FOM Hochschule für Oekonomie & Management

university location Bonn

Bachelor Thesis

in the study course Wirtschaftsinformatik

to obtain the degree of

Bachelor of Science (B.Sc.)

on the subject

Development of a Query Language for Full-Text Search in Relational Databases

by

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Matriculation Number:	539441
Submission:	October 3, 2022

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Index of Abbreviations

APT Automatically Programmed Tools
DDL Data Definition Language
DSL Domain-Specific Language
EBNF Extended Backus-Naur Form
GPL General-Purpose Language
HTML Hypertext Markup Language
MS Microsoft
PDF Portable Document Format
SQL Structured Query Language
XML Extensible Markup Language

Index of Symbols

p	precision
r	recall
n	number of relevant retrieved documents
d	total number of retrieved documents
v	total number of relevant documents
F_β	weighted harmonic mean
β	nonnegative weight

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1 Abstract

Abstract

2 Theory

2.1 Full-Text Search

Commercial database management has long focused on structured data and the industry requirements have matched those of structured storage applications quite well. The problem is that only a small part of the data stored is completely structured, while most of it is completely unstructured or only semi-structured, in the form of documents, emails, web pages, etc. (cf. HAMILTON, NAYAK 2001, p. 7) Full-text search describes a search technique in which all words of a document or a full-text database are matched with search criteria, whereby not only exact matches but also word reflections and the like can be searched. A full-text database, as opposed to a regular bibliographic database, contains not only metadata but also the complete textual content of books and similar documents. (cf. TENOPIR, RO 1990, pp. 2-3)

With large amounts of data, matching every word of all entries is time-consuming and non-performant. To improve this process, a full-text search is divided into an indexing and query phase. In the indexing phase, all words found to be irrelevant, e.g. 'and' or 'the', are ignored by matching them against stoplists, words are normalized, e.g. the capitalization of words, and are merged into an index. (cf. COLES, COTTER 2009, p. 11) In the query phase, full-text query predicates are used to execute search queries. These allow not only a search for exact matches but also generational forms. Generational forms can be, for example, words that stem from the same word or alternative search terms using a language-specific thesaurus. A query processor then calculates the most efficient query plan which delivers the required results. The previously created index is searched for documents and text passages that match the search, and the results are returned in a ranked order. (cf. COLES, COTTER 2009, pp. 11-12)

To determine a rank for a search result the quality has to be measured. Two key metrics are used when measuring the quality of search results: precision p and recall r . Precision is defined as the relation of relevant search results to irrelevant search results. If, for example, many results are desired about the Jupiter moon Europa, the search term 'Europa' has low precision, since results for the continent 'Europe', as well as for the mythological figure and the moon are displayed. The search term 'Europa Moon' will again have higher precision. Algebraically, precision can be represented as in Formula 1, where n represents the number of relevant retrieved documents and d represents the total number of retrieved documents.

Formula 1: Precision

$$p = \frac{n}{d} \tag{1}$$

Source: COLES, COTTER 2009, p. 14

The recall is defined as the relation between relevant search results and relevant documents that were not displayed. For example, if five documents in a database deal with the moon Europa and only two are displayed in a search recall is low. Formula 2 shows the mathematical definition, where v represents the total number of relevant documents.

Formula 2: Recall

$$r = \frac{n}{v} \tag{2}$$

Source: COLES, COTTER 2009, p. 14

Although it is nearly impossible to maximize both recall and precision it is still relevant to keep both values as high as possible. Formula 3 offers the possibility to prefer one of the two metrics precision and recall when calculating the quality of a search result. The nonnegative weight β weights both metrics equally for a value of 1.0. A value less than 1.0 prefers recall, while a value above 1.0 prefers precision.

Formula 3: Weigthed harmonic mean

$$F_\beta = \frac{\left(1+\beta^2\right)\cdot(p \cdot r)}{\beta^2 \cdot p + r} \tag{3}$$

Source: COLES, COTTER 2009, p. 15

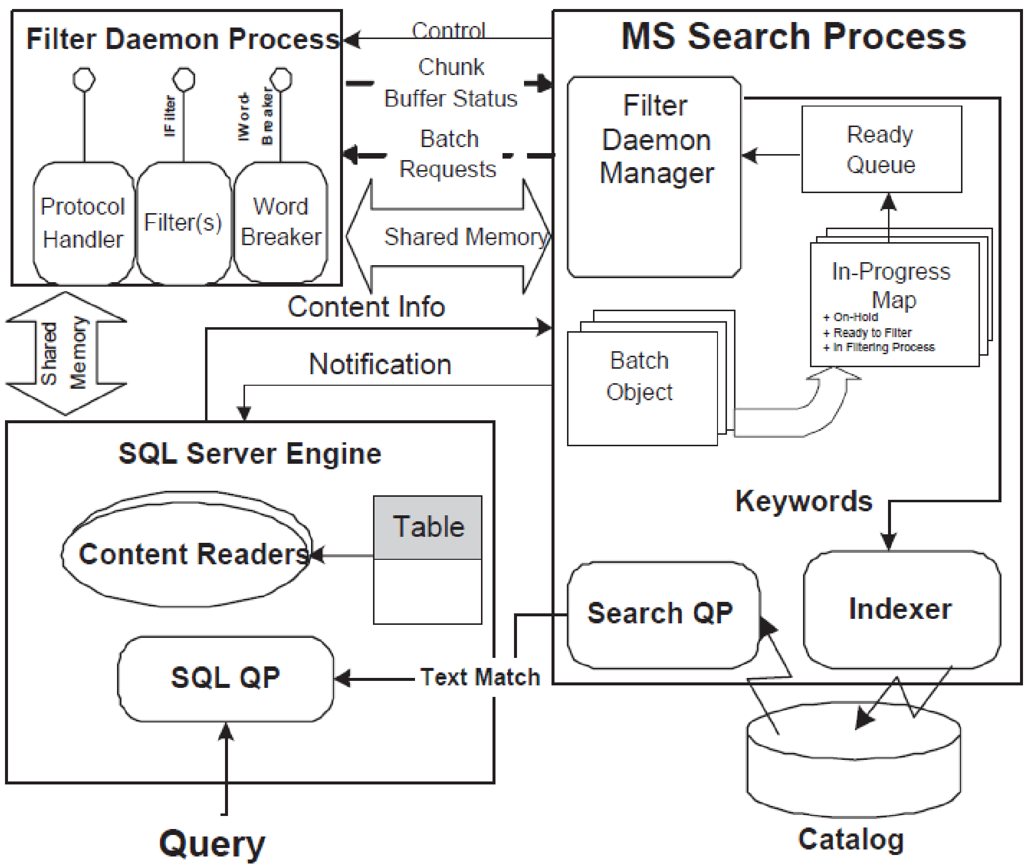
This means F_β represents the desired search quality and should be as high as possible, deciding whether to focus on recall or precision or both. (cf. COLES, COTTER 2009, pp. 13-15)

