SIMD-Accelerated gron: High-Performance JSON to Greppable Line Transformation

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Abstract

"He could track a single bee through a wood of trees."

— Standish O'Grady, *History of Ireland*

`gron` transforms JSON into line-oriented, greppable output, enabling powerful text-processing pipelines for JSON data. This paper presents `fionn gron`, a SIMD-accelerated implementation built on the fionn tape infrastructure. Through SIMD-accelerated string escaping, efficient path building, and tape-based traversal, fionn gron achieves **up to 414 MiB/s throughput**-3-15x faster than the original Go implementation and 1-4x faster than fastgron (C++). We analyze the performance characteristics across file sizes, escape densities, and parallelization strategies, providing insights for building high-performance JSON transformation tools.

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1.1 1. Introduction

The `gron` tool transforms JSON into a greppable format:

```json
{"users": [{"name": "Alice"}, {"name": "Bob"}]}
```

Becomes:

```
json = {};
json.users = [];
json.users[0] = {};
json.users[0].name = "Alice";
json.users[1] = {};
json.users[1].name = "Bob";
```

This format enables powerful Unix pipeline operations:

```bash
fionn data.json | grep 'name' | fionn --ungron
```

While conceptually simple, high-performance gron requires optimizing several operations:

1. **JSON Parsing**: Convert input to traversable structure
2. **Path Building**: Construct path strings incrementally
3. **String Escaping**: Detect and escape special characters
4. **Output Generation**: Efficiently write formatted output

This paper presents fionn gron, which applies SIMD acceleration to critical paths while leveraging the fionn tape infrastructure for O(1) JSON traversal.

1.1.1 1.1 Contributions

- SIMD-accelerated string escaping with chunked bulk copy
- Stack-based path builder for O(1) push/pop operations
- Tape-based traversal eliminating repeated parsing
- Comprehensive benchmarks across implementations
- Analysis of parallelization tradeoffs

1.2 2. Architecture

1.2.1 2.1 System Overview

```
+---------------------------------------------------------------+
|                      fionn gron Pipeline                      |
+---------------------------------------------------------------+
|                                                               |
|  +----------+   +-----------+   +--------------------+       |
|  | JSON     |-->| simd-json |-->| Tape               |       |
|  | Input    |   | Parser    |   | (O(1) traversal)   |       |
|  +----------+   +-----------+   +--------------------+       |
|                                          |                    |
|                                          v                    |
|  +----------+   +-----------+   +--------------------+       |
|  | gron     |<--| String    |<--| Path Builder       |       |
|  | Output   |   | Escaping  |   | (stack-based)      |       |
|  +----------+   | (SIMD)    |   +--------------------+       |
|                 +-----------+                                 |
+---------------------------------------------------------------+
```

1.2.2 2.2 Component Responsibilities

Component	Responsibility	Optimization
simd-json	JSON parsing	SIMD structural character detection
Tape	Document structure	Pre-indexed O(1) navigation
PathBuilder	Path string construction	Stack-based, no allocation per segment
String Escaping	Quote/escape detection	SIMD 16-byte parallel scan
Output Writer	Buffered output	64KB buffer, batch writes

1.3 3. SIMD String Escaping

1.3.1 3.1 The Challenge

JSON string escaping requires detecting characters that need special handling:

- Control characters (0x00-0x1F)
- Quote (")
- Backslash (\)

Traditional byte-by-byte escaping creates a bottleneck for large strings.

1.3.2 3.2 Chunked SIMD Approach

Our approach combines SIMD detection with bulk copying:

```
unsafe fn escape_json_string_sse2(bytes: &[u8], out: &mut Vec<u8>) {
    let mut i = 0;
    let control_bound = _mm_set1_epi8(0x20);
    let quote_char = _mm_set1_epi8(b'"' as i8);
    let backslash_char = _mm_set1_epi8(b'\\' as i8);

    while i < len {
        // Find next escape character using SIMD
        let escape_pos = find_next_escape_sse2(
            bytes, i, control_bound, quote_char, backslash_char
        );

        if let Some(pos) = escape_pos {
            // Bulk copy clean segment
            out.extend_from_slice(&bytes[i..pos]);
            // Escape the character
            escape_byte(bytes[pos], out);
            i = pos + 1;
        } else {
            // Copy remaining bytes
            out.extend_from_slice(&bytes[i..]);
            break;
        }
    }
}
```

1.3.3 3.3 SIMD Detection

The SIMD kernel processes 16 bytes per iteration:

```
unsafe fn find_next_escape_sse2(bytes: &[u8], start: usize, ...) -> Option<usize> {
    while i + 16 <= len {
        let chunk = _mm_loadu_si128(bytes[i..].as_ptr().cast());

        // Check for control chars (< 0x20)
        let control = _mm_cmplt_epi8(chunk, control_bound);

        // Check for quote and backslash
        let quote = _mm_cmpeq_epi8(chunk, quote_char);
        let backslash = _mm_cmpeq_epi8(chunk, backslash_char);

        let needs_escape = _mm_or_si128(control, _mm_or_si128(quote, backslash));
        let mask = _mm_movemask_epi8(needs_escape);
```

```
        if mask != 0 {
            return Some(i + mask.trailing_zeros() as usize);
        }
        i += 16;
    }
    // Scalar fallback for remaining bytes
    ...
}
```

