

# C++26 Reflection for JSON Serialization

## A Practical Journey

- Daniel Lemire, *University of Quebec* 
- Francisco Geiman Thiesen , *Microsoft* 

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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+	$4 \times 128$
Intel Lion Cove	2024	6	$4 \times 256$
AMD Zen 5	2024	6	$4 \times 512$

# 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
```

# 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™**

# 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));
```

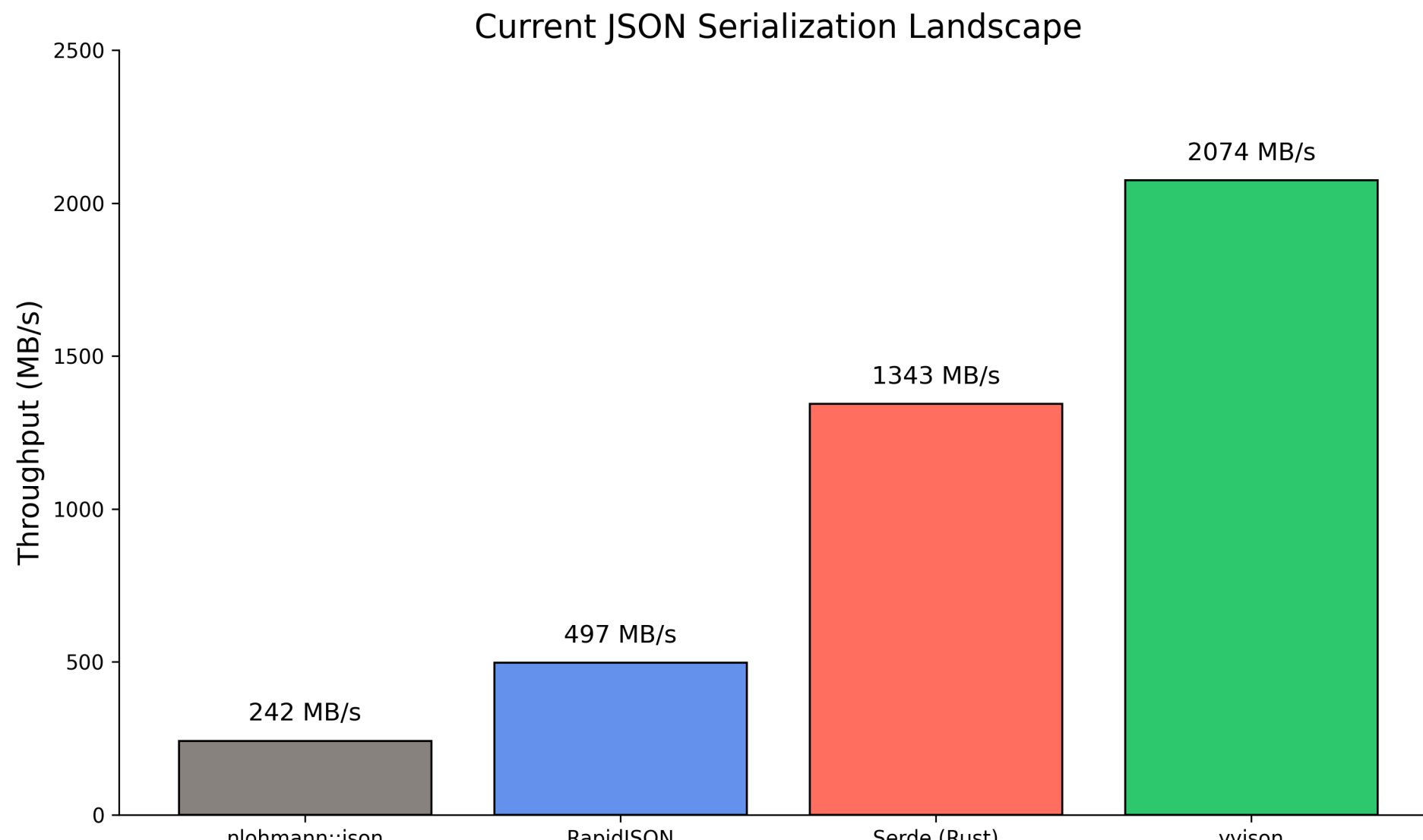
# Runtime dispatching is poor with quick functions