2.1.1 MS SQL Server Search Architecture

Structured Query Language (SQL) Server uses the same access method and infrastructure for full-text search as other Microsoft (MS) products and the Index Service for file

systems. This decision enables standardized semantics for full-text search of data in relational databases, web-hosted data, and data stored in the file system and mail systems. On SQL servers, not only simple strings can be indexed, but also data structures, such as Hypertext Markup Language (HTML) and Extensible Markup Language (XML), and even complex documents, such as Portable Document Format (PDF), Word, PowerPoint, Excel and other custom document formats. (cf. HAMILTON, NAYAK 2001, p. 7)
The architecture can be divided into five modules, which interact with each other to perform a full-text search. (See Figure 1)
The **content reader** scans indexed data stored in SQL Server tables to assemble data and its associated metadata packets. These packets are then injected into the main search engine, which triggers the search engine filter daemon to consume the data.
Depending on the content, the **filter daemon** calls different filters, which parse the content and output so-called chunks of the processed text. A chunk is a related section with relevant information about this section like the language-id of the text. These chunks are output separately for any properties, which can be elements like the title, an author or other content-specific elements.

Figure 1: Architecture of MS SQL Server Full-Text Search



Source: HAMILTON, NAYAK 2001, p. 8

Word breakers split the chunks into keywords and additionally provide alternative keywords and the corresponding position in the text. Word breakers can recognize human languages and on SQL Server several word breakers for different languages are installed by default. The generated keywords and metadata are passed on to the MS Search process, which processes the data with an indexer.
The **indexer** generates an inverted keyword list with a batch containing all keywords of one or more items. These indexes are compressed to use memory efficiently, this may lead to high costs for updates of these indexes. Therefore a stack of indexes is maintained. New documents first create their small indexes, which are regularly merged into a larger index, which in turn is merged into the base index. This stack can be deeper than three, but the concept remains and allows a strongly compressed index without driving the update costs too high. If a keyword is searched, all indexes are accessed, so the depth should still be kept reasonable.
A **query processor** manages the insertion and merge operations and collects statistics on distribution and frequency for ranking purposes and query execution. (cf. HAMILTON, NAYAK 2001, pp. 8-9)

2.1.2 MS SQL Server Full-Text Query Features

Full-text indexes can be created on SQL Servers with the Data Definition Language (DDL) statement `CREATE INDEX` and can make use of other SQL Server utilities; these include backup and restore and attachment of databases. There are three options to create and manage indexes on SQL Servers. **Full Crawl** always rebuilds the whole full-text index by scanning the entire table. **Incremental Crawl** logs the timestamp of the last re-index and retains changes by storing them in a column. **Change Tracking** enables a near real-time validity between the full-text index and the table by tracking changes to the indexed data using the SQL Server Query Processor. (cf. HAMILTON, NAYAK 2001, p. 9)
Full-text search is represented in SQL with three possible constructs: (cf. HAMILTON, NAYAK 2001, p. 9)

1. Contains Predicate: A contains predicate is true if one of the specified columns contains terms that satisfy the specified search condition. E.g. `Contains(author , ('Ag* or "Marc Miller"'))` will match entries where the column author contains words like 'Ag', 'Agatha', or 'Marc Miller'.

2. Freetext Predicate: Freetext predicates are true if one of the specified columns contains terms that stem from the terms in the specified search condition. E.g. `Freetext(content, 'fishing')` will match entries where content contains words like 'fishing', 'fish', or 'fisher'.

3. ContainsTable and FreetextTable: ContainsTable and FreetextTable are functions that match entries similar to their corresponding function, but additionally return multiple matches including a ranking for each entry and the entire corpus.

The search conditions of these constructs can be of various types to find the intended results: (cf. HAMILTON, NAYAK 2001, p. 9)

1. Keyword, phrase, prefix: E.g. 'fishing', 'Marc Miller', 'Ag*'
2. Inflections and Thesaurus: E.g. `Contains(*, 'FORMSOF(INFLECTIONAL, fishing)AND FORMSOF(THESAURUS, boat)')` will find all entries containing words that stem from 'fishing' and all words sharing the meaning with 'boat' (Thesaurus support).
3. Weighted terms: Keywords and phrases can be assigned a relative weight to impact the rank of entries. E.g. `ContainsTable(*, 'ISABOUT(generator weight (.7), full-text weight (.3))')` will rank entries higher in the result corpus which mention 'generator' over 'full-text'.
4. Proximity: E.g. `Contains(*, 'corn NEAR salad')` contains the proximity term 'NEAR' to match entries where 'corn' appears close to 'salad'.
5. Composition: E.g. `Contains(*, 'full-text AND NOT database')` uses two search query components that are composed using a term like 'AND', 'OR', or 'AND NOT'.

2.2 Domain-Specific Languages

Commonly known programming languages, such as C or Java, are also called a General-Purpose Language (GPL). GPLs are designed to handle any problem with relatively equal levels of efficiency and expressiveness. However, many applications do not require a multifunctional GPL and can describe a problem more naturally using a Domain-Specific Language (DSL). DSLs are languages that have been developed specifically for a particular application or domain, to be able to develop faster and more effectively. (cf. HUDAK 1997, p. 1) By tailoring notations and constructs to the domain in question, DSLs offer significant gains in expressiveness and usability compared to GPLs for the domain in question, with corresponding productivity gains and lower maintenance costs. (cf. MERNIK et al. 2005, p. 317) DSLs are by no means a product of modern software development but have existed since the beginning of programming. One of the first DSLs ever designed

was Automatically Programmed Tools (APT), which was used for the development of numerically controlled machine tools in 1957. (cf. ROSS 1978, pp. 283-284)
DSLs can be found everywhere in the world of IT, for example, this thesis was written with the help of LaTeX to design layout and formatting. Table 1 lists some well-known DSLs and their application/domain to give examples of what is classified as a DSL.

