SIMD-accelerated data processing

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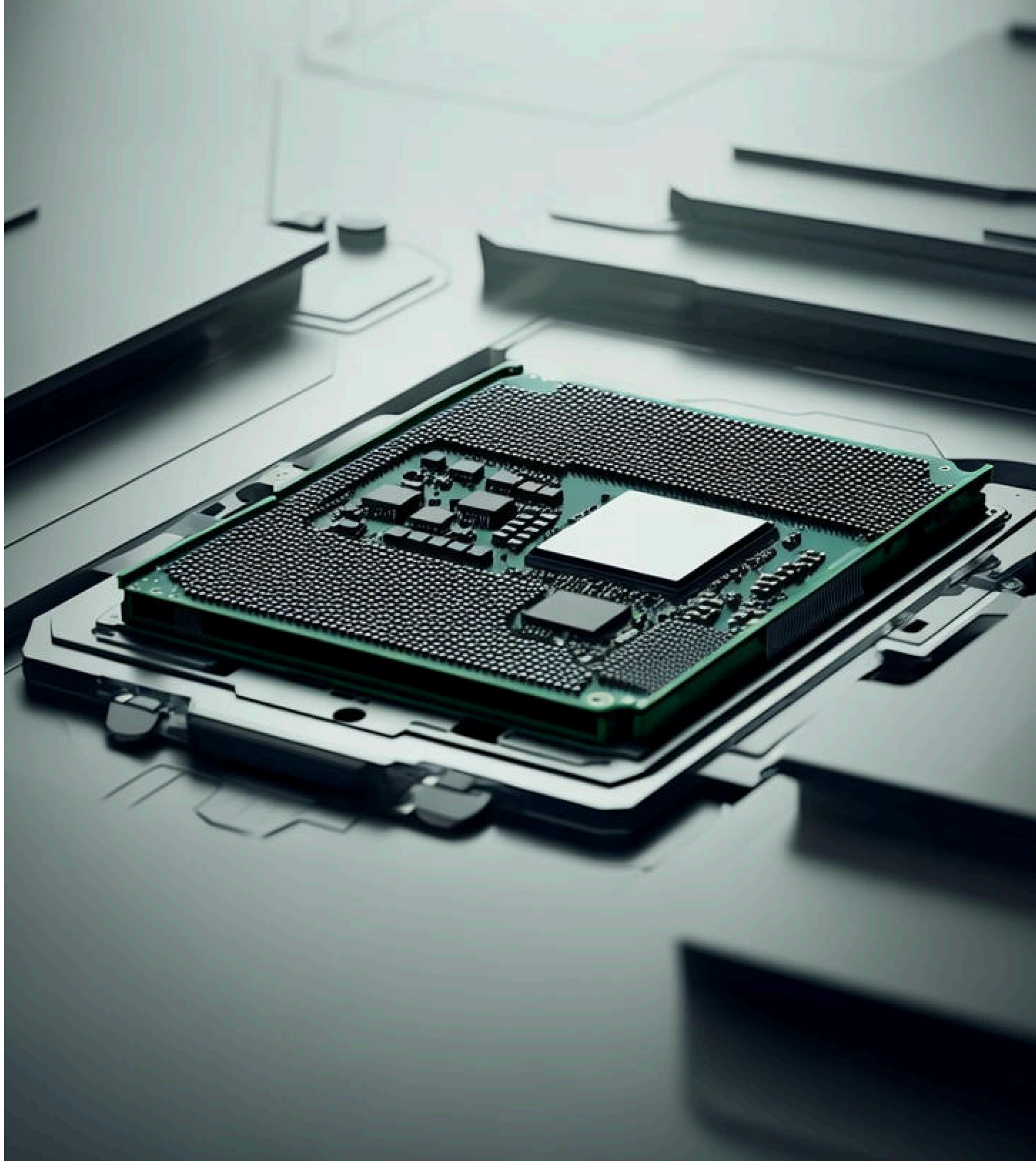
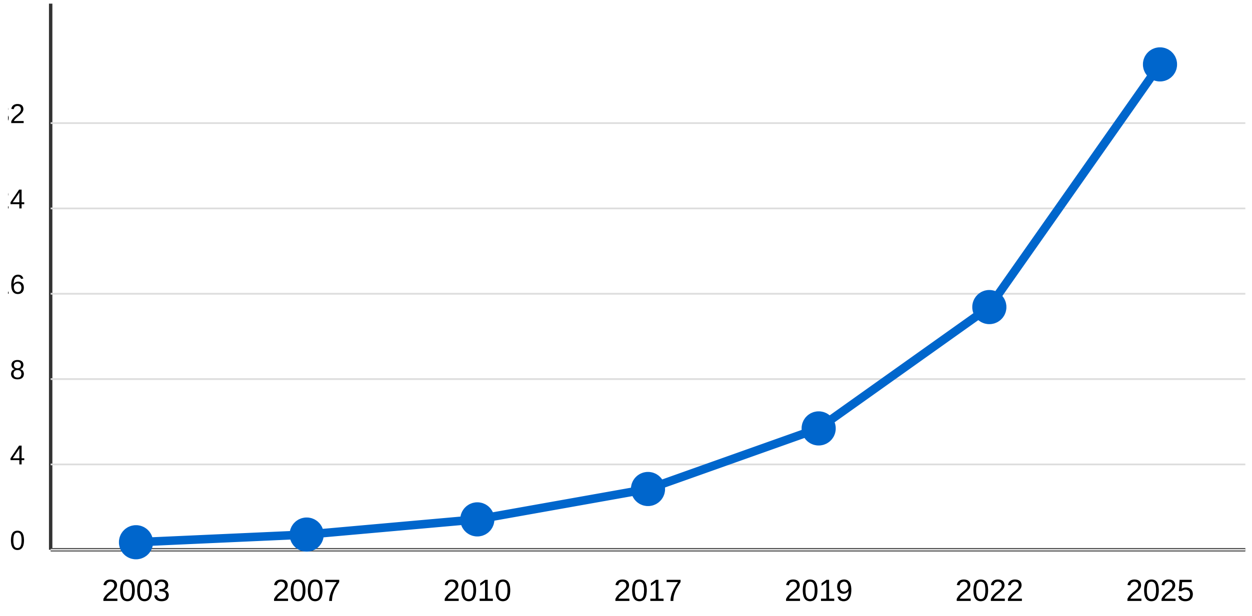


