

# Reflection-based JSON in C++ at Gigabytes per Second

CppCon 2025

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

# Why JSON Matters

```
{  
  "age": 5,  
  "name": "Daniel",  
  "toys": ["wooden dog", "little car"]  
}
```

- **Ubiquitous:** Predominant data format on public Web APIs, config files, data interchange
- **Human-readable:** Intuitive attribute-value pairs and arrays
- **MCP:** Format of choice for the design of the MCP protocol

# The C++ JSON Pain

## Performance Bottlenecks:

- Complex string handling
- Nested structure parsing
- Manual struct ↔ JSON mapping overhead
- Number parsing and serialization costs

## Safety Pitfalls:

- Runtime type mismatches
- Unexpected input (broken Unicode)
- No compile-time guarantees

## Other Languages Have It Easy

Rust (serde):

```
#[derive(Serialize, Deserialize)]
struct Person {
    age: u32,
    name: String,
}
// That's it! Automatic JSON conversion
```

**Similar ergonomics in:** Python, Go, C#, Java, Zig

**C++:** Still manual work... until now

# C++20 Sets the Stage

**Concepts:** Cleaner, constrained interfaces

```
template<Serializable T>  
void to_json(const T& obj);
```

**tag\_invoke:** Customization point mechanism

**constexpr:** Compile-time computation

*These lay groundwork but fall short of full automation*

# Enter C++26 Reflection (PR2996)

**What it is:** Introspect C++ types at compile time

- Field names, types, structure layout
- "The compiler knows your data structures"

**Why it's game-changing:** No more manual mapping!

**Current state:** Bloomberg's experimental LLVM fork

- [github.com/bloomberg/clang-p2996](https://github.com/bloomberg/clang-p2996)

# Simple Reflection Example

```
struct Person {  
    int age;  
    std::string name;  
};  
  
// Reflection automatically exposes:  
// - Field count: 2  
// - Field names: "age", "name"  
// - Field types: int, std::string  
// - Automatic JSON mapping possible!
```

# Our Implementation Strategy

**Core Idea:** Reflection auto-generates JSON mapping code

**Serialization:** `Person` → `{"age": 5, "name": "Daniel"}`

- Walk struct fields via reflection
- Emit JSON strings (compile-time optimized)

**Deserialization:** JSON → `Person`

- Parse tokens with type safety
- Populate struct fields automatically
- Comprehensive error handling



# Implementation Architecture

## Three-layer design:

1. **Lexer**: Tokenize JSON input
2. **Parser**: Build structured representation
3. **Reflection Binder**: Map to/from C++ structs

## Key insight: Reflection happens at compile time

- Field names become string literals
- Type safety enforced by compiler
- Zero runtime reflection overhead

## First Prototype: Reality Check

```
// Our first attempt was... not impressive
struct Data { /* ... */ };
auto start = std::chrono::high_resolution_clock::now();
Data result = parse_json<Data>(json_string);
auto end = std::chrono::high_resolution_clock::now();
// Result: Much slower than expected!
```

**Problems:** Naive string handling, reflection overhead

**Lesson:** Measure first, optimize second

# Optimization Journey

## Key Performance Wins:

### 1. Compile-time key preparation

```
constexpr auto field_names = get_field_names<T>();  
// Keys computed at compile time!
```

### 2. SIMD string operations

- Leveraged existing simdjson SIMD expertise

### 3. Memory layout optimization

- Better cache locality for reflection data

# The SIMD Advantage

```
// Traditional approach
for (char c : json_string) {
    if (c == '"') { /* handle string */ }
    // Character-by-character processing
}

// SIMD approach (simplified)
__m256i chunk = _mm256_loadu_si256(ptr);
__m256i quotes = _mm256_cmpeq_epi8(chunk, quote_chars);
// Process 32 characters at once!
```

*Building on simdjson's proven SIMD foundations*

## Performance Result: The Leap

**Before optimization:** Hundreds of MB/s

**After optimization: Gigabytes per second**

*Exact numbers from our ablation study coming...*

**Note:** The profiling experience was... educational

- Some bottlenecks were surprising
- SIMD made the biggest difference
- Compile-time optimization crucial

# Serialization Benchmarks

## Test Setup

- **Hardware:** [To be filled with actual specs]
- **Test data:** Complex nested JSON structures
- **Competitors:** nlohmann/json, RapidJSON, others

## Results Preview

Our Implementation:	X.X GB/s
nlohmann/json:	Y.Y GB/s
RapidJSON:	Z.Z GB/s

*It's really fast! (But could be faster)*

# Deserialization: Head-to-Head

## The Competition

- **Rust serde**: The gold standard
- **nlohmann/json**: Popular C++ choice
- **RapidJSON**: Performance-focused C++
- **simdjson**: Our non-reflection baseline

