C++26 Reflection for JSON Serialization

A Practical Journey

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CppCon 2025

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)

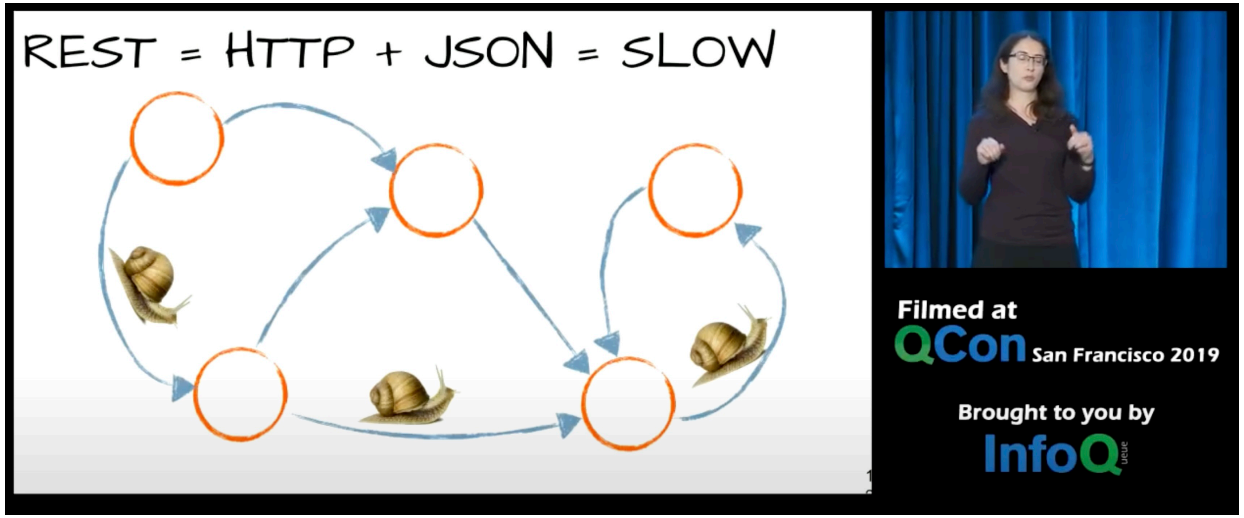
```json
{
    "username": "Alice",
    "level": 42,
    "health": 99.5,
    "inventory": ["sword", "shield", "potion"]
}
```

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++ 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)
- <Add a bullet point for language support voted on C++26>