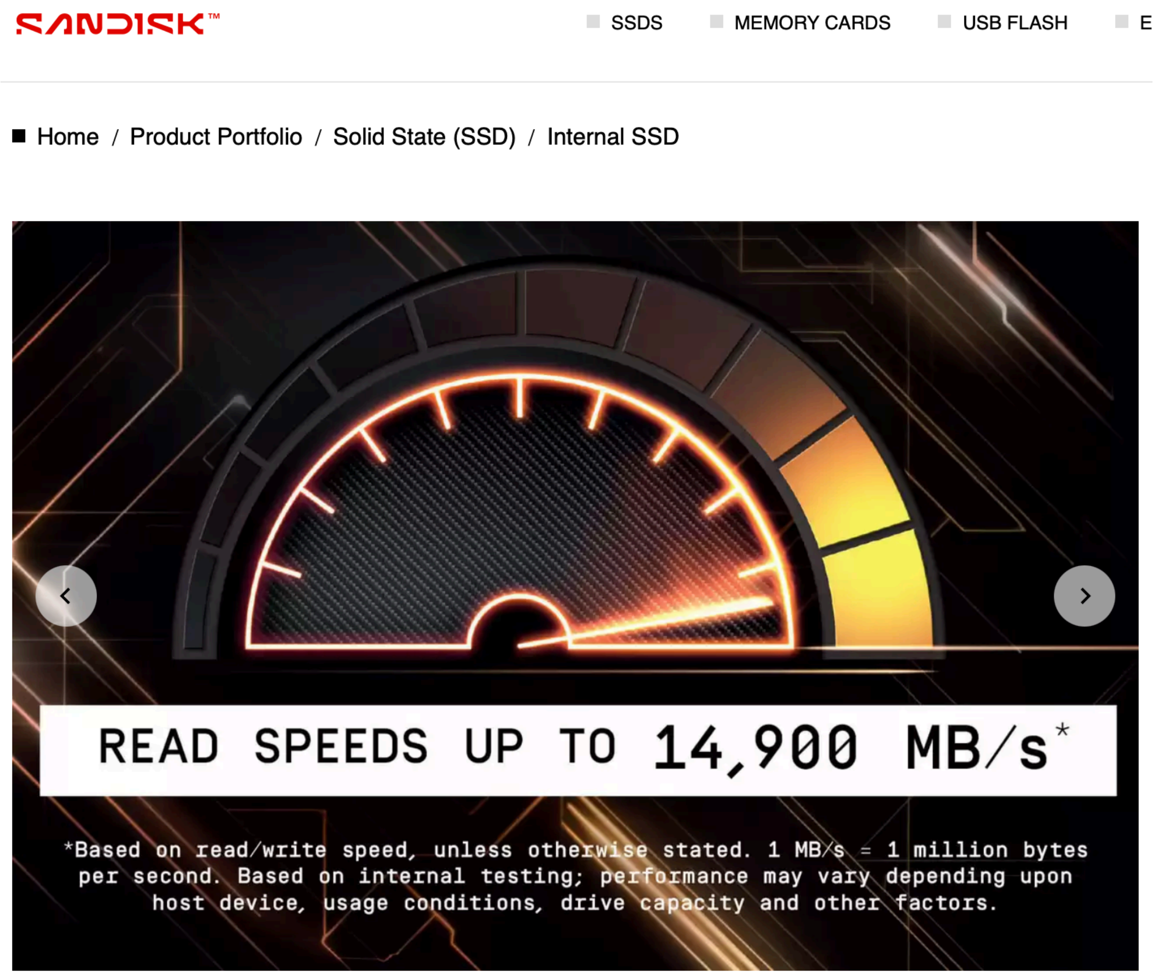
Doubles every 3 years

Specification	year	one channel
PCIe 1.x	2003	500 MB/s
PCIe 2.x	2007	1 GB/s
PCIe 3.x	2010	2 GB/s
PCIe 4.x	2017	4 GB/s
PCIe 5.x	2019	8 GB/s
PCIe 6.x	2022	16 GB/s
PCIe 7.x	2025	32 GB/s



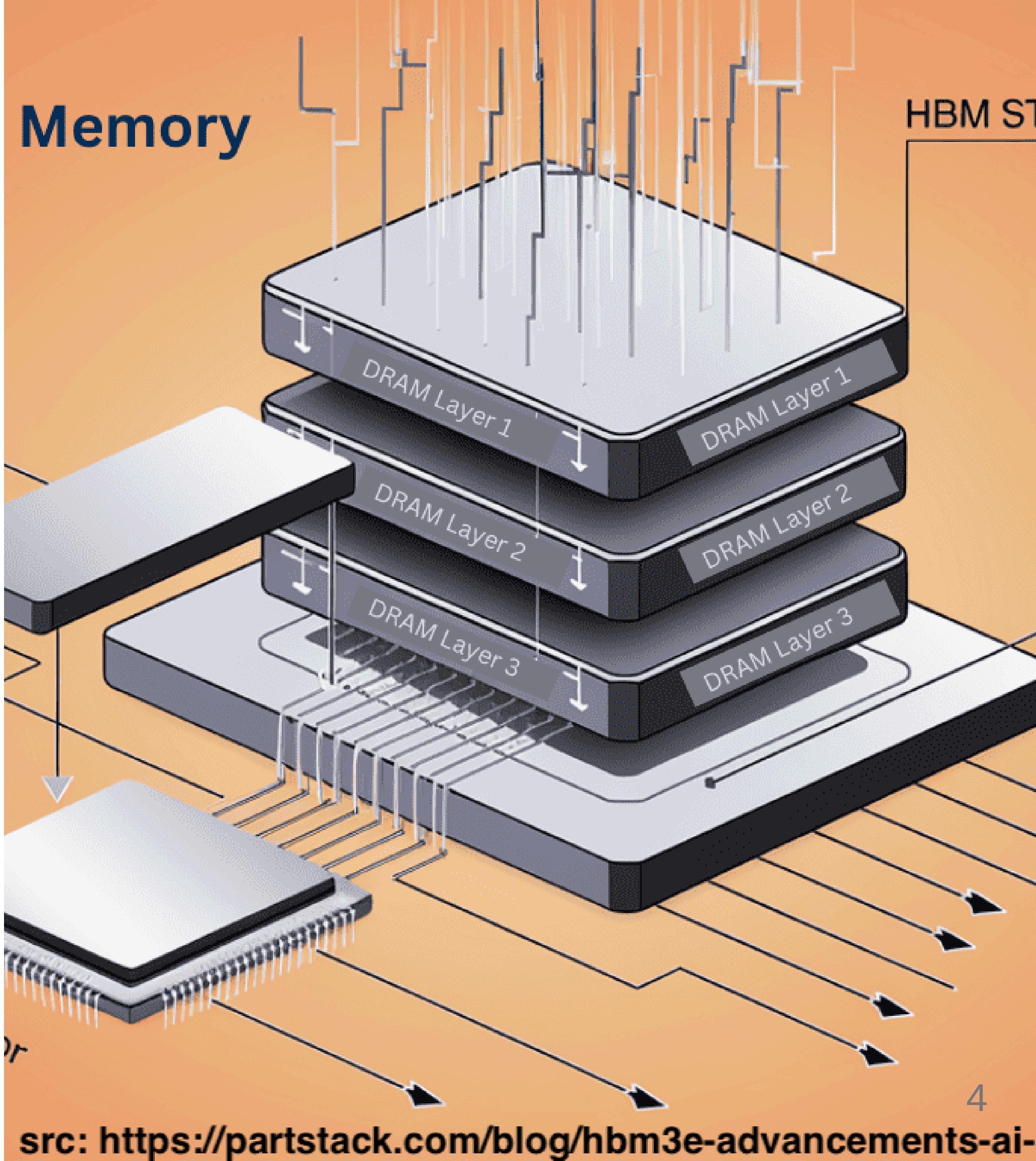
Disk at gigabytes per second

- Sony PlayStation 5 (2020): 5 GB/s
- Sony PlayStation 6 (2027): 15 GB/s (?)



