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

by

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## Index of Abbreviations

<b>APT</b>	Automatically Programmed Tools
<b>AST</b>	abstract syntax tree
<b>DDL</b>	Data Definition Language
<b>DSL</b>	Domain-Specific Language
<b>EBNF</b>	Extended Backus-Naur Form
<b>GPL</b>	General-Purpose Language
<b>HTML</b>	Hypertext Markup Language
<b>MS</b>	Microsoft
<b>PDF</b>	Portable Document Format
<b>SQL</b>	Structured Query Language
<b>XML</b>	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
$F_\beta$	weighted harmonic mean
$\beta$	nonnegative weight

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# 1 Abstract

Abstract

## 2 Theory

### 2.1 Full-Text Search

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

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

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

**Formula 1: Precision**

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

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  $\beta$  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  $F_{\beta}$  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  $\text{\LaTeX}$  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
$\text{\TeX}$ , $\text{\LaTeX}$ , 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:

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



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

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. If you want to define a full-text search, you usually use a combination of the given functions. In MSSQL this would be for example CONTAINS or FORMSOF. Therefore I want to develop a query language where you only have to specify this combination of functions and a few parameters to generate the corresponding SQL.

#### 3.1 Language definition

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'. For 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 being processed from left to right.

## 3.2 Lexer

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 definitions

```

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
35  #[derive(Debug, Clone, PartialEq)]
36  pub enum Expression {
37      WordOrPhrase(String),
38      Number(u64),
39      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>,
11     ParseError> {
12     let mut parser = Parser::new(tokens.iter());
13     // 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 }

:

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 {
76         return Ok(None);
77     }
78     Ok(Some(self.parse_statement(Precedence::Lowest)?))
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
    of functions
117 // Input: precedence
118 // Output: statement or error
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         },
    :
    :
325 // Weighted function expects pairs of words or phrases and
    a weight between 0 and 1
326 // All weights must add up to exactly 1
327 fn parse_weighted(&mut self) -> Result<Vec<(Expression,
    Expression)>, ParseError> {
328     self.expect_token_and_read(Token::Weighted)?;
329     self.expect_token_and_read(Token::Colon)?;
330     let mut parameter: Vec<(Expression, Expression)> = Vec
        ::new();
331     let mut sum_weights: f64 = 0.0;
332     while !self.current_is(Token::Colon) {
333         if self.current_is(Token::Comma) {
334             self.expect_token_and_read(Token::Comma)?;
335         }
336         let expression = match self.parse_expression(
            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
342             ::Lowest)? {
343             Expression::ZeroToOne(f) => {
344                 sum_weights += f;
345                 Expression::ZeroToOne(f)
346             }
347             _ => return Err(ParseError::UnexpectedToken(
348                 self.current.clone())),
349         };
350         parameter.push((expression, weight));
351     }
352     if sum_weights != 1.0 {
353         return Err(ParseError::WeightError(sum_weights));
354     }
355     self.expect_token_and_read(Token::Colon)?;
356     Ok(parameter)
357 }

```

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::discriminant(&token)
94     }
95
96     // Current token should match the one given
97     // Input: token
98     // Output: token or error
99     fn expect_token(&mut self, token: Token) -> Result<Token,
100         ParseError> {
101         if self.current_is(token) {
102             Ok(self.current.clone())
103         } else {
104             Err(ParseError::UnexpectedToken(self.current.clone()))
105         }
106     }

```

```

102         } else {
103             Err(ParseError::UnexpectedToken(self.current.clone
104                 ()))
105         }
106     }
107     // Current token should match the one given and read to
108     // next token
109     // Input: token
110     // Output: token or error
111     fn expect_token_and_read(&mut self, token: Token) -> Result
112     <Token, ParseError> {
113         let result = self.expect_token(token)?;
114         self.read();
115         Ok(result)
116     }

```

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,
157     // operator or combination of expressions
158     fn parse_expression(&mut self, precedence: Precedence) ->
159     Result<Expression, ParseError> {
160         let mut expr = match self.current.clone() {
161             Token::WordOrPhrase(s) => {
162                 self.expect_token_and_read(Token::WordOrPhrase(
163                     s.to_string()))?;
164                 Expression::WordOrPhrase(s.to_string())
165             }
166         }