Table 1: Popular DSLs

DSL	**Applicaiton**
Lex and Yacc	program lexing and parsing
PERL	text/file manipulation/scripting
VDL	hardware description
TeX, LaTeX, troff	document layout
HTML, SGML	document markup
SQL, LDL, QUEL	databases
pic, postscript	2D graphics
Open GL	high-level 3D graphics
Tcl, Tk	GUI scripting
Mathematica, Maple	symbolic computation
AutoLisp/AutoCAD	computer aided design
Csh	OS scripting (Unix)
IDL	component technology (COM/CORBA)
Emacs Lisp	text editing
Prolog	logic
Visual Basic	scripting and more
Excel Macro Language	spreadsheets and many things never intended

Source: HUDAK 1997, p. 3

Programs written in a DSL are considered to be more concise, quicker to write, easier to maintain and easier to reason about and most importantly they can be written by non-programmers. In particular, experts in the domain for which the DSL was developed can use DSLs to program applications without having to acquire programming skills. An expert of a domain already knows the semantics of the domain, all that is needed to start development is the corresponding notation that expresses these semantics. (cf. HUDAK 1997, pp. 2-4)

2.3 Building a language

For a compiler or an interpreter to be able to interpret a DSL, the language must be accurately and precisely defined. Accurately means that the language must be defined consistently down to the smallest detail. Precisely means in this case that all aspects of the language must be laid out. If parts of the language are inconsistent or too vague, authors of compilers are forced to interpret these aspects themselves. This inevitably leads to different authors having different approaches to the same problem. If a DSL is to be created that meets the criteria described above, two components are needed. The first component is a set of rules, also called syntax. The second component is a formal definition of the meaning, also called semantics. (cf. FARRELL 1995, p. 2)

2.3.1 Syntax

The first step when defining syntax is defining an alphabet. This alphabet consists of tokens, which do not necessarily have to be letters. Several tokens, formulated according to a set of rules, make up a sentence or string. The alphabet of the English language is, in the context of syntax, not a list of the permissible characters, which is predominantly called the alphabet or 'ABC', but the permissible tokens. E.g. in the sentence 'the donkey screams' the tokens 'the', 'donkey' and 'screams' are part of the alphabet of the English language. The token 'gHArFk' consists of permissible characters but is not part of the valid alphabet. However, the use of permissible tokens alone does not make a sentence correct. The sentence 'on sleep blue' consists of tokens that are part of the English alphabet, but it is still not a valid sentence. The correct application of the rule set is still missing, in this example a missing object. Only the correct use of the alphabet AND the set of rules make a sentence syntactically correct. (cf. FARRELL 1995, p. 2)
If the alphabet and the set of rules are notated in a normal form, they can be called grammar. Relevant to this thesis is the Extended Backus-Naur Form (EBNF), which will be described in section 2.3.2.

2.3.2 Extended Backus-Naur Form

EBNF, as the name suggests, is based on the Backus-Naur Form, which was proposed by a group of thirteen international representatives in 1960, to serve as a basic reference and guide for building compilers. Backus-Naur Form is a notation for describing computational processes and rules as arithmetic expressions, variables, and functions. (cf. BACKUS et al. 1960, p. 300)
The syntax can be described as a set of metalinguistic formulae best described with an example. The grammar describing a number can be written in Backus-Naur Form as:

$\langle number \rangle$ ::= $\langle positive \rangle$|-$\langle positive \rangle$|0
$\langle positive \rangle$ ::= $\langle digit\ not\ zero \rangle \langle optional \rangle$

$\langle \textit{optional} \rangle$ ::= $\langle \textit{digit} \rangle \langle \textit{optional} \rangle$|
$\langle \textit{digit} \rangle$ ::= $\langle \textit{digit not zero} \rangle$|0
$\langle \textit{digit not zero} \rangle$ ::= 1|2|3|4|5|6|7|8|9

Characters contained in angel brackets '<>' represent a metalinguistic variable. The character '::=' describes a definition of this variable. The character '|' represents the metalinguistic connective 'or'. Other characters in this example have no special meaning but only represent themselves. So the first line of the grammar means that the variable <number> can be defined or replaced as <positive> or -<positive> or as 0. Since the variable <positive> is mentioned in the definition, there must be a definition for this variable in the grammar, otherwise, the grammar would be incomplete. In the third line, we see a metalinguistic connective without content on its right side. This means that the variable <optional> can also be empty and thus without value. Furthermore, in this line, a variable calls itself recursively, which is allowed. (cf. BACKUS et al. 1960, pp. 301-303)
So following this grammar, numbers such as 42 or -3141592 are valid.
In 1977 Wirth proposed a new variant of the Backus-Naur Form to further improve language definition notation. The main goals of this new notation were to (cf. WIRTH 1977, p. 822)

- distinguish clearly between metaterminal and nonterminal symbols
- not exclude metaterminals as possible symbols of the language
- enable iteration without using recursion

This proposal was the basis for the ISO/IEC 14977:1996(E) which now defines the standard for EBNF. The major changes that EBNF brought can be summarized as: (cf. ISO/IEC 14977:1996(E) 1996, p. VI)

- Terminal symbols must be quoted so any symbol can be a terminal symbol of the language
- Added square brackets to indicate optional symbols and avoid the use of a <empty> symbol
- Added curly brackets to indicate repetition
- Every rule must have a final character
- Normal Brackets group items together, similar to their arithmetic use

The number example from above can be rewritten in EBNF as:

$\langle \textit{number} \rangle$ ::= (['-']$\langle \textit{digit not zero} \rangle \langle \textit{digit} \rangle$)|'0';
$\langle \textit{digit} \rangle$ ::= $\langle \textit{digit not zero} \rangle$|'0';
$\langle \textit{digit not zero} \rangle$ ::= '1'|'2'|'3'|'4'|'5'|'6'|'7'|'8'|'9';

This version of the grammar produces the same set of numbers but is more concise and arguably more readable for humans.

3 Implementation

When using the full-text search, large parts of the SQL statements needed to describe the search are the same, since the search criteria are defined as either WHERE conditions or JOIN criteria. If you want to define a full-text search, you usually use a combination of the given functions. In MSSQL this would be for example CONTAINS or FORMSOF. Therefore I want to develop a query language where you only have to specify this combination of functions and a few parameters to generate the corresponding SQL.

3.1 Language definition

Example code listing.

