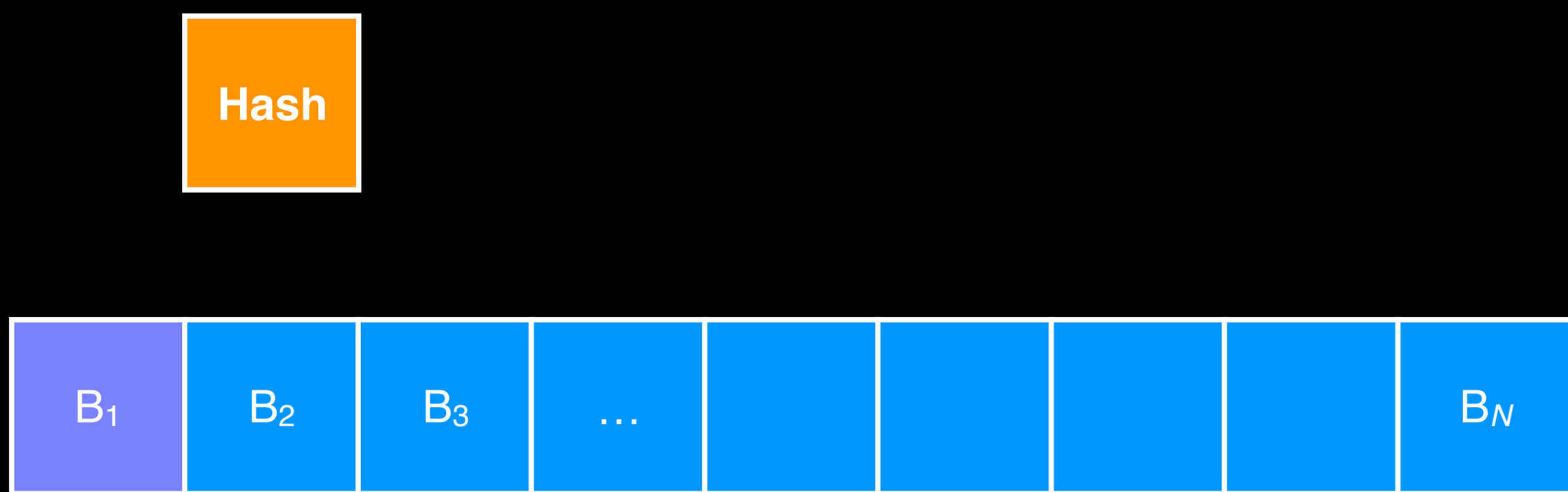

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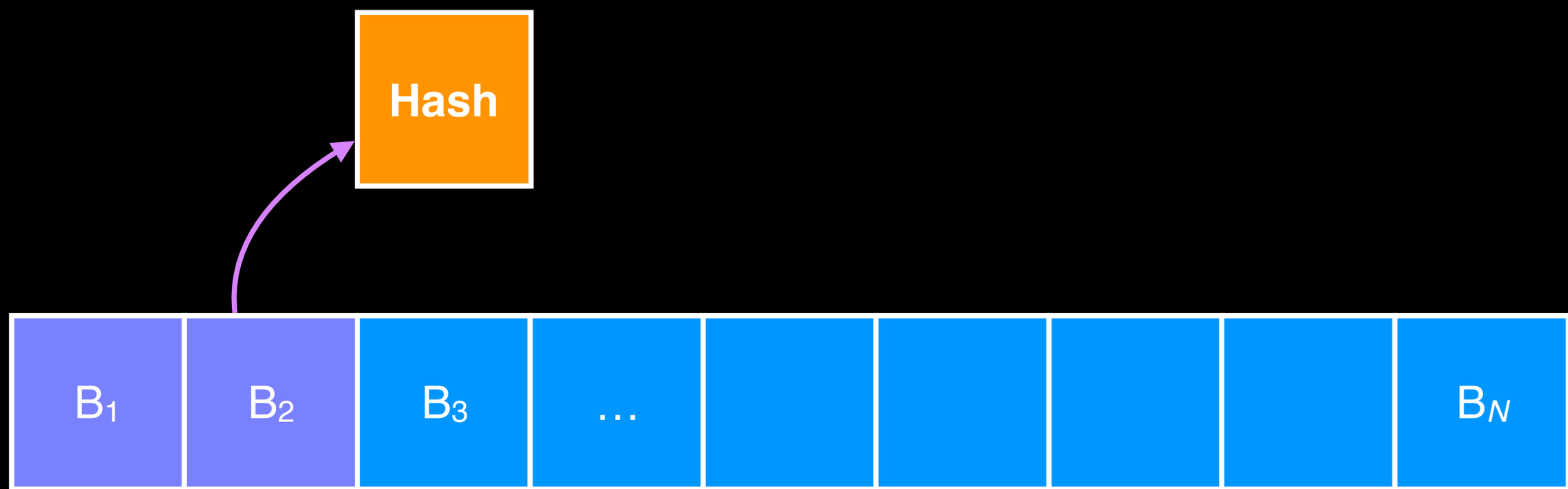

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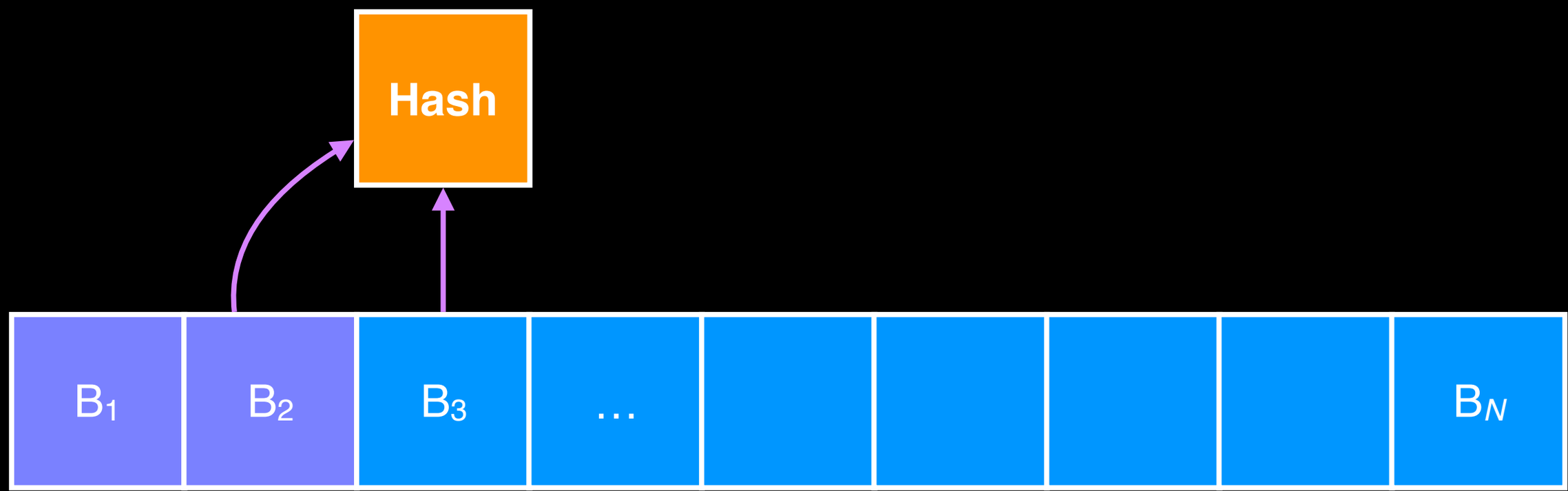

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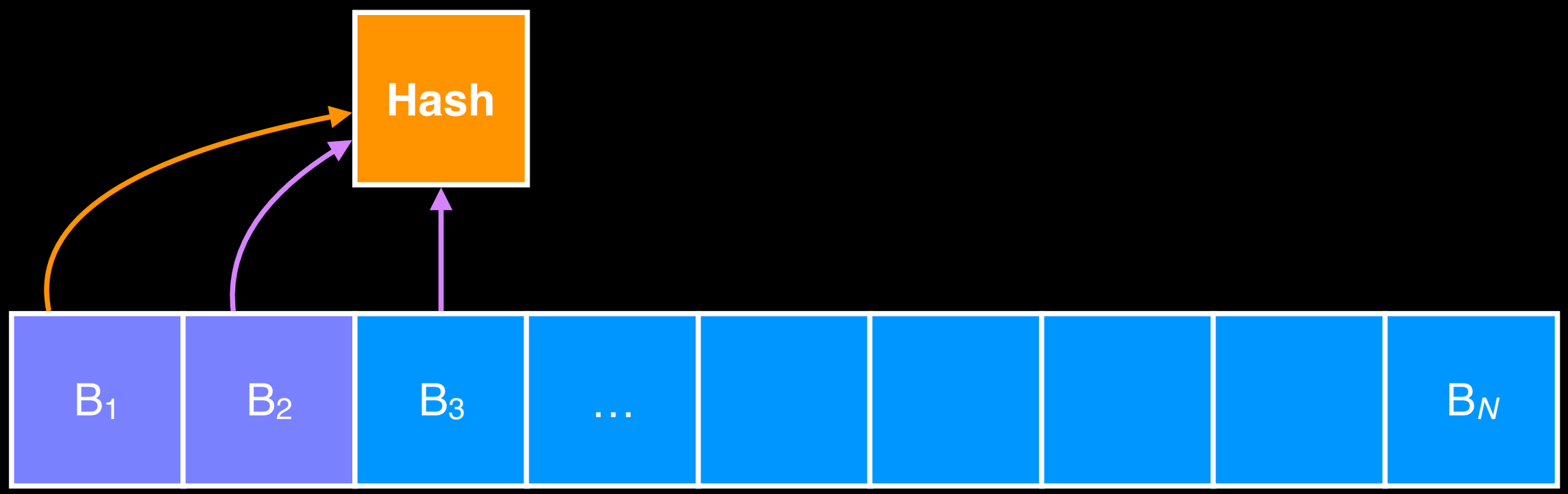

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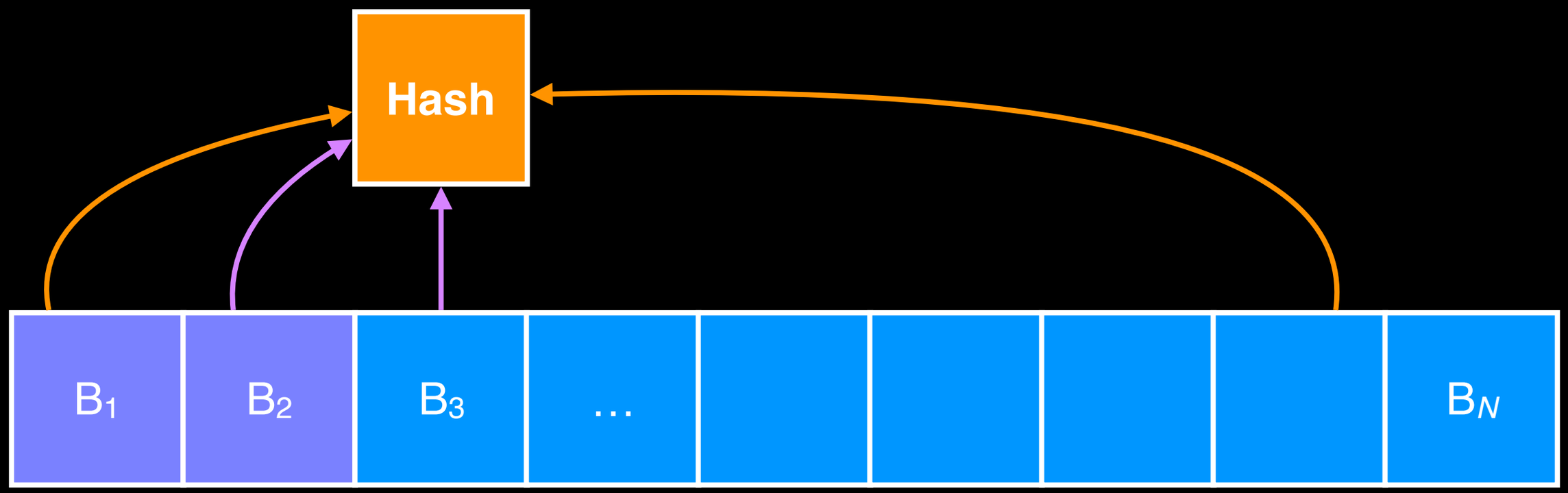

