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Compiler Compiler System with Isomorphic Runtime and Binary Structured Intermediate Representations

Self-hosting bootstrap, multi-language runtime emission, and JSON parser benchmarks.

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The system described in this paper is protected by US Patent 8,464,232 [1]. A complete technical specification [2] is available under commercial terms.

Abstract

The Compiler Compiler System (CCS) is a compiler-construction tool that, given a context-free grammar specification, produces a complete compiler for the language that grammar describes. CCS departs from the YACC, GNU Bison, and ANTLR lineage in six specific ways: (i) it replaces the parse tree as central intermediate representation with a structured first-class model of *Context*, *Name*, *Symbol*, and *Rule* and their relationships, instantiated as a `SyntaxControlledRuntime` object during parsing; (ii) it strictly separates syntax processing from semantic processing, with semantics consuming a grammar-defined application programming interface rather than being embedded in grammar actions; (iii) it defines syntax processing as a two-phase, formally bidirectional procedure between the runtime and a serialized form, the `SyntaxControlledBinary`, so that runtime, binary, and source text are interconvertible; (iv) it makes formal de-compilation back to source text a first-class operation rather than a debugging aid; (v) it derives the runtime and binary application programming interfaces from the grammar itself rather than from hand-written interface definitions; and (vi) the source grammar definition language (SGDL) is self- bootstrapped — its own grammar is defined in itself, and the compiler-compiler executable can regenerate itself from that meta- grammar. We present an empirical evaluation in which a CCS- generated JSON parser, distributed as a flat tagged binary artifact,

loads within approximately 2× of simdjson DOM and outperforms simdjson's per-leaf walk on every input in an O(1) grammar-derived walk implementation. The system has been exercised on the self-hosting round-trip oracle, on the JSON and XML target languages, and on integration with multiple AI-agent frameworks. This paper describes the parsing model, the runtime and binary forms, SGDL, the generator subsystem, the round-trip oracle, and the empirical results.

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1. Introduction

Compiler-compilers — tools that consume a grammar specification and produce a parser — have been a fixture of programming-language infrastructure for half a century. The YACC family [3] and its descendants ANTLR [4] and GNU Bison have shaped how new languages, file formats, and configuration languages get built. The shape they have given to this work is recognizable. A grammar specification describes the lexical and syntactic structure. A parser generator produces parsing code. The developer writes semantic actions attached to grammar rules, fills in the parse tree's internal structure, writes the code that traverses the tree to perform semantic analysis, and writes the code that emits whatever target form the language requires. The compiler-compiler addresses part of the engineering cost — the parser and tokenizer — but leaves the intermediate representation, the semantic actions, and the transmission story to the developer.

We refer to the residual engineering cost as the *compiler tax* [2, §2.1]. Every new programming abstraction, domain-specific language, file format, or interchange protocol bears it: a parser must be written, a tokenizer must be written, an intermediate representation must be designed and maintained, semantic actions must be interleaved with grammar rules, and the parsed program must be serialized and reloaded across process boundaries. The cumulative effect scales poorly as the number of small languages in a system grows. Contemporary systems frequently contain a dozen or more bespoke parsers and serializers, each carrying its own version of the tax.

This paper describes the Compiler Compiler System (CCS), a compiler-construction tool that addresses the compiler tax by reorganizing the activity of compilation around an intermediate representation that is, by construction: *structured* (so the developer does not design it), *grammar-defined* (so the application programming interface is automatic), *serializable* (so the in-memory and on-disk forms are interconvertible without extra machinery), *reversible* (so any of the three forms — source text, in-memory representation, on-disk binary — can be obtained from any other), and *transformation-friendly* (so operations such as obfuscation, access control, content rewriting, and inter-program communication are first-class binary-to-binary operations).

CCS was first described in US Patent 8,464,232 [1], granted June 2013, and elaborated in a 2015 technical whitepaper. The present paper updates and condenses that material for an academic audience, adds material on multi-language runtime emission across C++, Python, JavaScript, and Rust, and presents new empirical evaluation against JSON parser baselines.

The contributions of this paper are: (1) a precise statement of the parsing model that CCS uses to reorganize compilation work, (2) a description of the multi-language runtime and binary implementations that allow CCS-generated parsing artifacts to participate in heterogeneous-language systems, (3) the round-trip closure property that serves as a structural-correctness oracle for the system and its targets, and (4) empirical results on JSON parsing that compare CCS-generated artifacts against nlohmann/json and simdjson on standard benchmark inputs. We are explicit about what the paper does *not* claim. CCS is not a verified compiler; the round-trip property is empirically demonstrated by self-test sequences but not mechanically proved. CCS is not a multi-target back-end framework in the LLVM or MLIR sense; portability comes from the host C++ toolchain. CCS is closest in spirit to YACC and ANTLR — it generates compilers from grammar specifications — but reformulates that activity around an intermediate representation that supports bidirectionality.

The remainder of the paper is organized as follows. Section 2 positions CCS against related work in compiler construction, serialization, and language workbenches. Section 3 describes the parsing model. Section 4 describes the four-entity schema that the model shares between in-memory and on-disk forms. Section 5 describes the syntax-controlled runtime and binary in detail. Section 6 describes the source grammar definition language and the bootstrap loop by which CCS defines itself. Section 7 describes the generator subsystem and multi-language emission. Section 8 describes the round-trip closure oracle. Section 9 presents empirical evaluation against JSON parsing baselines. Section 10 describes the framework's extensibility surface through the worked addition of MeTTa as a new target language. Section 11 describes the addition of Rust as a new programming language for processing CCS-produced SCB artefacts. Section 12 discusses implications and applications. Section 13 notes limitations and future work.

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2. Background and Related Work

CCS occupies a position in the broader compiler-construction landscape that is best stated against several lines of prior art.

The YACC family. YACC [3] introduced the bottom-up LR compiler-compiler that has shaped subsequent practice. Its descendants — Bison, ANTLR [4], lemon, and others — refined the parsing algorithms, added top-down (LL(k), PEG, ALL(*)) alternatives, and improved error recovery. They retained the fundamental architecture: grammar specifications produce parsing code; semantic actions are attached to grammar rules; the parse tree is the central intermediate representation; the developer takes responsibility for tree traversal, semantic analysis, and emission. CCS preserves the outermost flow of this architecture — a grammar specification feeds a generator whose output, combined with implementation code, produces an executable — but changes nearly everything internal to that flow.

Tree-sitter and incremental parsing. Tree-sitter [5] is a contemporary compiler-compiler aimed at incremental, error- tolerant parsing for editor and language-server use. Its intermediate representation is a concrete syntax tree; its emphasis is on incremental re-parsing of small textual edits. CCS targets a different deployment shape: batch compilation producing a serialized intermediate that is consumed across process boundaries and across language runtimes.

Protocol Buffers, FlatBuffers, Cap'n Proto. A family of interchange-format compilers produces serialization code from schema specifications [6]. These tools occupy a different architectural niche than CCS: they emit only the serialization layer; they do not produce parsers for general context-free languages; they do not provide an in-memory tagged-instance form that round-trips against a textual source. CCS shares with this family the conviction that wire formats deserve compiler-grade treatment, but applies the conviction to the *parsed* form rather than to the schema-of-data form.

LLVM, MLIR, and multi-target back-end frameworks. LLVM and MLIR [7, 8] provide abstractions over multiple back-end code generators. CCS does not occupy this niche. It produces source- level intermediate code in C++ which is then compiled by the host C++ toolchain; its portability comes from the C++ toolchain, not from a CCS-internal back-end abstraction.

Language workbenches. Systems including JetBrains MPS, Xtext, and Spoofax [9] provide infrastructure for defining domain-specific languages with associated editors, type systems, and code generators. They share with CCS the conviction that specifications should be first-class artifacts. The architectural emphasis differs: workbenches typically prioritize the authoring experience for a single DSL, while CCS prioritizes the bidirectionality of the parsed form across textual, in-memory, and binary representations.

Model-driven engineering (MDE). A research and industry tradition spanning two decades, MDE promotes models to first-class artifacts and generates implementations from them [10]. The recurring obstacles to MDE adoption have been tooling burden, generated-artifact rigidity, and the modeling-language-to-working- code gap. CCS sits in this tradition; its specific contribution is the bidirectional-phase property between intermediate representations, which the MDE literature recognizes as desirable but typically achieves only on subsets of the modeled domain.

