Compilation

0368-3133

Lecture 1: Introduction

Noam Rinetzky

Admin

- Lecturer: Noam Rinetzky
  - *maon@tau.ac.il*
  - *http://www.cs.tau.ac.il/~maon*
- T.A.: Shachar Itzhaky
  - *shachar@tau.ac.il*
- Textbooks:
  - Modern Compiler Design
  - Compilers: principles, techniques and tools

Admin

- Compiler Project 40%
  - 4 practical exercises
  - Groups of 3
- 1 theoretical exercise 10%
  - Groups of 1
- Final exam 50%
  - must pass

Course Goals

- What is a compiler
- How does it work
- (Reusable) techniques & tools

Course Goals

- What is a compiler
- How does it work
- (Reusable) techniques & tools

- Programming language implementation
  - runtime systems
- Execution environments
  - Assembly, linkers, loaders, OS

What is a Compiler?

"A compiler is a computer program that transforms source code written in a programming language (source language) into another language (target language).

The most common reason for wanting to transform source code is to create an executable program."

--*Wikipedia*

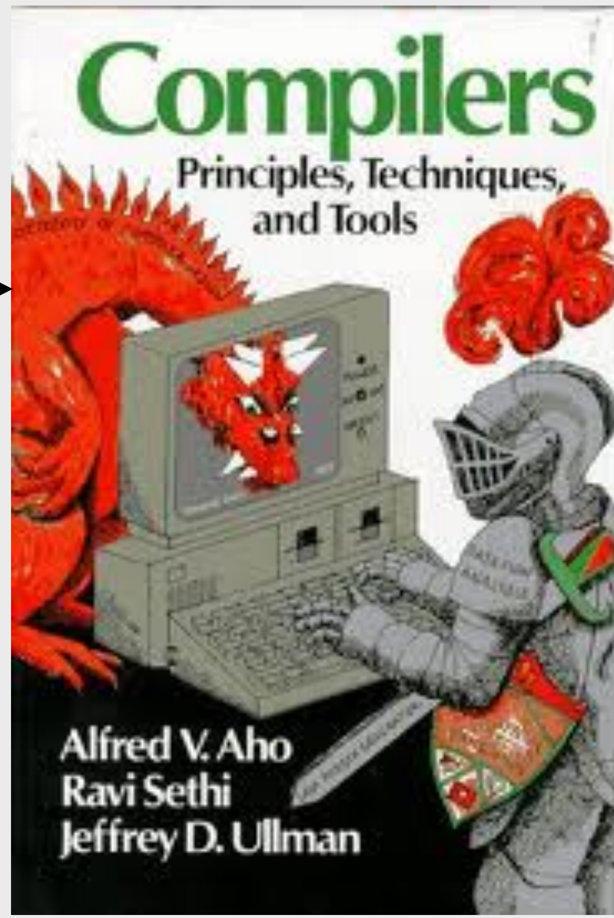
What is a Compiler?

source language

target language

txt

Source text



exe

Executable code

Compiler

What is a Compiler?

int a, b;
a = 2;
b = a*2 + 1;

MOV R1,2
SAL R1
INC R1
MOV R2,R1

What is a Compiler?

source language

C
C++
Pascal
Java

Postscript
TeX

Perl
JavaScript
Python
Ruby

Prolog

Lisp
Scheme
ML
OCaml

Compiler

target language

IA32
IA64
SPARC

C
C++
Pascal
Java

Java Bytecode

…

Lecture Outline

- High level programming languages
- Interpreters vs. Compilers
- Techniques and tools (1.1)
  - why study compilers …
- Handwritten toy compiler & interpreter (1.2)
- Summary

High Level Programming Languages

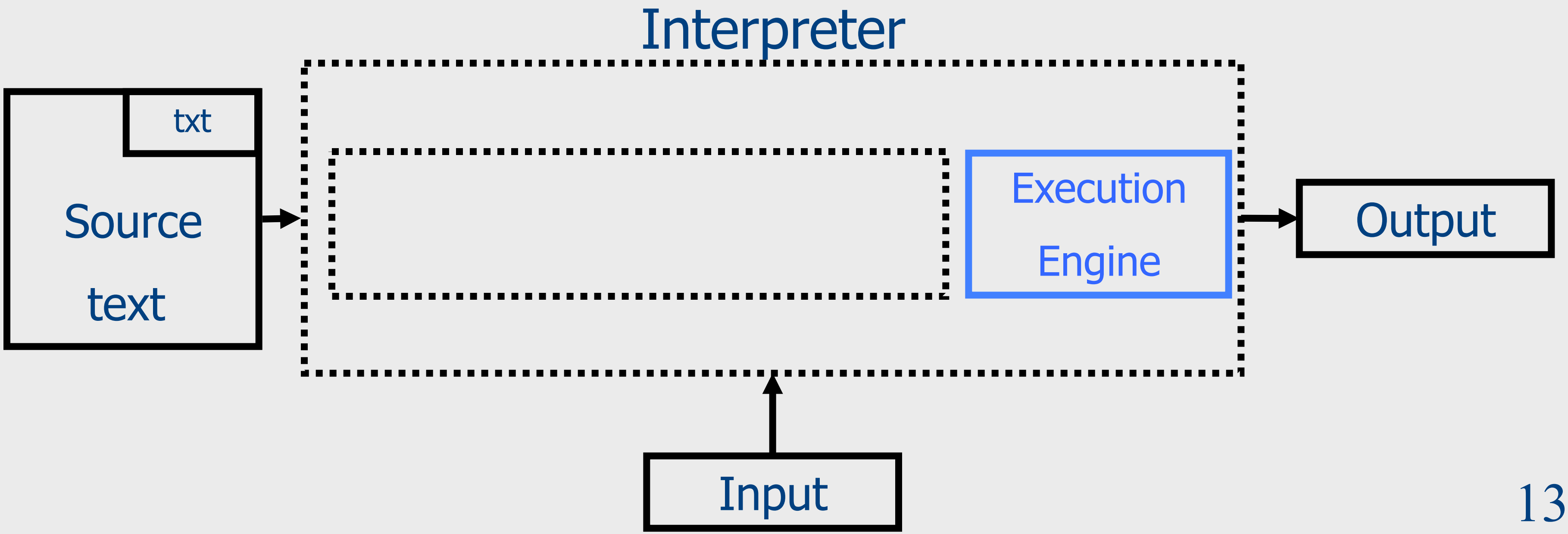
- Imperative Algol, PL1, Fortran, Pascal, Ada, Modula, C
  - Closely related to “von Neumann” Computers
- Object-oriented Simula, Smalltalk, Modula3, C++, Java, C#, Python
  - Data abstraction and ‘evolutionary’ form of program development
    - Class an implementation of an abstract data type (data+code)
    - Objects Instances of a class
    - Inheritance + generics
- Functional Lisp, Scheme, ML, Miranda, Hope, Haskel, OCaml, F#
- Logic Programming Prolog

Other Languages

- Hardware description languages VHDL
  - The program describes Hardware components
  - The compiler generates hardware layouts
- Scripting languages Shell, C-shell, REXX, Perl
  - Include primitives constructs from the current software environment
- Web/Internet HTML, Telescript, JAVA, Javascript
- Graphics and Text processing TeX, LaTeX, postscript
  - The compiler generates page layouts
- Intermediate-languages P-Code, Java bytecode, IDL

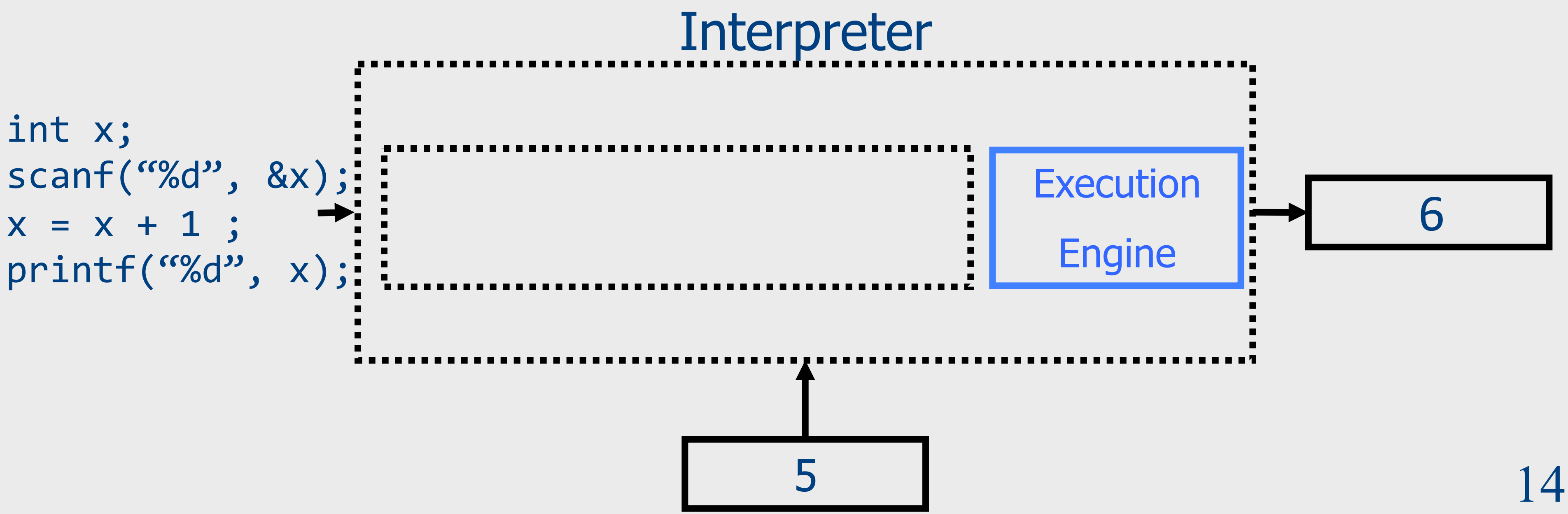
Interpreter

- A program which executes a program
- Input a program (P) + its input (x)
- Output the computed output (P(x))



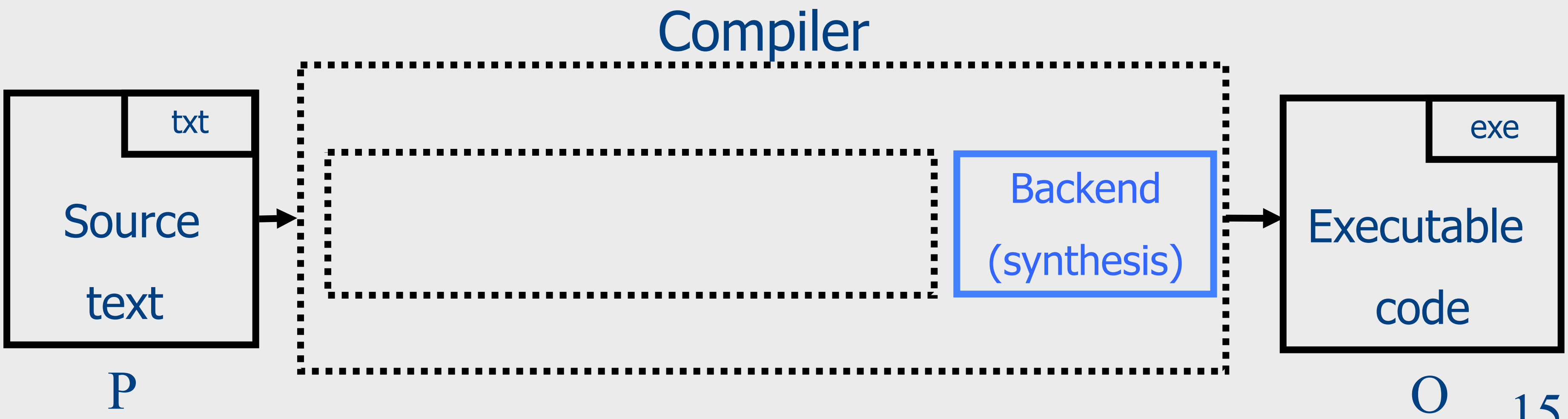
Interpreter

- A program which executes a program
- Input a program (P) + its input (x)
- Output the computed output ("P(x)")