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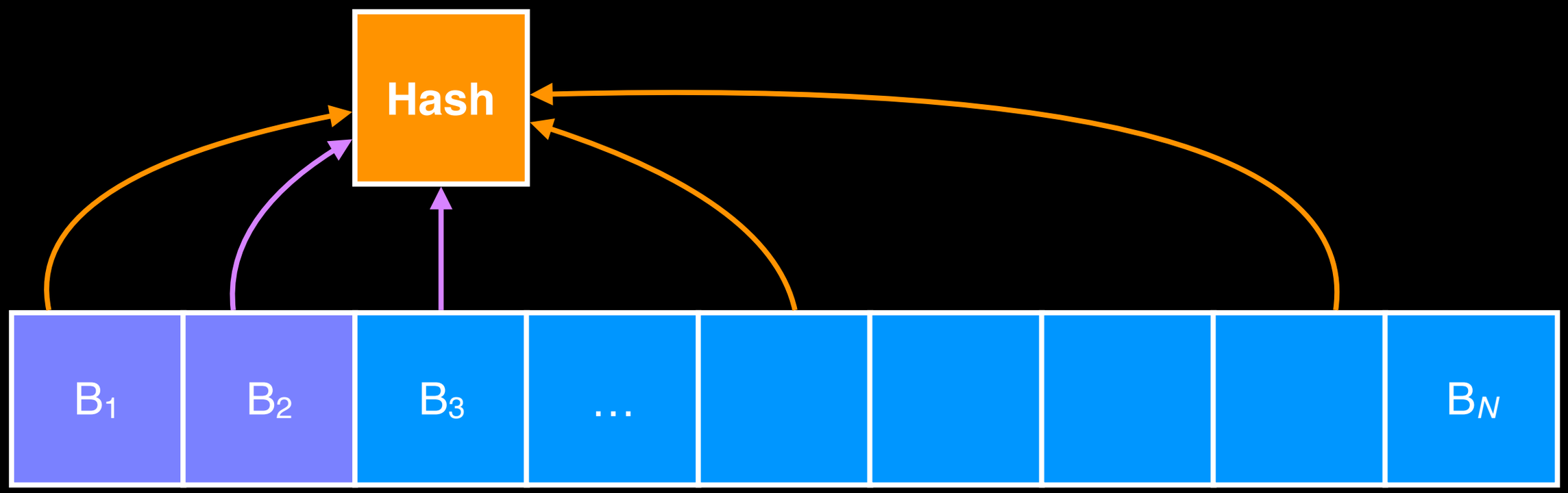

Balloon Hashing Algorithm

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A “mode of operation” for a cryptographic hash function

Balloon Hashing

A 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

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Proving Memory-Hardness

<u>Theorem</u> [informal]:
Computing the N-block R-round Balloon function w.h.p., when $\delta=7$, with space $\mathbf{S \leq N/8}$ requires time $\mathbf{T}$ such that

$$\mathbf{S} \cdot \mathbf{T} \geq (2^R - 1) / 32 \cdot \mathbf{N}^2 .$$

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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 **15,000**× more time

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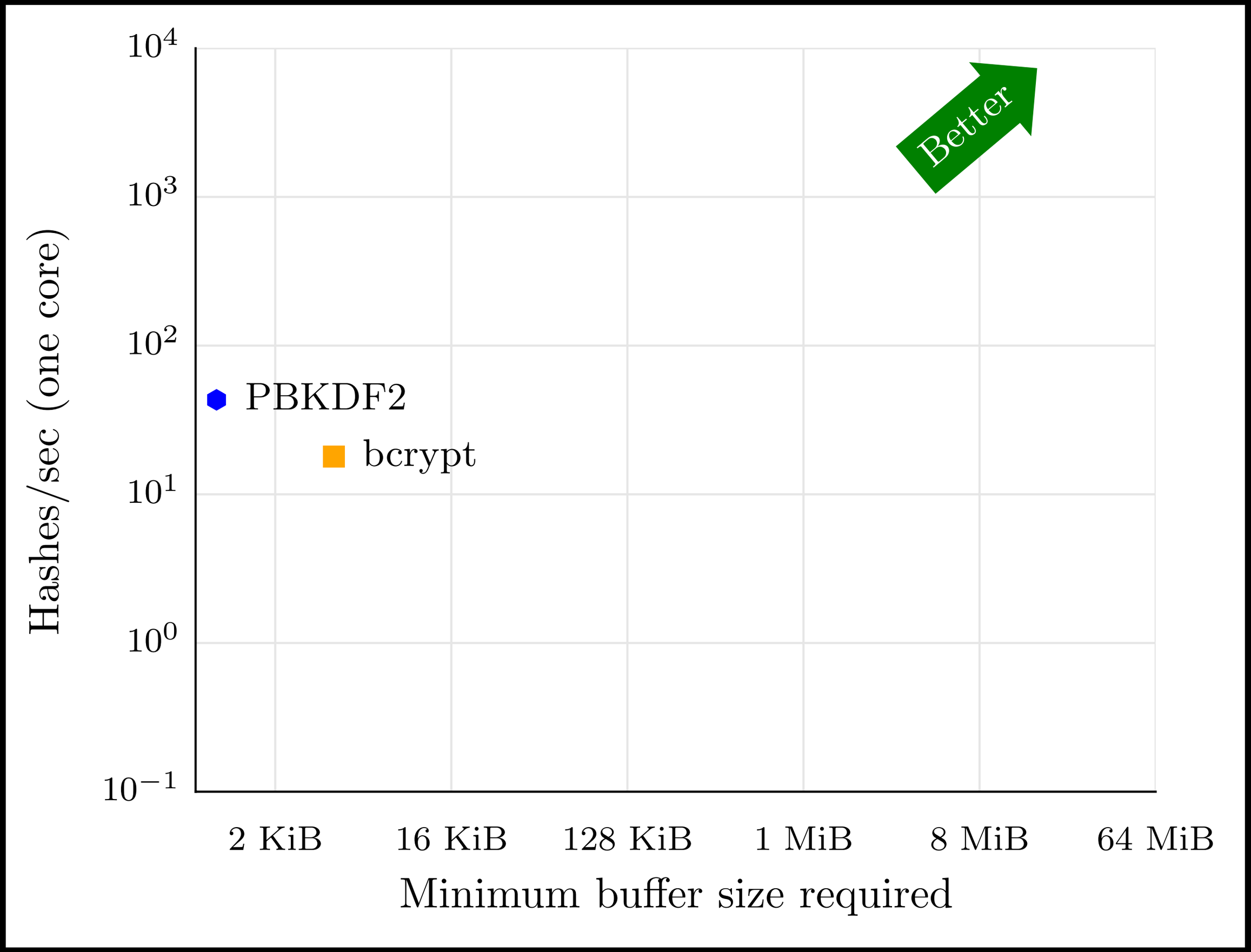
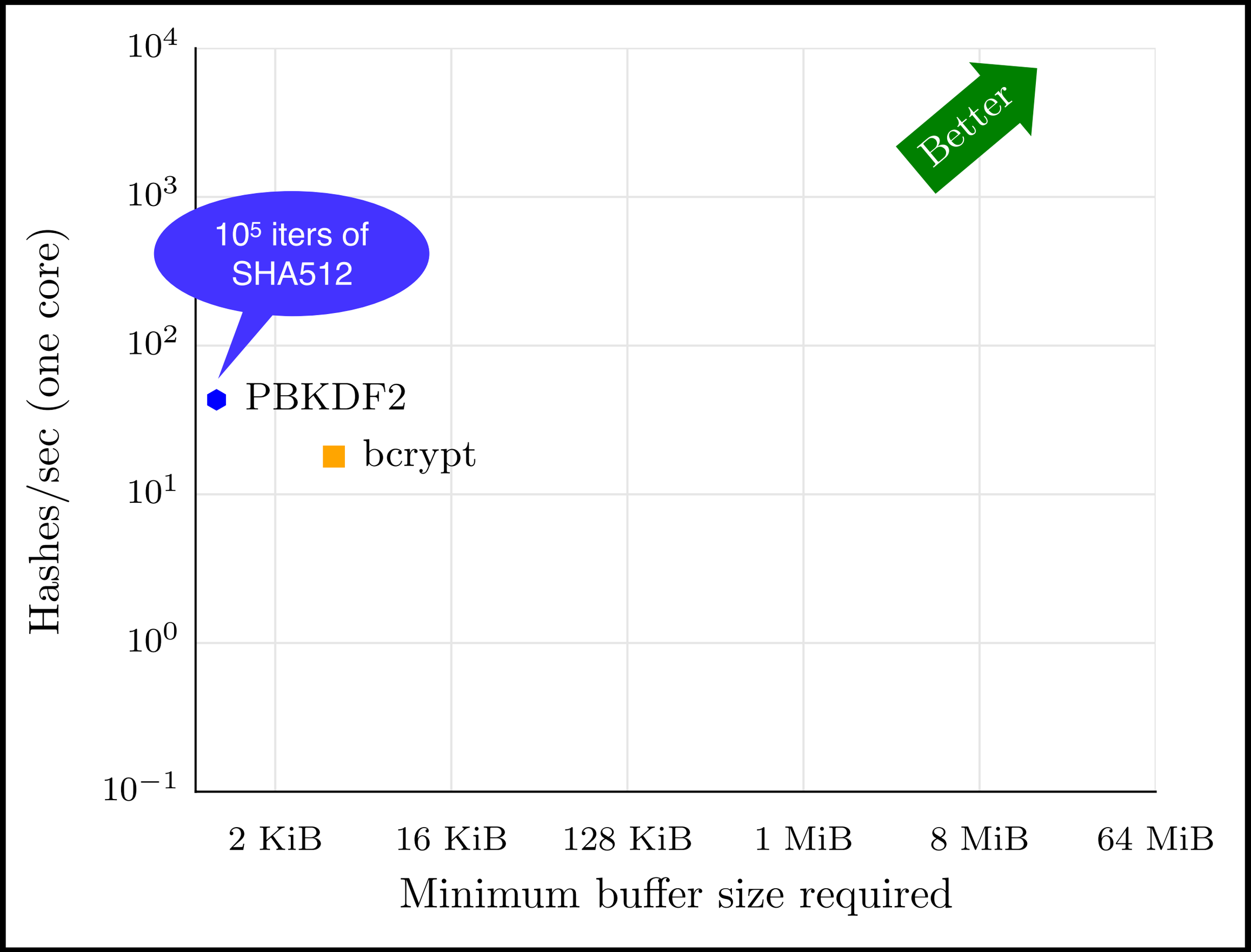
The proof works by inspecting the Balloon computation's data-dependency graph.

