Compiler Construction: Practical Introduction

Lecture 2
Lexical Analysis

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Lexical Analysis: the Outline

- Lexical analysis: why & what for?
- The notion of token, its meaning and implementation
- Some formal basis
- Scanners:
  - implementation techniques;
  - scanner generation tools
- Scanner & parser integration: the architecture
- Non-standard issues

Compilation: An Ideal Picture

From the previous lecture

A program written by a human (or by another program)

Source program text

↓

Lexical analysis ⇒ Syntax analysis ⇒ Semantic analysis ⇒ Code generation ⇒ Linking

↓

Target code
010101110011101010000
011011110101010110011
100110101011110001100

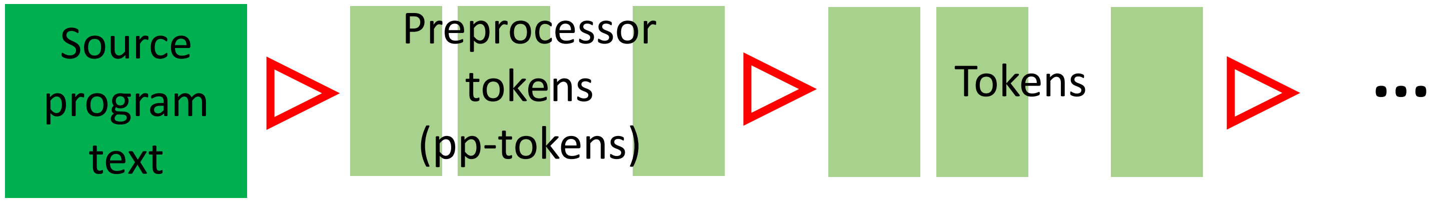
A program binary image suitable for immediate execution by a machine

Blue squares just denote some **actions** typical to any compiler; they are not necessarily actual compiler **components**.

Compilation Stages: Lexical Analysis

From the previous lecture

Components: preprocessor, scanner



- **Token** is the minimal element of the language alphabet. Examples are operator signs, delimiters, identifiers, keywords, literals.
- **Token representations** in the compiler can be either very simple (e.g., coded by integer values) or be a structure with a set of attributes.
- How lexical analysis **interacts** with other compiler components: either passing the current token "on demand" or buffering tokens and traversing those buffers (with returns) – see next lecture(s).

Lexical Analysis: the Overall View

Source program:
written by a developer and saved in a **disk file**

```
class Point{
    public int x, y;
}
```

Source program text from a compiler's point of view:
a **sequence of characters**

c	l	a	s	s	␣	P	o	i	n	t	␣	{	\n	\t	p	u	b	l	i	c	␣	i	n	t	␣	x	…

Reserved word: `class`

Whitespace

Identifier: `Point`

Delimiter: `{`

Whitespaces

Reserved word: `public`

Reserved word: `int`

Identifier: `x`

Lexical analyzer scans **character by character** trying to **identify** a subsequence of characters as a **minimal unit ("token")** that has a special meaning in the language

Lexical Analysis: the Overall View

Source program:
written by a developer
and saved in a **disk file**

```
class Point{
   public int x, y;
}
```

Lexical analyzer ⇒

Sequence of **tokens**

- Reserved word **class**
- Whitespace ␣
- Identifier Point
- Delimiter {
- Newline \n
- Hor. tab \t
- Reserved word **public**
- Reserved word **int**
- ...
- End-of-file EOF

Lexical Analysis: Preprocessing

file.c

```
int C=0;
```

```
#include "file.c"
#define A ++a
int x=A;
```

Sequence of pp-tokens

- Include directive
- String file.c
- Newline \n␣
- Define directive
- Identifier A
- Operator sign ++
- Identifier a
- Newline \n␣
- Reserved word int
- Whitespace ␣
- Identifier x
- Delimiter =
- Identifier A
- Delimiter ;
- …

The contents of file.c gets scanned and **included** into the current token sequence

The **macro definition** (the name and its token sequence) for A is stored by the preprocessor…

This is the **use** of the macro: its token sequence gets passed to the current sequence

Sequence of tokens

- Reserved word int
- Whitespace ␣
- Identifier C
- Delimiter =
- Integer literal 0
- Delimiter ;

