Introduction

Programming a Computer

- High level language (HLL) program: easy for human understanding and writing[a].
- Machine language program: a CPU can understand only this form and act.
- Assembly language program: intermediate form, a readable version of machine language program (and more).

[a] It is also generally easier for AI to work with and generate code in high-level programming languages. LLM is trained on human written code! (Google)

A Compiler

- A compiler is a program that accepts a HLL program (source language) as input. It translates the program to a target language program preserving the semantics.
- An example of source language may be C++ and the target language may be the assembly or machine language of some processors e.g. x86-64, or some virtual machine.

Compiling a Compiler

- A compiler for a language A may be written as a HLL program CP_A in some language B.
- Use a compiler of B, C_B, to compile CP_A to generate the executable code, C_A, of a compiler for A.
- If $A = B$, we are compiling a new compiler for the language A - a process known as bootstrapping.

An Interpreter

- An interpreter is a type of translator that works in a different mode.
- Normally it does not produce a complete translated version of the machine code. It interprets the translated intermediate representation of the HLL program, and performs necessary action on data.

An Interpreter

```
#! /usr/bin/python3
# Recursive function to compute gcd()

def gcd(a, b):
    if(b == 0): return a
    return gcd(b, a%b)

m = int(input("Enter a +ve integer: "))
n = int(input("Enter a +ve integer: "))
print('gcd('+str(m)+','+str(n)+') = ' +str(gcd(m,n))
```

An Interpreter

```
$ ./gcd.py
Enter a +ve integer: 12
Enter a +ve integer: 18
gcd(12,18) = 6
```

Abstract Syntax Tree (AST)

```
#! /usr/bin/python3
# pyfirst.py

print('My First Program')
```

Abstract Syntax Tree (AST) from Google

```
Module(
    body=[
        Expr(
            value=Call(
                func=Name(id='print', ctx=Load()),
                args=[
                    Constant(value='My First Program')
                ], keywords=[]
            )
        )
    ], type_ignores=[]
)
```

Abstract Syntax Tree (AST)

The Abstract Syntax Tree (AST) for the Python program
`print('My First Program')`
is a hierarchical representation of the code's structure. The AST does not include non-essential syntax like parentheses or semicolons, but captures the core components (Google).

AST Nodes

1. `Module`: This is the top-level node for a Python source file, containing a list of statements in its body.
2. `Expr`: This node indicates that an expression is being used as a standalone statement (the return value is discarded). The `print()` function call is an expression.

3. Call: This node represents a function call.

4. func: This attribute specifies the function being called, which is a Name node with the identifier (id) 'print'. The context (ctx) is Load(), meaning the name is being read/used.

5. args: This is a list of positional arguments passed to the function. In

this case, it contains a single element.

6. Constant: This node represents the constant value being passed as an argument, specifically the string 'My First Program'.

7. keywords: This list is empty because no keyword arguments (like sep or end) were used.

How to Dump AST

```
#! /usr/bin/python3
# astPyfirst.py
import ast

pyCode = """
print('My First Program')
          """
tree = ast.parse(pyCode)
treeDump = ast.dump(tree, annotate_fields=True,\
                                  include_attributes=False)
print(treeDump)
```

How to Dump AST

```
$ ./astPyfirst.py
Module(body=[Expr(value=Call(func=Name(id='print',
          ctx=Load()), args=[Str(s='My First Program')],
          keywords=[]))])
```

AST Dump from File

```
#! /usr/bin/python3
# fileToAST.py
import ast

def astFromFile(fileName):
    with open(fileName, 'r', encoding='utf-8') as file:
        code = file.read()
    tree = ast.parse(code, filename=fileName, mode='exec')
    treeDump = ast.dump(tree, annotate_fields=True,\
                        include_attributes=False)
    print(treeDump)
astFromFile('pyfirst.py')
```

AST Dump from File

```
$ ./fileToAST.py
Module(body=[Expr(value=Call(func=Name(id='print',
   ctx=Load()), args=[Str(s='My First Program')],
     keywords=[]))])
```

https://greentreesnakes.readthedocs.io/en/latest/index.html

Code → Compile → Execute

```
#! /usr/bin/python3
# cceS.py  the code is a string

# Code as a string
codeS = """
def gcd(a, b):
    if(b == 0): return a
    return gcd(b, a%b)

m = int(input("Enter a +ve integer: "))
n = int(input("Enter a +ve integer: "))
print('gcd('+str(m)+','+str(n)+') = ' +str(gcd(m,n)))
```

```
"""
codeO = compile(codeS, '<string>', 'exec')
exec(codeO)
```

Code → Compile → Execute

```
$ ./cce.py
Enter a +ve integer: 12
Enter a +ve integer: 18
gcd(12,18) = 6
```

Code → Compile → Execute

```
#! /usr/bin/python3
# cceS.py the code is a string

# Code string from a file
open('gcd.py', 'r', encoding='utf-8') as file:
   codeS = file.read()
codeO = compile(codeS, '<string>', 'exec')
exec(codeO)
```

Code → Compile → Execute

```
$ ./cceS.py
Enter a +ve integer: 24
Enter a +ve integer: 10
gcd(24,10) = 2
```

C Program

```
#include <stdio.h>
int main() // first0.c
{
    printf("My first program\n");
    return 0;
}
```

Assembly Language Program

$ cc -Wall -S first0.c ⇒ first0.s

```
    .file   "first0.c"
    .text
    .section    .rodata
.LC0:
    .string   "My first program"
    .text
    .globl   main
    .type   main, @function
main:
.LFB0:
    .cfi_startproc
```

```
    endbr64
    pushq   %rbp
    .cfi_def_cfa_offset 16
    .cfi_offset 6, -16
    movq    %rsp, %rbp
    .cfi_def_cfa_register 6
    leaq    .LC0(%rip), %rdi
    call    puts@PLT
    movl    $0, %eax
    popq    %rbp
    .cfi_def_cfa 7, 8
    ret
    .cfi_endproc
.LFE0:
```

```
    .size   main, .-main
    .ident   "GCC: (Ubuntu 9.4.0-1ubuntu1~20.04.2) 9.4.0"
    .section   .note.GNU-stack,"",@progbits
    .section   .note.gnu.property,"a"
    .align 8
    .long    1f - 0f
    .long    4f - 1f
    .long    5
0:
    .string    "GNU"
1:
    .align 8
    .long    0xc0000002
    .long    3f - 2f
```

```
2:
    .long    0x3
3:
    .align 8
4:
```