```

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
14     :
15
33 }
34
35 #[derive(Debug, Clone, PartialEq)]
36 pub enum Expression {
37
38     :
39
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(..)
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 }

```

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     }

```

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
189     // directly a new expression (here called postfix
190     // operator)
191     while !self.current_is(Token::EoF) && precedence <
192         Precedence::token(self.current.clone()) {
193         if let Some(expression) = self.
194             parse_postfix_expression(expr.clone())? {
195             expr = expression;
196         } else if let Some(expression) = self.
197             parse_infix_expression(expr.clone())? {
198             expr = expression
199         } else {
200             break;
201         }
202     }
203
204     :
205
206     // Infix operators AND and OR expect an expression on
207     // either side
208     fn parse_infix_expression(
209         &mut self,
210         expr: Expression,
211     ) -> Result<Option<Expression>, ParseError> {
212         Ok(match self.current {
213             Token::Plus | Token::And | Token::Or => {
214                 let token = self.current.clone();

```

```

228         self.read();
229         let sec_expr = self.parse_expression(Precedence
230             ::token(token.clone()))?;
231         Some(Expression::Infix(
232             Box::new(expr),
233             Operator::token(token),
234             Box::new(sec_expr),
235         ))
236     }
237     _ => None,
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
202     // , automatically inserting an AND inbetween
203     // Second Expression could have an NOT operator before the
204     // actual expression
205     fn parse_postfix_expression(
206         &mut self,
207         expr: Expression,
208     ) -> Result<Option<Expression>, ParseError> {
209         Ok(match self.current {
210             Token::Minus | Token::Bang | Token::WordOrPhrase
211             (..) => {
212                 let sec_expr = self.parse_expression(Precedence
213                     ::And)?;
214                 Some(Expression::Infix(
215                     Box::new(expr),
216                     Operator::And,
217                     Box::new(sec_expr),
218                 ))
219             }
220             _ => None,
221         })

```

```
217 |         } )  
218 |     }
```

Source: parser.rs



## 4 Summary

Summary

## Appendix

### Appendix 1: 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 // Transform string to list of tokens
36 let tokens = code_gen::lexer::lex(search.as_str());
37 // Parse tokens to an abstract syntax tree (ast)
38 let ast = code_gen::parser::parse(tokens);
39 match ast {
40     // If parser returns no error, start code generation
41     Ok(ast) => {
42         let generator = code_gen::generator::generate(ast);
43         // If generator returns no error, write SQL
44         // statement to file, otherwise throw an error
45         match generator {
46             Ok(generator) => write!(File::create(path)?, "
47                 {}", generator),
48             Err(gen_err) => Err(Error::new(ErrorKind::
49                 InvalidData, format!("{:?}", gen_err))),
50         }
51     }
52     // If parser returns error, throw an error aswell
53     Err(parse_err) => Err(Error::new(
54         ErrorKind::InvalidInput,
55         format!("{:?}", parse_err),
56     )),
57 }
58
59 // Runs a command to execute an sql statement to a local MSSQL
60 // Server
61 // Input: paths to the input file and where to write the result
62 // Output: txt file interpretation of the MSSQL Server result
63 fn execute_sql(sql_path: &str, results_path: &str) {
64     Command::new("cmd")
65         .args(&[
66             "/C",
67             "sqlcmd",
68             "-S",
69             "DESKTOP-JKNEH40\\SQLEXPRESS", //Local server name
70             "-i",
71             sql_path,
72             "-o",
73             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
114 // datatypes
115 #[derive(Deserialize)]
116 struct Search {
117     search: String,
118 }
119 #[derive(Serialize)]
120 struct Result {
121     title: String,
122     rank: u64,
123     link: String,
124 }
125
126 // Define functional parts of the search page
127 async fn search(tera: web::Data<Tera>) -> impl Responder {
128     let mut data = Context::new();
129     data.insert("title", "Search field");
130     let rendered = tera.render("search.html", &data).unwrap();
131     HttpResponse::Ok().body(rendered)
132 }
133
134 // Define functional parts of the result page
135 async fn result(tera: web::Data<Tera>, data: web::Form<Search>)
136     -> impl Responder {
137     let mut page_data = Context::new();
138     let mut results: Vec<Result> = Vec::new();
139     // Run code generator with the string from the search field
140     match run_code_gen(data.search.clone(), PATH_SQL) {
141         // If code generator returns no error execute SQL and
142         // read the results
143         Ok(_) => {
144             execute_sql(PATH_SQL, PATH_RESULTS);
145             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         }
157         None => {
158             page_data.insert("title", "Error");
159             page_data.insert(
160                 "search",
161                 &format!("{}", results cannot be read", &
162                     data.search),
163             );
164         }
165     }
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,
172                 &error.to_string()),
173         );
174     }
175     page_data.insert("results", &results);