Not all processors are equal

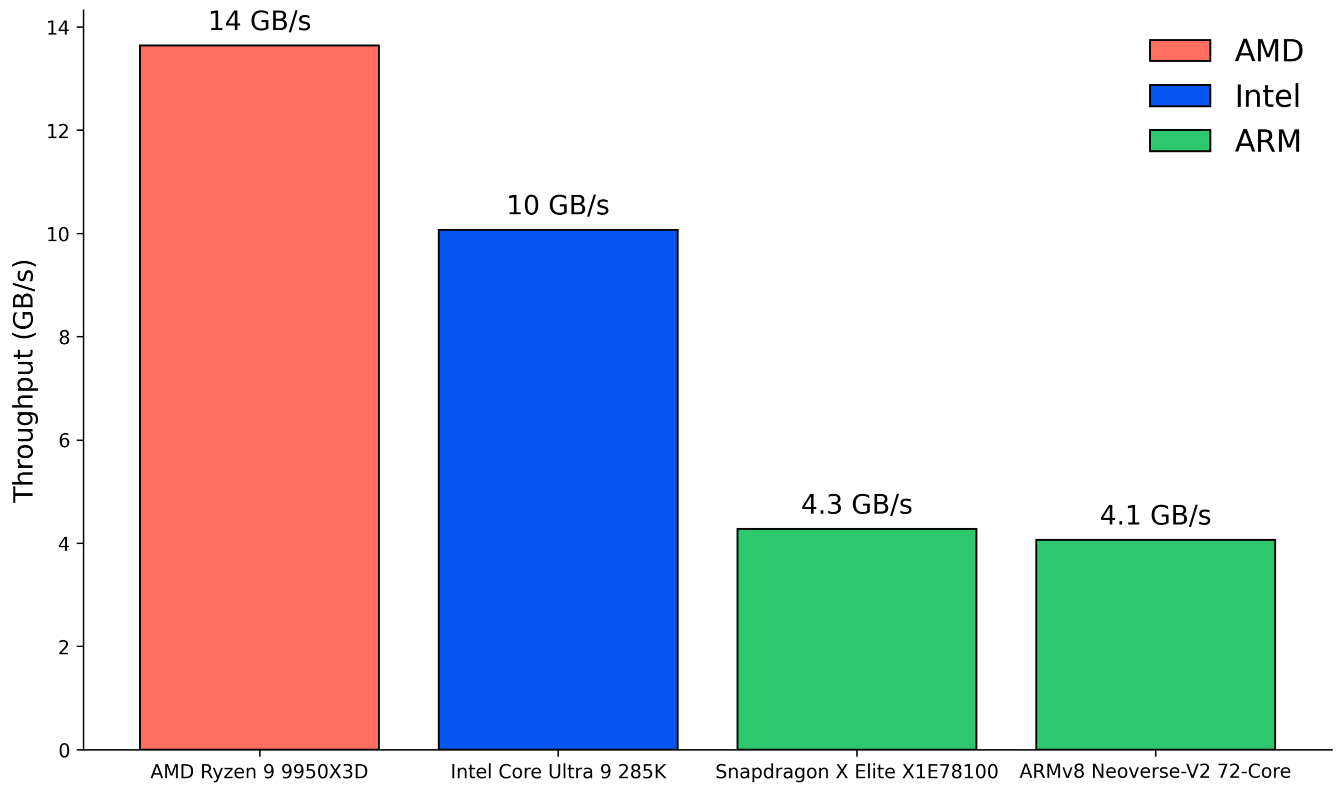
processor	year	arithmetic logic units	SIMD units
Apple M*	2019	6+	4×128
Intel Lion Cove	2024	6	4×256
AMD Zen 5	2024	6	4×512