Round-trip engineering. The property that transformations should be invertible — that emitted code should round-trip back to its source model under inverse transformation — has been recognized as a structural-correctness oracle in MDE and in compiler construction since the 1980s [11]. CCS treats round-trip closure as a load-bearing element: not a refinement applicable on favorable subsets, but a designed property of every CCS-produced parser/serializer pair, demonstrated empirically on the self-test suite documented in Section 8.

Self-hosting compiler-compilers. The tradition of compiler- compilers that compile their own meta-grammar goes back at least to YACC [3]; the property is recognized as a marker of internal consistency. CCS is in this tradition; the bootstrap loop described in Section 6 is the canonical demonstration.

AI-assisted programming. Recent tools including GitHub Copilot [12], Anthropic's Claude Code [13], Cursor, and agentic frameworks including LangGraph operate at the source-code generation surface. They consume the existing textual source substrate and produce more of it. The relationship between CCS and AI-assisted construction is discussed in Section 12; the present paper focuses on the compiler-compiler proper.

The combination of features described in the present paper — a structured intermediate representation with bidirectional phases, a canonical binary form interconvertible with that intermediate, multi-language emission, a self-bootstrapping specification language, and round-trip closure as a designed property — is, to our knowledge, not present in any single prior system. The individual components have antecedents; the combination is what the paper documents.

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3. The Parsing Model

The *Parsing Model* is the high-level architectural abstraction of CCS. It comprises three entities and the morphisms (procedural transformations) between them.

Grammar. A specification, written in SGDL (Section 6), of the source language whose programs CCS is to compile. In the case where CCS is bootstrapping itself, the grammar is the meta-grammar `meta.sgr` — an SGDL specification of SGDL itself.

SyntaxControlledRuntime. The in-memory representation of a successfully parsed program. The runtime is maintained by the parser as parsing proceeds: each grammar rule whose right-hand side is recognized causes corresponding *Context*, *Name*, *Symbol*, and *Rule* instances to be created or updated within the runtime. The runtime serves as the form in which the parser *builds* the parsing artifact, with full freedom to insert, modify, and rearrange entries.

SyntaxControlledBinary. The serialized representation of a successfully parsed program. The binary is generated as an independent phase, after compilation has succeeded — that is, after the front end has produced a runtime that is consistent with the grammar. The binary is a flat tagged vector that holds the same parsed information as the runtime in a layout suitable for memory-mapped read-only access, file storage, and inter- process transmission.

Three entities; five labeled morphisms (Figure 1). Phase 2.1a *compile* is the transformation from grammar plus source text to runtime — the parser proper. Phase 2.1b *de-compile* is the transformation from runtime back to source text — formal de- compilation as a first-class operation. Phase 2.2a is the transformation from runtime to binary; Phase 2.2b is its inverse, binary to runtime. Phase 2.2c is direct de-compilation from binary to source text, bypassing the runtime; it is provided as a convenience operation for read-only consumers.

```
            Grammar (SGDL source text)
                  /\         \
                 /  \         \
          Phase 2.1a Phase 2.1b Phase 2.2c
          compile    decompile  decompile
               /        \        \
              v          v        v
SyntaxControlledRuntime <-----> SyntaxControlledBinary
                    Phase 2.2a, 2.2b
                    (round-trip pair)
```

Figure 1 — The CCS Parsing Model. Three entities — grammar, runtime, binary — connected by five named morphisms. Compilation always passes through the runtime; there is no direct grammar-to- binary phase.

A property worth noticing on first encounter is the absence of a direct grammar → binary arrow. Compilation always passes through the runtime. The binary is a serialized form of the runtime, and any process that produces a binary must first produce a runtime. This is not arbitrary: it reflects the responsibilities assigned to each form. The runtime is the form in which the parser builds the parsing artifact, with the freedom that parsing requires; the binary is a finalized, read-only summary suitable for transport. Allowing direct grammar→binary compilation would require either a parser whose output were the read-only binary (impractical, since parsing is incremental and exploratory) or a separate code path duplicating the parser's logic. CCS chooses neither.

The bidirectionality property — that source text, runtime, and binary are mutually convertible by the five morphisms above — is the central structural feature of the parsing model. Where YACC-family compiler-compilers produce one-way pipelines (text → parse tree → semantic actions → output), CCS produces a bidirectional system in which any of the three forms can be obtained from any other through composition of the five labeled morphisms.

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4. The Four-Entity Schema

The runtime and binary forms share a common schema: the four entities *Context*, *Name*, *Symbol*, and *Rule*, and their relationships. Both forms hold the same information, organized in the same way; they differ only in physical representation (object graph in the runtime, flat tagged vector in the binary).

Context — the top-level scope of a parsing artifact. A program parsed by CCS is decomposed into one or more contexts. Each context owns its own collections of names, symbols, and rules. Most simple grammars produce a single context per program; nested or modular grammars may produce many.

Name — an identifier appearing in the source program: a variable name, a function name, a structure tag, a label. Each name lives in some context and is reachable by the textual identifier the source used as well as by a sequential index assigned during parsing. Both lookups are constant-time.

Symbol — a non-terminal grammar symbol (an entry in the grammar) together with the parsing record of all instances in which the parser recognized it. A symbol owns a collection of *Rule* instances, one per recognition occurrence.

Rule — a single recognition of a non-terminal symbol — a single point in the source where the parser matched the symbol's right- hand side. A rule has fixed and dynamic parts; the fixed part holds the values produced by terminals and embedded actions, the dynamic part holds references to other rules invoked during this recognition.

The relationships among the four entities are: each runtime contains a collection of *contexts*; each context contains a collection of *names* (indexed both alphabetically and sequentially) and a collection of *symbols*; each symbol contains a collection of *rules*. The binary form preserves these collections in a flat memory layout that supports the same access patterns as the runtime form, with the same asymptotic costs.

A reader familiar with parse-tree-based compiler-compilers will note an important absence: there is no node-and-edge tree structure here. The four-entity schema is *not* a tree. A *Rule* instance does refer to other *Rule* instances through its dynamic part — so the rule graph is, technically, walkable as a tree from the axiom rule downward — but the schema's primary access patterns are not tree walks. The runtime's application programming interface exposes lookups by name within a context, lookups by symbol within a context, lookups by rule instance within a symbol, and so on. These are constant-time index operations, not tree traversals. Semantic processing is therefore typically structured as a series of indexed accesses to the runtime, rather than as a recursive tree walk.

The architectural consequence is significant. In a parse-tree- based compiler, the semantic actions take responsibility for navigating the tree; in CCS, the runtime's grammar-derived application programming interface takes responsibility for exposing the parsed content. The semantic implementation does not need to know the tree's shape because there is no tree. It needs to know which contexts, names, symbols, and rules exist, and how they relate. The grammar — through the generator subsystem of Section 7 — produces the application programming interface that exposes them.

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5. Syntax-Controlled Runtime and Binary

This section describes the two implementation forms of the parsing artifact in more detail. The runtime and binary forms hold the same information; they differ in physical layout and in the operations they support efficiently.

The SyntaxControlledRuntime. The runtime is an in-memory object graph instantiating the four-entity schema. The root object owns a collection of contexts. Each context owns its collections of names and symbols; each symbol owns its collection of rules. The collections are implemented with constant-time sequential index access and constant-time identifier lookup; the specific data structures (hashed indices, sorted vectors) are implementation-internal.

The runtime is mutable during parsing: the parser proper inserts *Context*, *Name*, *Symbol*, and *Rule* instances as it processes the source. Once parsing completes, the runtime is treated as read-only by downstream consumers. Semantic analysis, transformation, and emission all consume the runtime through its grammar-derived application programming interface.

The SyntaxControlledBinary. The binary is a flat tagged vector — a contiguous memory region containing all parsed data in a layout suitable for memory-mapped read-only access. The vector holds tagged elements: each element is a small fixed-size record combining a *Tag* (identifying the element's category — context, name, symbol, or rule) with the payload values for that category. Auxiliary indexing structures map identifiers to vector offsets, preserving the constant-time lookup properties of the runtime.

The binary form has properties the runtime form does not. It is relocatable: the whole vector can be moved as a unit, by filesystem copy or network transmission, with no internal pointer fix-up required. It is read-only: consumers can safely share the binary across processes, including via memory-mapped shared storage. It is small: the binary's footprint is dominated by the parsed information itself, with low per-element overhead.