```

```

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

```

## Appendix 2: 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?üÜöÖäÄ; \._<>'`#$%
        %/\ \=€]+\"##, 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 3: 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
24 // priority)
25 #[derive(Debug, Clone, PartialEq, PartialOrd)]
26 enum Precedence {
27     Lowest,
28     Statement,
29     Or,
30     And,
31     Not,
32     Prefix,
33     Group,
34 }
35
36 // Match tokens to precedences
37 impl Precedence {
38     fn token(token: Token) -> Self {
39         match token {
40             Token::Bang | Token::Minus => Self::Not,
41             Token::Plus | Token::And | Token::WordOrPhrase(..)
42                 => Self::And,
43             Token::Or => Self::Or,
44             Token::LeftParen => Self::Group,
45             Token::Contains
46                 | Token::Starts
47                 | Token::Inflection
48                 | Token::Thesaurus
49                 | Token::Near
50                 | Token::Weighted => Self::Statement,
51             _ => Self::Lowest,
52         }
53     }
54 }

```

```

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 {
76             return Ok(None);
77         }
78         Ok(Some(self.parse_statement(Precedence::Lowest)?))
79     }
80
81     // Set current and peek one step further in the vec of
82     // tokens
83     fn read(&mut self) {
84         self.current = self.peek.clone();
85         self.peek = if let Some(token) = self.tokens.next() {
86             token.clone()
87         } else {
88             Token::EoF
89         };
90     }
91
92     // 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::
        discriminant(&token)
94 }
95
96 // Current token should match the one given
97 // Input: token
98 // Output: token or error
99 fn expect_token(&mut self, token: Token) -> Result<Token,
    ParseError> {
100     if self.current_is(token) {
101         Ok(self.current.clone())
102     } else {
103         Err(ParseError::UnexpectedToken(self.current.clone
            ()))
104     }
105 }
106
107 // Current token should match the one given and read to
    next token
108 // Input: token
109 // Output: token or error
110 fn expect_token_and_read(&mut self, token: Token) -> Result
    <Token, ParseError> {
111     let result = self.expect_token(token)?;
112     self.read();
113     Ok(result)
114 }
115
116 // Parse statement, can only be a function or combination
    of functions
117 // Input: precedence
118 // Output: statement or error
119 fn parse_statement(&mut self, precedence: Precedence) ->
    Result<Statement, ParseError> {
120     let mut statement = match self.current.clone() {
121         Token::Contains => Statement::Contains {
122             expression: self.parse_contains()?,
123             },

```

