Compilers and computer architecture: From strings to ASTs (1): lexing

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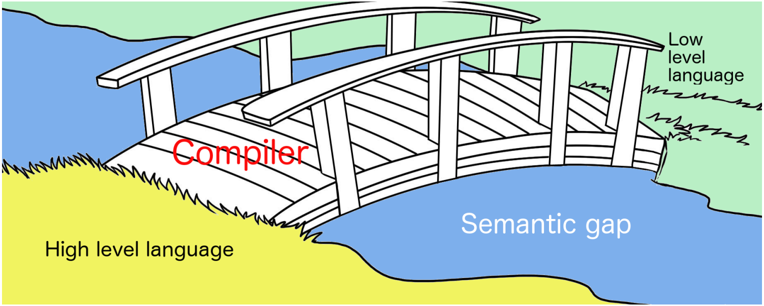
Recall the function of compilers



Plan for the next 9 weeks

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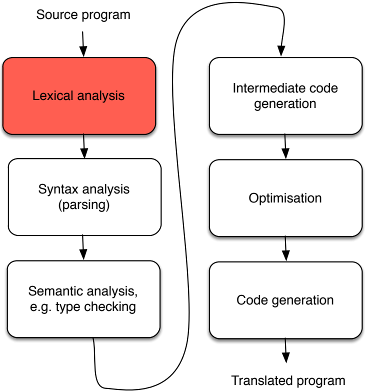
Source program

Lexical analysis

Syntax analysis (parsing)

Semantic analysis, e.g. type checking

Intermediate code generation

Optimisation

Code generation

Translated program

Remember the shape of compilers?

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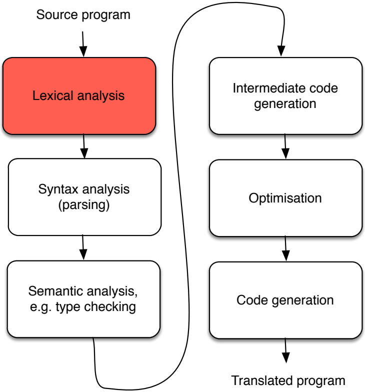

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For the next 9 weeks or so, we will explore this pipeline step-by-step, starting with lexing.

From strings to ASTs

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The purposes of the lexing and parsing phase is twofold.

- To convert the input from strings (a representation that is convenient for humans) to an abstract syntax tree (AST), a representation that is convenient for (type-checking and) code generation.
- Check syntactic correctness.

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We will later define in details what ASTs are, but for now, a picture says more than 1000 words. We want to go from the representation on the left to that on the right:

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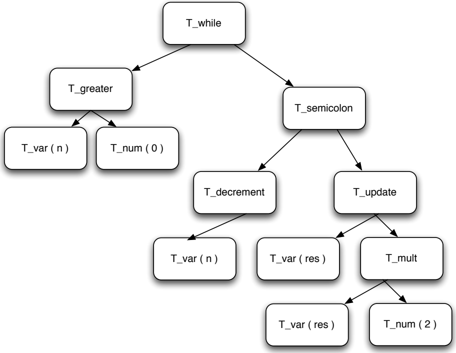
while( n > 0 ){
    n--;
    res *= 2; }
```



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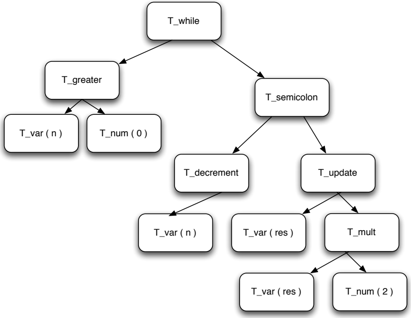

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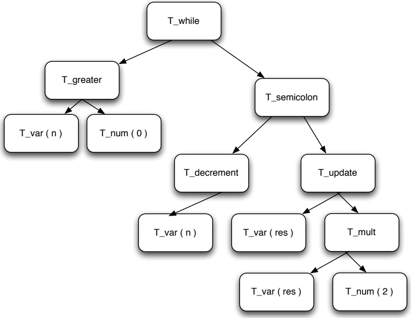

Why? To make the backend and type-checking much easier and faster: type-checking and code generation need acces to components of the program. E.g. to generate code for `if C then Q else R` we need to generate code for `C`. `Q` and `R`. This is **difficult directly from strings**. The AST is a data structure optimised for making this simple. ASTs use pointers (references) to point to program components. CPUs can maninpulate pointers very efficiently.

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This will involve a bit of language theory and automata, some of which you have already seen last year in one of the introductory courses. You will also learn about tools for generating lexers and parsers.

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Knowing about this, (e.g. regular expressions, context-free languages) is one of the most useful things to know as a programmer, even if you'll never write a compiler: just about every application you'll ever encounter will involve reading or creating formal languages.

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The purpose of lexing is to prepare the input for the parser.
This involves several related jobs.

- Removing irrelevant detail (e.g. whitespace, tab-stops, new-lines).
- Split the string into basic parts called tokens. You can think of them as ’atoms’.

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In other words, the program

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if n == 3 then x := 0 else x := 1
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is **syntactically** correct exactly when

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if numberOfUsers == 666 then y := 0 else z := 171717
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The precise choice of variable name is important later (for type-checking and for code generation) so we keep the name of the identifier for later phases. But syntactic correctness is decided independently of this detail.

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Information hiding / modularisation: for syntax analysis it's **not** important if the syntax for conditionals is `if then else` or `IF THENDO ELSEDO` etc. In other words, the reason why we deem

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to be **syntactically** correct (in one language) is exactly the same as the reason why we deem

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The precise choice of keywords name is irrelevant in later stages, so let's abstract it by way of a **token** representing concrete keywords. That makes it much easier to change language keywords later, only the lexer needs adaptation.

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... are **syntactically** correct in English.

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In practise, those steps are often excuted in one go for efficiency.

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Both are **much** easier using a list of tokens, rather than a string. So tokenisation is a form of simplification (information hiding): it shields the next stage (parsing) from having to deal with irrelevant information.

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In summary, lexing has two beneficial effects.

- It simplifies the next stage, parsing (which checks syntactic correctness and constructs the AST).
- It abstracts the rest of the compilers from the lexical detail of the source language.

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So the tokens are: Keywords, Identifiers, Integers, Floating point numbers, Binary operators, Left bracket, Right bracket, ...

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- Ident: “x”
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- Identifier: "z"
- Binop: ":="
- Unop: "-"
- Float "3.01"

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- Boundaries between tokens.

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- Inhabitation of tokens, i.e. decide which strings are classified by what tokens.
- An algorithm that inputs a strings and outputs a token list.
- What to do if we encounter an input that isn't well-formed, i.e. a string that cannot be broken down into a list of tokens.

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Can you see a problem with this?

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We must have a mechanism to deal with this: e.g. have priorities like: if a string is both a keyword and an identifier, it should be classified as a keyword. In other words, keywords have **priority** over identifiers.

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Allowing identifiers also to be keywords is rarely useful, so most modern programming languages prohibit it.

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What about the string “IFTHEN”? Should it be the tokens “IF” followed by “THEN”, or a single token standing for the identifier “IFTHEN”? Usual answer: use **longest match.**

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So the lexer can only classify strings by **looking ahead**.

How does the lexer know from looking ahead that the “for” in “formulaLength” isn’t a keyword? Answer: because we know what word boundaries are (such as whitespace, semicolon).

Tokens and their inhabitation

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The more lookahead required, the less efficient the lexing process. Some old language can require unbounded lookahead. Modern languages require little lookahead (typically 1 character). Bear that in mind when designing a language.

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- Get rid of semantically irrelevant information (e.g. whitespace, tab stops, syntax of keywords, ...)
- Give a rough classification (simplification) of the input to simplify the next stage (parsing). In detail:
  - Identify the lexical structure and tokens of the language.
  - Partition the input string into small units (tokens) used by the parser.

Lexing does a left-to-right scan of the input string, sometimes with lookahead.

Tasks for the lexical stage

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Let's rephrase what we've just said in a slightly different language. The point of the lexical phase is:

1. **Description** of the lexical structure of the language (determine token classes). We use **regular expressions** for this purpose.
2. From the description in (1) derive a scanning **algorithm**, called lexer, that determines the token class of each lexical unit. We use FSAs (**finite state automata**) for this.

Regular expressions

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Aside: Invented in the 1950s to study neurons / neural nets! (Then called “nerve nets”.)

Preparation for regular expressions

An **alphabet** is a set of characters. Examples $\{1, 4, 7\}$ is an alphabet as is $\{a, b, c, ..., z\}$, as is the empty set.

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Question: what are the strings that you can form over the empty set as alphabet?

