**langcc**: A Next-Generation Compiler Compiler

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**Abstract**

Traditionally, parsing has been a laborious and error-prone component of compiler development, and most parsers for full industrial programming languages are still written by hand. The author [Zim22] shows that automatic parser generation can be practical, via a number of new innovations upon the standard LR paradigm of Knuth et al. With this methodology, we can automatically generate efficient parsers for virtually all languages that are intuitively “easy to parse”. This includes Golang 1.17.8 and Python 3.9.12, for which our generated parsers are, respectively, 1.2x and 4.3x faster than the standard parsers. This document is a companion technical report which describes the software implementation of that work, which is available open-source at [https://github.com/jzimmerman/langcc](https://github.com/jzimmerman/langcc).

1 Introduction

**langcc** can be used as a replacement for the combination of **lex** and **yacc** (or **flex** and **bison**). However, **langcc** provides many additional features, including:

- Automatic generation of AST data structures, via a standalone datatype compiler (**datacc**).
- Full LR parser generation as the default, rather than the more restrictive LALR.
- Clear presentation of LR conflicts via explicit “confusing input pairs”, rather than opaque shift/reduce errors.
- Novel efficiency optimizations for LR automata.
- An extension of the LR paradigm to include recursive-descent (RD) parsing actions, resulting in significantly smaller and more intuitive automata.
- An extension of the LR paradigm to include per-symbol attributes, which are vital for the efficient implementation of many industrial language constructs.
- A general transformation for LR grammars (CPS), which significantly expands the class of grammars the tool can support.

Unlike previous compiler compilers, **langcc** is efficient and general enough to capture full industrial programming languages, including Python 3.9.12 (**grammars/py.lang**) and Golang 1.17.8 (**grammars/go.lang**). In both cases, **langcc** automatically generates a parser that is faster than the standard library parser for each language (resp., 1.2x and 4.3x faster). In fact, the class of grammars supported by **langcc** is general enough that the tool is self-hosting: that is, one can express the “language of languages” in the “language of languages” itself, and use **langcc** to generate its own compiler front-end. We do this in the canonical implementation; see the files **bootstrap.sh** and **grammars/meta.lang** in the source repository for more details.
2 Usage

2.1 langcc

langcc is a standalone command-line tool, which can be invoked as follows:

```
langcc X.lang gen_path
```

to compile a BNF-style language specification (X.lang) to a generated compiler front-end for that language (gen_path/X_gen.hpp, gen_path/X_gen.cpp). The tool automatically generates data structures for the abstract syntax (AST), a lexer, a parser, and a pretty-printer for terms in the language. In order to use the generated code, simply include the file gen_path/X_gen.hpp and compile and link against the file gen_path/X_gen.cpp.

2.2 datacc

datacc is an internal component which langcc uses to generate many of its data structures, but which can also be used as a standalone command-line tool. It can be invoked as follows:

```
datacc X.data gen_path
```

to compile a declarative specification of some algebraic datatypes (X.data) to generated C++ code that implements those datatypes (gen_path/X_data_gen.hpp, gen_path/X_data_gen.cpp).
datacc supports named product and sum types (with enums as a special case), as well as datatypes with type parameters. The generated code includes the (reference-counted) C++ implementations of the corresponding algebraic datatypes as structs with inheritance, as well as a number of other features: e.g., functions for testing and downcasting sum types, functions for substituting fields of product types, functions for debug-printing elements of each datatype, and functions for cached value-based SHA-256 hashing of elements of each datatype.

3 Input language

The input to langcc is a file X.lang, written in the “language of languages” (grammars/meta.lang). Such an input consists of the following stanzas:

- **tokens**: Describes the basic tokens that are to be emitted by the lexer. A token description is either an opaque declaration X <- e or an alias declaration X <= e, where e in either case is (roughly) a regular expression. For instance, one can write:

  ```
  int_lit <- '0' | ('1'..'9') digit*;
  digit <= '0'..'9';
  op <= '+' | '-' | '*' | '/';
  ```

  Backtick-quoted strings are used to represent literal sequences of characters that appear in the tokens. Expressions can be parenthesized, and many standard regex operators (e.g., concatenation, alternation, repetition, parenthesization, character ranges) are permitted. Standard escapes such as \n and \" are valid within backtick-quoted strings, and the backtick itself can be escaped via \'; however, single and double quotes do not need to be escaped.