Object File

```
$ cc -c first0.s ⇒ first0.o
$ objdump -d first0.o | less

0000000000000000 <main>:
   0: f3 0f 1e fa              endbr64
   4: 55                       push   %rbp
   5: 48 89 e5                 mov    %rsp,%rbp
   8: 48 8d 3d 00 00 00 00     lea    0x0(%rip),%rdi        #
   f: e8 00 00 00 00           callq  14 <main+0x14>
  14: b8 00 00 00 00           mov    $0x0,%eax
  19: 5d                       pop    %rbp
  1a: c3                       retq
```

Executable File

```
$ cc first0.o ⇒ a.out
$ objdump -d a.out | less

0000000000001149 <main>:
  1149:  f3 0f 1e fa           endbr64
  114d:  55                    push  %rbp
  114e:  48 89 e5              mov   %rsp,%rbp
  1151:  48 8d 3d ac 0e 00 00  lea   0xeac(%rip),%rdi
  1158:  e8 f3 fe ff ff        callq 1050 <puts@plt>
  115d:  b8 00 00 00 00        mov   $0x0,%eax
  1162:  5d                    pop   %rbp
  1163:  c3                    retq
```

a.out file contains more code than this.

Using Software Interrupt: x86-64

```
#include <asm/unistd.h>
#include <syscall.h>
#define STDOUT_FILENO 1

.file "first.S"
.section        .rodata
L1:
    .string "My First program\n"
L2:
.text
.globl _start
```

```
_start:
  movl  $(SYS_write), %eax      # eax <-- 1 (write)
                                # parameters to 'write'
  movq  $(STDOUT_FILENO), %rdi # rdi <-- 1 (stdout)
  movq  $L1, %rsi               # rsi <-- starting
                                #  address of string
  movq  $(L2-L1), %rdx          # rdx <-- L2 - L1
                                #   string length
  syscall                       # software interrupt
                                #  user process requesting
                                #  OS for service
  movl  $(SYS_exit), %eax       # eax <-- 60 (exit)
                                #   parameters to exit
```

```
movq  $0, %rdi                  # rdi <-- 0
syscall                         # software interrupt

ret                             # return
```

Preprocessor, assembler and Linker

```
$ /lib/cpp first.S first.s
$ as -o first.o first.s
$ ld first.o
$ ./a.out
My first program
```

first.s

```
.file "first.S"
.section .rodata
L1:
   .string "My First program\n"
L2:
.text
.globl _start

_start:
    movl $(1), %eax # eax <-- 1 (write)
                    # parameters to 'write'
    movq $(1), %rdi # rdi <-- 1 (stdout)
```

```
movq $L1, %rsi # rsi <-- starting
                    # address of string
movq $(L2-L1), %rdx # rdx <-- L2 - L1
                    # string length
syscall # software interrupt
                    # user process requesting
                    # OS for service
movl $(60), %eax # eax <-- 60 (exit)
                    # parameters to exit
movq $0, %rdi # rdi <-- 0
syscall # software interrupt
ret # return
```

objdump -d first.o

```
first.o:     file format elf64-x86-64
Disassembly of section .text:
0000000000000000 <_start>:
   0: b8 01 00 00 00          mov    $0x1,%eax
   5: 48 c7 c7 01 00 00 00    mov    $0x1,%rdi
   c: 48 c7 c6 00 00 00 00    mov    $0x0,%rsi
  13: 48 c7 c2 12 00 00 00    mov    $0x12,%rdx
  1a: 0f 05                   syscall
  1c: b8 3c 00 00 00          mov    $0x3c,%eax
  21: 48 c7 c7 00 00 00 00    mov    $0x0,%rdi
  28: 0f 05                   syscall
  2a: c3                      retq
```

objdump -d a.out

```
a.out:     file format elf64-x86-64
Disassembly of section .text:
0000000000401000 <_start>:
  401000:   b8 01 00 00 00          mov  $0x1,%eax
  401005:   48 c7 c7 01 00 00 00    mov  $0x1,%rdi
  40100c:   48 c7 c6 00 20 40 00    mov  $0x402000,%rsi
  401013:   48 c7 c2 12 00 00 00    mov  $0x12,%rdx
  40101a:   0f 05                   syscall
  40101c:   b8 3c 00 00 00          mov  $0x3c,%eax
  401021:   48 c7 c7 00 00 00 00    mov  $0x0,%rdi
  401028:   0f 05                   syscall
  40102a:   c3                      retq
```

Description/Specification of a Language

- Description of a well-formed program - syntax of a language.
- Description of the meaning of different constructs and their composition as a whole program - semantics of a language.

Description of Syntax

Syntax of a programming language is specified and verified in two stages.

1. Identification of the tokens (atoms of different syntactic categories) from the character stream of a program.
2. Correctness of the syntactic structure of the program from the stream of tokens.

Description of Syntax

- Tokens of a programming language are specified using regular expressions.
- Token identification is done by software where at its core there is a modified DFA or an NFA.

Description of Syntax

Structure of a programming language is specified using restricted class of context-free grammars e.g. LL(1), LALR(1), or LR(1).

Note

There are structural features of a programming language that are not specified by the grammar rules for efficiency reason and are handled differently.

Description of Meaning: Semantics

- Informal or semi-formal description by natural language and mathematical notations.
- Formal descriptions e.g. grammar rule with attributes, other formal specifications of semantics.

Users of Specification

- Programmer - often uses an informal description of the language construct.
- People who write language translators.
- People who want to verify a piece of program or who want to automate program writing (synthesis).

Source and Target

A source language is usually a high-level language. But there are different types of high level languages.
Imperative languages like C, object oriented languages like Java, functional languages like Haskell, logic programming languages like Prolog, languages for parallel and distributed programming etc.

Source and Target

- The target languages also have a wide spectrum. Assembly and machine languages of different architecture, byte code of a virtual machines, or even another HLL.
- Different machine architectures demand different types of code generation and improvements.

Front-end and Back-end

- The part of the compiler that analyzes the structure of the source program, extracts the semantic information and produces an internal representation of it is known as the front-end.
- The part that uses the internal representation and synthesis the semantically equivalent target program is called the back-end.

Compiler and Interpreter

- A compiler and an interpreter mainly differ in their back-ends.
- A compiler generates the target code from the intermediate representation.
- The target code can be executed again and again.

