C++26 Reflection for JSON Serialization

A Practical Journey

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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)

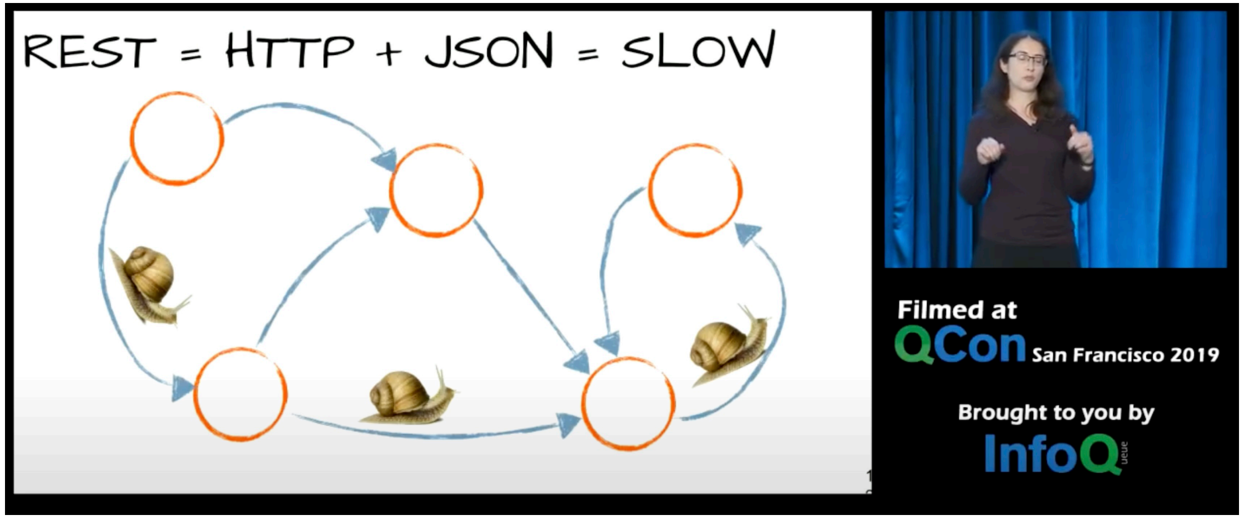
```json
{
    "username": "Alice",
    "level": 42,
    "health": 99.5,
    "inventory": ["sword", "shield", "potion"]
}
```

