

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)

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

JSON downside?

Reading and writing JSON can be *slow*. E.g., 20 MB/s to 200 MB/s.

- Slower than fast disks or fast networks

REST = HTTP + JSON = SLOW



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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.



Player

username: string

level: int

health: double

inventory: string, string, ...

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...

```
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

Goal: Seamless Serialization/Deserialization



The Solution: C++26 Static 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(const std::string& json_str) {  
    return simdjson::from<Player>(json_str); // That's it!  
}
```


Benefits

- No manual field mapping
- No maintenance burden
- Handles nested structures automatically
- Performance tuned by the library

C#

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



Rust (serde)

```
// 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 reflection.
- You cannot enumerate the methods of a struct. Either at runtime or at compile-time.
- Serde relies on annotation followed by re-parsing of the code.



Reflection as accessing the attributes of a struct.

| language | runtime reflection | compile-time reflection |
|----------|---|---|
| C++ 26 |  |  |
| Go |  |  |
| Java |  |  |
| C# |  |  |
| Rust |  |  |

With C++26: simple, maintainable, performant code

```
std::string json_str = simdjson::to_json(player);  
Player player = simdjson::from<Player>(json_str);
```

- no extra tooling required
- no annotation

How Does It Work?

The Key Insight: Compile-Time Code Generation

"How can compile-time reflection handle runtime JSON data?"

The answer: Reflection operates on **types and structure**, not runtime values.

It generates regular C++ code at compile time that handles your runtime data.

What Happens Behind the Scenes

```
// What you write:
Player p = simdjson::from<Player>(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, ...))...
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<Player>(json);  
// Runtime values flow through compile-time generated code
```

Real-World Benefits

Before Reflection (Our Game Server example)

- 1000+ lines of serialization code
- Prone to bugs due to serialization mismatching
- Adding new features can imply making tedious changes to boilerplate serialization code

After Reflection

- **0 lines** of serialization code
- **0 serialization bugs** (if it compiles, it works!)
- New features can be added much faster

The Bigger Picture

This pattern extends beyond games:

- **REST APIs:** Automatic request/response serialization
- **Configuration Files:** Type-safe config loading
- **Message Queues:** Serialize/deserialize messages
- **Databases:** Object-relational mapping
- **RPC Systems:** Automatic protocol generation

With C++26 reflection, C++ finally catches up to languages like Rust (serde), Go (encoding/json), and C# (System.Text.Json) in terms of ease of use, but with **better performance** thanks to simdjson's SIMD optimizations.

Try It Yourself

```
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<Meeting>(json);
```

Round-Trip Any Data Structure

```
struct TodoItem {
    std::string task;
    bool completed;
    std::optional<std::string> due_date;
};

struct TodoList {
    std::string owner;
    std::vector<TodoItem> items;
    std::map<std::string, int> tags; // tag -> count
};

// Serialize complex nested structures
TodoList my_todos = { /* ... */ };
std::string json = simdjson::to_json(my_todos);

// Deserialize back - perfect round-trip
TodoList restored = simdjson::from<TodoList>(json);
assert(my_todos == restored); // Works if you define operator==
```

The Entire API Surface

Just two functions. Infinite possibilities.

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

That's it.

No macros. No code generation. 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:

```
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™

Runtime dispatching

- One function semantically
- Several implementations
- Select the best one at runtime for performance.

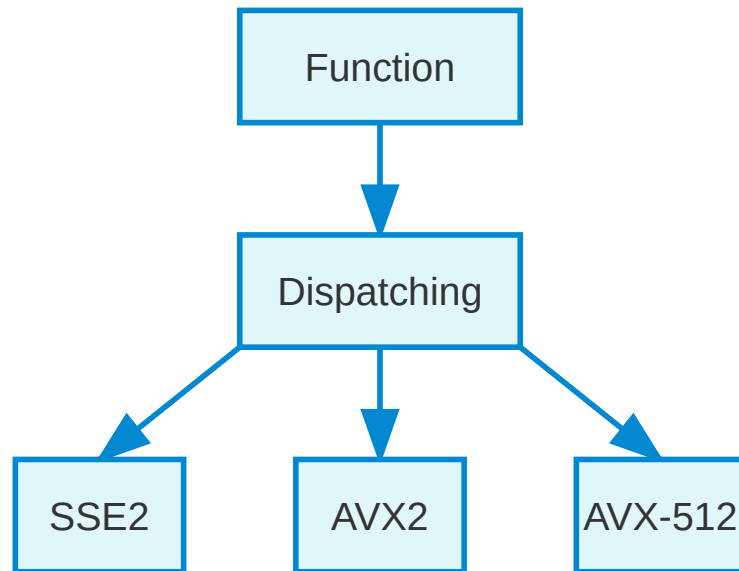
Issue: x64 processors support different instructions

A Zen 5 CPU and a Pentium 4 CPU can be quite different.

```
bool has_sse2() { /* query the CPU */ }  
bool has_avx2() { /* query the CPU */ }  
bool has_avx512() { /* query the CPU */ }
```

These functions cannot be `constexpr`.