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Do you see what's special about the last three examples?

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Do you see what's special about the last three examples? The languages are infinite!

Specifying languages

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Finite languages (= consisting of a finite number of strings) can be given by listing all strings. This is not possible for infinite languages (e.g. the language of all integers as a language over $\{0, ..., 9\}$).

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Regular expressions are a mechanism to specify finite and infinite languages.

This is the real point of regular expressions (and other formal accounts of languages like context free languages that we see later): to enable a **terse** description of languages that are too **large** (typically infinite) to enumerate.

The set of all (lexically/syntactically valid) Java/C/Python/Rust ... programs is infinite.

Regular expressions

Regular expressions

Regular expressions are a tool for specifying languages. You can think of them as a “domain specific language” or an ’API’ to specify languages. We will describe them precisely but informally now.

Regular expressions

Regular expressions

Let A be an alphabet, i.e. a set of characters. We now define two things in parallel:

- The **regular expressions** over A.
- The **language** of each regular expression over A. We denote the language of r.e. R by $\text{lang}(R)$.

Regular expressions

We have 7 (basic) kinds of regular expressions over alphabet A

- $\emptyset$.
- ϵ.
- $'c'$ for all $c \in A$.
- $R|R'$.
- RR'.
- R^*.
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Each specifies a **language**.

Regular expressions (1): $\emptyset$

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Let *A* be an alphabet, i.e. a set of characters. The **regular expressions** over *A* are given by the following rules.

$\emptyset$ is a regular expression, denoting the empty set $\{\}$. Now lang($\emptyset$) $= \{\}$.

Regular expressions (2): ϵ

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It's important to realise that $\emptyset$ and ϵ are different regular expressions, denoting different languages.

Regular expressions (3): alphabet characters

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Let *A* be an alphabet, i.e. a set of characters. The **regular expressions** over *A* are given by the following rules.

For each character *c* from *A*, $'c'$ is a regular expression, denoting the language

$$\text{lang}('c') = \{''c''\}.$$

Regular expressions (4): alternatives

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Let A be an alphabet, i.e. a set of characters. The **regular expressions** over A are given by the following rules.

If R and S are regular expression, then $R|S$ is a regular expression, denoting the language

$$\mathrm{lang}(R) \cup \mathrm{lang}(S).$$

You can think of $R|S$ as R **or** S.

Regular expressions (5): concatenation

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Let A be an alphabet, i.e. a set of characters. The **regular expressions** over A are given by the following rules.

If R and S are regular expression, then RS (pronounced R **concatenated** with S, or R **then** S) is a regular expression, denoting the language

$$\{rs | r \in \text{lang}(R), s \in \text{lang}(S)\}.$$

Here rs is the concatenation of the strings r and s. Example: if $r = "hello"$ and $s = "world"$, then rs is $"helloworld"$.

Regular expressions (6): star

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The regular expressions presented so far do not, on their own, allow as to define **infinite** languages. Why?

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The next operator changes this. It can be seen as a simple kind of ’recursion’ or ’loop’ construct for languages.

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Let A be an alphabet, i.e. a set of characters. The **regular expressions** over A are given by the following rules.

If R is a regular expression, then R^* (pronounced ***R*-star**) is a regular expression, denoting the language

$$\text{lang}(R^*) = \text{lang}(\epsilon) \cup \text{lang}(R) \cup \text{lang}(RR) \cup \text{lang}(RRR) \cup \cdots$$

In other words

$$\text{lang}(R^*) = \bigcup_{n \geq 0} \text{lang}(\underbrace{RRR...R}_{n})$$

So a string w is in $\text{lang}(R^*)$ exactly when some number n exists with $w \in \text{lang}(\underbrace{RRR...R}_{n \text{ times}})$.

Regular expressions (6): star

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Example: Let $A = \{0, 1, 2, ..., 9\}$, then the language of

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No!

Regular expressions (7): brackets

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Let A be an alphabet, i.e. a set of characters. The **regular expressions** over A are given by the following rules.

If R is a regular expression, then (R) is a regular expression with the same meaning as R, i.e.

$$\mathrm{lang}((R)) = \mathrm{lang}(R).$$

Regular expressions: summary

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Summary: the regular expressions over an alphabet A are

- $\emptyset$.
- ϵ.
- $'c'$ for all $c \in A$.
- $R|R'$, provided R and R' are regular expressions.
- RR', provided R and R' are regular expressions.
- R^*, provided R is a regular expressions.
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So $AB^*C|D$ should be read as $((A(B^*))C)|D$.

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Answer: the set of all binary strings containing 00 as a substring.

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Answer: $('0'|'1')('0'|'1')('0'|'1')('0'|'1')$.

Examples of REs

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Alphabet $A = \{0, 1\}$. What regular expression has only strings with at most one 0 as language?

Examples of REs

Alphabet $A = \{0, 1\}$. What regular expression has only strings with at most one 0 as language?

Answer: $'1'^*('0'|\epsilon)'1'^*$

Examples of REs

Examples of REs

Alphabet $A = \{-, 0, 1, ..., 9\}$. What regular expression has only strings representing positive and negative integers as language?

$$('-'|\epsilon)('0'|'1'|'2'|'3'|'4'|'5'|'6'|'7'|'8'|'9')('0'|...|'9')^*$$

Note that "..." is not part of regular expressions, I was just too lazy to type out all the relevant characters.

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- R^+ stands for RR^*. (Note R^+S is different from $R + S$)

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- Instead of $'a'' \; ''s''t''r''i''n''g'$ we write $'a\ string'$ or $''a\ string''$.
- Sometimes $R + S$ is written for $R|S$.
- R^+ stands for RR^*. (Note R^+S is different from $R + S$)
- If there's a 'natural' order on the alphabet we often specify ranges, e.g. $[a - z]$ instead of $a|b|c|...|y|z$ or $[0 - 9]$ instead of $0|1|2|3|4|5|6|7|8|9$, or $[2 - 5]$ for $2|3|4|5$. Etc.

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- We write $[a - zA - Z]$ instead of $[a - z]|[A - Z]$
- $R?$ for $R|\epsilon$

Lexical specification using REs

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Let us now give a lexical specification of a simple programming language using REs. We start with keywords.

