COP 3402 Systems Software

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Compilers
And
Interpreters

Outline

1. Compiler and interpreters
2. Compilation process
3. Interpreters
4. PL/0 Symbols (tokens)

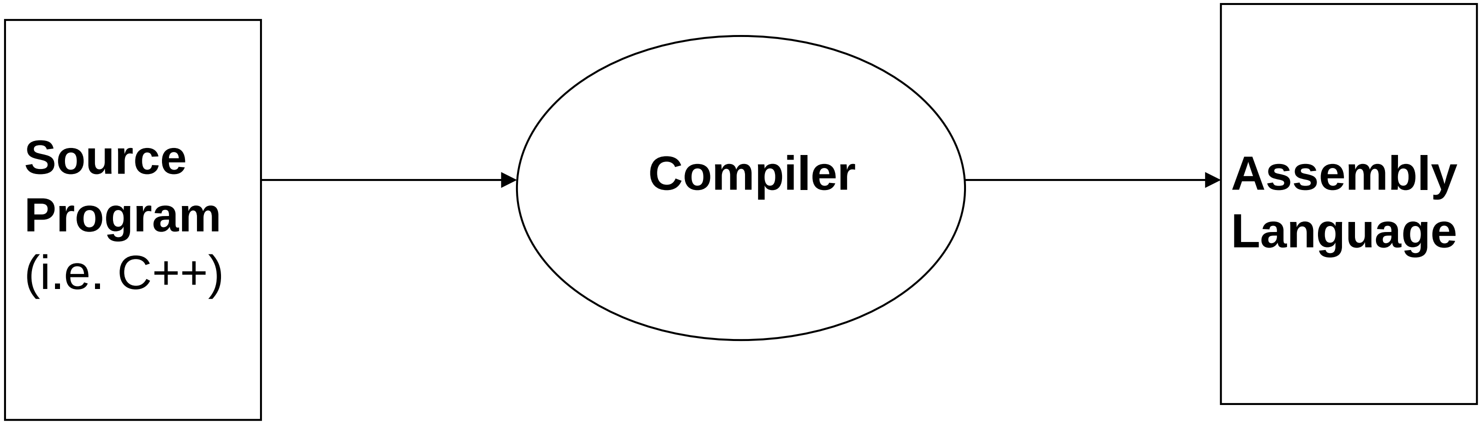
Compilers / Interpreters

- Programming languages are notations for describing computations to people and machines.
- Programming languages can be implemented by any of three general methods:

1. Compilation
2. Interpretation
3. Hybrid Implementation

Compilers

A compiler is a program that takes high level languages (i.e. Pascal, C, ML)as input , and translates it to a intermediate representation (For example: Assembly language).



Source Program (i.e. C++)

Compiler

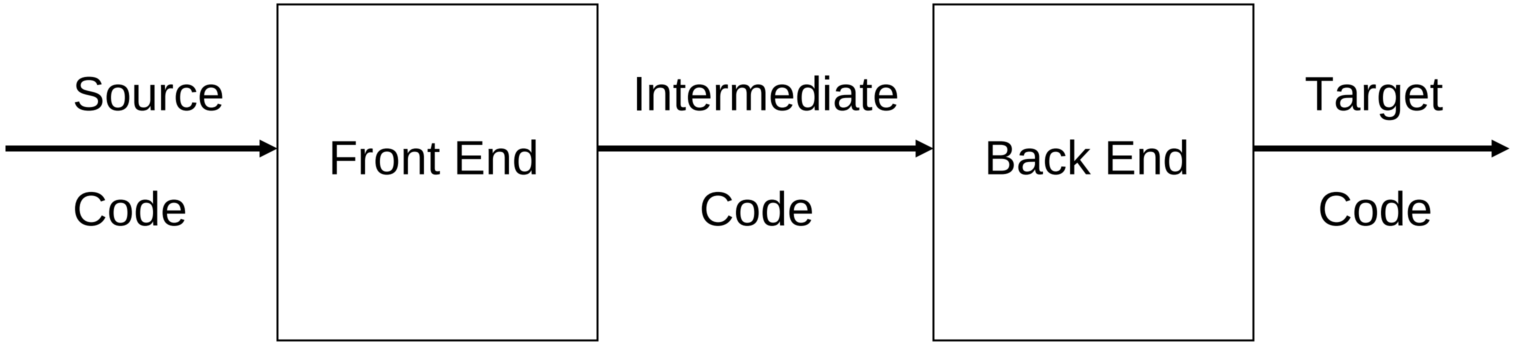
Assembly Language

Compilers

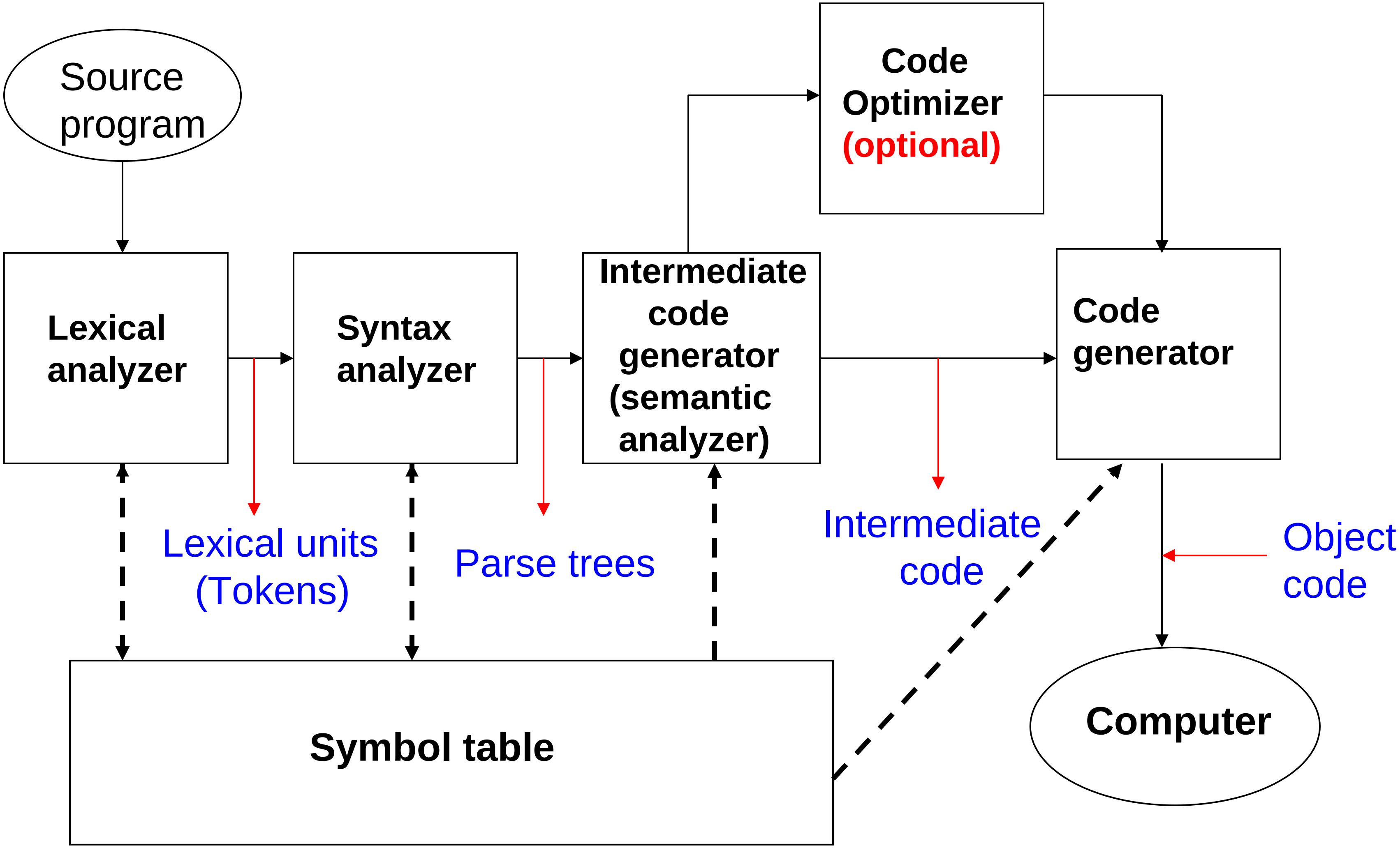
The process of compilation takes place in several phases:

Front end: Scanner → Parser → Semantic Analyzer

Back end: Code generator



Compilers


Source program
Code Optimizer
(optional)
Lexical analyzer
Syntax analyzer
Intermediate code generator (semantic analyzer)
Code generator
Lexical units (Tokens)
Parse trees
Intermediate code
Object code
Symbol table
Computer

EXAMPLE:

Fahrenheit := 32 + celsious * 1.8;

| f | a | h | r | e | n | h | e | i | t | : | = | 3 | 2 | + | c | e | l | s | i | o | u | s | * | 1 | . | 8 | ; |

Getchar()

Lexical analyzer (scanner)

(converts from character stream into a stream of tokens.)

index in name table

[id, 1] [: =][int, 32][+][id, 2][*][int, 1.8][;]

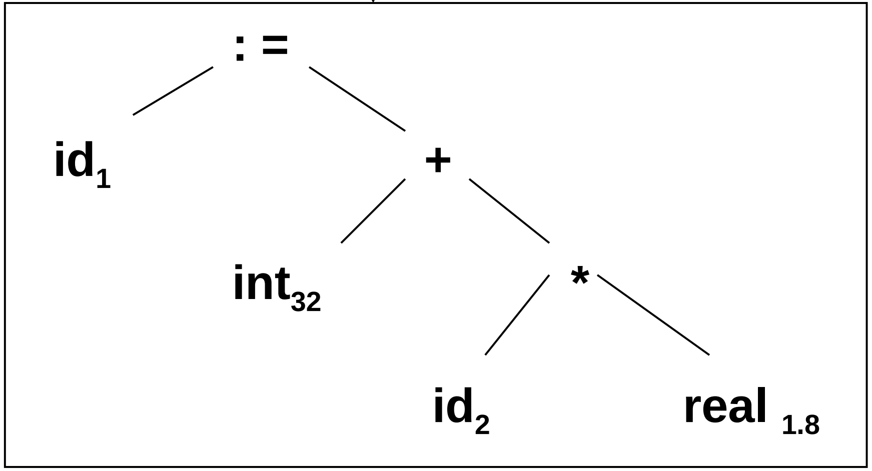
names table

1	fahrenhei
2	celsious

name

Syntax analyzer (parser)

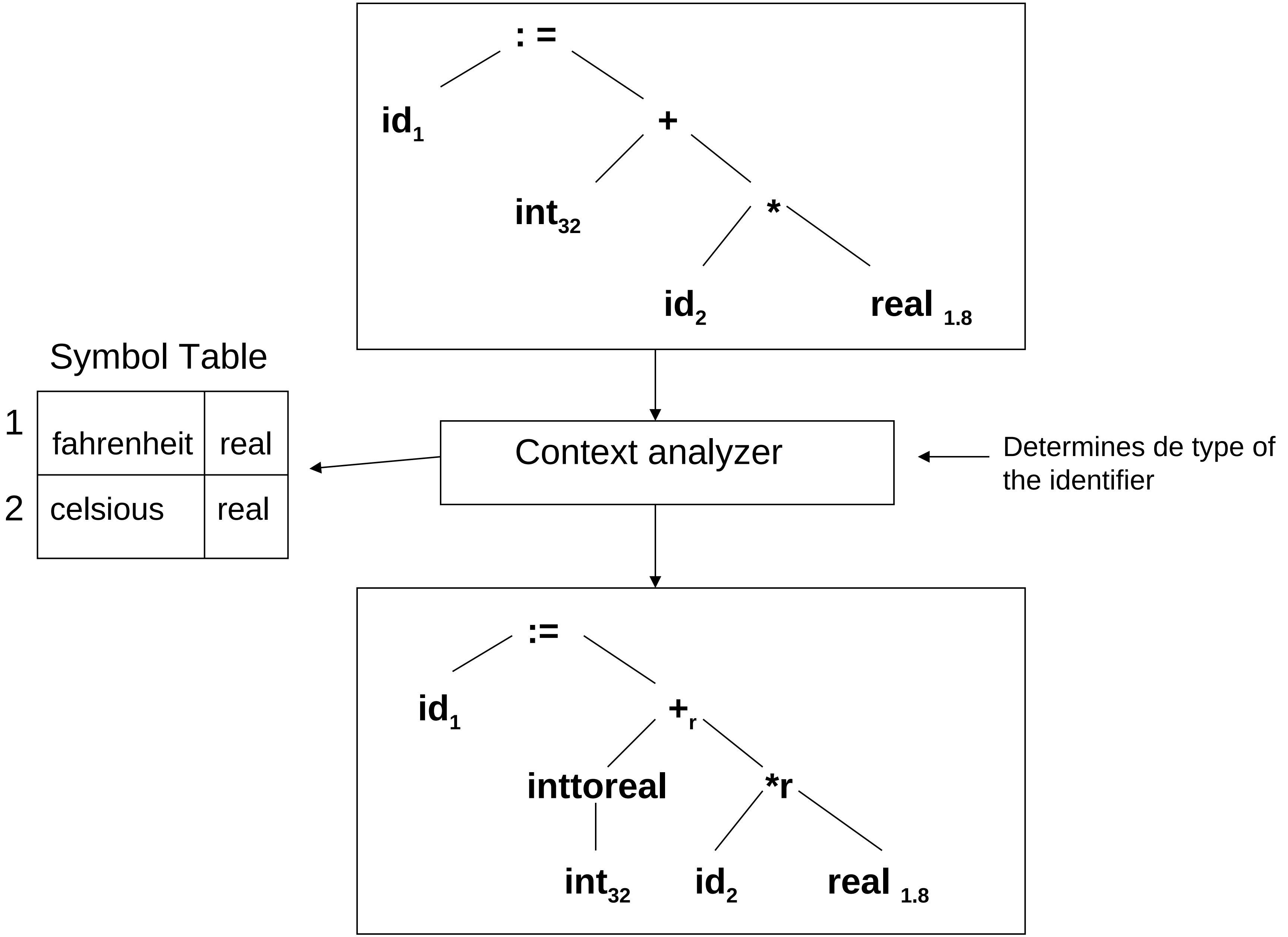
(Construct syntactic structure of the program)