```

124         Token::Starts => Statement::Starts {
125             expression: self.parse_starts()?,
126         },
127         Token::Inflection => Statement::Inflection {
128             expression: self.parse_inflection()?,
129         },
130         Token::Thesaurus => Statement::Thesaurus {
131             expression: self.parse_thesaurus()?,
132         },
133         Token::Near => {
134             let (parameter, proximity) = self.parse_near()
135                 ?;
136             Statement::Near {
137                 parameter,
138                 proximity,
139             }
140         },
141         Token::Weighted => Statement::Weighted {
142             parameter: self.parse_weighted()?,
143         },
144         _ => return Err(ParseError::UnexpectedToken(self.
145             current.clone())),
146     };
147     // After a function could be an infix operator
148     while !self.current_is(Token::EoF) && precedence <
149         Precedence::token(self.current.clone()) {
150         if let Some(in_statement) = self.
151             parse_infix_statement(statement.clone())? {
152             statement = in_statement
153         } else {
154             break;
155         }
156     }
157     Ok(statement)
158 }
159
160 // Parse expression, could be a search term, number,
161 // operator or combination of expressions
162 fn parse_expression(&mut self, precedence: Precedence) ->
163     Result<Expression, ParseError> {

```

```

158     let mut expr = match self.current.clone() {
159         Token::WordOrPhrase(s) => {
160             self.expect_token_and_read(Token::WordOrPhrase(
161                 s.to_string()))?;
162             Expression::WordOrPhrase(s.to_string())
163         }
164         Token::Number(u) => {
165             self.expect_token_and_read(Token::Number(0))?;
166             Expression::Number(u)
167         }
168         Token::ZeroToOne(f) => {
169             self.expect_token_and_read(Token::ZeroToOne
170                 (0.0))?;
171             Expression::ZeroToOne(f)
172         }
173         t @ Token::Minus | t @ Token::Bang => {
174             self.expect_token_and_read(t.clone())?;
175             Expression::Prefix(
176                 Operator::token(t),
177                 Box::new(self.parse_expression(Precedence::
178                     Prefix)?),
179             )
180         }
181         // Start a group which gets higher precedence
182         Token::LeftParen => {
183             let group_expression = match self.parse_group()
184             ? {
185                 Statement::Group { expression } =>
186                     expression,
187                 _ => return Err(ParseError::Unreachable),
188             };
189             group_expression
190         }
191         _ => return Err(ParseError::UnexpectedToken(self.
192             current.clone())),
193     };
194     // After an expression could be an infix operator or
195     // directly a new expression (here called postfix
196     // 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     }
198     Ok(expr)
199 }
200
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             let sec_expr = self.parse_expression(Precedence
                ::And)?;
210             Some(Expression::Infix(
211                 Box::new(expr),
212                 Operator::And,
213                 Box::new(sec_expr),
214             ))
215         }
216         _ => None,
217     })
218 }
219
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
230                 ::token(token.clone()))?;
231             Some(Expression::Infix(
232                 Box::new(expr),
233                 Operator::token(token),
234                 Box::new(sec_expr),
235             ))
236         }
237         _ => None,
238     })
239 }
240
241 // Infix operators AND and OR expect a statement on either
242 // side
243
244 fn parse_infix_statement(
245     &mut self,
246     statement: Statement,
247 ) -> Result<Option<Statement>, ParseError> {
248     Ok(match self.current {
249         Token::Plus | Token::And | Token::Or => {
250             let token = self.current.clone();
251             self.read();
252             let second_statement = self.parse_statement(
253                 Precedence::token(token.clone()))?;
254             Some(Statement::Infix {
255                 statement: Box::new(statement),
256                 operator: Operator::token(token),
257                 second_statement: Box::new(second_statement),
258             })
259         }
260         _ => None,

```



