



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

Sebastian Bunge

Advisor: Prof. Dr. Peter Steininger

Matriculation Number: 539441

Submission: October 18, 2022

Contents

Index of Figures	III
Index of Tables	IV
Index of Abbreviations	V
Index of Symbols	VI
Index of Formulae	VII
Index of Code Listings	VIII
1 Abstract	1
2 Theory	2
2.1 Full-Text Search	2
2.1.1 MS SQL Server Search Architecture	3
2.1.2 MS SQL Server Full-Text Query Features	5
2.2 Domain-Specific Languages	6
2.3 Building a language	7
2.3.1 Syntax	8
2.3.2 Extended Backus-Naur Form	8
3 Implementation	11
3.1 Language definition	11
3.2 Lexer	12
3.3 Parser	13
3.4 Parsing operators and groups	19
3.5 Generator	26
3.6 Interface with SQL server	34
3.7 Website as software interface	36
3.8 Error Handling	39
4 Summary	42
Appendix	43
Bibliography	75

Index of Figures

Figure 1: Architecture of MS SQL Server Full-Text Search	4
Figure 2: Parsed example AST	33

Index of Tables

Table 1: Popular DSLs	7
---------------------------------	---

Index of Abbreviations

APT	Automatically Programmed Tools
AST	abstract syntax tree
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

Index of Formulae

Formula 1: Precision	3
Formula 2: Recall	3
Formula 3: Weighed harmonic mean	3

Index of Code Listings

Code Listing 1: Token definitions	13
Code Listing 2: Parser struct	14
Code Listing 3: Statements and expressions	14
Code Listing 4: Parser read	15
Code Listing 5: Parse weighted	16
Code Listing 6: expect_token_and_read	18
Code Listing 7: Parse WordOrPhrase	19
Code Listing 8: Operator statements and expressions	20
Code Listing 9: Precedence	21
Code Listing 10: Parse NOT	22
Code Listing 11: Parse infix operator	22
Code Listing 12: Parse postfix operator	24
Code Listing 13: Parse groups	24
Code Listing 14: Parse infix operator in statements	25
Code Listing 15: Generate sql_parts	27
Code Listing 16: Generator struct	27
Code Listing 17: Generator write	28
Code Listing 18: Generate weighted	29
Code Listing 19: Generate infix operator statements	30
Code Listing 20: Generate expressions	31
Code Listing 21: Generate operator expressions	31
Code Listing 22: Generate operators	32
Code Listing 23: Generated example SQL	33
Code Listing 24: Execute SQL	34
Code Listing 25: SQL server results	35
Code Listing 26: HTTP Server	36
Code Listing 27: Website search	37
Code Listing 28: Website results	38
Code Listing 29: Error handling in parser	39
Code Listing 30: Error display	40

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

$$p = \frac{n}{d} \quad (1)$$

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

$$r = \frac{n}{v} \quad (2)$$

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: Weighed harmonic mean

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

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:

$$\begin{aligned}\langle number \rangle &::= \langle positive \rangle | -\langle positive \rangle | 0 \\ \langle positive \rangle &::= \langle digit \ not \ zero \rangle \langle optional \rangle\end{aligned}$$

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

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:

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

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. To define a full-text search, usually use a combination of the given functions is used. In Transact-SQL this would be for example CONTAINS or FORMSOF. Therefore the goal is to develop a query language where only a combination of functions and a few parameters is necessary to generate the corresponding SQL.

3.1 Language definition

The first step to defining a language is to define its purpose. In this case, there should be functions that represent full-text functions. Furthermore, one must be able to pass parameters to these functions and one should be able to combine both parameters and functions with logical operators and, or and not. To announce a function, this query language uses an '@', e.g. '@contains'. From programming languages of the C-family one recognizes the use of parentheses '()' to define parameters. To avoid later confusion with parentheses used for logical grouping, this language uses the colon ':' to enclose parameters. For now, a parameter is defined as a simple word or phrase, which is delimited with quotes '"'. These few rules already allow the definition of a query, such as `@contains:apple:` where 'contains' is the name of a function. This first set of rules can be written in EBNF as:

```

<search> ::= '@' <function> ':' <parameter> ':' ;
<function> ::= 'contains' ;
<parameter> ::= <word> | ' ' '[' <word> ']' ;
<word> ::= { 'a'-'z' | 'A'-'Z' } ;

```

Note that the function variable only includes 'contains'. In future definitions, it should accept the different functions that are going to be defined.

A feature that is also needed is the logical combination and negation of multiple search terms. For example, it should be possible to search for 'apple' or 'tree' and not 'worm'. To represent AND the language accepts the characters '&' and '+', for OR it accepts '|', and for negation it accepts '!' and '-'. To cover all possible logical operations, groups are also needed to allow precedence between the different operators. For this parentheses are used. Using groups it is now possible to build a logic like 'apple' AND NOT('tree' OR 'worm'), where the whole statement inside the parentheses is processed negated, and prioritized instead of simply being processed from left to right.

Contains should be a simple search for a search term or a combination of search terms.

Startswith searches for terms, which start with the given search term.

Thesaurus uses a thesaurus to search for entries with the same meaning as the search terms.

Weighted enables the search for multiple search terms and assigns each a weight to allow certain terms to be prioritized.

These specifications and rules define the language in EBNF as follows:

$$\langle function \rangle ::= '@contains';$$
$$\langle word \rangle ::= \{ 'a' - 'z' | 'A' - 'Z' \};$$

The first part of a code generator is the lexer. A lexer gets a file or in this case a string as input and divides this input into a series of tokens. So the input `@contains:apple:` becomes the tokens: `'@'`, `'contains'`, `':'`, `'apple'` and `':'`. These tokens are not interpreted yet but are only being recognized as separate characters. To achieve this in code the crate `logos` is used, to avoid writing redundant code. To understand the code written in `lexer.rs` what follows is a short explanation of how this crate is used in the context of this prototype. To define tokens, `Logos` can be added to the `derive` statement of an enumeration and a matching rule can be defined using a literal string or a regular expression. For example, in line 73 of code listing 1, a literal string is used to recognize the colon token, and line 33 uses a regular expression to recognize decimals between 0 and 1. It also calls an arbitrary function to `float` (code 1, 17-19) to define that in this case the data should be cast into the

datatype f64. Logos also requires an error type (code 1, 78-80), which is also used to skip whitespaces (cf. HIRSZ 2022, n.p.).

Code Listing 1: Token defintions

```

16 // helper function to format floats
17 fn to_float(lex: &mut Lexer<Token>) -> Option<f64> {
18     Some(lex.slice().parse().ok())
19 }
20
21 :
22
26 // List of all tokens that are accepted by the language
27 #[derive(Debug, Clone, Logos, PartialEq)]
28 pub enum Token {
29
30     :
31
32     // Regex: any float between 0 and 1
33     #[regex(r"0+(\.[0-9]+)?|1", to_float)]
34     ZeroToOne(f64),
35
36     :
37
72     // Colon to surround functions parameters
73     #[token(":")]
74     Colon,
75     // End of File
76     EoF,
77     // Error and skip whitespaces
78     #[error]
79     #[regex(r"[\s\t\n\f]+", logos::skip)]
80     Error,
81 }

```

Source: lexer.rs

These tokens are then compiled in a list and passed over to the parser as the work of the lexer is done.

3.3 Parser

In the parser, a large part of the heavy lifting is done, because here the list of tokens is interpreted and checked for their admissibility in the language. The parser of this custom

query language stores a copy of the token list still to be parsed and additionally the current token and the next one in the list. The current token is often used to make comparisons between it and the token that would be expected, while the peek token is often used to see whether the end of the token list has already been reached. When initializing the parser both the current and the peek token are set to `Token::EoF` which represents the edge case end of file (code 2, 66-67).

Code Listing 2: Parser struct

```

54 // Parser saves current and next tokens as attribute
55 struct Parser<'p> {
56     tokens: Iter<'p, Token>,
57     current: Token,
58     peek: Token,
59 }
60
61 impl<'p> Parser<'p> {
62     // Initial parser creation
63     fn new(tokens: Iter<'p, Token>) -> Self {
64         Self {
65             tokens,
66             current: Token::EoF,
67             peek: Token::EoF,
68         }
69     }

```

Source: parser.rs

In the parsing process, two different levels are distinguished: expressions and statements. Statements are the various functions that can be used in the language, such as 'near', which is defined with several expressions as 'parameters' and another expression as a 'proximity' variable (code 3, 25-28). Expressions are the several values that can appear in a search query, for example, words, phrases, or numbers (code 3, 37-38). The special cases of operators are also represented by both statements and expressions. These will be discussed in more detail later.

Code Listing 3: Statements and expressions

```

3 #[derive(Debug, Clone, PartialEq)]
4 pub enum Statement {
5
6     :
7
25     Near {

```

```

26         parameter: Vec<Expression>,
27         proximity: Expression,
28     },
29
30     :
31
32     #[derive(Debug, Clone, PartialEq)]
33     pub enum Expression {
34         WordOrPhrase(String),
35         Number(u64),
36         ZeroToOne(f64),

```

Source: ast.rs

The tokens are normally processed linearly, always watching out not to run past the end of the file (code 4, 74). With each call of read current and peek are updated and the next statement is parsed. Read is called manually twice at the beginning to overwrite the initial `Token::EoF` (code 4, 12-14). Otherwise, the next statements are parsed until the end of the token list is reached (code 4, 16-18).

Code Listing 4: Parser read

```

7  // Main function to start parsing process
8  // Input: vec of tokens
9  // Output: abstract syntax tree (vec of statements)
10 pub fn parse(tokens: Vec<Token>) -> Result<Vec<Statement>,
    ParseError> {
11     let mut parser = Parser::new(tokens.iter());
12     // read twice to overwrite initial EoF tokens
13     parser.read();
14     parser.read();
15     let mut ast: Vec<Statement> = Vec::new();
16     while let Some(statement) = parser.next()? {
17         ast.push(statement);
18     }
19     Ok(ast)
20 }
21
22 :
23
71 // Parse next statement if possible
72 // Output: statement or error
73 fn next(&mut self) -> Result<Option<Statement>, ParseError>
    {

```

```

74         if self.current == Token::EoF {
75             return Ok(None);
76         }
77         Ok(Some(self.parse_statement(Precedence::Lowest)?))
78     }
79
80     // Set current and peek one step further in the vec of
81     // tokens
82     fn read(&mut self) {
83         self.current = self.peek.clone();
84         self.peek = if let Some(token) = self.tokens.next() {
85             token.clone()
86         } else {
87             Token::EoF
88         };
89     }

```

Source: parser.rs

When parsing a statement there must be a function token at the beginning of a statement (code 5, 120+140). If this token is found, the procedure is different depending on the function. For example, the function weighted is parsed as follows: (code 5, 325-355)

First, a colon is expected, because according to the language definition the parameters are introduced with one. As parameters, there are expected to be combinations of a search term (word or phrase) and a decimal between 0 and 1. These must be separated by commas. These tuples are expected until a colon appears as a token again. The decimals representing weights must add up to exactly 1. If none of the rules are violated, the list of tuples is passed back to the function `parse_statement` and stored in the form of a statement enumeration (code 5, 140-142).

