Lecture 1: Course overview, lexical analysis

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601.428/628 Compilers and Interpreters

Welcome!

- Welcome to Compilers and Interpreters!
- Today:
  - Policies and syllabus
  - Course overview
  - Lexical analysis

Where to find information

- All *public* course information will be posted on the course website:

  https://jhucompilers.github.io/fall2020

  - Please check the course website frequently!
- Q&A, course announcements, and non-public course information will be on Piazza, https://piazza.com/jhu/fall2020/601428
- Assignment submission using Gradescope, https://www.gradescope.com
- Videos will be posted to Blackboard (my.jh.edu → Education → Blackboard)

Plan for remote instruction

- Slides and public materials posted on course website
- *For some classes*, video lectures posted on Blackboard, please watch these in advance
- Synchronous class meetings using Zoom
  - These will be recorded and posted to Blackboard
  - Will focus on review of readings, live Q&A, exercises
  - Depending on student availability/timezones there may be additional class meetings (for students who can't easily attend the usual class time)
- Use Piazza to ask questions (just like usual!)
- Office hours will be held using Zoom
- Exams will be take-home

Syllabus

- Syllabus is posted on course website:

  `https://jhucompilers.github.io/fall2020/syllabus.html`
- Please read it!
- This lecture just includes summary/highlights

Syllabus: communication policy

- Official course communication will use Piazza (check it regularly)
- Use Piazza for questions
  - If possible, make questions public (if they would benefit other students, and don't contain assignment code or personal information)
    - Please answer public questions if you can!
  - Otherwise, private questions are fine
  - We will make every effort to respond in a timely manner (usually the same day)
- Please check your email regularly
- Email me (daveho@cs.jhu.edu) if you have any concerns

Syllabus: academic ethics

- Follow the CS Academic Integrity Code:
  `https://www.cs.jhu.edu/academic-integrity-code/`
- Assignment submissions and exams must be entirely your work!
  Submitting someone else's work or allowing someone else to submit yours constitute a violation of academic ethics
- Cite all sources used
- If you aren't sure what is allowed and what isn't, ask!

Syllabus: grading

- Assignments: 60%
  - Series of projects to build interpreters and a compiler
- Exams: 40%
  - 4 take-home exams, each worth 10% of course grade

Course overview

Compilers and interpreters

- Compilers and interpreters are frequently-used strategies for implementing programming languages
- This course: practical techniques for implementing compilers and interpreters

What is a compiler?

- A compiler translates a program (or partial program) from a *source language* to a *target langauge*
- Source language is often a “high-level” language
  - E.g., C, C++
- Target language is often *assembly language* which can be translated into directly-executable *machine language*
  - E.g., x86-64 assembly language

What is an interpreter?

- An interpreter analyzes a source language program and carries out the computation it embodies
- The source program is represented as a data structure
  - Represents the program in "ready-to-execute" form
- The interpreter *evaluates* this data structure

Compilers vs. interpreters

- Compilation and interpretation are both useful ways to implement a programming language
- The “front-end” of a programming language implementation — the components which recognize and analyze the source program — are similar in both interpreters and compilers
- Interpreters tend to be less effort to implement
- Compilers tend to allow the program to execute at closer to machine-level performance
- Hybrid strategies such as virtual machines and just-in-time compilation are possible

Rough course outline

- Lexical analysis: recognizing the lexical units ("words") of a source program
- Parsing: recognizing the syntax (constructs) of a source program
- High-level intermediate representations: parse trees and abstract syntax trees
- Interpretation
- Semantic analysis and type checking
- Lower-level intermediate representations (e.g., control-flow graphs)
- Code generation
- Code optimization

Why is this course useful?

- Gain a deeper understanding of how programming languages are implemented
  - Know how the tools you are using work "under the hood"
- Compilation techniques can be used to create interesting tools for software engineering (static analyzers, instrumentation tools)
- Lexical analysis and parsing techniques can be applied to all kinds of structured data, not just source code