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

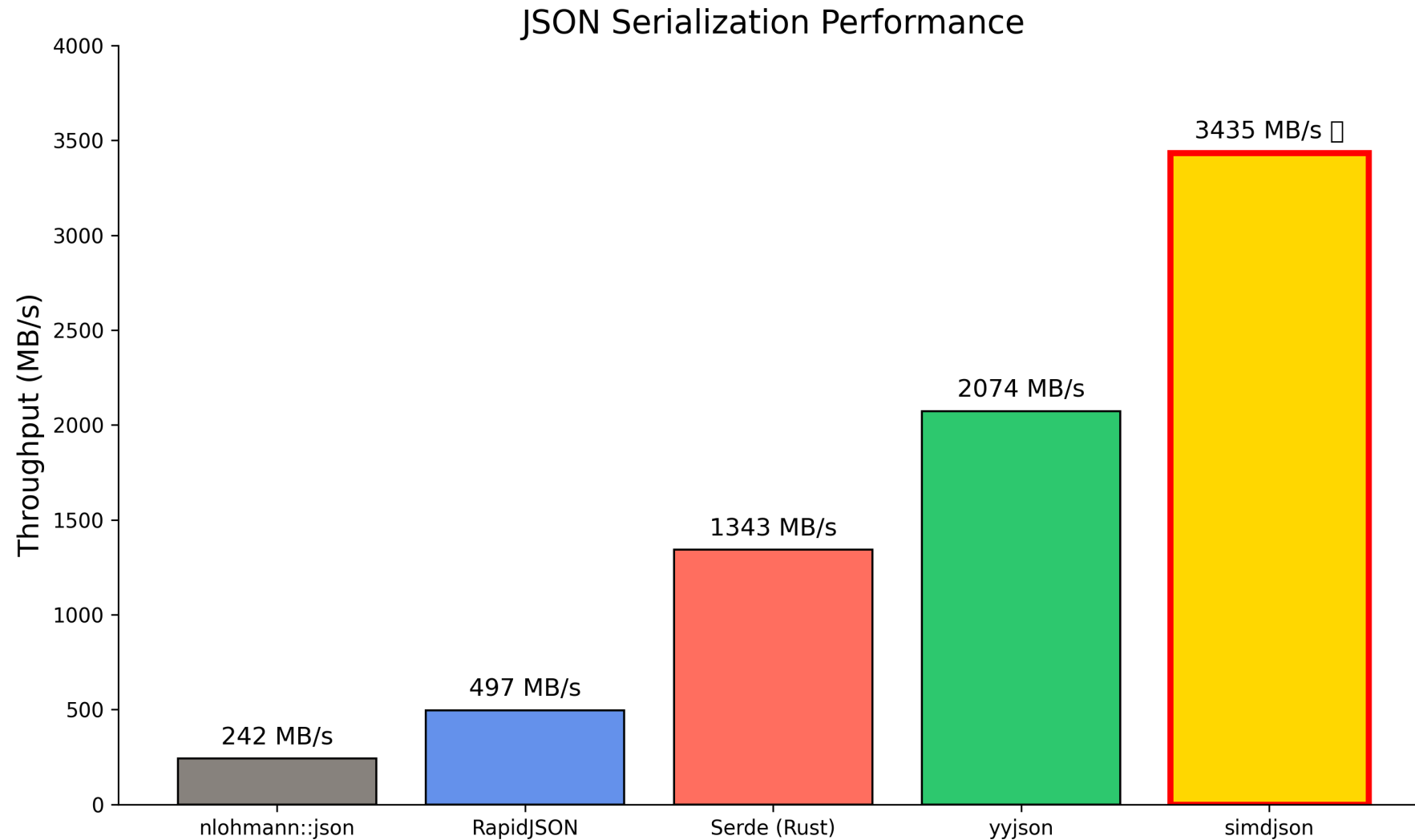
## Current solution

- 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%	<b>2.00x</b>
CITM	2,360 MB/s	978 MB/s	-59%	<b>2.41x</b>

## 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%	<b>1.42x</b>
CITM	2,360 MB/s	2,259 MB/s	-4%	<b>1.04x</b>

## 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	<b>1.06x</b>
CITM	2,360 MB/s	1,767 MB/s	<b>1.34x</b>

**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](https://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	<b>235x fewer!</b>
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! 🚀