Code Listing 5: Parse weighted

```

116     // Parse statement, can only be a function or combination
117     // of functions
118     // Input: precedence
119     // Output: statement or error
120     fn parse_statement(&mut self, precedence: Precedence) ->
121         Result<Statement, ParseError> {
122         let mut statement = match self.current.clone() {
123
124         :
125
126         Token::Weighted => Statement::Weighted {

```



```

141         parameter: self.parse_weighted()?,
142     },
143     :
144     :
145     :
325     // Weighted function expects pairs of words or phrases and
326     // a weight between 0 and 1
327     // All weights must add up to exactly 1
328     fn parse_weighted(&mut self) -> Result<Vec<(Expression,
329     Expression)>, ParseError> {
330         self.expect_token_and_read(Token::Weighted)?;
331         self.expect_token_and_read(Token::Colon)?;
332         let mut parameter: Vec<(Expression, Expression)> = Vec
333             ::new();
334         let mut sum_weights: f64 = 0.0;
335         while !self.current_is(Token::Colon) {
336             if self.current_is(Token::Comma) {
337                 self.expect_token_and_read(Token::Comma)?;
338             }
339             let expression = match self.parse_expression(
340                 Precedence::Lowest)? {
341                 Expression::WordOrPhrase(s) => Expression::
342                     WordOrPhrase(s),
343                 _ => return Err(ParseError::UnexpectedToken(
344                     self.current.clone())),
345             };
346             self.expect_token_and_read(Token::Comma)?;
347             let weight = match self.parse_expression(Precedence
348                 ::Lowest)? {
349                 Expression::ZeroToOne(f) => {
350                     sum_weights += f;
351                     Expression::ZeroToOne(f)
352                 }
353                 _ => return Err(ParseError::UnexpectedToken(
354                     self.current.clone())),
355             };
356             parameter.push((expression, weight));
357         }
358         if sum_weights != 1.0 {
359             return Err(ParseError::WeightError(sum_weights));
360         }

```

```

353         self.expect_token_and_read(Token::Colon)?;
354         Ok(parameter)
355     }

```

Source: parser.rs

In the `parse_statement` function, two different functions are called to process tokens. On the one hand, `expect_token_and_read` (code 6, 110-114) compares the current token with an input variable and reads past it without further logic. This function is mostly used for parsing syntactic tokens, such as the colon, which themselves have no impact on the content of the search.

Code Listing 6: `expect_token_and_read`

```

90     // See what the current token is
91     // Output: boolean
92     fn current_is(&self, token: Token) -> bool {
93         std::mem::discriminant(&self.current) == std::mem::
94             discriminant(&token)
95     }
96
97     // Current token should match the one given
98     // Input: token
99     // Output: token or error
100     fn expect_token(&mut self, token: Token) -> Result<Token,
101         ParseError> {
102         if self.current_is(token) {
103             Ok(self.current.clone())
104         } else {
105             Err(ParseError::UnexpectedToken(self.current.clone()
106                 ()))
107         }
108     }
109
110     // Current token should match the one given and read to
111     // next token
112     // Input: token
113     // Output: token or error
114     fn expect_token_and_read(&mut self, token: Token) -> Result
115         <Token, ParseError> {
116         let result = self.expect_token(token)?;
117         self.read();

```

```

113         Ok(result)
114     }

```

Source: parser.rs

The second function is `parse_expression`, which is similar in logic to `parse_statement`. Here the current token is compared to the possible expressions and returned as an expression enumeration. For example, with the `WordOrPhrase` token, the content is stored in the variable `s` and passed when the expression counterpart is generated (code 7, 159-161).

Code Listing 7: Parse WordOrPhrase

```

156     // Parse expression, could be a search term, number,
        operator or combination of expressions
157     fn parse_expression(&mut self, precedence: Precedence) ->
        Result<Expression, ParseError> {
158         let mut expr = match self.current.clone() {
159             Token::WordOrPhrase(s) => {
160                 self.expect_token_and_read(Token::WordOrPhrase(
                    "".to_string()))?;
161                 Expression::WordOrPhrase(s.to_string())
162             }

```

Source: parser.rs

With these building blocks, it is already possible to parse a token list, like

```

Near, Colon, WordOrPhrase("apple"), Comma, WordOrPhrase("tree"),
Comma, Number(9), Colon

```

into the statement

```

Near{parameter: (WordOrPhrase("apple"), WordOrPhrase("tree")),
proximity: Number(9)}.

```

While parsing, attention has been paid to the syntax of the language and the information has been reduced to the minimum necessary in a structured way.

3.4 Parsing operators and groups

In addition to simple search terms and the call of a single function, the query language should also offer the possibility to logically link search terms and use several functions simultaneously. To make this possible, operators such as AND, OR, and NOT, and groups come into play. To interpret these types of operators and groups and store them as part of

the abstract syntax tree (AST), there are separate types for them as both statement and expression. The statement enumeration (code 8, 8-12) is used to allow the use of multiple functions in the query language, while the expression enumerations (code 8, 40-41) are used to logically link search terms. The operators themselves are stored as a separate enumeration, with a function to translate tokens into operators (code 8, 52-59).

Code Listing 8: Operator statements and expressions

```

3  #[derive(Debug, Clone, PartialEq)]
4  pub enum Statement {
5      Group {
6          expression: Expression,
7      },
8      Infix {
9          statement: Box<Statement>,
10         operator: Operator,
11         second_statement: Box<Statement>,
12     },
13     :
33 }
34
35 #[derive(Debug, Clone, PartialEq)]
36 pub enum Expression {
37     :
40     Infix(Box<Expression>, Operator, Box<Expression>),
41     Prefix(Operator, Box<Expression>),
42 }
43
44 #[derive(Debug, Clone, PartialEq)]
45 pub enum Operator {
46     And,
47     Or,
48     Not,
49 }
50
51 impl Operator {
52     pub fn token(token: Token) -> Self {
53         match token {
54             Token::And | Token::Plus => Self::And,

```

```

55         Token::Or => Self::Or,
56         Token::Minus | Token::Bang => Self::Not,
57         _ => unreachable!("{:?}", token),
58     }
59 }
60 }

```

Source: ast.rs

The big challenge with operators and groups is that it is no longer sufficient to process the token list linearly because operators are partly written after the affected tokens and hierarchies exist between the operators. For example, the AND operator has a stronger binding power than the OR operator, and groups, or parentheses, have an even higher binding power. This binding power is in text and code further called precedence.

Precedence is implemented as an ordered enumeration, which allows them to be compared and assigned higher or lower precedence. As with operators, there is a function to translate tokens into precedence (code 9, 37-51). The concept of precedence already appears in the code listings 5 and 7 as an input variable for the functions `parse_statement` and `parse_expression`.

Code Listing 9: Precedence

```

22 // Precedence to enable priorities between operators
23 // Example: this OR that AND some (AND should have a higher
    priority)
24 #[derive(Debug, Clone, PartialEq, PartialOrd)]
25 enum Precedence {
26     Lowest,
27     Statement,
28     Or,
29     And,
30     Not,
31     Prefix,
32     Group,
33 }
34
35 // Match tokens to precedences
36 impl Precedence {
37     fn token(token: Token) -> Self {
38         match token {
39             Token::Bang | Token::Minus => Self::Not,

```

```

40         Token::Plus | Token::And | Token::WordOrPhrase(..)
           => Self::And,
41         Token::Or => Self::Or,
42         Token::LeftParen => Self::Group,
43         Token::Contains
           | Token::Starts
44         | Token::Inflection
45         | Token::Thesaurus
46         | Token::Near
47         | Token::Weighted => Self::Statement,
48         _ => Self::Lowest,
49     }
50 }
51 }
52 }

```

Source: parser.rs

Expression operators that are written before the token in question, such as the NOT operator, can be processed similarly to normal expressions. When the parser encounters one of the NOT tokens in `parse_expression` (code 10, 171-177), an `Expression::Prefix` is returned, where the actual search term is parsed with the parameter `Precedence::Prefix`, which is higher than the default `Precedence::Lowest`.

Code Listing 10: Parse NOT

```

171         t @ Token::Minus | t @ Token::Bang => {
172             self.expect_token_and_read(t.clone())?;
173             Expression::Prefix(
174                 Operator::token(t),
175                 Box::new(self.parse_expression(Precedence::
176                     Prefix)?),
177             )
178         }

```

Source: parser.rs

More complicated are operators which are written after an affected token. For this, in `parse_expression` after a token was parsed an attempt is made to parse a postfix or infix operator. At the same time, the precedence of the next token is compared to keep the corresponding hierarchies of the operators (code 11, 189-197). The expression parsed so far is passed to the `parse_infix_expression` function and it structures it into an `Expression::Infix`, where the next search term is parsed again with the corresponding precedence.

Code Listing 11: Parse infix operator

```

188         // Afer an expression could be an infix operator or
           directly a new expression (here called postfix
           operator)
189     while !self.current_is(Token::EoF) && precedence <
           Precedence::token(self.current.clone()) {
190         if let Some(expression) = self.
           parse_postfix_expression(expr.clone())? {
191             expr = expression;
192         } else if let Some(expression) = self.
           parse_infix_expression(expr.clone())? {
193             expr = expression
194         } else {
195             break;
196         }
197     }
    :
    :

220     // Infix operators AND and OR expect an expression on
           either side
221     fn parse_infix_expression(
222         &mut self,
223         expr: Expression,
224     ) -> Result<Option<Expression>, ParseError> {
225         Ok(match self.current {
226             Token::Plus | Token::And | Token::Or => {
227                 let token = self.current.clone();
228                 self.read();
229                 let sec_expr = self.parse_expression(Precedence
                    ::token(token.clone()))?;
230                 Some(Expression::Infix(
231                     Box::new(expr),
232                     Operator::token(token),
233                     Box::new(sec_expr),
234                 ))
235             }
236             _ => None,
237         })
238     }

```

Source: parser.rs

Postfix operators as such do not exist in the query language; instead, a search term written without an infix operator in between is parsed as a postfix AND (code 12, 203-218). So 'apple tree' is parsed as 'apple AND tree'. The second search term could potentially be negated, so the case 'apple -tree' is also covered and parsed as 'apple AND NOT tree'.

Code Listing 12: Parse postfix operator

```

201 // Postfix operator is called when two expressions are read
    , automatically inserting an AND inbetween
202 // Second Expression could have an NOT operator before the
    actual expression
203 fn parse_postfix_expression(
204     &mut self,
205     expr: Expression,
206 ) -> Result<Option<Expression>, ParseError> {
207     Ok(match self.current {
208         Token::Minus | Token::Bang | Token::WordOrPhrase
209         (..) => {
210             let sec_expr = self.parse_expression(Precedence
211                 ::And)?;
212             Some(Expression::Infix(
213                 Box::new(expr),
214                 Operator::And,
215                 Box::new(sec_expr),
216             ))
217         }
218         _ => None,
219     })
220 }
```

Source: parser.rs

Groups are delimited by parentheses and contain the highest precedence of all operators. Inside a group, an expression is expected (code 13, 360), which is then returned as soon as a right parenthesis is read. It should be emphasized that groups are not expressions, but only handle the included expression with higher precedence, so the inner expression itself is returned instead of some kind of group expression (code 13, 184).