The two forms are interconvertible: Phase 2.2a transforms a runtime to a binary by emitting the tagged vector in a specified canonical order; Phase 2.2b transforms a binary to a runtime by reading the vector and rebuilding the object graph. The two phases form a structural-correctness oracle: a runtime that round-trips through the binary should be byte-identical to its original serialization, and a binary that round-trips through the runtime should reproduce its original sequence of tagged records. CCS's self-test suite (Section 8) demonstrates this property empirically.

The binary form additionally supports two storage representations. The *decimal-text* (`.fgr`) form lists the tagged vector elements one per line in decimal; it is portable across hosts of differing byte order and is the historical form CCS used. The *raw-binary* (`.bfgr`) form writes the tagged vector as a contiguous native- byte-order block; it loads approximately twenty to thirty times faster than `.fgr` and is the form used in the empirical evaluation of Section 9. The two forms encode identical content; either is decompiled to the runtime through Phase 2.2b.

A unified application programming interface — a single C++ class hierarchy whose entries are derived from the grammar — exposes the runtime and binary forms to consumers. The same grammar specification produces the same API in C++, Python, JavaScript, and Rust (Section 7). A consumer in any of the four languages reads the same binary file, navigates the same logical structure, and performs the same operations.

6. Source Grammar Definition Language and the Bootstrap Loop

The input language of CCS is SGDL — the Source Grammar Definition Language. SGDL is a notation that extends Backus-Naur Form with three iteration constructs, two optionality constructs, and a macro substitution mechanism for embedded actions. SGDL is itself defined in SGDL: the file `meta.sgr` is an SGDL specification of SGDL, and the CCS executable parses `meta.sgr` using the same machinery it would apply to any user-supplied grammar.

The lexical structure is uniform across grammars: identifiers (used to name grammar non-terminals and predefined token classes), reserved words (the names of predefined token classes and the macro action delimiters), integer and string literals, and grammar terminals (strings enclosed in single quotes to distinguish them from identifiers and reserved words). Whitespace separates tokens but is otherwise insignificant; SGDL specifies no comment syntax, which simplifies de-compilation by ensuring no comment information could be lost in the round-trip.

SGDL is short enough to reproduce in full: the canonical `meta.sgr` is its own self-definition, given verbatim below.

```
(meta
  (grammar ::=
    0 ="  METAACTBEG();"=

    '(' grammarNameDef
            { rule }
    ')'

    0 ="  METAACTEND();"=
  )

  (grammarNameDef ::= identifier
  )

  (rule ::=     '(' nterm '::=' right ')'
  )

  (nterm     ::= identifier
  )

  (right ::= { element }
```

```
)

(element  ::=
      identAlt | alternative | identMiss | iteration | action
)

(action   ::= integerToken '=' { stringToken } '='
)

(actions  ::= '=' { action } '='
)

(identAlt ::=
      ntermtermact { Altpart }
)

(Altpart  ::= '|' ntermtermact
)

(ntermtermact ::= ntermterm [ actions ]
)

(ntermterm    ::=
      nterm | termToken
)

(alternative  ::= '(' identAlt ')'
)

(identMiss    ::= '[' identAlt ']'
)

(iteration    ::= '{' iterItemact iterItems '}'
)

(iterItems    ::=    { altIterItem }
)

(altIterItem  ::= '|' iterItemact
)

(iterItemact  ::= iterItem  [ actions ]
)
```

```
  (iterItem ::=
         nterm | maybeNterm
  )

  (maybeNterm   ::=
        '<' nterm '>'
  )
)
```

Several properties of this listing are worth noting. The grammar name `meta` appears as the first identifier inside the outer parentheses; the first rule defines `grammar` as the file structure consisting of a grammar name followed by zero or more rule definitions; the macro action delimiters `METAACTBEG()` and `METAACTEND()` mark optional embedded-action syntax positions; the four meta constructs are iteration, `{ X }` (zero-or-more), missing element, `[ X ]` (zero-or-one), the alternation `(X | Y)`, and `<X>` for `X` inside iteration, (zero-or-one) occurences. The complete SGDL specification is given in [2, Appendix C] along with SGDL extensions of BNF; the file `meta.sgr` is the canonical source of SGDL on SGDL.

The bootstrap loop. Because SGDL is defined in itself, the CCS executable can regenerate itself from `meta.sgr`. The operational sequence is:

1. The CCS executable reads `meta.sgr` and produces a `SyntaxControlledRuntime` (Phase 2.1a).
2. The runtime is converted to a `SyntaxControlledBinary` (Phase 2.2a).
3. The generator subsystem produces C++ source files corresponding to the meta-grammar's parser, generator, and keyword definitions.
4. The developer (or build automation) fills in the semantic implementation that SGDL requires — what its grammar rules *do* — against the auto-generated stubs. For the meta-grammar specifically, the CCS distribution ships this implementation.
5. The host C++ toolchain builds the new executable, identical in capability to the executable that initiated the cycle.

The bootstrap loop closes: a CCS executable can rebuild itself from a single SGDL file. There is no separately maintained boot grammar; there is no specially-cased C++ code that parses SGDL as opposed to user-grammar parsing. The CCS executable processes `meta.sgr` using the same machinery any user grammar exercises.

The bootstrap loop has a useful operational consequence. Because the loop closes, the system can be tested for round-trip fidelity: take any grammar (not necessarily the meta-grammar), compile it through Phase 2.1a to a runtime, de-compile via Phase 2.1b back to text, and compare the de-compiled text against the original source (modulo indentation). The expected result is identity. Take any binary: de-compile via Phase 2.2c back to text, and compare. Again the expected result is identity. Section 8 specifies the self-test sequences that exercise this property and the results we obtain on the meta-grammar and on each of the target-language grammars CCS has been applied to.

The bidirectionality property is empirically demonstrated, not formally proved. We do not claim that round-trip is bijective for every grammar SGDL can express; we claim that the CCS implementation maintains round-trip identity for all grammars that have been tested against it, including `meta.sgr` itself. The precise grammar class for which round-trip is bijective is not characterized in the present paper.

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7. Generator Subsystem and Multi-Language Emission

The generator subsystem produces the application-programming- interface source files that allow downstream consumers to access runtimes and binaries through entry points derived from the grammar rather than hand-written.

For a grammar named `X`, the generator produces:

- `XParser.{cc,h}` — the parser source that drives the tokenizer and the syntax-controlled runtime as it processes source text.
- `XGenerator.{cc,h}` — the generator source that emits language- specific artifacts from the runtime.
- `XKeyWordDefinition.{cc,h}` — the keyword definition source that exposes the grammar's predefined and grammar-derived terminals and non-terminals as compile-time-resolved identifiers.

These three files together define the C++ application programming interface for the grammar's runtime and binary. A consumer writes `X`-specific semantic processing against this interface — typically by subclassing the generated `Parser` class and providing semantic implementations of grammar rules whose recognition triggers application-specific behavior. The grammar *is* the interface; the developer does not separately design an application programming interface and a grammar.

CCS extends this multi-language. The same grammar specification produces equivalent application programming interfaces in Python, JavaScript, and Rust:

- `XKeyWordDefinition.py` — a Python module exposing the same keyword definitions for consumption by a Python runtime/binary reader.
- `XKeyWordDefinition.mjs` — a JavaScript module exposing the same for a JavaScript reader.
- `XKeyWordDefinition.rs` — a Rust module exposing the same for a Rust reader.

The four-language emission supports a deployment pattern in which a grammar-conformant content artifact — a runtime serialized to a binary, or a binary produced by parsing a source — can be read by consumers in any of the four supported runtime languages through the same logical application programming interface. We refer to this as the *SCB-API quartet*. The same `.bfgr` file is consumable by a C++ reader, a Python reader, a JavaScript reader, and a Rust reader; each reader sees the same contexts, names, symbols, and rules, and exposes the same lookup operations.

The economic property the quartet supports is that the cost of adding a new target language is one-time per target. Once the Python reader exists, every CCS-generated grammar emits its Python keyword definitions automatically; no per-grammar Python-side work is required. The same holds for JavaScript and Rust. Adding a new target language to CCS — say, Java or Go — would be one engineering effort against the runtime/binary form, after which all existing and future grammars become available in the new language.

The quartet has been exercised on the meta-grammar itself (producing meta-grammar parsing/walking across all four languages), on the JSON and XML target grammars (producing JSON and XML parsing/walking across all four languages), and on custom grammars used for AI-agent-framework integration. The runtime/binary forms produced in any of the four languages from the same grammar are interconvertible: a binary produced by the C++ parser is consumed correctly by the Python, JavaScript, and Rust readers, and vice versa.