  Note that in the example above, digit is an alias, and thus can be used in the definition of int_lit. However, int_lit, as an opaque declaration, cannot be used in the definition of other items in the lexer—as opposed to the parser, which does permit recursive structure.
The other key difference between alias and opaque token declarations is that opaque tokens will be emitted as such by the lexer, and can appear directly in parser expressions (e.g., `Expr.Int <- n:int_lit`); while if aliased tokens are emitted by the lexer, then the item that is actually emitted is the underlying opaque token expression (e.g., in the parser, below, we could write `Expr.Add <- x:Expr '+' y:Expr`, but we could not write `Expr.Binop <- x:Expr op y:Expr`, as `op` is not an opaque token emitted by the lexer).

- **lexer:** Describes the procedural operation of the lexer as it processes an input string to emit tokens. The lexer stanza consists of one or more lexer modes, as well as a main mode declaration. For instance, the following is a lexer stanza:

```plaintext
lexer {
  main { body }

  mode body {
    top => { emit; }
    ws_inline => { pass; }
    '\n' => { pass; }
    '//=' => { push comment_single; pass; }
    eof => { pop; }
  }

  mode comment_single {
    '\n' => { pop_extract; }
    eof => { pop_extract; }
    _ => { pass; }
  }
}
```

Here, the tokens `'eof'` and `\n` are built-in; the underscore `_` is a wildcard matching an arbitrary unicode code point; and we assume that the aliases `top`, `ws_inline` have been defined in the tokens section. The main mode is the one called `body`, and in this mode:

- If the lexer encounters a toplevel token (i.e., a character sequence matching one of the opaque constituents of the alias `top`), then it will emit that constituent, and proceed.
- If the lexer encounters inline whitespace, then it will pass over it and proceed.
- If the lexer encounters the newline character, then it will pass over it and proceed.
- If the lexer encounters the comment start sequence `//`, then it will push the mode `comment_single` onto its mode stack, pass over the `//`, and continue processing in the new mode. Note that the ordering of the two commands is significant. The second command, `pass`, means that the matched string `//` will be processed after the lexer is already in the new mode `comment_single`.
- If the lexer encounters the end-of-file marker (`eof`), then it will pop the main mode off the stack. Note that if at any point, the mode stack is empty, then the lexer halts; and it declares success if and only if this happens at the end of the input—if the mode stack is empty prematurely, this is a failure. Conversely, if the mode stack is nonempty at end-of-file, this is also a lexing failure.

while, in the mode `comment_single`:

- If the lexer encounters either a newline or the end-of-file marker, it will extract all of the characters that have been processed in the current mode (including those that have
been passed over), attach the result as extra data (not part of the AST), and pop the current mode off of the mode stack.

- If the lexer encounters any other character, it will pass over it, and proceed.

Note that there are two possible types of pop commands:

- pop_extract, which is used above. This will extract the characters processed in the current mode, and attach the result as extra data (not part of the AST).

- pop_emit tok, where tok names an opaque token. This will extract the characters processed in the current mode, and emit an instance of the token tok (to be consumed by the parser), where the included string contents of tok are the extracted characters.

The generated lexer is implemented via the standard NFA/DFA subset construction, and it will accept the longest matching substring starting at the current point in the input (in other words, it will only consider performing an action if the subsequent character would lead to a DFA state with no action). By construction of the DFA, the action of a compiled lexer is always uniquely determined. While some lexer/token definitions may lead to ambiguity, this can be detected statically in the subset construction, and this will generate an error during langcc’s compilation of X.lang rather than producing an ambiguity at lexing time.