Code Listing 13: Parse groups

```

178 // Start a group which gets higher precedence
179 Token::LeftParen => {
```



```

180         let group_expression = match self.parse_group()
181         ? {
182             Statement::Group { expression } =>
183                 expression,
184             _ => return Err(ParseError::Unreachable),
185         };
186         group_expression
187     }
188
189     :
190
357     // Groups must encapsulate an expression with parentheses
358     and have higher precedence than other operators
359     fn parse_group(&mut self) -> Result<Statement, ParseError>
360     {
361         self.expect_token_and_read(Token::LeftParen)?;
362         let expression = self.parse_expression(Precedence::
363             Statement)?;
364         self.expect_token_and_read(Token::RightParen)?;
365         Ok(Statement::Group { expression })
366     }

```

Source: parser.rs

Infix operators were also implemented at the statement level to allow multiple functions to be used in a single query. The logic is the same as that of code listing 11, except that statements are processed instead of expressions.

Code Listing 14: Parse infix operator in statements

```

145     // After a function could be an infix operator
146     while !self.current_is(Token::Eof) && precedence <
147         Precedence::token(self.current.clone()) {
148         if let Some(in_statement) = self.
149             parse_infix_statement(statement.clone())? {
150             statement = in_statement
151         } else {
152             break;
153         }
154     }
155
156     :
157
240     // Infix operators AND and OR expect a statement on either
241     side

```

```

241     fn parse_infix_statement (
242         &mut self,
243         statement: Statement,
244     ) -> Result<Option<Statement>, ParseError> {
245         Ok(match self.current {
246             Token::Plus | Token::And | Token::Or => {
247                 let token = self.current.clone();
248                 self.read();
249                 let second_statement = self.parse_statement (
250                     Precedence::token(token.clone())?;
251                 Some(Statement::Infix {
252                     statement: Box::new(statement),
253                     operator: Operator::token(token),
254                     second_statement: Box::new(second_statement),
255                 })
256             },
257             _ => None,
258         })
259     }

```

Source: parser.rs

These are all the building blocks needed to parse the entirety of the query language. The result of the parser is a list of statements or AST. This is now passed to the generator to generate SQL code from the logical sequence of operators and search terms.

3.5 Generator

The generator is the last step of the code generator because it does not convert the query language into bytecode or similar, but into another language, in this case, SQL. For this purpose, the generator is similarly structured to the parser, except that it receives an AST as input instead of output and generates a string from it.

In Transact-SQL there are two ways to initiate a full-text search. The use of predicates to specify criteria for the search in the WHERE clause of a query and the use of a CONTAINSTABLE or FREETEXTTABLE, which contains matching results and can be joined to the table to be searched. This generator uses a CONTAINSTABLE to represent all the functions offered by the query language in SQL. This method is preferred to predicates because it allows getting a list of results, sorted by how much they match the search criteria, also called a rank. In addition, CONTAINSTABLE is preferred to FREETEXTTABLE,

because FREETEXTTABLE is suitable for more fuzzy searches and less for searches that use defining functions to narrow down the results.

Based on these findings, a part of the SQL command can be preformulated with a few constants containing the metadata of the database (code 15, 7-10). So an INNER JOIN of the CONTAINSTABLE and the table to be searched is made, where the rank must be greater than five to weed out inaccurate matches (code 15, 29). From this, the title and rank are selected and sorted by rank in descending order. The top five results are then finally returned (code 15, 22). The exact specifications of the CONTAINSTABLE, which represent the search criteria, is the part that is filled by the generator (code 15, 26-28).

Code Listing 15: Generate sql_parts

```

6 // Database constants
7 const DB_NAME: &str = "Wikipedia";
8 const TBL_NAME: &str = "[dbo].[Real_Article]";
9 const RETURN_ATTRIBUTE: &str = "Title";
10 const TOP_ROWS: u64 = 5;
11
12 :
13
14
15
16
17
18
19
20 let mut sql_parts: Vec<String> = Vec::new();
21 sql_parts.push(format!(
22     "USE {}; SELECT TOP {} * FROM(SELECT FT_TBL.{}, KEY_TBL
23         .RANK FROM {} AS FT_TBL INNER JOIN CONTAINSTABLE({},
24         *, ' ",
25     DB_NAME, TOP_ROWS, RETURN_ATTRIBUTE, TBL_NAME, TBL_NAME
26 )));
27 // generate all functions as JOIN constraints
28 while let Some(sql_part) = generator.next()? {
29     sql_parts.push(sql_part);
30 }
31 sql_parts.push("'') AS KEY_TBL ON FT_TBL.[ID] = KEY_TBL.[KEY
32     ] WHERE KEY_TBL.RANK > 5) AS FS_RESULT ORDER BY
33     FS_RESULT.RANK DESC;".to_owned());

```

Source: generator.rs

Similar to the parser, the generator stores the list of statements and additionally the current and next statements as attributes, where the peek statement is used to check the end of the list. On initialization current and peek are set to `Statement:::EoF` (code 16, 45-46).

Code Listing 16: Generator struct

```

33 // Generator struct with current and next statements as
    attributes
34 struct Generator<'p> {
35     statements: Iter<'p, Statement>,
36     current: Statement,
37     peek: Statement,
38 }
39
40 impl<'p> Generator<'p> {
41     // Initial generator creation
42     fn new(statements: Iter<'p, Statement>) -> Self {
43         Self {
44             statements,
45             current: Statement::EoF,
46             peek: Statement::EoF,
47         }
48     }

```

Source: generator.rs

The logic to iterate through the list is similar to that of the parser with the use of a next function which checks if the end of the list has already been reached (code 17, 52) and generates the next element if not and a write function which updates the current and peek attributes (code 17, 60-65).

Code Listing 17: Generator write

```

50 // Generate next statement if possible
51 fn next(&mut self) -> Result<Option<String>, GenerateError>
    {
52     if self.current == Statement::EoF {
53         return Ok(None);
54     }
55     Ok(Some(self.generate_statement(self.current.clone())?))
    }
56
57
58 // Set current and peek one step further in the ast
59 fn write(&mut self) {
60     self.current = self.peek.clone();
61     self.peek = if let Some(statement) = self.statements.
        next() {

```

```

62         statement.clone()
63     } else {
64         Statement::EoF
65     };
66 }

```

Source: generator.rs

In the code, three functions are used to generate all elements of an AST. Similar to the parser, a distinction is made between statements and expressions and additionally operators.

The `generate_statement` function is passed a statement to be generated (code 18, 71). Usually, this statement is one of the implemented functions of the query language, for example, `weighted`. In the case of the `weighted` function, the stored attribute `'parameter'` is used to translate the statement into SQL as follows. First, the SQL function `ISABOUT` is called and a parenthesis is opened (code 18, 136). Then, for each tuple of search terms and their weights, the values are written down so that, for example, the values `'apple'` and `0.4` give `apple WEIGHT (0.4)`, (code 18, 137-142). Finally, the last comma is deleted, the parenthesis of `ISABOUT` is closed, and all parts are combined into one string and returned (code 18, 143-145+150).

Code Listing 18: Generate weighted

```

68     // Generate statement, always a function or combination of
        functions
69     // Input: statement to generate
70     // Output: string
71     fn generate_statement(&mut self, statement: Statement) ->
        Result<String, GenerateError> {
72         let sql: String = match statement {
        :
        :
133         // Weighted generates tuples of search criteria and
            their respective weight
134         Statement::Weighted { parameter } => {
135             let mut sql_parts: Vec<String> = Vec::new();
136             sql_parts.push(format!("ISABOUT("));
137             for (word_or_phrase_expr, weight_expr) in
                parameter {
138                 let word_or_phrase = self.
                    generate_expression(word_or_phrase_expr)
                    ?;

```

```

139         let weight = self.generate_expression(
            weight_expr)?;
140         sql_parts.push(format!("{}", WEIGHT({})),
            word_or_phrase, weight));
141         sql_parts.push(String::from(", "));
142     }
143     sql_parts.remove(sql_parts.len() - 1);
144     sql_parts.push(String::from(")"));
145     sql_parts.join("")
146 }
:
148 };
149 self.write();
150 Ok(sql)
151 }

```

Source: generator.rs

There is a special case in `generate_statement`, infix operators, this case calls `generate_statement` for the two statements and `generate_operator` for the operator (code 19, 79-81) and combines the results.

Code Listing 19: Generate infix operator statements

```

73     Statement::Infix {
74         statement,
75         operator,
76         second_statement,
77     } => {
78         let sql_parts = [
79             self.generate_statement(*statement)?,
80             self.generate_operator(operator)?,
81             self.generate_statement(*second_statement)
            ?,
82         ];
83         sql_parts.join(" ")
84     }

```

Source: generator.rs

In the example above for generating weighted, the `generate_expression` function was called in code listing 18 in lines 138 and 139 to generate the search terms and weights.

This function takes as input the expression it should generate and returns the value of the expression as a string if a normal expression was passed (code 20, 158-160).

Code Listing 20: Generate expressions

```

153     // Generate expression, any search criteria or number or
        combination of those
154     // Input: expression to generate
155     // Output: string
156     fn generate_expression(&mut self, expression: Expression)
        -> Result<String, GenerateError> {
157         let sql: String = match expression {
158             Expression::WordOrPhrase(s) => s,
159             Expression::Number(u) => u.to_string(),
160             Expression::ZeroToOne(f) => f.to_string(),
        :
186         };
187         Ok(sql)
188     }

```

Source: generator.rs

If a form of an operator is passed as an expression, the corresponding generate function is called for the operators (code 21, 167+181) and the respective expressions are passed to the generate_expression function. In the case of infix operators, parentheses are also set to safely represent the precedence as recognized by the parser (code 21, 164-170). Something to pay attention to in SQL is that if a NOT operator follows an infix operator, it must be written before the parenthesis, otherwise, SQL throws a syntax error. To cover this case, infix operator generation checks if the second expression is a negation and rewrites the string in that case (code 21, 173-176).

Code Listing 21: Generate operator expressions

```

161     // Infix operator enclose their expressions with
        parentheses to ensure precedence
162     Expression::Infix(expr1, operator, expr2) => {
163         let mut sql_parts = [
164             String::from("("),
165             self.generate_expression(*expr1)?,
166             String::from(")"),
167             self.generate_operator(operator)?,
168             String::from("("),

```

```

169         self.generate_expression(*expr2.clone())?,
170         String::from(")"),
171     ];
172     // If the second expression is a not operator
173     // it must write NOT before the parenthesis
174     match *expr2 {
175         Expression::Prefix(Operator::Not, ..) =>
176             sql_parts[4] = String::from("NOT ("),
177         _ => (),
178     }
179     sql_parts.join(" ")
180 }
181 Expression::Prefix(operator, expr) => {
182     let sql_parts = [
183         self.generate_operator(operator)?,
184         self.generate_expression(*expr)?,
185     ];
186     sql_parts.join(" ")
187 }

```

Source: generator.rs

The third and simplest generate function is `generate_operator`, which translates operators into a string (code 22, 195-196). Noticeable here is the NOT operator, which is already treated separately in code listing 21 lines 173-176.