- Reserved word int
- Whitespace ␣
- Identifier x
- Delimiter =
- Operator sign ++
- Identifier a

- Delimiter ;
- …

Tokens & Lexemes: Terminology

From the “Dragon Book”

Token **Lexeme’s category**	**Pattern** **Generalized category description**	**Lexeme** **A concrete text snippet, that falls under a certain category**
Keyword `if`	Joint sequence of characters `i` and `f`, with neither letter nor digit after it.	`if`
Comparison operator sign	One of signs < or >, or one of sequences `<=, >=, == or !=`	`>=`
Identifier	A sequence of letters, digits and underscore characters starting with letter of underscore.	`abracadabra` `a_long_identifier`

Integer unsigned constant	A sequence of decimal digits.	`0`
		`17`
		`123456789`

Token categories: Identifiers & Keywords (1)

- The category depends on the context: PL/I

```
IF IF == THEN THEN THEN = ELSE ELSE ELSE = END END
```

```
IF IF == THEN
THEN
    THEN = ELSE
ELSE
    ELSE = END
END
```

```
IF IF == THEN
THEN
    THEN = ELSE
ELSE
    ELSE = END
END
```

- Keywords are a **fixed set** of identifiers with special meaning: Pascal, C/C++, Java/C# etc.

Java: 51+ keywords
`abstract`, `assert`, `boolean`, `break`, `byte`, …
C++: 81 keywords
`alignas`, `alignof`, `asm`, `auto`, `bool`, `break`, …

Token categories: Identifiers & Keywords (2)

- Keywords are explicitly marked (by leading underscore or by quotes): *Algol-60, Algol-68, Эль-76*

```
_если итерация = последняя _то
    ЗакончилиЦикл := _истина; Выход!(777)
_все;
```

```
'if' a > b
'then' 'begin'
    a := b;
    b := 0
'end'
```

- Keywords & identifiers are lexically identical.

```
if ( alpha != beta ) alpha = 0;
else gamma = 777;
```

Token categories: Identifiers & Keywords (3)

- The meaning of the token depends on the context

```
class C {
    public int p { get; }
    public f() {
        int get;
    }
}
```

C#

The first **get** is the keyword, whereas the second one is a usual local variable…

Token categories: Spaces (1)

Spaces (blanks, whitespaces)

- Spaces are treated non-meaningful everywhere in the program (*and* inside identifiers)

```
This is the valid identifier in some langs := 777;
```

Fortran: dramatic error:

```
DO 5 I = 1.25

DO 5 I = 1,25
```

This is **the assignment**: a real value of `1.25` is assigned to the variable `DO5I` (spaces are not considered).

This is **the loop header**! Loop variable `I` sequentially gets values from the range `1..25`. (The end of the loop is marked by the label 5.)

Token categories: Spaces (2)

- Spaces always separate tokens and are never a part of any token (except strings).
- Two adjacent identifiers, or a constant following the identifier, of two adjacent constants – all are treated as lexical errors.

```
A  B
A  5
5  10
```

Error: this is **not** identifier AB

Error: this is **not** identifier A5.

Error: this is **not** integer value 510.

- Tricky question ☺: how to interpret C++/Java constructs like `C c;` ?

Token categories: Comments (1)

- Typically, comments are treated as *whitespaces*; they do not alter the program semantics => they are dropped by the lexical analyzer.
- Short & long comments:

```
// This is the short (one-line) comment

/* This is the “long”,
   or multi-line
   comment */
```

- Comment can OR cannot nest:

```
/* Some languages
   do /* not */ allow
   nesting comments
*/
```

Token categories: Comments (2)

- ***Documenting comments***: they do not alter the program semantics, but compiler should process them somehow (they even may go to the object code!)

```
// This is just a comment

/// <summary>This is «documenting» comment (C#).
/// </summary>

/** This is also documenting comment (Java) */
```

- Typically, documenting comments serve as a prototype for creating <u>program documentation</u> – either by compiler itself, or by a standalone tool.

Formal Basics (1)

- Lexeme's structure is typically described by **regular grammars**. All the grammar rules have the following configuration:

  `A -> Ba` or `A -> a`

  Here, `A`, `B` – **nonterminal** symbols, `a` – a **terminal** symbol: an element of the grammar's **alphabet**.