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

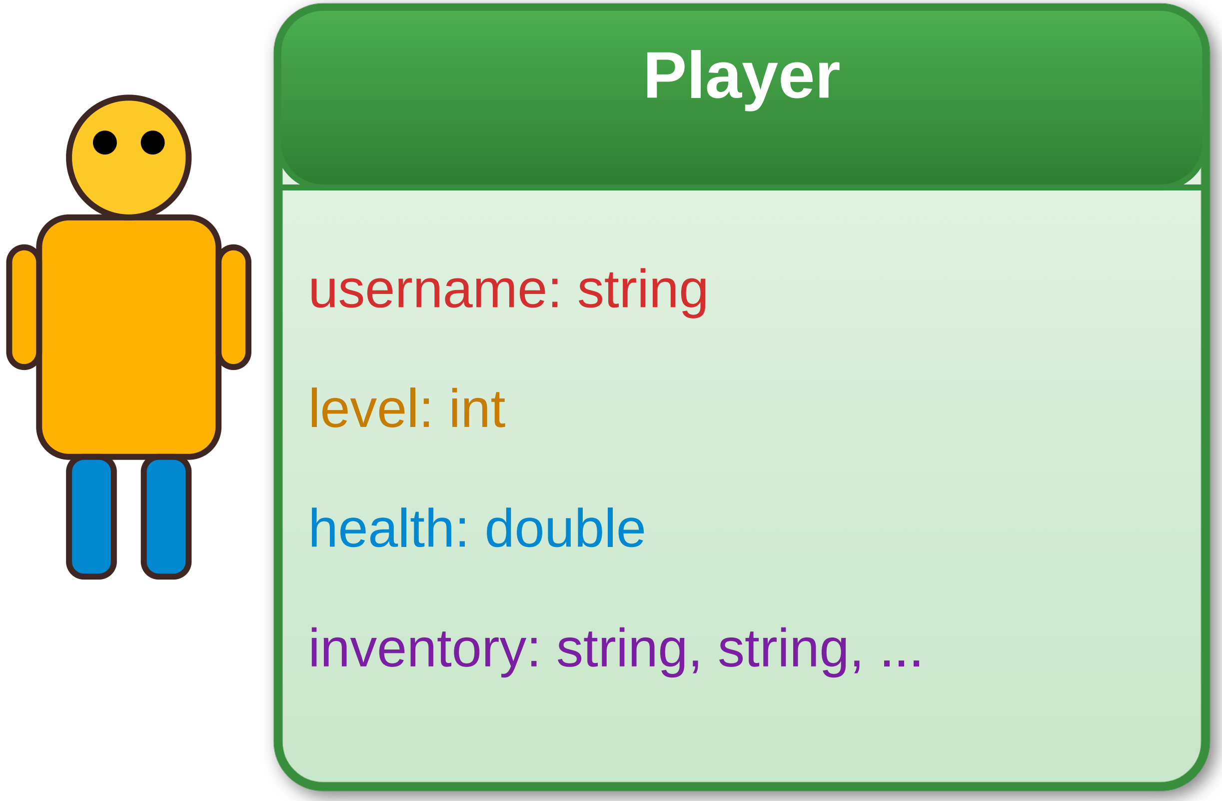
Usage

The simdjson library is found in...

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

The Problem

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



You start simple:

```
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:

```
// 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...

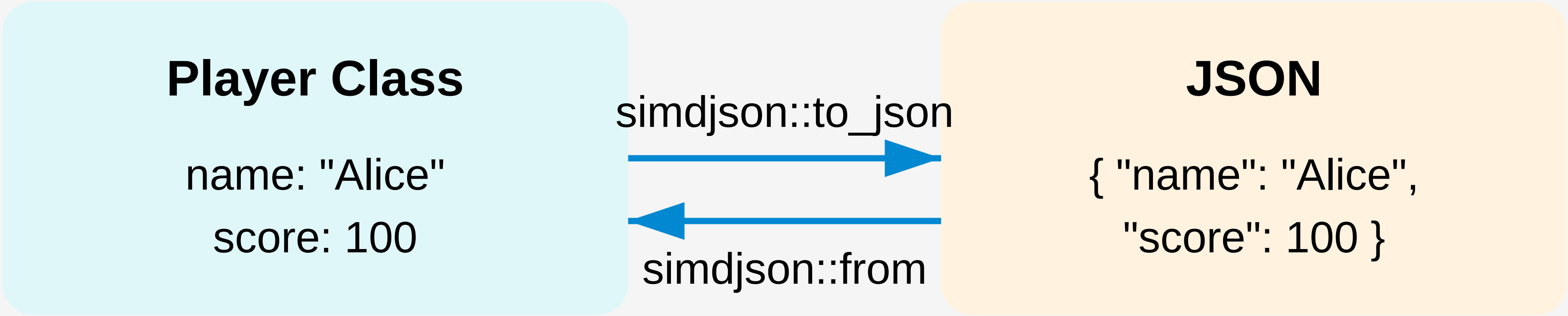
```cpp
struct Equipment {
    std::string name;
    int damage; int durability;
};
struct Achievement {
    std::string title; std::string description; bool unlocked;
    std::chrono::system_clock::time_point unlock_time;
};
struct Player {
    std::string username;
    int level; double health;
    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	👎	👎

Now it's our turn to have reflection!

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

```
// 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

```
// 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 It Yourself

```cpp
struct Meeting {
    std::string title;
    std::chrono::system_clock::time_point 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::system_clock::now(),
    .attendees = {"Alice", "Bob", "Charlie"},
    .location = "Denver",
    .is_recurring = true
});

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

The Entire API Surface

Just two functions. Infinite possibilities.

```
simdjson::to_json(object)  // → JSON string
simdjson::from(json)     // → T object
```

That's it.

No macros. No class/struct instrusion. No external tools.

Just simdjson leveraging C++26 reflection.

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: Without Concepts

Without concepts, you'd need a separate function for EACH container type:

```
// 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..."**

```
// 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:

```cpp
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™

Does your string need escaping?

- In JSON, you must escape control characters, quotes.
- Most strings in practice do not need escaping.