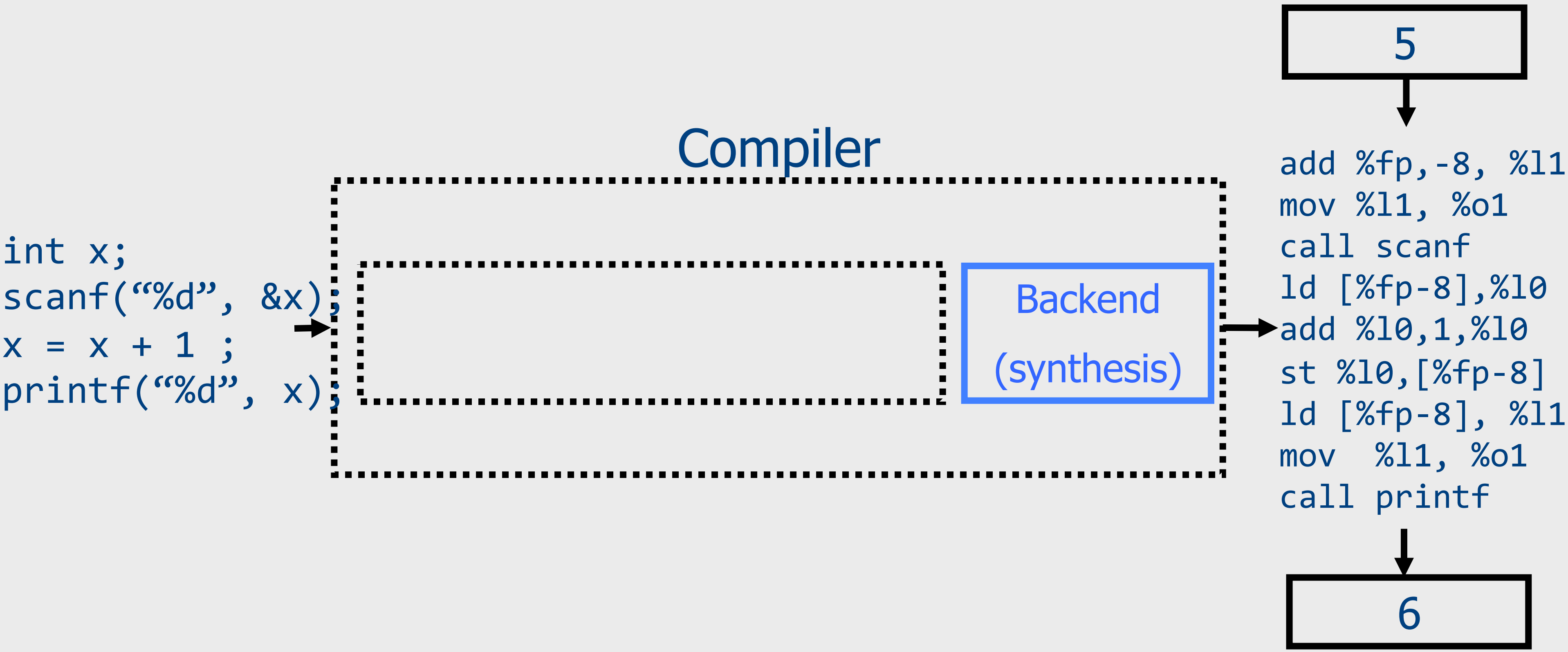


Compiler

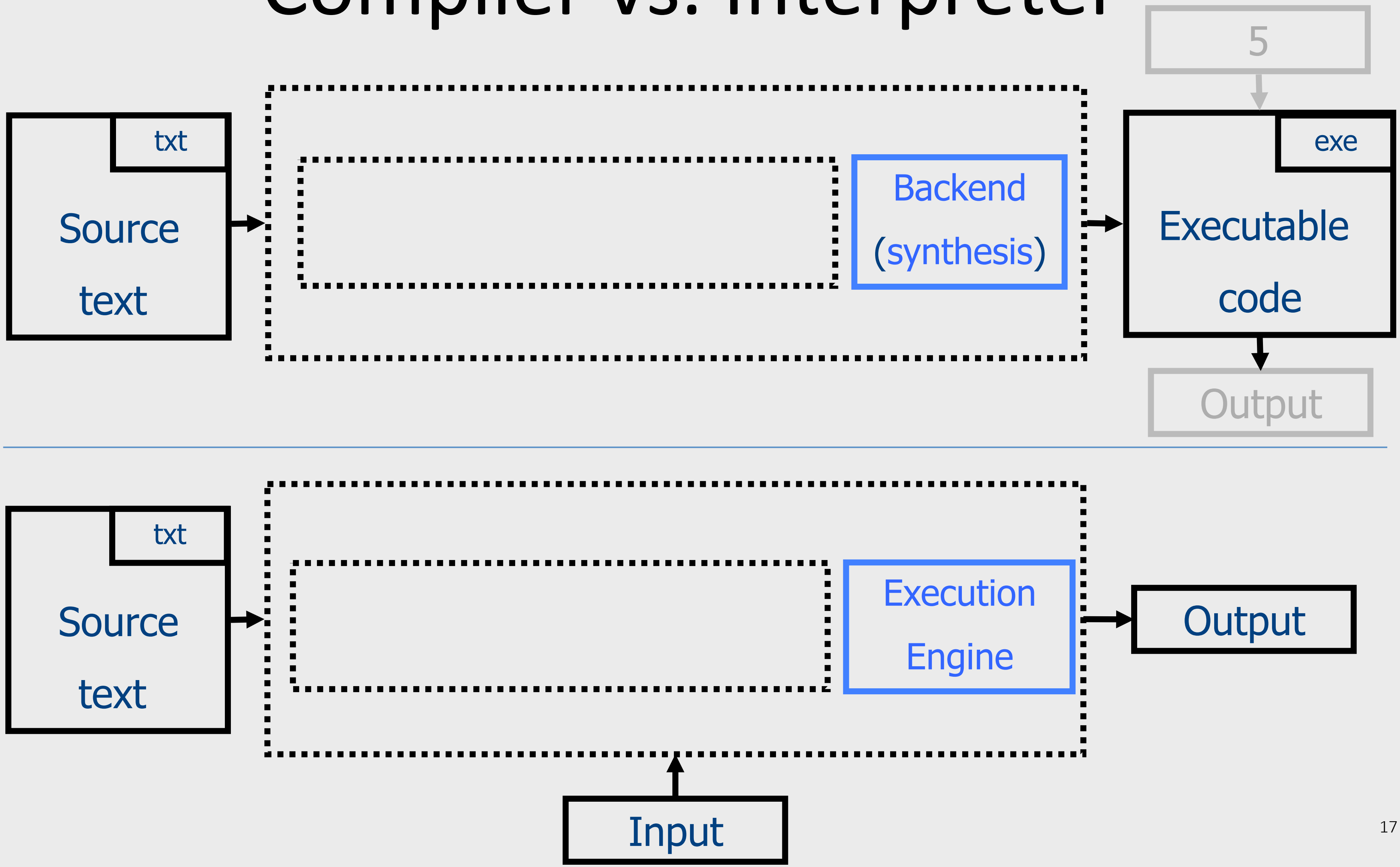
- A program which transforms programs
- Input a program (P)
- Output an object program (O)
  - For any x, “O(x)” = “P(x))”



Example


5
Compiler
int x;
scanf(“%d”, &x);
x = x + 1 ;
printf(“%d”, x);
Backend
(synthesis)
add %fp,-8, %l1
mov %l1, %o1
call scanf
ld [%fp-8],%l0
add %l0,1,%l0
st %l0,[%fp-8]
ld [%fp-8], %l1
mov %l1, %o1
call printf
6

Compiler vs. Interpreter

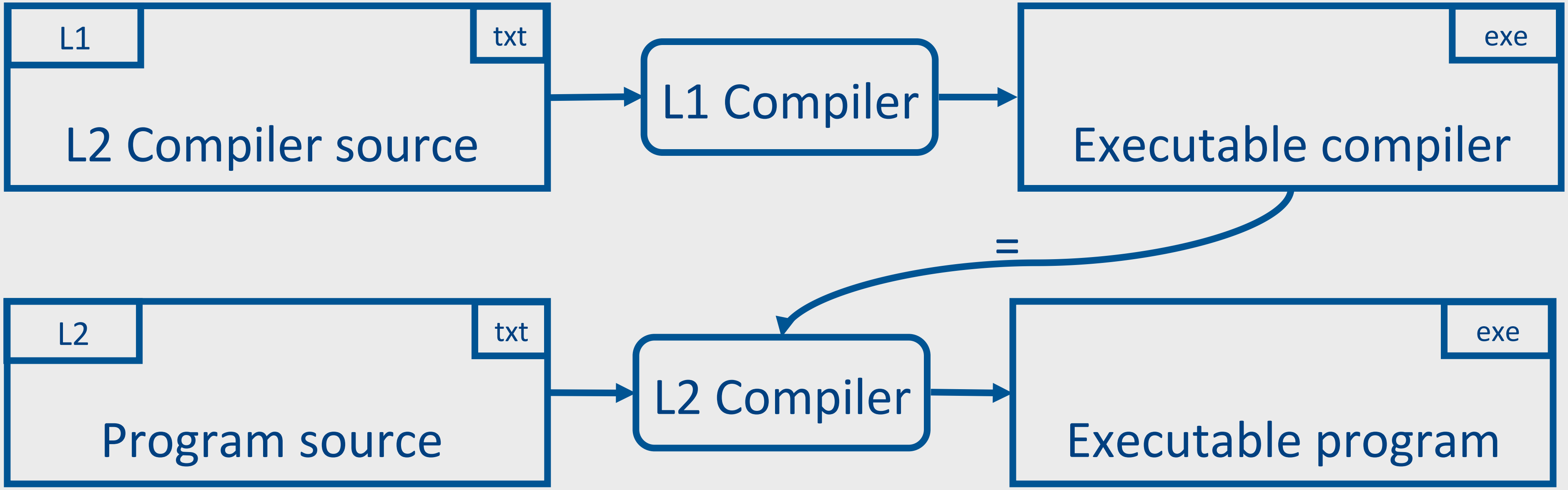


Remarks

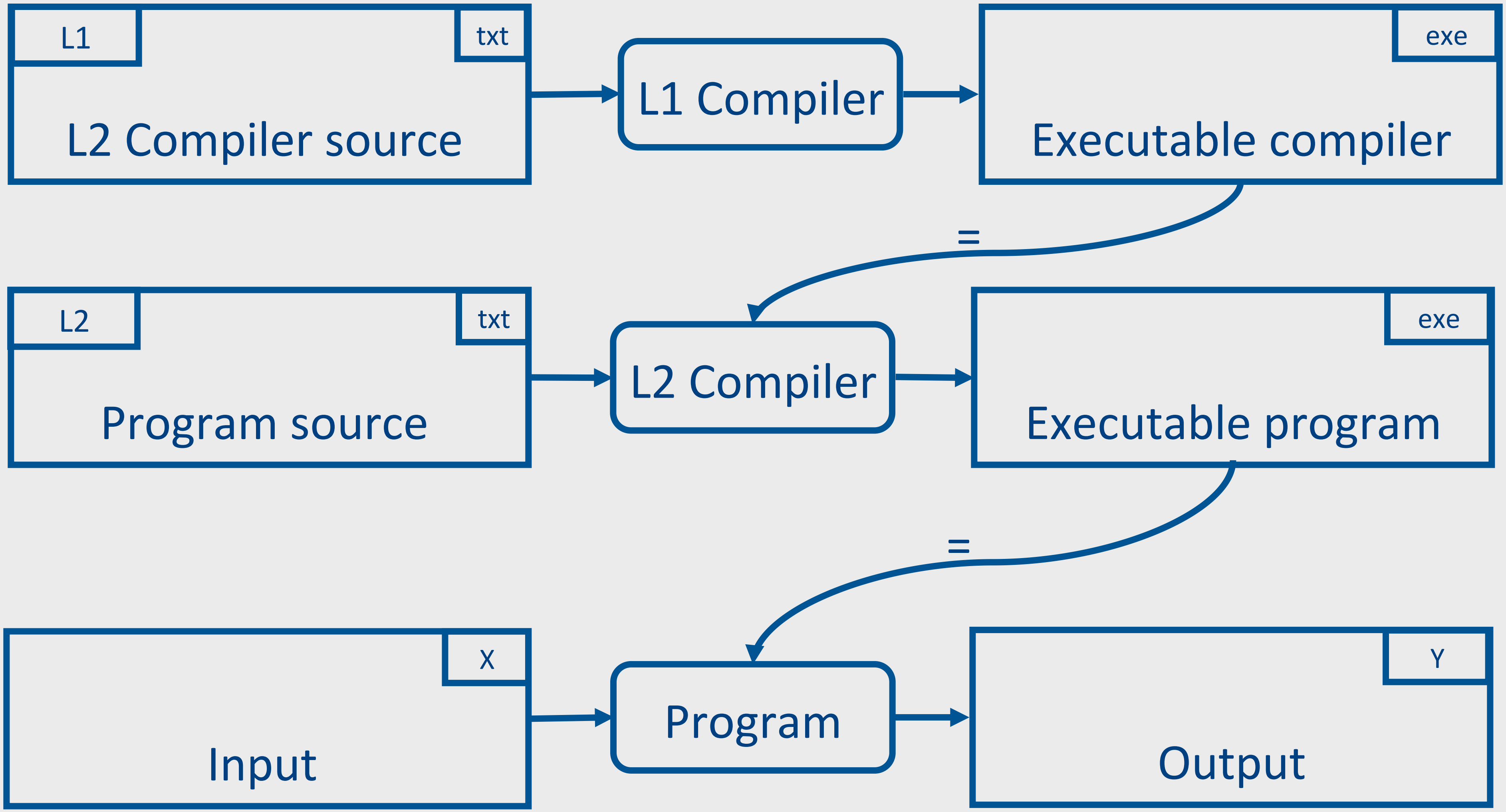
- Both compilers and interpreters are programs written in high level languages
  - Requires additional step to compile the compiler/interpreter
- Compilers and interpreters share functionality

How to write a compiler?