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)
```



Source: Gwen (Chen) Shapira

Micron shows off world's fastest PCIe 6.0 SSD, hitting 27 GB/s speeds — Astera Labs PCIe 6.0 switch enables impressive sequential reads

News

By Sunny Grimm published March 8, 2025

The next-gen of networking and storage is hitting the trade shows

Performance

- simdjson was the first library to break the gigabyte per second barrier
  - Parsing Gigabytes of JSON per Second, VLDB Journal 28 (6), 2019
  - On-Demand JSON: A Better Way to Parse Documents? SPE 54 (6), 2024
- JSON for Modern C++ (nlohmann/json) can be $100\times$ slower!

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)

Not all processors are equal

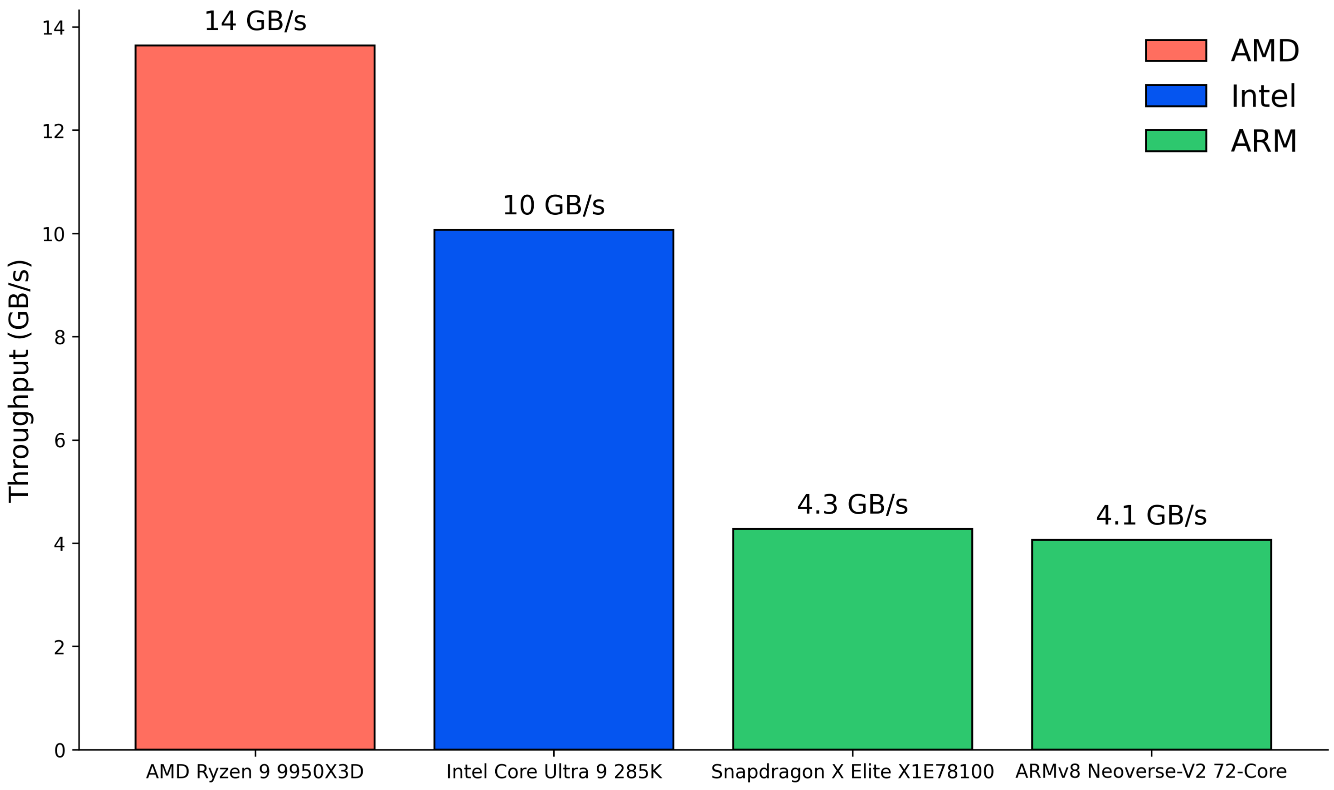