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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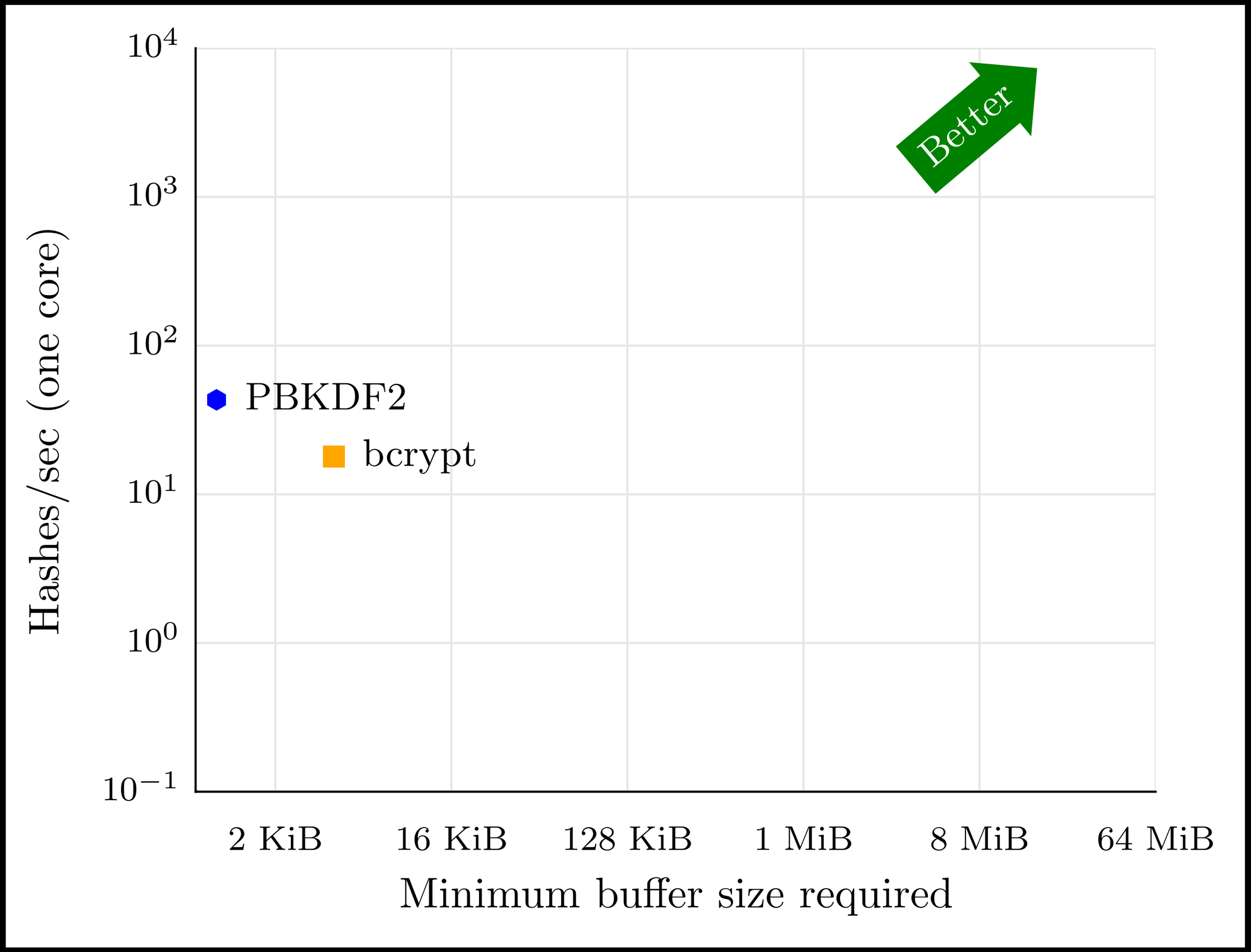

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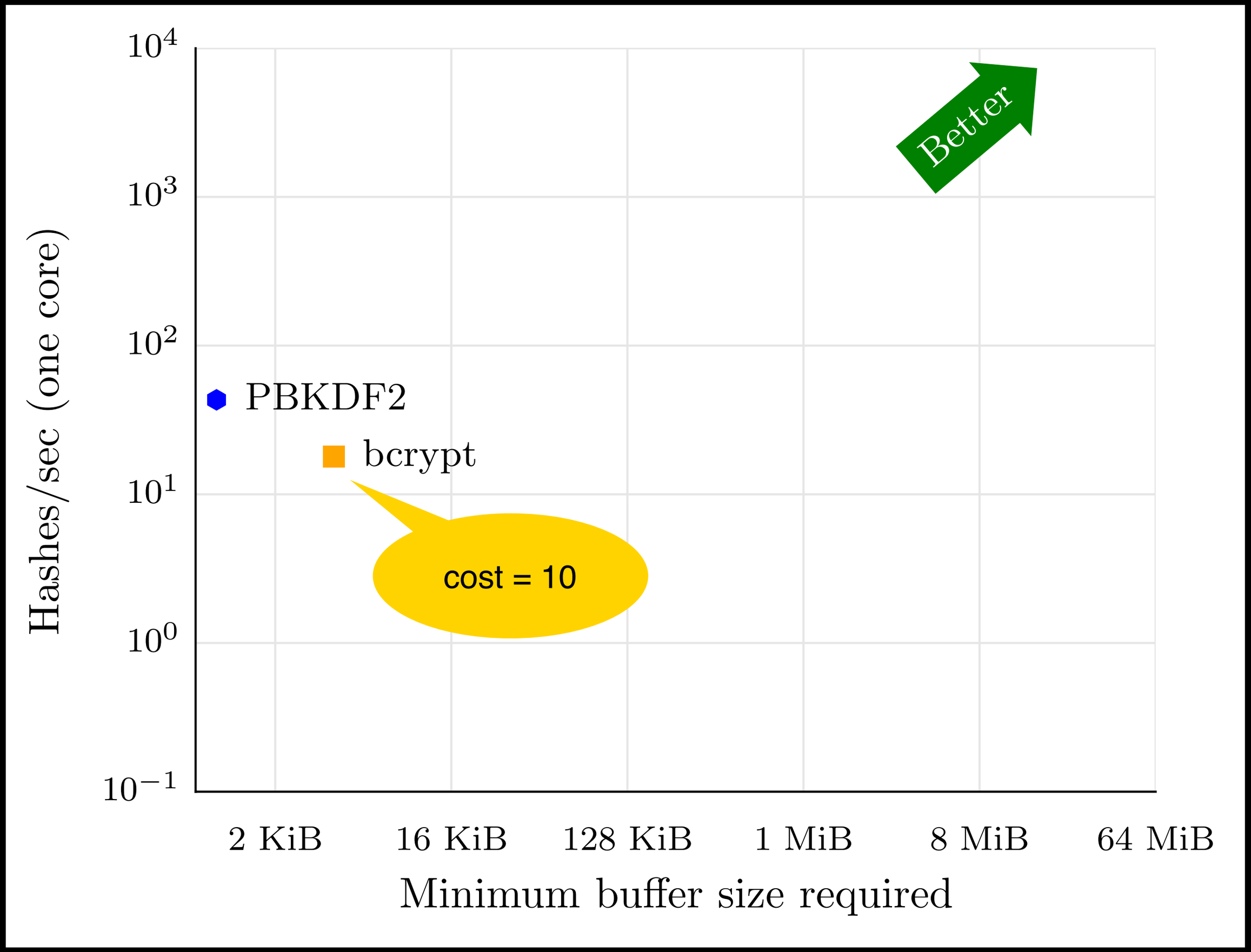

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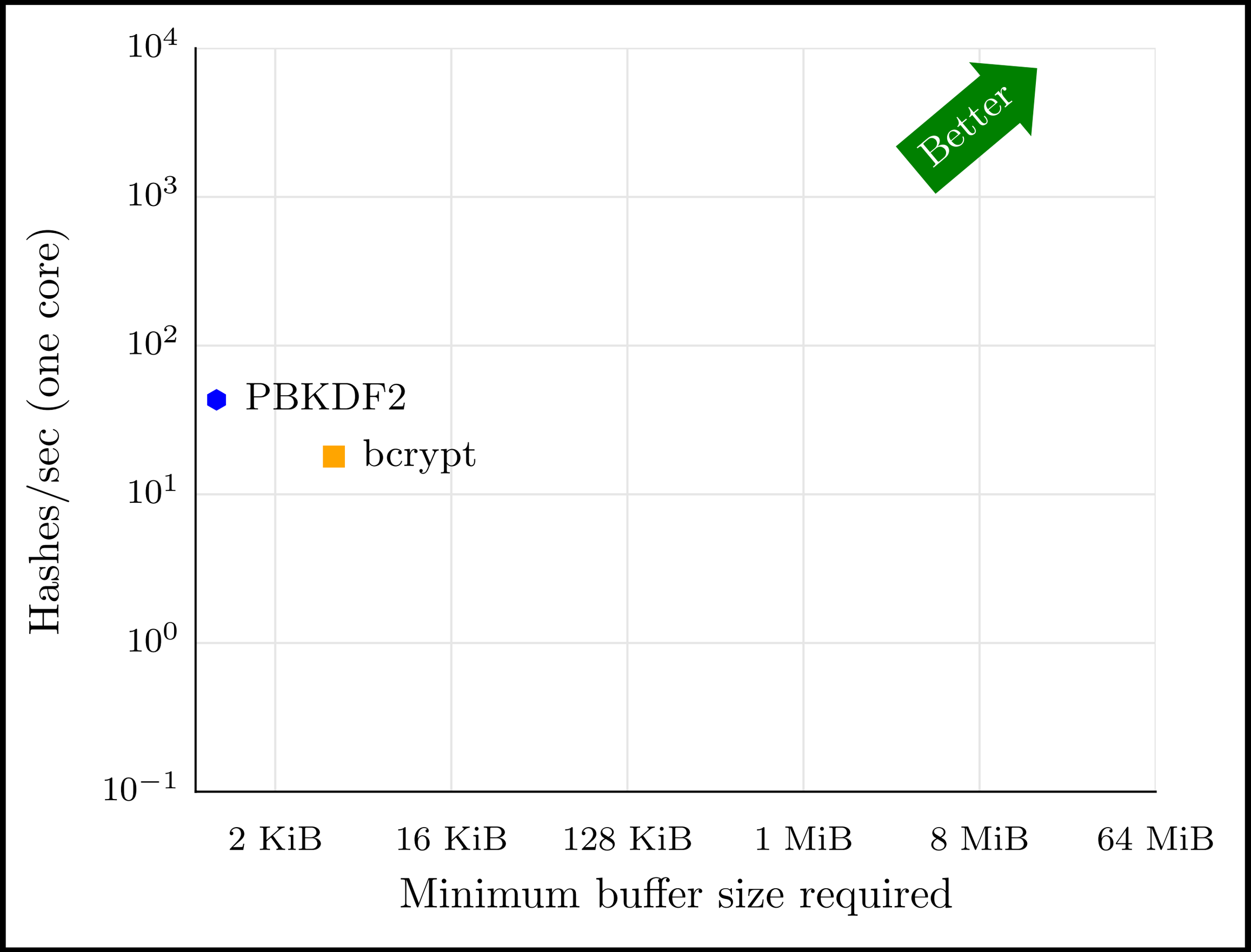