Compiler and Interpreter

- An interpreter on the other hand performs action specified by the program fragment (extracted in the intermediate form) on its data.
- The code generating back-end of a compiler is replaced by a set of routines for interpretation.

Compiler and Interpreter

- Usually it is expected that the compiled code is more time efficient.
- But an interpreter may have better error reporting as the source program is available during interpretation.
- An interpreter may be more portable and easier to write (!). People also claim that an interpreter is better in terms of security.

Basic Phases of Compilation

- Read the program text - this is the most time consuming part as it involves I/O.
- Preprocessing - a phase before the actual compilation. It may involve inclusion (reading) of several files.
- Lexical analysis - identification of the syntactic symbols of the language and collecting their attributes.

Basic Phases of Compilation

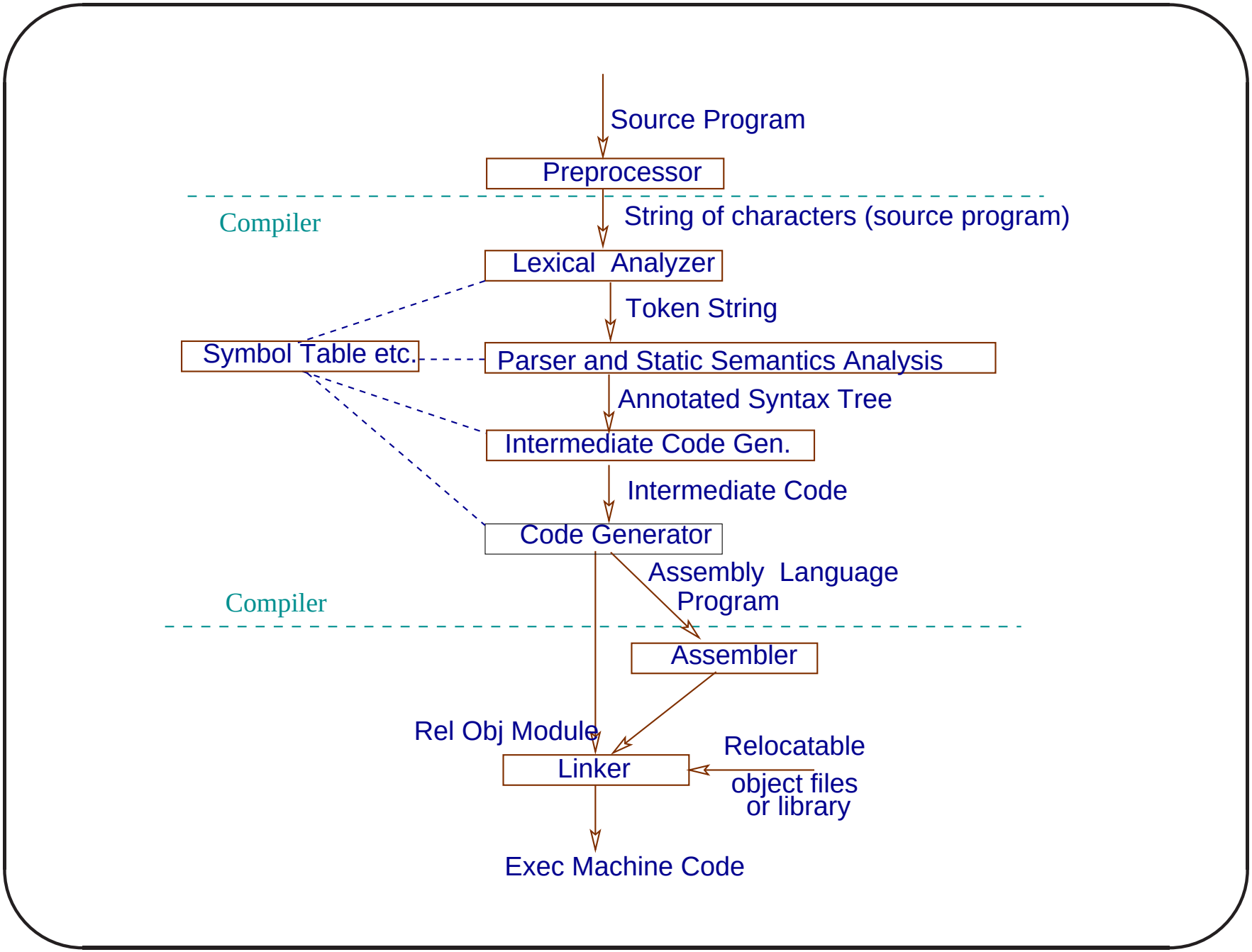
- Syntax checking and static semantic analysis - the stream of token is parsed to form the parse tree or syntax tree. The semantic information is collected from the context and the syntax tree is annotated.