- parser: Describes the context-free grammar which should be used by the generated parser, defined in terms of the basic lexer tokens. For instance, the following is a parser stanza:

```plaintext
parser {
  main { Stmt, Expr }

  prec {
    Expr.BinOp1 assoc_left;
    Expr.BinOp2 assoc_left;
    Expr.UnaryPre prefix;
    Expr.BinOp3 assoc_left;
    Expr.Id Expr.Lit.Int Expr.Paren;
  }

  prop { name_strict; }

  Stmt.Assign <- x:Expr[I] _ '=' _ y:Expr;
  Stmt.Expr <- x:Expr;

  Expr.Id[I] <- name:id;
  Expr.Lit.Int_ <- val:int_lit;
  Expr.UnaryPre <- op:#Alt[Neg:'-'] x:Expr;
  Expr.BinOp1 <- x:Expr _ op:(Add:'+' | Sub:'-') _ y:Expr;
  Expr.BinOp2 <- x:Expr _ op:(Mul:'*' | Div:'/') _ y:Expr;
  Expr.BinOp3 <- x:Expr op:#Alt[Pow:'^'] y:Expr;
  Expr.Paren <- '(', x:Expr[pr=*] ')';
}
```

In addition to supplementary directives (e.g., `main`, `prec`, `prop`), the parser stanza consists of a series of declarative, BNF-style rules of the form `X <- e`, where `X` is the name of the rule
(possibly consisting of multiple components, with dots), and e is the definition of the rule. Note that rules of the form X.A, X.B, and X.C.D all indicate the same nonterminal X for the left-hand side of the resulting context-free grammar rules, but in the generated ASTs, X::A, X::B, and X::C::D will be subclasses of the sum type X.

We mention a number of additional features of the parser stanza:

- The main sub-stanza indicates a set of nonterminals that can be parsed at the top level, i.e., for which we can call parse in the generated API. Of these, the first one listed is the default if no nonterminal is specified at parsing time.

- The prec sub-stanza indicates a series of precedence levels for the rules. The details of precedence are detailed more fully in the original report [Zim22, Sections 1.4, 3.5]. Note that unlike tools such as yacc, our precedence spec operates at the level of rules, rather than at the level of operators. Concretely, it is implemented in terms of attribute constraints [Zim22, Section 3.5]. We also note that the subexpression Expr[pr=*] in the Expr.Paren rule indicates an expression of arbitrary precedence, overriding what would otherwise be a highest-precedence constraint.

- The prop sub-stanza determines the configuration of langcc when processing the language definition. In particular, prop { name_strict; } indicates that every subexpression that corresponds to a field or a sum case in the AST must have a name (e.g., in ‘x:Expr’, ‘x’ is the name). Without the name_strict annotation, fields may be unnamed, which will cause langcc to automatically generate names in the resulting AST—this is still valid, but makes it more difficult to write code against the generated API.

- The annotation [I] on Expr.Id[I] and x:Expr[I] indicates a boolean-valued attribute named I [Zim22, Sections 1.4, 3.5]. Specifically, this means that only Expr instances arising from the Expr.Id rule will have the attribute I, and conversely, in the Stmt.Assign rule, only Expr nonterminals which bear this attribute are valid at the indicated point in the right-hand side. Attributes can also be constrained via a standalone attr sub-stanza, similar to the prec sub-stanza (see grammars/go.lang in the source repository for examples). When attributes are specified inline, however (as in the example above), we adopt the general convention that an attribute mentioned in the right-hand side of a rule is a requirement, and an attribute mentioned in the left-hand side is a declaration that the attribute is satisfied. Further details can be found in [Zim22, Section 3.5].

- Many other features are available in parser BNF expressions, e.g.:
  * A literal string may be passed over in the parser, written @('contents'). At parse time, this subexpression is ignored, but at pretty-print time, the contents of the string are inserted. This is often used for formatting strings such as @(' ') (a space) or @('\n') (a newline); in fact, the former is so common that we have the special notation _ (as used in the example above) to denote @(' ').
  * The special expression eps may be used to denote the empty concatenation.
  * The special expression #Alt(e) may be used to denote the singleton alternation. To the parser, this is equivalent to the expression e, but it may be important semantically for the generated AST.
  * The expression e* may be used to denote a repeated expression e. In the generated AST, this automatically produces a vector.
  * The expression e+ may be used to denote a nonzero-repeated expression e. In the generated AST, this automatically produces a vector.
  * The expression #L[e::delim] may be used to denote a list of e, delimited by delim.
In the generated AST, this automatically produces a vector. In addition, there are several variants of the list expression:

- \(#L[e::delim:]\), a list with a trailing delimiter.
- \(#L[e::delim:?]\), a list with an optional trailing delimiter.
- \(#L[e::+delim]\), a list with at least one element.
- \(#L[e::++delim]\), a list with at least two elements.
- \(#B[e::delim]\), a list which renders as an indented block in the pretty-printer.
- \(#B2[e::delim]\), a list which renders as an indented double-spaced block in the pretty-printer.
- \(#T[e::delim]\), a list which renders as a top-level block in the pretty-printer.
- \(#T2[e::delim]\), a list which renders as a top-level double-spaced block in the pretty-printer.

\* The expression \(e?\) may be used to denote an optional expression \(e\); in the generated AST, this automatically produces an option type or a boolean, as appropriate.

\* The expression \(\sim X\) may be used to indicate that the nonterminal \(X\) should be unfolded, i.e., that its beginning does not need to be predicted in recursive-descent style. If all nonterminals in the right-hand side are unfolded, this results in LR-style parsing (shift/reduce); if no nonterminals are unfolded, it results in RD-style parsing (shift/reduce/recur/ret). For further details, see [Zim22, Section 3.6].

- **compile_test** (optional): Describes a series of compilation tests to be performed when **langcc** compiles the language. Compilation tests are of the form LR\((k)\) (resp., \(!LR(k)\)), where \(k\) is a nonnegative integer, indicating that LR compilation should succeed (resp., fail due to conflicts) for the given value of \(k\).

- **test** (optional): Describes a series of parsing tests to be performed when **langcc** compiles the language. Parsing tests are of the form ‘abc’; (resp., ‘abc##def;’), indicating that parsing should succeed (resp., fail at the position indicated by ##) on the given string. In addition, by default, parsing tests will verify that the pretty-printer outputs the same string as was parsed. If this is not desired for a given example, one may append the special marker <<>>, as in ‘contents’ <<>>;.

### 4 Conflict tracing

The underlying parsing theory [Zim22] indicates that if **langcc** successfully compiles a language, then the behavior of the parser is fully determined—though it may produce a parse error on strings that are not in the language, it will not fail by virtue of ambiguity. However, not all grammars reach this point; some have LR conflicts, which **langcc** will report if it fails to compile a language for this reason. When reporting LR conflicts, **langcc** endeavors to produce an exemplar, a short “confusing input pair”, that explains the conflict in a way that is much more intuitive than the opaque shift/reduce errors produced by tools such as yacc. Further details of the conflict tracing procedure are described in [Zim22, Section 3.4]; here we only provide a basic example. The following is a conflict that arises if we attempt to run **langcc** on a simple arithmetic expression language, without using the appropriate precedence declarations.
On the left side, we see the expression that produced the conflicting prefix (Expr X0 Expr), and on the right side, a concrete input that might correspond to this expression (id ‘+’ id). Below this are the two conflicting actions, (1) Reduce by the indicated production Expr → Expr X0 Expr and (2) Shift the next token. Finally, there is a completion of the “confusing input pair”, showing that either action is possible with the given $k = 1$ lookahead (‘+’). In this example, the language is actually ambiguous; one cannot decide whether to parse id+id+id as (id+id)+id or as id+(id+id). However, a language need not be ambiguous in order to present LR conflicts—in general, all that is required is that the parser is unable to determine what LR action to take with $k$ tokens of lookahead.

5 Output API

When a language $\mathsf{X.lang}$ is successfully compiled, $\mathsf{langcc}$ outputs files $\mathsf{gen.path/\mathsf{X}_gen.hpp}$ and $\mathsf{gen.path/\mathsf{X}_gen.cpp}$, which contain the AST definitions, lexer, parser, and pretty-printer, as well as miscellaneous utilities such as debug-printers and hashing functions. The following is a basic example of how to use the generated API (from examples/calc):

```cpp
auto L = lang::calc::init();
auto Q = L->quote_env();
unordered_map<string, Int> env;
string l;
while (true) {
    getline(cin, l);
    if (!cin.good()) {
        return 0;
    }

    auto gen = make_rc<Gensym>();
    auto parse = L->parse_ext(
        vec_from_std_string(l), None<string>(), gen, nullptr);
    if (!parse->is_success()) {
        LG_ERR("\nParse error: {}", parse->err_.as_some());
        continue;
    }
```