Symbol Table

1	fahrenheit	real
2	celsious	real

Name attribute

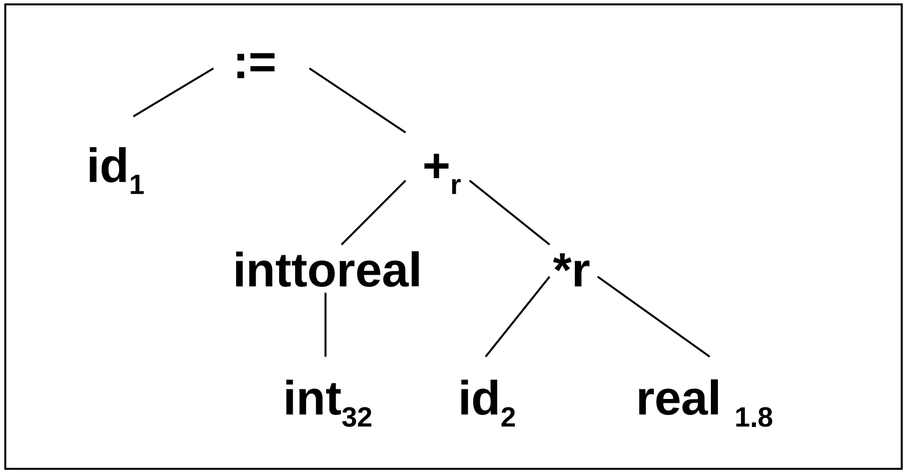


Symbol Table

1	fahrenheit	real
2	celsious	real

Context analyzer

Determines de type of the identifier



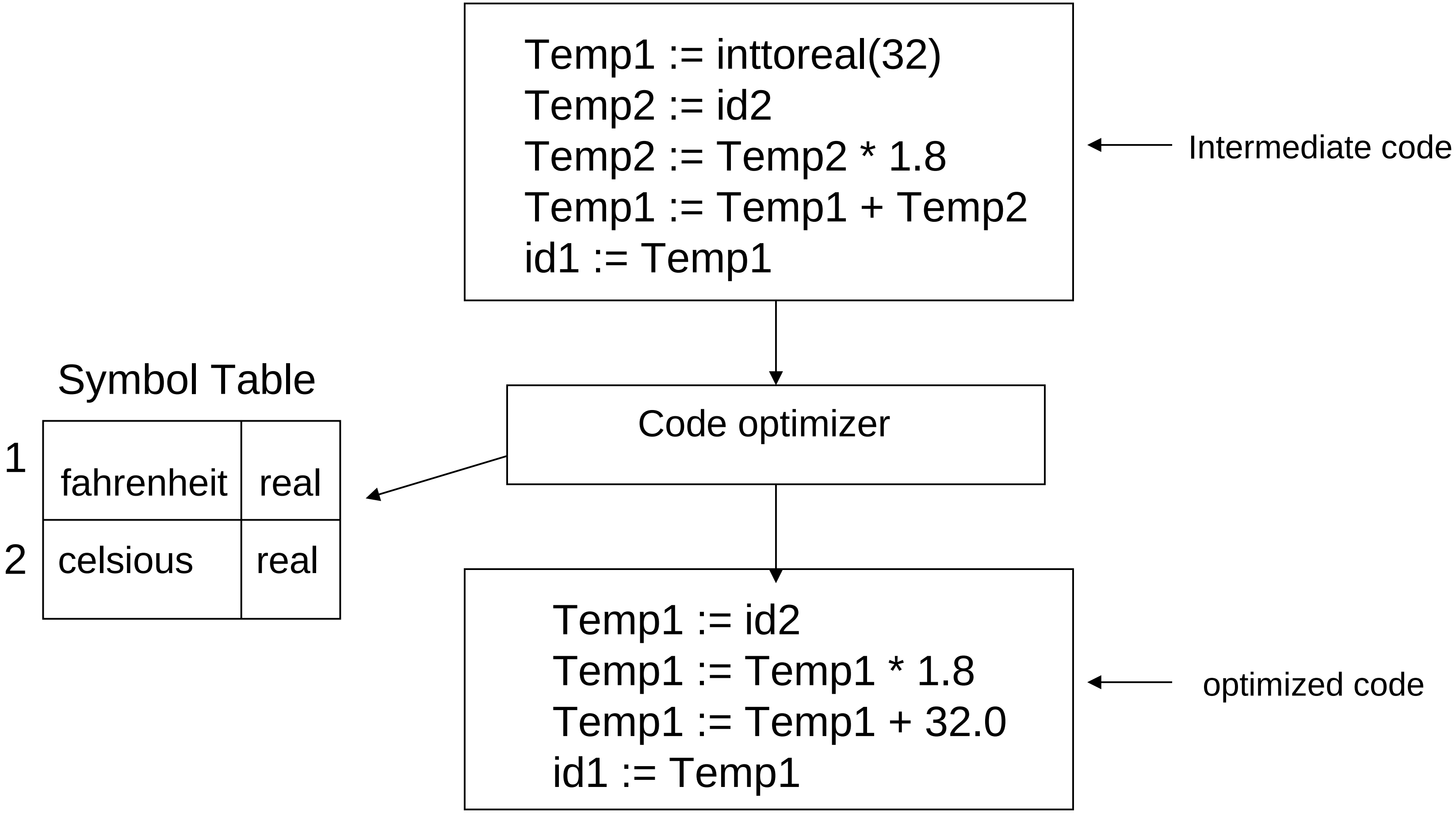
Symbol Table

1	fahrenheit	real
2	celsious	real

Intermediate code generator

```
Temp1 := inttoreal(32)
Temp2 := id2
Temp2 := Temp2 * 1.8
Temp1 := Temp1 + Temp2
id1 := Temp1
```