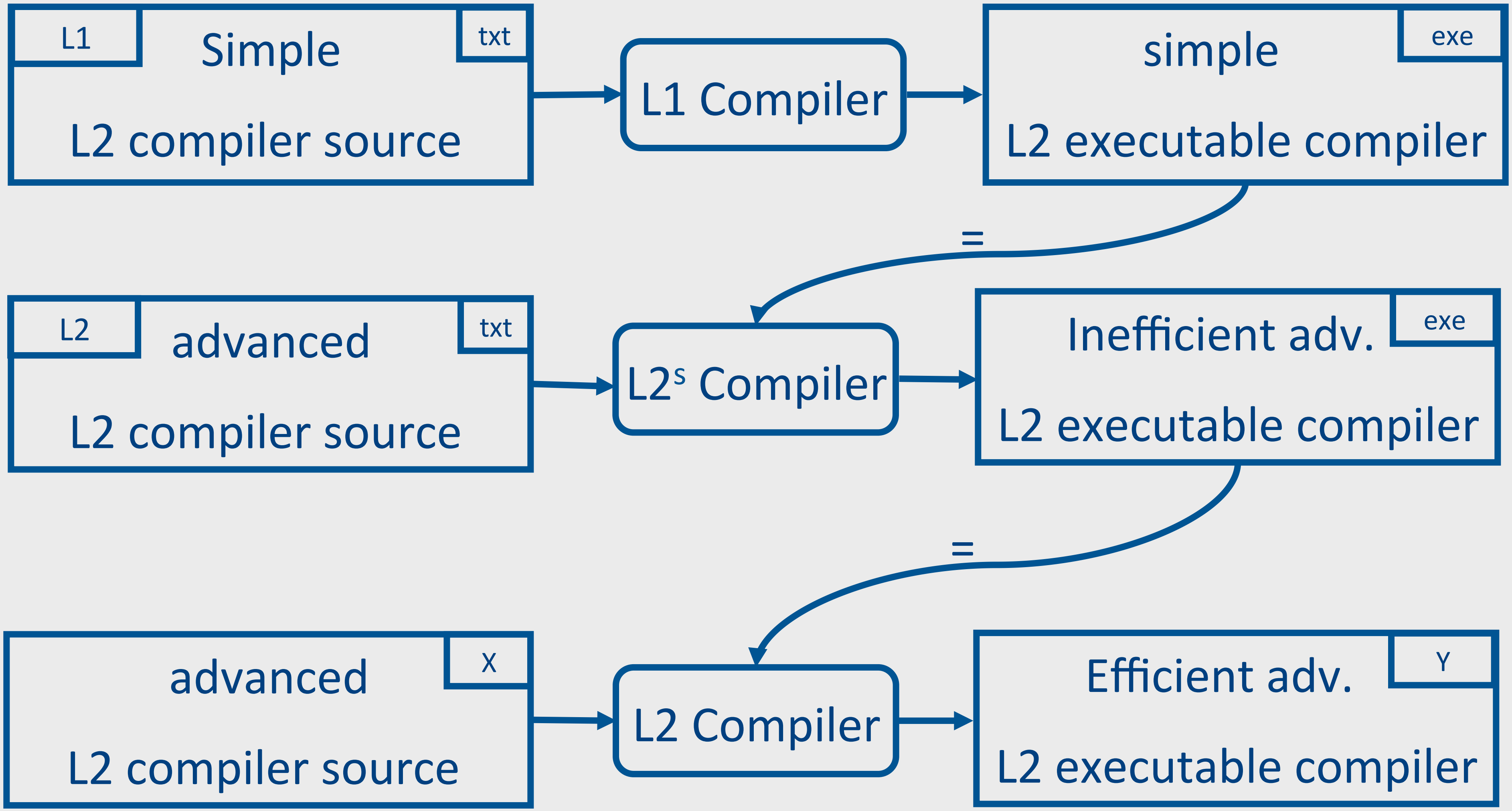
How to write a compiler?



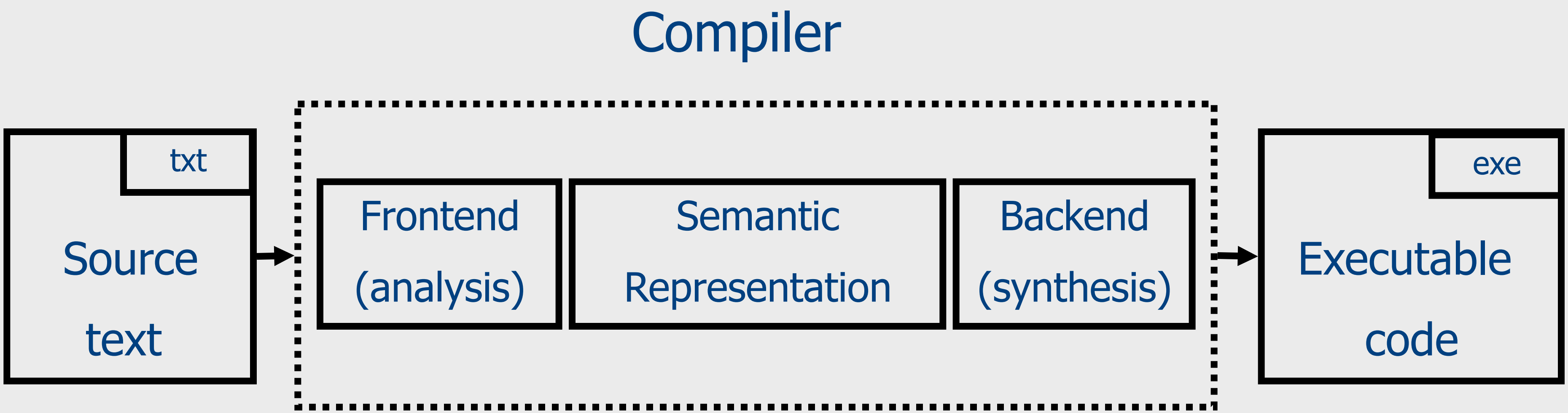
How to write a compiler?



Bootstrapping a compiler



Conceptual structure of a compiler



Interpreter vs. Compiler

- Conceptually simpler
  - “define” the prog. lang.
- Can provide more specific error report
- Easier to port
- Faster response time
- [More secure]

- How do we know the translation is correct?
- Can report errors before input is given
- More efficient code
  - Compilation can be expensive
  - move computations to compile-time
- *compile-time + execution-time* < *interpretation-time* is possible

Interpreters report input-specific definite errors

- Input-program

```
scanf("%d",  &y);
if (y < 0)
     x = 5;
...
If (y <= 0)
     z = x + 1;
```

- Input data
  - y = -1
  - y = 0

Compilers report input-independent possible errors

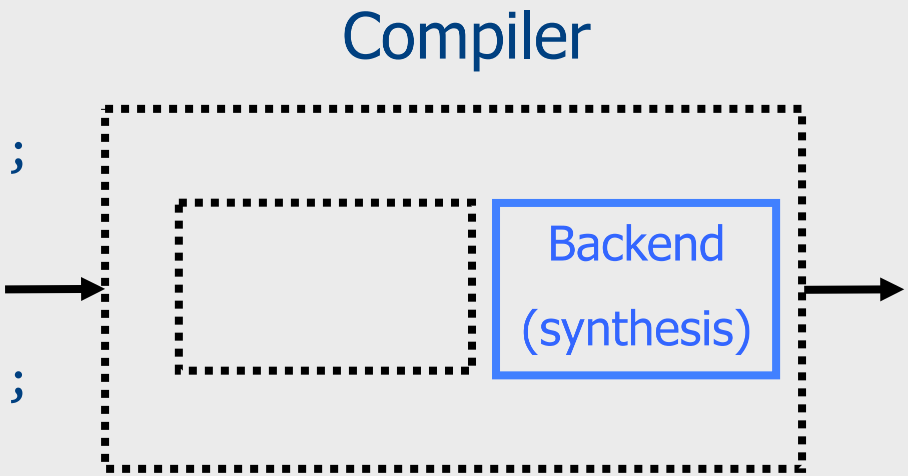
- Input-program

```
scanf(“%d”,  &y);
if (y < 0)
     x = 5;
...
If (y <= 0)
     z = x + 1;
```

- Compiler-Output
  - “line 88: x may be used before set''

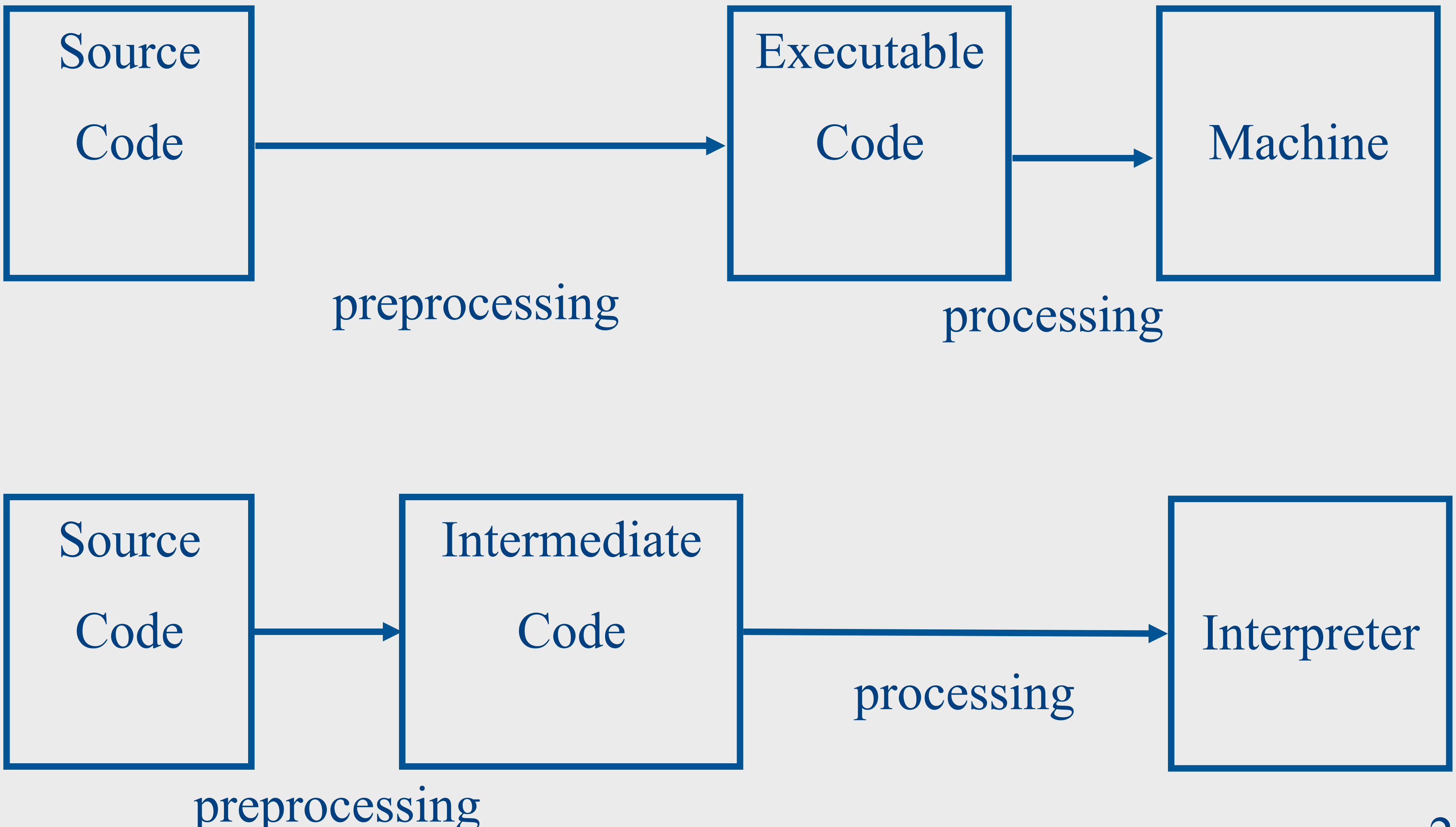
Compiled programs are usually more efficient than

```
scanf("%d",&x);
y = 5 ;
z = 7 ;
x = x + y * z;
printf("%d",x);
```




```
add   %fp,-8, %l1
mov   %l1, %o1
call  scanf
mov   5, %l0
st    %l0,[%fp-12]
mov   7,%l0
st    %l0,[%fp-16]
ld    [%fp-8], %l0
ld    [%fp-8],%l0
add   %l0, 35 ,%l0
st    %l0,[%fp-8]
ld    [%fp-8], %l1
mov   %l1, %o1
call  printf
```

Compiler vs. Interpreter



Lecture Outline

- High level programming languages
- Interpreters vs. Compilers
- Techniques and tools (1.1)
  - why study compilers …
- Handwritten toy compiler & interpreter (1.2)
- Summary

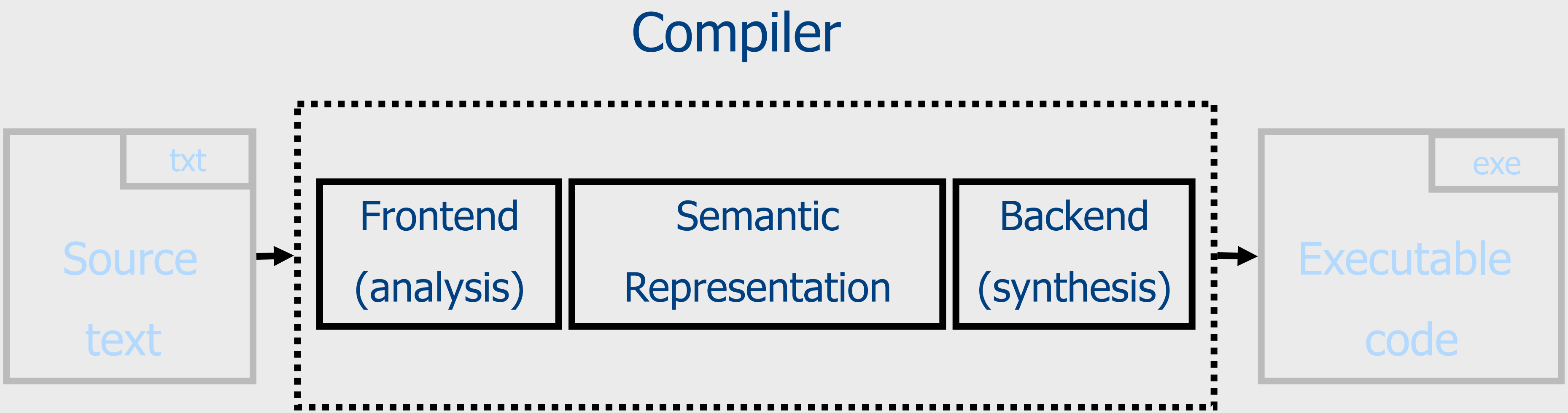
Why Study Compilers?