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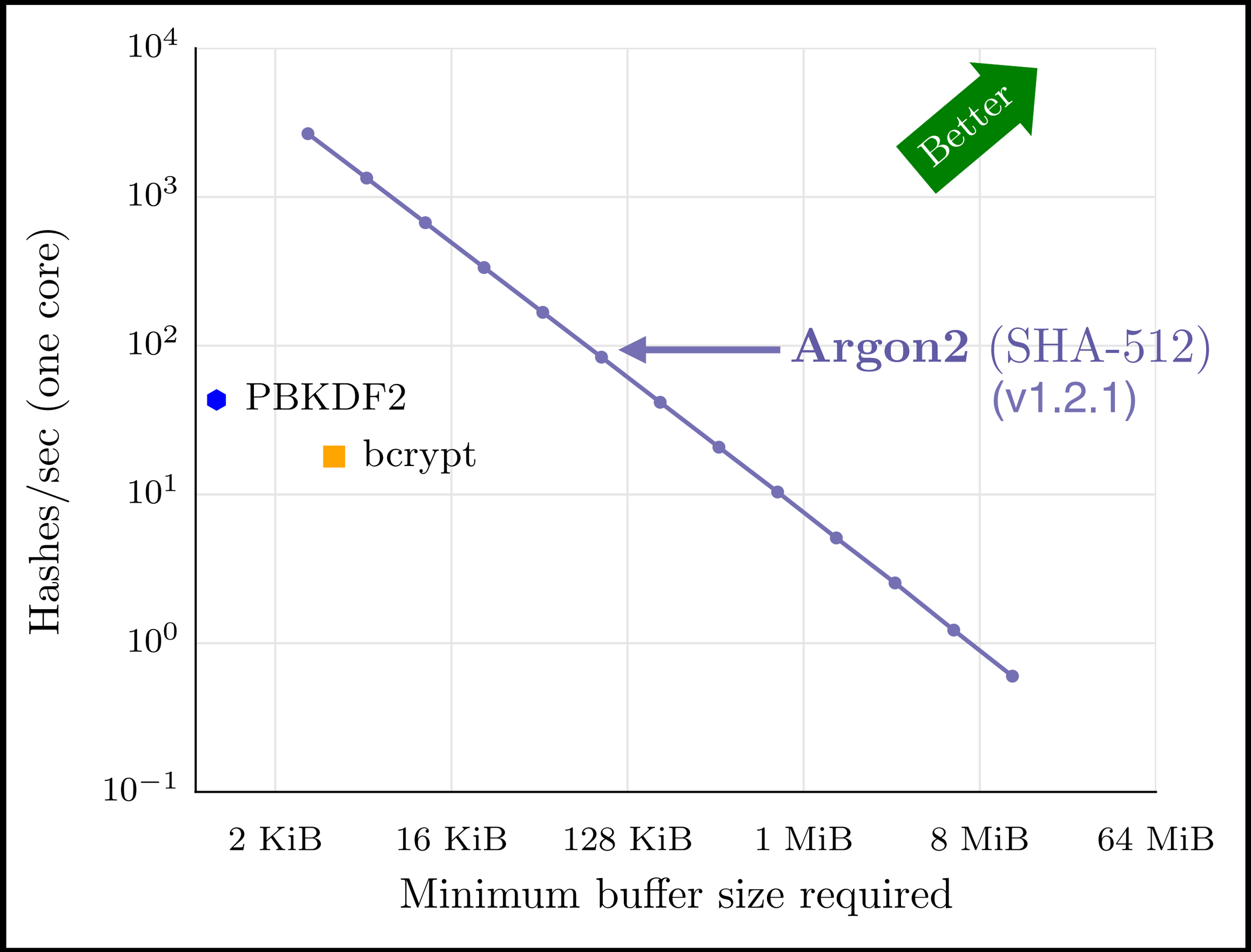

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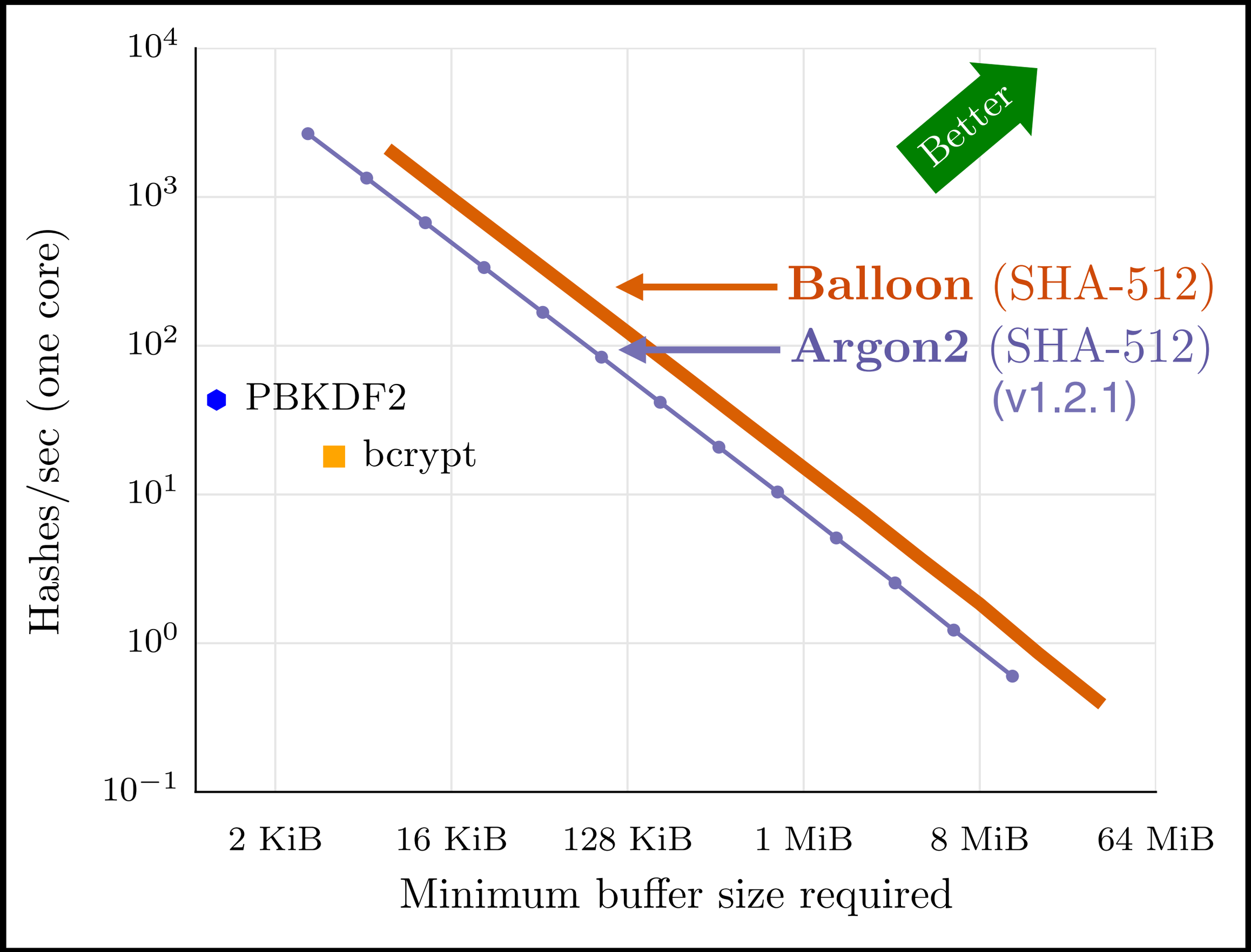

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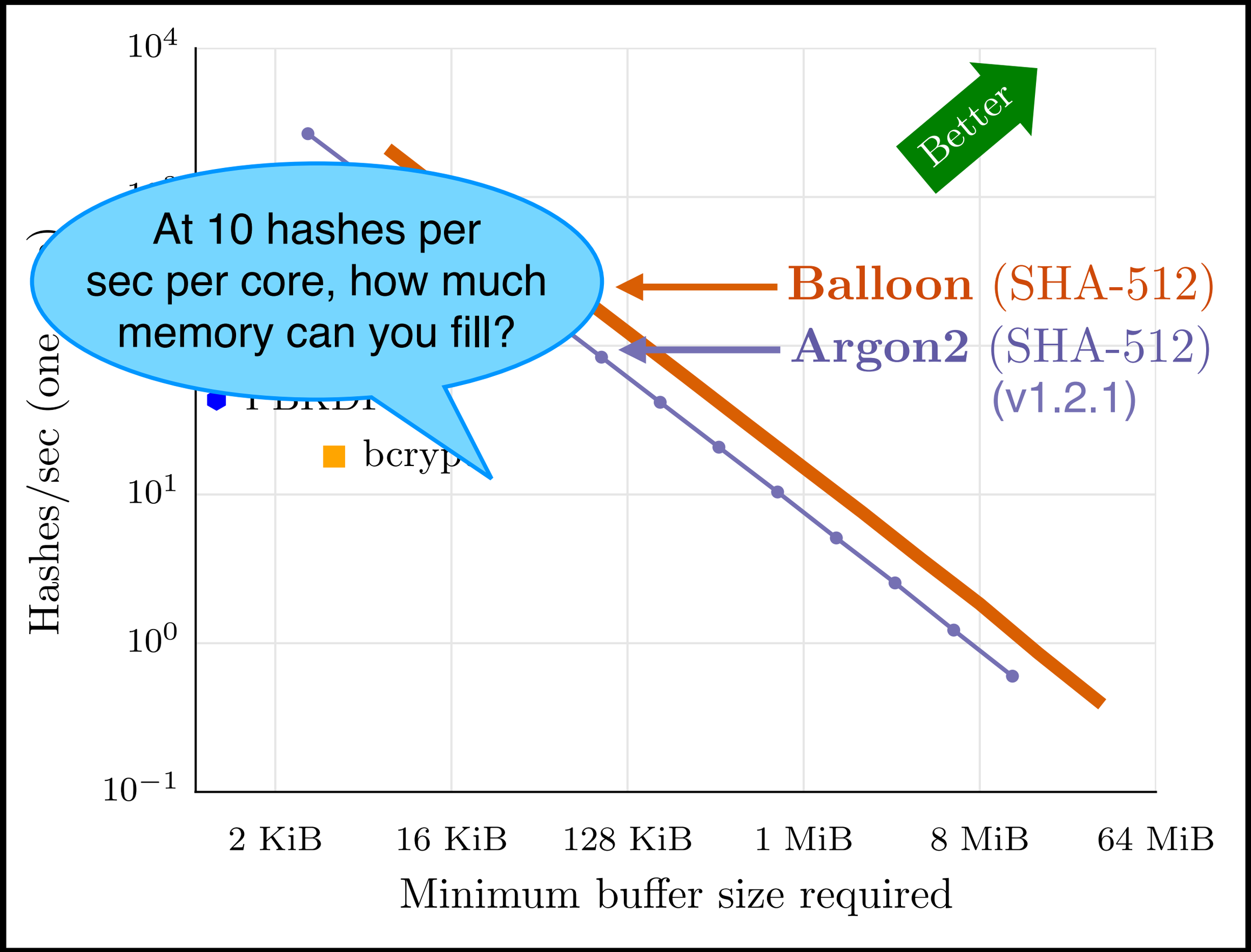