processor	year	arithmetic logic units	SIMD units
Apple M*	2019	6+	4×128
Intel Lion Cove	2024	6	4×256
AMD Zen 5	2024	6	4×512

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*

simdjson: Parsing design

- First scan identifies the structural characters, start of all strings at about 10 GB/s using SIMD instructions.
- Validates Unicode (UTF-8) at 30 GB/s.
- Rest of parsing relies on the generated index.
- Allows fast skipping. (Only parse what we need)



https://openbenchmarking.org/test/pts/simdjson

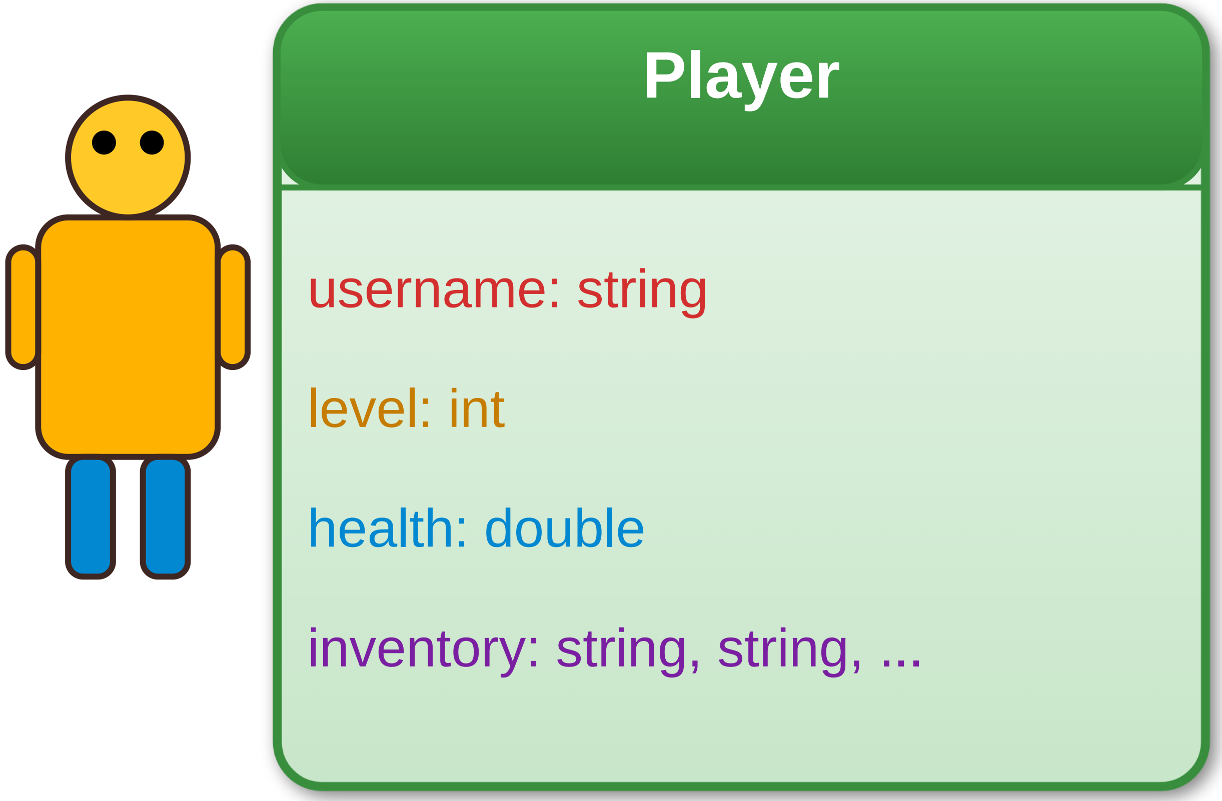
Usage

The simdjson library is found in...

- Node.js, Electron, ...
- ClickHouse
- Velox
- Milvus
- QuestDB
- StarRocks

The Problem

Imagine you're building a game server that needs to persist player data.



You start simple:

```cpp
struct Player {
    std::string username;
    int level;
    double health;
    std::vector<std::string> inventory;
};
```

The Traditional Approach: Manual Serialization

Without reflection, you may write this tedious code:

```cpp
// Serialization - converting Player to JSON
fmt::format(
        "{{"
        "\"username\":\"{}\","
        "\"level\":{},"
        "\"health\":{},"
        "\"inventory\":{}"
        "}}",
        escape_json(p.username),
        p.level,
        std::isfinite(p.health) ? p.health : -1.0,
        p.inventory| std::views::transform(escape_json)
);
```

Manual Deserialization (simdjson)

```
object obj = val.get_object();
p.username = obj["username"].get_string();
p.level = obj["level"].get_int64();
p.health = obj["health"].get_double();
array arr = obj["inventory"].get_array();
for (auto item : arr) {
    p.inventory.emplace_back(item.get_string());
}
```

When Your Game Grows...

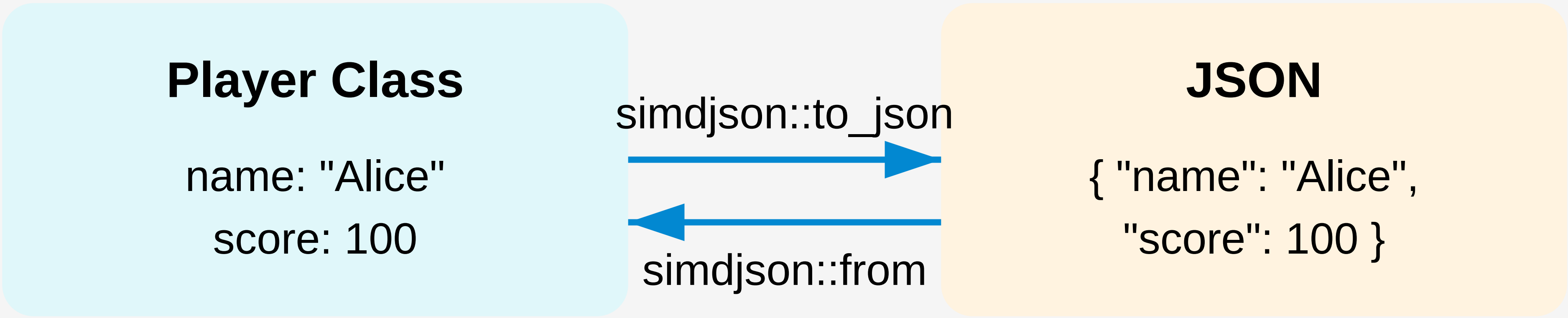
```cpp
struct Equipment {
    std::string name;
    int damage; int durability;
};
struct Achievement {
    std::string title; std::string description; bool unlocked;
    std::chrono::system_clock::time_point unlock_time;
};
struct Player {
    std::string username;
    int level; double health;
    std::vector<std::string> inventory;
    std::map<std::string, Equipment> equipped;     // New!
    std::vector<Achievement> achievements;         // New!
    std::optional<std::string> guild_name;         // New!
};
```

The Pain Points

This manual approach has several problems:

1. **Maintenance Nightmare**: Add a new field? Update both functions!
2. **Error-Prone**: Typos in field names, forgotten fields, type mismatches

Our goal: Seamless Serialization/Deserialization



How do other languages do it?

C#

```csharp
string jsonString = JsonSerializer.Serialize(player, options);
Player deserializedPlayer = JsonSerializer.Deserialize<Player>(jsonInput, options);
```

Why can C# implementation be so elegant?

It is using **reflection** to access the attributes of a struct during runtime.

Rust (serde)

```rust
// Rust with serde
let json_str = serde_json::to_string(&player)?;
let player: Player = serde_json::from_str(&json_str)?;
```

Rust reflection

- Rust does not have any built-in reflection capabilities.
- Serde relies on annotation and macros.

Reflection as accessing the attributes of a struct.

language	runtime reflection	compile-time reflection
C++ 26	❌	✅
Go	✅	❌
Java	✅	❌
C#	✅	❌
Rust	❌ (macros)	❌

Now it's our turn to have reflection!

With C++26 reflection and simdjson, **all that boilerplate disappears**:

```cpp
// Just define your struct - no extra code needed!
struct Player {
    std::string username;
    int level;
    double health;
    std::vector<std::string> inventory;
    std::map<std::string, Equipment> equipped;
    std::vector<Achievement> achievements;
    std::optional<std::string> guild_name;
};
```

Automatic Serialization

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

Automatic Deserialization

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

Runnable example at https://godbolt.org/z/Efr7bK9jn

Benefits of our implementation

- **No manual field mapping**
- **Minimal maintenance burden**
- **Handles nested and user-defined structures and containers automatically**
- **You can still customize things if and when you want to**

What Happens Behind the Scenes

```cpp
// What you write:
Player p = simdjson::from(runtime_json_string);

// What reflection generates at COMPILE TIME (conceptually):
Player deserialize_Player(const json& j) {
    Player p;
    p.username = j["username"].get<std::string>();
    p.level = j["level"].get<int>();
    p.health = j["health"].get<double>();
    p.inventory = j["inventory"].get<std::vector<std::string>>();
    // ... etc for all members
    return p;
}
```

The Actual Reflection Magic

```
// Simplified snippet, members stores information about the class
// obtained via std::define_static_array(std::meta::nonstatic_data_members_of(^^T, ...))...
ondemand::object obj;

template for (constexpr auto member : members) {
    // These are compile-time constants
    constexpr std::string_view field_name = std::meta::identifier_of(member);
    constexpr auto member_type = std::meta::type_of(member);