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8. Round-Trip Closure as Structural Oracle

Section 6 noted that the bootstrap loop's closure has a useful consequence: it provides a structural-correctness oracle for the system. This section makes the oracle precise and describes how it is applied in practice.

The oracle's logical form is the following. Let `F` be the transformation from textual source `X` to one of the intermediate forms `Y` (runtime or binary). Let `G` be the inverse transformation from `Y` back to text. Then `F`-then-`G` applied to `X` should produce `X'` with `X' = X` under whatever equality relation applies to the formats. For SGDL grammars and for CCS- generated binaries the equality is exact (modulo indentation rules specified in [2, Chapter 8]).

The oracle has two important properties. First, it does not require the test author to know what the output should be in absolute terms. It requires only that the round-trip pair be internally consistent. This makes the oracle applicable to arbitrary inputs: any well-formed SGDL grammar can be round-trip tested, regardless of whether anyone has stated in advance what its de-compilation should look like. Second, the oracle is mechanical: success and failure are byte-comparison decisions, not human-judgment decisions. Both properties together support testing at high throughput against large input corpora.

The self-test sequence implemented in `scripts/roundtrip.sh` exercises the oracle on the meta-grammar:

1. Compile `meta.sgr` through Phase 2.1a, producing `meta.sgr.urt` (runtime decompilation) and `meta.sgr.fgr` (binary decompilation).
2. Recompile `meta.sgr.urt` (treating it as a grammar in its own right) and verify that the second-pass runtime decompilation is byte-identical to the first-pass `meta.sgr.urt`.
3. Decompile `meta.sgr.fgr` through Phase 2.2c (binary → text), producing `meta.sgr.ubr` (binary decompilation as text).
4. Recompile `meta.sgr.ubr` and verify that the second-pass binary decompilation is byte-identical to the first-pass `meta.sgr.ubr`.

If both diffs are empty, the system has maintained round-trip fidelity under the operations exercised. The script prints `PASS` and exits with status `0`. Run on the CCS reference implementation, the script PASSes on the meta-grammar in every version we have tested.

The same script structure applies to user grammars. We have run analogous round-trip oracles on the JSON grammar, the XML grammar, the MeTTa grammar (a small S-expression-based language with permissive symbol naming), and on grammars defining custom binary protocols used in AI-agent framework integration. In every case the oracle's identity expectation has held —

within the limits of CCS's documented constraints (Section 13). The oracle does not certify *correctness* of the CCS implementation against any external specification; it certifies *internal consistency* of the CCS-produced parser/serializer pair against itself.

The structural value of the oracle is what it makes testable. Validation of artifacts produced by AI-assisted grammar development — for example, an LLM proposing an SGDL grammar fragment for a new file format — can be checked mechanically at the rate the LLM produces proposals, rather than at the rate a human reviewer can verify them. The throughput multiplier this enables is discussed in Section 12.

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9. Empirical Evaluation: JSON Parsing Benchmarks

This section presents empirical results comparing CCS-generated JSON parsing artifacts against two contemporary baselines — nlohmann/json (a widely-used header-only C++ JSON library known for its API ergonomics and substantial parsing cost) and simdjson (a SIMD-accelerated JSON parser with state-of-the-art parsing throughput) — across three standard benchmark inputs.

Methodology. The benchmark harness (`bench/main.cc`) loads a JSON sample from disk, then runs the configured number of iterations against each parsing baseline, measuring wall-clock time. Each baseline configuration measures both parsing (loading the input into the parser's intermediate representation) and walking (traversing the parsed structure to tally a six-field `Counts` aggregate over string / integer / floating-point / true / false / null leaves). The "walk" measurement isolates the cost of consuming the parsed form after the parse has completed; the CCS columns measure walking through the SCB application programming interface against the same `Counts` aggregate.

Compiler: g++ -O2 -std=c++17. Iterations: 100. The CCS columns load the canonical-binary `.bfgr` form (the raw native-byte-order representation introduced in Section 5); the JSON-to-`.bfgr` compilation cost is one-time per input and is not included in the parse-time measurement. The samples are widely-cited public JSON benchmark corpora (twitter, citm_catalog, canada).

Parse-time results. Table 1 reports per-iteration wall-clock time for parsing each sample. Each value is in microseconds per parse.

```
Table 1 — Parse time (microseconds per parse, 100 iterations)
+----------------------------+---------+---------+---------+----------+
```

Input	nlohmann	simdjson	CCS .fgr	CCS .bfgr
twitter.json (632 KB)	4299	134	8749	300
citm_catalog.json (1.7 MB)	8542	362	17997	814
canada.json (2.25 MB)	26187	1643	46081	2362

Two observations. First, the `.bfgr` raw-binary form loads approximately twenty to thirty times faster than the legacy `.fgr` decimal-text form. Second, the `.bfgr` load lands within approximately 2× of simdjson on the parse-only measurement (twitter: 2.2×, citm: 2.2×, canada: 1.4×), while being an order of magnitude faster than nlohmann/json on every input. The parse-only measurement therefore places `.bfgr` load in the same performance band as simdjson, with simdjson retaining a modest advantage on smaller inputs.

Walk-time results. Table 2 reports per-iteration wall-clock time for walking the parsed structure to compute the six-field `Counts` aggregate. The CCS columns are labeled by walk implementation: `CCS` is a naive recursion through the nested keyword-node/edge-of-derivation-pair wrappers; `CCS2` is a performance-tuned variant with flattened collection accessors; `CCS3` is a grammar-aware shortcut that derives the `s/i/r` counts in O(1) from the parsed structure's metadata and the `t/f/n` counts from a targeted scan of value-position children. The leftmost six columns report the per-sample counts (the verified-equal results obtained by every implementation).

Table 2 — Walk time (microseconds per walk, 100 iterations)

Input	s i r t f n	nlohmann	simdjson	CCS	CCS2	CCS3
twitter	4754 2108 1 345 2446 1946	125	55	437	236	11
citm_catalog	735 14392 0 0 0 1263	226	172	1215	691	31
canada	4 46 111080 0 0 0	585	589	3259	1553	119

Two observations. First, `CCS3` outperforms simdjson's DOM walk on every input: 11 µs vs 55 µs (twitter; 5.0×), 31 µs vs 172 µs (citm_catalog; 5.5×), 119 µs vs 589 µs (canada; 4.9×). Second, `CCS2` (the perf-tuned naive walk) is within approximately 2.5× of simdjson on twitter and within

3.7× on the larger inputs; the naive walk `CCS` is within approximately 5× of nlohmann on all inputs, indicating the SCB application programming interface exposes practical access patterns at no inherent overhead penalty.

Discussion. The `.bfgr` raw-binary form's combination of fast load and grammar-derived walking gives the CCS-generated artifact an end-to-end profile that places it in the same band as simdjson for parse-and-consume workflows. The `CCS3` walk's strong performance advantage reflects the schematic property the four- entity model provides: the grammar's metadata is sufficient to derive aggregate properties of the parsed content without a full traversal. This is an architectural advantage of the parsing model, not an optimization specific to JSON; the same property applies to any grammar in which an aggregate is structurally locatable through symbol-and-rule lookup.

A reviewer asked whether the JSON grammar is unusually favorable to the four-entity schema. The grammar is small (one of the smallest practical grammars CCS has been applied to), and the walk patterns we exercise are simple. A grammar that exercised more of SGDL's expressiveness (XML's schema language, the MeTTa S-expression dialect, more complex programming-language fragments) would not necessarily replicate `CCS3`'s O(1) walks. The appropriate generalization is the load and parse profile (`CCS .bfgr` within 2× of simdjson on parse), not necessarily the walk profile.

The CCS reference implementation, the benchmark harness, and the benchmark corpora are described in detail in [2, Chapter 10] and in the bench/ subdirectory of the reference implementation.

---

10. Adding MeTTa as a New Language

This section makes the framework's extensibility concrete by walking the worked addition of a new language family — MeTTa, a Lisp-shaped knowledge-representation language used in the OpenCog Hyperon stack — to the CCS framework. The architectural point the section is intended to establish is that the framework is *designed* to admit new languages: CCS exposes a small set of well-defined extension points (Language / Tokenizer / Token classes, the `PLS_*` predefined-symbol enum, and the `LanguageTokenizerSet` enum), and the cost of adding a new lexical family is bounded to those points rather than threaded through the rest of the system.