```
257         })
258     }
259
260     // Functions all have a similar strucure needing colons to
261     // surround their parameters
262
263     // Contains function only expects one word or phrase or
264     // combination of expressions
265     fn parse_contains(&mut self) -> Result<Expression,
266         ParseError> {
267         self.expect_token_and_read(Token::Contains)?;
268         self.expect_token_and_read(Token::Colon)?;
269         let expression: Expression = self.parse_expression(
270             Precedence::Statement)?;
271         self.expect_token_and_read(Token::Colon)?;
272         Ok(expression)
273     }
274
275     // Startswith function only expects one one word or phrase
276     // or combination of expressions
277     fn parse_starts(&mut self) -> Result<Expression, ParseError
278     > {
279         self.expect_token_and_read(Token::Starts)?;
280         self.expect_token_and_read(Token::Colon)?;
281         let expression: Expression = self.parse_expression(
282             Precedence::Statement)?;
283         self.expect_token_and_read(Token::Colon)?;
284         Ok(expression)
285     }
286
287     // Inflection function only expects one one word or phrase
288     // or combination of expressions
289     fn parse_inflection(&mut self) -> Result<Expression,
290         ParseError> {
291         self.expect_token_and_read(Token::Inflection)?;
292         self.expect_token_and_read(Token::Colon)?;
293         let expression: Expression = self.parse_expression(
294             Precedence::Statement)?;
295         self.expect_token_and_read(Token::Colon)?;
296         Ok(expression)
```

```

287     }
288
289     // Thesaurus function only expects one one word or phrase
290     // or combination of expressions
291     fn parse_thesaurus(&mut self) -> Result<Expression,
292     ParseError> {
293         self.expect_token_and_read(Token::Thesaurus)?;
294         self.expect_token_and_read(Token::Colon)?;
295         let expression: Expression = self.parse_expression(
296             Precedence::Statement)?;
297         self.expect_token_and_read(Token::Colon)?;
298         Ok(expression)
299     }
300
301     // Near function expects multiple comma-seperated words or
302     // phrases with an optional number as the last parameter
303     fn parse_near(&mut self) -> Result<(Vec<Expression>,
304     Expression), ParseError> {
305         self.expect_token_and_read(Token::Near)?;
306         self.expect_token_and_read(Token::Colon)?;
307         let mut parameter: Vec<Expression> = Vec::new();
308         // Proximity has a default value of 5 if no number is
309         // given
310         let mut proximity = Expression::Number(5);
311         while !self.current_is(Token::Colon) {
312             if self.current_is(Token::Comma) {
313                 self.expect_token_and_read(Token::Comma)?;
314             }
315             match self.parse_expression(Precedence::Lowest)? {
316                 Expression::WordOrPhrase(s) => parameter.push(
317                     Expression::WordOrPhrase(s)),
318                 Expression::Number(u) => {
319                     if self.current_is(Token::Colon) {
320                         proximity = Expression::Number(u)
321                     } else {
322                         return Err(ParseError::UnexpectedToken(
323                             self.current.clone()));
324                     }
325                 }
326             }
327         }

```

```

318         _ => return Err(ParseError::UnexpectedToken(
319             self.current.clone())),
320     }
321     self.expect_token_and_read(Token::Colon)?;
322     Ok((parameter, proximity))
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)? {
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));

```

```

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
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 }
367
368 // Types of errors covered by the parser
369 #[derive(Debug, Error)]
370 pub enum ParseError {
371     #[error("Unexpected token {0:?}.")]
372     UnexpectedToken(Token),
373     #[error("Entered unreachable code.")]
374     Unreachable,
375     #[error("Weights do not add up to 1.0. Sum of all weights: {0}")]
376     WeightError(f64),
377 }

```

## Appendix 4: 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 5: 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,
16     GenerateError> {
17     let mut generator = Generator::new(ast.iter());
18     // write twice to overwrite initial EOF tokens
19     generator.write();
20     generator.write();
21     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 token 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         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.
62             next() {
63             statement.clone()
64         } else {
65             Statement::EoF
66         };
67     }
68     // Generate statement, always a function or combination of
69     // functions
70     // Input: statement to generate
71     // Output: string
72     fn generate_statement(&mut self, statement: Statement) ->
73     Result<String, GenerateError> {
74         let sql: String = match statement {
75             Statement::Infix {
76                 statement,
77                 operator,
78                 second_statement,
79             } => {
80                 let sql_parts = [
81                     self.generate_statement(*statement)?,
82                     self.generate_operator(operator)?,
83                     self.generate_statement(*second_statement)
84                     ?,
85                 ];
86                 sql_parts.join(" ")
87             }
88         }
89         // Contains generates it's search condition without
90         // mutation
91         Statement::Contains { expression } => {
92             format!("{}", self.generate_expression(
93                 expression)?)