Intermediate code



```
Temp1 := inttoreal(32)
Temp2 := id2
Temp2 := Temp2 * 1.8
Temp1 := Temp1 + Temp2
id1 := Temp1
```

Intermediate code

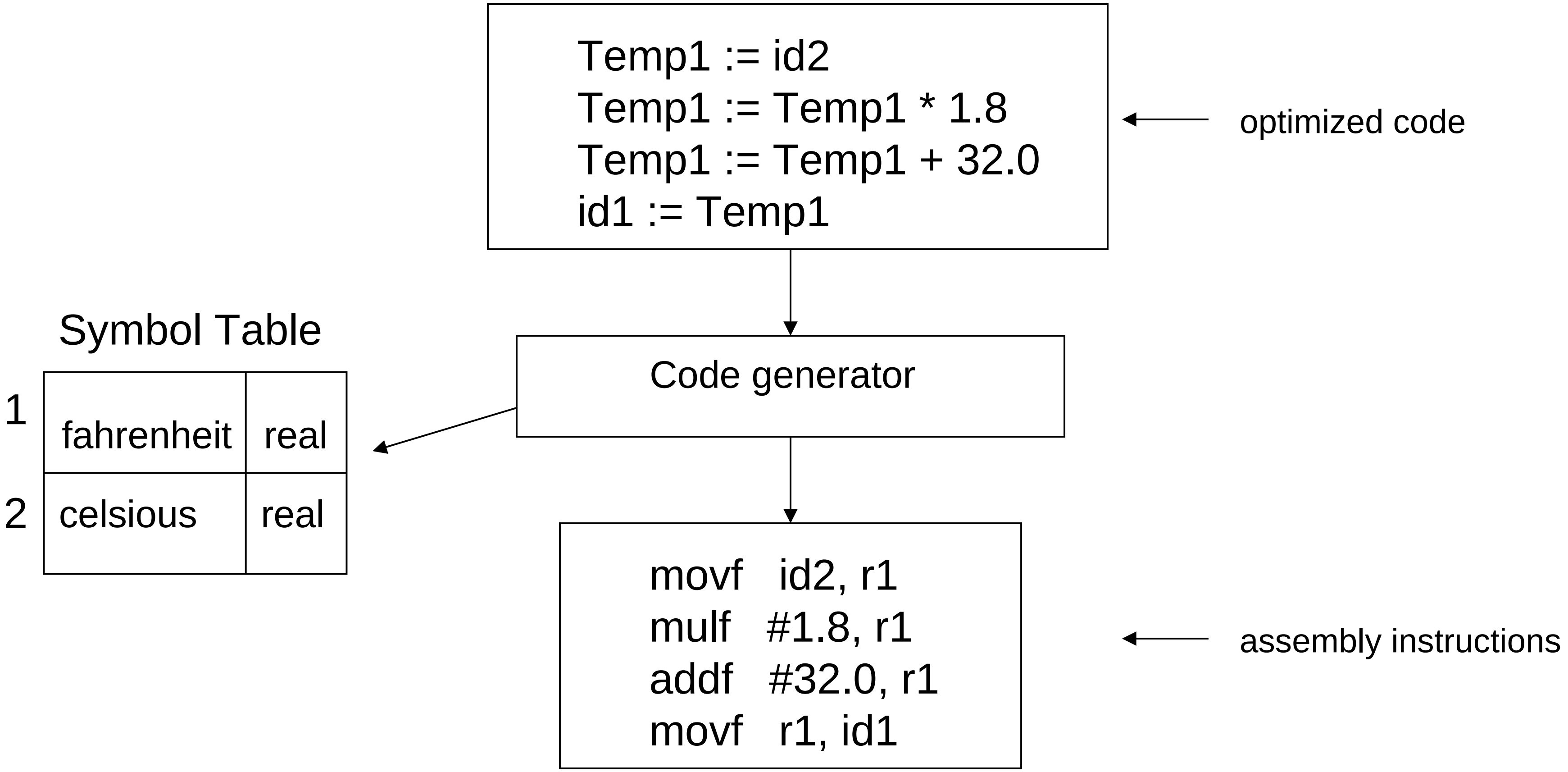
Code optimizer

```
Temp1 := id2
Temp1 := Temp1 * 1.8
Temp1 := Temp1 + 32.0
id1 := Temp1
```

optimized code

Symbol Table

1	fahrenheit	real
2	celsious	real



```
Temp1 := id2
Temp1 := Temp1 * 1.8
Temp1 := Temp1 + 32.0
id1 := Temp1
```

optimized code

Code generator

Symbol Table

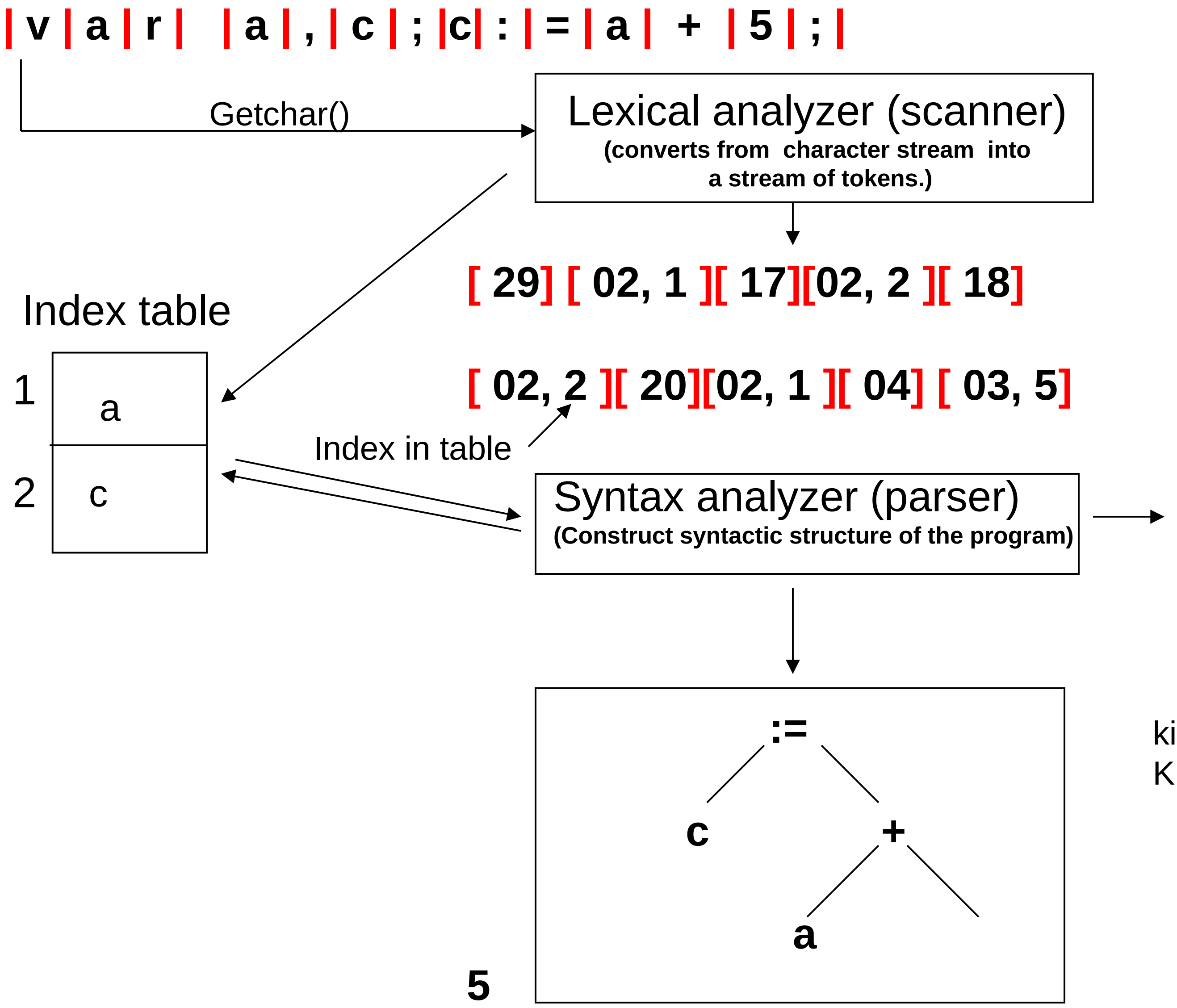
1	fahrenheit	real
2	celsious	real

```
movf   id2, r1
mulf   #1.8, r1
addf   #32.0, r1
movf   r1, id1
```