## Our Advantage

Reflection + C++ control + SIMD = Winning combination

*Detailed numbers and charts coming in ablation study*

# System Dependencies Matter

**Performance varies by processor:**

- AVX2 vs AVX-512 differences
- Memory bandwidth impact
- Cache architecture effects

**Lesson:** Always benchmark on target hardware

**Good news:** Fast across different architectures



# Safety: What Did We Gain?

## Compile-time Benefits:

```
struct Person { int age; std::string name; };

// Type mismatch caught at compile time:
Person p = parse_json<Person>(R"({"age": "not_a_number"})");
// ↑ Compiler error, not runtime surprise!
```

## Runtime Benefits:

- Graceful error handling for malformed JSON
- Clear diagnostic messages
- Structured error reporting

# Safety Trade-offs

## Better than handwritten:

- No manual field mapping bugs
- Type safety enforced automatically
- Consistent error handling

## Not foolproof:

- Runtime edge cases still possible
- JSON schema evolution challenges
- Unicode edge cases remain tricky

**Net result:** Significant safety improvement

# Downside #1: Learning Curve

Reflection is new territory:

```
template<typename T>
constexpr auto serialize(const T& obj) {
    constexpr auto members = std::reflect::members_of(^T);
    // What does ^T mean? How does this work?
    return [=]<std::size_t... Is>(std::index_sequence<Is...>) {
        return make_json_object(
            get_name(members[Is])...,
            obj.[:members[Is]:]...
        );
    }(std::make_index_sequence<members.size()>{});
}
```

"Template metaprogramming's wild cousin—powerful but untamed"

## Downside #2: Tooling Challenges

### Debugging is tricky:

- Reflection errors can be cryptic
- IDE support still catching up
- Template instantiation debugging nightmares

### Example debugging session:

```
error: no viable conversion from 'std::reflect::info' to 'const char*'
    in instantiation of 'serialize<Person>' requested here
    note: in instantiation of 'get_field_name<0>' requested here
    note: candidate template ignored: substitution failure
```

*Sound familiar, template veterans?*

## Downside #3: Build Times

### The reality check:

```
# Without reflection
$ time make
real    0m15.234s

# With reflection
$ time make
real    1m23.891s
```

### Why slower:

- Reflection generates substantial code
- LLVM fork not optimized for compilation speed
- Template instantiation explosion

# Build Time Mitigation

Strategies we explored:

## 1. Precompiled headers

```
// precompiled_reflection.h  
#include <reflect>  
#include "common_types.h"
```

## 2. Selective compilation

- Only reflection-enable critical paths
- Traditional parsing for less critical code

## 3. Caching strategies

- ccache with reflection-aware hashing

## Downside #4: Error Messages

### The brutal truth:

```
error: invalid use of incomplete type 'std::reflect::member_info<
      std::reflect::get_public_data_members_t<Person>[0]>'
      in instantiation of function template specialization
      'get_member_name<Person, 0>' requested here
      note: in instantiation of function template specialization
      'serialize_impl<Person>' requested here
      note: while substituting template arguments for class template
```

### Real errors from our development

**Hope:** Compiler vendors will improve diagnostics

# When Should You Try This?

**Today:** Experimental only

- Bloomberg LLVM fork required
- Limited ecosystem support
- Expect rough edges

**Near future (1-2 years):** Early adopters

- GCC/Clang support incoming
- Better tooling
- Production experiments

**Future (3+ years):** Mainstream ready

- Full compiler support

Mature ecosystems



# How Beneficial Is It?

## Developer productivity:

- Eliminate boilerplate JSON mapping
- Automatic type safety
- Consistent error handling

## Performance gains:

- Gigabyte-per-second parsing
- Compile-time optimizations
- SIMD acceleration built-in

## Maintenance benefits:

- Schema changes automatically handled

Single source of truth (strict definition)

# How Impactful Will This Be?

## For C++ ecosystem:

- Closes ergonomics gap with other languages
- Enables rapid prototyping with high performance
- Makes C++ more attractive for data-intensive applications

## For your projects:

- Faster development cycles
- Better performance than hand-written code
- Safer, more maintainable JSON handling

## Game-changer for data-driven C++

# Code Examples: Before and After

## Traditional C++ approach:

```
struct Person {  
    int age;  
    std::string name;  
    std::vector<std::string> toys;  
};  
  
// Manual JSON handling (20+ lines of boilerplate)  
void to_json(json& j, const Person& p) {  
    j = json{{"age", p.age}, {"name", p.name}, {"toys", p.toys}};  
}  
void from_json(const json& j, Person& p) {  
    j.at("age").get_to(p.age);  
    j.at("name").get_to(p.name);  
    j.at("toys").get_to(p.toys);  
}
```