Lexical analysis

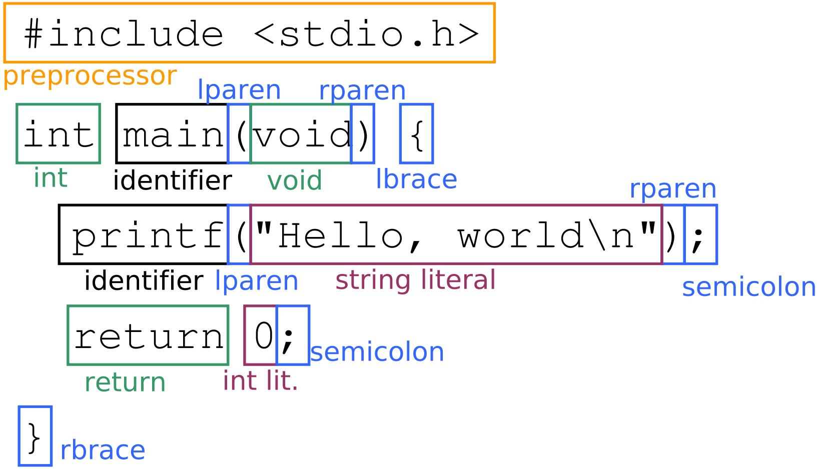
Lexical analysis

- Source code is generally represented as text: in other words, a sequence of characters
- *Lexical analysis* (also known as *scanning*) refers to the task of grouping sequences of input characters into *lexical units*, also known as *tokens*
- Tokens are the “words” of a source program

Hello, world

```
#include <stdio.h>

int main(void) {

  printf("Hello, world\n");

  return 0;

}
```

Hello, world (lexical structure)


```c
#include <stdio.h>
int main(void) {
    printf("Hello, world\n");
    return 0;
}
```

What is a token?

- Token kind: value (usually integer or enumerated) representing what kind of token it is
- Lexeme: the exact text of the token in the source code
  - Some kinds of token can only ever have one lexeme (keywords, punctuation, etc.)
  - Some kinds of token can have a variety of lexemes (identifiers, literal values)

Source information

It is also useful to represent where in the source code the token occured:

- Source file
- Line number
- Column number

Keeping track of this information helps the compiler or interpreter generate useful error messages

Example token representation

```
enum TokenKind {
  TOK_INT_KEYWORD,
  TOK_RETURN_KEYWORD,
  TOK_IDENTIFIER,
  TOK_LPAREN,
  // etc. for other kinds of tokens
};

struct Token {
  enum TokenKind kind;
  char *lexeme;
  const char *filename;
  int row, col;
}
```

Lexical analyzer design

- The job of a *lexical analyzer* is to break down source code text into a sequence of tokens
- Typical approach: lexical analyzer produces one token at a time, on demand
  - The *parser* will consume the scanned tokens, more about this soon...

Interfaces and implementations

Interfaces and implementations

- Compilers and interpreters are complex software artifacts
- To manage the complexity, we need to design and implement them in a modular fashion
- Approach: *interfaces* and *implementations* using *opaque data types*
- By following this approach, we help ensure that modules can be modified independently of each other

Interfaces

An interface defines an *opaque data type*, and declarations of functions to

- create instances
- destroy instances
- do operations on instances

Opaque data types in C and C++

When a `struct` data type is defined as a *forward reference* (without a full definition), code *using* the type

- Can declare pointers and references to instances, and pass them to functions
  - This means that instances must be dynamically allocated
- *Cannot* access fields directly $\rightarrow$ encapsulation is enforced

Example interface: tree node data type

```
// node.h

struct Node;  // forward declaration

struct Node *node_alloc(int tag);   // create a Node instance
void node_destroy(struct Node *n);  // destroy a Node instance

// operations/accessors
int node_get_tag(struct Node *n);
int node_get_num_kids(struct Node *n);
void node_add_kid(struct Node *n, struct Node *kid);
struct Node *node_get_kid(struct Node *n, int index);
// etc...
```

Implementation of an interface

An implementation of an interface is simply a source module where

- The opaque data type is defined concretely
- The functions associated with the data type are defined

The implementation module is the only module in which the data type is not opaque!

Example implementation: tree node data type

```
// node.c
#include "node.h"

struct Node {
  int tag, num_kids, capacity,
  struct Node **kids;
  // ...other fields...
};

struct Node *node_alloc(int tag) {
  struct Node *n = malloc(sizeof(struct Node));
  n->tag = tag;
  n->num_kids = 0;
  n->capacity = 1;
  n->kids = malloc(sizeof(struct Node *) * n->capacity);
  return n;
}

// ...implementations of other functions...
```

Lexical analyzer design and implementation

A prefix calculator language

- A *prefix expression* is one where operators precede their operand(s)
- Example: $\boxed{\texttt{+ - 4 1 5}}$ means $(4 - 1) + 5$
- The "prefix calculator language" accepts inputs which are a series of prefix expressions, each terminated by a semicolon (`;`)
    - Primary expressions: literal integers and identifiers
    - Numeric operators: $\boxed{\texttt{+ - * /}}$
    - Assignment: $\boxed{\texttt{=}}$ (first operand must be an identifier)
    - Result of evaluation is the result of the last expression
- Code: `https://github.com/daveho/pfxcalc`