Runtime dispatching



Example: Sum function

```
using SumFunc = float (*)(const float *, size_t);
```

Setup a reassignable implementation

```
SumFunc &get_sum_fnc() {  
    static SumFunc sum_impl = sum_init;  
    return sum_impl;  
}
```

We initialize it with some special initialization function.


```
float sum_init(const float *data, size_t n) {  
    SumFunc &sum_impl = get_sum_fnc();  
    if (has_avx2()) {  
        sum_impl = sum_avx2;  
    } else if (has_sse2()) {  
        sum_impl = sum_sse2;  
    } else {  
        sum_impl = sum_generic;  
    }  
    return sum_impl(data, n);  
}
```

On first call, `get_sum_fnc()` is modified, and then it will remain constant.

Runtime dispatching and metaprogramming

- Metaprogramming is at compile-time.
- Runtime dispatching is fundamentally at runtime.

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));
```

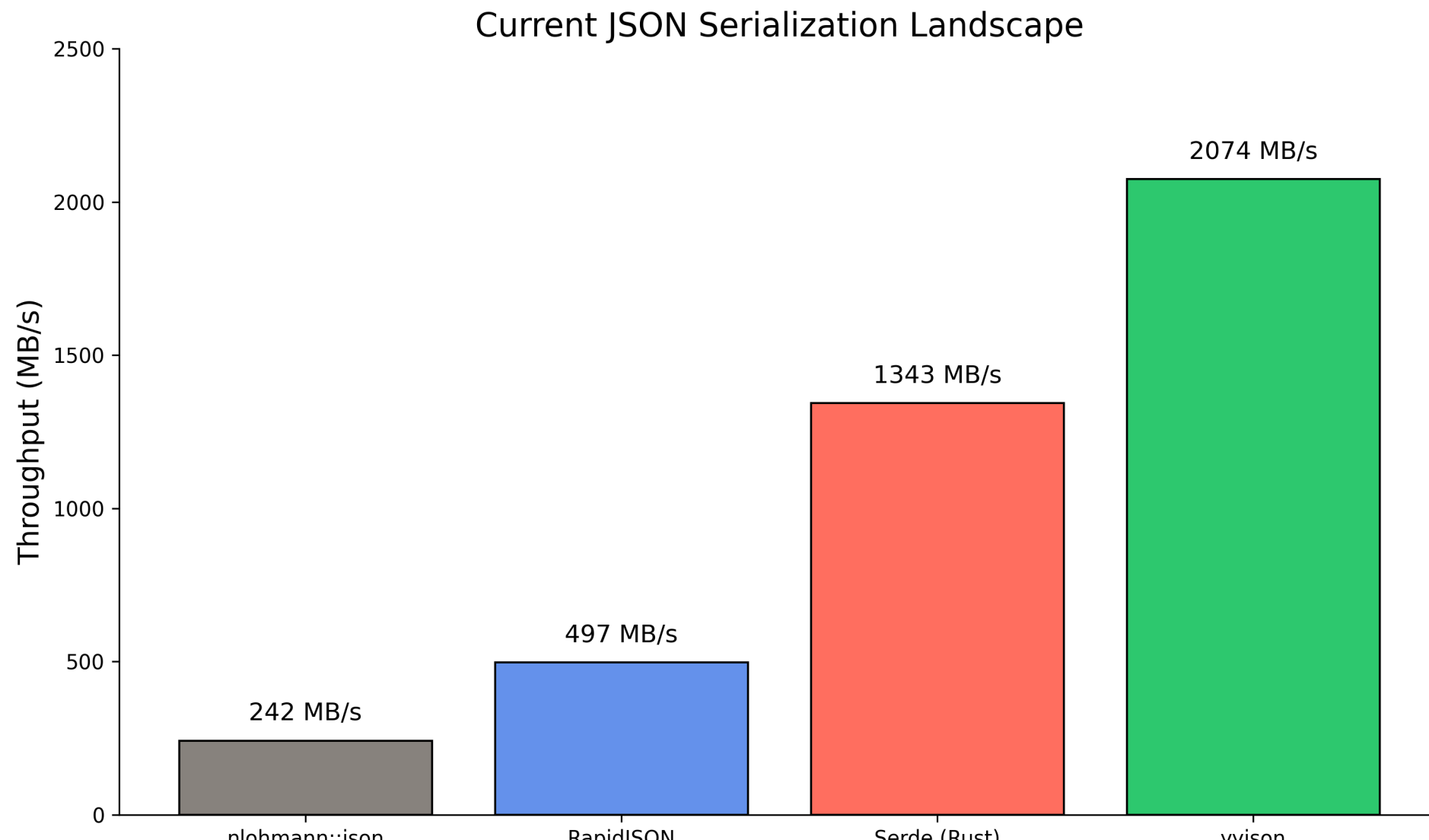
Runtime dispatching is poor with quick functions