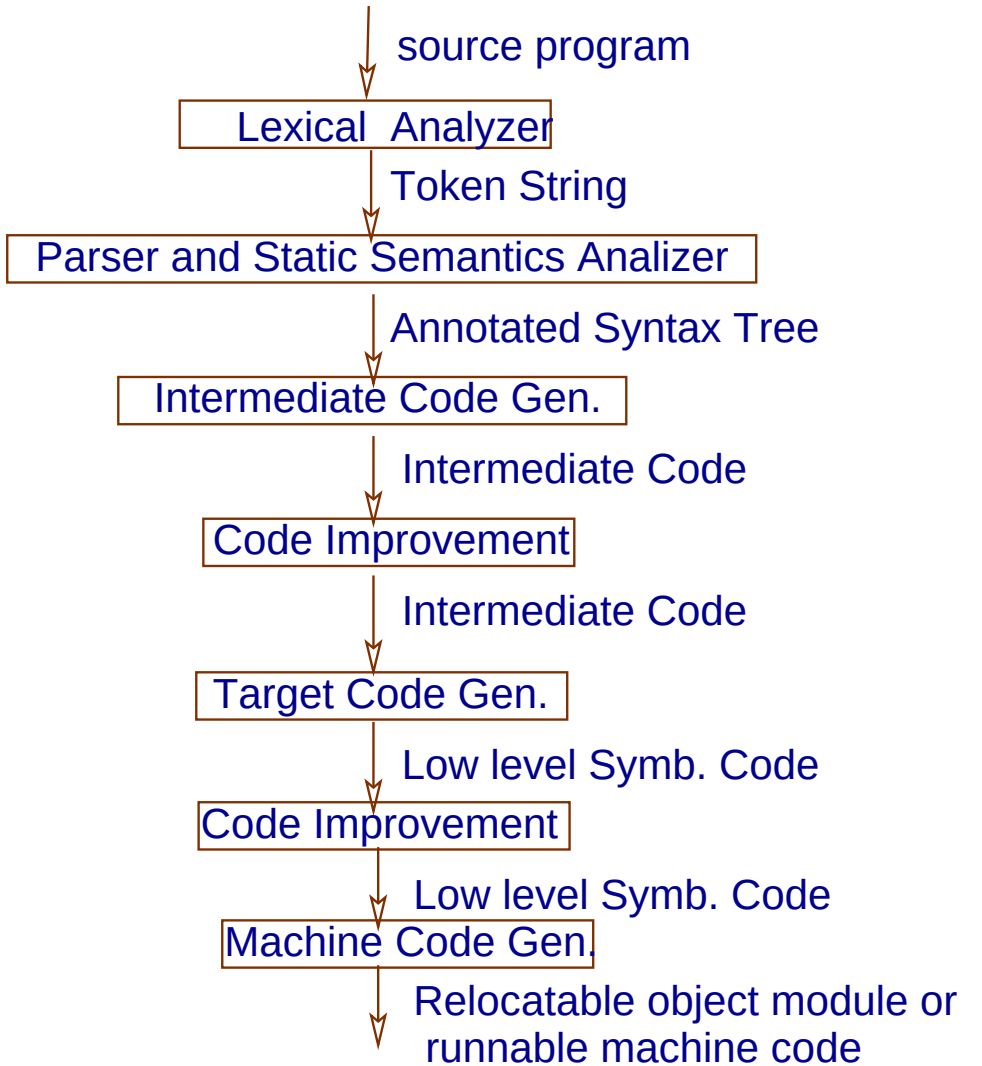
Basic Phases of Compilation

- Intermediate code generation and code improvement - language specific constructs are translated to more general and simple constructs. As an example a long expressions is broken down to expressions with fixed number of parameters. Different optimizations are performed on this intermediate code.

Basic Phases of Compilation

- Symbolic target code generation and architecture specific code improvement - the intermediate representation is translated to target code in symbolic form, and architecture specific code optimization is performed.
- Low level machine code generation.


Source Program
Preprocessor
Compiler
String of characters (source program)
Lexical Analyzer
Token String
Symbol Table etc.
Parser and Static Semantics Analysis
Annotated Syntax Tree
Intermediate Code Gen.
Intermediate Code
Code Generator
Assembly Language Program
Compiler
Assembler
Rel Obj Module
Relocatable object files or library
Linker
Exec Machine Code


source program
Lexical Analyzer
Token String
Parser and Static Semantics Analizer
Annotated Syntax Tree
Intermediate Code Gen.
Intermediate Code
Code Improvement
Intermediate Code
Target Code Gen.
Low level Symb. Code
Code Improvement
Low level Symb. Code
Machine Code Gen.
Relocatable object module or
runnable machine code

Independence of Front and back Ends

- In an idealistic situation the front-end of a compiler does not know anything of the target language. Its job is to transform the source program to intermediate representation.
- Similarly, the back-end is not aware of the source language. It works on the intermediate representation to generate the target code.

Compiler and Interpreter

- If the intermediate representation of the source program and the input data to it is available, the 'translator' can perform the action on the data specified by the source program using the intermediate representation. There is no need to generate the target code explicitly.
- This is what is done by an interpreter.

Scanner or Lexical Analyzer

A scanner or lexical analyzer breaks the program text (string of ASCII characters) into the alphabet of the language (into syntactic categories) called a tokens.

A token may be encoded as a number and it may have one or more attributes.

An Example

Consider the following C function.

```
double CtoF(double cel) {
        return cel * 9 / 5.0 + 32 ;
}
```

Scanner or Lexical Analyzer

- A scanner uses the finite automaton model to identify different tokens.
- Software e.g. flex takes the specifications of tokens as regular expressions and generates a program that works as the scanner.
- The process is completely automated.

Scanner or Lexical Analyzer

- A syntax analyzer does not differentiate between different identifiers or different integer constants. They are identified as identifier token and integer token.
- But the actual values are preserved as attributes for use in subsequent phases.

Syntactic Category, Token and Attribute

String	Type	Token	Attribute
"`double`"	keyword	302	
"`CtoF`"	identifier	401	"`CtoF`"
"`(`"	delimiter	40	
"`double`"	keyword	302	
"`cel`"	identifier	401	"`cel`"
"`)`"	delimiter	41	
"{"	delimiter	123	
"`return`"	keyword	315	

String	Type	Token	Attribute
"cel"	identifier	401	"cel"
"*"	operator	42	
"9"	int-numeral	504	9
"/"	operator	47	
"5.0"	double-numeral	507	5.0
"+"	operator	43	
"32"	int-numeral	504	32
";"	delimiter	59	
"}"	delimiter	125	

Parser or Syntax Analyzer

- A parser or syntax analyzer checks whether the token stream generated by the scanner, forms a valid program.
- It uses a restricted class of context-free grammars as model to specify the language constructs.
- The restriction is primarily from the efficiency consideration.

