Project 1 Guide

CS236 - Discrete Structures
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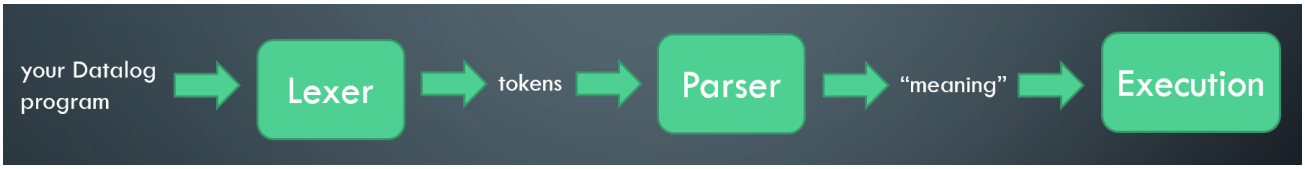
CS236 Projects Overview

There are five projects for CS236 that are each a piece of creating an interpreter for Datalog programs (see `https://www.geeksforgeeks.org/compiler-vs-interpreter-2/` for details about interpreters). An interpreter is comprised of three components: the Lexer, the Parser, and the Execution engine. In Project 1 you will build the Lexer. In Project 2 you will create the Parser. In Projects 3, 4, and 5 you will develop the Execution engine.
Here is a graphical representation:



A lexer is a program that takes as input a program file and scans the file for tokens. The output to the lexer is a collection of tokens. These tokens can then be read by the parser. The parser determines the meaning of the program based on the order and type of tokens. This meaning is then given to the execution engine, which executes the program.

Why Tokens?

You might be questioning the reason we are converting programming files into tokens. Programming languages are created to allow each programmer to use variable names, method names, comments, strings, etc. that are specific to him or her or the application domain. These items are very important for readability and organization to the programmer, but they are not essential for the computer to execute the code. A lexer turns programmer-specific "items" into programmer-independent structures called "tokens." Each token contains the information the computer needs, namely three items: 1) a token name, which is selected from a set of predefined names, e.g. "STRING"; 2) the specific "item" for that token, e.g. `"Hello World"`; and 3) a line number. This information allows the computer to get one step closer to execution.

Project 1: Lexer

Building a lexer will help us apply our study of finite-state machines and automata. The lexer is either an implementation – a finite-state machine or several finite-state automata – that takes the Datalog program file as its input and outputs a collection of tokens. Good software design is about breaking out the functionality into smaller pieces, which we call decomposition. All projects are required to be completed in C++ and we *strongly* recommend using sound Object Oriented (OO) design practices. These guides are meant to help you learn and use such practices.

This guide contains two approaches to Project 1. The first (called 'Peek and Patch') is an OO design that uses encapsulation and can easily be unit tested. The second (called 'Parallel and Max') is an OO design that more closely matches finite-state automata theory, and uses inheritance and a tokenizing algorithm. You are not *required* to do either approach, but experience shows that if you do not it may lead to lots of debugging and confusion, not to mention issues with later projects. Remember, this project is the start of your interpreter; it will be used in *every* other project in this course. With either approach, develop your code in an iterative manner: create a small piece of functionality and test it as you go. This will save you time in the long run – nothing takes more time than coding by the "Hack and Pray" philosophy.

Approach 1: Peek and Patch

First, make sure you watch the Project 1 video in its entirety before reading this.
Here are some recommendations on how to decompose your lexer:

- `Token` - a class that encapsulates the information contained in a `Token` instance. It should contain an enumerated type that defines the possible values for a token type (note we could use inheritance for this, but our tokens will essentially be handled all the same way).
- `Tokenizer` - a class that handles the scanning and tokenizing of inputs (this is where the finite-state machine gets implemented). Here is an example `.h` file:

```
class Tokenizer {
    private:
        std::string input;
    public:
        Tokenizer(std::string& input);
        Token getNextToken();
};
```

  Thus the `Tokenizer` needs the input of the Datalog file as a string. It will scan and generate each `Token`, when at a time for successive calls to `getNextToken()`. The

`Tokenizer` is complete when it gives an end-of-file (EOF) `Token`. Note that this structure for the `Tokenizer` facilitates unit testing: you can give it any input and make sure it gives you the correct `Token`(s).