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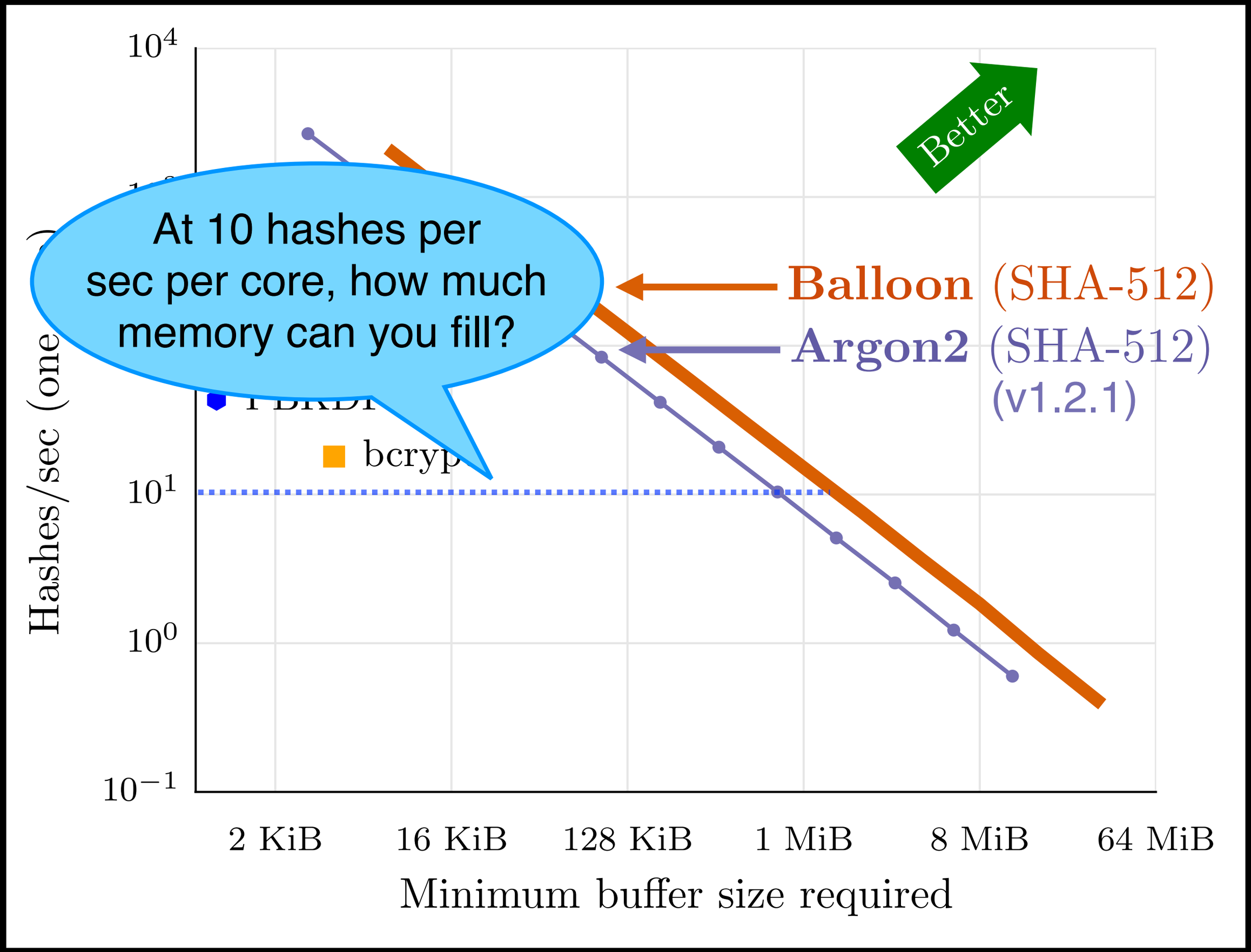

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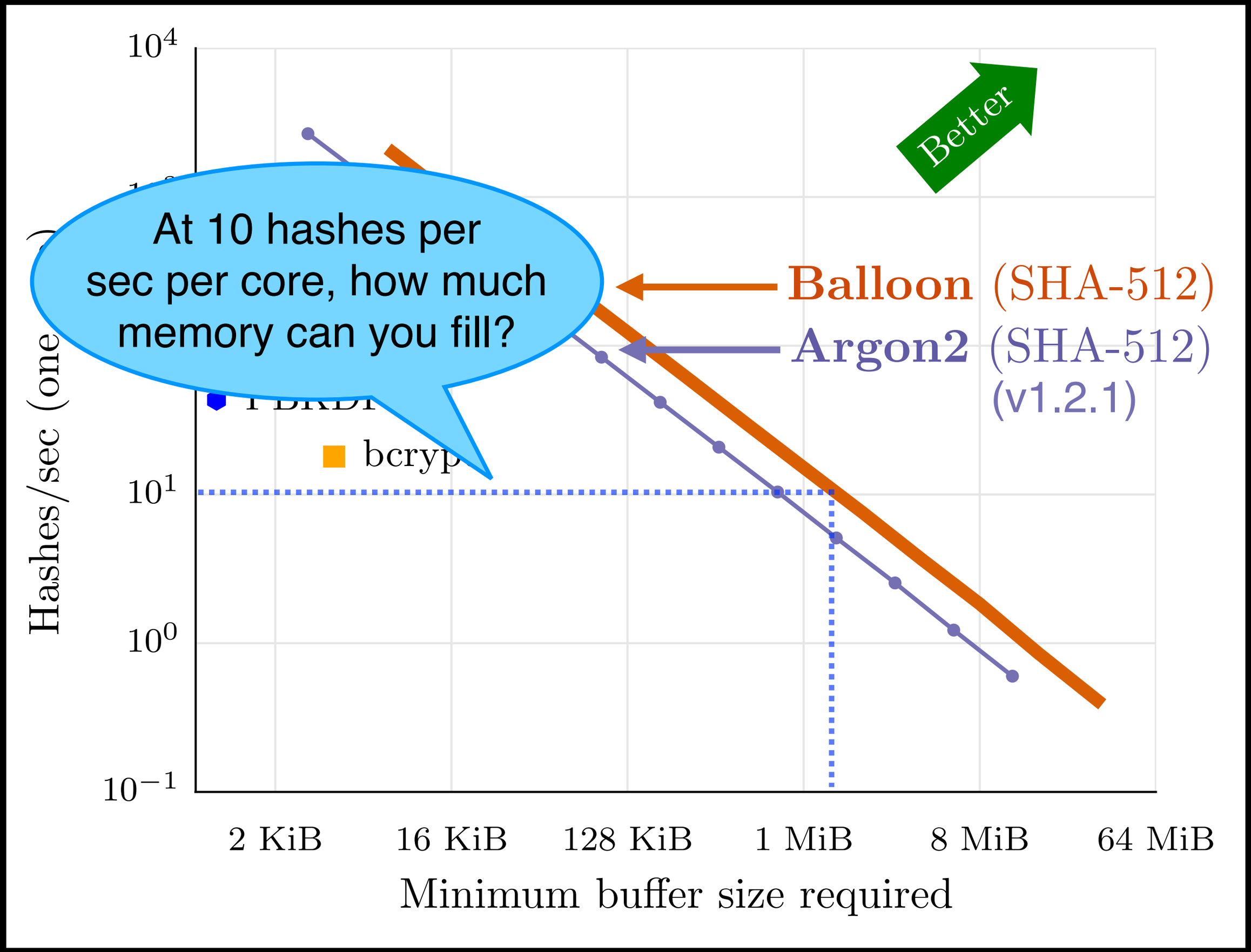

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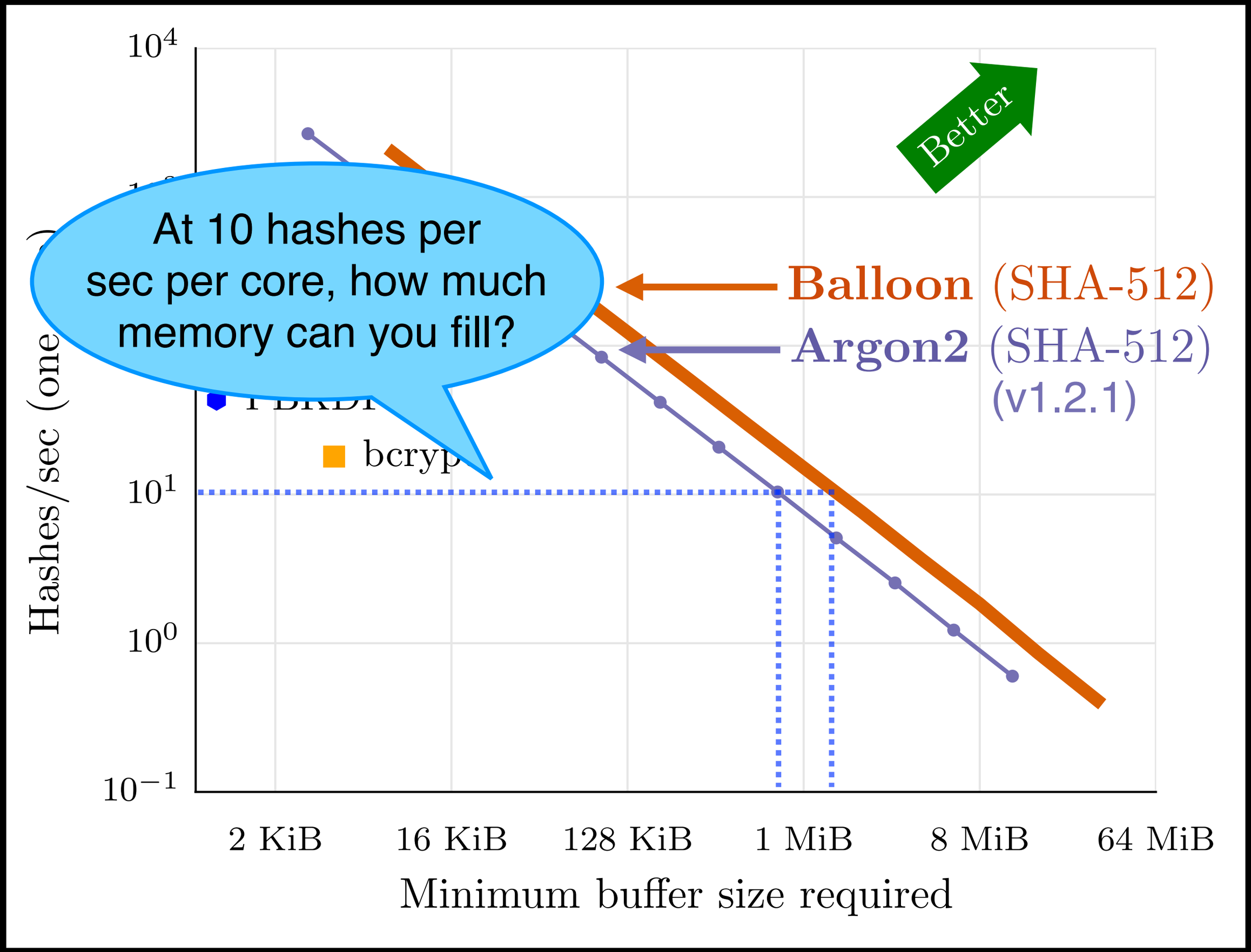