Running the prefix calculator

```
$ ./pfxcalc
= a 1;
= b 3;
* + a b 6;
Result: 24
```

Lexical analyzer (“lexer”) interface

```
// lexer.h
#include <stdio.h>
#include "node.h"

struct Lexer;

struct Lexer *lexer_create(FILE *in, const char *filename);
void lexer_destroy(struct Lexer *lexer);

struct Node *lexer_next(struct Lexer *lexer);
struct Node *lexer_peek(struct Lexer *lexer);
```

Lexer operations

- `lexer_next` consumes one token from the input (calling `lexer_next` repeatedly will consume all tokens in the input)
- `lexer_peek` returns the next token, *without* consuming it
  - Parsers will use this function for *lookahead*
- Note that tokens are represented using the `struct Node` data type
  - This is useful for building parse trees, more about this soon

Token kinds

```
// token.h
enum TokenKind {
  TOK_IDENTIFIER,
  TOK_INTEGER_LITERAL,
  TOK_PLUS,
  TOK_MINUS,
  TOK_TIMES,
  TOK_DIVIDE,
  TOK_ASSIGN,
  TOK_SEMICOLON,
};
```

These will be used as the “tag” values for the `struct Node` instances representing tokens

Lexer implementation

```
// lexer.cpp
#include <string>
#include "token.h"
#include "lexer.h"

struct Lexer {
private:
  // ... private fields ...

public:
  Lexer(FILE *in, const std::string &filename);
  ~Lexer();
  struct Node *next();
  struct Node *peek();

private:
  // ... private member functions...
};
```

Module implementation in C++

- Note that `struct Lexer` is implemented as a C++ type with constructor, destructor, member functions, etc.
- C code can use instances of this type by calling the functions defined by the interface
- Recommendation: use C++ to implement opaque data types in your projects for this course
  - This will allow you to take advantage of C++ string and container types

Lexer implementation (functions)

```
struct Lexer *lexer_create(FILE *in, const char *filename) {
  return new Lexer(in, filename);
}

void lexer_destroy(struct Lexer *lexer) {
  delete lexer;
}

struct Node *lexer_next(struct Lexer *lexer) {
  return lexer->next();
}

struct Node *lexer_peek(struct Lexer *lexer) {
  return lexer->peek();
}
```

Function implementation

- The interface functions (`lexer_create`, `lexer_next`, etc.) are implemented in C++ and can call member functions of the `struct Lexer` data type
- Because these functions have `extern "C"` linkage, they can be called from C code

How does the lexer actually work?

Let's look at the `next` and `peek` member functions:

```
struct Node *Lexer::next() {
  fill();
  Node *tok = m_next;
  m_next = nullptr;
  return tok;
}

struct Node *Lexer::peek() {
  fill();
  return m_next;
}
```

- `fill` is a private member function that calls the `read_token` private member function if a token object is not available
- `m_next` is a pointer to the available token object
- `next` and `peek` are similar; the main difference is that `next` sets `m_next` to null

fill function

```
void Lexer::fill() {
  if (!m_eof && !m_next) {
    m_next = read_token();
  }
}
```

- `m_eof` is a boolean member variable that is set to `true` when end of file is reached
- The `read_token` private member function does the actual work of reading a token

read_token function

```
struct Node *Lexer::read_token() {
  // ... lots of code, read it yourself on Gitub ...
}
```

Ad-hoc lexical analysis

Basic idea for implementing ad-hoc lexical analysis (as in the prefix calculator's `read_token` member function):

- Skip whitespace (if any)
- Read a character; if EOF is reached, then there are no more tokens
- Based on what character is read, start scanning a particular kind of token
  - E.g., if an alphabetic character was read, scan an identifier
- Keep reading characters that are a valid continuation of the current lexeme
- When a character that isn't a valid continuation is read, or EOF is reached, create the token object

Disadvantages of ad-hoc lexical analysis

- Ad-hoc lexical analyzers are somewhat tedious to implement
- Would be nice to have a declarative way to do lexical analysis:
  - Specify regular expression patterns for each kind of token
  - Have a tool generate a custom lexical analyzer from this specification
- Good news: *lexical analyzer generators* exist, and this is precisely what they do!
  - We will cover these soon

Next time

Next time we will discuss grammars and parsing techniques