```
bool simple_needs_escaping(std::string_view v) {
  for (unsigned char c : v) {
    if(json_quotable_character[c]) { return true; }
  }
  return false;
}
```

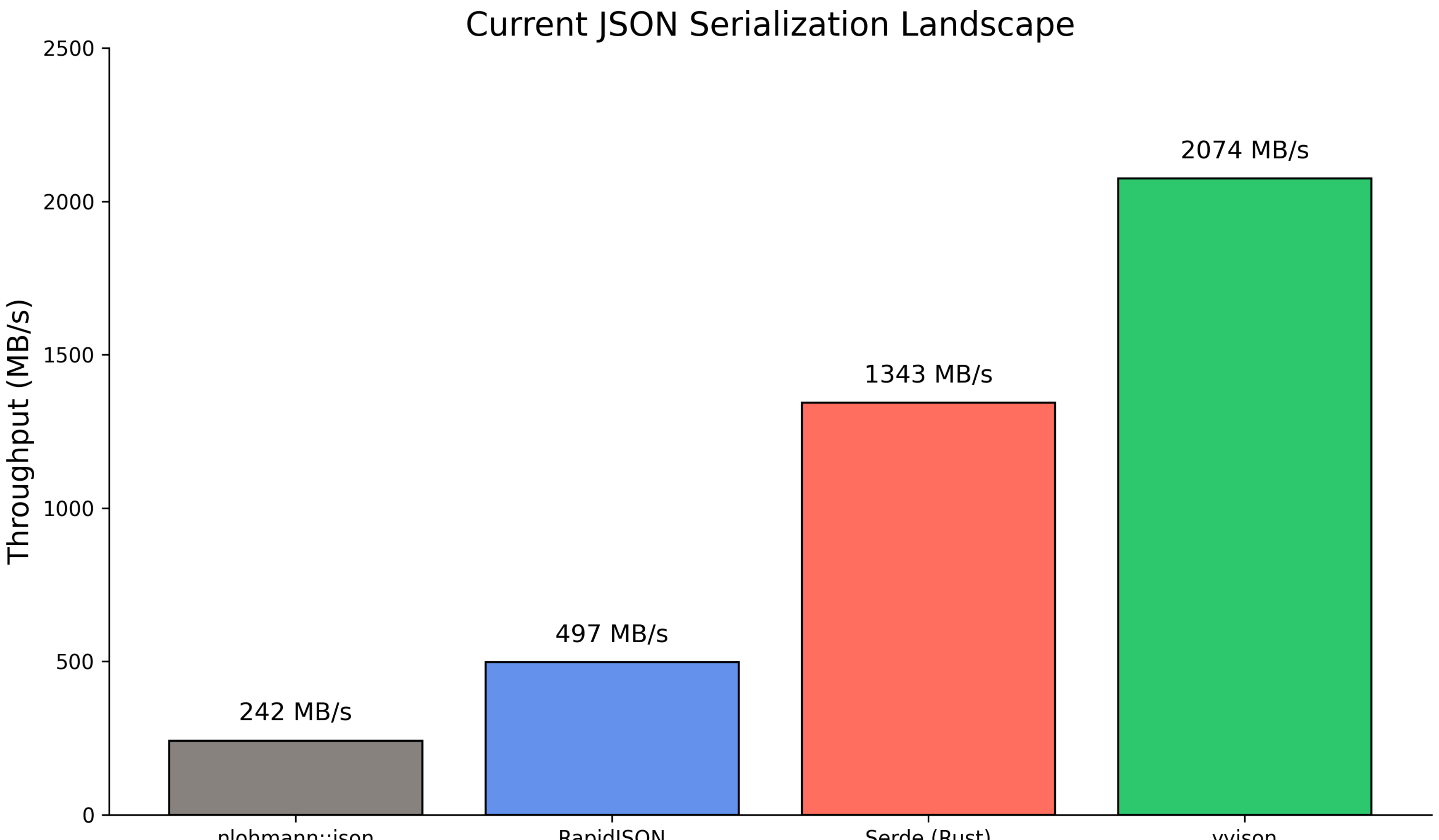
SIMD (Pentium 4 and better)