Code Listing 1: run-code-gen function

```rust
// Code generator to translate an input to SQL
// Input: search string and path to write result to
// Output: SQL statement written to a file
fn run_code_gen(search: String, path: &str) -> std::io::Result
    <()> {
     // Transform string to list of tokens
     let tokens = code_gen::lexer::lex(search.as_str());
     // Parse tokens to an abstract syntax tree (ast)
     let ast = code_gen::parser::parse(tokens);
     match ast {
         // If parser returns no error, start code generation
         Ok(ast) => {
             let generator = code_gen::generator::generate(ast);
             // If generator returns no error, write SQL
                statement to file, otherwise throw an error
             match generator {
                 Ok(generator) => write!(File::create(path)?, "
                    {}", generator),
                 Err(gen_err) => Err(Error::new(ErrorKind::
                    InvalidData, format!("{:?}", gen_err))),
             }
         }
         // If parser returns error, throw an error aswell
         Err(parse_err) => Err(Error::new(
             ErrorKind::InvalidInput,
             format!("{:?}", parse_err),
         )),
     }
}
```

Source: main.rs lines 31-55

4 Summary

Summary

Appendix

Appendix 1: main.rs

```
use actix_web::{web, App, HttpResponse, HttpServer, Responder};
use regex::Regex;
use serde::{Deserialize, Serialize};
use std::fs::{read_to_string, File};
use std::io::{Error, ErrorKind, Write};
use std::process::Command;
use tera::{Context, Tera};

mod code_gen;

// Path Variables
const PATH_SQL: &str = "files\\fulltext.sql";
const PATH_RESULTS: &str = "files\\results.txt";

// Main function to start website on localhost:8080
// Run using 'cargo watch -x run'
#[actix_web::main]
async fn main() -> std::io::Result<()> {
    HttpServer::new(|| {
        let tera = Tera::new("templates/**/*").unwrap();
        App::new()
            .data(tera)
            .route("/", web::get().to(search))
            .route("/", web::post().to(result))
    })
    .bind("127.0.0.1:8080")?
    .run()
    .await
}

// Code generator to translate an input to SQL
// Input: search string and path to write result to
// Output: SQL statement written to a file
fn run_code_gen(search: String, path: &str) -> std::io::Result
    <()> {
```

```
    // Transform string to list of tokens
    let tokens = code_gen::lexer::lex(search.as_str());
    // Parse tokens to an abstract syntax tree (ast)
    let ast = code_gen::parser::parse(tokens);
    match ast {
        // If parser returns no error, start code generation
        Ok(ast) => {
            let generator = code_gen::generator::generate(ast);
            // If generator returns no error, write SQL statement to file, otherwise throw an error
            match generator {
                Ok(generator) => write!(File::create(path)?, "{}", generator),
                Err(gen_err) => Err(Error::new(ErrorKind::InvalidData, format!("{:?}", gen_err))),
            }
        }
        // If parser returns error, throw an error aswell
        Err(parse_err) => Err(Error::new(
            ErrorKind::InvalidInput,
            format!("{:?}", parse_err),
        )),
    }
}

// Runs a command to execute an sql statement to a local MSSQL Server
// Input: paths to the input file and where to write the result
// Output: txt file interpretation of the MSSQL Server result
fn execute_sql(sql_path: &str, results_path: &str) {
    Command::new("cmd")
        .args(&[
            "/C",
            "sqlcmd",
            "-S",
            "DESKTOP-JKNEH40\\SQLEXPRESS", //Local server name
            "-i",
            sql_path,
            "-o",
            results_path,
```

```
        ])
        .output()
        .expect("failed to execute operation");
}

// Reads the txt file result and extracts the actual results
// Input: path to the txt file
// Output: vec of titles and their search rank
fn read_results(path: &str) -> Option<Vec<(String, u64)>> {
    let contents = read_to_string(path).unwrap();
    let mut contents_vec: Vec<&str> = contents.split("\n").
       collect();
    // In case of error message, break
    if contents_vec.len() < 6 {
        return None;
    }
    // Remove metadata rows
    // First 3-4 rows and last three rows
    while !contents_vec[0].starts_with("---") {
        contents_vec.remove(0);
    }
    contents_vec.remove(0);
    contents_vec.remove(contents_vec.len() - 1);
    contents_vec.remove(contents_vec.len() - 1);
    contents_vec.remove(contents_vec.len() - 1);
    // Go through each row and extract the titles and their
       ranks
    let mut results: Vec<(String, u64)> = Vec::new();
    for row in contents_vec {
        // Remove unnecessary whitespaces
        let row = row.replace("\r", "");
        let re = Regex::new(r"\s+").unwrap();
        let row = re.replace_all(&row, " ").to_string();
        // Extract last 'word' as rank and save the rest as the
           title
        let mut words: Vec<&str> = row.split(" ").collect();
        let rank = words[words.len() - 1].parse::<u64>().unwrap
           ();
        words.remove(words.len() - 1);
        let title = words.join(" ");
```

```
            results.push((title, rank));
        }
        Some(results)
}

// Search and Result structs to (de)serialize rust and website
    datatypes
#[derive(Deserialize)]
struct Search {
    search: String,
}
#[derive(Serialize)]
struct Result {
    title: String,
    rank: u64,
    link: String,
}

// Define functional parts of the search page
async fn search(tera: web::Data<Tera>) -> impl Responder {
    let mut data = Context::new();
    data.insert("title", "Search field");
    let rendered = tera.render("search.html", &data).unwrap();
    HttpResponse::Ok().body(rendered)
}

// Define functional parts of the result page
async fn result(tera: web::Data<Tera>, data: web::Form<Search>)
    -> impl Responder {
    let mut page_data = Context::new();
    let mut results: Vec<Result> = Vec::new();
    // Run code generator with the string from the search field
    match run_code_gen(data.search.clone(), PATH_SQL) {
        // If code generator returns no error execute SQL and
           read the results
        Ok(_) => {
            execute_sql(PATH_SQL, PATH_RESULTS);
            let results_vec = read_results(PATH_RESULTS);
```

```
            // Fit search results into Result struct to properly display on the page, otherwise diplay error
            match results_vec {
                Some(results_vec) => {
                    for result in results_vec {
                        results.push(Result {
                            title: result.0.clone(),
                            rank: result.1,
                            // link to the Wikipedia article is also provided, whitespaces need to be replaced
                            link: result.0.replace(" ", "_"),
                        })
                    }
                    page_data.insert("title", "Results");
                    page_data.insert("search", &data.search);
                }
                None => {
                    page_data.insert("title", "Error");
                    page_data.insert(
                        "search",
                        &format!("{} results cannot be read", &data.search),
                    );
                }
            }
        }
        // If code generator returns error, display error instead of search results
        Err(error) => {
            page_data.insert("title", "Error");
            page_data.insert(
                "search",
                &format!("{} threw an error: {}", &data.search, &error.to_string()),
            );
        }
    }
    page_data.insert("results", &results);
```

```
    let rendered = tera.render("result.html", &page_data).
       unwrap();
    HttpResponse::Ok().body(rendered)
}
```