7
auto stmt = parse->res_.as_some()->as_Stmt();
try {
    fmt(cerr, "{}
    , stmt_eval(stmt, env));
} catch (const CalcError& err) {
    LG_ERR("\nError: {}
    , err.desc_,
    , parse->lex->location_fmt_str(err.e_blame_->bounds_));
    continue;
}

Note that the generated parsing procedure returns a structure parse, and if !parse->is_success(), then parse->err contains the parse error; when formatted, it can be printed in user-readable form, resulting in a message like the following:

Parse error: Unexpected token: '/'
Line 1, column 10:

7 + (5 + / 3)
^

If, on the other hand, parsing succeeds, then the resulting AST element is given by parse->res_. By default, it is a generic lang::calc::Node_T (a sum type), but in this case, the toplevel parse is known to be a Stmt, and we downcast it with as_Stmt(), then call our function stmt_eval, which in turn calls expr_eval on constituent expressions. The following is excerpted from expr_eval:

    Int expr_eval(Expr_T e, const unordered_map<string, Int>& env) {
        if (e->is_Lit()) {
            auto val_str = e->as_Lit()->as_Int_()->val_.to_std_string();
            return string_to_int(val_str).as_some();
        } else if (e->is_BinOp2()) {
            auto cc = e->as_BinOp2();
            auto xr = expr_eval(cc->x_, env);
            auto yr = expr_eval(cc->y_, env);
            if (cc->op_->is_Mul()) {
                return xr * yr;
            } else if (cc->op_->is_Div()) {
                if (yr == 0) {
                    throw CalcError(fmt_str("Division by zero"), cc->op_);
                }
                return xr / yr;
            } else {
                AX();
                // ...
            }
        } else {
            // ...
        }

As this example shows, it is straightforward to decompose the AST sum types to obtain the values enclosed. We mention one additional feature: note that in the case of division by zero, we throw
an error that includes the syntax element $cc->op$. In fact, this syntax element carries with it its position in the input, which enables us to produce, at top level, error messages of the following form:

```
Error: Division by zero
Line 1, column 3:
4 / (3 - (15 / 5))
```

indicating precisely which division triggered the error. Evidently, this functionality easily generalizes to source-position error reporting in more complex languages.

## 6 Bootstrapping

We finally mention one additional property of langcc: the class of grammars is general enough that the tool is self-hosting—that is, one can express the “language of languages” in the “language of languages” itself, and use langcc to generate its own compiler front-end. In fact, we do this in the canonical implementation; see the files `bootstrap.sh` and `grammars/meta.lang` in the source repository for more details. The metalanguage is surprisingly concise, requiring only 189 lines of code. The following is a brief excerpt:

```plaintext
ParseExpr.Pass <- '@' '(' s:str_lit ')';
ParseExpr.Paren <- '(' x:ParseExpr[pr=*] ')';
ParseExpr.Name <- name:IdBase ':' e:ParseExpr;
ParseExpr.List <- ty:`ParseExprListType`
  ['
    elem:ParseExpr[pr=*]
    num:ParseExprListNum
    delim:ParseExpr[pr=*]
    end_delim:(NONE:eps | OPTIONAL:':?' | SOME:'::')
  ']';
ParseExpr.Unfold <- `~` e:ParseExpr;
ParseExpr.AttrReq <- e:ParseExpr '[` attrs:#L[AttrReq::','_] `]';

  AttrReq.Base <- k:IdBase;
  AttrReq.PrecStar <- `pr` '=' `*';

ParseExprListType.List <- `#L`;
ParseExprListType.Block <- `#B`;
// ...
```

We note that the syntax is very compact, and corresponds to little more than one would write on the whiteboard for an informal BNF grammar.

## References

[Zim22] Joe Zimmerman. Practical LR parser generation. *arXiv*, 2022.