  Example:

```
identifier -> letter
identifier -> identifier letter
identifier -> identifier digit
letter -> "a"
letter -> "b"
  ...
letter -> "z"
digit -> "0"
  ...
digit -> "9"
```

Formal Basics (2)

- Regular grammars are often represented in a more compact notation called **regular expressions**.

  Example:

  ```
  identifier -> letter [ letter | digit ]*
  letter -> ["a".."z"]
  digit -> ["0".."9"]
  ```

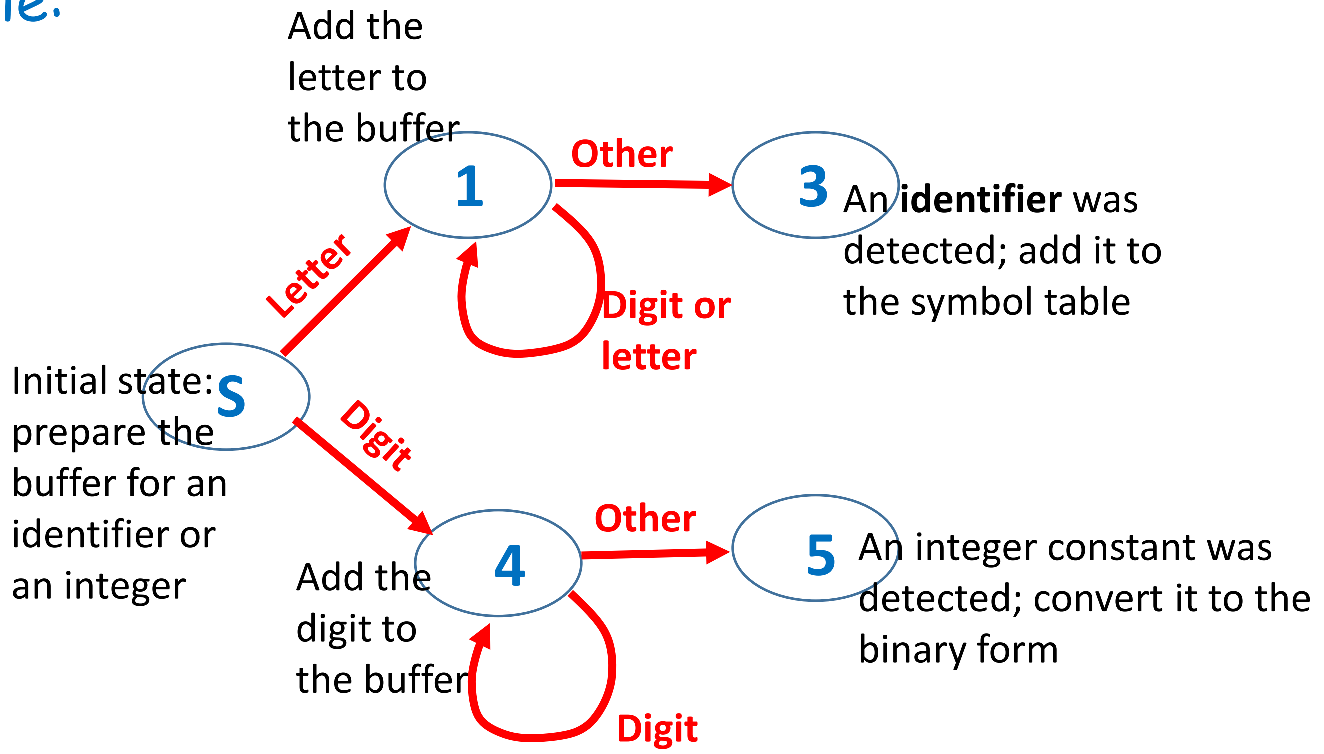
- The main statement concerning regular grammars: to scan a token successfully (and therefore, to determine that a token belongs to the given grammar) it's enough to know the **current** scanner **state** and **only one** input character.

- A scanner for regular expressions can be defined by the notion of the **finite state machine**.