Code Listing 22: Generate operators

```

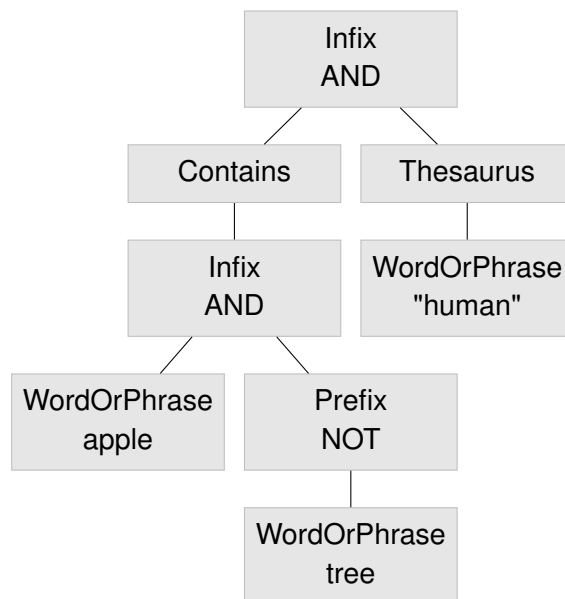
190     // Generate operator
191     // Input: operator to generate
192     // Output: string
193     fn generate_operator(&mut self, operator: Operator) ->
194         Result<String, GenerateError> {
195         let op = match operator {
196             Operator::And => "AND",
197             Operator::Or => "OR",
198             // has to be set in front of parentheses, see
199             // generate_expression for infix
200             Operator::Not => "",
201         };
202         Ok(op.to_owned())
203     }

```


Source: generator.rs

All parts up to the generator combined already make up a working code generator for a custom query language. For example the input `@contains:apple -tree: + @thesaurus:"human":`, the lexer converts into a list of tokens. The parser then interprets these tokens into an AST, one exemplary representation can be seen in figure 2.

Figure 2: Parsed example AST



Source: Own representation

The generator then takes the AST and generates from it the SQL in code listing 23. Lines 1 to 9 and 11 to 14 are the more or less pre-formulated part using the constants of the test database. Line 10 is the intriguing part, which is generated from the passed functions and search criteria.

Code Listing 23: Generated example SQL

```

1 USE Wikipedia;
2 SELECT TOP 5 *
3 FROM(
4     SELECT FT_TBL.Title,
5           KEY_TBL.RANK
6     FROM [dbo].[Real_Article] AS FT_TBL
7     INNER JOIN CONTAINSTABLE(
8         [dbo].[Real_Article],
9         *,

```

```

10         ' ( apple ) AND NOT ( tree ) AND FORMSOF (
           THESAURUS,"human") '
11     ) AS KEY_TBL ON FT_TBL.[ID] = KEY_TBL.[KEY]
12     WHERE KEY_TBL.RANK > 5
13 ) AS FS_RESULT
14 ORDER BY FS_RESULT.RANK DESC;

```

Source: Own code generator

3.6 Interface with SQL server

To interface with the SQL server hosting the full-text index and test data a connection must be established to run any queries. Since the server is hosted on the same machine as the Rust script, the local command line can be used. The command is passed the SQL as a path to the respective file and the result is then written to a path by the server as well (code 24, 67-70).

Code Listing 24: Execute SQL

```

57 // Runs a command to execute an sql statement to a local MSSQL
   Server
58 // Input: paths to the input file and where to write the result
59 // Output: txt file interpretation of the MSSQL Server result
60 fn execute_sql(sql_path: &str, results_path: &str) {
61     Command::new("cmd")
62         .args(&[
63             "/C",
64             "sqlcmd",
65             "-S",
66             "DESKTOP-JKNEH40\\SQLEXPRESS", //Local server name
67             "-i",
68             sql_path,
69             "-o",
70             results_path,
71         ])
72     .output()
73     .expect("failed to execute operation");
74 }

```

Source: main.rs

The result of the server is stored in a txt file. The content is formatted to be easier for a human to read, but less suitable for machine processing. The first and last lines of the file contain query metadata, such as column names and numbers, and characters to visually delimit them, so they are removed (code 25, 86-94). The results themselves are formatted with unnecessary whitespace, and the last entry in a row is interpreted as the rank value (code 25, 99-106).

Code Listing 25: SQL server results

```

76 // Reads the txt file result and extracts the actual results
77 // Input: path to the txt file
78 // Output: vec of titles and their search rank
79 fn read_results(path: &str) -> Option<Vec<(String, u64)>> {
80     let contents = read_to_string(path).unwrap();
81     let mut contents_vec: Vec<&str> = contents.split("\n").
        collect();
82     // In case of error message, break
83     if contents_vec.len() < 6 {
84         return None;
85     }
86     // Remove metadata rows
87     // First 3-4 rows and last three rows
88     while !contents_vec[0].starts_with("--") {
89         contents_vec.remove(0);
90     }
91     contents_vec.remove(0);
92     contents_vec.remove(contents_vec.len() - 1);
93     contents_vec.remove(contents_vec.len() - 1);
94     contents_vec.remove(contents_vec.len() - 1);
95     // Go through each row and extract the titles and their
        ranks
96     let mut results: Vec<(String, u64)> = Vec::new();
97     for row in contents_vec {
98         // Remove unnecessary whitespaces
99         let row = row.replace("\r", "");
100        let re = Regex::new(r"\s+").unwrap();
101        let row = re.replace_all(&row, " ").to_string();
102        // Extract last 'word' as rank and save the rest as the
            title
103        let mut words: Vec<&str> = row.split(" ").collect();

```

```

104         let rank = words[words.len() - 1].parse::() .unwrap
            ();
105         words.remove(words.len() - 1);
106         let title = words.join(" ");
107
108         results.push((title, rank));
109     }
110     Some(results)
111 }

```

Source: main.rs

These two functions enable the automatic execution and evaluation of queries on the SQL server, where any kind of test data can be stored.

3.7 Website as software interface

To interact with the code generator a website is used as an interface. To create a simple website the Rust crate `actix_web` is used, which provides a web framework for Rust, and the crate `tera`, which enables the use of templates to quickly create a working frontend. To host a website using `actix_web`, an HTTP server must be started in an asynchronous main function (cf. EDE 2022, n.p.). With the help of `tera`, HTML templates can now be used (cf. PROUILLET 2022, n.p.) to pass data to the server (code 26, 20+22). The HTML code of the website can be found in the appendix. The HTTP server hosts two subpages (code 26, 23-24). These are the start page, where a search query can be submitted, and the result page, where the search results will be displayed.

Code Listing 26: HTTP Server

```

15 // Main function to start website on localhost:8080
16 // Run using 'cargo watch -x run'
17 #[actix_web::main]
18 async fn main() -> std::io::Result<()> {
19     HttpServer::new(|| {
20         let tera = Tera::new("templates/**/*.html").unwrap();
21         App::new()
22             .data(tera)
23             .route("/", web::get().to(search))
24             .route("/", web::post().to(result))
25     })
26     .bind("127.0.0.1:8080")?

```

```

27     .run()
28     .await
29 }

```

Source: main.rs

The interface between the website and Rust code serves two structs, which can exchange data between the two parties. For this purpose, the crate `serde` is used, with which structs can be easily serialized (cf. TOLNAY, TRYZELAAR 2017, n.p.). A struct for the search query including a string is needed (code 27, 114-117), and a struct for the search results, which contain a title and link as a string and a rank as an unsigned integer each (code 27, 118-123).

Each of the subpages is assigned a function, which defines for the respective page, what functionally happens on it. The search page is straightforward, a text field that can be submitted (code 27, 125-131).

Code Listing 27: Website search

```

113 // Search and Result structs to (de)serialize rust and website
    datatypes
114 #[derive(Deserialize)]
115 struct Search {
116     search: String,
117 }
118 #[derive(Serialize)]
119 struct Result {
120     title: String,
121     rank: u64,
122     link: String,
123 }
124
125 // Define functional parts of the search page
126 async fn search(tera: web::Data<Tera>) -> impl Responder {
127     let mut data = Context::new();
128     data.insert("title", "Search field");
129     let rendered = tera.render("search.html", &data).unwrap();
130     HttpResponse::Ok().body(rendered)
131 }

```

Source: main.rs

The function of the result page is a bit more complex because here the code generator is run, the SQL is executed and the results are read. Because the result page resembles a

POST request the function is passed the data of the search page. From this the search query is extracted and the code generator is executed (code 28, 138). With the help of two functions, the generated SQL is executed and the results are read (code 28, 141-142). The results of the query are in the form of a string-integer tuple and are now fitted into the form of the result struct (code 28, 146-153). The link attribute is very similar to the title, but all blanks are replaced with `_` so that this attribute can be used to link directly to the associated Wikipedia article, a small quirk of the chosen test data.

Code Listing 28: Website results

```

133 // Define functional parts of the result page
134 async fn result(tera: web::Data<Tera>, data: web::Form<Search>)
    -> impl Responder {
135     let mut page_data = Context::new();
136     let mut results: Vec<Result> = Vec::new();
137     // Run code generator with the string from the search field
138     match run_code_gen(data.search.clone(), PATH_SQL) {
139         // If code generator returns no error execute SQL and
            read the results
140         Ok(_) => {
141             execute_sql(PATH_SQL, PATH_RESULTS);
142             let results_vec = read_results(PATH_RESULTS);
143             // Fit search results into Result struct to
                properly display on the page, otherwise display
                error
144             match results_vec {
145                 Some(results_vec) => {
146                     for result in results_vec {
147                         results.push(Result {
148                             title: result.0.clone(),
149                             rank: result.1,
150                             // link to the Wikipedia article is
                                also provided, whitespaces need
                                to be replaced
151                             link: result.0.replace(" ", "_"),
152                         })
153                     }
154                     page_data.insert("title", "Results");
155                     page_data.insert("search", &data.search);
156                 }
            }
        }
    }

```

```

:
175     page_data.insert("results", &results);
176     let rendered = tera.render("result.html", &page_data).
        unwrap();
177     HttpResponse::Ok().body(rendered)
178 }

```

Source: main.rs

More specifications about the build and display of the website can be found in the appendix in the HTML files.

3.8 Error Handling

To prevent a simple input error or faulty communication between the SQL server, script, or website from crashing the software immediately, instead of displaying clarifying error messages, proper error handling must be implemented. This is not only relevant for the finished prototype and thus a reasonable user experience, but also helpful during development to detect and fix errors early on.

To handle errors caused by incorrect user input in the search field, the error token has already been introduced in the lexer (code 1, 78-80). In the parser, grammar errors must be handled. For this purpose, several custom error types are defined with the help of the crate `thiserror`. To do this, the derive statement must be passed `Error` (cf. TOLNAY 2019, n.p.), as in the case of the parser in code listing 29 line 367.

These errors are then used in all parse functions, such as `parse_statement` and `parse_weighted`, by returning a datatype called `Result` (code 29, 119+327). Every time an error case is encountered in the code, the corresponding error message is returned (code 29, 143+351). This procedure using results as datatype allows the use of a '?' operator when calling the function to forward an error in case one is returned (code 29, 141).

Code Listing 29: Error handling in parser

```

119     fn parse_statement(&mut self, precedence: Precedence) ->
        Result<Statement, ParseError> {
120         let mut statement = match self.current.clone() {
:
140         Token::Weighted => Statement::Weighted {
141             parameter: self.parse_weighted()?,

```

```

142         },
143         _ => return Err(ParseError::UnexpectedToken(self.
               current.clone())),
144     };
    :
327     fn parse_weighted(&mut self) -> Result<Vec<(Expression,
               Expression)>, ParseError> {
    :
350         if sum_weights != 1.0 {
351             return Err(ParseError::WeightError(sum_weights));
352         }
    :
366 // Types of errors covered by the parser
367 #[derive(Debug, Error)]
368 pub enum ParseError {
369     #[error("Unexpected token {0:?}.")]
370     UnexpectedToken(Token),
371     #[error("Entered unreachable code.")]
372     Unreachable,
373     #[error("Weights do not add up to 1.0. Sum of all weights:
               {0}")]
374     WeightError(f64),
375 }

```

Source: parser.rs

A similar approach can be found in the generator.