- `Lexer` - a class that contains the `Tokenizer` and all `Tokens` which it generates (consider using a `vector<Token>` or `vector<Token*>`). The logic of when to call `getNextToken()` should be contained here.
- `main.cpp` - your main file should contain only the `main` function. No global variables. Your `main` function should be small and serve the following purposes: verify command-line arguments, instantiate instance of the `Lexer` class, and pass the input to `Lexer` and let it run. For this project, your main will then need to get the Tokens from the `Lexer` and print them out in a specified format (so the pass-off driver can check it for correctness). At the end, your `main` function should perform any clean up (e.g. deallocation of memory).

Approach 2: Parallel and Max

First, make sure you watch the Project 1 video in its entirety before reading this.
WARNING: this approach will take more upfront effort to learn the algorithm, but if you understand inheritance, it will make the overall coding much easier.

In this approach we take advantage of FSA theory and string recognition. Note that each valid `Token` is a specific string that could be generated by a regular expression (reminder, you cannot use a regular expression library for this project). That means that each type of token could define a language accepted by a finite-state automaton. We can use this to decompose the problem of tokenization into multiple finite-state automata, instead of one, monolithic finite-state machine.

(If you have read the first approach above, in this approach you will not need the `Tokenizer` class, but you will still need the `Lexer` and `Token` classes as described.)

To implement this in code, the `Lexer` class should store a collection of finite-state automata. It also needs to store all the generated tokens. See the started code below:

```
class Lexer {
  private:
    std::vector<Token*> tokens;
    std::vector<Automaton*> automata;

  public:
      Lexer::Lexer() {
        tokens = new std::vector<Token*>();
        automata = new std::vector<Automaton*>();
        // Add all of the Automaton instances
        //automata.push_back(new ColonAutomaton());
        //automata.push_back(new ColonDashAutomaton());
```

```
        ...
      }
    // Other needed methods here
    ...
}
```

The Parallel and Max algorithm is implemented in public method. This algorithm does the following:

- Initialize two variables: maximum read value to 0 and corresponding maximum finite-state automaton (denoted as the "max automaton") to the first finite-state automaton in the collection
- For each finite-state automaton
  - Give it the input string and have it return whether or not it accepts the string (first n-symbols of the string)
  - Get the number of symbols (characters) read by it
  - Update the maximum read value if more than the current value and then update max automaton to reference the current finite-state automaton
- Now that we've found the finite-state automaton that will read the maximum amount of characters, tell it to generate a `Token` given the input it could accept
- Store new `Token` and update the input string (remove the characters read – remember the number of characters in stored in our variable
- While the input has more characters repeat

Here is pseudo code (not syntactically correct C++ code):

```
Lexer::Run(string input) {
    set lineNumber to 1
    // While there are more characters to tokenize
    loop on input.size() > 0 {
        set maxRead to 0
        set maxAutomaton to the first automaton in automata

        // TODO: you need to handle whitespace inbetween tokens

        // Here is the "Parallel" part of the algorithm
        //   Each automaton runs with the same input
        foreach automaton in automata {
            inputRead = automaton.Start(input)
            if (inputRead > maxRead) {
                set maxRead to inputRead
                set maxAutomaton to automaton
```

```
            }
        }
        // Here is the "Max" part of the algorithm
        if maxRead > 0 {
            set newToken to maxAutomaton.CreateToken(...)
            increment lineNumber by maxAutomaton.NewLinesRead()
            add newToken to collection of all tokens
        }
        // No automaton accepted input; create invalid token
        else {
            set maxRead to 1
            set newToken to a  new invalid Token
                (with first character of input)
            add newToken to collection of all tokens
        }
        // Update ‘input‘ by removing characters read to create Token
        remove maxRead characters from input
    }
}
```

Note that you must keep track of line numbers for each token. The above pseudo code and algorithm rely on inheritance. There must be some base class for all automata, e.g. `Automaton`, that contains the following virtual methods: `Start`, `NewLinesRead`, and `CreateToken`. Your `Automaton` class definition should resemble the following:

```
class Automaton
{
protected:
    int inputRead = 0;
    int newLines = 0;
    TokenType type;

public:
    Automaton(TokenType type) { this->type = type; }

    // Start the automaton and return the number of characters read
    //   read == 0 indicates the input was rejected
    //   read  > 0 indicates the input was accepted
    virtual int Start(const std::string& input) = 0;

    virtual Token* CreateToken(std::string input, int lineNumber) {
        return new Token(type, input, lineNumber); }

    virtual int NewLinesRead() const { return newLines; }
};
```

Note that default implementations are given for both `CreateToken` and `NewLinesRead`, but that `Start` is a pure-virtual method.