- Calling a fast function like `fast_needs_escaping` without inlining prevents useful optimizations.
- Runtime dispatching implies a function call!

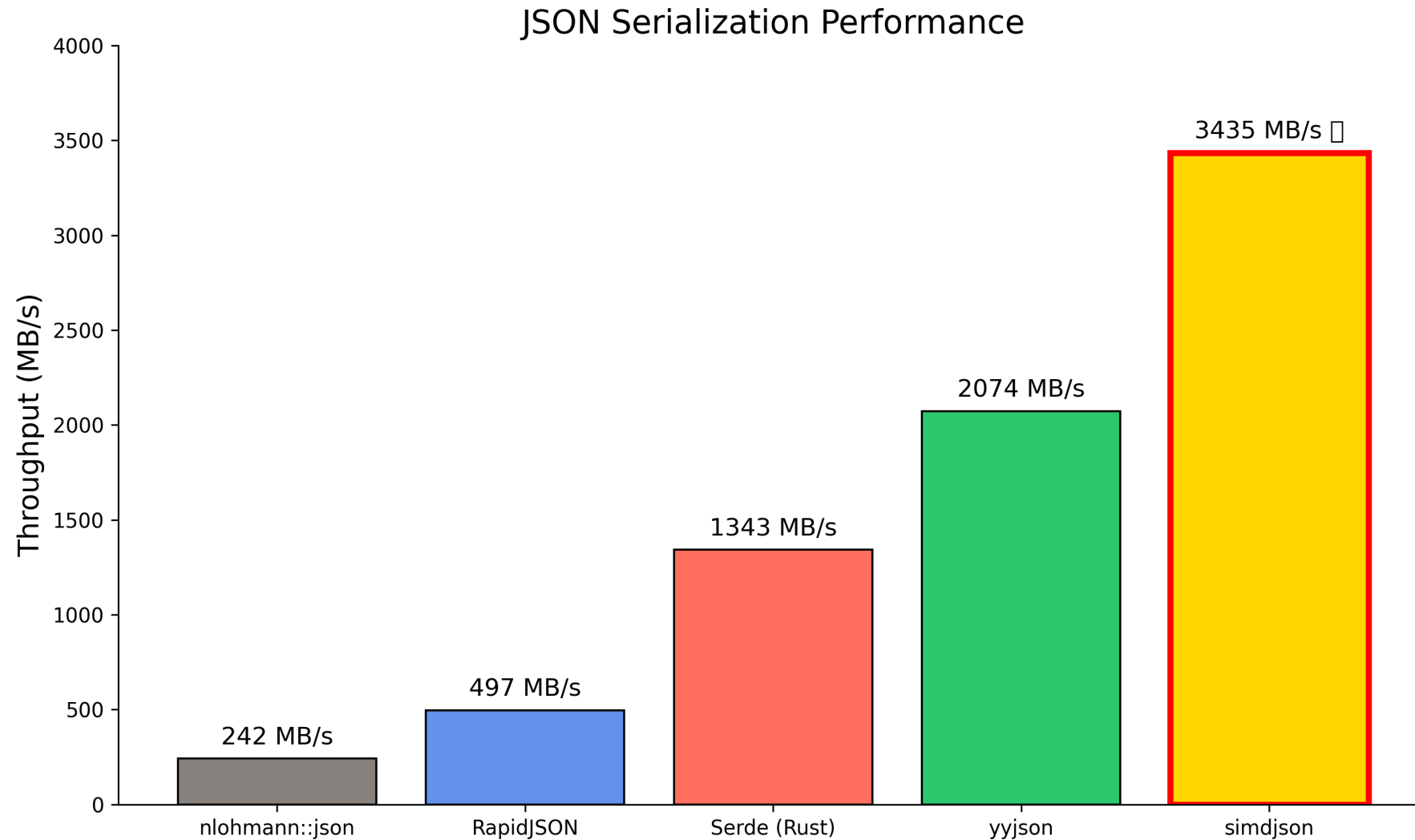
Current solution

- No runtime dispatching (*sad face*).
- All x64 processors support Pentium 4-level SIMD. Use that in a short function.
- *Easy* if programmer builds for specific machine (`-march=native`), use fancier tricks.

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:** $(\text{Baseline} - \text{Disabled}) / \text{Disabled}$

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

Conclusion

C++26 Reflection + simdjson =

-  Zero boilerplate
-  Compile-time safety
-  Blazing fast performance
-  Clean, modern API

Welcome to the future of C++ serialization! 

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):

```
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 `simdjson::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! 🚀