Formal Basics (3)

- **Finite State Machine**:
  A (virtual) system that can have a **state** at each moment.
  When a character comes to the machine it changes its **state** and performs an **action**.

  Example:



Scanner Generator

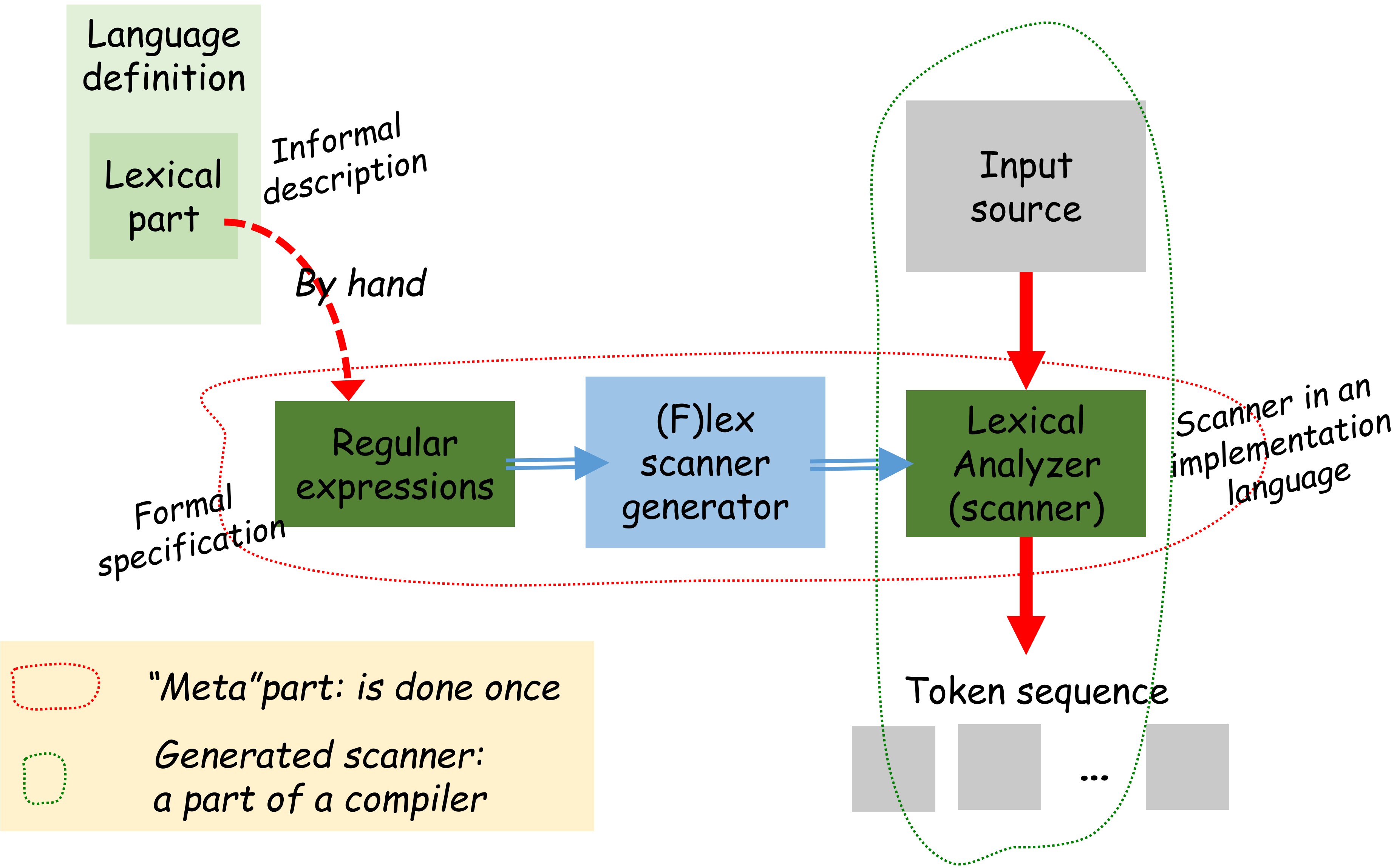
- **lex/flex**
  For a given formal specification (consisting of regular expressions) generates a program that detects tokens in accordance with the specification.