Appendix 2: lexer.rs

```
use logos::{Lexer, Logos};

// Main function to start lexing process
// Input: string
// Output: vec of tokens
pub fn lex(input: &str) -> Vec<Token> {
    Token::lexer(input).collect()
}

// helper function to format strings
fn to_string(lex: &mut Lexer<Token>) -> Option<String> {
    let string = lex.slice().to_string();
    Some(string)
}

// helper function to format floats
fn to_float(lex: &mut Lexer<Token>) -> Option<f64> {
    Some(lex.slice().parse().ok()?)
}

// helper function to format unsigned integer
fn to_u64(lex: &mut Lexer<Token>) -> Option<u64> {
    Some(lex.slice().parse().ok()?)
}

// List of all tokens that are accepted by the language
#[derive(Debug, Clone, Logos, PartialEq)]
pub enum Token {
    // Regex: phrase starting and ending with " and escaped
       character \" or just a word allowing a list of special
       characters
    #[regex(r##""(?:[^"\\]|\\.)*"|[a-zA-Zß?üÜöÖäÄ;\._<>´`#§$
       %/\\=€]+"##, to_string)]
```

```
    WordOrPhrase(String),
    // Regex: any float between 0 and 1
    #[regex(r"0+(\.[0-9]+)?|1", to_float)]
    ZeroToOne(f64),
    // Regex: any postive integer
    #[regex(r"[0-9]+", to_u64)]
    Number(u64),
    // ! and - for NOT
    #[token("!")]
    Bang,
    #[token("-")]
    Minus,
    // & and + for AND
    #[token("&")]
    And,
    #[token("+")]
    Plus,
    // | for OR
    #[token("|")]
    Or,
    // Parenthesis for grouping
    #[token("(")]
    LeftParen,
    #[token(")")]
    RightParen,
    // Comma for parameter separation
    #[token(",")]
    Comma,
    // Functions
    #[token("@contains")]
    Contains,
    #[token("@startswith")]
    Starts,
    #[token("@inflection")]
    Inflection,
    #[token("@thesaurus")]
    Thesaurus,
    #[token("@near")]
    Near,
    #[token("@weighted")]
```

```
    Weighted,
    // Colon to surround functions parameters
    #[token(":")]
    Colon,
    // End of File
    EoF,
    // Error and skip whitespaces
    #[error]
    #[regex(r"[\s\t\n\f]+", logos::skip)]
    Error,
}

// Enable tokens to be casted as strings
impl Into<String> for Token {
    fn into(self) -> String {
        match self {
            Token::WordOrPhrase(s) => s,
            _ => unreachable!(),
        }
    }
}
```