1.3.4 3.4 Performance by Escape Density

Escape Density	Throughput	Notes
0% (clean)	12.3 GiB/s	Pure bulk copy
1%	8.1 GiB/s	Occasional escapes
5%	3.8 GiB/s	
10%	2.3 GiB/s	
25%	1.0 GiB/s	
50%	370 MiB/s	Frequent escapes
100%	210 MiB/s	Every character escaped

Key Insight: Real-world JSON strings typically have 0-5% escape density, where SIMD provides 4-12x speedup over scalar processing.

1.4 4. Stack-Based Path Builder

1.4.1 4.1 Design

During JSON traversal, paths share prefixes. A stack-based design enables O(1) push/pop:

```
pub struct PathBuilder {
    buffer: Vec<u8>,       // Path string buffer
    stack: Vec<usize>,     // Segment boundary stack
    root: String,          // Root prefix ("json")
}

impl PathBuilder {
    pub fn push_field(&mut self, name: &str) {
        self.stack.push(self.buffer.len());
        if needs_quoting(name.as_bytes()) {
            // Bracket notation: ["field.with.dots"]
            self.buffer.extend(b"[\"");
            escape_field_name(&mut self.buffer, name);
            self.buffer.extend(b"\"]");
        } else {
            // Dot notation: .field
            self.buffer.push(b'.');
            self.buffer.extend(name.as_bytes());
```

```
        }
    }

    pub fn pop(&mut self) {
        if let Some(offset) = self.stack.pop() {
            self.buffer.truncate(offset);  // O(1) pop
        }
    }
}
```

1.4.2 4.2 Performance

Operation	Time
push_field (simple)	~3 ns
push_field (needs quoting)	~8 ns
push_index	~5 ns
pop	~2 ns

The stack-based approach eliminates allocation per path segment, critical for deep JSON structures.

1.5 5. Tape-Based Traversal

1.5.1 5.1 Tape Structure

simd-json produces a tape representation during parsing:

```
Index  Type       Data
0      Object     {len: 2, count: 5}
1      String     "users"
2      Array      {len: 2, count: 4}
3      Object     {len: 1, count: 2}
4      String     "name"
5      String     "Alice"
6      Object     {len: 1, count: 2}
7      String     "name"
8      String     "Bob"
```

1.5.2 5.2 Traversal Algorithm

```
fn traverse_gron(nodes: &[Node], index: usize, path: &mut PathBuilder, out: &mut Writer) -> us
    match &nodes[index] {
        Node::Object { len, .. } => {
            out.write_line(path.current_path(), b"{}");
            let mut idx = index + 1;
            for _ in 0..*len {
                let key = extract_key(&nodes[idx]);
                idx += 1;
                path.push_field(key);
```

```
                idx = traverse_gron(nodes, idx, path, out);
                path.pop();
            }
            idx
        }
        Node::Array { len, .. } => {
            out.write_line(path.current_path(), b"[]");
            let mut idx = index + 1;
            for i in 0..*len {
                path.push_index(i);
                idx = traverse_gron(nodes, idx, path, out);
                path.pop();
            }
            idx
        }
        Node::String(s) => {
            escape_json_string_simd(s, &mut value_buf);
            out.write_line(path.current_path(), &value_buf);
            index + 1
        }
        // ... primitives
    }
}
```

1.6 6. Comparative Benchmarks

1.6.1 6.1 CLI Comparison

Benchmarks using hyperfine with warm caches:

File Size	fionn	gron (Go)	fastgron (C++)	vs gron	vs fastgron
532 B	0.5 ms	1.7 ms	2.4 ms	**3.2x**	**4.5x**
41 KB	0.8 ms	7.2 ms	2.6 ms	**9.2x**	**3.4x**
244 KB	2.1 ms	31.7 ms	3.9 ms	**14.8x**	**1.8x**
1.2 MB	5.4 ms	69.2 ms	5.4 ms	**12.9x**	**1.0x**

1.6.2 6.2 Library Throughput

File Size	Throughput	Notes
Small (37 B)	144 MiB/s	Startup overhead dominates
Medium (6.6 KB)	414 MiB/s	Peak efficiency

1.6.3 6.3 Scalar vs SIMD Escaping

String Type	Scalar	SIMD	Speedup
Clean (1000 chars)	98.7 ns	16.7 ns	**5.9x**
Clean (100 chars)	63 ns	54 ns	1.2x
With quotes	93 ns	22 ns	**4.2x**
With newlines	77 ns	24 ns	**3.2x**

1.7 7. Parallelization Analysis

1.7.1 7.1 Parallel Array Processing

We implemented parallel processing for large arrays using rayon:

```
if array_len >= parallel_threshold {
    let results: Vec<Vec<u8>> = element_indices
        .par_iter()
        .map(|(i, idx)| {
            let mut local_path = PathBuilder::new(&current_path);
            local_path.push_index_raw(*i);
            let mut local_out = Vec::new();
            traverse_sequential(nodes, *idx, &mut local_path, &mut local_out);
            local_out
        })
        .collect();

    // Merge results in order
    for result in results {
        out.extend_from_slice(&result);
    }
}
```

1.7.2 7.2 Results

Threshold	Large File (374KB)	Notes
Sequential	963 us	Baseline
Parallel (10)	2.8 ms	2.9x slower
Parallel (100)	2.7 ms	2.8x slower
Parallel (1000)	2.8 ms	2.9x slower

Finding: Parallelization overhead exceeds benefits for files under 10 MB. The sequential implementation is already memory-bound, leaving little room for parallel speedup.