- **Lex - A Lexical Analyzer Generator**
  M. E. Lesk and E. Schmidt
  http://dinosaur.compilertools.net/lex/index.html

- Typically, lex/flex is used together with the parser generator **yacc/bison**.

Versions of lex & yacc are available for many languages

(F)lex Scanner Generator



Scanner implementation (1)

```
// Token codes
// for keywords
// and operator signs
enum Code {
   ...
   tkInt,
   tkFloat,
   tkSwitch,
   tkWhile,
   ...
   tkNOT_EQUAL_EQUAL,
   tkNOT_EQUAL,
   tkEXCLAMATION,
   tkPERCENT_EQUAL,
   tkPERCENT,
   ...
}
```

This is the way I usually recommend for implementing scanners in student projects

```
ch = get();
switch (ch)
{
    ...
    case '!':                              // ! or != or !==
        if (get() == '=')
        {
            if (get() == '=')
                tokCode = tkNOT_EQUAL_EQUAL;
            else
                tokCode = tkNOT_EQUAL;
        }
        else
            tokCode = tkEXCLAMATION;
        break;
    case '%':                              // % or %=
        if (get() == '=')
            tokCode = tkPERCENT_EQUAL;
        else
            tokCode = tkPERCENT;
        break;
    ...
```

The get() function returns the next character from the input

Scanner implementation (2)

```
...
elsif Slen = 3 then
    C1 := Source(Token_Ptr + 1);
    C2 := Source(Token_Ptr + 2);
    C3 := Source(Token_Ptr + 3);
    if (C1 = 'A' or else C1 = 'a') and then  -- AND
       (C2 = 'N' or else C2 = 'n') and then
       (C3 = 'D' or else C3 = 'd')
    then
       Token_Name := Name_Op_And;
    elsif (C1 = 'A' or else C1 = 'a') and then -- ABS
          (C2 = 'B' or else C2 = 'b') and then
          (C3 = 'S' or else C3 = 's')
    then
       Token_Name := Name_Op_Abs;
...
```

Taken from the sources of the **GNAT Ada compiler**

Scanner implementation (3)

How to distinguish identifier from a keyword?

- Directly:

```
// Token codes
enum Code {
   ...
   tkInt,
   tkFloat,
   tkSwitch,
   tkWhile,
   ...
}
```

```
// Suppose letters composing identifier are here
char buffer[maxLen];

...
if      (strcmp(buffer,"switch")==0) return tkSwitch;
else if (strcmp(buffer,"while")==0) return tkWhile;
else if (strcmp(buffer,"int")==0) return tkInt;
...
else return tkIdentifier;
```

Scanner implementation (4)

How to distinguish identifier from a keyword?

- A bit smarter: using hash functions

Hash function maps an unlimited set of strings (e.g., identifiers) to a set of integer values within a range `[1..N]`, where `N` is the number of keywords so that for the given set of strings (representing keywords) the function returns different values.

```
int hash(char* keyword)
{
   // Maps the set of keywords of the given
   // language to the set of integers in the
   // range 1..nKW, where nKW – the common
   // amount of keywords.
}
int Table[nKW] =
  { tokIdentifier, tokSwitch,
    tokWhile, tokInt, ... };

// the buffer with the id/keyword
char buffer[maxLen];
...
return Table[hash(buffer)];
```

Hash Function: An Example

```
uint HashFunction ( string identifier )
{
   const uint hash_module = 511; // or 211: the prime number
   uint g;  // for calculating hash
   const uint hash_mask = 0xF0000000;

   uint hash_value = 0;

   for ( int i=0; i<identifier.Length; i++ )
   {
       // Calculating hash: see Dragon Book, Fig. 7.35
       hash_value = (hash_value << 4) + (byte)identifier[i];
       if ( (g = hash_value & hash_mask) != 0 )
       {
        // hash_value ^= g >> 24 ^ g;
           hash_value = hash_value ^ (hash_value >> 24);
           hash_value ^= g;
       }
   }
   // final hash value for identifier
   return hash_value % hash_module;
}
```

Taken from the **Dragon Book**

Scanner implementation (5)

How to distinguish identifier from a keyword?