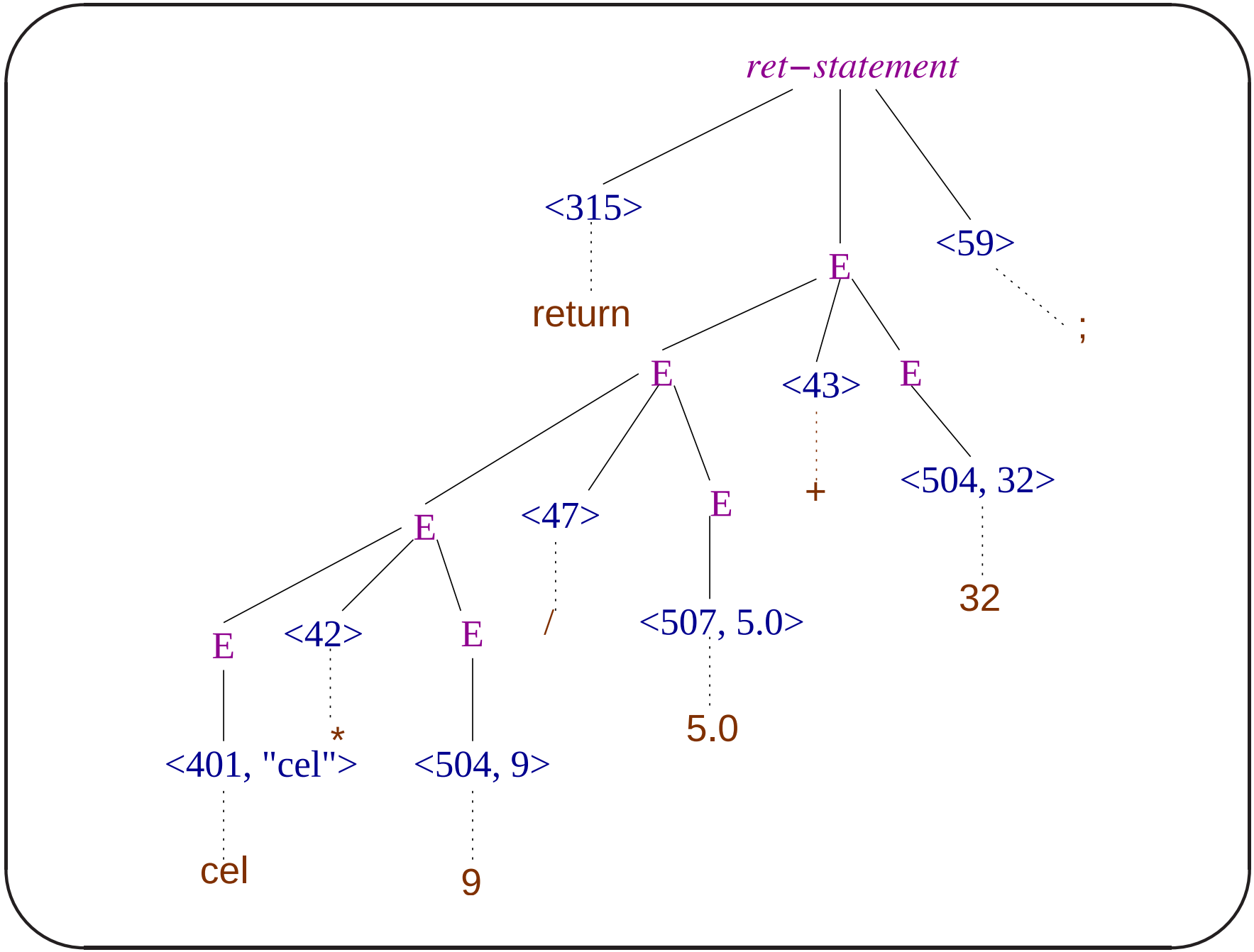
Context-Free Grammar

$$
\begin{aligned}
\text{function-definition} &\rightarrow \text{decl-spec decl comp-stat} \\
\text{decl-spec} &\rightarrow \text{type-spec} \mid \cdots \\
\text{type-spec} &\rightarrow \texttt{double} \mid \cdots \\
\text{decl} &\rightarrow \text{d-decl} \mid \cdots \\
\text{d-decl} &\rightarrow \text{ident} \mid \text{ident } \texttt{(}\ \text{par-list}\ \texttt{)} \\
\text{par-list} &\rightarrow \text{par-dcl} \mid \cdots \\
\text{par-dcl} &\rightarrow \text{decl-spec decl} \mid \cdots
\end{aligned}
$$

Expression Grammar

$$E \rightarrow E + E \mid E - E \mid E * E \mid E/E \mid (E) \mid$$
$$-E \mid \text{var} \mid \text{float-cons} \mid \text{int-cons} \mid \cdots$$

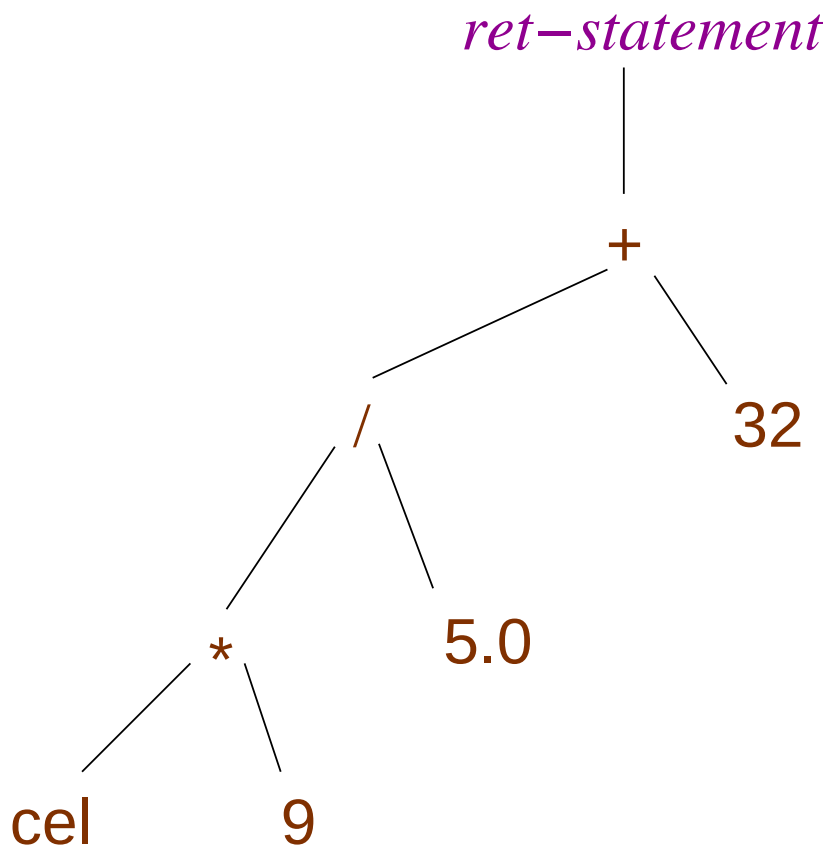
Parse Tree


ret−statement
<315>
return
E
<59>
;
E
<43>
E
+
<504, 32>
32
E
<47>
E
/
<507, 5.0>
5.0
E
<42>
E
*
<504, 9>
9
E
<401, "cel">
cel