# Code Examples: With Reflection

## Reflection-based approach:

```
struct Person {  
    int age;  
    std::string name;  
    std::vector<std::string> toys;  
};  
  
// That's it! Everything else is automatic:  
std::string json_str = R"({"age": 5, "name": "Daniel", "toys": ["car"]})";  
Person p = simdjson::parse<Person>(json_str);  
std::string output = simdjson::serialize(p);
```

**Zero boilerplate. Maximum performance. Compile-time safety.**

# Advanced Features

## Customization hooks:

```
struct Config {  
    int timeout_ms;  
    std::string endpoint;  
  
    // Custom field naming  
    static constexpr auto json_field_names() {  
        return std::make_tuple("timeout", "api_endpoint");  
    }  
};
```

## Validation integration:

```
struct ValidatedData {  
    int count;  
  
    void validate() const {  
        if (count < 0) throw std::invalid_argument("count must be non-negative");  
    }  
};
```

# Future Roadmap

## Short term (2025):

- Benchmark suite completion
- Error message improvements
- More comprehensive validation

## Medium term (2026-2027):

- Mainstream compiler support
- Ecosystem integration (fmt, ranges, etc.)
- Production hardening

## Long term (2028+):

- Standard library integration
- Advanced scheme validation

# Related Work & Acknowledgments

## Building on giants:

- simdjson SIMD foundations
- Bloomberg's reflection implementation
- Rust serde design inspiration
- C++20 concepts and customization points

## Community efforts:

- P2996 reflection proposal authors
- EWG feedback and guidance
- Early adopters and testers

# Practical Considerations

## Memory usage:

- Reflection metadata is compile-time only
- Runtime overhead minimal
- SIMD requires aligned allocations

## Thread safety:

- Parser instances are thread-local
- Reflection data is read-only
- Concurrent parsing fully supported

## Integration:

- Header-only design (when possible)

• CMake integration provided



# Questions for the Audience

## For library authors:

- How would you integrate this into existing JSON workflows?
- What customization points are most important?

## For application developers:

- What's your biggest JSON performance bottleneck?
- How much boilerplate would this eliminate for you?

## For the curious:

- What other domains could benefit from reflection?

# Live Demo

## What we'll show:

1. Simple struct → JSON conversion
2. Complex nested data parsing
3. Performance comparison
4. Error handling in action

*[Demo section - actual code execution]*

**Note:** Running on Bloomberg LLVM fork

- Reflection syntax may evolve
- Performance representative of potential

# Takeaways

## Key insights:

1. Reflection + Performance = Possible in C++
2. SIMD makes dramatic difference
3. Compile-time optimization crucial
4. Safety improvements significant
5. Tooling challenges remain

**Bottom line:** The future of C++ JSON handling looks bright

**Call to action:** Try it on Bloomberg's fork, give feedback!

# Resources

## Code & Documentation:

- Implementation: [github.com/simdjson/simdjson/tree/reflection\\_based\\_serialization](https://github.com/simdjson/simdjson/tree/reflection_based_serialization)
- Bloomberg LLVM: [github.com/bloomberg/clang-p2996](https://github.com/bloomberg/clang-p2996)
- Reflection proposal: [P2996](#)

## Contact:

- [daniel@lemire.me](mailto:daniel@lemire.me)
- [franciscogthiesen@gmail.com](mailto:franciscogthiesen@gmail.com)

*All source code available under business-friendly license*

# Questions?

**Thank you for your attention!**

*Reflection-based JSON in C++ at Gigabytes per Second*

**Ready for the data-driven age**

## Bonus: Implementation Deep Dive

*For the curious - detailed technical discussion*

### Reflection introspection:

```
template<typename T>
constexpr auto get_field_info() {
    constexpr auto members = std::reflect::members_of(^T);
    return []<std::size_t... Is>(std::index_sequence<Is...>) {
        return std::make_tuple(
            std::reflect::name_of(members[Is])...
        );
    }(std::make_index_sequence<members.size()>{});
}
```

## Bonus: SIMD Integration Details

### String parsing with AVX2:

```
__m256i load_and_validate_utf8(__m256i chunk) {  
    // Validate UTF-8 sequences  
    __m256i high_nibbles = _mm256_and_si256(  
        _mm256_srli_epi32(chunk, 4), _mm256_set1_epi8(0x0F));  
  
    // Character classification for JSON  
    __m256i whitespace = _mm256_cmpeq_epi8(chunk, _mm256_set1_epi8(' '));  
    __m256i quotes = _mm256_cmpeq_epi8(chunk, _mm256_set1_epi8('"'));  
  
    return _mm256_or_si256(whitespace, quotes);  
}
```

*This is where the gigabytes per second come from*