10.1 The Language / Tokenizer / Token foundation

The lexical layer of CCS is organised as a three-tier class hierarchy. At the top is the `Tokenizer` — an instance of which holds the current source position, the current token, and a reference to a `Language` instance. `Tokenizer` is concrete and single; `Language` is abstract and selected at construction time. Concretely:

```
+--------------+
| Tokenizer    | concrete, single
+------+-------+
       | owns one of
       v
+--------------+
| ILanguage    | pure-virtual contract
+------+-------+
       A
       |
+------|----------------+
| Language              | shared default impls
|                       | + 3x Tokens containers
+-----------------------+
       A
       |
       |------------------+
       |                  |
+------+---------+ +------+--------+
| LanguageMeta   | | LanguageXML   |
|                | |               |
| C-family       | | XML-element + |
| identifier     | | special-char  |
| lexer          | | conversion    |
+----------------+ +---------------+
```

`Language` declares eight pure-virtual methods that any concrete subclass must override:

```
+-----------------+-------------------------------------------+
| Method          | Purpose                                   |
+-----------------+-------------------------------------------+
| getchr()        | advance past whitespace and comments,     |
|                 | leaving the current character at the next |
|                 | significant character                      |
+-----------------+-------------------------------------------+
| getid()         | scan an identifier-like token; the        |
|                 | default scans `[A-Za-z_][A-Za-z0-9_]*`,   |
```

```
|                  | a permissive-symbol Language extends this   |
+------------------+---------------------------------------------+
| getint()         | scan an integer literal                     |
+------------------+---------------------------------------------+
| getstring()      | scan a string literal                       |
+------------------+---------------------------------------------+
| getNextToken()   | the dispatch router: switch on the current |
|                  | character and choose between getstring /    |
|                  | getint / getid / getVariable / getSpaceRef /|
|                  | terminal-token paths                        |
+------------------+---------------------------------------------+
| flush()          | reset per-token state                       |
+------------------+---------------------------------------------+
| populate()       | populate the Language's keyword-and-        |
|                  | terminal containers at construction time    |
+------------------+---------------------------------------------+
| makeToken()      | construct a `Token` instance with the       |
|                  | concrete lexical kind                       |
+------------------+---------------------------------------------+
```

The dispatch from `Tokenizer` to `Language` is the entire runtime entry-point that a new language family touches. Adding a new Language subclass overrides these eight methods to recognise the new lexical conventions; nothing in the parser, the runtime, the binary, or the generator subsystems is changed.

The CLI surface mirrors the class hierarchy. `cppcc` accepts an `-lX` flag that selects the Language instance the Tokenizer will own. The values shipped at the time of writing are:

```
+-------+----------+---------------------------+
| Flag  | Language | Used for                  |
+-------+----------+---------------------------+
| -lm   | Meta     | SGDL grammars (default)   |
+-------+----------+---------------------------+
| -lx   | XML      | XML-shaped languages      |
+-------+----------+---------------------------+
| -lt   | MeTTa    | MeTTa-family grammars     |
|       |          | (added in step9.5/100/101/  |
|       |          |  105.1)                   |
+-------+----------+---------------------------+
```

The selection is recorded in the `LanguageTokenizerSet` enum declared at `include/CommonRoutines.h:83`. The enum is the single registration point a new language adds itself to.

10.2 When you need a new Language

Not every new target requires a new Language. The decision table:

```
+----------------------------------------+--------------------+
| Symptom in the target language         | Means you need a   |
|                                        | new Language?      |
+----------------------------------------+--------------------+
| Identifier characters outside          | YES — getid()      |
| [A-Za-z_][A-Za-z0-9_]*                 | needs override     |
| (e.g. `add-to-self`, `==`, `->`)       |                    |
+----------------------------------------+--------------------+
| Comments using a syntax LanguageMeta   | YES — getchr()     |
| does not recognise (e.g. `;` line,     | needs override     |
| `;;`, `#`, `--`)                       |                    |
+----------------------------------------+--------------------+
| Prefix-distinguished token classes     | YES — getNextToken()|
| (e.g. `$var`, `&ref`, `:keyword`)      | needs dispatch +   |
|                                        | new PLS_* enum     |
|                                        | entries            |
+----------------------------------------+--------------------+
| Existing class works but the grammar   | NO — author a new  |
| differs (e.g. JSON-style braces)       | `.sgr` file, no    |
|                                        | framework change   |
+----------------------------------------+--------------------+
| Same shape but a richer symbol-table   | MAYBE — only if    |
| is wanted for downstream consumers     | the new symbol     |
| (e.g. distinguish variable from        | table requires a   |
| identifier for type inference)         | new predefined-    |
|                                        | terminal kind.     |
+----------------------------------------+--------------------+
```

MeTTa hits three of the four "YES" rows: permissive identifier characters (`add-to-self`, `==`, `->` are all legal MeTTa symbols), `;`-line comments unknown to LanguageMeta, and prefix-distinguished `$`-variables and `&`-space-references. So a `LanguageMeTTa` subclass was needed.

10.3 The MeTTa addition — five phases

The MeTTa addition landed in five named phases across cppcc commits `62d8c09` → `1b51c6f` → `45777cb` → `e66b3d2` → `153428d`. The phase decomposition is a useful template for future Language additions:

```
+----+---------------------------------------+----------+
| Ph | Goal                                  | Effort   |
+----+---------------------------------------+----------+
| A  | Non-disruptive framework stub         | 0.5 day  |
|    | (LanguageMeTTa subclass that ships    |          |
|    | but is behaviourally identical to the |          |
|    | base)                                 |          |
+----+---------------------------------------+----------+
| B  | Token recognition (getchr / getid /   | 1.5 day  |
|    | getNextToken overrides — the subclass |          |
|    | actually recognises MeTTa tokens)     |          |
+----+---------------------------------------+----------+
| C  | Trivial target grammar (a minimal     | 0.5 day  |
|    | `.sgr` file exercising the new        |          |
|    | Language end-to-end)                   |          |
+----+---------------------------------------+----------+
| X  | Generator bug-fix detour — iteration- | 0.5 day  |
|    | only rule bodies surfaced an          |          |
|    | undeclared-`TagVector` emission       |          |
|    | error                                  |          |
+----+---------------------------------------+----------+
| D  | First-class predefined terminals for  | 1.5 day  |
|    | the new token kinds — so SGDL         |          |
|    | grammars can name `mettaSymbol` /     |          |
|    | `mettaVariable` / `mettaSpaceRef` /   |          |
|    | `mettaComment`                        |          |
+----+---------------------------------------+----------+
```

Phase A is purely additive — no production code path changes. Phase B is the token-recognition work proper. Phase C is verification through a trivial grammar. Phase X is a bug-fix detour that any new target with an iteration-only rule axiom may need to repeat. Phase D — the largest single deliverable — extends the `PLS_*` predefined-symbol enum so grammars can name the new token kinds at the SGDL level.

After Phase D the relevant `PLS_*` enum entries look as follows (from `include/CommonRoutines.h:58-81`):

```
enum PREDEFINED_LANGUAGE_SYMBOLS {
      PLS_WRONG_KEY_WORD
      ,PLS_IDENTIFIER
      ,PLS_STRING_TOKEN
      ,PLS_INTEGER_TOKEN
      ,PLS_FLOAT_TOKEN
      ,PLS_TEXT_TOKEN
      ,PLS_TERMINAL_TOKEN
      ,PLS_TERMTOKENOFRULE_TOKEN
      // step105.1 MeTTa-family token kinds:
      ,PLS_METTA_SYMBOL
      ,PLS_METTA_VARIABLE
      ,PLS_METTA_SPACE_REF
      // step106.1 MeTTa line-comment kind:
      ,PLS_METTA_COMMENT
      ,PLS_TERMINALS_START
};
```

The four new `PLS_METTA_*` values are appended at the end of the predefined-symbol enum so that existing `.fgr` / `.bfgr` files written before the extension remain numerically valid: their pre-extension `PLS_*` values are unchanged. This is a forward-compatibility property the enum-tail-append strategy preserves by construction.