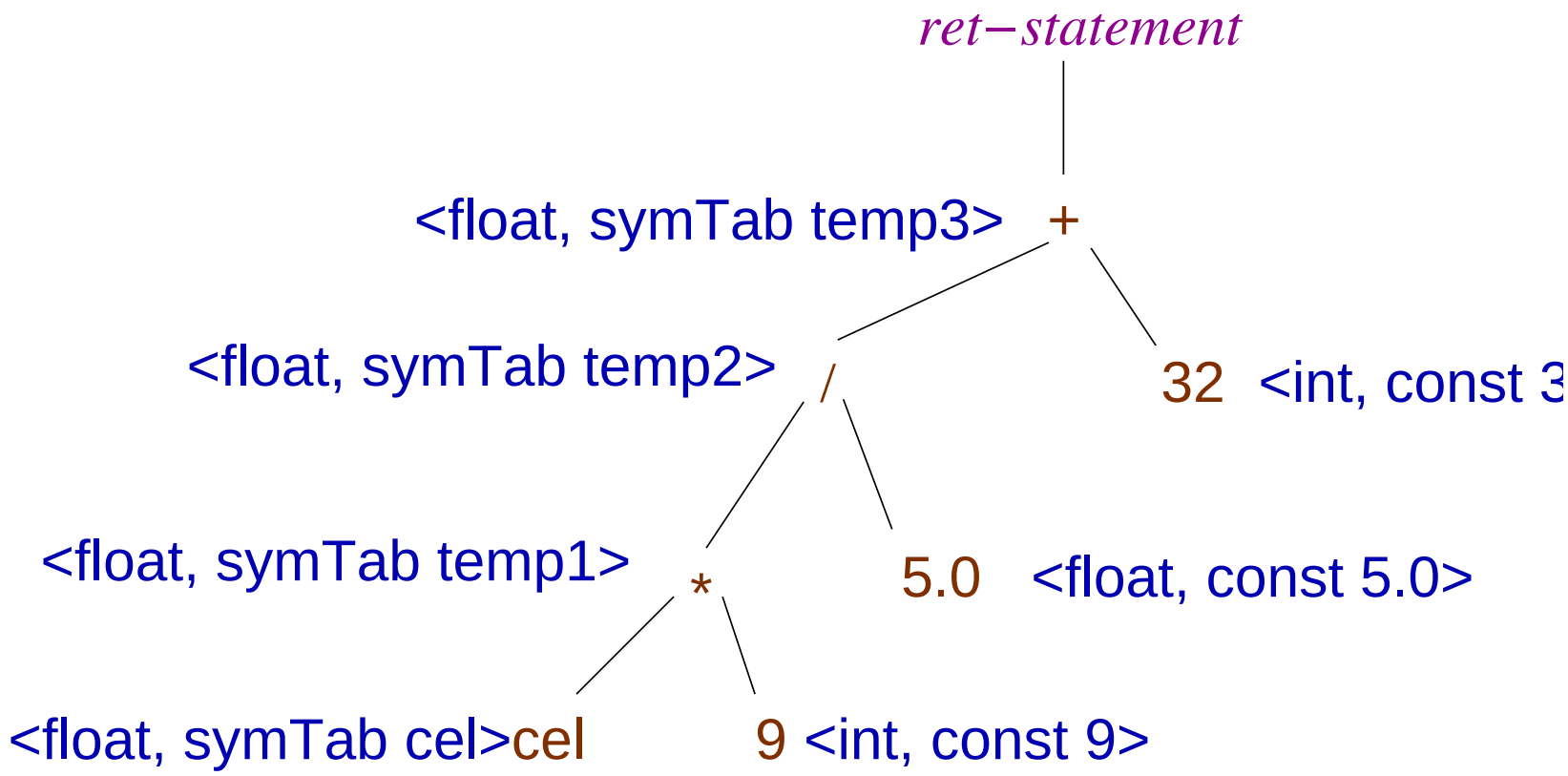
Abstract Syntax Tree

- The parse tree generated during syntax checking is often stored in a modified and compact form, known as an abstract syntax tree (AST).
- Semantic information are stored in the nodes of AST (annotated AST) as attributes. It is used for intermediate code generation, error checking and code improvement.

Abstract Syntax Tree (AST)



Annotated AST



Symbol Table

The compiler maintains an important data structure called the symbol table to store variety of names and their attributes it encounters. A few examples are - variables, named constants, function names, type names, labels etc.

Symbol Table

- The symbol table corresponding to the function `CtoF` should have an entry for the parameter `cel` with its type.
- The return type of the function etc. information.

Semantic Analysis

The constant 9 is of type `int`. It is to be converted to 9.0 of type `double` (completely different representation) before it can be multiplied with `cel`.
Similar is the case for 32.

Semantic Analysis

It is not enough to know that `x = x + 5;` is syntactically correct.

- The operation is meaningful only if the variable `x` is declared as a datatype where the binary operation '+' is defined.
- Even if `x` is a number, the generated code will be different depending on whether it is an `int`, `float` or an `address`.