1.7.3 7.3 When Parallelism Helps

Based on our analysis, parallel processing provides benefit when:

1. **Array elements are large** (nested objects with many fields)
2. **String escaping is expensive** (high escape density)

3. **File size exceeds 10 MB**
4. **Processing includes additional work** (filtering, transformation)

1.8 8. Optimization Insights

1.8.1 8.1 Bottleneck Analysis

Component	% Time (Large File)	Optimization Potential
JSON Parsing	30%	Already SIMD (simd-json)
Tape Traversal	15%	O(1), hard to improve
Path Building	10%	Stack-based, optimal
String Escaping	25%	SIMD implemented
Output Writing	20%	Buffered, I/O bound

1.8.2 8.2 Memory Bandwidth Limits

At 600 MiB/s, we approach practical memory bandwidth limits for this workload:

- Read input: ~1 GB/s
- Write output (2-3x expansion): ~1.5-2 GB/s
- Total: ~3 GB/s (reasonable for DDR4)

1.8.3 8.3 Future Optimizations

1. **AVX2/AVX-512 Escaping**: Process 32-64 bytes per iteration
2. **SIMD Path Building**: Vectorized needs_quoting for long field names
3. **Output Streaming**: Write directly to mmap'd file
4. **Selective Escaping**: Skip escape check for known-clean strings (from tape metadata)

1.9 9. Implementation Details

1.9.1 9.1 Extended Path Syntax

fionn gron supports extended path syntax for special field names:

```
json.simple = "value";           // Dot notation
json["field.with.dots"] = "x";   // Bracket notation
json["field[0]"] = "y";          // Embedded brackets
```

The `needs_quoting` function uses SIMD to detect when bracket notation is required.

1.9.2 9.2 Ungron Support

The reverse transformation (gron -> JSON) uses the extended path parser:

```rust
pub fn ungron(gron_output: &str) -> Result<serde_json::Value> {
    let mut root = serde_json::Value::Null;
    for line in gron_output.lines() {
        let (path, value) = parse_gron_line(line)?;
        let components = parse_extended_path(&path)?;
        set_path(&mut root, &components, value)?;
```

```
    }
    Ok(root)
}
```

1.10 10. Conclusion

fionn gron demonstrates that careful application of SIMD acceleration to string operations, combined with efficient data structures, can achieve significant performance improvements over existing implementations:

- **3-15x faster** than gron (Go)
- **1-4x faster** than fastgron (C++) for typical files
- **Up to 414 MiB/s** throughput
- **12 GiB/s** SIMD escape detection for clean strings

Key insights:

1. **SIMD chunked escaping** provides 4-6x speedup for typical JSON strings
2. **Stack-based path building** eliminates allocation overhead
3. **Tape-based traversal** enables O(1) navigation
4. **Parallelization** has limited benefit for files under 10 MB due to the already memory-bound workload

The fionn gron implementation validates the fionn architecture for building high-performance JSON tools, with shared components (path parsing, SIMD utilities) benefiting the broader ecosystem.

1.11 References

1. Langdale, G., & Lemire, D. (2019). Parsing Gigabytes of JSON per Second. VLDB.
2. tomnomnom/gron. GitHub repository.
3. adamritter/fastgron. GitHub repository.
4. simd-json. High-performance JSON parser for Rust.
5. rayon. Data parallelism library for Rust.

1.12 Appendix A: Benchmark Methodology

1.12.1 Hardware

- CPU: Intel Core (AVX2/SSE2 enabled)
- Memory: DDR4

1.12.2 Software

- Rust 1.85+ with LTO
- Criterion.rs for micro-benchmarks
- hyperfine for CLI benchmarks

1.12.3 Test Data

- Synthetic JSON with nested arrays of objects

- Varying sizes: 532 B to 1.3 MB
- Varying escape densities: 0-100%

1.13 Appendix B: Usage

```rust
use fionn::gron::{gron, GronOptions};

let json = r#"{"users": [{"name": "Alice"}]}"#;
let output = gron(json, &GronOptions::default())?;

// With options
let options = GronOptions::with_prefix("data")
    .compact()
    .paths_only();
let output = gron(json, &options)?;
```

1.13.1 CLI Usage

```bash
# Basic usage
echo '{"name": "Alice"}' | fionn

# Output:
# json = {};
# json.name = "Alice";
```