- High-level solution - in case the implementation language supports the following:

```
// A sequence of letters/digits from the input
string WordFromInput;
...
switch ( WordFromInput ) {
    case "switch": return tkSwitch;
    case "while" : return tkWhile;
    case "int"   : return tkInt;
    ...
    else return tkIdentifier;
}
...
```

Java & C# do support this (pattern matching)

Hashing is under the hood!

Token Representation (1)

- Simple cases:
  each token is encoded by an integer value.

- What about identifiers and literals?

- A proposed structure with attributes:

  - Token code (pattern)
  - Token source coordinates ("span")
  - Token category (optional)
  - Binary representation (for literals)
  - Token source image (for identifiers)

```
struct Token {
   Span span;        // for all tokens
   unsigned int code;  // token code
   int intValue;     // for integer constants
   long realValue; // for real constants
   string id;        // for identifiers
   ...
};
```

```
struct Span {
   long lineNum;
   int posBegin, posEnd;
};
```

Token Representation (2)

- *Advanced approach: OO architecture*

```
// Common notion of token
class Token {
    // Attributes common
    // to all token categories
  Span span;
  unsigned int code;
};
```

```
class Identifier : Token {
    // Attributes specific for identifiers
  string identifier;
}
```

```
class Integer : Token {
    // Attributes specific for integer constants
  long value;
}
```

```
class Real : Token {
    // Attributes specific for real constants
  long double value;
}
```

Lexical Analysis: Two Aspects

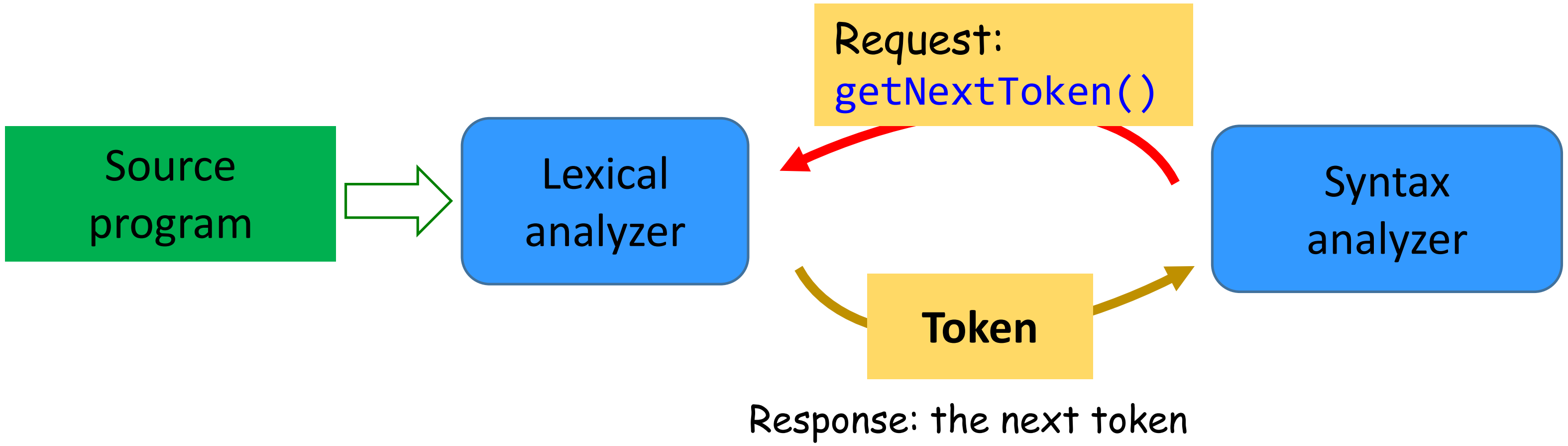
How lexical analyzer interacts with other compiler components?

- Two “extreme” cases, and…

- Many mixed cases.

Extreme Case (1)

Scanner & parser: getting token on demand



- For language with the simple syntax rules, where lookahead is not necessary (that is, we do not need to look at the next token to detect the current one).

Extreme Case (2)

Scanner & parser: getting token on demand

- Ambiguity example: the Ada language.

```
A(0..10)
```

No square brackets in Ada

- A function call?
- Access to an array element?
- A sub-array?

