

# C++26 Reflection for JSON Serialization

## A Practical Journey

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# JSON

- Portable, simple
- Douglas Crockford (2001)
- RFC 8259 (December 2017)

# JSON

- scalar values
  - strings (controls and quotes must be escaped)
  - numbers (but not `NaN` or `Inf` )
  - `true` , `false` , `null`
- composed values
  - objects (key/value)
  - arrays (list)

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

# JSON downside?

JSON can be *slow*. E.g., 20 MB/s.

- Much slower than disk or network

# 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

- Stands for Single instruction, multiple data
- Allows us to process 16 (or more) bytes or more with one instruction
- Supported on all modern CPUs (phone, laptop)

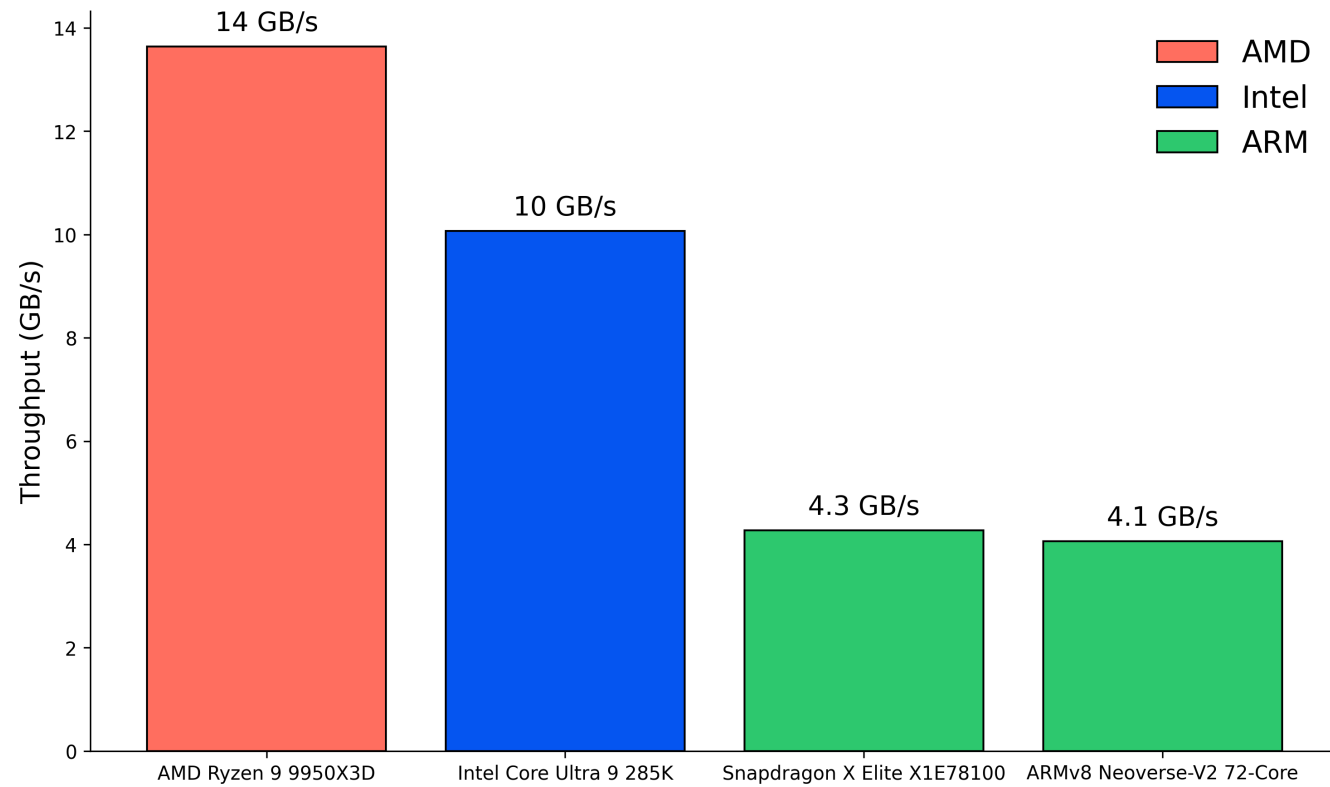


# Superscalar vs. SIMD execution

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

# 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 index.
- Allows fast skipping.



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

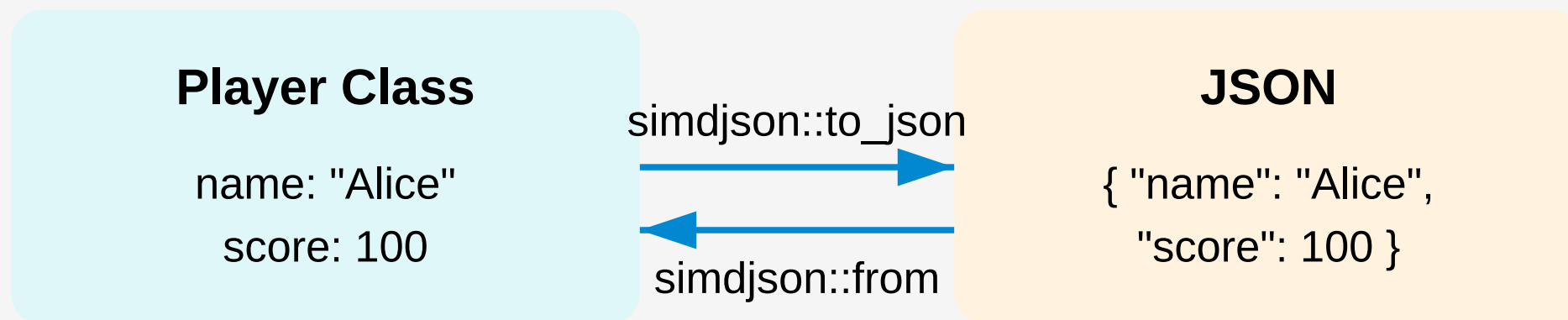
# Usage

The simdjson library is found in...

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



# Automate the serialization/deserialization process.



# 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)
);
```



## With a library (JSON for Modern C++)

Or you might use a library.

```
std::string to_json(Player& p) {  
    return nlohmann::json>{"username", p.username},  
                                   {"level", p.level},  
                                   {"health", p.health},  
                                   {"inventory", p.inventory}}  
        .dump();  
}
```

# 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());
}
```

# The Pain Points

This manual approach has several problems:

1. **Repetition:** Every field needs to be handled twice (serialize + deserialize)
2. **Maintenance Nightmare:** Add a new field? Update both functions!
3. **Error-Prone:** Typos in field names, forgotten fields, type mismatches
4. **Boilerplate Explosion:** 30+ lines for a simple 4-field struct
5. **Performance:** You may fall into performance traps

# 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!  
};
```