You now need to create a class that inherits from `Automaton` for each type of `Token`. Somewhat counter-intuitive, you also need to create a subclass for invalid types of `Token`: multi-block comments that never end and strings that are never closed. After reading the project specification, you will notice that most of the `Tokens` are defined, specific strings. You need not create a different subclass for each of these. Instead, all of these finite-state automata do the exact same thing and could be implemented using one generic class:

```
class MatcherAutomaton :
    public Automaton
{
private:
    std::string toMatch;

public:
    MatcherAutomaton(std::string toMatch, TokenType tokenType);

    int Start(const std::string& input);
};
```

and

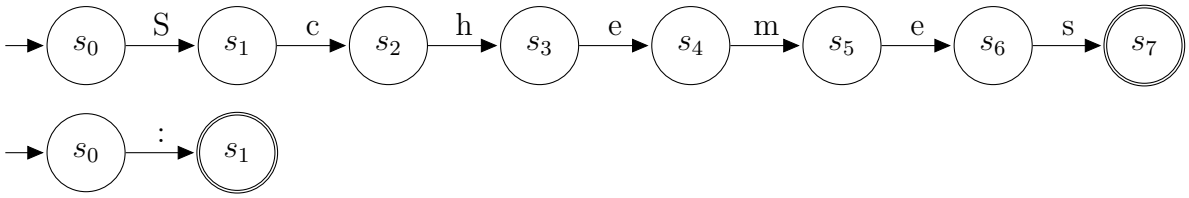
```
int MatcherAutomaton::Start(const std::string& input) {
    bool isMatch = true;
    inputRead = 0;  // member variable inherited from Automaton class
    for (int i = 0; i < (int)toMatch.size() && isMatch; i++) {
        if (input[i] != toMatch[i]) {
            isMatch = false;
        }
    }
    if (isMatch) {
        inputRead = toMatch.size();
    }
    return inputRead;
}
```

IMPORTANT: The order of the automata in your collection *does* matter. `MatcherAutomaton` instances should come first since they correlate to special keywords and symbols. This will make sure your automaton for a keywords is chosen as the "max automaton" instead of your identifier automaton (see below for why).

You may be wondering how this algorithm works (or if it even does). Let's consider the syntax of a C++ program (you should be able to relate this to the syntax of the Datalog program you are parsing). How does a compiler tokenize the following line: `int intx = 5;`? These are the corresponding tokens (note the whitespace is important for separating tokens, but is just consumed): <integer><identifier="intx"><assignmentoperator>

<numberliteral="5"><semicolon>. The compiler has to be able to tokenize "int" differently from "intx." Using our algorithm, we'd have an automaton to check for the keyword "int." We'd also have an automaton for identifiers. When the input is "intx = 5;" (after tokenizing the first two tokens) the keyword automaton will say that it can accept up to 3 characters: 'i', 'n', 't', but the identifier will say that is can accept up to 4 characters, so the identifier automaton will be chosen to create the next token, instead of the keyword. Now let's consider the first "int." As long as your keyword automaton for `int` is checked first, when the identifier automaton says it also can read 3 characters, it will not be selected, since there is already an automaton (your `int` one) that said it can read 3 characters.

The first place to start is by create FSA diagrams for each of the automaton you will need. Doing this upfront will reduce coding time and help you work out your understanding of the token types. Learning how to create diagrams and then turn them into code is an important software engineering skill. Let's show the FSA diagrams for the automata that will recognize the 'Schemes' token and the ':' token.



Both of these automata can use the `MatcherAutomaton` code for their implementation. We just need create two instances and set the member variable `toMatch` to 'Schemes' and ':' respectively. Try to make as much reuse of each `Automaton` class as possible (this is good software engineering). Drawing out the diagrams first will make it more clear which automata can be represented by the same code.

Note that this approach is very easy to unit test. Each `Automaton` class can be tested separately. The overall algorithm in the `Lexer` class can also be tested separately. You can incrementally build new automata classes and add them to the `Lexer` for testing, thus increasing the functionality a step at a time.

Conclusion

Start this project as early as possible. You will code better when not rushed, and you will be more inclined to test as you go (which will reduce overall coding time). See Project 1 on the course website for requirements and specifications.