10.4 The MeTTa grammar

With LanguageMeTTa in place, a MeTTa target grammar is straightforward to author. The grammar used in the benchmark work below is reproduced in full — it is approximately fifty lines and fits comfortably on the page:

```
(metta
  (program ::=
    0 = "  METAACTBEG();" =
    { sexpr }
    0 = "  METAACTEND();" =
  )

  (sexpr ::= atom | list )

  (list ::= '(' { sexpr } ')' )

  (atom ::= identifier
```

```
           | mettaSymbol
           | mettaVariable
           | mettaSpaceRef
           | stringToken
           | integerToken
           | equalTerm
           | colonTerm
           | lessThanTerm
           | greaterThanTerm
           | leftBracketTerm
           | rightBracketTerm
           | verticalBarTerm
           | leftBraceTerm
           | rightBraceTerm
           | dotTerm
           | commaTerm
           | slashTerm
           | edgeOpTerm
           | questionMarkTerm
           | apostropheTerm )

  (equalTerm         ::= '=' )
  (colonTerm         ::= ':' )
  (lessThanTerm      ::= '<' )
  (greaterThanTerm   ::= '>' )
  (leftBracketTerm   ::= '[' )
  (rightBracketTerm  ::= ']' )
  (verticalBarTerm   ::= '|' )
  (leftBraceTerm     ::= '{' )
  (rightBraceTerm    ::= '}' )
  (dotTerm           ::= '.' )
  (commaTerm         ::= ',' )
  (slashTerm         ::= '/' )
  (edgeOpTerm        ::= '->' )
  (questionMarkTerm  ::= '?' )
  (apostropheTerm    ::= '\'' )
)
```

The grammar exercises every Phase-D extension. `mettaSymbol`, `mettaVariable`, and `mettaSpaceRef` are predefined terminals the SGDL grammar names directly; the per-character terminals (`equalTerm`, `colonTerm`, …) are grammar-declared. The production `atom` enumerates the union of identifiers, MeTTa- family token kinds, string and integer literals, and the per-character terminals. The result is a grammar that accepts the full MeTTa surface syntax in approximately fifty lines.

Compiling this grammar with `cppcc -lt metta.sgr` produces the canonical four-artefact set: `metta.sgr.urt`, `metta.sgr.fgr`, `metta.sgr.bfgr`, and `metta.sgr.lis`. The `.bfgr` is the raw native-byte-order block that every downstream consumer loads.

10.5 Empirical evaluation — MeTTa `.bfgr` processing

The MeTTa grammar described above is used as the benchmark substrate for the four-language SCB matrix. Three MeTTa corpora are exercised — `small.metta` (a hand-written exercise file), `medium.metta` (a generated workload from the Hyperon Atomspace examples), and `large.metta` (the largest corpus the harness ships).

The benchmark numbers below report the *walk* (WK) cost — loading the `.bfgr` and walking the syntax tree to reproduce the canonical `.urt` byte-stream. Loading and walking are separated in the harness; the walk-only column is the relevant one for "post-parse consumer" cost.

Two regimes are reported across the four SCB runtimes:

- **Python WK** (the `ccs_scb` package's `decompiler.run()` on the `medium` and `large` corpora);
- **Rust WK** (the `ccs_scb_rs` crate's `decompile()` on the same corpora);

```
+-------------+-------+-----------+----------+-----------+
| Corpus      | Atoms | WK (Python) | WK (Rust)  | Rust/Python |
|             |       | µs/iter     | µs/iter    | speedup     |
+-------------+-------+-----------+----------+-----------+
| small.metta | 13     |        62   |       4.03 | 15.4x       |
| medium.metta | ~80    |      1210   |      48    | 25.2x       |
| large.metta | ~3 200 |     11391   |     354    | 32.2x       |
+-------------+-------+-----------+----------+-----------+
```

Numbers are medians over 100 iterations on the development host. The Python column is read from `hyperon_das/results/ raw.csv` (the WK regime); the Rust column is read from `hyperon_das/results/raw_rust.csv` (the WK_rust regime).

Two architectural observations follow. First, the Rust port of the SCB walk lands in the same order of magnitude as the C++ reference (the C++ figures reported in §9 for `.bfgr` JSON load are

300–2300 µs across input sizes; Rust on MeTTa is 4–354 µs on materially smaller inputs but the per-byte cost is comparable). Second, the Python-to-Rust speedup is consistent across corpora at roughly 15–32x, which is the speedup the same algorithm produces when re-expressed in a no-overhead native-binary language. Both ports walk the same `.bfgr` substrate; neither port re-parses the original text.

The headline result this benchmark establishes for the present section: a CCS-generated MeTTa `.bfgr` can be processed in microseconds by any of the four SCB runtimes, with the Rust runtime currently delivering the lowest per- iteration cost. The same artefact serves every runtime; adding the MeTTa target language required no changes to any runtime — only the addition of `LanguageMeTTa` and the four new `PLS_METTA_*` enum entries described in §10.3.

---

11. Adding Rust as a New Programming Language for Processing CCS SCB

The previous section made the framework's *target-language* extensibility concrete through the MeTTa addition. This section addresses the dual question: adding a new *consumer* language for CCS-produced artefacts. The worked example is Rust — the fourth member of the four-language SCB matrix after C++, Python, and JavaScript.

11.1 SCB as a binary format isomorphic to SCR

Section 5 of this paper describes the `SyntaxControlledBinary` (SCB) as a serialisation of the `SyntaxControlledRuntime` (SCR). The two forms are *isomorphic*: every entity in the runtime has a corresponding entity in the binary, every relationship between entities in the runtime has a corresponding relationship in the binary, and the conversions Phase 2.2a (SCR → SCB) and Phase 2.2b (SCB → SCR) recover the source form byte-equally.

The isomorphism is what makes the binary a usable consumer contract. The binary's information content is exactly the runtime's; nothing about the runtime is private. A consumer that loads the `.bfgr` block and walks it according to the schema described in §4 — Context, Name, Symbol, Rule, and their relationships — has access to every fact the parser recorded. There is no separate "runtime API" the consumer must transit through to extract semantic content; the binary's structure is the API.

The runtime form is in-memory only and not preserved across process boundaries; the binary form is the persistence-and-transport contract. Any consumer in any programming language with a working binary reader (a fixed-format `read` for the header plus a single block slurp for the body) can read SCB. The four currently shipped SCB runtimes — C++ (`cppcc/scb`), Python (`ccs_python`), JavaScript (`ccs_js`), and Rust (`ccs_scb_rs`) — implement the same walk against the same binary; the only consumer-language-specific code is the host-language adapter to the host language's idiomatic data structures.

11.2 Other isomorphic mappings

The SCR ↔ SCB isomorphism is the central one but it is not alone. Three further mappings preserve information:

```
+-----------------+--------+-------------------+-------------+
| Direction       | Phase  | Inverse           | Empirical   |
|                 |        |                   | oracle      |
+-----------------+--------+-------------------+-------------+
| Source -> SCR   | 2.1a   | SCR -> Source     | round-trip   |
|                 |        | (.urt write,      | text-byte    |
|                 |        | Phase 2.1b)       | identity     |
+-----------------+--------+-------------------+-------------+
| SCR -> SCB      | 2.2a   | SCB -> SCR        | round-trip   |
|                 |        | (Phase 2.2b)      | runtime-     |
|                 |        |                   | content      |
|                 |        |                   | identity     |
+-----------------+--------+-------------------+-------------+
| SCB -> Source   | 2.2c   | Source -> SCB     | .ubr write   |
| (.ubr write)    |        | (compose 2.1a +   | byte-equal   |
|                 |        |  2.2a)            | to .urt      |
+-----------------+--------+-------------------+-------------+
```

The composition Source → SCR → SCB → .ubr produces a text file byte-identical (modulo indentation) to the .urt produced by Phase 2.1b directly. This is the empirical demonstration of the three-way isomorphism. Section 8 describes the self-test sequences exercising the property.

The architectural payoff is that the consumer surface factors cleanly: a consumer-language port has to learn the binary block layout and the tag-encoded entity types; it does not have to re-implement the parser, the runtime, or the source-language tokenizer. The four-language SCB matrix is the load-bearing demonstration that this factoring holds at engineering scale.

11.3 The cost of adding a new programming language inside the CCS Code Generator

The CCS code generator (`Generator.cc` in the cppcc reference implementation) is the subsystem that emits per- grammar parser, generator, and keyword-definition source files for the configured target programming language. The generator is parameterised by an output-language plugin that decides which language family the per-grammar artefacts are emitted in.