When the code generator is executed, it checks after each step to see if an error was thrown. If so, an error is also thrown and the error message is passed. In the result function of the website, where the code generator is executed, a check is made whether an error was thrown (code 30, 167-173). In this case, the website is not passed a list of results, but an error message to display.

Code Listing 30: Error display

```

134 async fn result(tera: web::Data<Tera>, data: web::Form<Search>)
    -> impl Responder {
135     let mut page_data = Context::new();
136     let mut results: Vec<Result> = Vec::new();

```



```
137 | // Run code generator with the string from the search field
138 | match run_code_gen(data.search.clone(), PATH_SQL) {
    |
    |
166 | // If code generator returns error, display error
    | instead of search results
167 | Err(error) => {
168 |     page_data.insert("title", "Error");
169 |     page_data.insert(
170 |         "search",
171 |         &format!("{}", threw an error: {}", &data.search,
    |             &error.to_string()),
172 |     );
173 | }
```

Source: main.rs

There are many other small prompts to catch errors, but the above examples are the most important elements of the code generator itself.

4 Summary

Summary

Appendix

Appendix 1: Cargo.toml

```
1 [package]
2 name = "fulltext_search_code_gen"
3 version = "0.1.0"
4 edition = "2021"
5
6 # See more keys and their definitions at https://doc.rust-lang.
   org/cargo/reference/manifest.html
7
8 [dependencies]
9 logos = "0.12.1"
10 thiserror = "1"
11 regex = "1"
12 actix-web = "3"
13 tera = "1.17.0"
14 serde = "1"
```

Appendix 2: main.rs

```
1 use actix_web::{web, App, HttpResponse, HttpServer, Responder};
2 use regex::Regex;
3 use serde::{Deserialize, Serialize};
4 use std::fs::{read_to_string, File};
5 use std::io::{Error, ErrorKind, Write};
6 use std::process::Command;
7 use tera::{Context, Tera};
8
9 mod code_gen;
10
11 // Path Variables
12 const PATH_SQL: &str = "files\\fulltext.sql";
13 const PATH_RESULTS: &str = "files\\results.txt";
14
15 // Main function to start website on localhost:8080
16 // Run using 'cargo watch -x run'
```

```

17 #[actix_web::main]
18 async fn main() -> std::io::Result<()> {
19     HttpServer::new(|| {
20         let tera = Tera::new("templates/**/*.html").unwrap();
21         App::new()
22             .data(tera)
23             .route("/", web::get().to(search))
24             .route("/", web::post().to(result))
25     })
26     .bind("127.0.0.1:8080")?
27     .run()
28     .await
29 }
30
31 // Code generator to translate an input to SQL
32 // Input: search string and path to write result to
33 // Output: SQL statement written to a file
34 fn run_code_gen(search: String, path: &str) -> std::io::Result
35     <()> {
36     // Transform string to list of tokens
37     let tokens = code_gen::lexer::lex(search.as_str());
38     // Parse tokens to an abstract syntax tree (ast)
39     let ast = code_gen::parser::parse(tokens);
40     match ast {
41         // If parser returns no error, start code generation
42         Ok(ast) => {
43             let generator = code_gen::generator::generate(ast);
44             // If generator returns no error, write SQL
45             // statement to file, otherwise throw an error
46             match generator {
47                 Ok(generator) => write!(File::create(path)?, "
48                     {}", generator),
49                 Err(gen_err) => Err(Error::new(ErrorKind::
50                     InvalidData, format!("{:?}", gen_err))),
51             }
52         }
53         // If parser returns error, throw an error aswell
54         Err(parse_err) => Err(Error::new(
55             ErrorKind::InvalidInput,
56             format!("{:?}", parse_err),

```

```

53        )),
54     }
55 }
56
57 // Runs a command to execute an sql statement to a local MSSQL
    Server
58 // Input: paths to the input file and where to write the result
59 // Output: txt file interpretation of the MSSQL Server result
60 fn execute_sql(sql_path: &str, results_path: &str) {
61     Command::new("cmd")
62         .args(&[
63             "/C",
64             "sqlcmd",
65             "-S",
66             "DESKTOP-JKNEH40\\SQLEXPRESS", //Local server name
67             "-i",
68             sql_path,
69             "-o",
70             results_path,
71         ])
72         .output()
73         .expect("failed to execute operation");
74 }
75
76 // Reads the txt file result and extracts the actual results
77 // Input: path to the txt file
78 // Output: vec of titles and their search rank
79 fn read_results(path: &str) -> Option<Vec<(String, u64)>> {
80     let contents = read_to_string(path).unwrap();
81     let mut contents_vec: Vec<&str> = contents.split("\n").
        collect();
82     // In case of error message, break
83     if contents_vec.len() < 6 {
84         return None;
85     }
86     // Remove metadata rows
87     // First 3-4 rows and last three rows
88     while !contents_vec[0].starts_with("---") {
89         contents_vec.remove(0);
90     }

```

```

91     contents_vec.remove(0);
92     contents_vec.remove(contents_vec.len() - 1);
93     contents_vec.remove(contents_vec.len() - 1);
94     contents_vec.remove(contents_vec.len() - 1);
95     // Go through each row and extract the titles and their
        ranks
96     let mut results: Vec<(String, u64)> = Vec::new();
97     for row in contents_vec {
98         // Remove unnecessary whitespaces
99         let row = row.replace("\r", "");
100        let re = Regex::new(r"\s+").unwrap();
101        let row = re.replace_all(&row, " ").to_string();
102        // Extract last 'word' as rank and save the rest as the
            title
103        let mut words: Vec<&str> = row.split(" ").collect();
104        let rank = words[words.len() - 1].parse::<u64>().unwrap
            ();
105        words.remove(words.len() - 1);
106        let title = words.join(" ");
107
108        results.push((title, rank));
109    }
110    Some(results)
111 }
112
113 // Search and Result structs to (de)serialize rust and website
        datatypes
114 #[derive(Deserialize)]
115 struct Search {
116     search: String,
117 }
118 #[derive(Serialize)]
119 struct Result {
120     title: String,
121     rank: u64,
122     link: String,
123 }
124
125 // Define functional parts of the search page
126 async fn search(tera: web::Data<Tera>) -> impl Responder {

```

```

127     let mut data = Context::new();
128     data.insert("title", "Search field");
129     let rendered = tera.render("search.html", &data).unwrap();
130     HttpResponse::Ok().body(rendered)
131 }
132
133 // Define functional parts of the result page
134 async fn result(tera: web::Data<Tera>, data: web::Form<Search>)
135     -> impl Responder {
136     let mut page_data = Context::new();
137     let mut results: Vec<Result> = Vec::new();
138     // Run code generator with the string from the search field
139     match run_code_gen(data.search.clone(), PATH_SQL) {
140         // If code generator returns no error execute SQL and
141         // read the results
142         Ok(_) => {
143             execute_sql(PATH_SQL, PATH_RESULTS);
144             let results_vec = read_results(PATH_RESULTS);
145             // Fit search results into Result struct to
146             // properly display on the page, otherwise display
147             // error
148             match results_vec {
149                 Some(results_vec) => {
150                     for result in results_vec {
151                         results.push(Result {
152                             title: result.0.clone(),
153                             rank: result.1,
154                             // link to the Wikipedia article is
155                             // also provided, whitespaces need
156                             // to be replaced
157                             link: result.0.replace(" ", "_"),
158                         })
159                     }
160                     page_data.insert("title", "Results");
161                     page_data.insert("search", &data.search);
162                 }
163                 None => {
164                     page_data.insert("title", "Error");
165                     page_data.insert(
166                         "search",

```

```

161         &format!("{}", results cannot be read", &
162             data.search),
163     );
164 }
165 }
166 // If code generator returns error, display error
167 // instead of search results
168 Err(error) => {
169     page_data.insert("title", "Error");
170     page_data.insert(
171         "search",
172         &format!("{}", threw an error: {}", &data.search,
173             &error.to_string()),
174     );
175 }
176 page_data.insert("results", &results);
177 let rendered = tera.render("result.html", &page_data).
178     unwrap();
179 HttpResponse::Ok().body(rendered)
180 }

```

Appendix 3: lexer.rs

```

1 use logos::{Lexer, Logos};
2
3 // Main function to start lexing process
4 // Input: string
5 // Output: vec of tokens
6 pub fn lex(input: &str) -> Vec<Token> {
7     Token::lexer(input).collect()
8 }
9
10 // helper function to format strings
11 fn to_string(lex: &mut Lexer<Token>) -> Option<String> {
12     let string = lex.slice().to_string();
13     Some(string)
14 }

```



```

15
16 // helper function to format floats
17 fn to_float(lex: &mut Lexer<Token>) -> Option<f64> {
18     Some(lex.slice().parse().ok()?)
19 }
20
21 // helper function to format unsigned integer
22 fn to_u64(lex: &mut Lexer<Token>) -> Option<u64> {
23     Some(lex.slice().parse().ok()?)
24 }
25
26 // List of all tokens that are accepted by the language
27 #[derive(Debug, Clone, Logos, PartialEq)]
28 pub enum Token {
29     // Regex: phrase starting and ending with " and escaped
        character \" or just a word allowing a list of special
        characters
30     #[regex(r#"#""(?:[^\\"|\\.|\\.) *"| [a-zA-Zß?üÛöÖäÄ; \. _ < > ' ` # $ % / \ = € ] + "#, to_string)]
31     WordOrPhrase(String),
32     // Regex: any float between 0 and 1
33     #[regex(r#"0+(\.[0-9]+)?|1", to_float)]
34     ZeroToOne(f64),
35     // Regex: any postive integer
36     #[regex(r#"0-9]+", to_u64)]
37     Number(u64),
38     // ! and - for NOT
39     #[token("!")]
40     Bang,
41     #[token("-")]
42     Minus,
43     // & and + for AND
44     #[token("&")]
45     And,
46     #[token("+")]
47     Plus,
48     // | for OR
49     #[token("|")]
50     Or,
51     // Parentheses for grouping

```

```

52     #[token("(")]
53     LeftParen,
54     #[token(")")]
55     RightParen,
56     // Comma for parameter separation
57     #[token(",")]
58     Comma,
59     // Functions
60     #[token("@contains")]
61     Contains,
62     #[token("@startswith")]
63     Starts,
64     #[token("@inflection")]
65     Inflection,
66     #[token("@thesaurus")]
67     Thesaurus,
68     #[token("@near")]
69     Near,
70     #[token("@weighted")]
71     Weighted,
72     // Colon to surround functions parameters
73     #[token(":")]
74     Colon,
75     // End of File
76     EoF,
77     // Error and skip whitespaces
78     #[error]
79     #[regex(r"[\s\t\n\f]+", logos::skip)]
80     Error,
81 }
82
83 // Enable tokens to be casted as strings
84 impl Into<String> for Token {
85     fn into(self) -> String {
86         match self {
87             Token::WordOrPhrase(s) => s,
88             _ => unreachable!(),
89         }
90     }
91 }