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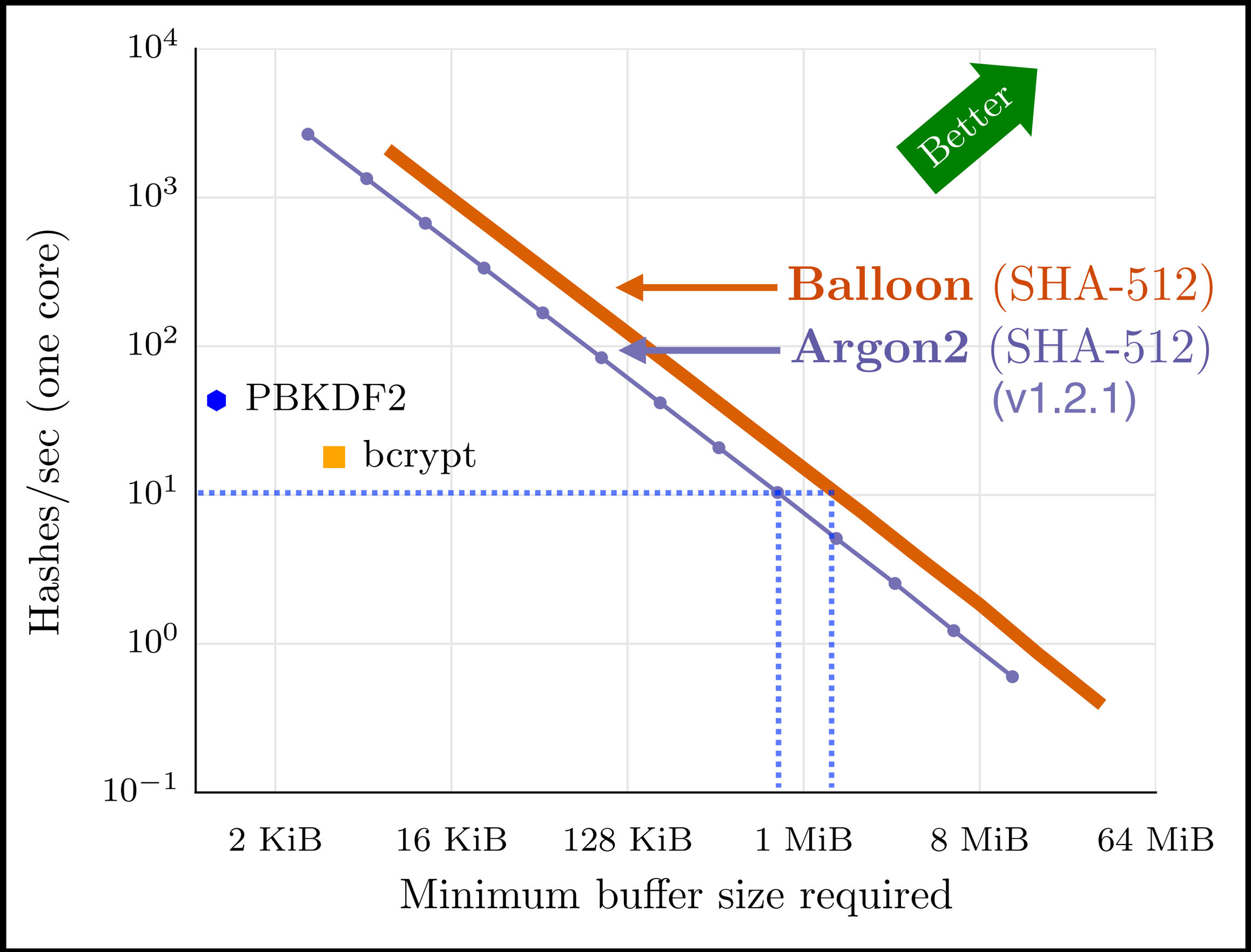

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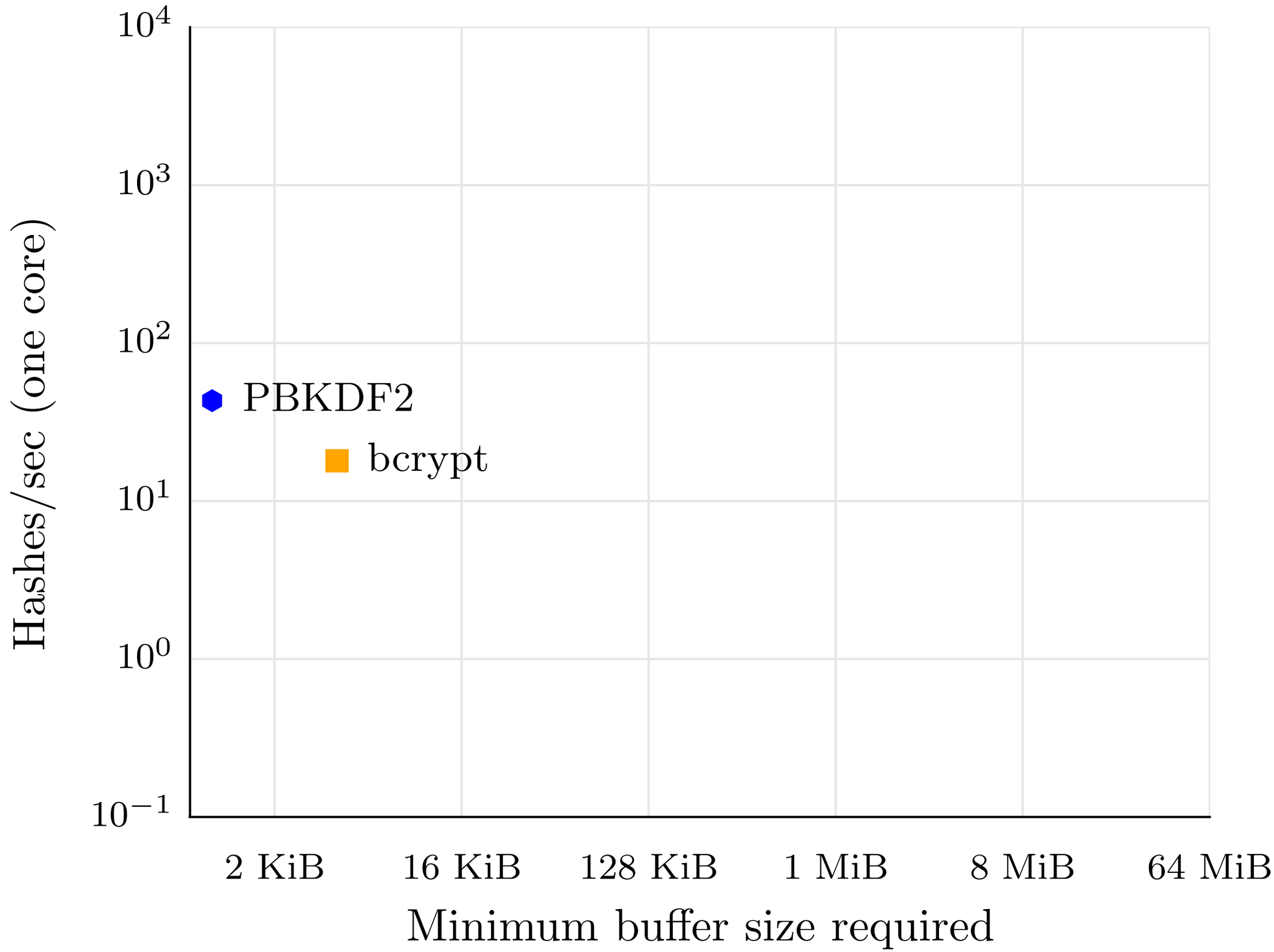

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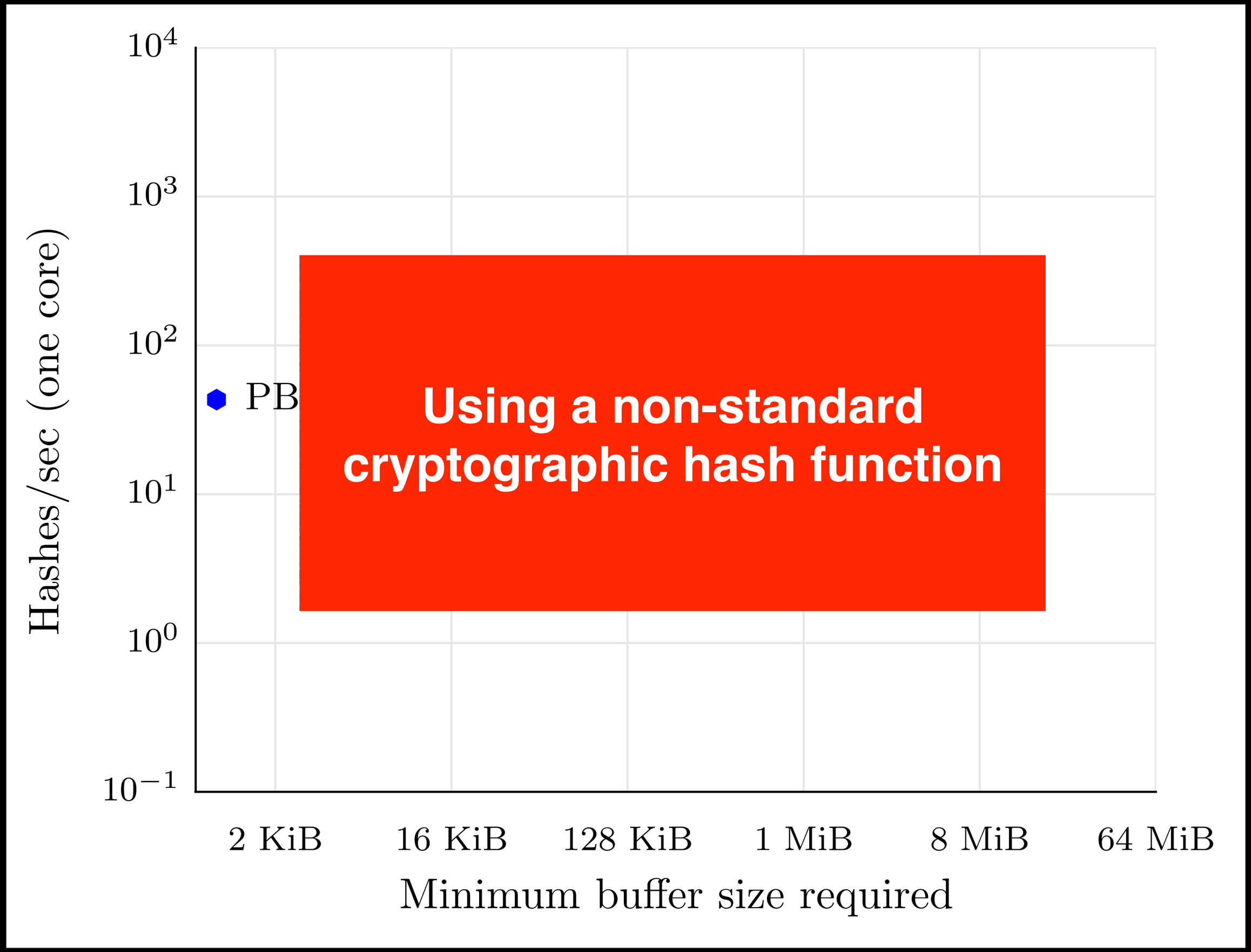