Appendix 3:   parser.rs

```
use std::slice::Iter;
use thiserror::Error;

use crate::code_gen::ast::*;
use crate::code_gen::lexer::Token;

// Main function to start parsing process
// Input: vec of tokens
// Ouput: abstract syntax tree (vec of statements)
pub fn parse(tokens: Vec<Token>) -> Result<Vec<Statement>,
   ParseError> {
    let mut parser = Parser::new(tokens.iter());
    // read twice to overwrite intial EoF tokens
    parser.read();
    parser.read();
```

```
    let mut ast: Vec<Statement> = Vec::new();
    while let Some(statement) = parser.next()? {
        ast.push(statement);
    }
    Ok(ast)
}

// Precedence to enable priorities between expressions
// Example: this OR that AND some (AND should have a higher
   priority)
#[derive(Debug, Clone, PartialEq, PartialOrd)]
enum Precedence {
    Lowest,
    Statement,
    Or,
    And,
    Not,
    Prefix,
    Group,
}

// Match tokens to precedences
impl Precedence {
    fn token(token: Token) -> Self {
        match token {
            Token::Bang | Token::Minus => Self::Not,
            Token::Plus | Token::And | Token::WordOrPhrase(..)
                => Self::And,
            Token::Or => Self::Or,
            Token::LeftParen => Self::Group,
            Token::Contains | Token::Starts | Token::Inflection
                => Self::Statement,
            _ => Self::Lowest,
        }
    }
}

// Parser saves current and next tokens as attribute
struct Parser<'p> {
    tokens: Iter<'p, Token>,
```

```
    current: Token,
    peek: Token,
}

impl<'p> Parser<'p> {
    // Initial parser creation
    fn new(tokens: Iter<'p, Token>) -> Self {
        Self {
            tokens,
            current: Token::EoF,
            peek: Token::EoF,
        }
    }

    // Parse next statement if possible
    // Output: statement or error
    fn next(&mut self) -> Result<Option<Statement>, ParseError>
        {
        if self.current == Token::EoF {
            return Ok(None);
        }
        Ok(Some(self.parse_statement(Precedence::Lowest)?))
    }

    // Set current and peek one step further in the vec of
       tokens
    fn read(&mut self) {
        self.current = self.peek.clone();
        self.peek = if let Some(token) = self.tokens.next() {
            token.clone()
        } else {
            Token::EoF
        };
    }

    // See what the current token is
    // Output: boolean
    fn current_is(&self, token: Token) -> bool {
        std::mem::discriminant(&self.current) == std::mem::
           discriminant(&token)
```

```
    }

    // Current token should match the one given
    // Input: token
    // Output: token or error
    fn expect_token(&mut self, token: Token) -> Result<Token, ParseError> {
        if self.current_is(token) {
            Ok(self.current.clone())
        } else {
            Err(ParseError::UnexpectedToken(self.current.clone()))
        }
    }

    // Current token should match the one given and read to next token
    // Input: token
    // Output: token or error
    fn expect_token_and_read(&mut self, token: Token) -> Result<Token, ParseError> {
        let result = self.expect_token(token)?;
        self.read();
        Ok(result)
    }

    // Parse statement, can only be a function or combination of functions
    // Input: precedence
    // Output: statement or error
    fn parse_statement(&mut self, precedence: Precedence) -> Result<Statement, ParseError> {
        let mut statement = match self.current.clone() {
            Token::Contains => Statement::Contains {
                expression: self.parse_contains()?,
            },
            Token::Starts => Statement::Starts {
                expression: self.parse_starts()?,
            },
            Token::Inflection => Statement::Inflection {
```

```
                expression: self.parse_inflection()?,
            },
            Token::Thesaurus => Statement::Thesaurus {
                expression: self.parse_thesaurus()?,
            },
            Token::Near => {
                let (parameter, proximity) = self.parse_near()?;
                Statement::Near {
                    parameter,
                    proximity,
                }
            }
            Token::Weighted => Statement::Weighted {
                parameter: self.parse_weighted()?,
            },
            _ => return Err(ParseError::UnexpectedToken(self.current.clone())),
        };
        // After a function could be an infix operator
        while !self.current_is(Token::EoF) && precedence < Precedence::token(self.current.clone()) {
            if let Some(in_statement) = self.parse_infix_statement(statement.clone())? {
                statement = in_statement
            } else {
                break;
            }
        }
        Ok(statement)
    }

    // Parse expression, could be a search term, number, operator or combination of epxressions
    fn parse_expression(&mut self, precedence: Precedence) -> Result<Expression, ParseError> {
        let mut expr = match self.current.clone() {
            Token::WordOrPhrase(s) => {
                self.expect_token_and_read(Token::WordOrPhrase("".to_string()))?;
```

```
                    Expression::WordOrPhrase(s.to_string())
                }
                Token::Number(u) => {
                    self.expect_token_and_read(Token::Number(0))?;
                    Expression::Number(u)
                }
                Token::ZeroToOne(f) => {
                    self.expect_token_and_read(Token::ZeroToOne(0.0))?;
                    Expression::ZeroToOne(f)
                }
                t @ Token::Minus | t @ Token::Bang => {
                    self.expect_token_and_read(t.clone())?;
                    Expression::Prefix(
                        Operator::token(t),
                        Box::new(self.parse_expression(Precedence::Prefix)?),
                    )
                }
                // Start a group which gets higher precedence
                Token::LeftParen => {
                    let group_expression = match self.parse_group()? {
                        Statement::Group { expression } => expression,
                        _ => return Err(ParseError::Unreachable),
                    };
                    group_expression
                }
                _ => return Err(ParseError::UnexpectedToken(self.current.clone())),
            };
            // Afer an expression could be an infix operator or directly a new expression (here called postfix operator)
            while !self.current_is(Token::EoF) && precedence < Precedence::token(self.current.clone()) {
                if let Some(expression) = self.parse_postfix_expression(expr.clone())? {
                    expr = expression;
```

```
            } else if let Some(expression) = self.parse_infix_expression(expr.clone())? {
                expr = expression
            } else {
                break;
            }
        }
        Ok(expr)
    }

    // Postfix operator is called when two expressions are read, automatically inserting an AND inbetween
    // Second Expression could have an NOT operator before the actual expression
    fn parse_postfix_expression(
        &mut self,
        expr: Expression,
    ) -> Result<Option<Expression>, ParseError> {
        Ok(match self.current {
            Token::Minus | Token::Bang | Token::WordOrPhrase(..) => {
                let sec_expr = self.parse_expression(Precedence::And)?;
                Some(Expression::Infix(
                    Box::new(expr),
                    Operator::And,
                    Box::new(sec_expr),
                ))
            }
            _ => None,
        })
    }

    // Infix operators AND and OR expect an expression on either side
    fn parse_infix_expression(
        &mut self,
        expr: Expression,
    ) -> Result<Option<Expression>, ParseError> {
        Ok(match self.current {
```

```
            Token::Plus | Token::And | Token::Or => {
                let token = self.current.clone();
                self.read();
                let sec_expr = self.parse_expression(Precedence
                   ::token(token.clone()))?;
                Some(Expression::Infix(
                    Box::new(expr),
                    Operator::token(token),
                    Box::new(sec_expr),
                ))
            }
            _ => None,
        })
    }

    // Infix operators AND and OR expect a statement on either
       side
    fn parse_infix_statement(
        &mut self,
        statement: Statement,
    ) -> Result<Option<Statement>, ParseError> {
        Ok(match self.current {
            Token::Plus | Token::And | Token::Or => {
                let token = self.current.clone();
                self.read();
                let second_statement = self.parse_statement(
                   Precedence::token(token.clone()))?;
                Some(Statement::Infix {
                    statement: Box::new(statement),
                    operator: Operator::token(token),
                    second_statement: Box::new(second_statement
                       ),
                })
            }
            _ => None,
        })
    }

    // Functions all have a similar strucure needing colons to
       surround their parameters
```

```

    // Contains function only expects one word or phrase or combination of expressions
    fn parse_contains(&mut self) -> Result<Expression, ParseError> {
        self.expect_token_and_read(Token::Contains)?;
        self.expect_token_and_read(Token::Colon)?;
        let expression: Expression = self.parse_expression(Precedence::Statement)?;
        self.expect_token_and_read(Token::Colon)?;
        Ok(expression)
    }

    // Startswith function only expects one one word or phrase or combination of expressions
    fn parse_starts(&mut self) -> Result<Expression, ParseError> {
        self.expect_token_and_read(Token::Starts)?;
        self.expect_token_and_read(Token::Colon)?;
        let expression: Expression = self.parse_expression(Precedence::Statement)?;
        self.expect_token_and_read(Token::Colon)?;
        Ok(expression)
    }

    // Inflection function only expects one one word or phrase or combination of expressions
    fn parse_inflection(&mut self) -> Result<Expression, ParseError> {
        self.expect_token_and_read(Token::Inflection)?;
        self.expect_token_and_read(Token::Colon)?;
        let expression: Expression = self.parse_expression(Precedence::Statement)?;
        self.expect_token_and_read(Token::Colon)?;
        Ok(expression)
    }

    // Thesaurus function only expects one one word or phrase or combination of expressions
```

```
    fn parse_thesaurus(&mut self) -> Result<Expression, ParseError> {
        self.expect_token_and_read(Token::Thesaurus)?;
        self.expect_token_and_read(Token::Colon)?;
        let expression: Expression = self.parse_expression(Precedence::Statement)?;
        self.expect_token_and_read(Token::Colon)?;
        Ok(expression)
    }

    // Near function expects multiple comma-seperated words or phrases with an optional number as the last parameter
    fn parse_near(&mut self) -> Result<(Vec<Expression>, Expression), ParseError> {
        self.expect_token_and_read(Token::Near)?;
        self.expect_token_and_read(Token::Colon)?;
        let mut parameter: Vec<Expression> = Vec::new();
        // Proximity has a default value of 5 if no number is given
        let mut proximity = Expression::Number(5);
        while !self.current_is(Token::Colon) {
            if self.current_is(Token::Comma) {
                self.expect_token_and_read(Token::Comma)?;
            }
            match self.parse_expression(Precedence::Lowest)? {
                Expression::WordOrPhrase(s) => parameter.push(Expression::WordOrPhrase(s)),
                Expression::Number(u) => {
                    if self.current_is(Token::Colon) {
                        proximity = Expression::Number(u)
                    } else {
                        return Err(ParseError::UnexpectedToken(self.current.clone()));
                    }
                }
                _ => return Err(ParseError::UnexpectedToken(self.current.clone())),
            }
        }
        self.expect_token_and_read(Token::Colon)?;
```

```
        Ok((parameter, proximity))
    }

    // Weighted function expects pairs of words or phrases and a weight between 0 and 1
    // All weights must add up to exactly 1
    fn parse_weighted(&mut self) -> Result<Vec<(Expression, Expression)>, ParseError> {
        self.expect_token_and_read(Token::Weighted)?;
        self.expect_token_and_read(Token::Colon)?;
        let mut parameter: Vec<(Expression, Expression)> = Vec::new();
        let mut sum_weights: f64 = 0.0;
        while !self.current_is(Token::Colon) {
            if self.current_is(Token::Comma) {
                self.expect_token_and_read(Token::Comma)?;
            }
            let expression = match self.parse_expression(Precedence::Lowest)? {
                Expression::WordOrPhrase(s) => Expression::WordOrPhrase(s),
                _ => return Err(ParseError::UnexpectedToken(self.current.clone())),
            };
            self.expect_token_and_read(Token::Comma)?;
            let weight = match self.parse_expression(Precedence::Lowest)? {
                Expression::ZeroToOne(f) => {
                    sum_weights += f;
                    Expression::ZeroToOne(f)
                }
                _ => return Err(ParseError::UnexpectedToken(self.current.clone())),
            };
            parameter.push((expression, weight));
        }
        if sum_weights != 1.0 {
            return Err(ParseError::WeightError(sum_weights));
        }
        self.expect_token_and_read(Token::Colon)?;
```

```
        Ok(parameter)
    }

    // Groups must encapsulate an expression with parenthesis
       and have higher precedence then other operators
    fn parse_group(&mut self) -> Result<Statement, ParseError>
       {
        self.expect_token_and_read(Token::LeftParen)?;
        let expression = self.parse_expression(Precedence::
           Statement)?;
        self.expect_token_and_read(Token::RightParen)?;
        Ok(Statement::Group { expression })
    }
}

// Types of errors covered by the parser
#[derive(Debug, Error)]
pub enum ParseError {
    #[error("Unexpected token {0:?}.")]
    UnexpectedToken(Token),
    #[error("Entered unreachable code.")]
    Unreachable,
    #[error("Weights do not add up to 1.0. Sum of all weights:
       {0}")]
    WeightError(f64),
}
```