- Become a compiler writer
  - New programming languages
  - New machines
  - New compilation modes: “just-in-time”
  - New optimization goals (energy)
- Using some of the techniques in other contexts
- Design a very big software program using a reasonable effort

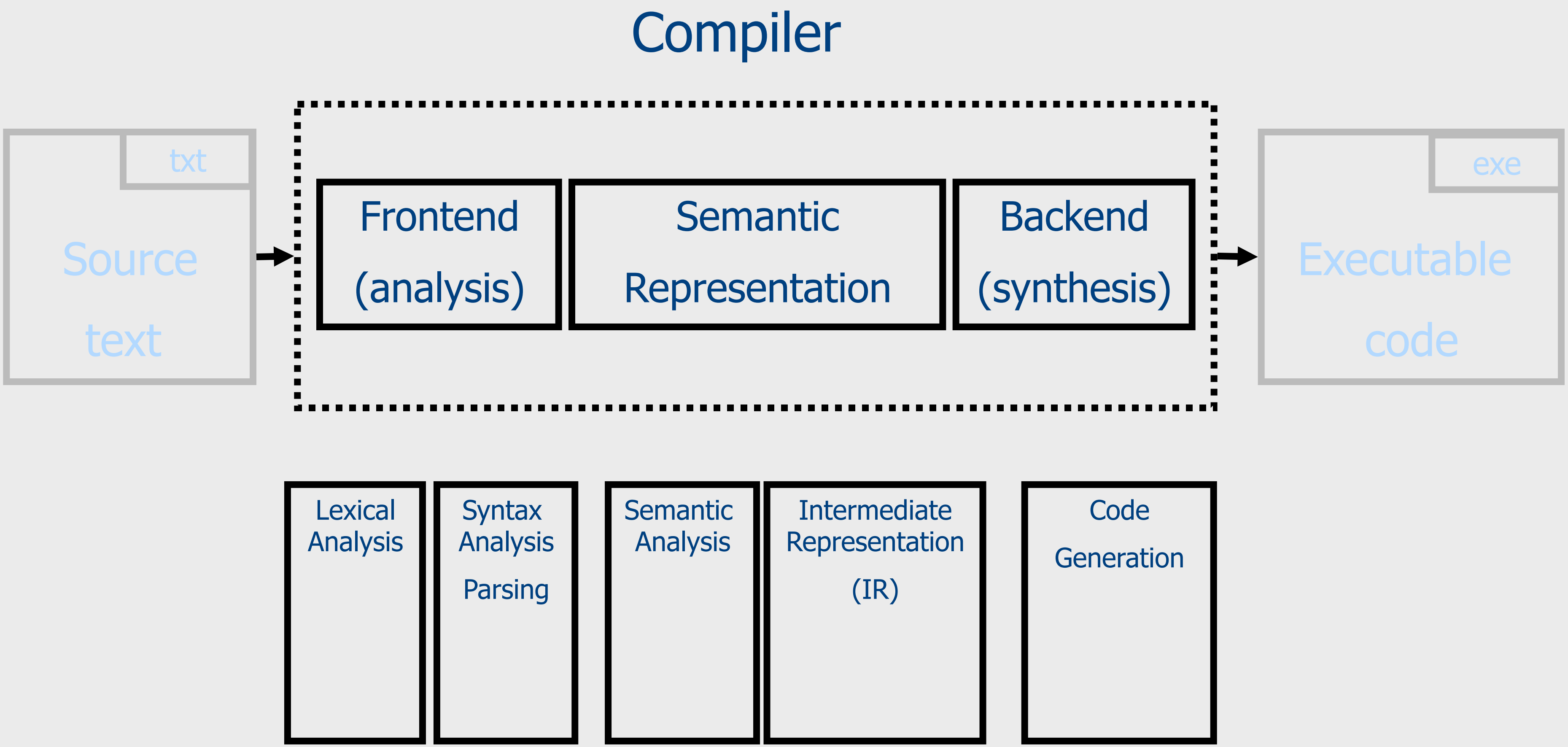
Why Study Compilers?

- Compiler construction is successful
  - Clear problem
  - Proper structure of the solution
  - Judicious use of formalisms
- Wider application
  - Many conversions can be viewed as compilation
- Useful algorithms

Conceptual Structure of a Compiler

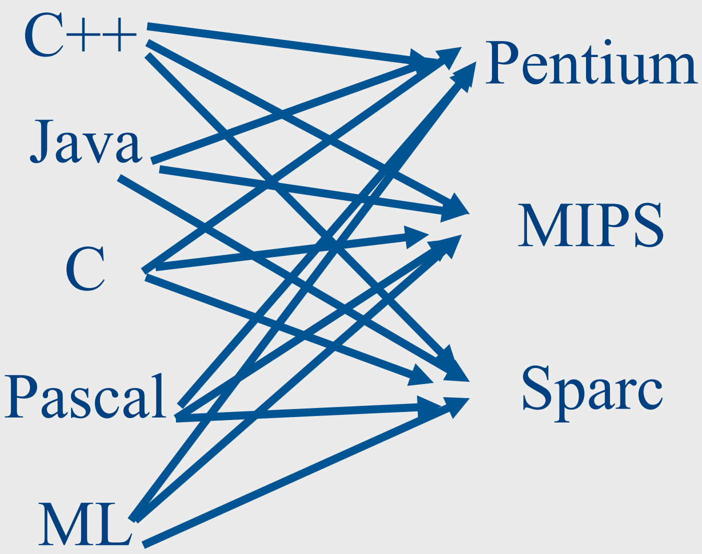


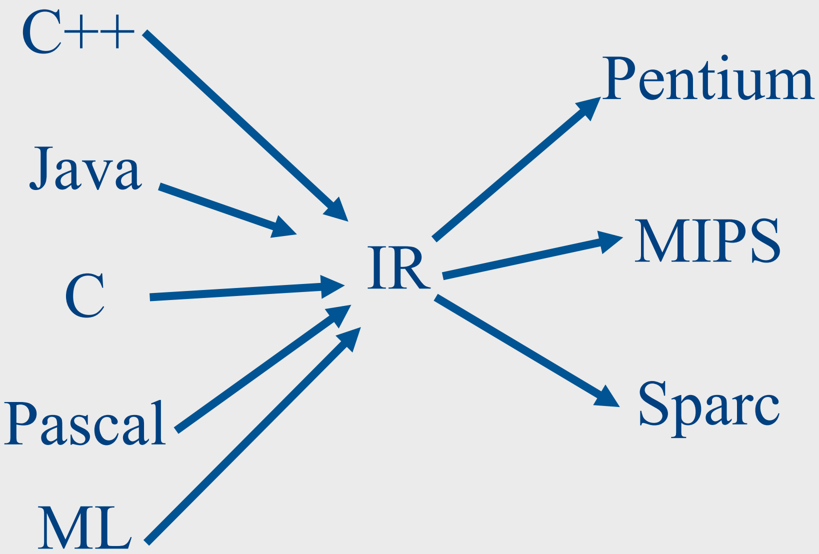
Conceptual Structure of a Compiler



Proper Design

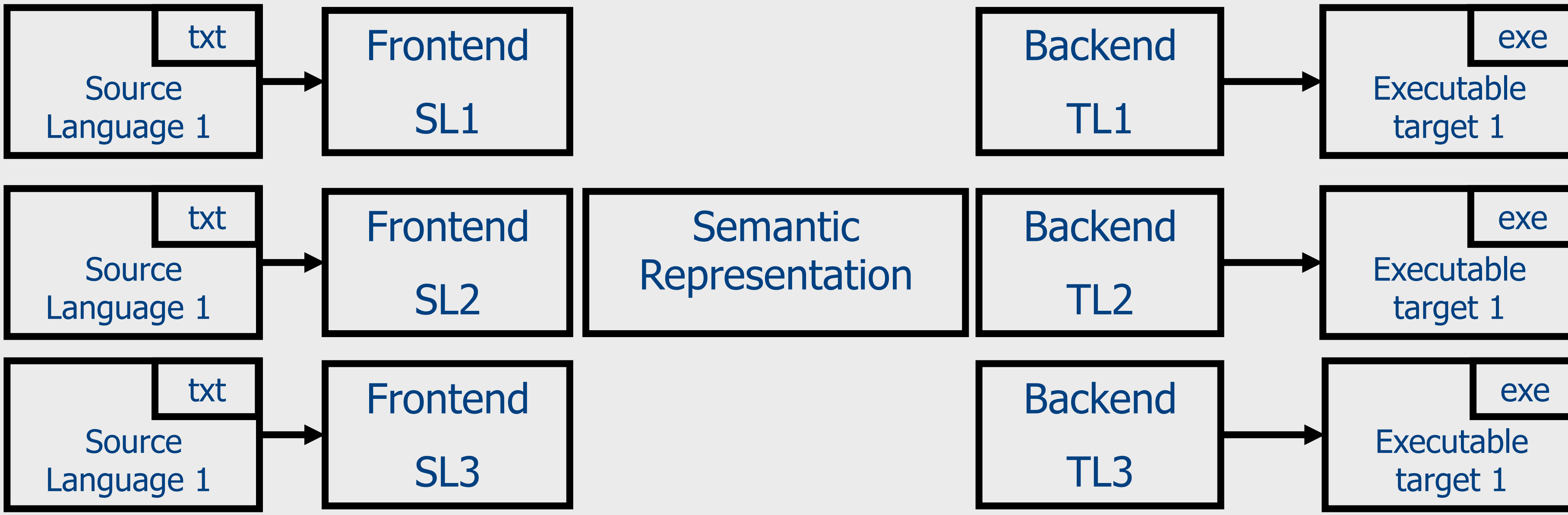
- Simplify the compilation phase
  - Portability of the compiler frontend
  - Reusability of the compiler backend
- Professional compilers are integrated





Modularity

```
SET   R1,2
STORE #0,R1
SHIFT R1,1
STORE #1,R1
ADD   R1,1
STORE #2,R1
```

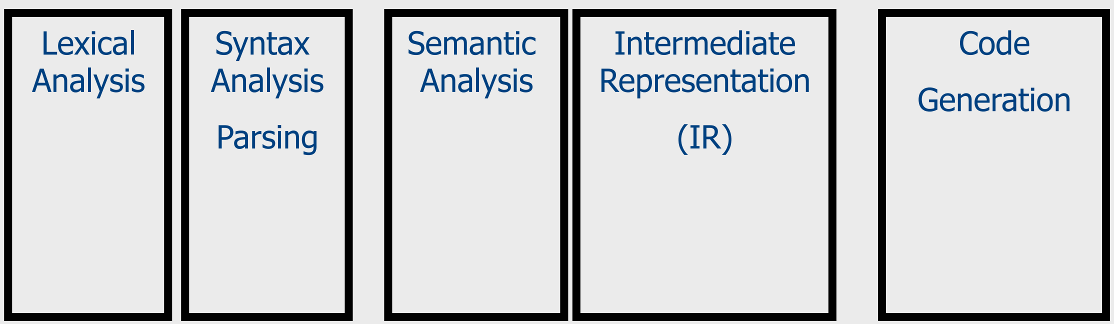



```
int a, b;
a = 2;
b = a*2 + 1;
```

```
MOV R1,2
SAL R1
INC R1
MOV R2,R1
```

Judicious use of formalisms

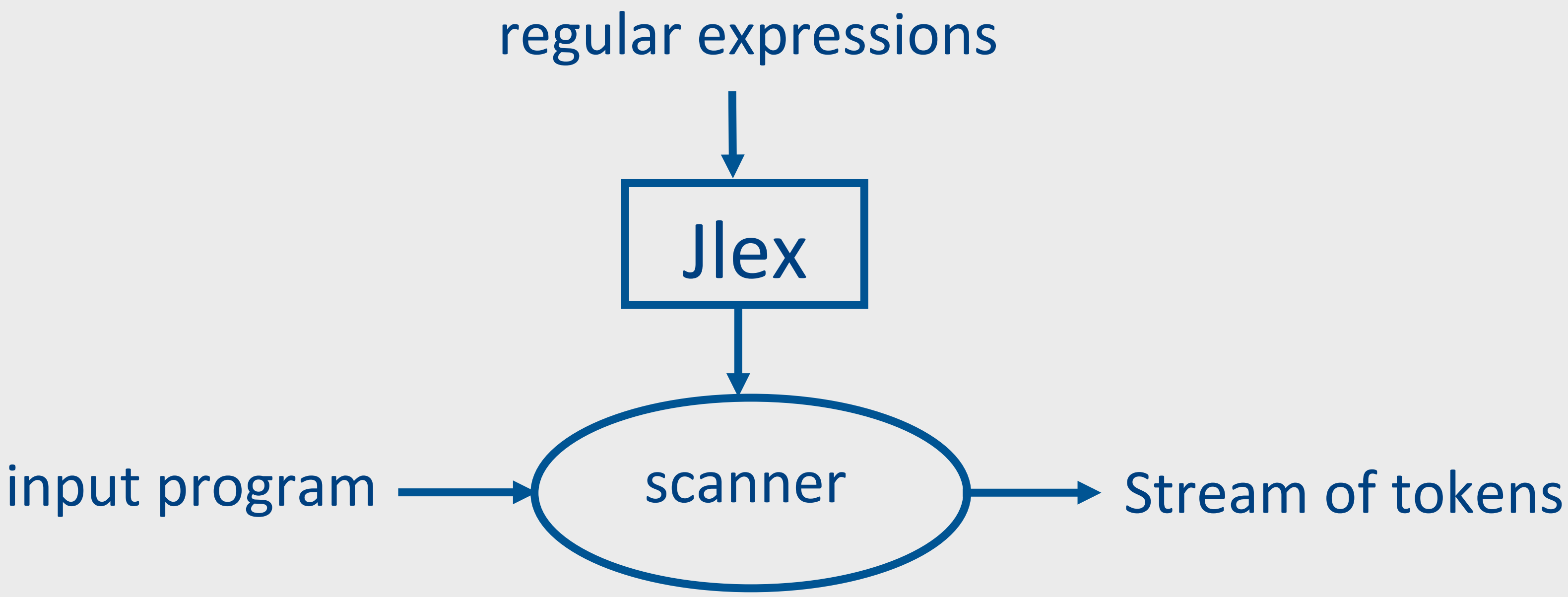
- Regular expressions (lexical analysis)
- Context-free grammars (syntactic analysis)
- Attribute grammars (context analysis)
- Code generator generators (dynamic programming)