    // This generates code for each member
    obj[field_name].get(out.[:member:]);
}
```

See full implementation on GitHub

Compile-Time vs Runtime: What Happens When

```
struct Player {
    std::string username;    // ← Compile-time: reflection sees this
    int level;               // ← Compile-time: reflection sees this
    double health;           // ← Compile-time: reflection sees this
};

// COMPILE TIME: Reflection reads Player's structure and generates:
// - Code to read "username" as string
// - Code to read "level" as int
// - Code to read "health" as double

// RUNTIME: The generated code processes actual JSON data
std::string json = R"({"username":"Alice","level":42,"health":100.0})";
Player p = simdjson::from(json);
// Runtime values flow through compile-time generated code
```

Try out this example at https://godbolt.org/z/WWGjhnjWW

```
struct Meeting {
    std::string title;
    long long start_time;
    std::vector<std::string> attendees;
    std::optional<std::string> location;
    bool is_recurring;
};

// Automatically serializable/deserializable!
std::string json = simdjson::to_json(Meeting{
    .title = "CppCon Planning",
    .start_time = std::chrono::duration_cast<std::chrono::milliseconds>(
        std::chrono::system_clock::now().time_since_epoch()
    ).count(),
    .attendees = {"Alice", "Bob", "Charlie"},
    .location = "Denver",
    .is_recurring = true
});

Meeting m = simdjson::from(json);
```

The Container Challenge

We can say that serializing/parsing the basic types and custom classes/structs is pretty much effortless.

How do we automatically serialize ALL these different containers?

- `std::vector<T>`, `std::list<T>`, `std::deque<T>`
- `std::map<K,V>`, `std::unordered_map<K,V>`
- `std::set<T>`, `std::array<T,N>`
- Custom containers from libraries
- **Future containers not yet invented**

The Naive Approach

```
// The OLD way - repetitive and error-prone! 😱
void serialize(string_builder& b, const std::vector<T>& v) { /* ... */ }
void serialize(string_builder& b, const std::list<T>& v) { /* ... */ }
void serialize(string_builder& b, const std::deque<T>& v) { /* ... */ }
void serialize(string_builder& b, const std::set<T>& v) { /* ... */ }
// ... 20+ more overloads for each container type!
```

Problem: New container type? Write more boilerplate!

The Solution: Concepts as Pattern Matching

Concepts let us say: **"If it walks like a duck and quacks like a duck..."**