```

Appendix 4: parser.rs

```

1 use std::slice::Iter;
2 use thiserror::Error;
3
4 use crate::code_gen::ast::*;
5 use crate::code_gen::lexer::Token;
6
7 // Main function to start parsing process
8 // Input: vec of tokens
9 // Output: abstract syntax tree (vec of statements)
10 pub fn parse(tokens: Vec<Token>) -> Result<Vec<Statement>,
    ParseError> {
11     let mut parser = Parser::new(tokens.iter());
12     // read twice to overwrite initial EOF tokens
13     parser.read();
14     parser.read();
15     let mut ast: Vec<Statement> = Vec::new();
16     while let Some(statement) = parser.next()? {
17         ast.push(statement);
18     }
19     Ok(ast)
20 }
21
22 // Precedence to enable priorities between operators
23 // Example: this OR that AND some (AND should have a higher
    priority)
24 #[derive(Debug, Clone, PartialEq, PartialOrd)]
25 enum Precedence {
26     Lowest,
27     Statement,
28     Or,
29     And,
30     Not,
31     Prefix,
32     Group,
33 }
34
35 // Match tokens to precedences
36 impl Precedence {

```

```

37     fn token(token: Token) -> Self {
38         match token {
39             Token::Bang | Token::Minus => Self::Not,
40             Token::Plus | Token::And | Token::WordOrPhrase(..)
41                 => Self::And,
42             Token::Or => Self::Or,
43             Token::LeftParen => Self::Group,
44             Token::Contains
45                 | Token::Starts
46                 | Token::Inflection
47                 | Token::Thesaurus
48                 | Token::Near
49                 | Token::Weighted => Self::Statement,
50             _ => Self::Lowest,
51         }
52     }
53
54     // Parser saves current and next tokens as attribute
55     struct Parser<'p> {
56         tokens: Iter<'p, Token>,
57         current: Token,
58         peek: Token,
59     }
60
61     impl<'p> Parser<'p> {
62         // Initial parser creation
63         fn new(tokens: Iter<'p, Token>) -> Self {
64             Self {
65                 tokens,
66                 current: Token::EoF,
67                 peek: Token::EoF,
68             }
69         }
70
71         // Parse next statement if possible
72         // Output: statement or error
73         fn next(&mut self) -> Result<Option<Statement>, ParseError>
74             {
75             if self.current == Token::EoF {

```

```

75         return Ok(None);
76     }
77     Ok(Some(self.parse_statement(Precedence::Lowest)?))
78 }
79
80 // Set current and peek one step further in the vec of
81 // tokens
82 fn read(&mut self) {
83     self.current = self.peek.clone();
84     self.peek = if let Some(token) = self.tokens.next() {
85         token.clone()
86     } else {
87         Token::EoF
88     };
89 }
90
91 // See what the current token is
92 // Output: boolean
93 fn current_is(&self, token: Token) -> bool {
94     std::mem::discriminant(&self.current) == std::mem::discriminant(&token)
95 }
96
97 // Current token should match the one given
98 // Input: token
99 // Output: token or error
100 fn expect_token(&mut self, token: Token) -> Result<Token,
101 ParseError> {
102     if self.current_is(token) {
103         Ok(self.current.clone())
104     } else {
105         Err(ParseError::UnexpectedToken(self.current.clone()
106         ()))
107     }
108 }
109
110 // Current token should match the one given and read to
111 // next token
112 // Input: token
113 // Output: token or error

```

```

110 fn expect_token_and_read(&mut self, token: Token) -> Result
111     <Token, ParseError> {
112     let result = self.expect_token(token)?;
113     self.read();
114     Ok(result)
115 }
116
117 // Parse statement, can only be a function or combination
118 // of functions
119 // Input: precedence
120 // Output: statement or error
121 fn parse_statement(&mut self, precedence: Precedence) ->
122     Result<Statement, ParseError> {
123     let mut statement = match self.current.clone() {
124         Token::Contains => Statement::Contains {
125             expression: self.parse_contains()?,
126         },
127         Token::Starts => Statement::Starts {
128             expression: self.parse_starts()?,
129         },
130         Token::Inflection => Statement::Inflection {
131             expression: self.parse_inflection()?,
132         },
133         Token::Thesaurus => Statement::Thesaurus {
134             expression: self.parse_thesaurus()?,
135         },
136         Token::Near => {
137             let (parameter, proximity) = self.parse_near()
138                 ?;
139             Statement::Near {
140                 parameter,
141                 proximity,
142             }
143         },
144         Token::Weighted => Statement::Weighted {
145             parameter: self.parse_weighted()?,
146         },
147         _ => return Err(ParseError::UnexpectedToken(self.
148             current.clone())),
149     };

```

```

145     // After a function could be an infix operator
146     while !self.current_is(Token::EoF) && precedence <
        Precedence::token(self.current.clone()) {
147         if let Some(in_statement) = self.
            parse_infix_statement(statement.clone())? {
148             statement = in_statement
149         } else {
150             break;
151         }
152     }
153     Ok(statement)
154 }

155
156 // Parse expression, could be a search term, number,
    operator or combination of expressions
157 fn parse_expression(&mut self, precedence: Precedence) ->
    Result<Expression, ParseError> {
158     let mut expr = match self.current.clone() {
159         Token::WordOrPhrase(s) => {
160             self.expect_token_and_read(Token::WordOrPhrase(
                "".to_string()))?;
161             Expression::WordOrPhrase(s.to_string())
162         }
163         Token::Number(u) => {
164             self.expect_token_and_read(Token::Number(0))?;
165             Expression::Number(u)
166         }
167         Token::ZeroToOne(f) => {
168             self.expect_token_and_read(Token::ZeroToOne
                (0.0))?;
169             Expression::ZeroToOne(f)
170         }
171         t @ Token::Minus | t @ Token::Bang => {
172             self.expect_token_and_read(t.clone())?;
173             Expression::Prefix(
174                 Operator::token(t),
175                 Box::new(self.parse_expression(Precedence::
                    Prefix)?),
176             )
177         }

```

```

178         // Start a group which gets higher precedence
179         Token::LeftParen => {
180             let group_expression = match self.parse_group()
181                 ? {
182                     Statement::Group { expression } =>
183                         expression,
184                     _ => return Err(ParseError::Unreachable),
185                 };
186             group_expression
187         }
188         _ => return Err(ParseError::UnexpectedToken(self.
189             current.clone())),
190     };
191     // After an expression could be an infix operator or
192     // directly a new expression (here called postfix
193     // operator)
194     while !self.current_is(Token::EoF) && precedence <
195         Precedence::token(self.current.clone()) {
196         if let Some(expression) = self.
197             parse_postfix_expression(expr.clone())? {
198             expr = expression;
199         } else if let Some(expression) = self.
200             parse_infix_expression(expr.clone())? {
201             expr = expression
202         } else {
203             break;
204         }
205     }
206     Ok(expr)
207 }

```

// 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

```

203 fn parse_postfix_expression(
204     &mut self,
205     expr: Expression,
206 ) -> Result<Option<Expression>, ParseError> {
207     Ok(match self.current {

```



```

208         Token::Minus | Token::Bang | Token::WordOrPhrase
209         (..) => {
210             let sec_expr = self.parse_expression(Precedence
211                 ::And)?;
212             Some(Expression::Infix(
213                 Box::new(expr),
214                 Operator::And,
215                 Box::new(sec_expr),
216             ))
217         }
218     }
219
220     // Infix operators AND and OR expect an expression on
221     // either side
222     fn parse_infix_expression(
223         &mut self,
224         expr: Expression,
225     ) -> Result<Option<Expression>, ParseError> {
226         Ok(match self.current {
227             Token::Plus | Token::And | Token::Or => {
228                 let token = self.current.clone();
229                 self.read();
230                 let sec_expr = self.parse_expression(Precedence
231                     ::token(token.clone()))?;
232                 Some(Expression::Infix(
233                     Box::new(expr),
234                     Operator::token(token),
235                     Box::new(sec_expr),
236                 ))
237             }
238             _ => None,
239         })
240     }
241
242     // Infix operators AND and OR expect a statement on either
243     // side
244     fn parse_infix_statement(
245         &mut self,

```

```

243     statement: Statement,
244 ) -> Result<Option<Statement>, ParseError> {
245     Ok(match self.current {
246         Token::Plus | Token::And | Token::Or => {
247             let token = self.current.clone();
248             self.read();
249             let second_statement = self.parse_statement(
250                 Precedence::token(token.clone()))?;
251             Some(Statement::Infix {
252                 statement: Box::new(statement),
253                 operator: Operator::token(token),
254                 second_statement: Box::new(second_statement),
255             })
256         }
257         _ => None,
258     })
259 }
260
261 // Functions all have a similar structure needing colons to
262 // surround their parameters
263
264 // Contains function only expects one word or phrase or
265 // combination of expressions
266 fn parse_contains(&mut self) -> Result<Expression,
267     ParseError> {
268     self.expect_token_and_read(Token::Contains)?;
269     self.expect_token_and_read(Token::Colon)?;
270     let expression: Expression = self.parse_expression(
271         Precedence::Statement)?;
272     self.expect_token_and_read(Token::Colon)?;
273     Ok(expression)
274 }
275
276 // Startswith function only expects one one word or phrase
277 // or combination of expressions
278 fn parse_starts(&mut self) -> Result<Expression, ParseError>
279 > {
280     self.expect_token_and_read(Token::Starts)?;
281     self.expect_token_and_read(Token::Colon)?;

```

```

275         let expression: Expression = self.parse_expression(
276             Precedence::Statement)?;
277         self.expect_token_and_read(Token::Colon)?;
278         Ok(expression)
279     }
280
281     // Inflection function only expects one one word or phrase
282     // or combination of expressions
283     fn parse_inflection(&mut self) -> Result<Expression,
284         ParseError> {
285         self.expect_token_and_read(Token::Inflection)?;
286         self.expect_token_and_read(Token::Colon)?;
287         let expression: Expression = self.parse_expression(
288             Precedence::Statement)?;
289         self.expect_token_and_read(Token::Colon)?;
290         Ok(expression)
291     }
292
293     // Thesaurus function only expects one one word or phrase
294     // or combination of expressions
295     fn parse_thesaurus(&mut self) -> Result<Expression,
296         ParseError> {
297         self.expect_token_and_read(Token::Thesaurus)?;
298         self.expect_token_and_read(Token::Colon)?;
299         let expression: Expression = self.parse_expression(
300             Precedence::Statement)?;
301         self.expect_token_and_read(Token::Colon)?;
302         Ok(expression)
303     }
304
305     // Near function expects multiple comma-seperated words or
306     // phrases with an optional number as the last parameter
307     fn parse_near(&mut self) -> Result<(Vec<Expression>,
308         Expression), ParseError> {
309         self.expect_token_and_read(Token::Near)?;
310         self.expect_token_and_read(Token::Colon)?;
311         let mut parameter: Vec<Expression> = Vec::new();
312         // Proximity has a default value of 5 if no number is
313         // given
314         let mut proximity = Expression::Number(5);