- But also some nitty-gritty programming

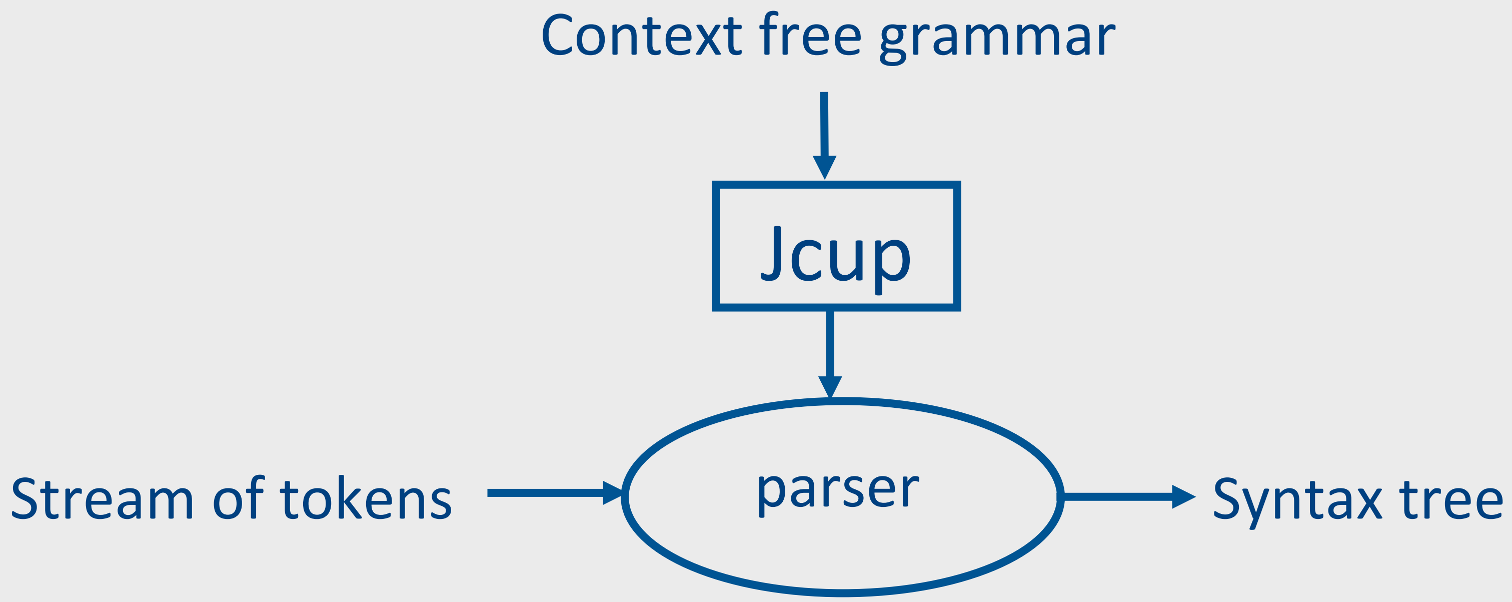
Use of program-generating tools

- Parts of the compiler are automatically generated from specification



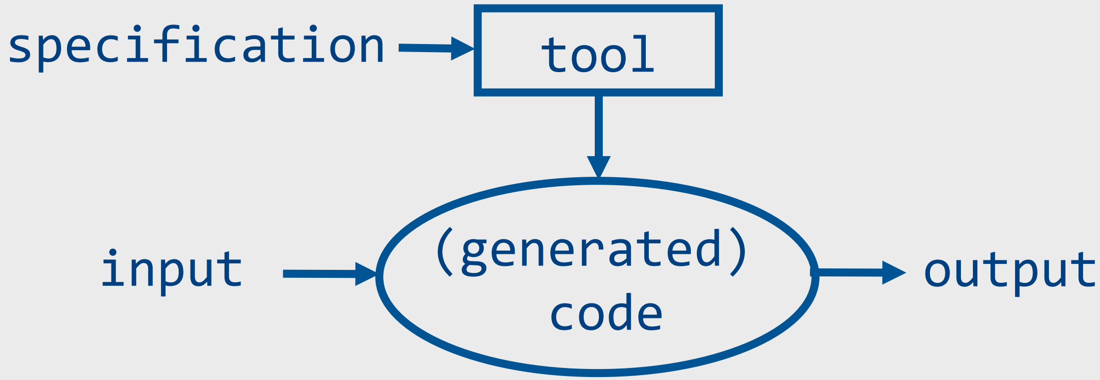
Use of program-generating tools

- Parts of the compiler are automatically generated from specification



Use of program-generating tools

- Simpler compiler construction
  - Less error prone
  - More flexible
- Use of pre-canned tailored code
  - Use of dirty program tricks
- Reuse of specification



Wide applicability

- Structured data can be expressed using context free grammars
  - HTML files
  - Postscript
  - Tex/dvi files
  - …

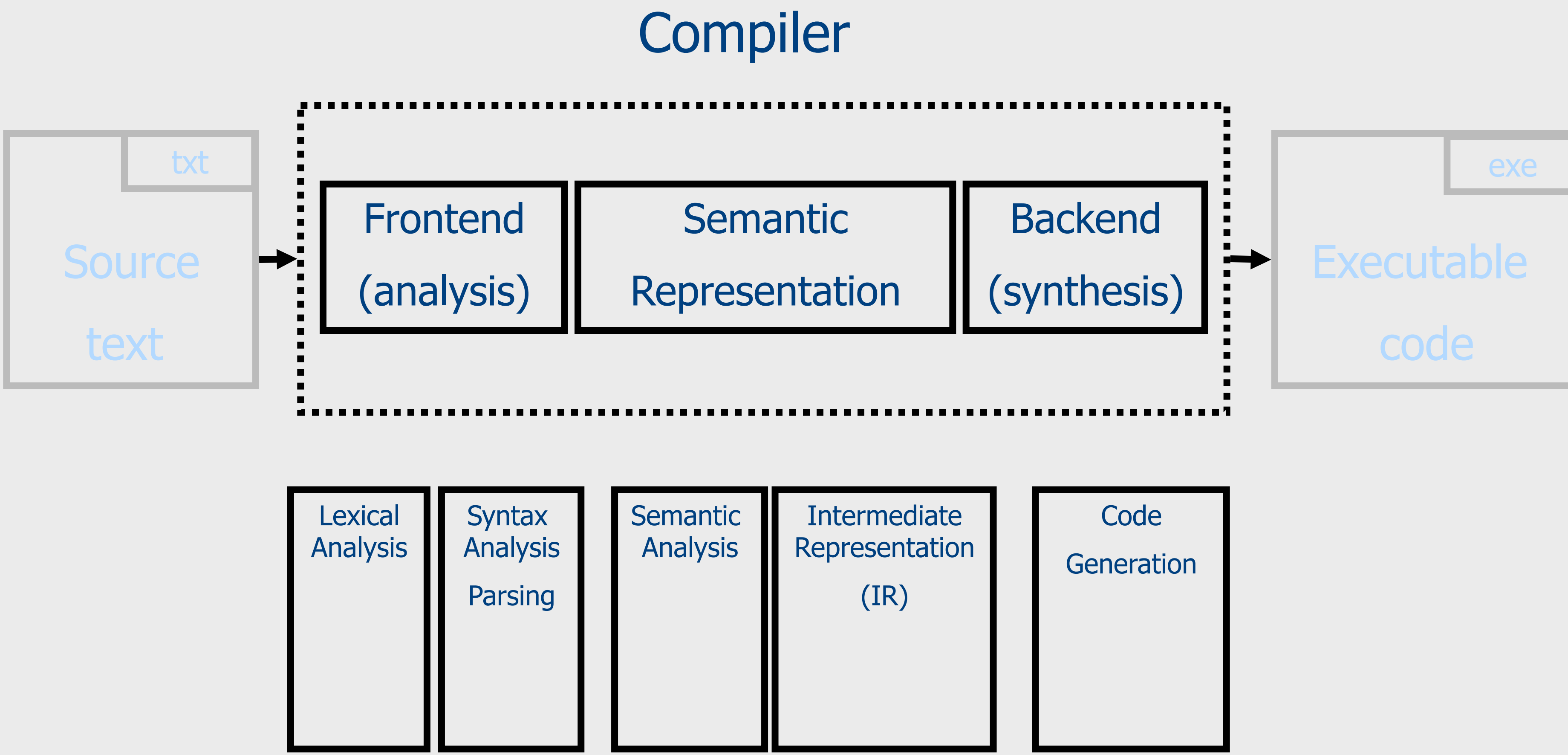
Generally useful algorithms

- Parser generators
- Garbage collection
- Dynamic programming
- Graph coloring

Lecture Outline

- High level programming languages
- Interpreters vs. Compilers
- Techniques and tools (1.1)
  - why study compilers …
- Handwritten toy compiler & interpreter (1.2)
- Summary

Conceptual Structure of a Compiler



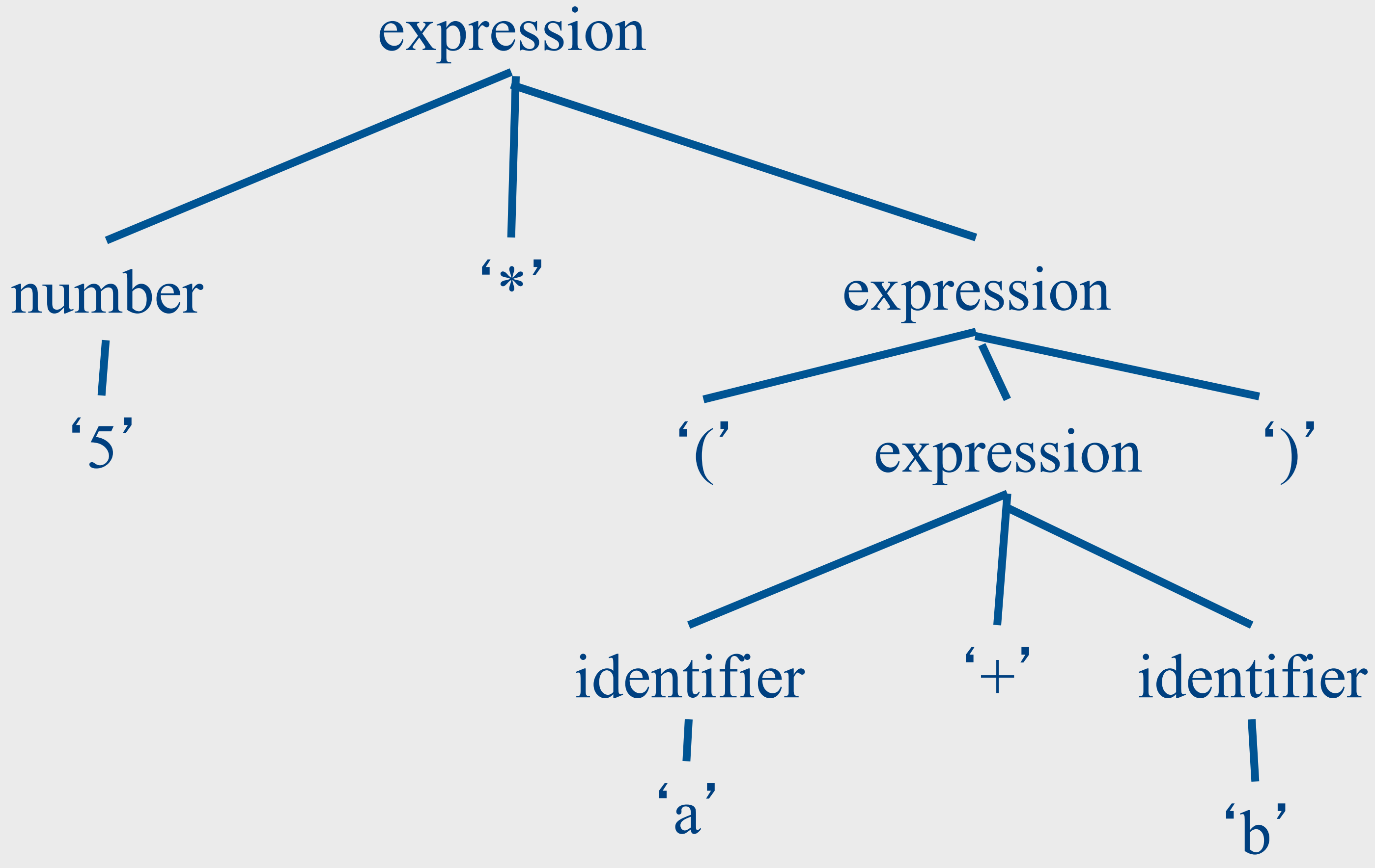
Toy compiler/interpreter (1.2)