Appendix 4: ast.rs

```
use crate::code_gen::lexer::Token;

#[derive(Debug, Clone, PartialEq)]
pub enum Statement {
    Group {
        expression: Expression,
    },
    Infix {
        statement: Box<Statement>,
        operator: Operator,
```

```
        second_statement: Box<Statement>,
    },
    Contains {
        expression: Expression,
    },
    Starts {
        expression: Expression,
    },
    Inflection {
        expression: Expression,
    },
    Thesaurus {
        expression: Expression,
    },
    Near {
        parameter: Vec<Expression>,
        proximity: Expression,
    },
    Weighted {
        parameter: Vec<(Expression, Expression)>,
    },
    EoF,
}

#[derive(Debug, Clone, PartialEq)]
pub enum Expression {
    WordOrPhrase(String),
    Number(u64),
    ZeroToOne(f64),
    Infix(Box<Expression>, Operator, Box<Expression>),
    Prefix(Operator, Box<Expression>),
}

#[derive(Debug, Clone, PartialEq)]
pub enum Operator {
    And,
    Or,
    Not,
}

```

```
impl Operator {
    pub fn token(token: Token) -> Self {
        match token {
            Token::And | Token::Plus => Self::And,
            Token::Or => Self::Or,
            Token::Minus | Token::Bang => Self::Not,
            _ => unreachable!("{:?}", token),
        }
    }
}
```