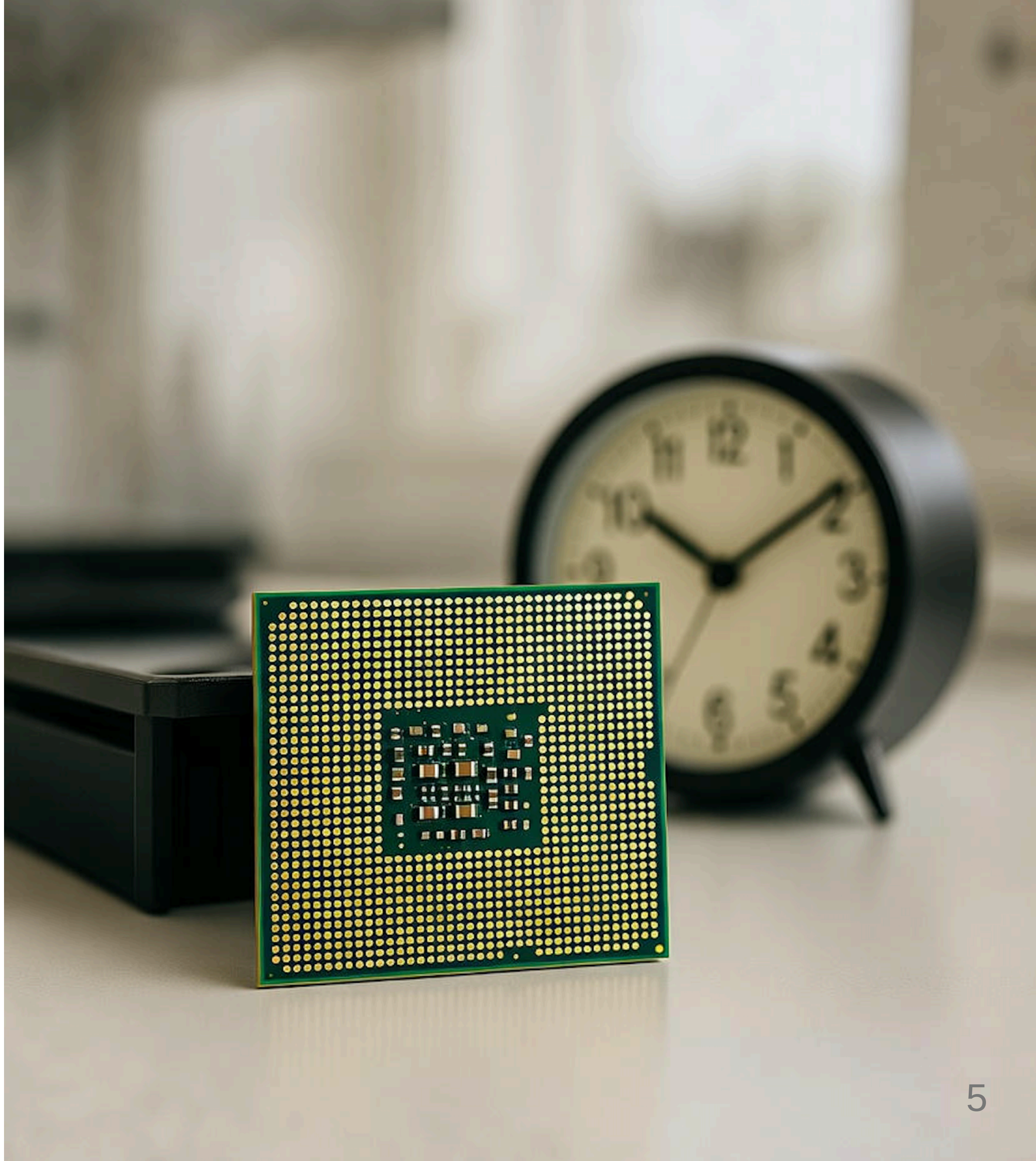
High Bandwidth Memory

- Xeon Max processors contain 64 GB of HBM
- Bandwidth 800 GB/s



Some numbers

- Processors: 4 GHz
- One byte per cycle: 4 GB/s
- **Easily CPU bound**



JSON

- Portable, simple
- Used by ~97% of API requests. [Landscape of API Traffic 2021 - Cloudflare]
- scalar values
  - strings (must be escaped)
  - numbers (but not `NaN` or `Inf`)
- composed values
  - objects (key/value)
  - arrays (list)

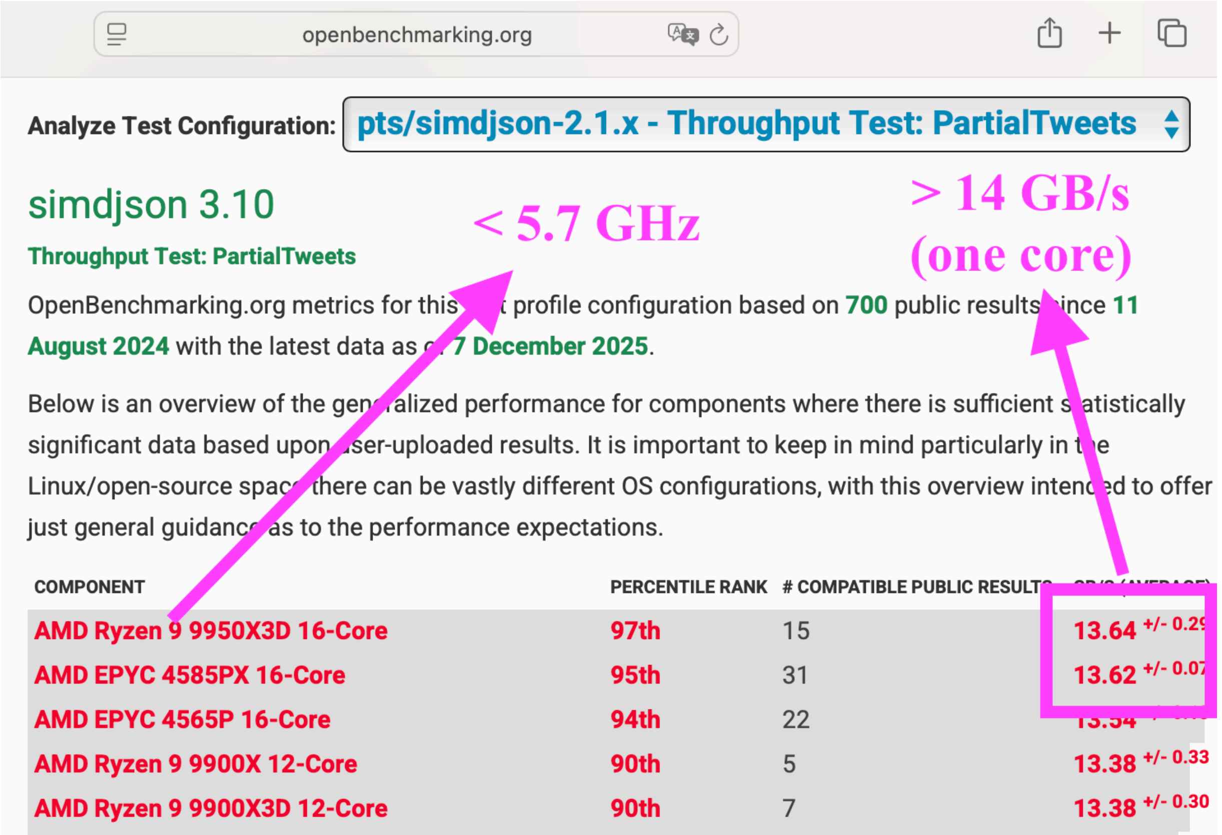
JSON Downside?

Reading and writing JSON can be *slow*. E.g., 100 MB/s to 300 MB/s.