Suddenly you need to write hundreds of lines of serialization code! 🤖

# 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



# Python

```
# Python
import json
json_str = json.dumps(player.__dict__)
player = Player(**json.loads(json_str))
```



# Python reflection

```
def inspect_object(obj):  
    print(f"Class name: {obj.__class__.__name__}")  
    for attr, value in vars(obj).items():  
        print(f"  {attr}: {value}")
```

# Go

```
jsonData, err := json.MarshalIndent(player, "", "  ")
if err != nil {
    log.Fatalf("Error during serialization: %v", err)
}
var deserializedPlayer Player
err = json.Unmarshal([]byte(jsonStr), &deserializedPlayer)
```



# Go reflection

- Runtime reflection only

```
typ := reflect.TypeOf(obj)
for i := 0; i < typ.NumField(); i++ {
    field := typ.Field(i)
}
```

# Java and C#

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



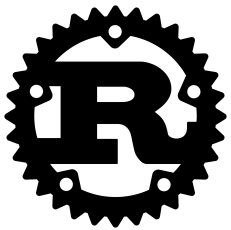
# Java and C# reflection

- Runtime reflection only.

```
Class<?> playerClass = Player.class;  
Object playerInstance = playerClass.getDeclaredConstructor().newInstance();  
Field nameField = playerClass.getDeclaredField("name");
```

# 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 introspection.
- You cannot enumerate the methods of a struct. Either at runtime or at compile-time.
- Rust relies on annotation (serde) 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);
```

- **AT COMPILE TIME**
- with no extra tooling
- 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

```
template <typename T>
    requires(std::is_class_v<T>) // For user-defined types
error_code deserialize(auto& json_value, T& out) {
    simdjson::ondemand::object obj;
    auto er = json_value.get_object().get(obj);
    if(er) { return er; }
    // capture the attributes:
    constexpr auto members = std::define_static_array(std::meta::nonstatic_data_members_of(^^T,
        std::meta::access_context::unchecked()));

    // This for loop happens at COMPILE TIME
    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
        auto err = obj[field_name].get(out.[:member:]);
        if (err && err != simdjson::NO_SUCH_FIELD) {
            return err;
        }
    };

    return simdjson::SUCCESS;
}
```