```



```

88     }
89     // Startswith adds a * to end of a word or before
    the last " in a phrase
90     Statement::Starts { expression } => {
91         let mut word_or_phrase = self.
            generate_expression(expression)?;
92         if word_or_phrase.starts_with('"') &&
            word_or_phrase.ends_with('"') {
93             word_or_phrase.insert(word_or_phrase.len()
                - 1, '*');
94         } else {
95             word_or_phrase.push('*');
96         }
97         format!("{}", word_or_phrase)
98     }
99     // Inflection calls the inflection function from
    MSSQL
100    Statement::Inflection { expression } => {
101        let mut word_or_phrase = self.
            generate_expression(expression)?;
102        if word_or_phrase.starts_with('"') &&
            word_or_phrase.ends_with('"') {
103            word_or_phrase.remove(0);
104            word_or_phrase.remove(word_or_phrase.len()
                - 1);
105        }
106        format!("FORMSOF (INFLECTIONAL, \"{}\") ",
            word_or_phrase)
107    }
108    // Thesaurus calls the thesaurus function from
    MSSQL
109    Statement::Thesaurus { expression } => {
110        let mut word_or_phrase = self.
            generate_expression(expression)?;
111        if word_or_phrase.starts_with('"') &&
            word_or_phrase.ends_with('"') {
112            word_or_phrase.remove(0);
113            word_or_phrase.remove(word_or_phrase.len()
                - 1);
114        }

```

```

115         format!("FORMSOF (THESAURUS, \("{}\")",
116             word_or_phrase)
117     }
118     // Near generates a parameter list of all search
119     // criteria and proximity in the end
120     Statement::Near {
121         parameter,
122         proximity,
123     } => {
124         let mut sql_parts: Vec<String> = Vec::new();
125         sql_parts.push(format!("NEAR("));
126         for expression in parameter {
127             let string = self.generate_expression(
128                 expression)?;
129             sql_parts.push(format!("{}", string));
130             sql_parts.push(String::from(", "));
131         }
132         sql_parts.remove(sql_parts.len() - 1);
133         sql_parts.push(format!("{}", self.
134             generate_expression(proximity)?));
135         sql_parts.join("")
136     }
137     // Weighted generates tuples of search criteria and
138     // their respective weight
139     Statement::Weighted { parameter } => {
140         let mut sql_parts: Vec<String> = Vec::new();
141         sql_parts.push(format!("ISABOUT("));
142         for (word_or_phrase_expr, weight_expr) in
143             parameter {
144             let word_or_phrase = self.
145                 generate_expression(word_or_phrase_expr)
146                 ?;
147             let weight = self.generate_expression(
148                 weight_expr)?;
149             sql_parts.push(format!("{}", WEIGHT({},
150                 word_or_phrase, weight)));
151             sql_parts.push(String::from(", "));
152         }
153         sql_parts.remove(sql_parts.len() - 1);
154         sql_parts.push(String::from(")"));