```
__m128i word = _mm_loadu_si128(data); // load 16 bytes
// check for control characters:
_mm_cmpeq_epi8(_mm_subs_epu8(word, _mm_set1_epi8(31)),
                                _mm_setzero_si128());
```

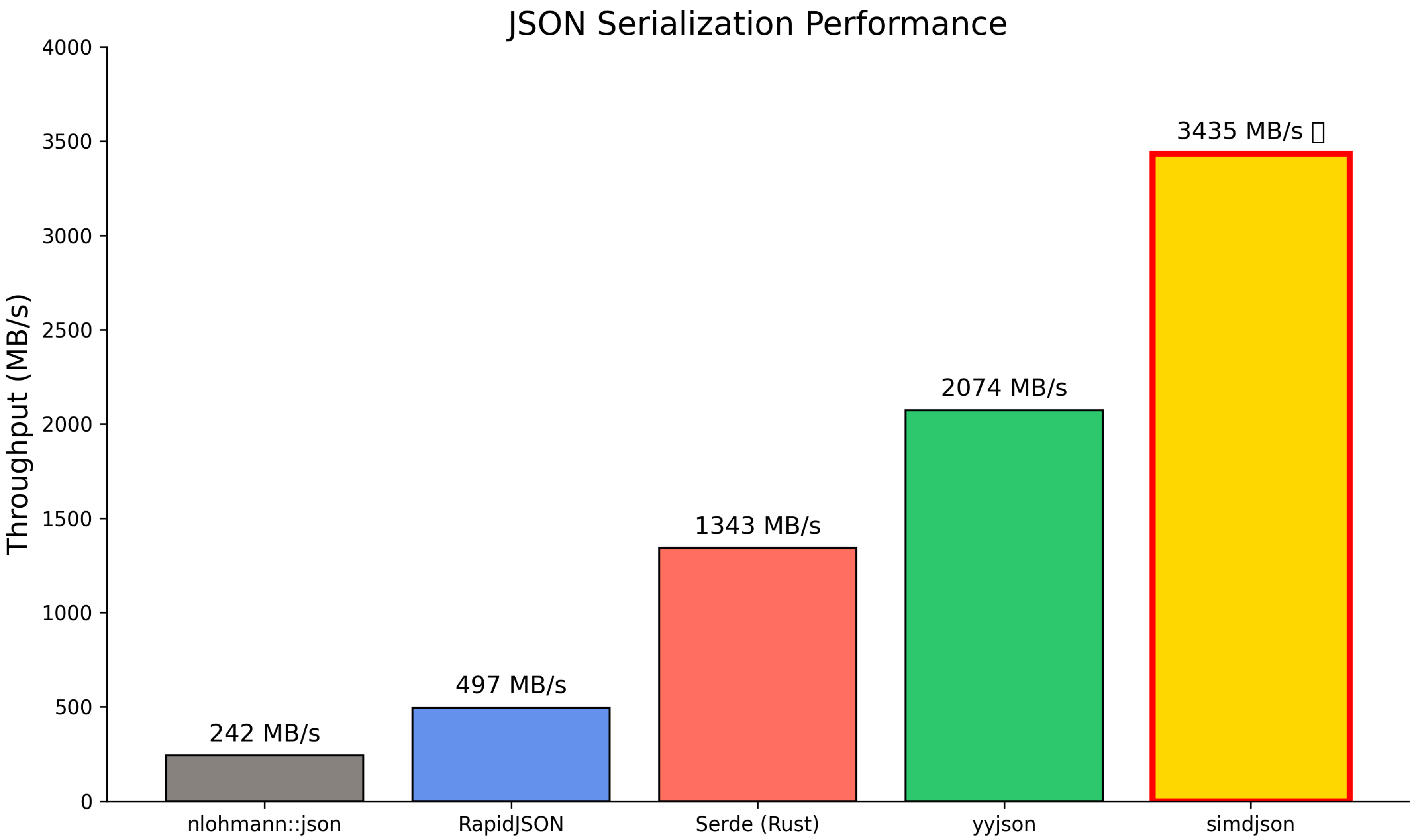
SIMD (AVX-512)

```
__m512i word = _mm512_loadu_si512(data); // load 64 bytes
// check for control characters:
_mm512_cmple_epu8_mask(word, _mm512_set1_epi8(31));
```

Current JSON Serialization Landscape



How fast are we? ...



Ablation Study: How We Achieved 3.2 GB/s

What is Ablation?

From neuroscience: systematically remove parts to understand function

Our Approach (Apple Silicon M2):

1. **Baseline**: All optimizations enabled (3,211 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 Digit Counting**: Optimized digit count
4. **Branch Prediction Hints**: CPU pipeline optimization
5. **Buffer Growth Strategy**: Smart memory allocation

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!
```

Consteval Performance Impact (Apple Silicon)

Dataset	Baseline	No Consteval	Impact	Speedup
Twitter	3,211 MB/s	1,607 MB/s	-50%	**2.00x**
CITM	2,360 MB/s	978 MB/s	-59%	**2.41x**

Twitter Example (100 tweets):

- 100 tweets × 15 fields = **1,500 field names**
- Without: 1,500 runtime escape operations
- With: **0 runtime operations**

Result: 2-2.6x faster serialization!