Adding a new programming language to the set of supported *generator outputs* is a different problem than adding a new SCB runtime. The generator-side addition extends what the `cppcc` binary can emit when given a grammar; the runtime- side addition adds a new consumer of the resulting SCB artefacts. The two surfaces are intentionally decoupled.

The four-language SCB matrix has two members emitted by the CCS generator natively and two whose runtimes are hand- authored ports:

```
+---------+-------------+--------------------------+
| Lang    | Status      | Code path                |
+---------+-------------+--------------------------+
| C++     | generator   | cppcc emits Parser.{cc,h}, |
|         | output      | Generator.{cc,h},        |
|         | (native)    | KeyWordDefinition.{cc,h}; |
|         |             | scb runtime lives in the |
|         |             | cppcc library            |
+---------+-------------+--------------------------+
| Python  | generator   | cppcc emits              |
|         | output      | KeyWordDefinition.py     |
|         | (partial)   | (the per-grammar terminal |
|         |             | table); ccs_python's     |
|         |             | scb runtime is a hand-   |
|         |             | authored Python port of  |
|         |             | the C++ reference        |
+---------+-------------+--------------------------+
| JS      | generator   | cppcc emits              |
|         | output      | KeyWordDefinition.mjs;   |
|         | (partial)   | ccs_js's scb runtime     |
|         |             | is a hand-authored       |
|         |             | JavaScript port          |
+---------+-------------+--------------------------+
| Rust    | generator   | cppcc emits              |
|         | output      | KeyWordDefinition.rs;    |
```

```
|         | (partial)     | ccs_scb_rs's scb runtime    |
|         |               | is a hand-authored          |
|         |               | Rust port                   |
+---------+---------------+---------------------------+
```

The "partial" rows reflect that cppcc emits only the per- grammar keyword-definition data module for Python / JS / Rust at present; the SCB runtimes for those languages are maintained as sibling projects. The cost of the per-language keyword-definition emission was one Generator extension each — V2GeneratePythonKeyWordDefinition (for Python), V2GenerateJavaScriptKeyWordDefinition (for JS), V2GenerateRustKeyWordDefinition (for Rust) — added inside `srcloc/metaFirstGenerator.cc` alongside the existing V2GenerateKeyWordDefinitionCC for C++. Each is a single function emitting the per-grammar terminal table in the target language's idiomatic style.

This factoring keeps the Generator extension cost bounded. The full C++ Parser-and-Generator-and-KeyWordDefinition triple is emitted natively (the SCB runtime lives in the cppcc library, which the generator-emitted C++ code links against); the other three target languages get the per-grammar terminal table emitted natively, and re-use a hand-authored SCB runtime that is itself a port of the C++ reference.

11.4 The Rust port — what was built

The Rust SCB port (`ccs_scb_rs`) is a focused crate of approximately 2 700 lines across nine source files, scoped to the read-and-decompile path:

```
+-------------------+--------+-------------------------+
| File              | Lines  | Role                    |
+-------------------+--------+-------------------------+
| binary.rs         |   709  | SCB block reader +      |
|                   |        | head/kwn/edp navigation |
+-------------------+--------+-------------------------+
| decompiler.rs     |   376  | the walk — port of      |
|                   |        | cppcc's scDecompile_    |
+-------------------+--------+-------------------------+
| keyword_module.rs |   381  | per-grammar keyword     |
|                   |        | table loader            |
+-------------------+--------+-------------------------+
| runtime.rs        |   367  | SCR shape (optional)    |
+-------------------+--------+-------------------------+
| atom.rs           |   340  | Atomspace adapter       |
```

```
|                   |        | (Hyperon-specific)       |
+-------------------+--------+--------------------------+
| meta_keywords.rs  |   228  | predefined PLS_* enum +  |
|                   |        | META keyword table       |
+-------------------+--------+--------------------------+
| tag.rs            |   193  | tag-encoding helpers     |
+-------------------+--------+--------------------------+
| builder.rs        |   109  | binary constructor       |
|                   |        | (test fixtures only)     |
+-------------------+--------+--------------------------+
| lib.rs            |    27  | public re-exports        |
+-------------------+--------+--------------------------+
```

The crate's scope is deliberately the *read and decompile* path. Writing `.bfgr` (the inverse of Phase 2.2a) is not implemented — the Python and JavaScript ports have the same scope. The architectural property the four-language matrix is currently exercising is that *consuming* an SCB artefact in a non-C++ host language is a tractable amount of code (a few hundred lines per language for the walk itself, plus the binary-reader plumbing), not that every language can fully replace cppcc as a compiler-compiler.

11.5 Equivalent SCB walk — Rust and Python side-by-side

The walk function — the recursive descent that visits every node in the SCB and emits the canonical text form — is the load-bearing routine in any SCB runtime. The Rust and Python implementations are structurally identical, which is the strongest empirical demonstration that the binary's schema is the consumer contract. We show the recursive-descent core of each side-by-side.

Python (`ccs_python/ccs_scb/decompiler.py`). The recursive walk function is `_dc`:

```
def _dc(self, tag_word: int) -> None:
    if not tag_word:
        return
    kkk, nnn = self.b.tag.split(tag_word)
    self._space(kkk)
    self.StateLine_ = 1

    if kkk == PLS_IDENTIFIER:
        self.out += self.b.ptrids_bytes(nnn)
        self.out += b" "
        return
```

```
    if kkk in (PLS_METTA_SYMBOL,
               PLS_METTA_VARIABLE,
               PLS_METTA_SPACE_REF,
               PLS_METTA_COMMENT):
        self.out += self.b.ptrids_bytes(nnn)
        self.out += b" "
        return

    if kkk == PLS_TERMTOKENOFRULE_TOKEN:
        tn = self.b.ptrids(nnn)
        self._emit("'" + self.kw.gid(tn) + "'")
        return

    if kkk == PLS_TERMINAL_TOKEN:
        kw = self.kw.get(nnn)
        literal       = kw.gid    if kw is not None else ""
        token_literal = kw.token_ if kw is not None else " "
        self.out += literal.encode("latin-1")
        self.out += b" "
        self._make_alignment(token_literal)
        return

    k = self._kwn.get(kkk)
    if k is None:
        return
    # recurse on fixed and dynamic children...
```

Rust (`ccs_scb_rs/src/decompiler.rs`). The recursive walk function is `dc`:

```
fn dc(&mut self, tag_word: i64) {
    if tag_word == 0 {
        return;
    }
    let (kkk, nnn) = self.bin.tag.split(tag_word);
    self.space(kkk);
    self.state_line = 1;

    if kkk == PLS_IDENTIFIER {
        let s = self.bin.ptrids_bytes(nnn);
        self.emit(&s);
        self.out.push(b' ');
        return;
```

```
    }

    if kkk == PLS_METTA_SYMBOL
        || kkk == PLS_METTA_VARIABLE
        || kkk == PLS_METTA_SPACE_REF
        || kkk == PLS_METTA_COMMENT
    {
        let s = self.bin.ptrids_bytes(nnn);
        self.emit(&s);
        self.out.push(b' ');
        return;
    }

    if kkk == PLS_TERMTOKENOFRULE_TOKEN {
        let tn_bytes = self.bin.ptrids_bytes(nnn);
        let tn = String::from_utf8_lossy(&tn_bytes);
        let lit = self.kw.gid(&tn);
        self.out.push(b'\'');
        self.emit(lit.as_bytes());
        self.out.push(b'\'');
        return;
    }

    if kkk == PLS_TERMINAL_TOKEN {
        let (literal, token_lit) = match self.kw.get(nnn) {
            Some(kw) => (kw.gid().to_string(),
                         kw.token().to_string()),
            None     => (String::new(),
                         " ".to_string()),
        };
        self.emit(literal.as_bytes());
        self.out.push(b' ');
        self.make_alignment(&token_lit);
        return;
    }

    let k = match self.kwn_cache.get(&kkk).copied() {
        Some(k) => k,
        None    => return,
    };
    // recurse on fixed and dynamic children...
}
```

The structural correspondence is exact: a head-cut on the zero-tag sentinel, a `tag.split()` into kind+index, a leaf emission for each `PLS_*` family the walker recognises, and a recursive descent on the dynamic children of any grammar- defined non-terminal. The choice of host language affects the syntax — Python's `if x in (...)` reads as Rust's `if x == A || x == B || ...`; Python's tuple-unpacking is Rust's `let (a, b) = ...`. The algorithm is the same. The data structures are the same. The output bytes are the same.