- Trivial programming language
- Stack machine
- Compiler/interpreter written in C
- Demonstrate the basic steps

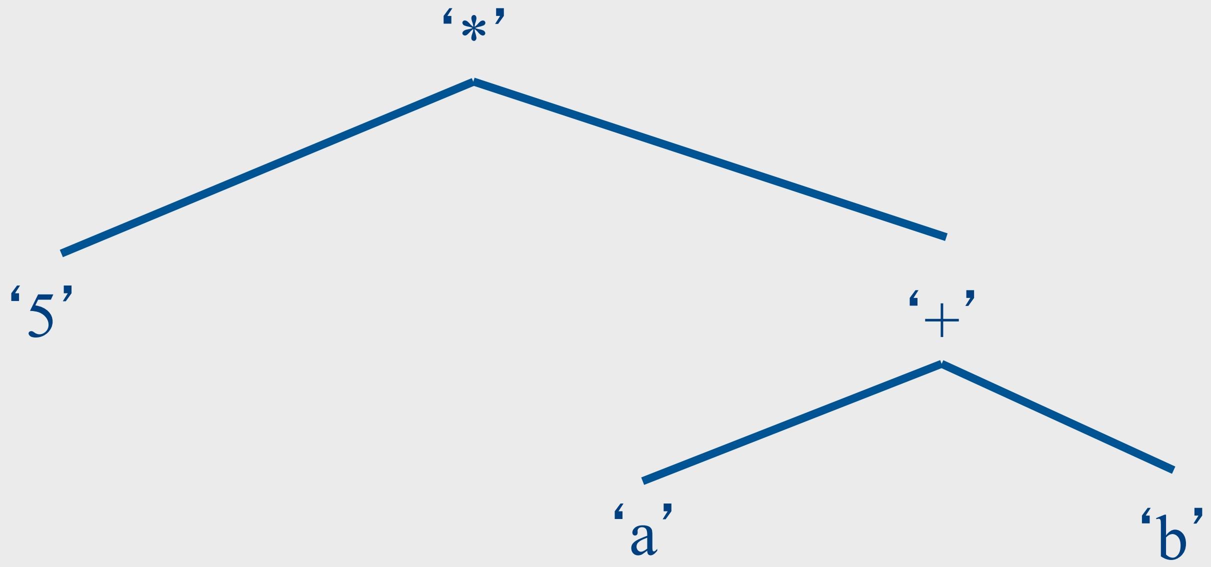
The abstract syntax tree (AST)

- Intermediate program representation
- Defines a tree
  - Preserves program hierarchy
- Generated by the parser
- Keywords and punctuation symbols are not stored
  - Not relevant once the tree exists

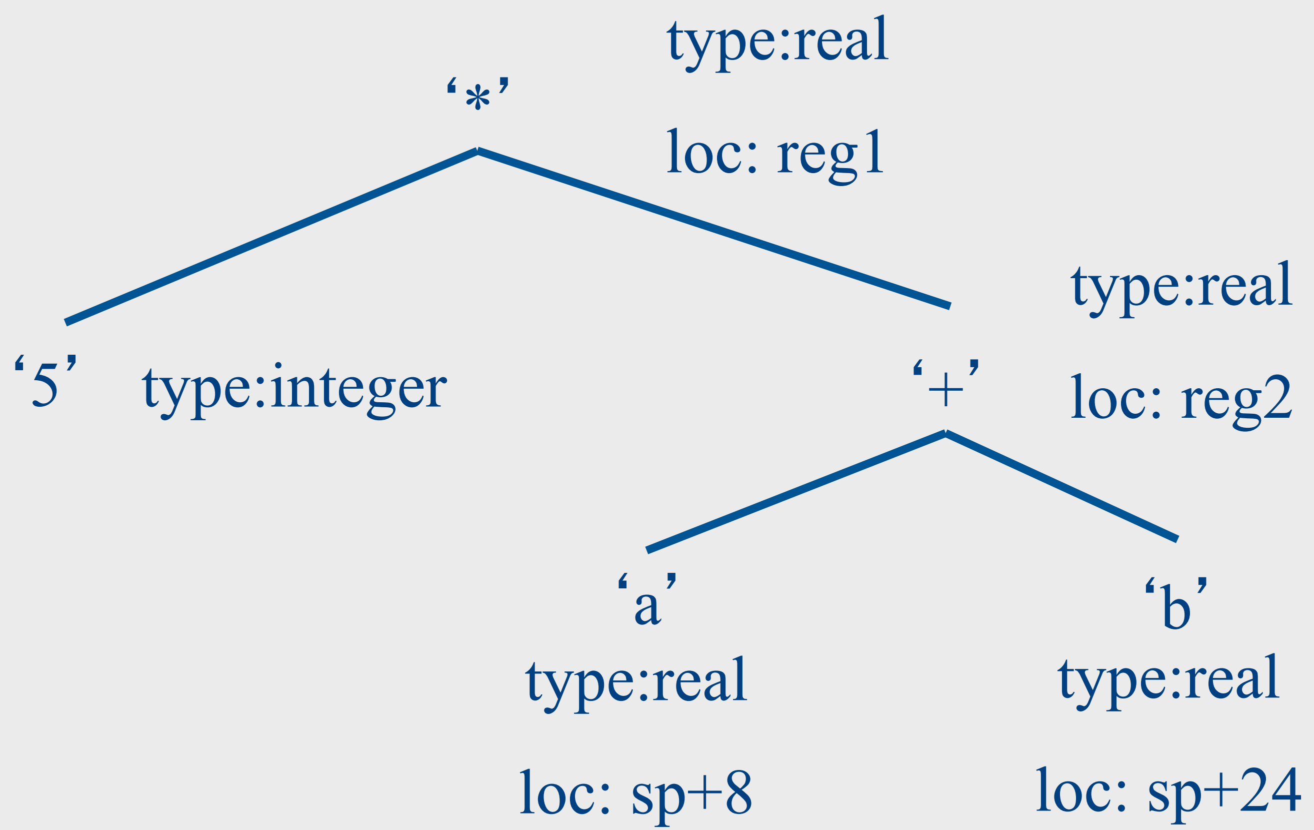
Syntax tree for 5*(a+b)



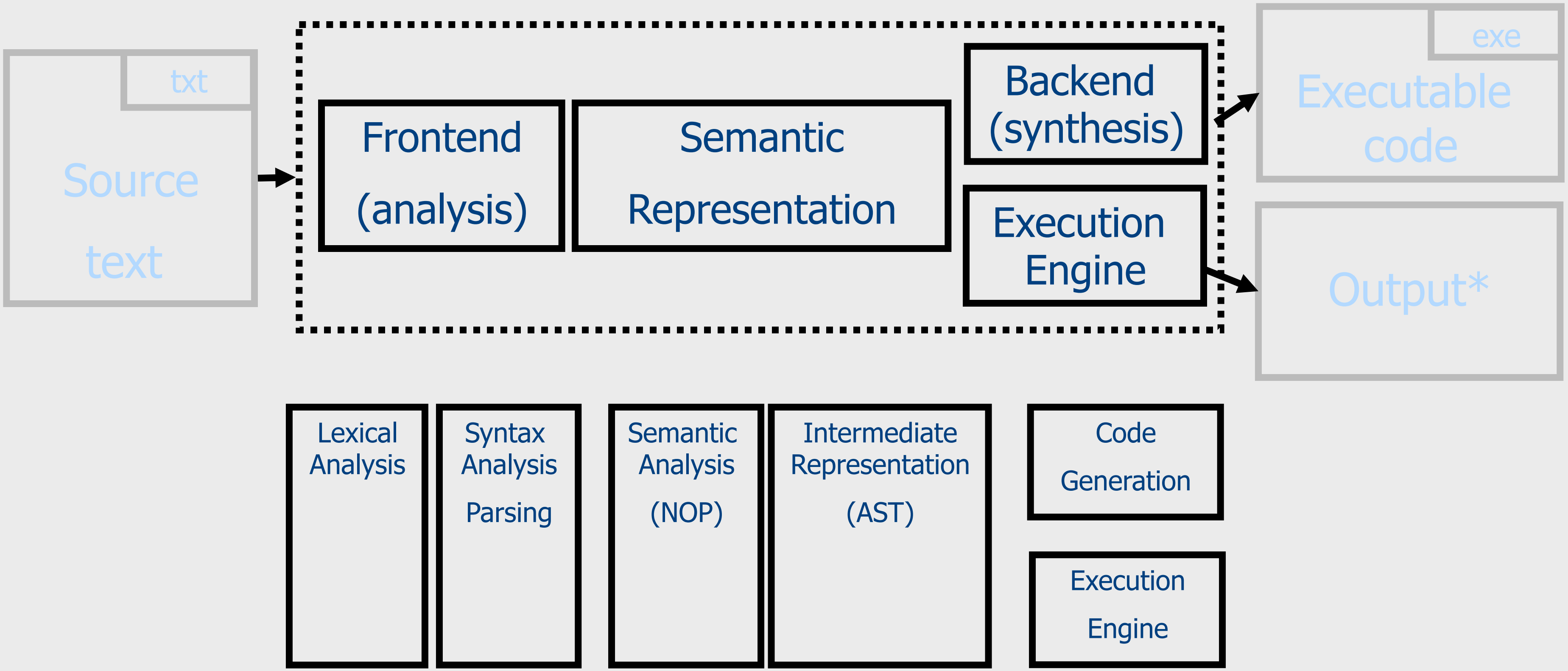
Abstract Syntax tree for 5*(a+b)



Annotated Abstract Syntax tree



Structure of toy Compiler / interpreter



* Programs in our PL do not take input

Source Language

- Fully parameterized expressions
- Arguments can be a single digit
  - ✓ (4 + (3 * 9))
  - ✗ 3 + 4 + 5
  - ✗ (12 + 3)

expression → digit | ‘(‘ expression operator expression ‘)’

operator → ‘+’ | ‘*’

digit → ‘0’ | ‘1’ | ‘2’ | ‘3’ | ‘4’ | ‘5’ | ‘6’ | ‘7’ | ‘8’ | ‘9’

Driver for the Toy Compiler

```
#include    "parser.h"       /* for type AST_node */
#include    "backend.h"      /* for Process() */
#include    "error.h"        /* for Error() */

int main(void) {
    AST_node *icode;

    if (!Parse_program(&icode)) Error("No top-level expression");
    Process(icode);

    return 0;
}
```

Lexical Analysis

- Partitions the inputs into tokens
  - DIGIT
  - EOF
  - ‘*’
  - ‘+’
  - ‘(‘
  - ‘)’
- Each token has its representation
- Ignores whitespaces

lex.h: Header File for Lexical Analysis

```
/* Define class constants */
/* Values 0-255 are reserved for ASCII characters */
#define EoF     256
#define DIGIT   257
typedef struct {
        int class;
        char repr;} Token_type;

extern  Token_type Token;
extern  void get_next_token(void);
```

Lexical Analyzer

```
#include "lex.h"
token_type Token;                // Global variable

void get_next_token(void) {
    int ch;
    do {
        ch = getchar();
        if (ch < 0) {
            Token.class = EoF; Token.repr = '#';
            return;
        }
    } while (Layout_char(ch));
    if ('0' <= ch && ch <= '9') {Token.class = DIGIT;}
    else {Token.class = ch;}
    Token.repr = ch;
}

static int Layout_char(int ch) {
    switch (ch) {
        case ' ': case '\t': case '\n': return 1;
        default:                        return 0;
    }
}
```

Parser

- Invokes lexical analyzer
- Reports syntax errors
- Constructs AST

Driver for the Toy Compiler

```
#include    "parser.h"      /* for type AST_node */
#include    "backend.h"     /* for Process() */
#include    "error.h"       /* for Error() */

int main(void) {
    AST_node *icode;

    if (!Parse_program(&icode)) Error("No top-level expression");
    Process(icode);

    return 0;
}
```