```

```

305     while !self.current_is(Token::Colon) {
306         if self.current_is(Token::Comma) {
307             self.expect_token_and_read(Token::Comma)?;
308         }
309         match self.parse_expression(Precedence::Lowest)? {
310             Expression::WordOrPhrase(s) => parameter.push(
311                 Expression::WordOrPhrase(s)),
312             Expression::Number(u) => {
313                 if self.current_is(Token::Colon) {
314                     proximity = Expression::Number(u)
315                 } else {
316                     return Err(ParseError::UnexpectedToken(
317                         self.current.clone()));
318                 }
319             }
320             _ => return Err(ParseError::UnexpectedToken(
321                 self.current.clone())),
322         }
323     }
324
325     // Weighted function expects pairs of words or phrases and
326     // a weight between 0 and 1
327     // All weights must add up to exactly 1
328     fn parse_weighted(&mut self) -> Result<Vec<(Expression,
329         Expression)>, ParseError> {
330         self.expect_token_and_read(Token::Weighted)?;
331         self.expect_token_and_read(Token::Colon)?;
332         let mut parameter: Vec<(Expression, Expression)> = Vec
333             ::new();
334         let mut sum_weights: f64 = 0.0;
335         while !self.current_is(Token::Colon) {
336             if self.current_is(Token::Comma) {
337                 self.expect_token_and_read(Token::Comma)?;
338             }
339             let expression = match self.parse_expression(
340                 Precedence::Lowest)? {

```

```

337         Expression::WordOrPhrase(s) => Expression::
            WordOrPhrase(s),
338         _ => return Err(ParseError::UnexpectedToken(
            self.current.clone())),
339     };
340     self.expect_token_and_read(Token::Comma)?;
341     let weight = match self.parse_expression(Precedence
        ::Lowest)? {
342         Expression::ZeroToOne(f) => {
343             sum_weights += f;
344             Expression::ZeroToOne(f)
345         }
346         _ => return Err(ParseError::UnexpectedToken(
            self.current.clone())),
347     };
348     parameter.push((expression, weight));
349 }
350 if sum_weights != 1.0 {
351     return Err(ParseError::WeightError(sum_weights));
352 }
353 self.expect_token_and_read(Token::Colon)?;
354 Ok(parameter)
355 }
356
357 // Groups must encapsulate an expression with parentheses
    and have higher precedence than other operators
358 fn parse_group(&mut self) -> Result<Statement, ParseError>
    {
359     self.expect_token_and_read(Token::LeftParen)?;
360     let expression = self.parse_expression(Precedence::
        Statement)?;
361     self.expect_token_and_read(Token::RightParen)?;
362     Ok(Statement::Group { expression })
363 }
364 }
365
366 // Types of errors covered by the parser
367 #[derive(Debug, Error)]
368 pub enum ParseError {
369     #[error("Unexpected token {0:?}.")]

```

```

370     UnexpectedToken(Token),
371     #[error("Entered unreachable code.")]
372     Unreachable,
373     #[error("Weights do not add up to 1.0. Sum of all weights:
           {0}")]
374     WeightError(f64),
375 }

```

Appendix 5: ast.rs

```

1 use crate::code_gen::lexer::Token;
2
3 #[derive(Debug, Clone, PartialEq)]
4 pub enum Statement {
5     Group {
6         expression: Expression,
7     },
8     Infix {
9         statement: Box<Statement>,
10        operator: Operator,
11        second_statement: Box<Statement>,
12    },
13    Contains {
14        expression: Expression,
15    },
16    Starts {
17        expression: Expression,
18    },
19    Inflection {
20        expression: Expression,
21    },
22    Thesaurus {
23        expression: Expression,
24    },
25    Near {
26        parameter: Vec<Expression>,
27        proximity: Expression,
28    },
29    Weighted {

```

```

30         parameter: Vec<(Expression, Expression)>,
31     },
32     EOF,
33 }
34
35 #[derive(Debug, Clone, PartialEq)]
36 pub enum Expression {
37     WordOrPhrase(String),
38     Number(u64),
39     ZeroToOne(f64),
40     Infix(Box<Expression>, Operator, Box<Expression>),
41     Prefix(Operator, Box<Expression>),
42 }
43
44 #[derive(Debug, Clone, PartialEq)]
45 pub enum Operator {
46     And,
47     Or,
48     Not,
49 }
50
51 impl Operator {
52     pub fn token(token: Token) -> Self {
53         match token {
54             Token::And | Token::Plus => Self::And,
55             Token::Or => Self::Or,
56             Token::Minus | Token::Bang => Self::Not,
57             _ => unreachable!("{:?}", token),
58         }
59     }
60 }

```

Appendix 6: generator.rs

```

1 use std::slice::Iter;
2 use thiserror::Error;
3
4 use crate::code_gen::ast::{Expression, Operator, Statement};
5

```

```

6 // Database constants
7 const DB_NAME: &str = "Wikipedia";
8 const TBL_NAME: &str = "[dbo].[Real_Article]";
9 const RETURN_ATTRIBUTE: &str = "Title";
10 const TOP_ROWS: u64 = 5;
11
12 // Main function to start the generation process
13 // Input: vec of statements (ast)
14 // Output: string (sql statement)
15 pub fn generate(ast: Vec<Statement>) -> Result<String,
    GenerateError> {
16     let mut generator = Generator::new(ast.iter());
17     // write twice to overwrite initial EOF statements
18     generator.write();
19     generator.write();
20     let mut sql_parts: Vec<String> = Vec::new();
21     sql_parts.push(format!(
22         "USE {}; SELECT TOP {} * FROM(SELECT FT_TBL.{}, KEY_TBL
            .RANK FROM {} AS FT_TBL INNER JOIN CONTAINSTABLE({},
            *, ' ",
23         DB_NAME, TOP_ROWS, RETURN_ATTRIBUTE, TBL_NAME, TBL_NAME
24     ));
25     // generate all functions as JOIN constraints
26     while let Some(sql_part) = generator.next()? {
27         sql_parts.push(sql_part);
28     }
29     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());
30     Ok(sql_parts.join(" "))
31 }
32
33 // Generator struct with current and next statements as
    attributes
34 struct Generator<'p> {
35     statements: Iter<'p, Statement>,
36     current: Statement,
37     peek: Statement,
38 }
39

```

```

40 impl<'p> Generator<'p> {
41     // Initial generator creation
42     fn new(statements: Iter<'p, Statement>) -> Self {
43         Self {
44             statements,
45             current: Statement::EoF,
46             peek: Statement::EoF,
47         }
48     }
49
50     // Generate next statement if possible
51     fn next(&mut self) -> Result<Option<String>, GenerateError>
52     {
53         if self.current == Statement::EoF {
54             return Ok(None);
55         }
56         Ok(Some(self.generate_statement(self.current.clone())?))
57     }
58
59     // Set current and peek one step further in the ast
60     fn write(&mut self) {
61         self.current = self.peek.clone();
62         self.peek = if let Some(statement) = self.statements.
63             next() {
64                 statement.clone()
65             } else {
66                 Statement::EoF
67             };
68     }
69
70     // Generate statement, always a function or combination of
71     // functions
72     // Input: statement to generate
73     // Output: string
74     fn generate_statement(&mut self, statement: Statement) ->
75     Result<String, GenerateError> {
76         let sql: String = match statement {
77             Statement::Infix {
78                 statement,

```

```

75         operator,
76         second_statement,
77     } => {
78         let sql_parts = [
79             self.generate_statement(*statement)?,
80             self.generate_operator(operator)?,
81             self.generate_statement(*second_statement)
82             ?,
83         ];
84         sql_parts.join(" ")
85     }
86     // Contains generates it's search condition without
87     // mutation
88     Statement::Contains { expression } => {
89         format!("{}", self.generate_expression(
90             expression?))
91     }
92     // Startswith adds a * to end of a word or before
93     // the last " in a phrase
94     Statement::Starts { expression } => {
95         let mut word_or_phrase = self.
96             generate_expression(expression)?;
97         if word_or_phrase.starts_with('"') &&
98             word_or_phrase.ends_with('"') {
99             word_or_phrase.insert(word_or_phrase.len()
100                 - 1, '*');
101         } else {
102             word_or_phrase.push('*');
103         }
104         format!("{}", word_or_phrase)
105     }
106     // Inflection calls the inflection function from
107     // MSSQL
108     Statement::Inflection { expression } => {
109         let mut word_or_phrase = self.
110             generate_expression(expression)?;
111         if word_or_phrase.starts_with('"') &&
112             word_or_phrase.ends_with('"') {
113             word_or_phrase.remove(0);

```

```

104         word_or_phrase.remove(word_or_phrase.len()
105                                - 1);
106     }
107     format!("FORMSOF (INFLECTIONAL, \"{}\")",
108            word_or_phrase)
109 }
110 // Thesaurus calls the thesaurus function from
111 MSSQL
112 Statement::Thesaurus { expression } => {
113     let mut word_or_phrase = self.
114         generate_expression(expression)?;
115     if word_or_phrase.starts_with('"') &&
116        word_or_phrase.ends_with('"') {
117         word_or_phrase.remove(0);
118         word_or_phrase.remove(word_or_phrase.len()
119                                - 1);
120     }
121     format!("FORMSOF (THESAURUS, \"{}\")",
122            word_or_phrase)
123 }
124 // Near generates a parameter list of all search
125 criteria and proximity in the end
126 Statement::Near {
127     parameter,
128     proximity,
129 } => {
130     let mut sql_parts: Vec<String> = Vec::new();
131     sql_parts.push(format!("NEAR("));
132     for expression in parameter {
133         let string = self.generate_expression(
134             expression)?;
135         sql_parts.push(format!("{}", string));
136         sql_parts.push(String::from(", "));
137     }
138     sql_parts.remove(sql_parts.len() - 1);
139     sql_parts.push(format!("{}", self.
140         generate_expression(proximity)?));
141     sql_parts.join("")
142 }

```

```

133         // Weighted generates tuples of search criteria and
134         // their respective weight
135         Statement::Weighted { parameter } => {
136             let mut sql_parts: Vec<String> = Vec::new();
137             sql_parts.push(format!("ISABOUT("));
138             for (word_or_phrase_expr, weight_expr) in
139                 parameter {
140                 let word_or_phrase = self.
141                     generate_expression(word_or_phrase_expr)
142                     ?;
143                 let weight = self.generate_expression(
144                     weight_expr)?;
145                 sql_parts.push(format!("{}", WEIGHT({}),",",
146                     word_or_phrase, weight));
147                 sql_parts.push(String::from(", "));
148             }
149             sql_parts.remove(sql_parts.len() - 1);
150             sql_parts.push(String::from(")"));
151             sql_parts.join("")
152         }
153         _ => return Err(GenerateError::UnexpectedStatement(
154             self.current.clone())),
155     };
156     self.write();
157     Ok(sql)
158 }
159
160 // Generate expression, any search criteria or number or
161 // combination of those
162 // Input: expression to generate
163 // Output: string
164 fn generate_expression(&mut self, expression: Expression)
165 -> Result<String, GenerateError> {
166     let sql: String = match expression {
167         Expression::WordOrPhrase(s) => s,
168         Expression::Number(u) => u.to_string(),
169         Expression::ZeroToOne(f) => f.to_string(),
170         // Infix operator enclose their expressions with
171         // parentheses to ensure precedence
172         Expression::Infix(expr1, operator, expr2) => {