- Slower than fast disks or fast networks

```
$ go run parse_twitter.go
Parsed 0.63 GB in 6.961 seconds (90.72 MB/s)
```

- openbenchmarking.org
- 14 GB/s, less than 5.7 GHz
- Parsing JSON at better than 2.5 bytes per cycle



SIMD (Single Instruction, multiple data)

- Allows us to process 16 (or more) bytes or more with one instruction
- Supported on all modern CPUs (phone, laptop)
- Data-parallel types (SIMD) (recently added to C++26)

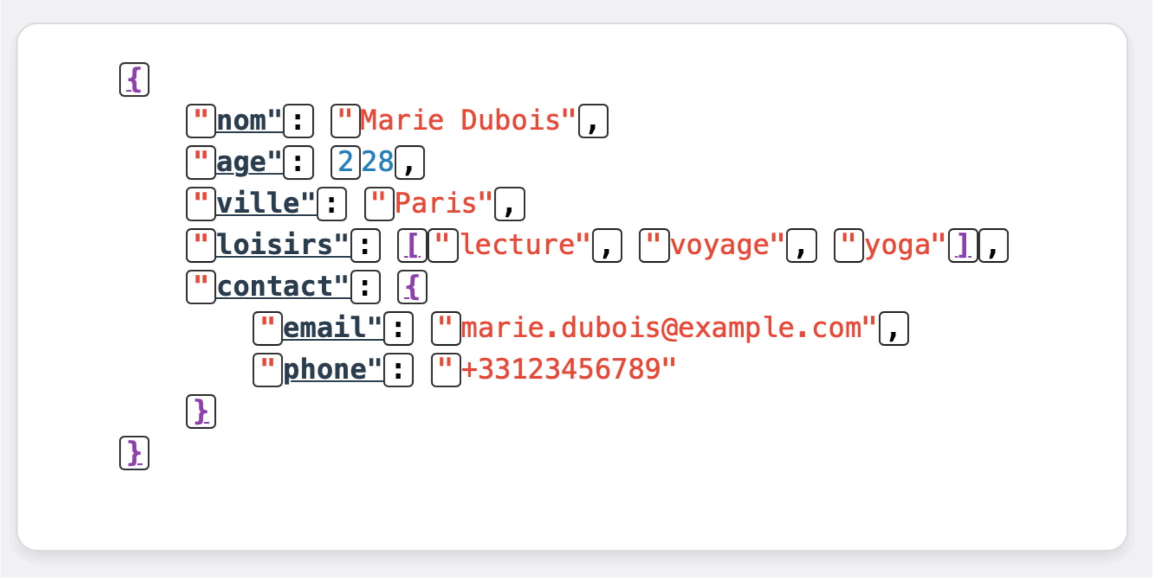
processor	year	arithmetic logic units	SIMD units
Pentium 4	2000	2	2×128
AMD Zen 2	2019	4	2×256
AMD Zen 5	2024	6	4×512

SIMD Support in simdjson

- x64: SSSE3 (128-bit), AVX-2 (256-bit), AVX-512 (512-bit)
- ARM NEON
- POWER (PPC64)
- Loongson: LSX (128-bit) and LASX (256-bit)
- RISC-V: *upcoming*

You are probably using simdjson

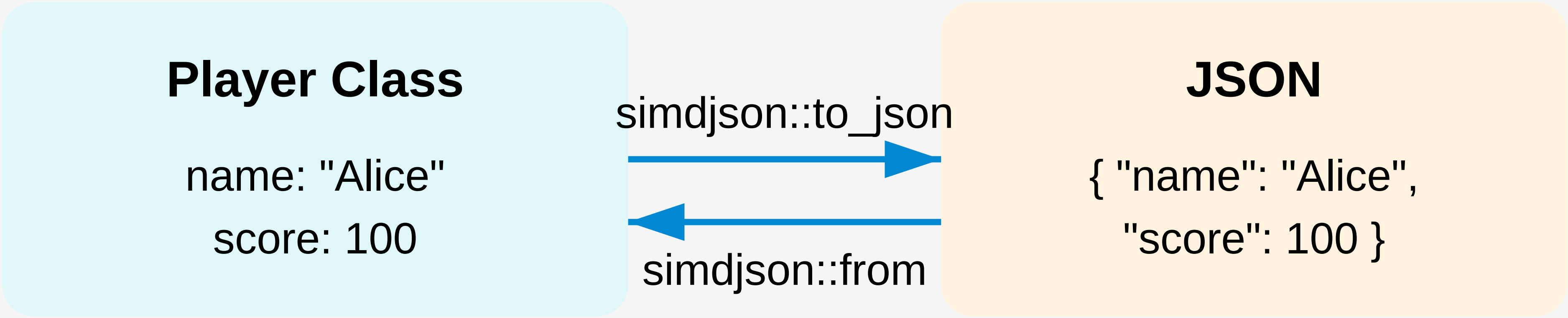
- Node.js, Electron,...
- ClickHouse
- WatermelonDB, Apache Doris, Meta Velox, Milvus, QuestDB, StarRocks



simdjson: Design

- First scan identifies the structural characters, start of all strings at about 10 GB/s using SIMD instructions.
- Validates Unicode at 30 GB/s.
- Rest of parsing relies on the generated index.
- Allows fast skipping. (Only parse what we need)
- Can minify JSON at 10 to 20 GB/s

C++26 (compile-time reflection)



Automatic Deserialization (C++26)

```
struct Player {
    \\ ....
}

// Deserialization - one line!
Player load_player(std::string& json_str) {
    return simdjson::from(json_str);  // That's it!
}
```

Automatic Serialization (C++26)

```cpp
// Serialization - one line!
void save_player(const Player& p) {
    std::string json = simdjson::to_json(p);  // That's it!
    // Save json to file...
}
```

Classifying characters

- comma (0x2c) `,`
- colon (0x3a) `:`
- brackets (0x5b,0x5d, 0x7b, 0x7d): `[, ], {, }`
- white-space (0x09, 0x0a, 0x0d, 0x20)
- others

Vectorized classification

- Most SIMD ISAs support 'vectorized lookup tables' (at least 16-element)
- If we had 256-element tables, we could do `H(c)`.
- For 16-element tables, need two tables `H1` and `H2`.
- Find two tables `H1` and `H2` such as the bitwise AND of the look classify the characters: `H1(low(& 0xf) & H2(c >> 4)`