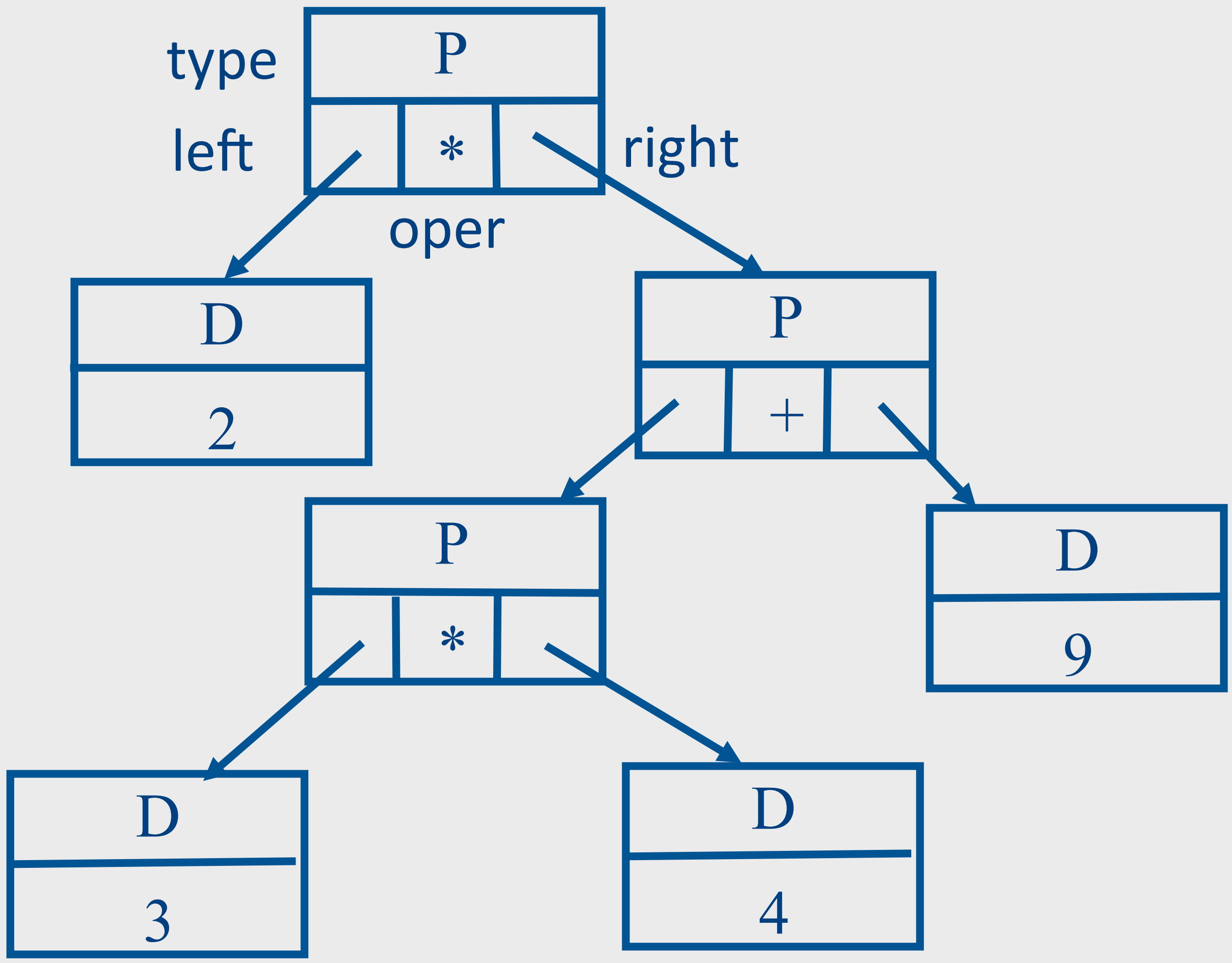
Parser Environment

```
#include "lex.h”, "error.h”, "parser.h"

static Expression *new_expression(void) {
    return (Expression *)malloc(sizeof (Expression));
}
static void free_expression(Expression *expr) {
    free((void *)expr);
}

static int Parse_operator(Operator *oper_p);
static int Parse_expression(Expression **expr_p);
int Parse_program(AST_node **icode_p) {
    Expression *expr;
    get_next_token();           /* start the lexical analyzer */
    if (Parse_expression(&expr)) {
        if (Token.class != EoF) {
            Error("Garbage after end of program");
        }
        *icode_p = expr;
        return 1;
    }
    return 0;
}
```

Parser Header File

```
typedef int Operator;
typedef struct _expression {
    char type;    /* 'D' or 'P' */
    int value;    /* for 'D' type expression */
    struct _expression *left, *right;    /* for 'P' type expression */
    Operator oper;                       /* for 'P' type expression */
} Expression;

typedef Expression AST_node;             /* the top node is an Expression */
extern int Parse_program(AST_node **);
```

AST for (2 * ((3*4)+9))



Top-Down Parsing

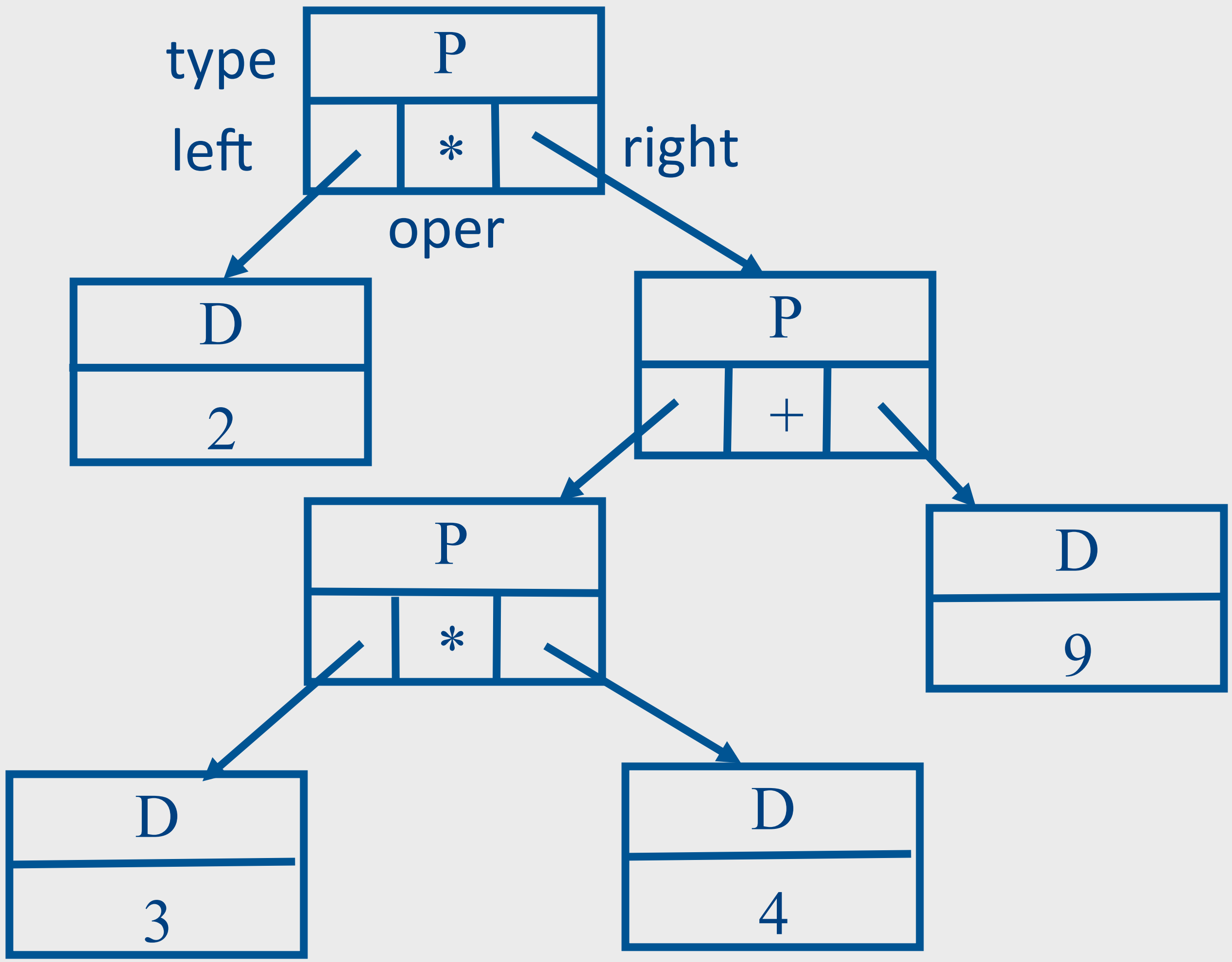
- Optimistically build the tree from the root to leaves
- For every P → A1 A2 … An | B1 B2 … Bm
  - If A1 succeeds
    - If A2 succeeds & A3 succeeds & …
    - Else fail
  - Else if B1 succeeds
    - If B2 succeeds & B3 succeeds & ..
    - Else fail
  - Else fail

- Recursive descent parsing
  - Simplified: no backtracking
- Can be applied for certain grammars

Parser

```
static int Parse_expression(Expression **expr_p) {
    Expression *expr = *expr_p = new_expression();
    if (Token.class == DIGIT) {
        expr->type = 'D'; expr->value = Token.repr - '0';
        get_next_token();    return 1;
    }
    if (Token.class == '(') {
        expr->type = 'P';  get_next_token();
        if (!Parse_expression(&expr->left)) {  Error("Missing expression"); }
        if (!Parse_operator(&expr->oper)) { Error("Missing operator"); }
        if (!Parse_expression(&expr->right)) { Error("Missing expression"); }
        if (Token.class != ')') {  Error("Missing )"); }
        get_next_token();
        return 1;
    }
    /* failed on both attempts */
    free_expression(expr); return 0;
}

static int Parse_operator(Operator *oper) {
    if (Token.class == '+') {
        *oper = '+'; get_next_token(); return 1;
    }
    if (Token.class == '*') {
        *oper = '*'; get_next_token(); return 1;
    }
    return 0;
}
```

AST for (2 * ((3*4)+9))



Semantic Analysis

- Trivial in our case
- No identifiers
- No procedure / functions
- A single type for all expressions

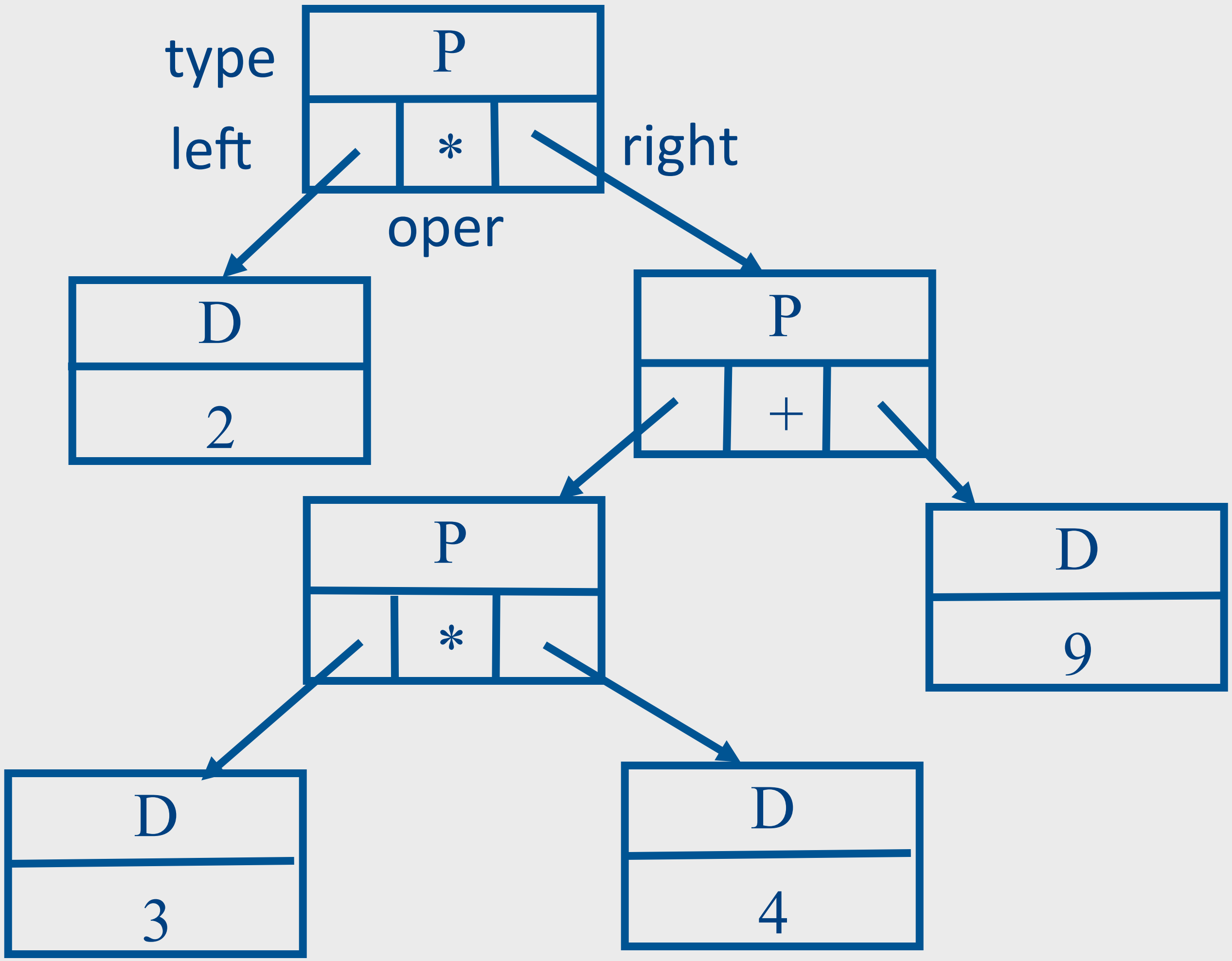
Code generation

- Stack based machine
- Four instructions
  - PUSH n
  - ADD
  - MULT
  - PRINT

Code generation

```
#include    "parser.h"
#include    "backend.h"
static void Code_gen_expression(Expression *expr) {
    switch (expr->type) {
    case 'D':
        printf("PUSH %d\n", expr->value);
        break;
    case 'P':
        Code_gen_expression(expr->left);
        Code_gen_expression(expr->right);
        switch (expr->oper) {
        case '+': printf("ADD\n"); break;
        case '*': printf("MULT\n"); break;
        }
        break;
    }
}
void Process(AST_node *icode) {
    Code_gen_expression(icode); printf("PRINT\n");
}
```

Compiling (2*((3*4)+9))



PUSH 2

PUSH 3

PUSH 4

MULT

PUSH 9

ADD

MULT

PRINT

Generated Code Execution

	Stack	Stack'
→ PUSH 2		
PUSH 3		2
PUSH 4		
MULT		
PUSH 9		
ADD		
MULT		
PRINT		

Generated Code Execution

PUSH 2

PUSH 3

PUSH 4

MULT

PUSH 9

ADD

MULT

PRINT

Stack	Stack'
2	3
	2

Generated Code Execution

PUSH 2

PUSH 3

PUSH 4

MULT

PUSH 9

ADD

MULT

PRINT

Stack	Stack’
3	4
2	3
	2

Generated Code Execution

Code	Stack	Stack'
PUSH 2		
PUSH 3	4	12
PUSH 4	3	2
→ MULT	2	
PUSH 9		
ADD		
MULT		
PRINT		