# The template for Statement

The `template for` statement is the key:

- It's like a **compile-time for-loop**
- E.g., it generates code for each struct member
- By the time your program runs, all reflection has been *expanded* into normal C++ code

This means:

- **Zero runtime overhead**
- **Full optimization opportunities**
- **Type safety at compile time**

# 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
```

# Compile-Time Safety: Catching Errors Before They Run

```
// ❌ COMPILE ERROR: Type mismatch detected
struct BadPlayer {
    int username; // Oops, should be string!
};
// simdjson::from<BadPlayer>(json) won't compile if JSON has string

// ❌ COMPILE ERROR: Non-serializable type
struct InvalidType {
    std::thread t; // Threads can't be serialized!
};
// simdjson::to_json(InvalidType{}) fails at compile time

// ✅ COMPILE SUCCESS: All types are serializable
struct GoodType {
    std::vector<int> numbers;
    std::map<std::string, double> scores;
    std::optional<std::string> nickname;
};
```



# Zero Overhead: Why It's Fast

Since reflection happens at compile time, there's no runtime penalty:

1. **No runtime type inspection** - everything is known at compile time
2. **No string comparisons for field names** - they become compile-time constants
3. **Optimal code generation** - the compiler sees the full picture
4. **Inline everything** - generated code can be fully optimized

The generated code is often **faster than hand-written code** because:

- It's consistently optimized
- No human errors or inefficiencies
- Leverages simdjson's SIMD parsing throughout

# Performance: The Best Part

You might think "automatic = slow", but with simdjson + reflection:

- **Compile-time code generation:** No runtime overhead from reflection
- **SIMD-accelerated parsing:** simdjson uses CPU vector instructions
- **Zero allocation:** String views and in-place parsing
- **Throughput:** ~2-4 GB/s on modern hardware

The generated code is often *faster* than hand-written code!

## On-Demand: parse only what you need

```
auto car = doc["Jean-Claude"].get<Car>()
```

- Seeks `"Jean-Claude"` with index, and then parses directly to `Car` .
- No intermediate, no extra parsing

# 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.

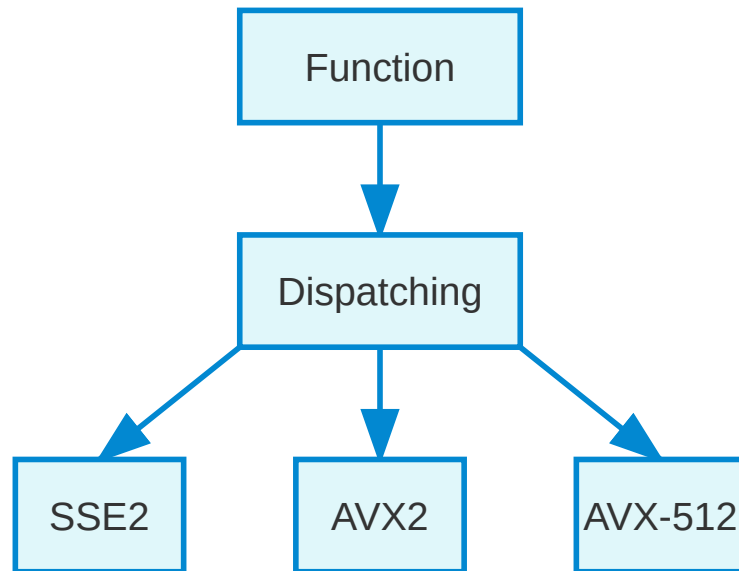
# Issue: x64 processors support different instructions

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.