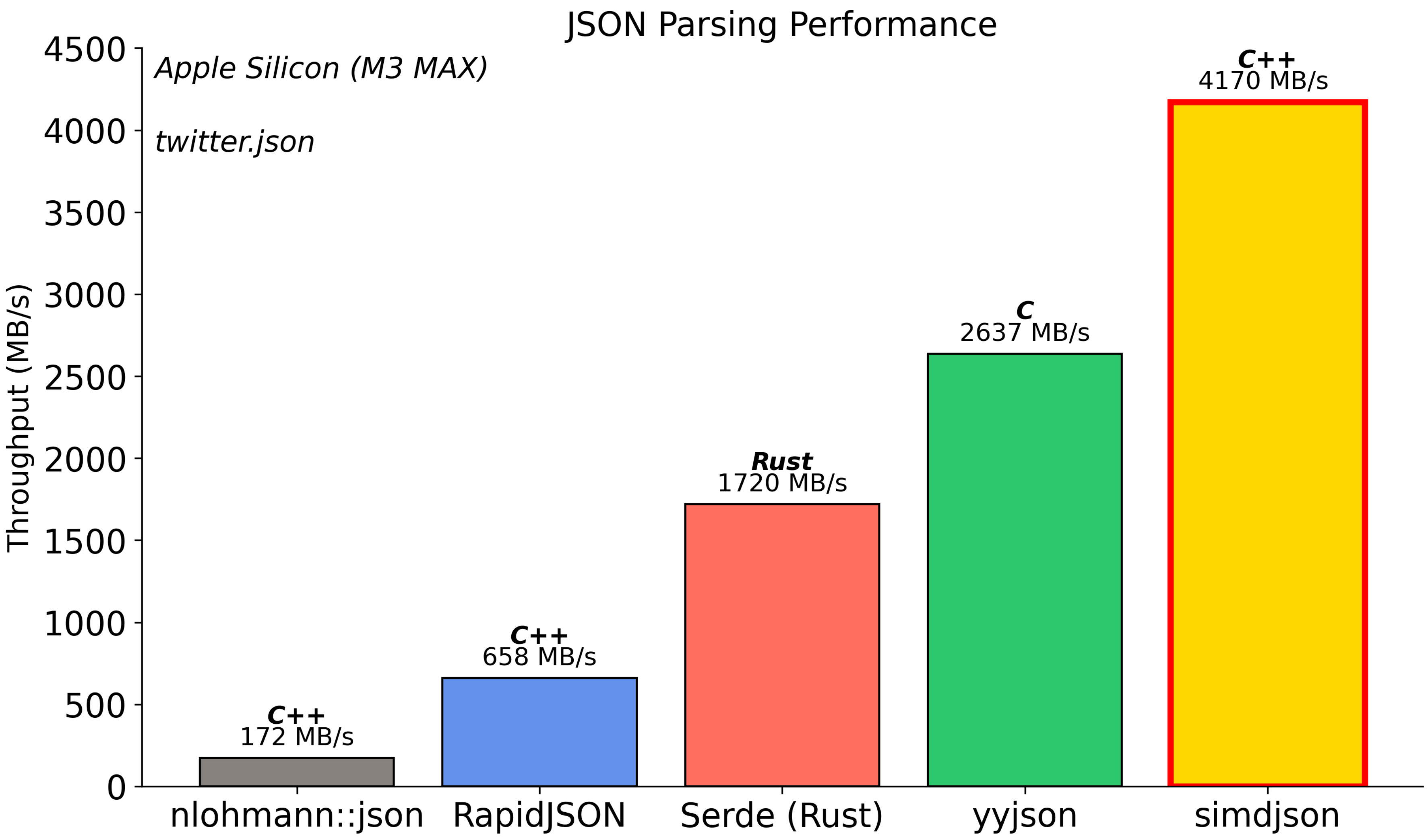
```
low_nibble_mask = {16, 0, 0, 0, 0, 0, 0, 0, 0, 8, 12, 1, 2, 9, 0, 0};
high_nibble_mask = {8, 0, 18, 4, 0, 1, 0, 1, 0, 0, 0, 3, 2, 1, 0, 0};
```

Five instructions:

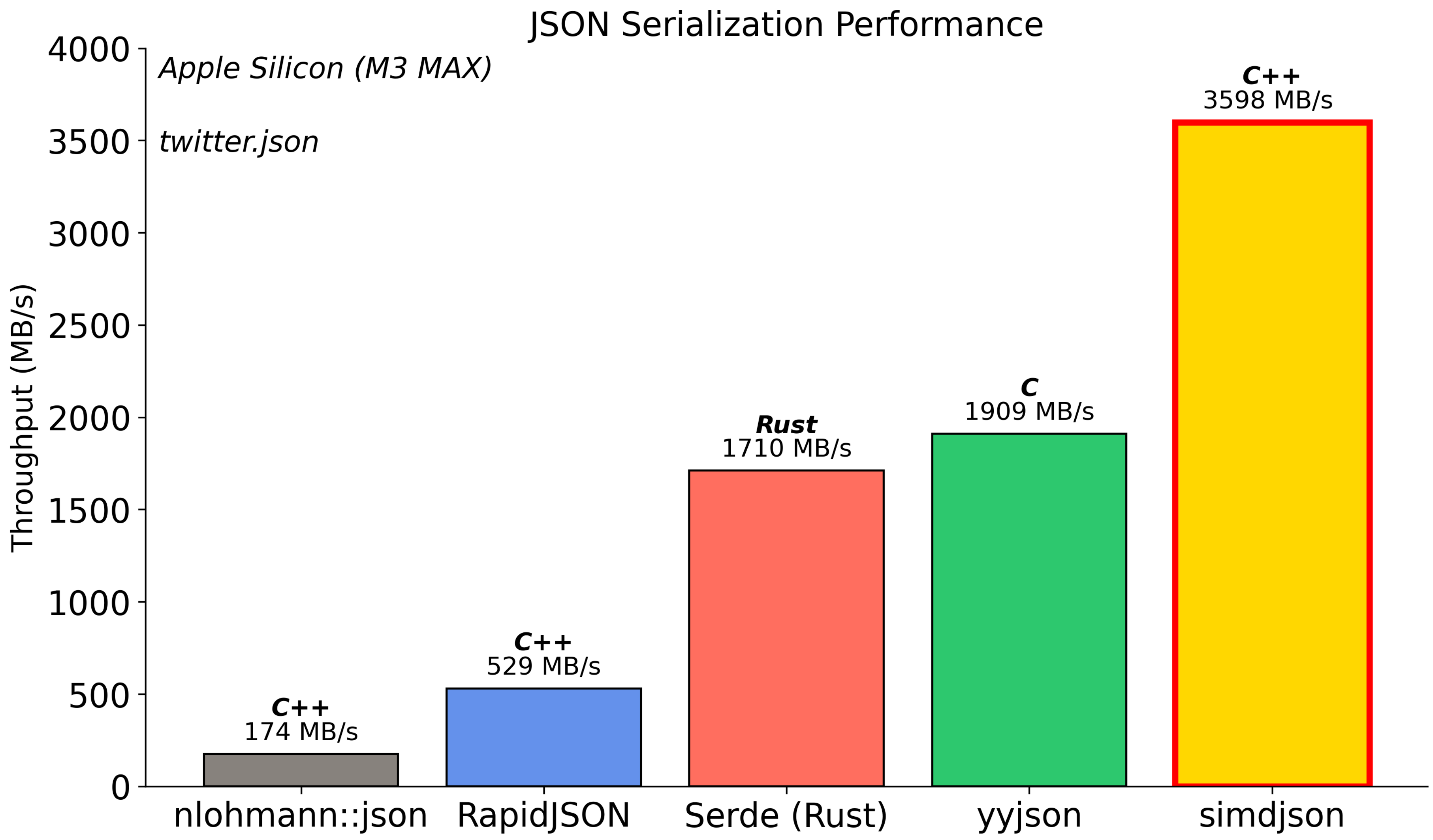
```
    nib_lo = input & 0xf;
    nib_hi = input >> 4;
    shuf_lo = lookup(low_nibble_mask, nib_lo);
    shuf_hi = lookup(high_nibble_mask, nib_hi);
    return shuf_lo & shuf_hi;
```

- comma (0x2c): 1
- colon (0x3a): 2
- brackets (0x5b,0x5d, 0x7b, 0x7d): 4
- most white-space (0x09, 0x0a, 0x0d): 8
- white space (0x20): 16
- others: 0

Deserialization (Apple Silicon)



Serialization (Apple Silicon)



Optimization #1: Consteval

The Power of Compile-Time

The Insight: JSON field names are known at compile time!