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):

```
__m128i chunk = load_16_bytes(str);
__m128i needs_escape = check_all_conditions_parallel(chunk);
if (!needs_escape)
    return false;  // Fast path!
```

SIMD Escaping Performance Impact (Apple Silicon)

Dataset	Baseline	No SIMD	Impact	Speedup
Twitter	3,211 MB/s	2,269 MB/s	-29%	**1.42x**
CITM	2,360 MB/s	2,259 MB/s	-4%	**1.04x**

Why Different Impact?

- **Twitter**: Long text fields (tweets, descriptions) → Big win
- **CITM**: Mostly numbers → Small impact

Optimization #3: Fast Digit Counting

Traditional:

```
std::to_string(value).length();  // Allocates string just to count!
```

Optimized:

```
fast_digit_count(value);  // Bit operations + lookup table
```

Dataset	Baseline	No Fast Digits	Speedup
Twitter	3,211 MB/s	3,035 MB/s	**1.06x**
CITM	2,360 MB/s	1,767 MB/s	**1.34x**

CITM has ~10,000+ integers!

Optimizations #4 & #5: Branch Hints & Buffer Growth

Branch Prediction:

```
if (UNLIKELY(buffer_full)) {  // CPU knows this is rare
    grow_buffer();
}
// CPU optimizes for this path
```

Buffer Growth:

- Linear: 1000 allocations for 1MB
- Exponential: 10 allocations for 1MB

Both Optimizations	Impact	Speedup
Twitter & CITM	~1%	1.01x

Combined Performance Impact

All Optimizations Together:

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)
Branch Hints	+1%	+5%
Buffer Growth	-0.4%	+2%
TOTAL	**~2.9x faster**	**~3.4x faster**

From Baseline to Optimized:

- Twitter: ~1,100 MB/s → 3,211 MB/s

Real-World Impact

API Server Example:

- 10 million API responses/day
- Average response: ~5KB JSON
- Total: 50GB JSON serialization/day

Serialization Time:

```
nlohmann::json:    210 seconds (3.5 minutes)
RapidJSON:         102 seconds (1.7 minutes)
Serde (Rust):       38 seconds
yyjson:             24 seconds
simdjson:           14.5 seconds ⭐
```

Time saved: 195 seconds vs nlohmann (93% reduction)

Key Technical Insights

1. **Compile-Time optimizations can be awesome**
   - Consteval: 2-2.6x speedup alone
   - C++26 reflection enables unprecedented optimization
2. **SIMD Everywhere**
   - Not just for parsing anymore
   - String operations benefit hugely
3. **Avoid Hidden Costs**
   - Hidden allocations: `std::to_string()`
   - Hidden divisions: `log10(value)`
   - Hidden mispredictions: rare conditions

Thank You!

Special Recognition

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
- Essential for validating our reflection approach
- Enabling rapid prototyping before integration

Questions?

Daniel Lemire and Francisco Geiman Thiesen

GitHub: github.com/simdjson/simdjson

Thank you!

BONUS: Assembly Deep Dive

Want to see the actual machine code?

Let's look under the hood! 🔧

The Shocking Truth: Instruction Counts

Instruction Count Analysis

The Numbers:

- **Manual:** 1,635 instructions
- **Reflection:** 648 instructions
- **Speedup:** 2.5x fewer!

You Write:

- **Manual:** 70+ lines of C++
- **Reflection:** 1 line!