```

```

163         let mut sql_parts = [
164             String::from("("),
165             self.generate_expression(*expr1)?,
166             String::from(")"),
167             self.generate_operator(operator)?,
168             String::from("("),
169             self.generate_expression(*expr2.clone())?,
170             String::from(")"),
171         ];
172         // If the second expression is a not operator
173         // it must write NOT before the parenthesis
174         match *expr2 {
175             Expression::Prefix(Operator::Not, ..) =>
176                 sql_parts[4] = String::from("NOT "),
177             _ => (),
178         }
179         sql_parts.join(" ")
180     }
181     Expression::Prefix(operator, expr) => {
182         let sql_parts = [
183             self.generate_operator(operator)?,
184             self.generate_expression(*expr)?,
185         ];
186         sql_parts.join(" ")
187     }
188 };
189 Ok(sql)
190 }
191
192 // Generate operator
193 // Input: operator to generate
194 // Output: string
195 fn generate_operator(&mut self, operator: Operator) ->
196     Result<String, GenerateError> {
197     let op = match operator {
198         Operator::And => "AND",
199         Operator::Or => "OR",
200         // has to be set infront of parentheses, see
201         // generate_expression for infix
202         Operator::Not => "",
203     };

```

```
199         };
200         Ok(op.to_owned())
201     }
202 }
203
204 // Types of error covered by the generator
205 #[derive(Debug, Error)]
206 pub enum GenerateError {
207     #[error("Unexpected statement {0:?}.")]
208     UnexpectedStatement(Statement),
209 }
```

Appendix 7: mod.rs

```
1 mod ast;
2 pub mod generator;
3 pub mod lexer;
4 pub mod parser;
```

Appendix 8: base.html

```
1 <!DOCTYPE html>
2 <html lang="en">
3     <head>
4         <meta charset="utf-8">
5         <title>{{title}}</title>
6     </head>
7     <body>
8         {% block content %}
9         {% endblock %}
10    </body>
11 </html>
```

Appendix 9: search.html

```
1 {% extends "base.html" %}
2
3 {% block content %}
```

```
4 <form action="" method="POST">
5     <div>
6         <label for="search">Search:</label>
7         <input type="text" name="search">
8     </div>
9     <input type="submit" value="Submit">
10 </form>
11 {% endblock %}
```

Appendix 10: result.html

```
1 {% extends "base.html" %}
2
3 {% block content %}
4 <div>
5     <p>{{ search }}</p>
6 </div>
7 {% for result in results %}
8 <div>
9     <a href="https://en.wikipedia.org/wiki/{{ result.link }}">
10         {{ result.title }}</a>
11     <small>{{ result.rank }}</small>
12 </div>
13 {% endfor %}
14 {% endblock %}
```

Appendix 11: convert_wiki_to_csv.py

```
1 from lxml import etree
2 from glob import glob
3 import bz2
4 import codecs
5 import csv
6 import time
7 import os
8
9 PATH_WIKI_XML = "/Users/light/Documents/Wikipedia/"
10 FILENAME_ARTICLES = "articles.csv"
11
```

```

12
13 def hms_string(sec_elapsed):
14     h = int(sec_elapsed / (60 * 60))
15     m = int((sec_elapsed % (60 * 60)) / 60)
16     s = sec_elapsed % 60
17     return "{:}:{:>02}:{:>05.2f}".format(h, m, s)
18
19
20 def get_parser(filename):
21     ns_token = "{http://www.mediawiki.org/xml/export-0.10/}ns"
22     title_token = "{http://www.mediawiki.org/xml/export-0.10/}title"
23     revision_token = "{http://www.mediawiki.org/xml/export-0.10/}revision"
24     text_token = "{http://www.mediawiki.org/xml/export-0.10/}text"
25
26     with bz2.BZ2File(filename, "rb") as bz2_file:
27         for event, element in etree.iterparse(bz2_file, events
28             =("end",)):
29             if element.tag.endswith("page"):
30                 namespace_tag = element.find(ns_token)
31
32                 if namespace_tag.text == "0":
33                     title_tag = element.find(title_token)
34                     text_tag = element.find(revision_token).
35                         find(text_token)
36                     yield title_tag.text, text_tag.text
37
38                 element.clear()
39
40 def pluck_wikipedia_titles_text(
41     out_file, pattern="enwiki-*-pages-articles-multistream*.xml
42     -*.bz2"
43 ):
44     totalCount = 0
45     longestTitle = 0
46     longestText = 0
47     with codecs.open(out_file, "a+b", "utf8") as out_file:

```

```

46     writer = csv.writer(out_file)
47     for bz2_filename in sorted(
48         glob(pattern),
49         key=lambda a: int(a.split("articles-multistream")
50             [1].split(".")[0]),
51     ):
52         print(bz2_filename)
53         parser = get_parser(bz2_filename)
54         for title, text in parser:
55             if not (text.startswith("#REDIRECT") or text.
56                 startswith("#redirect")):
57                 totalCount += 1
58                 writer.writerow([title, text])
59                 longestTitle = (
60                     len(title) if len(title) > longestTitle
61                     else longestTitle
62                 )
63                 longestText = len(text) if len(text) >
64                     longestText else longestText
65                 if totalCount > 1 and (totalCount % 100000)
66                     == 0:
67                     print("{:,}".format(totalCount))
68                 if totalCount >= 1000:
69                     break
70     print(
71         f"Total Count: {totalCount}\nLongest Title: {
72             longestTitle}\nLongest Text: {longestText}"
73     )
74
75 pathArticles = os.path.join(PATH_WIKI_XML, FILENAME_ARTICLES)
76
77 start_time = time.time()
78
79 pluck_wikipedia_titles_text(pathArticles)
80
81 time_took = time.time() - start_time
82 print(f"Total runtime: {hms_string(time_took)}")

```

Appendix 12: create_article.sql

```
1 USE Wikipedia;
2 DROP TABLE Real_Article;
3 CREATE TABLE [dbo].[Real_Article] (
4     [Title] [varchar](255) NULL,
5     [Text] [varchar](max) NULL
6 );
7 INSERT INTO Real_Article (Title, Text)
8 VALUES ('Example', 'Fulltext');
9 SELECT *
10 FROM Real_Article;
11 DELETE FROM Real_Article
12 WHERE Title = 'Example';
```

Appendix 13: bulk_insert.sql

```
1 USE Wikipedia;
2 BULK
3 INSERT Real_Article
4 FROM 'C:\Users\light\Documents\Wikipedia\enwiki-20220901-pages-
5     articles-multistream-no-redirect.csv' WITH (
6     FIRSTROW = 1,
7     FIELDQUOTE = '\',
8     , FIELDTERMINATOR = ',
9     , ROWTERMINATOR = ' \ n ',
10    TABLOCK);
```

Appendix 14: alter_id.sql

```
1 USE Wikipedia;
2 ALTER TABLE [dbo].[Real_Article]
3 ADD ID INT IDENTITY(1, 1) PRIMARY KEY
```

Bibliography

BACKUS, J. W. et al.: Report on the algorithmic language ALGOL 60. en. In: *Communications of the ACM* 3 (May 1960) Nr. 5. Ed. by NAUR, Peter, pp. 299–314. ISSN: 0001-0782, 1557-7317. DOI: 10.1145/367236.367262. URL: <https://dl.acm.org/doi/10.1145/367236.367262> (visited on 08/16/2022)

COLES, Michael; COTTER, Hilary: *Pro full-text search in SQL Server 2008*. The expert's voice in SQL server. Berkeley, CA: Apress, 2009. ISBN: 978-1-4302-1594-3

EDE, Rob: *Actix Web: A powerful, pragmatic, and extremely fast web framework for Rust*. Jan. 2022. URL: <https://github.com/actix/actix-web> (visited on 10/14/2022)

FARRELL, James Alan: Compiler Basics. en. In: (Aug. 1995), p. 7. URL: <http://www.cs.man.ac.uk/~pjj/farrell/compmain.html> (visited on 08/16/2022)

HAMILTON, James R.; NAYAK, Tapas K.: Microsoft SQL server full-text search. In: *IEEE Data Eng. Bull.* 24 (2001) Nr. 4. Publisher: Citeseer, pp. 7–10

HIRSZ, Maciej: *Logos: Create ridiculously fast Lexers*. June 2022. URL: <https://github.com/maciejhirsz/logos> (visited on 10/05/2022)

HUDAK, Paul: Domain-specific languages. In: *Handbook of programming languages* 3 (1997) Nr. 39-60, p. 21

ISO/IEC 14977:1996(E): Information Technology - Syntactic Metalanguage - Extended BNF. In: (1996). URL: <https://www.cl.cam.ac.uk/~mgk25/iso-14977.pdf> (visited on 08/16/2022)

MERNIK, Marjan; HEERING, Jan; SLOANE, Anthony M.: When and how to develop domain-specific languages. en. In: *ACM Computing Surveys* 37 (Dec. 2005) Nr. 4, pp. 316–344. ISSN: 0360-0300, 1557-7341. DOI: 10.1145/1118890.1118892. URL: <https://dl.acm.org/doi/10.1145/1118890.1118892> (visited on 08/15/2022)

PROUILLET, Vincent: *Tera: A template engine for Rust based on Jinja2/Django*. Aug. 2022. URL: <https://github.com/Keats/tera> (visited on 10/14/2022)

ROSS, Douglas T.: Origins of the APT language for automatically programmed tools. enin: WEXELBLAT, Richard L. (ed.): *History of programming languages*. New York, NY, USA: ACM, June 1978, pp. 279–338. ISBN: 978-0-12-745040-7. DOI: 10.1145/800025.1198374. URL: <http://dl.acm.org/doi/10.1145/800025.1198374> (visited on 08/15/2022)

TENOPIR, Carol; RO, Jung Soon: *Full text databases*. New directions in information management no. 21. New York: Greenwood Press, 1990. ISBN: 978-0-313-26303-3

TOLNAY, David: *Thiserror*. Oct. 2019. URL: <https://github.com/dtolnay/thiserror> (visited on 10/17/2022)

TOLNAY, David; TRYZELAAR, Erick: *Serde: Serialization framework for Rust*. Apr. 2017. URL: <https://github.com/serde-rs/serde> (visited on 10/15/2022)

WIRTH, Niklaus: What can we do about the unnecessary diversity of notation for syntactic definitions?. en. In: *Communications of the ACM* 20 (Nov. 1977) Nr. 11, pp. 822–823. ISSN: 0001-0782, 1557-7317. DOI: 10.1145/359863.359883. URL: <https://dl.acm.org/doi/10.1145/359863.359883> (visited on 08/16/2022)

Declaration in lieu of oath

I hereby declare that I produced the submitted paper with no assistance from any other party and without the use of any unauthorized aids and, in particular, that I have marked as quotations all passages which are reproduced verbatim or near-verbatim from publications. Also, I declare that the submitted print version of this thesis is identical with its digital version. Further, I declare that this thesis has never been submitted before to any examination board in either its present form or in any other similar version. I herewith agree that this thesis may be published. I herewith consent that this thesis may be uploaded to the server of external contractors for the purpose of submitting it to the contractors' plagiarism detection systems. Uploading this thesis for the purpose of submitting it to plagiarism detection systems is not a form of publication.

Bonn, 18.10.2022

(Location, Date)

A handwritten signature in blue ink, appearing to read 'S. Bunge', is written above a horizontal line.

(handwritten signature)