assembly instructions

EXAMPLE: associated to HW2

```
var a,c;
c := a + 5;
```



| v | a | r | | a | , | c | ; |c| : | = | a | + | 5 | ; |

Getchar()

Lexical analyzer (scanner)
(converts from character stream into a stream of tokens.)

[29] [02, 1][17][02, 2][18]

[02, 2][20][02, 1][04] [03, 5]

Index in table

Syntax analyzer (parser)
(Construct syntactic structure of the program)

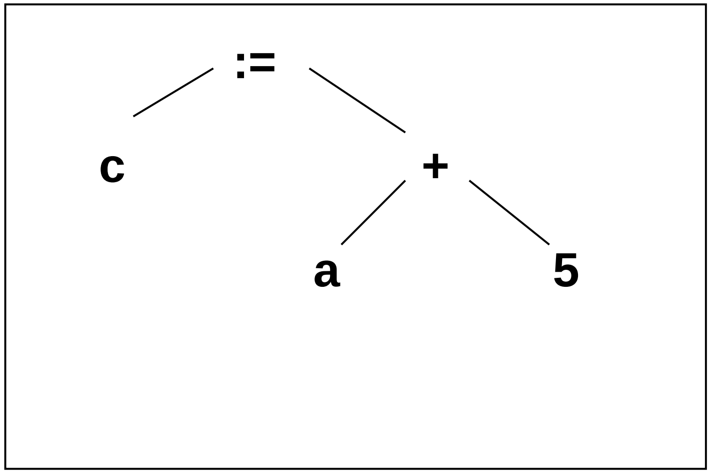
Index table

1	a
2	c

Symbol table

	1	2	3
name	a	c	
address	3	4	
kind	2	2	

kind 2 means variable name
Kind 3 means procedure name



Symbol table

	1	**2**	**3**
name	a	c	
address	3	4	
kind	2	2	

code generator

```
INC    0    5
LOD    0    3
LIT    0    5
ADD    0    2
STO    0    4
SYS    0    3
```

Intermediate code
(VM assembly language)

Compilers

Lexical analyzer:

Gathers the characters of the source program into lexical units.

Lexical units of a program are:

- identifiers
- special words (reserved words)
- operators
- special symbols
- **Comments are ignored!**

a:= b + c;
02 a 20 02 b 04 02 c 18

+ a ; b := c
04 02 a 18 02 b 20 02 c

Syntax analyzer:

Takes tokens from the lexical analyzer and use them to construct a hierarchical structure called **parse tree**

Parse trees represent the syntactic structure of the program.

Compilers

Intermediate code:

Produces a program in a different lenguage representation:

Assembly language
Similar to assembly language
Something higher than assembly language

Note: semantic analysis is an integral part of the intermediate code generator

Optimization:

Makes programs smaller or faster or both.

Most optimization is done in the intermediate code.
(i.e. tree reduction, vectorization)

Compilers

Code generator:

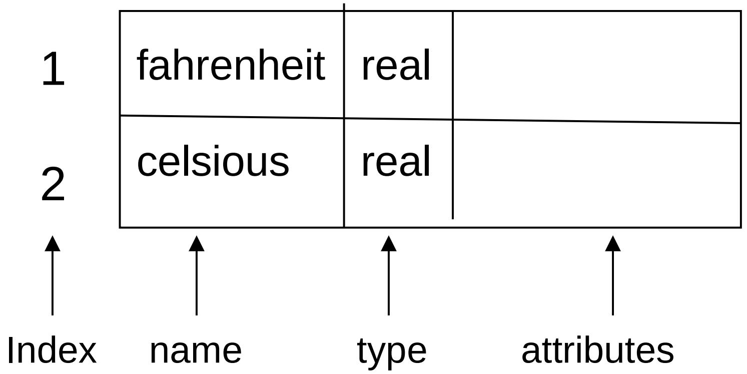
Translate the optimized intermediate code into machine language.

The symbol table:

Serve as a database for the compilation process.

Contents type and attribute information of each user-defined name in the program.

Symbol Table



Index	name	type	attributes
1	fahrenheit	real	
2	celsious	real	

Compilers

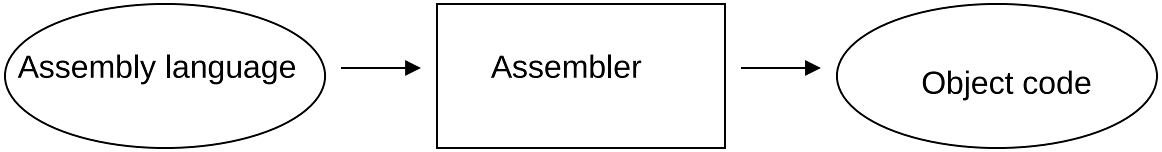
Machine language

A program in its machine language form needs in general

-- To be translated to object code for execution

-- To translate the program from its machine language form (assembly language) into object code, an assembler is required.