Sub-array! (“Slice”)

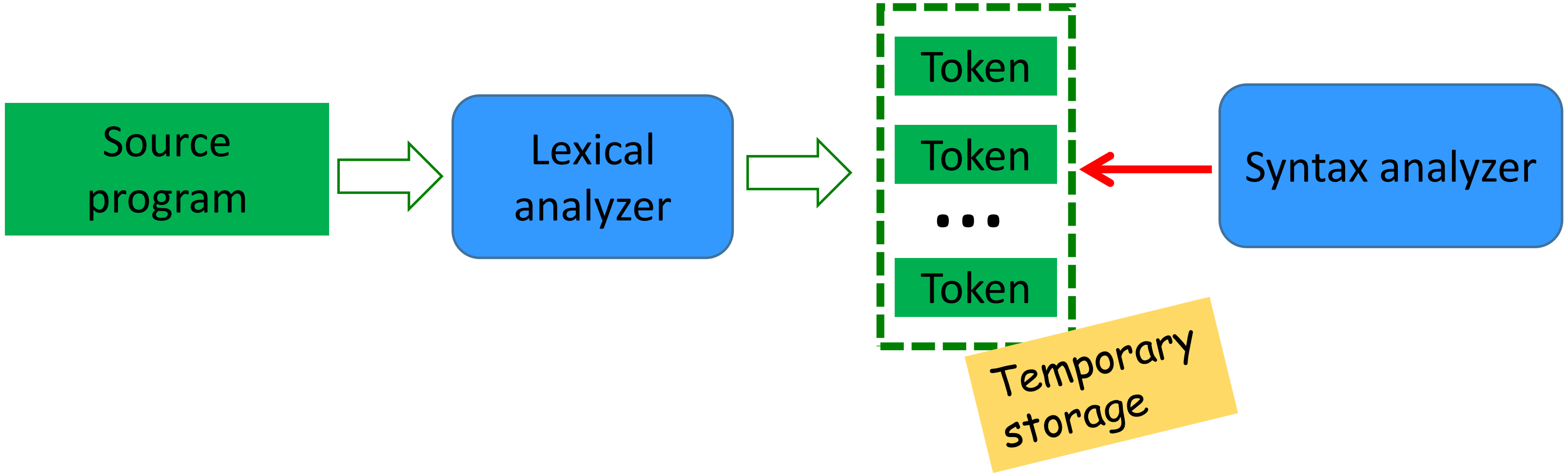
- Another example (also Ada ☺):
  Token «apostroph» (single quote) is used in two meanings: either for attributes, or for character constants:

```
x := A'Range;
y := 'L';
```

- Lookahead?
- Keep previous tokens?
- Anything else?

Another Extreme Case

- Scanner & parser: two independent components



- Pros: More flexible alternative; more convenient for the parser; allows to process non-trivial language grammars.

- Cons: Consumes more memory for storing all program tokens.

Mixed Approach (1)

Example:

```
int a = 0;
class C {
public:
    void f() { a = 7; }
    int a;
};
int main() {
    C c;
    c.f();
    cout << a; // what is output: 0 or 7?
}
```

C++ Standard:

- Function member bodies are processed <u>in the full class context.</u>
- Class declaration is <u>full</u> when the final "}" token is achieved

Mixed Approach (2)

Example: C++

```
int a = 0;
class C {
public:
    void f() { a = 7; }
    int a;

} * ;
int main() {
    C c;
    c.f();
    cout << a; // what is output: 0 or 7?
}
```

Conclusions for compiler developers:

- Member function body should be processed only after completing processing all class members.
- Tokens comprising function bodies should be kept until the final “}” is achieved and should be compiled after it.

Mixed Approach (3)

Example: Java

```
class oneClass
{
   secondClass a;
    ...
   int x = a.m;
}
  ...
class secondClass
{
    ...
}
*
```

The problem:

- Syntax/semantic analyzers cannot determine the type of `a`.
- Syntax/semantic analyzers cannot conclude whether `a.m` is valid or not.

Conclusion for compiler developers:

- All cases with using `a` should be processed after `secondClass` declaration is processed.
- This means that tokens comprising class bodies should be kept until all class names are recognized. Only then token sequences of class bodies should be syntactically analyzed.