Using a non-standard cryptographic hash function

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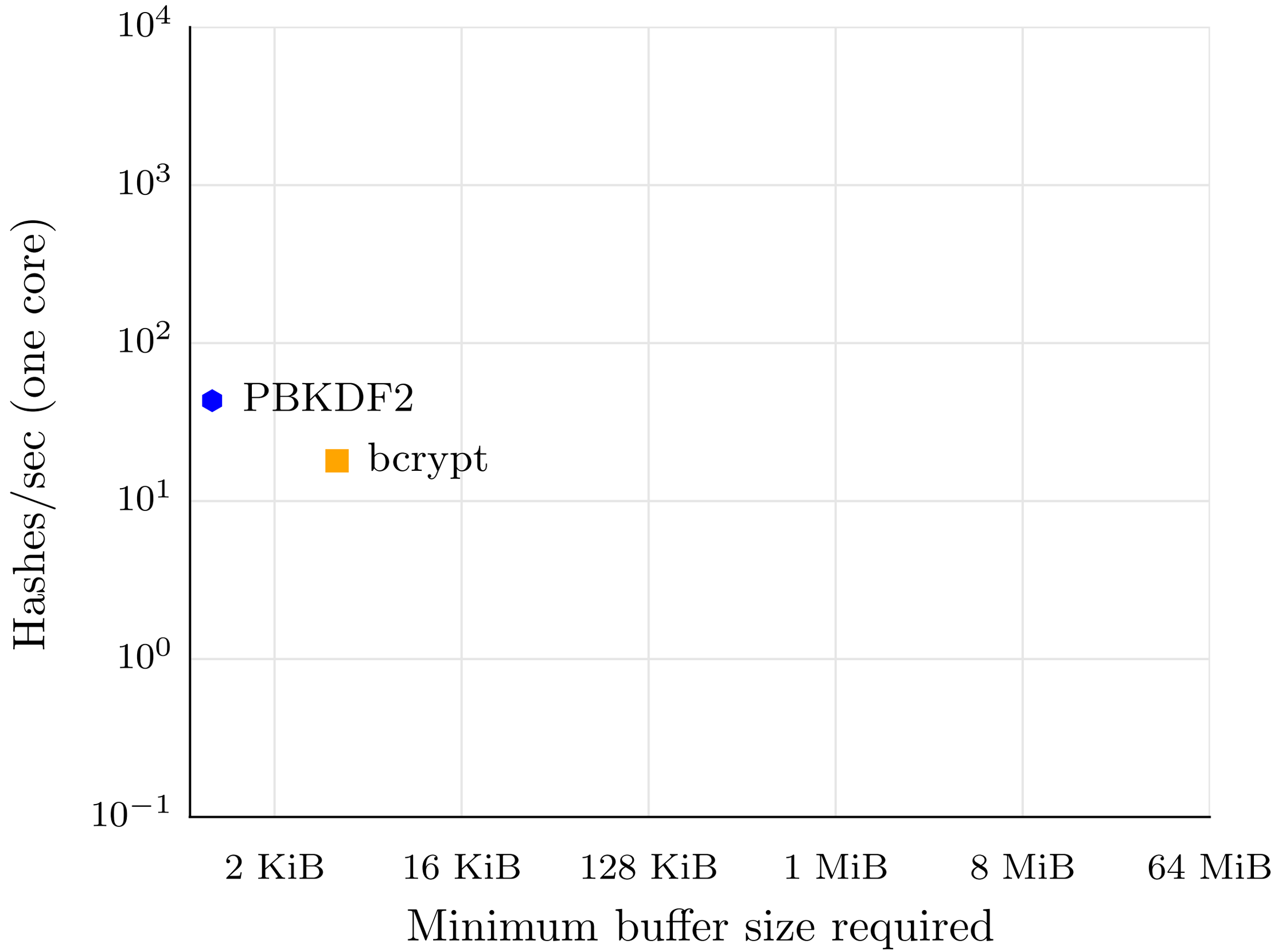

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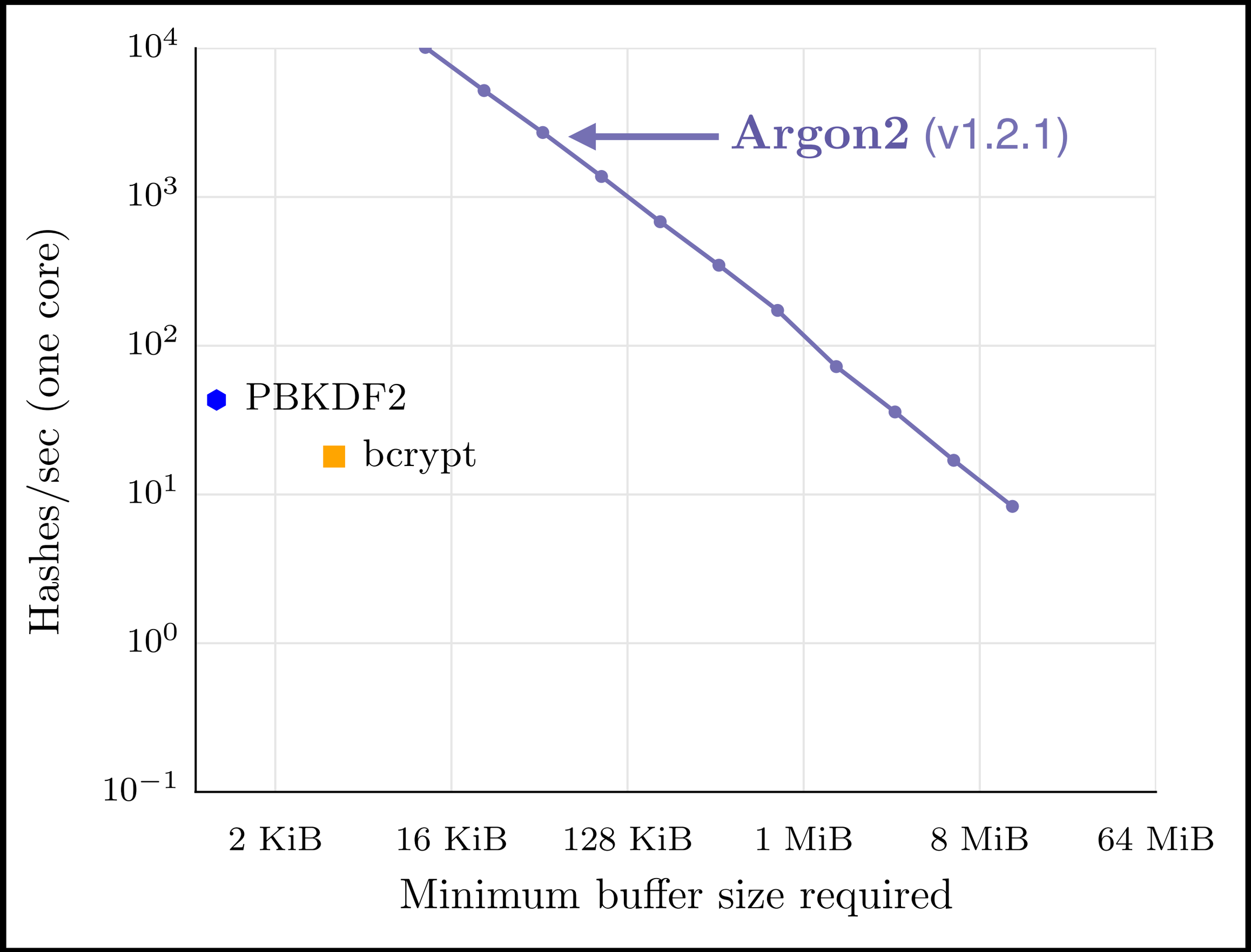

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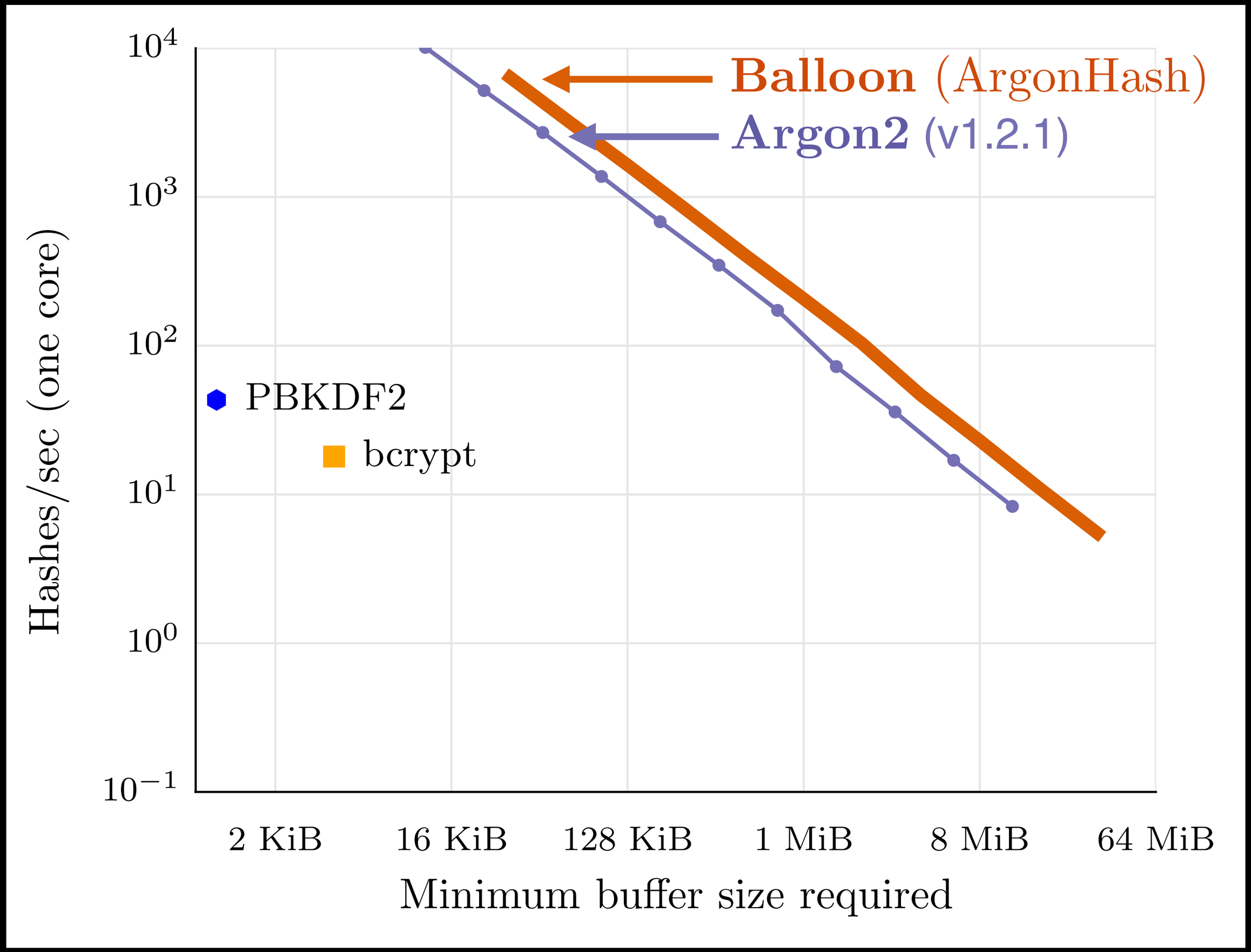