```

```

145         sql_parts.join("")
146     }
147     _ => return Err(GenerateError::UnexpectedStatement(
148         self.current.clone())),
149 };
150 self.write();
151 Ok(sql)
152 }
153
154 // Generate expression, any search criteria or number or
155 // combination of those
156 // Input: expression to generate
157 // Output: string
158 fn generate_expression(&mut self, expression: Expression)
159 -> Result<String, GenerateError> {
160     let sql: String = match expression {
161         Expression::WordOrPhrase(s) => s,
162         Expression::Number(u) => u.to_string(),
163         Expression::ZeroToOne(f) => f.to_string(),
164         // Infix operator enclose their expressions with
165         // parentheses to ensure precedence
166         Expression::Infix(expr1, operator, expr2) => {
167             let mut sql_parts = [
168                 String::from("("),
169                 self.generate_expression(*expr1)?,
170                 String::from(")"),
171                 self.generate_operator(operator)?,
172                 String::from("("),
173                 self.generate_expression(*expr2.clone())?,
174                 String::from(")"),
175             ];
176             // If the second expression is a not operator
177             // it must write NOT before the parentheses
178             match *expr2 {
179                 Expression::Prefix(Operator::Not, ..) =>
180                     sql_parts[4] = String::from("NOT "),
181                 _ => (),
182             }
183             sql_parts.join(" ")
184         }
185     }

```

```

179         Expression::Prefix(operator, expr) => {
180             let sql_parts = [
181                 self.generate_operator(operator)?,
182                 self.generate_expression(*expr)?,
183             ];
184             sql_parts.join(" ")
185         }
186     };
187     Ok(sql)
188 }
189
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 }
204
205 // Types of error covered by the generator
206 #[derive(Debug, Error)]
207 pub enum GenerateError {
208     #[error("Unexpected statement {0:?}.")]
209     UnexpectedStatement(Statement),
210 }

```

## Appendix 6: mod.rs

```

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

```

## Appendix 7: 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 8: 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 9: 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 }}">
        {{ result.title }}</a>
10     <small>{{ result.rank }}</small>
11 </div>
12 {% endfor %}
13 {% endblock %}

```

## Appendix 10: 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
            = ("end",)):

```

```

28         if element.tag.endswith("page"):
29             namespace_tag = element.find(ns_token)
30
31             if namespace_tag.text == "0":
32                 title_tag = element.find(title_token)
33                 text_tag = element.find(revision_token).
34                     find(text_token)
35                 yield title_tag.text, text_tag.text
36
37             element.clear()
38
39 def pluck_wikipedia_titles_text(
40     out_file, pattern="enwiki-*-pages-articles-multistream*.xml
41     -*-bz2"
42 ):
43     totalCount = 0
44     longestTitle = 0
45     longestText = 0
46     with codecs.open(out_file, "a+b", "utf8") as out_file:
47         writer = csv.writer(out_file)
48         for bz2_filename in sorted(
49             glob(pattern),
50             key=lambda a: int(a.split("articles-multistream")
51                 [1].split(".")[0]),
52         ):
53             print(bz2_filename)
54             parser = get_parser(bz2_filename)
55             for title, text in parser:
56                 if not (text.startswith("#REDIRECT") or text.
57                     startswith("#redirect")):
58                     totalCount += 1
59                     writer.writerow([title, text])
60                     longestTitle = (
61                         len(title) if len(title) > longestTitle
62                         else longestTitle
63                     )
64                     longestText = len(text) if len(text) >
65                         longestText else longestText

```

```
61         if totalCount > 1 and (totalCount % 100000)
           == 0:
62             print("{:,}".format(totalCount))
63         if totalCount >= 1000:
64             break
65     print(
66         f"Total Count: {totalCount}\nLongest Title: {
           longestTitle}\nLongest Text: {longestText}"
67     )
68
69
70 pathArticles = os.path.join(PATH_WIKI_XML, FILENAME_ARTICLES)
71
72 start_time = time.time()
73
74 pluck_wikipedia_titles_text(pathArticles)
75
76 time_took = time.time() - start_time
77 print(f"Total runtime: {hms_string(time_took)}")
```

## Appendix 11: 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 12: bulk\_insert.sql

```
1 USE Wikipedia;
2 BULK
```



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

## Appendix 13: alter\_id.sql

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

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(Location, Date)

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

(handwritten signature)