```
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

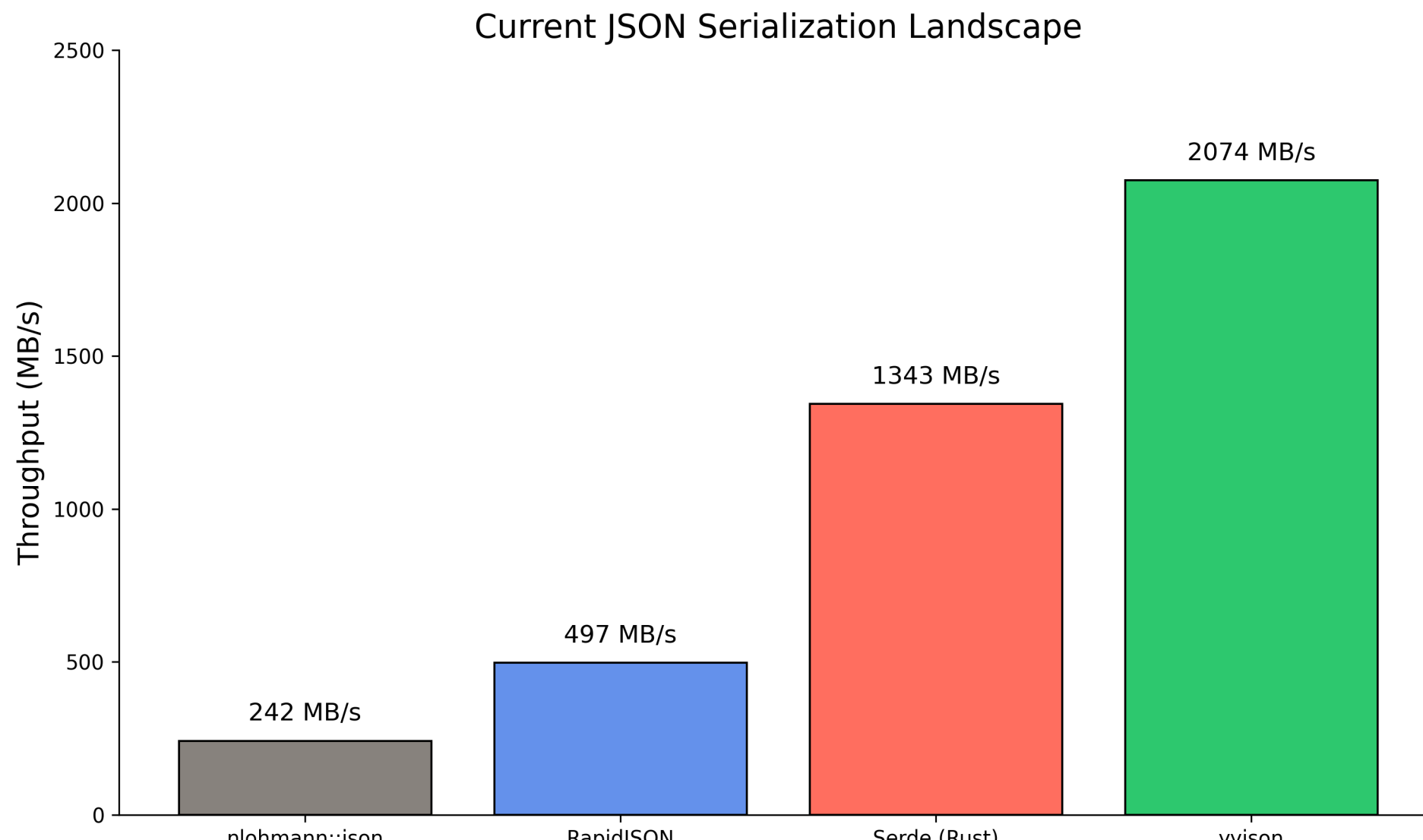
- Calling a fast function like `fast_needs_escaping` without inlining prevents useful optimizations.
- Runtime dispatching implies a function call!