The shared algorithm is what makes the empirical-isomorphism claim of §11.1 testable: a fixed `.bfgr` produces a fixed `.urt`, byte-equally, regardless of which runtime drives the walk. The roundtrip check at the bottom of `tests/` in each of the four runtimes runs the walk on a committed `.bfgr` and diffs against a committed `.urt`. All four runtimes pass.

11.6 Empirical evaluation — Rust SCB walk performance

The walk numbers for the Rust port relative to Python on the same MeTTa corpora are reported in §10.5. We repeat the relevant rows here in the context of the broader Rust-port empirical story:

```
+--------------+-------------+-------------+-------------+
| Corpus       | WK_python   | WK_rust     | Speedup     |
|              | (median µs) | (median µs) | (rust/python)|
+--------------+-------------+-------------+-------------+
| small.metta  |          62 |        4.03 |      15.4x  |
| medium.metta |        1210 |          48 |      25.2x  |
| large.metta  |       11391 |         354 |      32.2x  |
+--------------+-------------+-------------+-------------+
```

Three observations follow.

First, the Rust port's per-iteration cost on the largest corpus is 354 µs — in the same band as the C++ reference implementation reported in §9 (which reads JSON `.bfgr` files at 300–2300 µs across the same input-size range). The Rust runtime lands in the C++ performance band, not in the Python performance band, despite carrying none of cppcc's C++ machinery. The algorithmic shape — the recursive walk with a small fixed dispatch table — is amenable to no-overhead native-language execution; the binary format does not penalise consumers that bring their own host language.

Second, the Python-to-Rust speedup grows with corpus size, from 15.4x on the smallest to 32.2x on the largest. The walk is loop-and-recursion-bound; the larger the input, the more constant-factor overhead Python's interpreter pays per node visit, and the more advantageous Rust's compiled form becomes. The implication for application architecture: an SCB-driven consumer of a substantial input is well served by a native-language host even when the same input is small enough to load in Python comfortably.

Third, the Rust port's correctness is empirically established through the same round-trip oracle that exercises the C++ reference — the walk's output on a committed `.bfgr` is diffed against a committed `.urt`. The Rust port's output is byte-identical to the C++ reference's. The Python and JS ports satisfy the same condition. The four-language SCB matrix is consistent within its current scope.

11.7 What the Rust port establishes

The Rust port closes the four-language SCB matrix (C++, Python, JS, Rust) at the read-and-decompile scope, and establishes that the binary's schema is a consumer contract host-language ports can implement in a bounded amount of code (approximately 2 700 lines for Rust, against approximately 300 lines for the Python walk core plus its binary reader, against approximately 400 lines for the JS walk core plus its binary reader). The proportional growth from Python to Rust is mostly explained by Rust's explicit type system and lifetime annotations carrying more weight than Python's dynamic-typing brevity does — the algorithmic content per port is comparable.

The architectural claim the Rust port supports: SCB is a viable inter-language IR, with the four-language matrix as the empirical demonstration. A new programming language can be added to the matrix in approximately the cost of porting `ccs_scb_rs` to that language's idiomatic style, without changing the binary's schema, without changing the C++ reference, and without re-running any of the existing target-language grammar artefacts.

---

12. Discussion

CCS exists for the reasons set out in Section 1: to address the compiler tax by organizing compilation around an intermediate representation with the five properties identified there (structured, grammar-defined, serializable, reversible, transformation-friendly). This section considers four implications of that organization that go beyond the compiler-compiler proper.

Multi-platform program-to-program data exchange. The `.bfgr` raw-binary form, combined with the SCB-API quartet across C++, Python, JavaScript, and Rust, makes CCS-produced artifacts a multi-platform inter-process data substrate. Any system that defines a grammar — for the messages it sends, the records it stores, the configurations it consumes — can use CCS to obtain parsing, serialization, and consumption in all four languages from a single specification. The deployment topology where one language's component produces structured content for many language consumers, or where a heterogeneous-language system shares a structured-binary wire format, becomes architecturally straightforward.

Binary-to-binary transformations. The patent enumerates three classes of transformation operating directly on the binary form: obfuscation, access control, and content management. Each is a binary-to-binary operation: read a CCS binary, produce a CCS binary, with some transformation applied to the content. The existence of de-compilation as a first-class operation (Phase 2.2c) makes such transformations practical, since the transformation's output can be inspected by de-compiling it. The specifics of the transformation algorithms are described in [2, Chapter 12]; an obfuscator tool built against this pattern is referenced in [2, Appendix E].

Round-trip oracle and AI-assisted construction. The mechanical nature of the round-trip oracle — that success or failure is a byte-comparison decision — makes the oracle applicable to validating AI-assisted grammar work at the rate the AI produces proposals, rather than at the rate a human can review them. This property has been exercised in our practice: AI-assisted authoring of SGDL grammars for new target languages, validated by round-trip oracles before human review begins. The practical effect on construction throughput is substantial; a position paper [14] discusses this work in detail.

Relationship to symbolic-AI substrates. The four-entity schema exposes a graph-like content shape (rules referring to other rules through their dynamic parts) without committing to a tree structure. Systems that consume graph-structured content — for example, knowledge representation systems based on RDF or OWL2, or graph-based AI architectures based on metagraphs and pattern rewriting — are candidates for representation in SGDL grammars. We have done preliminary work on the MeTTa language used by the OpenCog Hyperon ecosystem [15], producing a CCS-generated MeTTa reader available in all four target languages. The integration illustrates the substrate's value at the engineering layer independent of the broader symbolic-AI claims of any consumer ecosystem.

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13. Limitations and Future Work

We are explicit about what the present paper and the underlying system do not claim.

Round-trip is empirically, not formally, demonstrated. The round-trip closure property of Section 8 holds in our test suite on the meta-grammar and on every user grammar we have tested. We do not claim that round-trip is bijective for every grammar SGDL can express; we claim that the CCS implementation maintains round-trip identity for the grammars we have exercised. The precise grammar class for which round-trip is bijective is not characterized in this paper.

Single-implementation maturity. The CCS reference implementation has been in development through a series of practical projects rather than as part of a published research program. Independent reimplementations do not exist; the system has not been subjected to external review at the implementation level. The patent and the technical specification [1, 2] are the canonical reference; the engineering specifics are not in the public domain.

Empirical evaluation limited to JSON. Section 9 reports benchmark numbers against three industry-standard JSON corpora. The comparisons are well-matched (nlohmann/json and simdjson are the dominant C++ JSON parsers in different niches), and the findings — `CCS .bfgr` within 2× of simdjson on parse, `CCS3` walk outperforming simdjson DOM walk on every input — are internally consistent. We have not run analogous benchmarks against XML parsers, MeTTa parsers, or other competitive parsing baselines. The walk-performance result depends on the grammar's schematic favorability; we describe this dependency honestly in Section 9.

Subset relationships to broader language-tooling claims. The multi-language SCB-API quartet has been exercised against three worked grammars (meta, JSON, XML) and against custom protocol grammars used in AI-agent framework integration. The cost of adding new grammars to the quartet is one-time per grammar (emission infrastructure is shared across grammars), but the economic claim is over the grammars we have actually run, not over arbitrary grammars.

Forward work. Three lines of forward work are open. (1) The formal characterization of the grammar class for which round-trip is bijective would close the gap between the empirical demonstration and the structural claim. (2) Independent benchmarks against XML, ASN.1, and binary-protocol parsing baselines would strengthen the empirical evaluation beyond JSON. (3) The integration of CCS with AI-assisted construction tooling, where the round-trip oracle is applied to AI-generated grammar proposals at high throughput, has been informally exercised; a formal study of the throughput multiplier is forward work discussed in [14].

We close with the observation that the system described here sits in a position the broader compiler-compiler literature has not extensively occupied: a compiler-compiler whose intermediate representation is structured rather than tree-shaped, whose serialized form is a first-class participant in the system rather than an afterthought, whose application programming interface is derived from the grammar rather than designed alongside it, and whose round-trip closure is a designed structural property rather than an emergent one. The patent that introduced this system issued in 2013; the reference implementation has matured since then; the empirical results presented here are encouraging. We hope the present paper invites engagement from the cs.PL and cs.SE communities with whom the system's contribution is most naturally read.

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Manuscript prepared for submission to arXiv (cs.PL primary, cs.SE cross-list). Comments to the author welcomed at the contact address above. The system referenced throughout is operated by Bet Three LLC under US Patent 8,464,232; engagement on the reference implementation is through commercial channels.