Traditional (Runtime):

```
// Every serialization call:
write_string("\"username\"");  // Quote & escape at runtime
write_string("\"level\"");     // Quote & escape again!
```

With Consteval (Compile-Time):

```
constexpr auto username_key = "\"username\":";  // Pre-computed!
b.append_literal(username_key);  // Just memcpy!
```

Optimization #2: SIMD String Escaping

The Problem: JSON requires escaping `"`, `\`, and control chars

Traditional (1 byte at a time):

```
for (char c : str) {
    if (c == '"' || c == '\\' || c < 0x20)
        return true;
}
```

SIMD (16 bytes at once):

```
auto chunk = load_16_bytes(str);
auto needs_escape = check_all_conditions_parallel(chunk);
if (!needs_escape)
    return false;  // Fast path!
```

- Part of Safari, Chrome, and most browsers
- Process Unicode and Base64 formats at gigabytes per second
- Support LoongArch, x64, ARM, POWER, RISC-V

simdutf

Unicode (UTF-16)

- Code points from U+0000 to U+FFFF, a single 16-bit value.
- Beyond: a surrogate pair `[U+D800 to U+DBFF]` followed by `U+DC00 to U+DFFF`

Validate

- Check whether we have a lone code unit ($x \leq \mathrm{0xD7FF} \vee x \geq \mathrm{0xDBFF}$), if so ok
- Check whether we have the first part of the surrogate ($\mathrm{0xD800} \leq x \leq \mathrm{0xDBFF}$) and if so check that we have the second part of a surrogate

Validate

```
PROCEDURE validate_utf16(code_units)
    i ← 0
    WHILE i < |code_units|
        unit ← code_units[i]
        IF unit ≤ 0xD7FF OR unit ≥ 0xE000 THEN
            INCREMENT i
            CONTINUE
        IF unit ≥ 0xD800 AND unit ≤ 0xDBFF THEN
            IF i + 1 ≥ |code_units| THEN
                RETURN false
            next_unit ← code_units[i + 1]
            IF next_unit < 0xDC00 OR next_unit > 0xDFFF THEN
                RETURN false
            i ← i + 2  // Valid surrogate pair
            CONTINUE
        RETURN false
    RETURN true
```

toWellFormed()

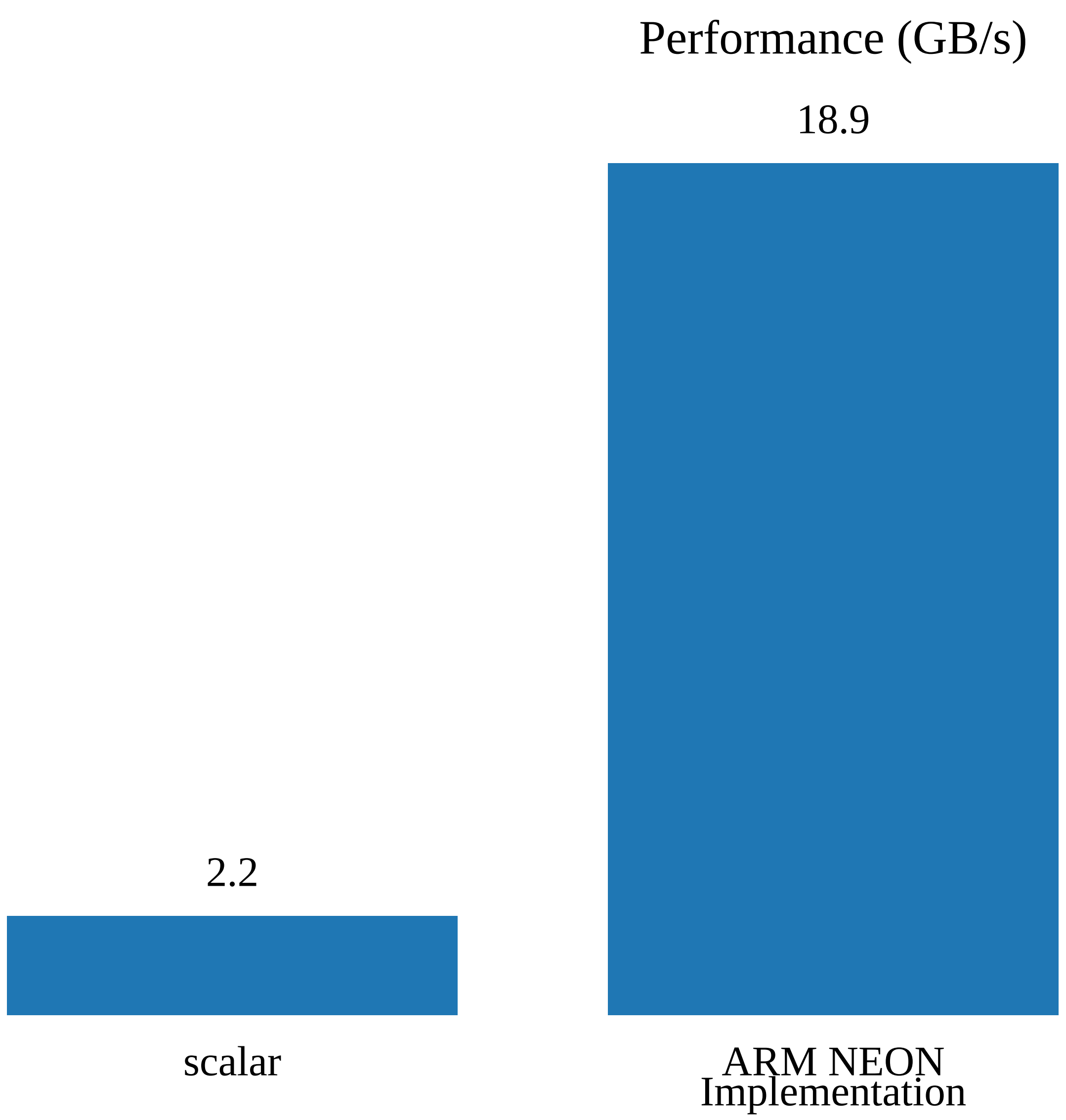
```
const str = "ab\uD800";
console.log(str.toWellFormed());
// "ab�"
```

UTF-16

- Write SIMD correction function (not just validation)
- Actually deployed in v8 (Google Chrome, Microsoft Edge)

UTF-16 correction, Apple M4

	scalar	ARM NEON
GB/s	2.2	18.9
ins/byte	12.0	0.9



In Browser (Apple M4)

- Chromium : 16 GB/s (**uses our new function**)
- Firefox : 3.4 GB/s
- Safari : 1.2 GB/s

https://lemire.github.io/browserwellformed/

Base64

- Encodes binary data to text using 64 characters (A-Z, a-z, 0-9, +, /)
- 3 bytes input → 4 characters output (33% overhead)
- Used in data URLs, email, web APIs

Example

- `text = "Hello, World!"`


```
SGVsbG8sIFdvcmxkIQ==
```

New JavaScript functions

```
const b64 = Uint8Array.toBase64(bytes);      // string
const recovered = Uint8Array.fromBase64(b64); // Uint8Array, matches original 'bytes'
```

- SIMD accelerates encoding/decoding to gigabytes per second
- Part of simdutf: fast, portable implementations