Appendix 5: generator.rs

```
use std::slice::Iter;
use thiserror::Error;

use crate::code_gen::ast::{Expression, Operator, Statement};

// Database constants
const DB_NAME: &str = "Wikipedia";
const TBL_NAME: &str = "[dbo].[Real_Article]";
const RETURN_ATTRIBUTE: &str = "Title";
const TOP_ROWS: u64 = 5;

// Main function to start the generation process
// Input: vec of statements (ast)
// Output: string (sql statement)
pub fn generate(ast: Vec<Statement>) -> Result<String,
    GenerateError> {
    let mut generator = Generator::new(ast.iter());
    // write twice to overwrite initial EoF tokens
    generator.write();
    generator.write();
    let mut sql_parts: Vec<String> = Vec::new();
    sql_parts.push(format!(
        "USE {}; SELECT TOP {} * FROM(SELECT FT_TBL.{}, KEY_TBL
            .RANK FROM {} AS FT_TBL INNER JOIN CONTAINSTABLE({},
            *, '",
        DB_NAME, TOP_ROWS, RETURN_ATTRIBUTE, TBL_NAME, TBL_NAME
```

```
    ));
    // generate all functions as JOIN constraints
    while let Some(sql_part) = generator.next()? {
        sql_parts.push(sql_part);
    }
    sql_parts.push("') AS KEY_TBL ON FT_TBL.[ID] = KEY_TBL.[KEY
       ] WHERE KEY_TBL.RANK > 5) AS FS_RESULT ORDER BY
       FS_RESULT.RANK DESC;".to_owned());
    Ok(sql_parts.join(" "))
}

// Generator struct with current and next token as attributes
struct Generator<'p> {
    statements: Iter<'p, Statement>,
    current: Statement,
    peek: Statement,
}

impl<'p> Generator<'p> {
    // Initial generator creation
    fn new(statements: Iter<'p, Statement>) -> Self {
        Self {
            statements,
            current: Statement::EoF,
            peek: Statement::EoF,
        }
    }

    // Generate next statement if possible
    fn next(&mut self) -> Result<Option<String>, GenerateError>
        {
        if self.current == Statement::EoF {
            return Ok(None);
        }
        Ok(Some(self.generate_statement(self.current.clone())?)
           )
    }

    // Set current and peek one step further in the ast
    fn write(&mut self) {
```

```
        self.current = self.peek.clone();
        self.peek = if let Some(statement) = self.statements.
            next() {
            statement.clone()
        } else {
            Statement::EoF
        };
    }

    // Generate statement, always a function or combination of
       functions
    // Input: statement to generate
    // Output: string
    fn generate_statement(&mut self, statement: Statement) ->
       Result<String, GenerateError> {
        let sql: String = match statement {
            Statement::Infix {
                statement,
                operator,
                second_statement,
            } => {
                let sql_parts = [
                    self.generate_statement(*statement)?,
                    self.generate_operator(operator)?,
                    self.generate_statement(*second_statement)
                        ?,
                ];
                sql_parts.join(" ")
            }
            // Contains generates it's search condition without
                mutation
            Statement::Contains { expression } => {
                format!("{}", self.generate_expression(
                    expression)?)
            }
            // Startswith adds a * to end of a word or before
               the last " in a phrase
            Statement::Starts { expression } => {
                let mut word_or_phrase = self.
                    generate_expression(expression)?;
```

```
            if word_or_phrase.starts_with('"') && word_or_phrase.ends_with('"') {
                word_or_phrase.insert(word_or_phrase.len() - 1, '*');
            } else {
                word_or_phrase.push('*');
            }
            format!("{}", word_or_phrase)
        }
        // Inflection calls the inflection function from MSSQL
        Statement::Inflection { expression } => {
            let mut word_or_phrase = self.generate_expression(expression)?;
            if word_or_phrase.starts_with('"') && word_or_phrase.ends_with('"') {
                word_or_phrase.remove(0);
                word_or_phrase.remove(word_or_phrase.len() - 1);
            }
            format!("FORMSOF(INFLECTIONAL,\"{}\")", word_or_phrase)
        }
        // Thesaurus calls the thesaurus function from MSSQL
        Statement::Thesaurus { expression } => {
            let mut word_or_phrase = self.generate_expression(expression)?;
            if word_or_phrase.starts_with('"') && word_or_phrase.ends_with('"') {
                word_or_phrase.remove(0);
                word_or_phrase.remove(word_or_phrase.len() - 1);
            }
            format!("FORMSOF(THESAURUS,\"{}\")", word_or_phrase)
        }
        // Near generates a parameter list of all search criteria and proximity in the end
        Statement::Near {
```

```
                parameter,
                proximity,
            } => {
                let mut sql_parts: Vec<String> = Vec::new();
                sql_parts.push(format!("NEAR(("));
                for expression in parameter {
                    let string = self.generate_expression(expression)?;
                    sql_parts.push(format!("{}", string));
                    sql_parts.push(String::from(", "));
                }
                sql_parts.remove(sql_parts.len() - 1);
                sql_parts.push(format!("), {})", self.generate_expression(proximity)?));
                sql_parts.join("")
            }
            // Weighted generates tuples of search criteria and their respective weight
            Statement::Weighted { parameter } => {
                let mut sql_parts: Vec<String> = Vec::new();
                sql_parts.push(format!("ISABOUT("));
                for (word_or_phrase_expr, weight_expr) in parameter {
                    let word_or_phrase = self.generate_expression(word_or_phrase_expr)?;
                    let weight = self.generate_expression(weight_expr)?;
                    sql_parts.push(format!("{} WEIGHT({})", word_or_phrase, weight));
                    sql_parts.push(String::from(", "));
                }
                sql_parts.remove(sql_parts.len() - 1);
                sql_parts.push(String::from(")"));
                sql_parts.join("")
            }
            _ => return Err(GenerateError::UnexpectedStatement(self.current.clone())),
        };
        self.write();
```

```
        Ok(sql)
    }

    // Generate expression, any search criteria or number or combination of those
    // Input: expression to generate
    // Output: string
    fn generate_expression(&mut self, expression: Expression) -> Result<String, GenerateError> {
        let sql: String = match expression {
            Expression::WordOrPhrase(s) => s,
            Expression::Number(u) => u.to_string(),
            Expression::ZeroToOne(f) => f.to_string(),
            // Infix operator enclose their expressions with parenthesis to ensure precedence
            Expression::Infix(expr1, operator, expr2) => {
                let mut sql_parts = [
                    String::from("("),
                    self.generate_expression(*expr1)?,
                    String::from(")"),
                    self.generate_operator(operator)?,
                    String::from("("),
                    self.generate_expression(*expr2.clone())?,
                    String::from(")"),
                ];
                // If the second expression is a not operator it must write NOT before the parenthesis
                match *expr2 {
                    Expression::Prefix(Operator::Not, ..) => sql_parts[4] = String::from("NOT ("),
                    _ => (),
                }
                sql_parts.join(" ")
            }
            Expression::Prefix(operator, expr) => {
                let sql_parts = [
                    self.generate_operator(operator)?,
                    self.generate_expression(*expr)?,
                ];
                sql_parts.join(" ")
```

```
            }
        };
        Ok(sql)
    }

    // Generate operator
    // Input: operator to generate
    // Output: string
    fn generate_operator(&mut self, operator: Operator) -> Result<String, GenerateError> {
        let op = match operator {
            Operator::And => "AND",
            Operator::Or => "OR",
            // has to be set infront of parenthesis, see generate_expression for infix
            Operator::Not => "",
        };
        Ok(op.to_owned())
    }
}

// Types of error covered by the generator
#[derive(Debug, Error)]
pub enum GenerateError {
    #[error("Unexpected statement {0:?}.")]
    UnexpectedStatement(Statement),
}
```

Appendix 6: mod.rs

```
mod ast;
pub mod generator;
pub mod lexer;
pub mod parser;
```

Appendix 7: base.html

```
<!DOCTYPE html>
<html lang="en">
```

```
    <head>
        <meta charset="utf-8">
        <title>{{title}}</title>
    </head>
    <body>
        {% block content %}
        {% endblock %}
    </body>
</html>
```

Appendix 8: search.html

```
{% extends "base.html" %}

{% block content %}
<form action="" method="POST">
    <div>
        <label for="search">Search:</label>
        <input type="text" name="search">
    </div>
    <input type="submit" value="Submit">
</form>
{% endblock %}
```

Appendix 9: result.html

```
{% extends "base.html" %}

{% block content %}
<div>
    <p>{{ search }}</p>
</div>
{% for result in results %}
<div>
    <a href="https://en.wikipedia.org/wiki/{{ result.link }}">
       {{ result.title }}</a>
    <small>{{ result.rank }}</small>
</div>
{% endfor %}
```

```
{% endblock %}
```

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