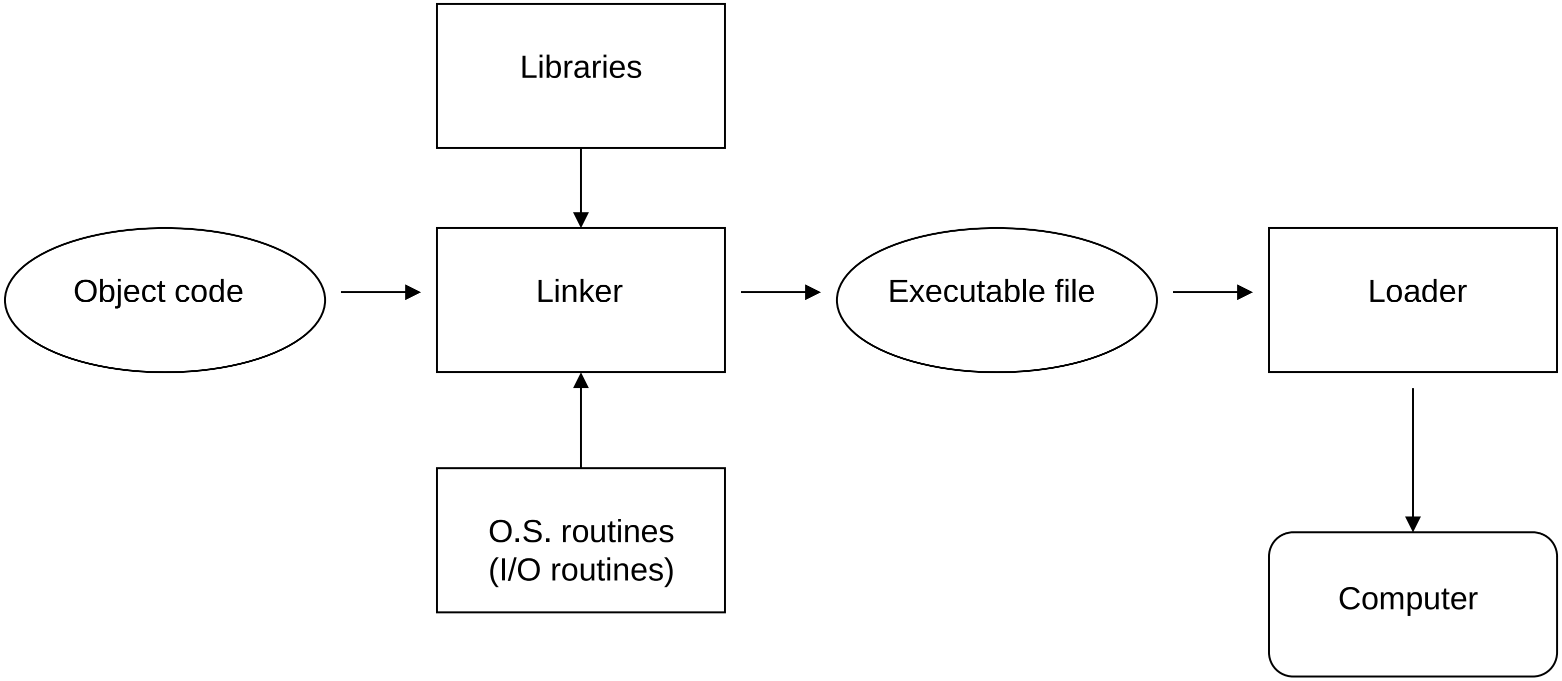
-- An assembler is a program that translate machine code into object code



Compilers

Machine language

To run a program in its object code form, it needs in general
-- some other code (libraries)
-- programs from the O.S. (i.e. input/output routines)



Interpreters

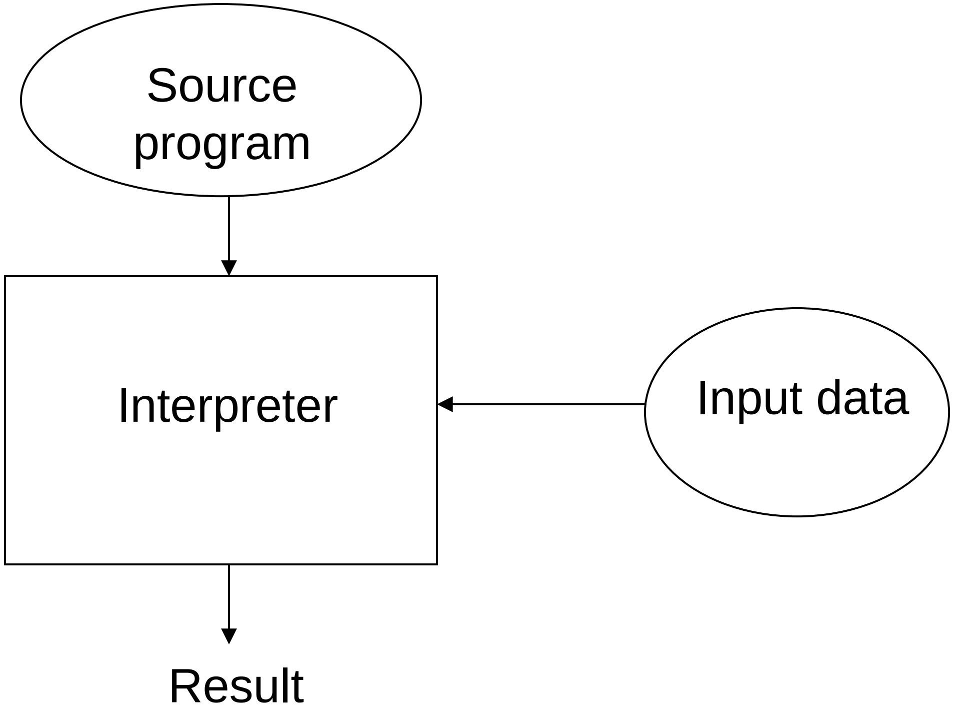
Programs are interpreted (executed) by another program called the interpreter.

Advantages: Easy implementation of many source-level debugging operations, because all run-time errors operations refer to source-level units.

Disadvantages: 10 to 100 times slower because statements are interpreted each time the statement is executed.