```cpp
// The NEW way - one function handles ALL array-like containers!
template<typename T>
  requires(has_size_and_subscript<T>)  // "If it has .size() and operator[]"
void serialize(string_builder& b, const T& container) {
    b.append('[');
    for (size_t i = 0; i < container.size(); ++i) {
        serialize(b, container[i]);
    }
    b.append(']');
}
```

✅ Works with `vector`, `array`, `deque`, custom containers...

Concepts + Reflection = Automatic Support

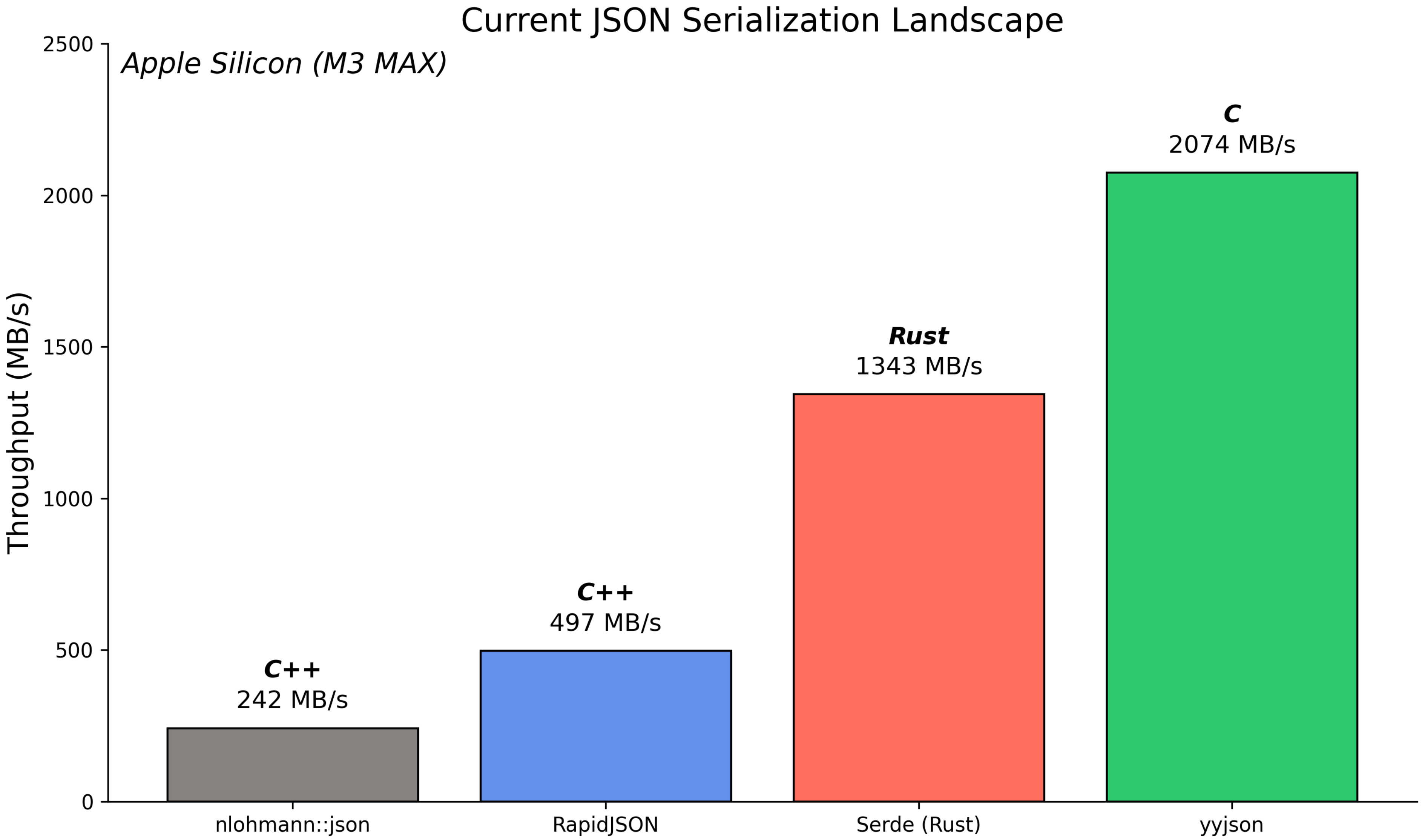
When you write:

```
struct GameData {
    std::vector<int> scores;              // Array-like → [1,2,3]
    std::map<string, Player> players;  // Map-like → {"Alice": {...}}
    MyCustomContainer<Item> items;      // Your container → Just works!
};
```

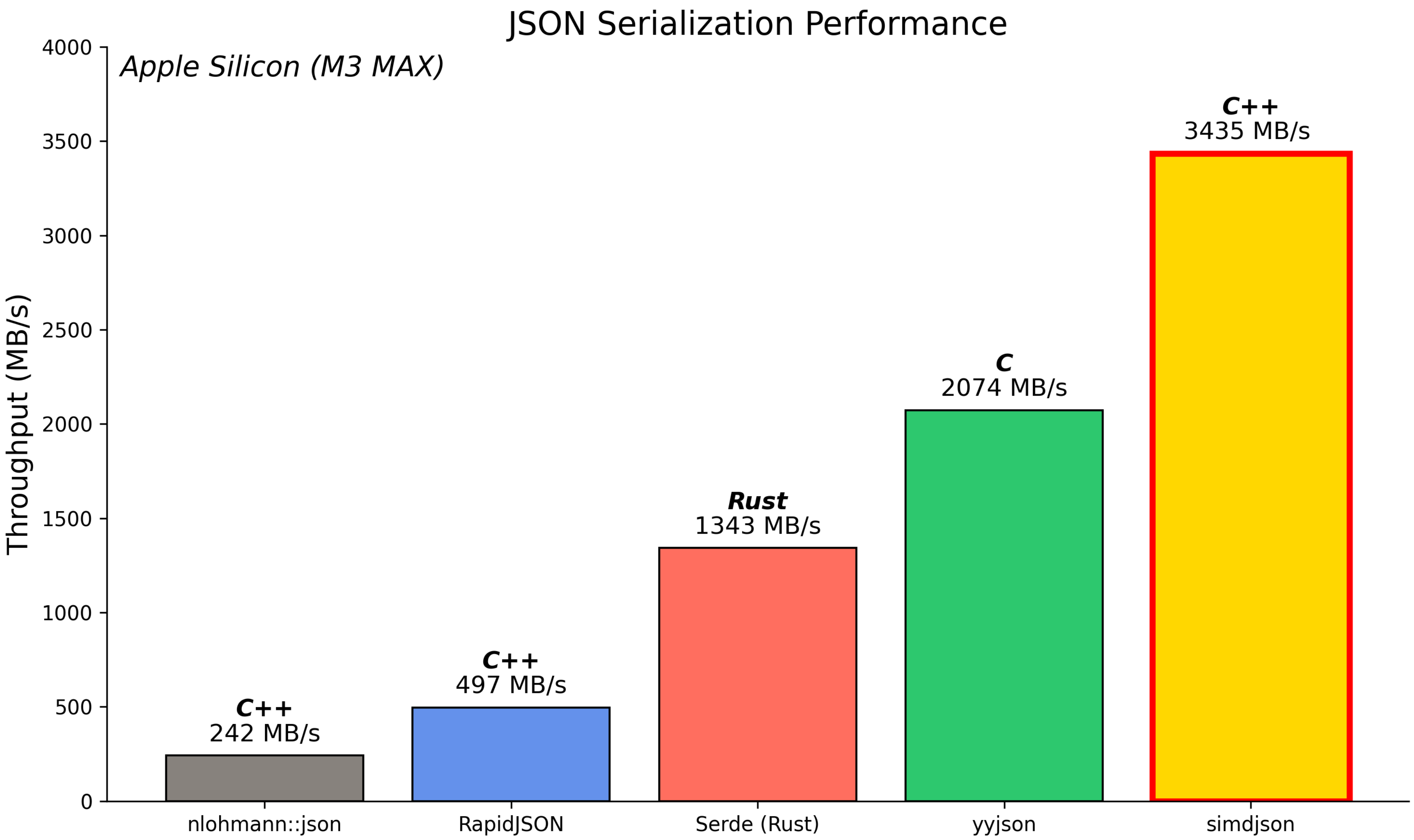
The magic:

1. **Reflection** discovers your struct's fields
2. **Concepts** match container behavior to serialization strategy
3. **Result**: ALL containers work automatically - standard, custom, or future!

Write once, works everywhere™


Current JSON Serialization Landscape
Apple Silicon (M3 MAX)
Throughput (MB/s)
2500
2000
1500
1000
500
0
C++
242 MB/s
C++
497 MB/s
Rust
1343 MB/s
C
2074 MB/s
nlohmann::json
RapidJSON
Serde (Rust)
yyjson

How fast are we?



Ablation Study: How We Achieved 3.4 GB/s

What is Ablation?

From neuroscience: systematically remove parts to understand function

Our Approach (Apple Silicon M3 MAX):

1. **Baseline**: All optimizations enabled (3,400 MB/s)
2. **Disable one optimization** at a time
3. **Measure performance impact**
4. **Calculate contribution**: `(Baseline - Disabled) / Disabled`

Five Key Optimizations

1. **Consteval**: Compile-time field name processing
2. **SIMD String Escaping**: Vectorized character checks
3. **Fast Integer Serialization**: Optimized number handling

Combined Performance Impact

Optimization	Twitter Contribution	CITM Contribution
Consteval	+100% (2.00x)	+141% (2.41x)
SIMD Escaping	+42% (1.42x)	+4% (1.04x)
Fast Digits	+6% (1.06x)	+34% (1.34x)

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!
```