## Current solution

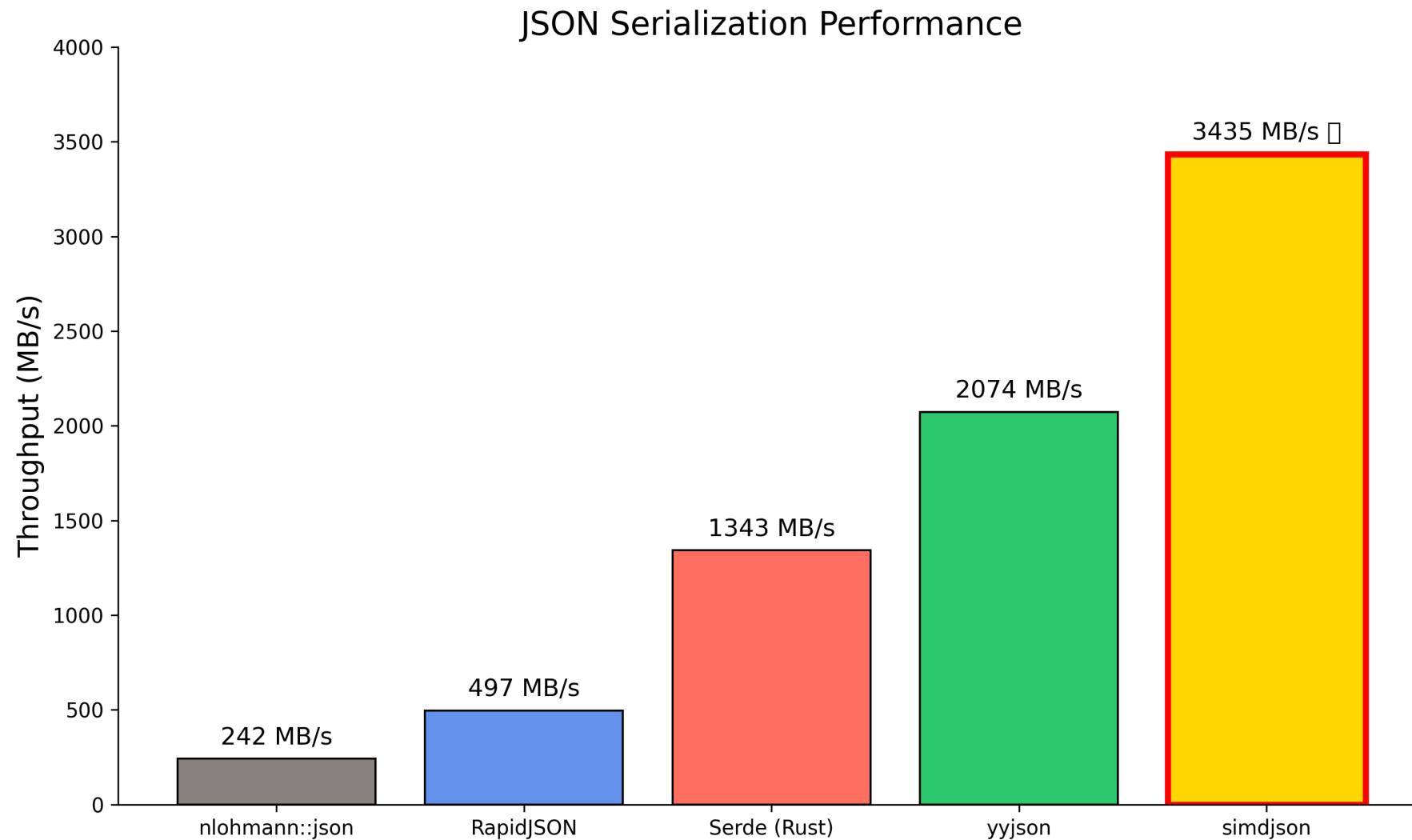
- No runtime dispatching (*sad face*).
- All x64 processors support Pentium 4-level SIMD. Use that in a short function.
- *Easy* if programmer builds for specific machine ( `-march=native` ), use fancier tricks.



# Current JSON Serialization Landscape



# How fast are we? ...



# Ablation Study: How We Achieved 3.4 GB/s

## What is Ablation?

From neuroscience: systematically remove parts to understand function

## Our Approach:

1. **Baseline:** All optimizations enabled (3,435 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

Dataset	Baseline	No Consteval	Impact	Speedup
Twitter	3,231 MB/s	1,624 MB/s	-50%	<b>1.99x</b>
CITM	2,341 MB/s	883 MB/s	-62%	<b>2.65x</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

Dataset	Baseline	No SIMD	Impact	Speedup
Twitter	3,231 MB/s	2,245 MB/s	-31%	<b>1.44x</b>
CITM	2,341 MB/s	2,273 MB/s	-3%	<b>1.03x</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	3,231 MB/s	3,041 MB/s	<b>1.06x</b>
CITM	2,341 MB/s	1,841 MB/s	<b>1.27x</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	~2%	1.02x

# Combined Performance Impact

All Optimizations Together:

Optimization	Twitter Contribution	CITM Contribution
Consteval	+99% (1.99x)	+165% (2.65x)
SIMD Escaping	+44% (1.44x)	+3% (1.03x)
Fast Digits	+6% (1.06x)	+27% (1.27x)
Branch Hints	+1.5%	+1.5%
Buffer Growth	+0.8%	+0.8%
TOTAL	~2.95x faster	~3.5x faster

From Baseline to Optimized:

- Twitter: ~1,100 MB/s → 3,231 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! 

# Questions?

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GitHub: [github.com/simdjson/simdjson](https://github.com/simdjson/simdjson)

Thank you!