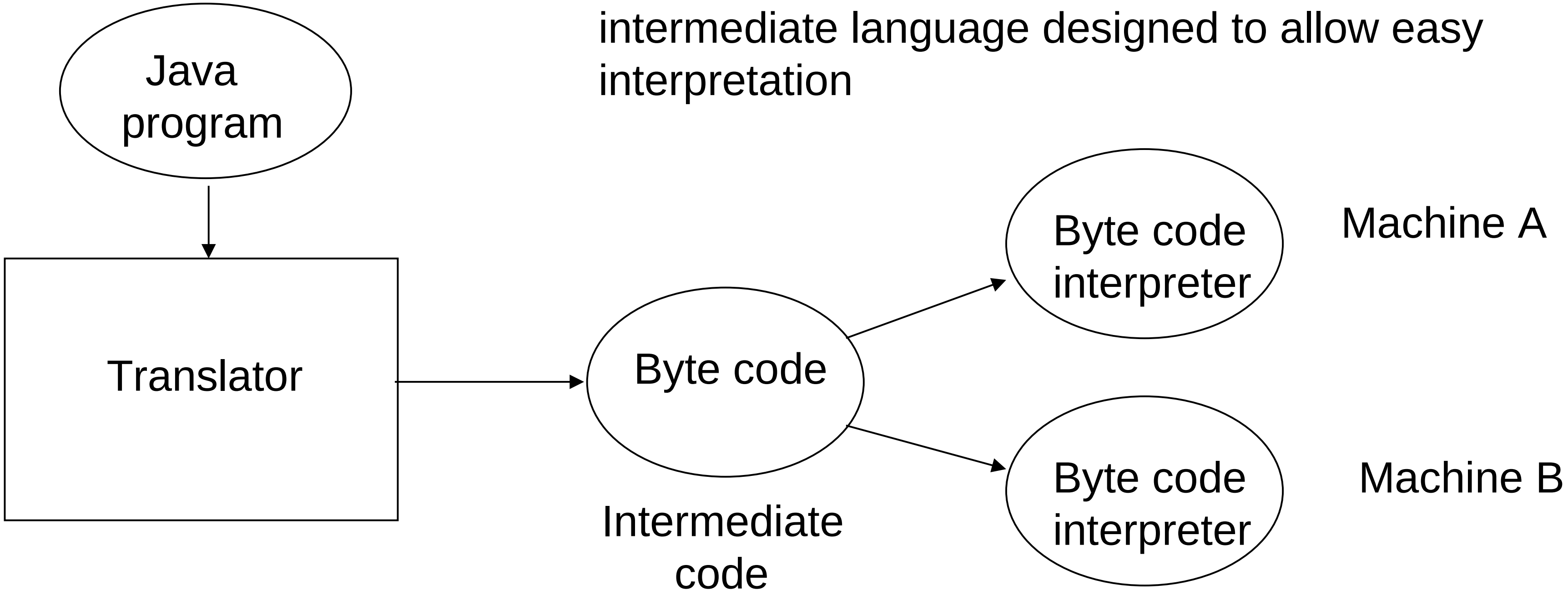
Background:
Early sixties → APL, SNOBOL, Lisp.
By the 80s → rarely used.
Recent years → Significant comeback (some Web scripting languages: JavaScript, php)

Interpreters



Hybrid implementation systems

They translate high-level language programs to an intermediate language designed to allow easy interpretation



Java program

Translator

Byte code

Intermediate code

Byte code interpreter

Machine A

Byte code interpreter

Machine B

Example: PERL and initial implementations of Java

Interpreters

Just-In-Time (JIT) implementation

Programs are translated to an intermediate language.

During execution, it compiles intermediate language methods into machine code when they are called.

The machine code version is kept for subsequent calls.

.NET and Java programs are implemented with JIT system.

PL/0 Symbols

Given the following program written in PL/0:

```
const m = 7, n = 85;
var  i,x,y,z,q,r;
procedure mult;
   var a, b;
begin
  a := x;  b := y; z := 0;
  while b > 0 do
    begin
      if odd x then z := z+a;
      a := 2*a;
      b := b/2;
    end
end;
begin     // Main program begins here
  x := m;
  y := n;
  call mult;
end.
```

As in any language, in PL/0 we need to identify what is the vocabulary and what are the valid names and special symbols that we accept as valid:

PL/0 Symbols

Given the following program written in PL/0:

```
const m = 7, n = 85;
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procedure mult;
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       b := b/2;
    end
end;
begin
  x := m;
  y := n;
  call mult;
end.
```

As in any language, in PL/0 we need to identify what is the vocabulary and what are the valid names and special symbols that we accept as valid:

For instance, in the on the example we notice that there are many reserved words (keywords)

PL/0 Symbols

Given the following program written in PL/0:

```
const m = 7, n = 85;
var  i,x,y,z,q,r;
procedure mult;
   var a, b;
begin
  a := x;  b := y; z := 0;
  while b > 0 do
    begin
       if odd x then z := z + a;
       a := 2 *  a;
       b := b / 2;
    end
end;
begin
  x := m;
  y := n;
  call mult;
end.
```

Also there are some operators and special symbols:

a) Operators (+, -, *, /, <, =, >, <=, <>, >=, :=)

Example on creating tokens:

if x > 7 then x := x + 64;

23 02 x 13 03 7 24 02 x 20 02 x 04 03 64 18

+ if 64 x then x := ; > x 7

04 23 03 64 02 x 24 02 x 20 18 13 02 x 03 7

PL/0 Symbols

Given the following program written in PL/0:

```
const m = 7, n = 85;
var  i, x, y, z, q, r;
procedure mult;
   var a, b;
begin
  a := x;  b := y; z := 0;
  while b > 0 do
    begin
       if odd x then z := z + a;
       a := 2 *  a;
       b := b / 2;
    end
end;
begin
  x := m;
  y := n;
  call mult;
end.
```

Also there are some operators and special symbols:

a) Operators (+, -, *, /, <, =, >, <=, <>, >=, :=)

b) Special symbols

(,) , [,] , , , . , : , ;

PL/0 Symbols

Given the following program written in PL/0:

```
const m = 7, n = 85;
var  i, x, y, z, q, r;
procedure mult;
   var a, b;
begin
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  while b > 0 do
    begin
       if odd x then z := z + a;
       a := 2 *  a;
       b := b / 2;
    end
end;
begin
  x := m;
  y := n;
  call mult;
end.
```

There are also:
Numerals such as : 5, 0, 85, 2, 346, . . .

PL/0 Symbols

Given the following program written in PL/0:

```
const m = 7, n = 85;
var  i, x, y, z, q, r;
procedure mult;
   var a, b;
begin
  a := x;  b := y; z := 0;
  while b > 0 do
    begin
       if odd x then z := z + a;
       a := 2 *  a;
       b := b / 2;
    end
end;
begin
  x := m;
  y := n;
  call mult;
end.
```

There are also:
Numerals such as : 5, 0, 85, 2, 346, . . .

And names (identifiers):
A letter
or a letter followed by more letters
or a letter followed by more letters or digits.