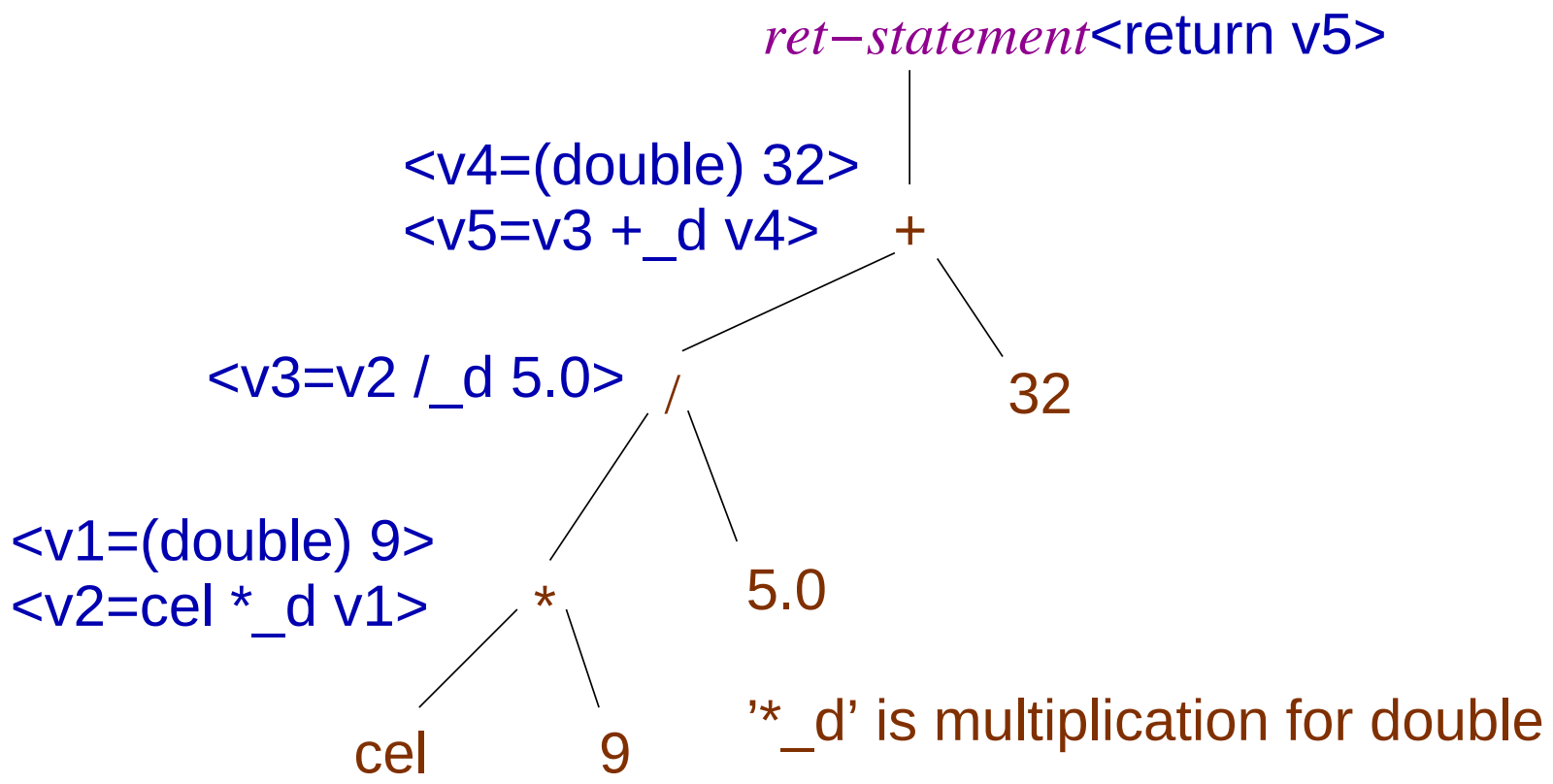
Intermediate Code Generation

- The language specific AST may be translated to other intermediate constructs such as 3-address codes.
- The form of the intermediate code should be suitable for code improvement and target code generation.
- A interpreter may directly work on the AST.

Intermediate Code Generation

- A while-loop in a C-like language may be replaced by test, and conditional and unconditional jumps.
- A compiler may use more than one intermediate representations for different phases.

Intermediate Code



Intermediate Code

param cel

v1 = (double) 9 # compile time

v2 = cel $*_d$ v1

v3 = v2$/_d$5.0

v4 = (double)32 # compile time

v5 = v3 $+_d$ v4

return v5

Note

`v1, v2, v3, v4, v5` are called virtual registers. Finally they will be mapped to actual registers or memory locations. The distinct names of the virtual registers helps better in code improvement (SSA - static single assignment).

GCC IC - GIMPLE

```
$ cc -Wall -fdump-tree-gimple -S ctof.c

CtoF (double cel)
{
  double D.1796;


  _1 = cel * 9.0e+0;
  _2 = _1 / 5.0e+0;
  D.1796 = _2 + 3.2e+1;
  return D.1796;
}
```

Raw GIMPLE Code

```
$ cc -Wall -fdump-tree-gimple-raw -S ctof.c

CtoF (double cel)
gimple_bind <
  double D.1796;

  gimple_assign <mult_expr, _1, cel, 9.0e+0, NULL>
  gimple_assign <rdiv_expr, _2, _1, 5.0e+0, NULL>
  gimple_assign <plus_expr, D.1796, _2, 3.2e+1, NULL>
  gimple_return <D.1796 NULL>
>
```

Intermediate Code Improvement

- Different code improvement transformations are performed on the intermediate code.
- A few examples are constant propagation, constant folding, strength reduction, copy propagation, elimination of common sub-expression, $\cdots$, code in-lining etc.

Target Code Generation

- Program variables and temporary variables are allocated to memory and registers.
- Translates the intermediate code to a target language code e.g. sequence of assembly language instructions of a machine.

Target Code Improvement

- The sequence of target code e.g. assembly language code of an architecture may be modified to improve the quality of code.
- It may replace a sequence of instructions by a better sequence to make the code faster on an architecture.

64-bit Intel Code

```
    .file   "ctof.c"
    .text
.globl CtoF
    .type   CtoF, @function
CtoF:
.LFB2:
  pushq   %rbp                  # save old base pointer
.LCFI0:
  movq    %rsp, %rbp            # rbp <-- rsp new base pointer
.LCFI1:
  movsd   %xmm0, -8(%rbp)       # cel <-- xmm0 (parameter)
  movsd   -8(%rbp), %xmm1       # xmm1 <-- cel
```

```
movsd   .LC0(%rip), %xmm0 # xmm0 <--- 9.0, PC relative
                          # addressing of read-only data
mulsd   %xmm0, %xmm1      # xmm1 <-- xmm1*xmm0 (cel*9.0)
movsd   .LC1(%rip), %xmm0 # xmm0 <-- 5.0
                          # 5.0 is saved as read-only dat
divsd   %xmm0, %xmm1      # xmm1 <-- xmm1/xmm0
                          #       cel*9.0/5.0
movsd   .LC2(%rip), %xmm0 # xmm0 <-- 32.0
                          # 32.0 is saved as read-only da
addsd   %xmm1, %xmm0      # xmm0 <-- xmm0+xmm1
                          #       32.0+cel*9.0/5.0
                          # return value in xmm0
leave
ret
```

```
.LFE2:
    .size   CtoF, .-CtoF
    .section        .rodata
    .align 8
.LC0:
    .long   0
    .long   1075970048
    .align 8
.LC1:
    .long   0
    .long   1075052544
    .align 8
.LC2:
    .long   0
```

```
.long   1077936128
```

9.0 in IEEE-754 Double Prec.

63

0 | 1000 0000 010 | 0010 0000 0000 0000 0000

31

0000 0000 0000 0000 0000 0000 0000 0000

Exponent Bias: 1023,
Actual exponent: $1026 - 1023 = 3$.
$9.0_{10} = 1001.0_2 = 1.001 \times 2^3$.