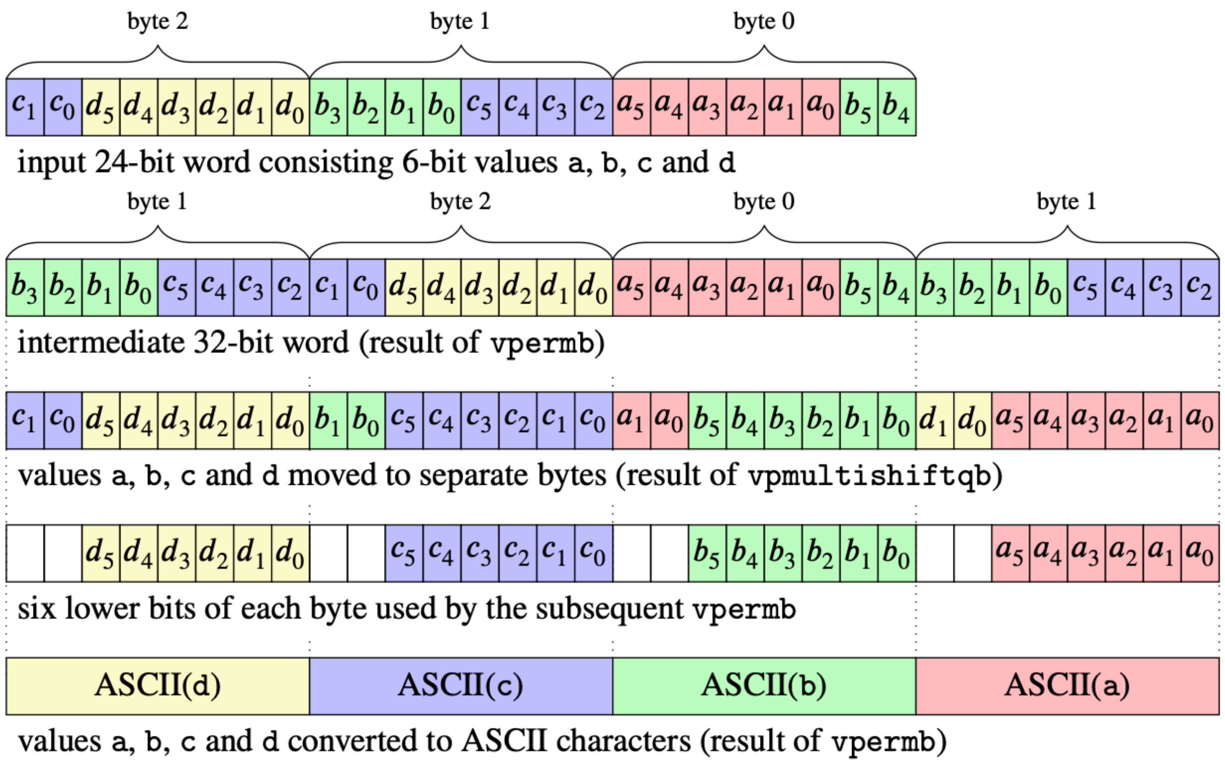
Result in the browser (Safari, Apple M4)

function	speed
`Uint8Array.fromBase64()`	11 GiB/s
`Uint8Array.toBase64()`	20 GiB/s

Test in your browser at https://simdutf.github.io/browserbase64/

AVX-512 base64 encoding/decoding

- Encoding a 64-byte block requires only two non-memory instructions `vpermb` (twice) and `vpmultishiftqb`.



Interested? Check these projects

- simdjson: The fastest JSON parser in the world https://simdjson.org
    - Node.js, Electron,...
    - ClickHouse, WatermelonDB, Apache Doris, Meta Velox, Milvus, QuestDB, StarRocks
- simdutf: Unicode routines (UTF8, UTF16, UTF32) and Base64 https://github.com/simdutf/simdutf
    - Node.js, Bun, WebKit (Safari), Chromium (Chrome, Edge)

Credit

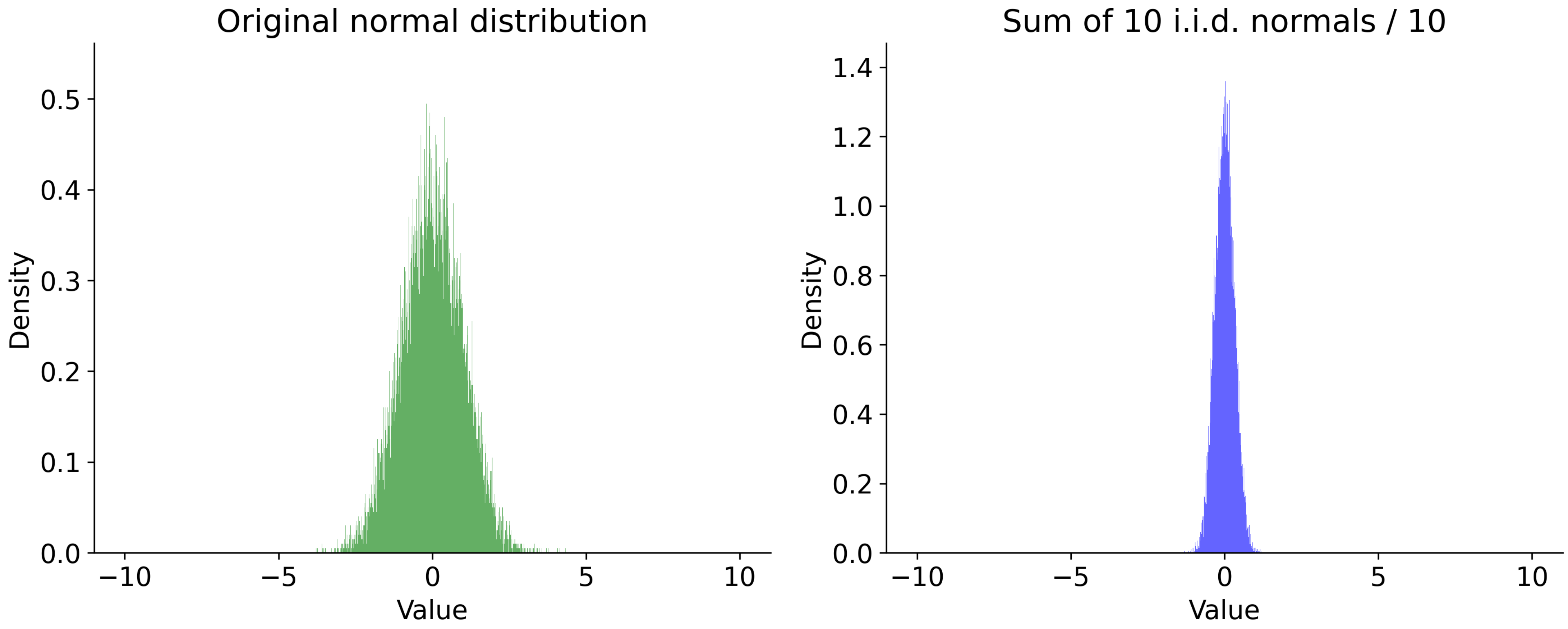
- simdjson reflection work with Francisco Geiman Thiesen (Microsoft)
- simdutf UTF-16 correction is joint work with Robert Clausecker
- simdjson and simdutf are community efforts (Geoff Langdale, John Keiser, Paul Dreik, Yagiz Nizipli and others)