Examples: x, m, celsious, mult, intel486

Scanner

Given the following program written in PL/0:

```
const m = 7, n = 85;
var  i,x,y,z,q,r;
procedure mult;
   var a, b;
begin
  a := x;  b := y; z := 0;
  while b > 0 do
    begin
       if odd x then z := z+a;
       a := 2*a;
       b := b/2;
    end
end;
begin
  x := m;
  y := n;
  call mult;
end.
```

In addition there are also:

Comments:

/* in C */

(* in Pascal *)

Separators:

white spaces

invisible characters like: tab “\t”

new line “\n”

Example: **\t a := □ 2 * a;\n**

Scanner

Given the following program written in PL/0:

```
const m = 7, n = 85;
var  i,x,y,z,q,r;
procedure mult;
   var a, b;
begin
  a := x;  b := y; z := 0;
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       if odd x then z := z+a;
       a := 2*a;
       b := b/2;
    end
end;
begin
  x := m;
  y := n;
  call mult;
end.
```

Every language has an alphabet (a finite set of characters)

PL/0 alphabet { a, b, c, d, e , f, g, h, i, j, k, l , m ,n,

o, p q, r, s, t, u, v, w, x, y, z, 0, 1, 2,

3, 4, 5, 6, 7, 8, 9,   , +, -, *, /, <, =, >, :,

. , , , ; }

Using concatenation (joining two or more characters) we obtain a string of symbols.

Scanner

A language L, is simply <u>any</u> set of strings over a fixed alphabet.

Alphabet	**Languages**
{0,1}	{0,10,100,1000,100000…}
	{0,1,00,11,000,111,…}
{a,b,c}	{abc,aabbcc,aaabbbccc,…}
{A, … ,Z}	{TEE,FORE,BALL,…}
	{FOR,WHILE,GOTO,…}

{A,…,Z, a,…,z,0,…9, +,-,…,<,>,…}	{ All legal PASCAL, C, PL/0 progs}
	{ All grammatically correct English sentences }

Special Languages: ∅ - EMPTY LANGUAGE

∈ - contains ∈ string only

Scanner

The purpose of the lexical analyzer (scanner) is to decompose the source program into Its elementary symbols or tokens:

1. **Read input characters of the source program.**
2. **Group them into lexemes (a lexeme is a sequence of characters that matches the pattern for a token).**
3. **Produce a token for each lexeme**

A lexeme (lowest level syntactic unit) is a sequence of characters in the source program

Scanner

Scan Input

- **Remove WS, NL, …**
- **Identify Tokens**
- **Generate Errors**
- **Send Tokens to Parser**

A lexeme (lowest level syntactic unit) is a sequence of characters in the source program

Scanner

The ordinal number of a character *ch* is computed from its coordinates (X,Y) in the table as:

ord(*ch*) = 16 * X + Y

Example:

ord(‘A’) = 16 * 4 + 1 = 65

ord(‘0’) = 16 * 3 + 0 = 48

ord(‘5’) = 16 * 3 + 5 = 53

ASCII Character Set

X

Y

	0	1	2	3	4	5	6	7
0	NUL	DLE	SP	0	@	P	`	p
1	SOH	DC1	!	1	A	Q	a	q
2	STX	DC2	"	2	B	R	b	r
3	ETX	DC3	#	3	C	S	c	s
4	EOT	DC4	$	4	D	T	d	t
5	ENQ	NAK	%	5	E	U	e	u
6	ACK	SYN	&	6	F	V	f	v
7	BEL	ETB	'	7	G	W	g	w
8	BS	CAN	(	8	H	X	h	x
9	HT	EM	)	9	I	Y	i	y
10(A)	LF	SUB	*	:	J	Z	j	z
11(B)	VT	ESC	+	;	K	[	k	{
12(C)	FF	FS	,	<	L	\	l	|
13(D)	CR	GS	-	=	M	]	m	}
14(E)	SO	RS	.	>	N	^	n	~
15(F)	SI	US	/	?	O	_	o	DEL

ASCII character table

Dec	Hex	ASCII	Dec	Hex	ASCII	Dec	Hex	ASCII
0	00	NUL (null)	16	10	DLE (data link escape)	32	20	SP (space)
1	01	SOH (start of heading)	17	11	DC1 (device control 1)	33	21	!
2	02	STX (start of text)	18	12	DC2 (device control 2)	34	22	"
3	03	ETX (end of text)	19	13	DC3 (device control 3)	35	23	#
4	04	EOT (end of transmission)	20	14	DC4 (device control 4)	36	24	$
5	05	ENQ (enquiry)	21	15	NAK (negative acknowledge)	37	25	%
6	06	ACK (acknowledge)	22	16	SYN (synchronous idle)	38	26	&
7	07	BEL (bell)	23	17	ETB (end of transmission block)	39	27	'
8	08	BS (backspace)	24	18	CAN (cancel)	40	28	(
9	09	HT (horizontal tab)	25	19	EM (end of medium)	41	29	)
10	0A	LF (line feed)	26	1A	SUB (substitute)	42	2A	*
11	0B	VT (vertical tab)	27	1B	ESC (escape)	43	2B	+
12	0C	FF (form feed)	28	1C	FS (file separator)	44	2C	,
13	0D	CR (carriage return)	29	1D	GS (group separator)	45	2D	-
14	0E	SO (shift out)	30	1E	RS (record separator)	46	2E	.
15	0F	SI (shift in)	31	1F	US (unit separator)	47	2F	/

ASCII character table

Dec	Hex	ASCII	Dec	Hex	ASCII	Dec	Hex	ASCII
48	30	0	64	40	@	80	50	P
49	31	1	65	41	A	81	51	Q
50	32	2	66	42	B	82	52	R
51	33	3	67	43	C	83	53	S
52	34	4	68	44	D	84	54	T
53	35	5	69	45	E	85	55	U
54	36	6	70	46	F	86	56	V
55	37	7	71	47	G	87	57	W
56	38	8	72	48	H	88	58	X
57	39	9	73	49	I	89	59	Y
58	3A	:	74	4A	J	90	5A	Z
59	3B	;	75	4B	K	91	5B	[
60	3C	<	76	4C	L	92	5C	\
61	3D	=	77	4D	M	93	5D	]
62	3E	>	78	4E	N	94	5E	^
63	3F	?	79	4F	O	95	5F	_

ASCII character table

Dec	Hex	ASCII	Dec	Hex	ASCII
96	60	`	112	70	p
97	61	a	113	71	q
98	62	b	114	72	r
99	63	c	115	73	s
100	64	d	116	74	t
101	65	e	117	75	u
102	66	f	118	76	v
103	67	g	119	77	w
104	68	h	120	78	x
105	69	i	121	79	y
106	6A	j	122	7A	z
107	6B	k	123	7B	{
108	6C	l	124	7C	|
109	6D	m	125	7D	}
110	6E	n	126	7E	~
111	6F	o	127	7F	DEL

The End

Compilers

And

Interpreters