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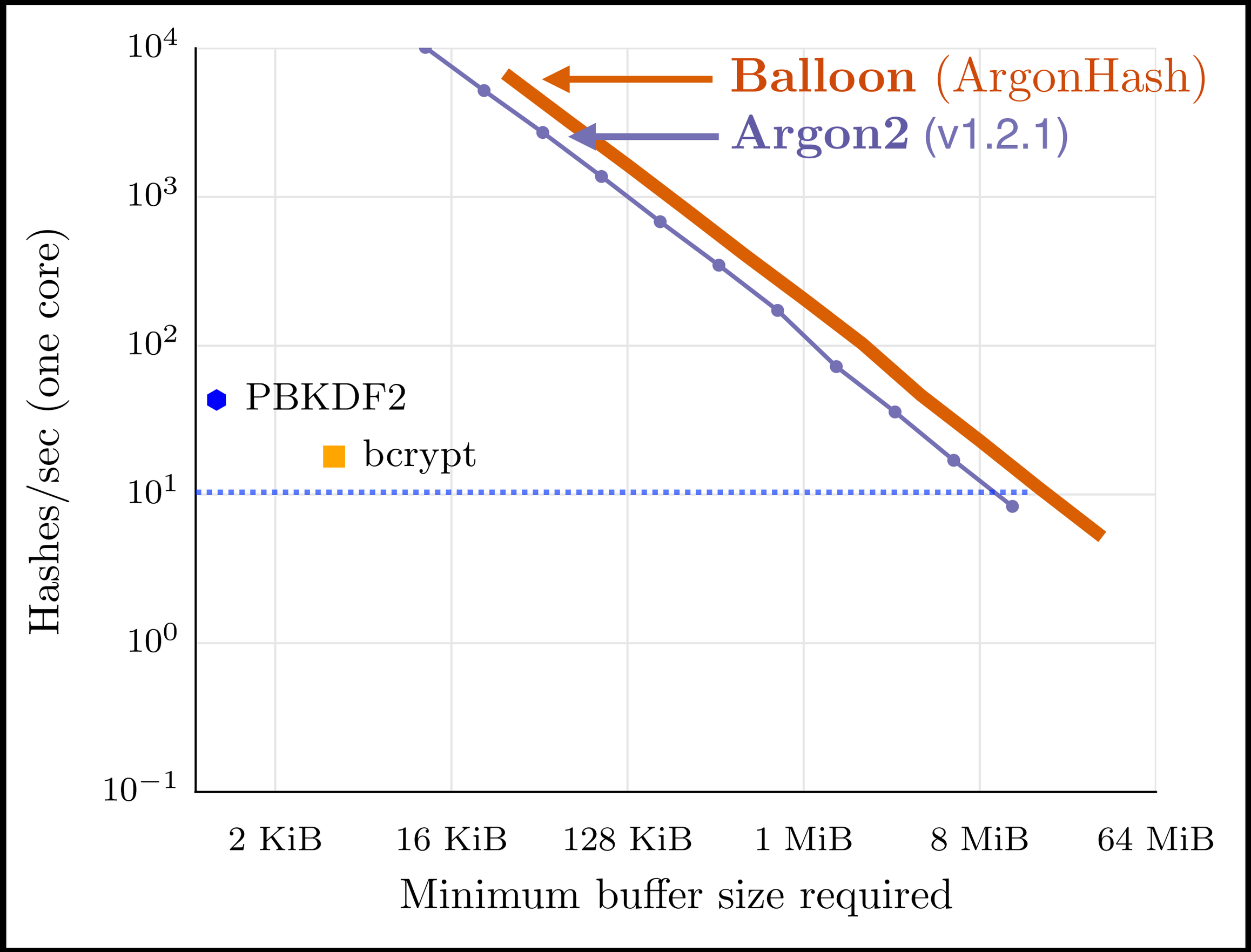

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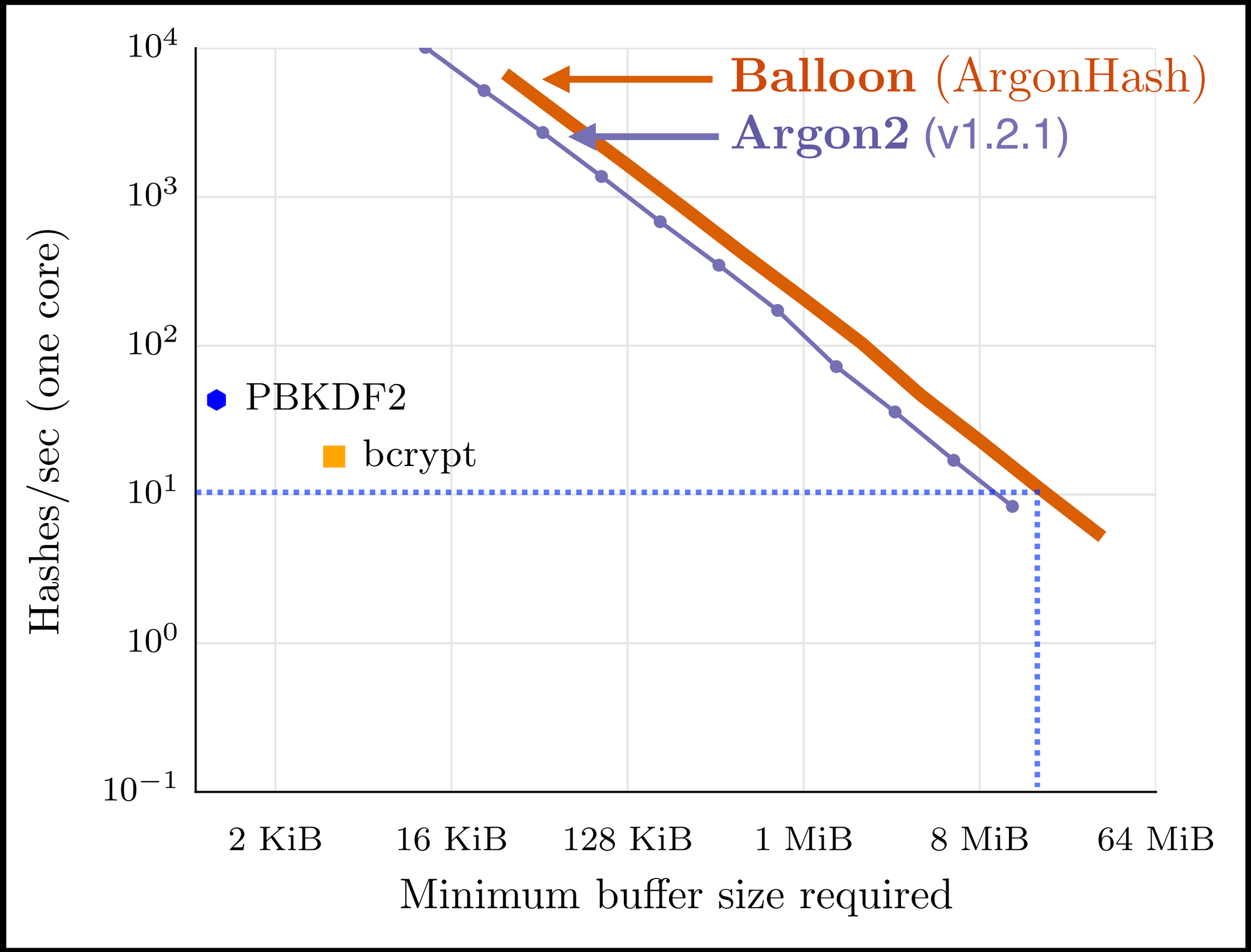

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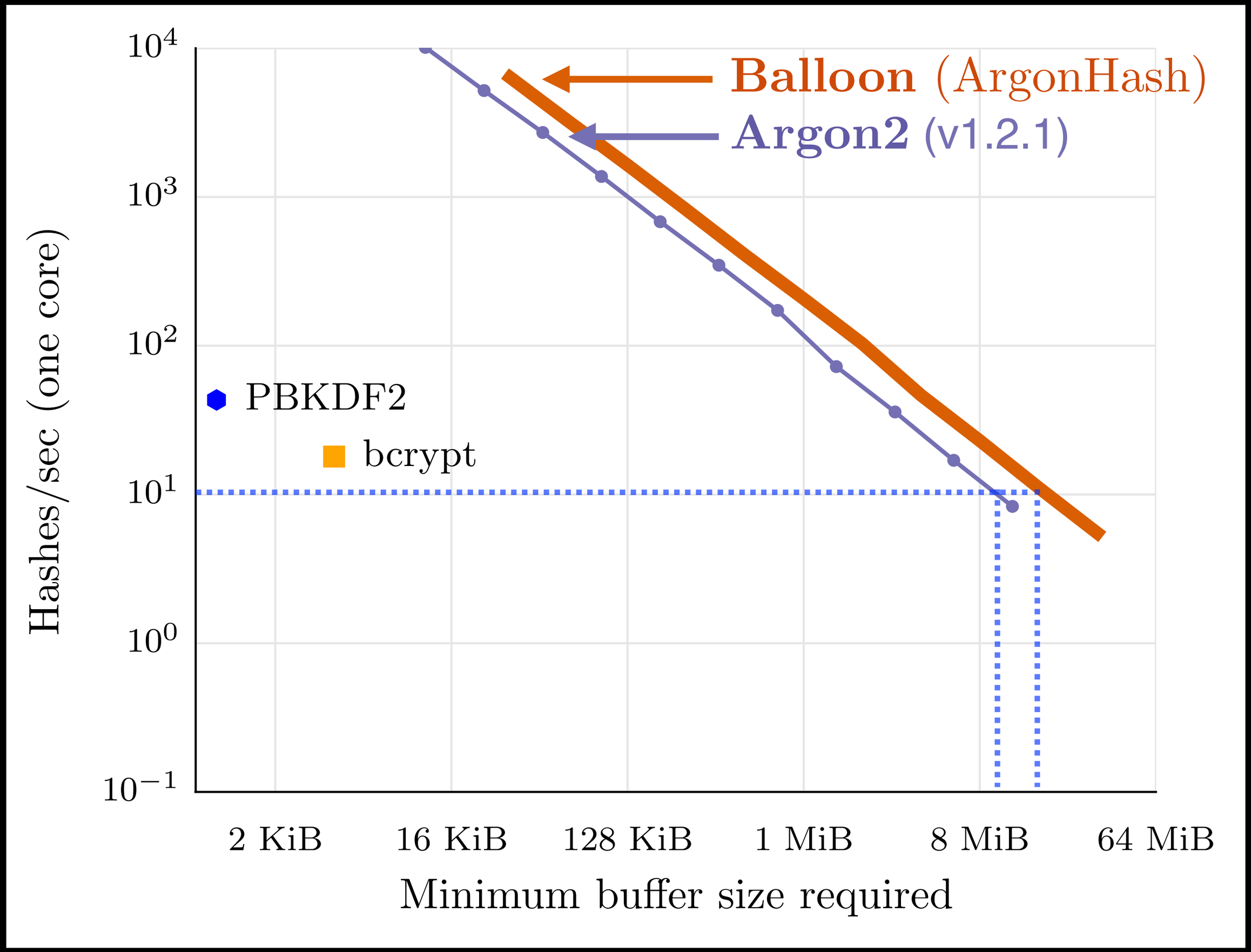

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II. Goals

III. The Balloon algorithm

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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
https://github.com/henrycg/balloon/

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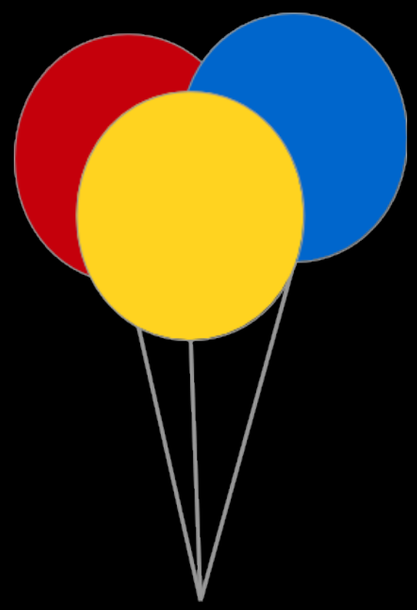

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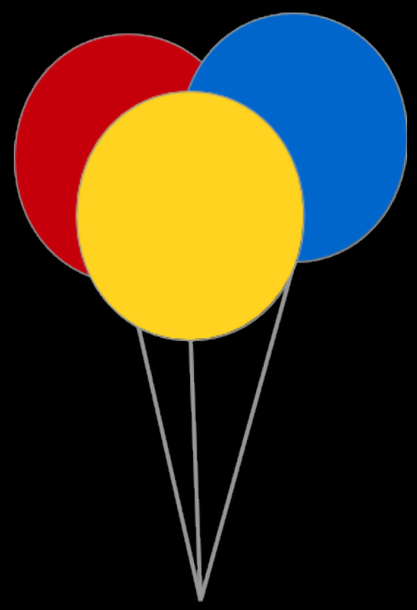

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