Measurements

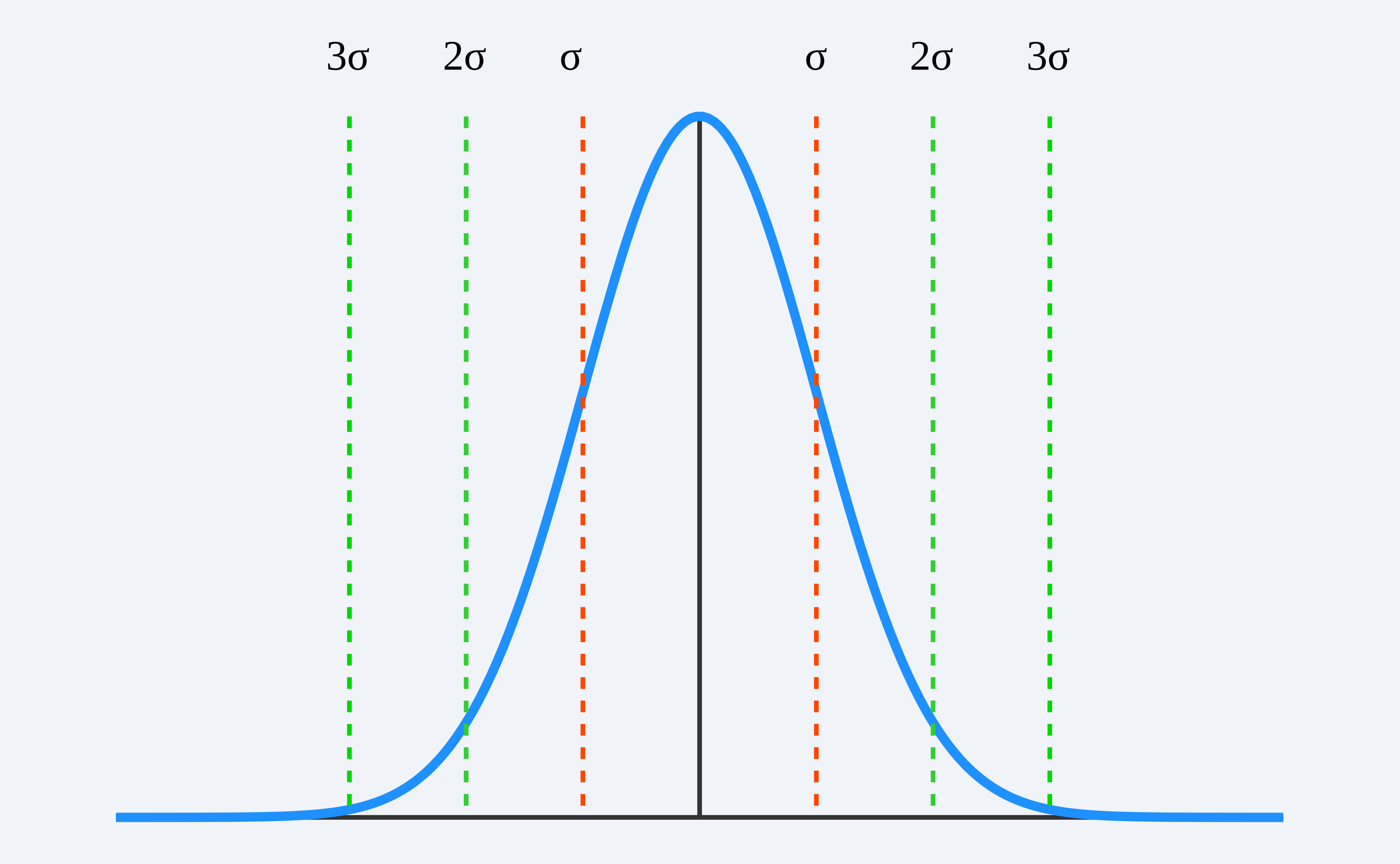
- We often assume that measurements (timings) are normally distributed.
- It is often an incorrect assumption.

Measurements

- If your measurements are normally distributed, the 'error' falls off as $1/\sqrt{N}$

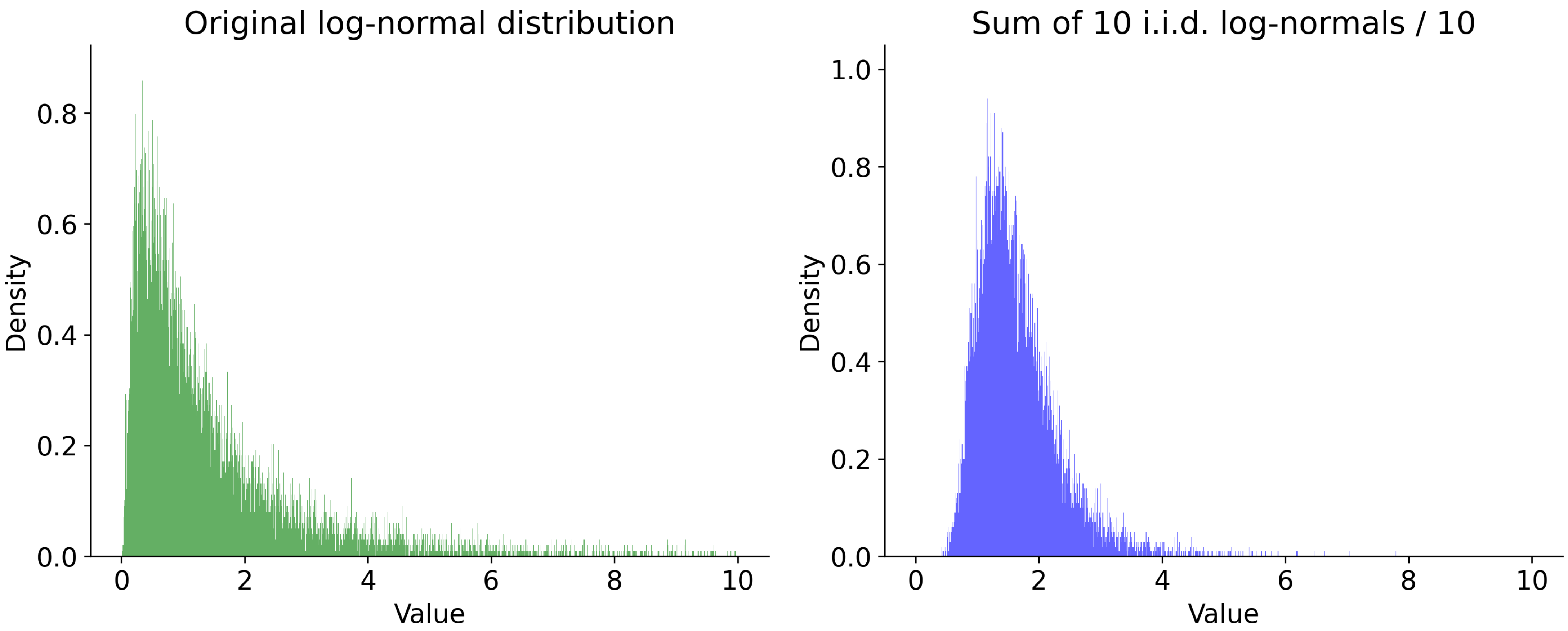

Original normal distribution
Density
0.0
0.1
0.2
0.3
0.4
0.5
−10
−5
0
5
10
Value
Sum of 10 i.i.d. normals / 10
Density
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
−10
−5
0
5
10
Value

Sigma events



- 1-sigma is 32%
- 2-sigma is 5%
- 3-sigma is 0.3% (once every 300 trials)
- 4-sigma is 0.00669% (once every 15000 trials)
- 5-sigma is 5.9e-05% (once every 1,700,000 trials)
- 6-sigma is 2e-07% (once every 500,000,000)
- $e^{-n^2/2}/(n * \sqrt{\pi/2}) \times 100$ for $n > 3$

What if we dealt with log-normal distributions?



Real-world measurements

- You cannot assume normality
- Measurements are **not independent**.
- Reality: the absolute minimum is often a *reliable metric*
- Margin: difference between mean and minimum

Conclusion

- Processors are getting much better! Wider!
- 'hot spot' engineering can fail, better to reduce overall instruction count.
- Branchy code can do well in synthetic benchmarks, but be careful.