Try it yourself →

Field Names: The Power of Compile-Time Constants

Manual: Byte-by-byte

```
mov  byte ptr [rdx], 34      ; '"'
mov  byte ptr [rdx+1], 109   ; 'm'
mov  byte ptr [rdx+2], 97    ; 'a'
mov  byte ptr [rdx+3], 107   ; 'k'
mov  byte ptr [rdx+4], 101   ; 'e'
mov  byte ptr [rdx+5], 34    ; '"'
mov  byte ptr [rdx+6], 58    ; ':'
; ... plus bounds checks
```

50+ instructions per field name

Reflection: 64-bit constant


```
movabs  rax, 0x223A656B616D22
```

Branch Prediction: The Hidden Performance Killer

Manual: 311 branches! 😱

```
cmp     al, 34          ; quote?
je      .LBB0_19        ; branch!
cmp     al, 92          ; backslash?
je      .LBB0_27        ; branch!
cmp     al, 10          ; newline?
je      .LBB0_35        ; branch!
cmp     al, 13          ; return?
je      .LBB0_42        ; branch!
; ... 300+ more conditions
```

Problem: Each branch = potential CPU pipeline stall

Reflection: 20 branches 🎯

```
call simdjson::to_json_string
; Most logic inside optimized
```

Memory Allocation: Death by a Thousand Cuts

Operation	Manual	Reflection	Impact
String appends	40	5	8x fewer
Memory reallocations	235	1	**235x fewer!**
Escape checks	600+	(inside lib)	Bulk SIMD

Manual: Growing pain

```
std::string json = "{";              // alloc 1
json += "\"make\":\"";               // realloc 2
json += car.make;                    // realloc 3
json += "\",\"model\":\"";           // realloc 4
// ... 231 more reallocations!
```

Reflection: Pre-sized perfection

Real Code Comparison

What developers write (Manual):

```cpp
std::string serialize_manual(const Car& car) {
    std::string json = "{";
    json += "\"make\":\"";
    for (char c : car.make) {
        switch(c) {
            case '"':  json += "\\\""; break;
            case '\\': json += "\\\\"; break;
            case '\n': json += "\\n"; break;
            // ... more escape cases
            default: json += c;
        }
    }
    json += "\",\"model\":\"";
    // ... 70+ more lines of similar code
}
```

Branch Complexity Analysis

Branch Complexity

What the Numbers Mean:

- **Manual:** 311 conditional branches in assembly
- **Reflection:** 20 conditional branches in assembly
- **Impact:** Fewer branches = fewer potential mispredictions
- **Note:** Actual performance depends on data patterns

How Reflection Optimizes

Compile-Time Field Discovery

```
template for (constexpr auto member :
                 std::meta::nonstatic_data_members_of(^^Car)) {
    // Field names known at compile time!
    // Compiler generates optimal code for each field
}
```

Result: Pre-computed Constants

- Field names → 64-bit integers
- String lengths → compile-time constants
- Escape sequences → eliminated entirely
- Buffer sizes → calculated at compile time

Escape Processing: Different Approaches

Manual: Character-by-character checking

```
for (char c : str) {
    if (c == '"') output += "\\\"";
    else if (c == '\\') output += "\\\\";
    else if (c < 0x20) {
        // Unicode escape sequence
        snprintf(buf, 7, "\\u%04x", c);
        output += buf;
    }
    // ... more checks
}
```

Reflection: Library handles escaping

- Escaping logic encapsulated in simdjson

Try It Yourself!

Compiler Explorer Links:

1. **Basic Comparison** (Manual vs Reflection):
   https://godbolt.org/z/1n539e7cq

2. **Reflection-Only Serialization**:
   https://godbolt.org/z/94jPx6bEb

3. **Full simdjson Integration** (requires reflection support):

   ```
   clang++ -std=c++26 -freflection \
           -fexpansion-statements -O3
   ```

What to Look For:

- Search for [illegible] instructions with large numbers

Why This Matters for Real Applications

Benefits Compound:

1. Fewer instructions → Better I-cache usage
2. Fewer branches → Better speculation
3. Compile-time strings → Better D-cache usage
4. SIMD-ready layout → Vectorization opportunities

Key Takeaways from Assembly Analysis

1. **Reflection generates highly optimized code**
    - Consistently applies optimizations
    - Eliminates manual boilerplate
    - Reduces opportunity for errors
2. **Compile-time is powerful**
    - Field names become constants
    - No runtime string building
    - Pre-computed buffer sizes
3. **Modern C++ delivers on its promises**
    - Zero-overhead abstraction is real

End of Bonus Section

Return to main presentation or explore the code yourself!

Remember: The assembly doesn't lie! 🚀