9.0 and .LC0

Interpreted as integer we have the higher order 32-bits as $2^{30} + 2^{21} + 2^{17} = 1075970048$ and the lower order 32-bits as 0.

In the little-endian (lsb) data storage, lower bytes comes first.

9.0 and .LC0

```
    .align 8
.LC0:
    .long   0
    .long   1075970048
```

is 9.0.

Improved Code $ cc -Wall -S -O2 ctof.c

```
    .file   "ctof.c"
    .text
    .p2align 4,,15
.globl CtoF
    .type   CtoF, @function
CtoF:
.LFB2:
    mulsd   .LC0(%rip), %xmm0
    divsd   .LC1(%rip), %xmm0
    addsd   .LC2(%rip), %xmm0
    ret
.LFE2:
```

```
    .size   CtoF, .-CtoF
    .section        .rodata.cst8,"aM",@progbits,8
    .align 8
.LC0:
    .long   0
    .long   1075970048
    .align 8
.LC1:
    .long   0
    .long   1075052544
    .align 8
.LC2:
    .long   0
    .long   1077936128
```

Constant Folding

```
#include <stdio.h>
int main(){ // constFold.c
    int n;

    n = 24*25;
    printf("n: %d\n", n);
    return 0;
}
```

Constant Folding

```
$ cc -Wall -S constFold.c
```

```
  movl  $600, -4(%rbp)     # n <-- 600, constant folding
  movl  -4(%rbp), %eax     # eax <-- n
  movl  %eax, %esi         # 2nd argument, data in n
  leaq  .LC0(%rip), %rdi   # 1st argument, format
  movl  $0, %eax
  call  printf@PLT
  movl  $0, %eax
```

Constant Propagation

```
$ cc -Wall -O2 -S constFold.c
```

```
  movl $600, %edx          # 3rd argument 600 directly
  movl $1, %edi            # edi <-- 1, 1st argument
                           # Stack overflow flag (?)
  xorl %eax, %eax
  leaq .LC0(%rip), %rsi    # 2nd argument, format
  call __printf_chk@PLT
  xorl %eax, %eax
```

Strength Reduction

```
#include <stdio.h>
int main(){ // strengthRed.c
    int n, m;

    scanf("%d", &n);
    m = 48*n;
    printf("m: %d\n", m);
    return 0;
}
```

Strength Reduction

```
$ cc -Wall -S strengthRed.c
```

```
  movl  -16(%rbp), %edx   # edx <-- n
  movl  %edx, %eax        # eax <-- edx (n)
  addl  %eax, %eax        # eax <-- 2n
  addl  %edx, %eax        # eax <-- eax + edx (3n)
  sall  $4, %eax          # eax <-- 2**4*(3*n)
                          # arithmetic shift left
                          # by 4-bits
```

Strength Reduction: not Beneficial

```
#include <stdio.h>
int main(){ // strengthRed1.c
    int n, m;

    scanf("%d", &n);
    m = 47*n;                  // 48 replaced by 47
    printf("m: %d\n", m);
    return 0;
}
```

Strength Reduction: not Beneficial

```
$ cc -Wall -S strengthRed1.c
```

```
    movl   -16(%rbp), %eax
    imull $47, %eax, %eax
```

Common Subexpression

```
#include <stdio.h>
int main(){ // commonSubExp.c
    int n, a, b;

    scanf("%d", &n);
    a = 47*n;
    b = 47*n+2;
    printf("a: %d, b: %d\n", a, b);
    return 0;
}
```

Common Subexpression: no Elimination

```
$ cc -Wall -S commonSubExp.c
```

```
    movl    -20(%rbp), %eax  # eax <-- n
    imull $47, %eax, %eax    # eax <-- 47*n
    movl  %eax, -16(%rbp)    # a <-- eax (47n)
    movl  -20(%rbp), %eax    # eax <-- n
    imull $47, %eax, %eax    # eax <-- 47*n
    addl  $2, %eax           # eax <-- eax + 2 (47n+2)
    movl  %eax, -12(%rbp)    # b <-- eax (47n+2)
```

Common Subexpression: Elimination

```
$ cc -Wall -O2 -S commonSubExp.c
```

```
    imull $47, 4(%rsp), %edx   # edx <-- 47*n (param a)
    leaq    .LC1(%rip), %rsi   # rsi <-- 2nd param (format)
    movl    $1, %edi           # edi <-- 1, 1st param
    leal    2(%rdx), %ecx      # ecx <-- rdx + 2 (param b)
                               # rdx contains 47*n
```

Loop-Invariant Code

```
#include <stdio.h>
int main(){ // loopInv.c
    int n, sum=0, i;

    scanf("%d", &n);
    for(i=1; i<5*n+7; ++i) sum = sum+i;
    printf("sum: %d\n", sum);
    return 0;
}
```

Loop-Invariant Code: no Code Motion

```
$ cc -Wall -S loopInv.c
```

```
   movl  $1, -12(%rbp)       # i <-- 1
   jmp   .L2                 # goto .L2
.L3:
   movl    -12(%rbp), %eax   # eax <-- i
   addl    %eax, -16(%rbp)   # sum <-- sum + i
   addl    $1, -12(%rbp)     # i++
.L2:
   movl    -20(%rbp), %edx   # edx <-- n
   movl    %edx, %eax        # eax <-- edx (n)
   sall    $2, %eax          # eax <-- 4*n
   addl    %edx, %eax        # eax <-- 4n+n
```

```
addl    $6, %eax            # eax <-- 5n+6 (!)
cmpl    %eax, -12(%rbp)     # compare i and 5n+6
jle     .L3                 # goto .L3 if i <= 5n+6
```

Loop-Invariant Code: Code Motion

```
$ cc -Wall -O2 -S loopInv.c
```

```
   movl  4(%rsp), %eax          # eax <-- n
   leal  (%rax,%rax,4), %ecx    # ecx <-- 4n+n
   addl  $7, %ecx               # ecx <-- 5n+7
   movl  $1, %eax               # eax <-- 1 (i)
   xorl  %edx, %edx             # edx <-- 0 (sum)
.L3:
   addl  %eax, %edx             # edx <-- edx (sum)+eax (i)
   addl  $1, %eax               # i <-- i+1
   cmpl  %eax, %ecx             # compare i and 5n+7
   jne   .L3                    # if i not = 5n+7
                                #    goto .L3
```