```
"if" | "else" | "for" | "while"
```

Recall that `"if"` is a shorthand for `′i″f′`.

Lexical specification using REs

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Next are digits and integers. Digits are:

```
0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9
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We want to refer to this RE later, so we name it.

```
digit = [0-9]
```

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Abbreviations are helpful for readability (writing `epsilon` for ϵ).

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whitespace = (’ ’ | ’\n’ | ’\t’)+
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When specifying the lexical level of programming languages we also need to specify whitespace (why?). Often the following is used.

```
whitespace = (' ' | '\n' | '\t')+
```

What does '\n' and '\t' mean?

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Here is a more realistic example: specification of numbers in a real programming language. Examples 234, 3.141526 or 6.2E-14

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```
digit          = [0-9]
digits         = digit+
optFraction    = ('.'digits) | eps
optExponent    = ( 'E'( '-' | eps ) digits )
               | eps
num            = digits optFraction optExponent
```

(Writing `eps` for `epsilon`.)

Real languages

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Java's (JDK 13) lexical spec: `https://docs.oracle.com/javase/specs/jls/se13/html/jls-3.html`

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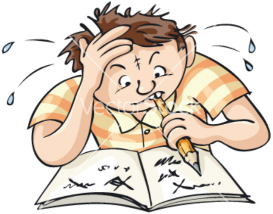

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2. How to decide, given a string s and a regular expression R, if $s \in lang(R)$? Answer: FSA as **algorithms** to **decide** the language defined by REs.

The material in the textbooks

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- Dragon Book: Chapter 2.6 and Chapter 3.

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- "Engineering a compiler": Chapter 2.1 and 2.2