Optimization #3: Fast Integer serialization

(`std::to_chars`)

```
while(number >= 10) {
     *write_pointer-- = char('0' + (number % 10));
     number /= 10;
}
*write_pointer = char('0' + number);
```

Writing from the end

Two digits at a time

```
while(number >= 100) {
    memcpy(write_pointer - 1, &decimal_table[(pv % 100)*2], 2);
    write_pointer -= 2;
    pv /= 100;
}
if(number >= 10) {
     *write_pointer-- = char('0' + (number % 10));
     number /= 10;
}
*write_pointer = char('0' + number);
```

Know where to start writing

- Useful to compute quickly the number of digits

```
template <typename number_type>
int int_log2(number_type x) {
  return 63 - leading_zeroes(uint64_t(x) | 1);
}

int fast_digit_count_64(uint64_t x) {
  static uint64_t table[] = {9,
                             99,
                             999,
                             //...
                             9999999999999999ULL,
                             99999999999999999ULL,
                             999999999999999999ULL,
                             9999999999999999999ULL};
  int y = (19 * int_log2(x) >> 6);
  y += x > table[y];
  return y + 1;
```

Could use SIMD if we wanted to

Don't try to understand::

```
__m128i to_string_avx512ifma(uint64_t n) {
  uint64_t n_15_08  = n / 100000000;
  uint64_t n_07_00  = n % 100000000;
  __m512i bcstq_h   = _mm512_set1_epi64(n_15_08);
  __m512i bcstq_l   = _mm512_set1_epi64(n_07_00);
  __m512i zmmzero   = _mm512_castsi128_si512(_mm_cvtsi64_si128(0x1A1A400));
  __m512i zmmTen    = _mm512_set1_epi64(10);
  __m512i asciiZero = _mm512_set1_epi64('0');
  __m512i ifma_const    = _mm512_setr_epi64(0x00000000002af31dc, ...);
  __m512i permb_const   = _mm512_castsi128_si512(_mm_set_epi8(0x78, ...));
  __m512i lowbits_h     = _mm512_madd52lo_epu64(zmmzero, bcstq_h, ifma_const);
  __m512i lowbits_l     = _mm512_madd52lo_epu64(zmmzero, bcstq_l, ifma_const);
  __m512i highbits_h    = _mm512_madd52hi_epu64(asciiZero, zmmTen, lowbits_h);
  __m512i highbits_l    = _mm512_madd52hi_epu64(asciiZero, zmmTen, lowbits_l);
  __m512i perm          = _mm512_permutex2var_epi8(highbits_h, permb_const, highbits_l);
  __m128i digits_15_0   = _mm512_castsi512_si128(perm);
  return digits_15_0;
}
```

Does fast integer processing matter?

- Replace fast digit count by naive approach based on `std::to_string`

  ```
  std::to_string(value).length();
  ```

- Only 34% worse in one dataset.

What about compilation time?

We've observed a 6% slow-down when compiling simdjson with static reflection enabled. (clang p2996 experimental branch).

Key Technical Insights

1. **With reflection and concepts**
    - your code becomes shorter
    - your code becomes more general
2. **Compilation time not much slower**
3. **Compile-Time optimizations can be awesome**
    - Consteval: 2-2.6x speedup alone
4. **SIMD** String operations benefit
5. **Every Optimization Matters**
    - Small gains compound into huge improvements

Thank You!

C++ Reflection Paper Authors

- The authors of P2996 for making compile-time reflection a reality

Compiler Implementation Teams

- Everyone that implemented P2996 and made it publicly available.
- Early adopters testing and providing feedback

Compiler Explorer Team

- Matt Godbolt and contributors

simdjson Community

- All contributors and users (John Keiser, Geoff Langdale, Paul Dreik...)

Questions?

Daniel Lemire and Francisco Geiman Thiesen

GitHub: github.com/simdjson/simdjson

Thank you!