Generated Code Execution

	Stack	Stack'
PUSH 2		
PUSH 3	12	9
PUSH 4	2	12
MULT		2
→ PUSH 9		
ADD		
MULT		
PRINT		

Generated Code Execution

PUSH 2
PUSH 3
PUSH 4
MULT
PUSH 9
→ ADD
MULT
PRINT

Stack	Stack'
9	21
12	2
2	

Generated Code Execution

	Stack	Stack'
PUSH 2		
PUSH 3	21	42
PUSH 4	2	
MULT		
PUSH 9		
ADD		
→ MULT		
PRINT		

Generated Code Execution

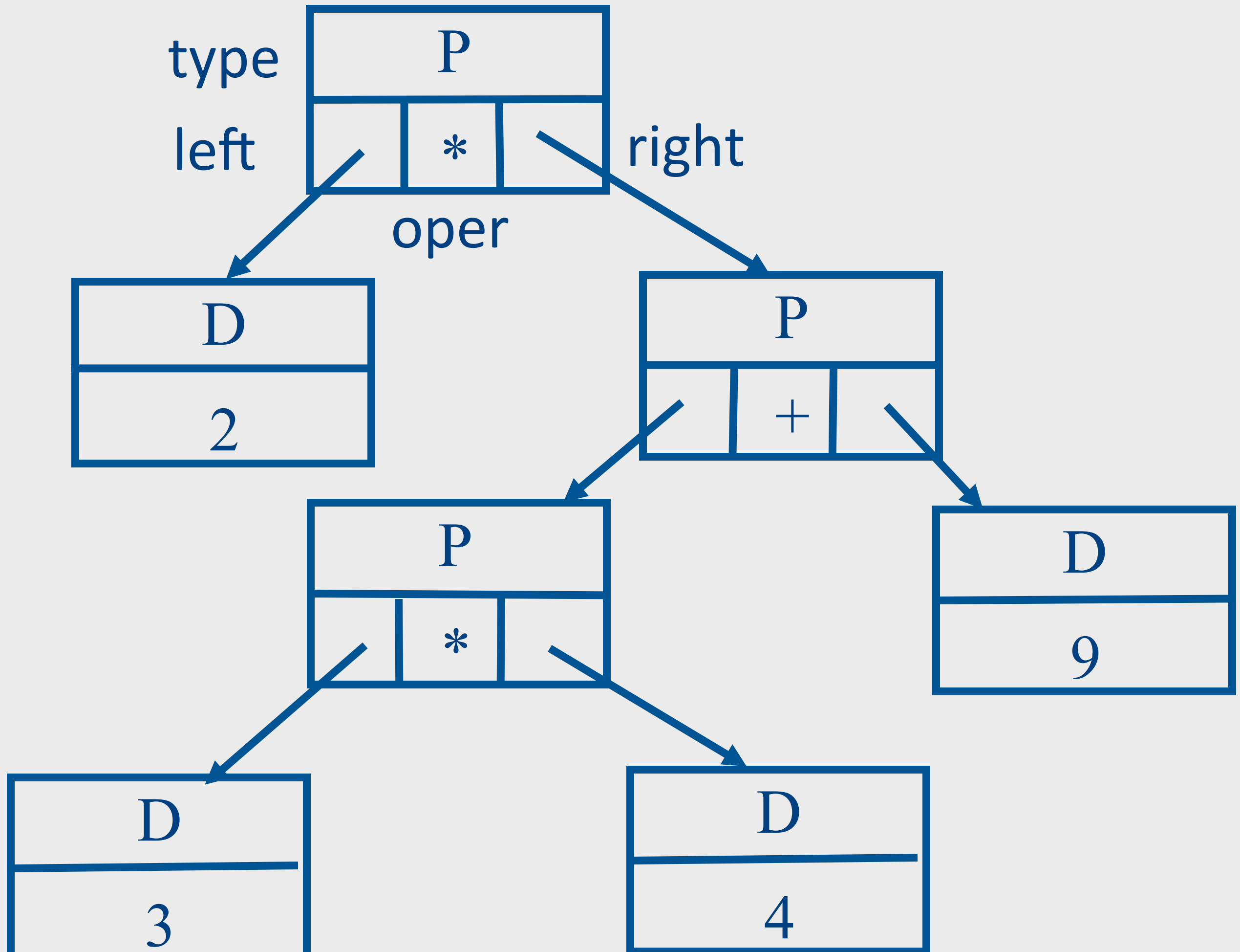
	Stack	Stack'
PUSH 2		
PUSH 3	42	
PUSH 4		
MULT		
PUSH 9		
ADD		
MULT		
→ PRINT		

Interpretation

- Bottom-up evaluation of expressions
- The same interface of the compiler

```
#include "parser.h"
#include "backend.h”

static int Interpret_expression(Expression *expr) {
    switch (expr->type) {
    case 'D':
        return expr->value;
        break;
    case 'P':
        int e_left = Interpret_expression(expr->left);
        int e_right = Interpret_expression(expr->right);
        switch (expr->oper) {
        case '+': return e_left + e_right;
        case '*': return e_left * e_right;
        break;
    }
}

void Process(AST_node *icode) {
    printf("%d\n", Interpret_expression(icode));
}
```

Interpreting (2*((3*4)+9))



Lecture Outline

- High level programming languages
- Interpreters vs. Compilers
- Techniques and tools (1.1)
  - why study compilers …
- Handwritten toy compiler & interpreter (1.2)
- Summary

Summary: Journey inside a compiler

txt

x = b*b – 4*a*c

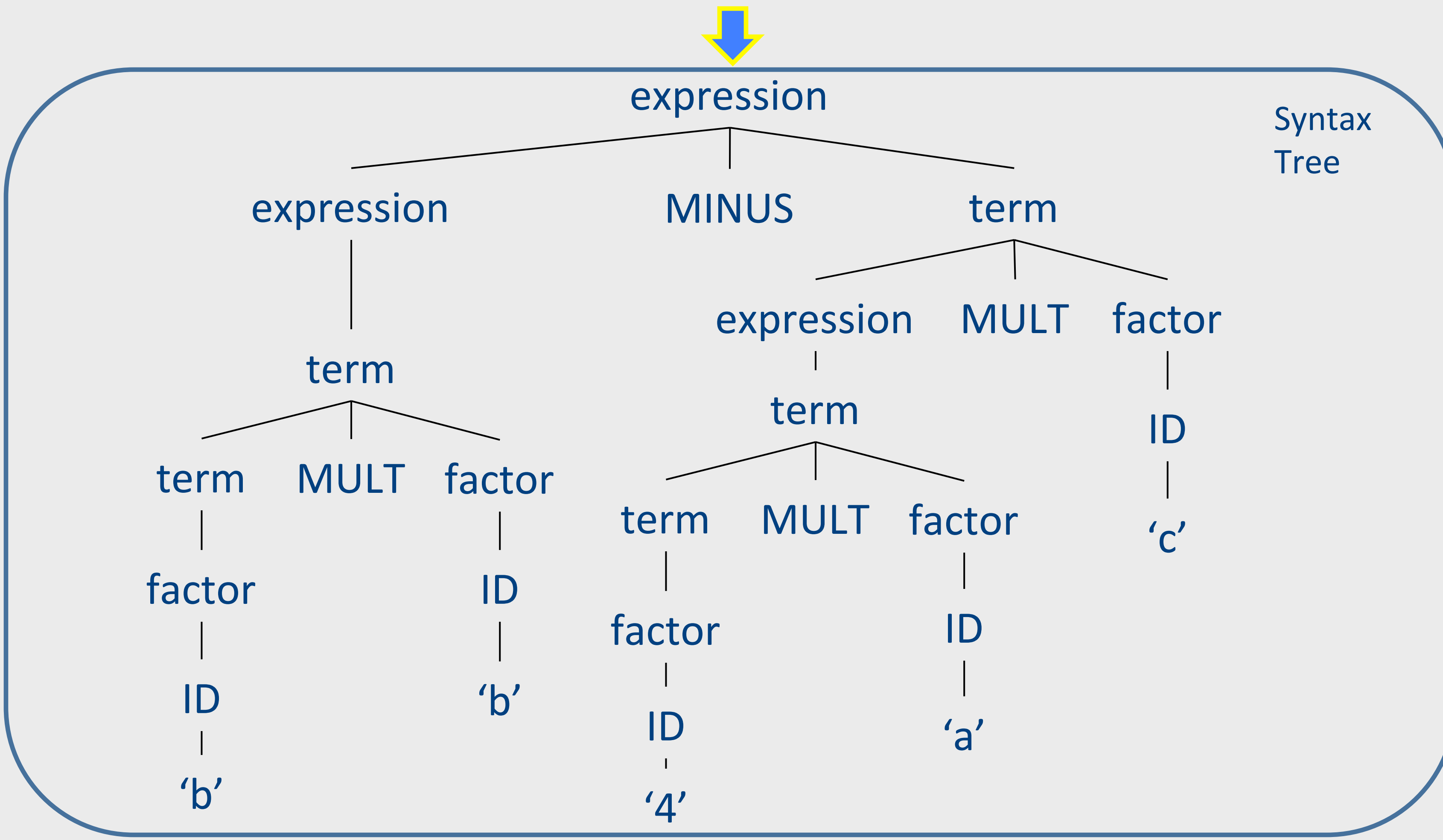
Token Stream

<ID,"x"> <EQ> <ID,"b"> <MULT> <ID,"b"> <MINUS> <INT,4> <MULT> <ID,"a"> <MULT> <ID,"c">

Lexical Analysis | Syntax Analysis | Sem. Analysis | Inter. Rep. | Code Gen.

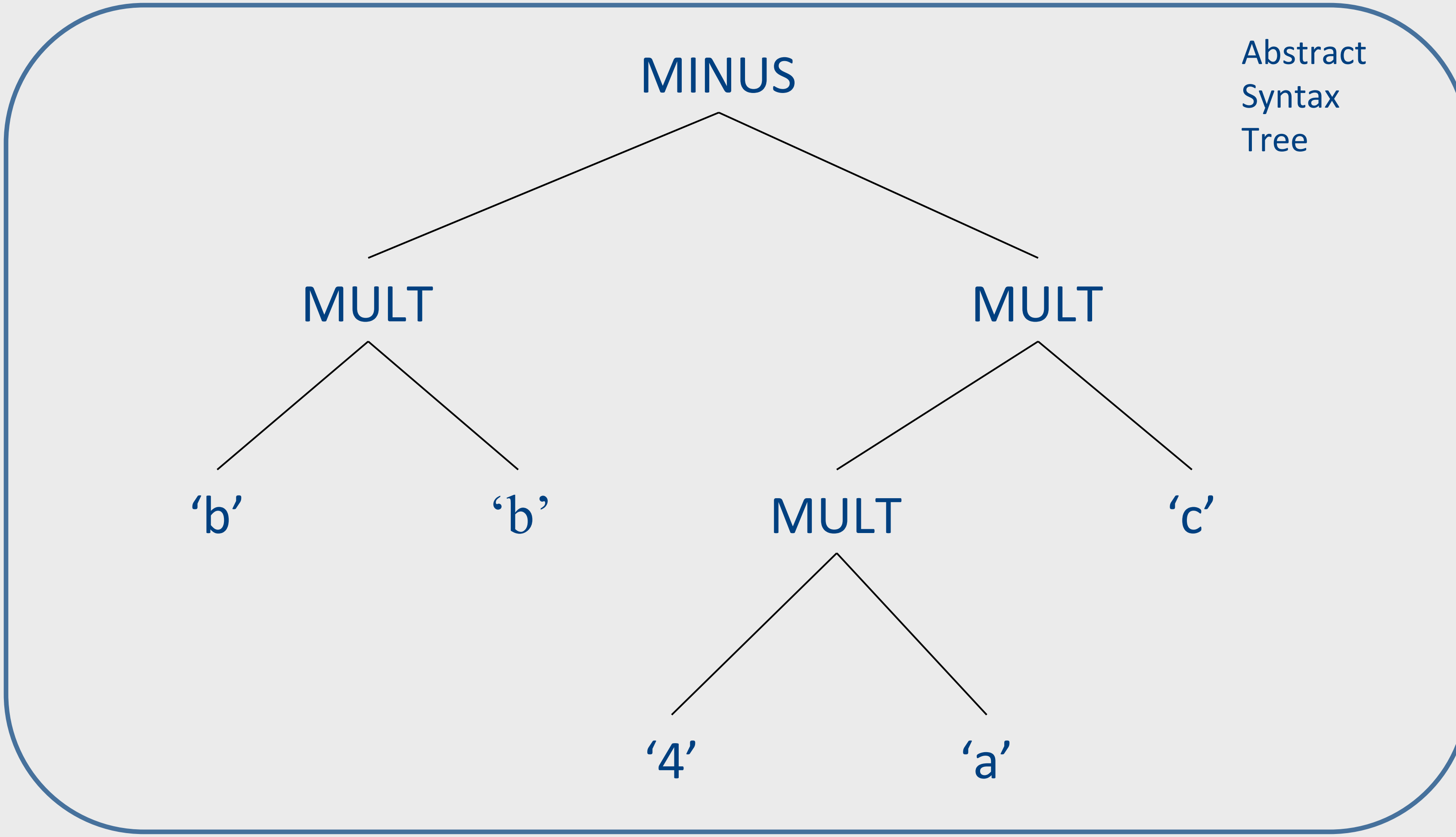
Summary: Journey inside a compiler

<ID,”x”> <EQ> <ID,”b”> <MULT> <ID,”b”> <MINUS> <INT,4> <MULT> <ID,”a”> <MULT> <ID,”c”>

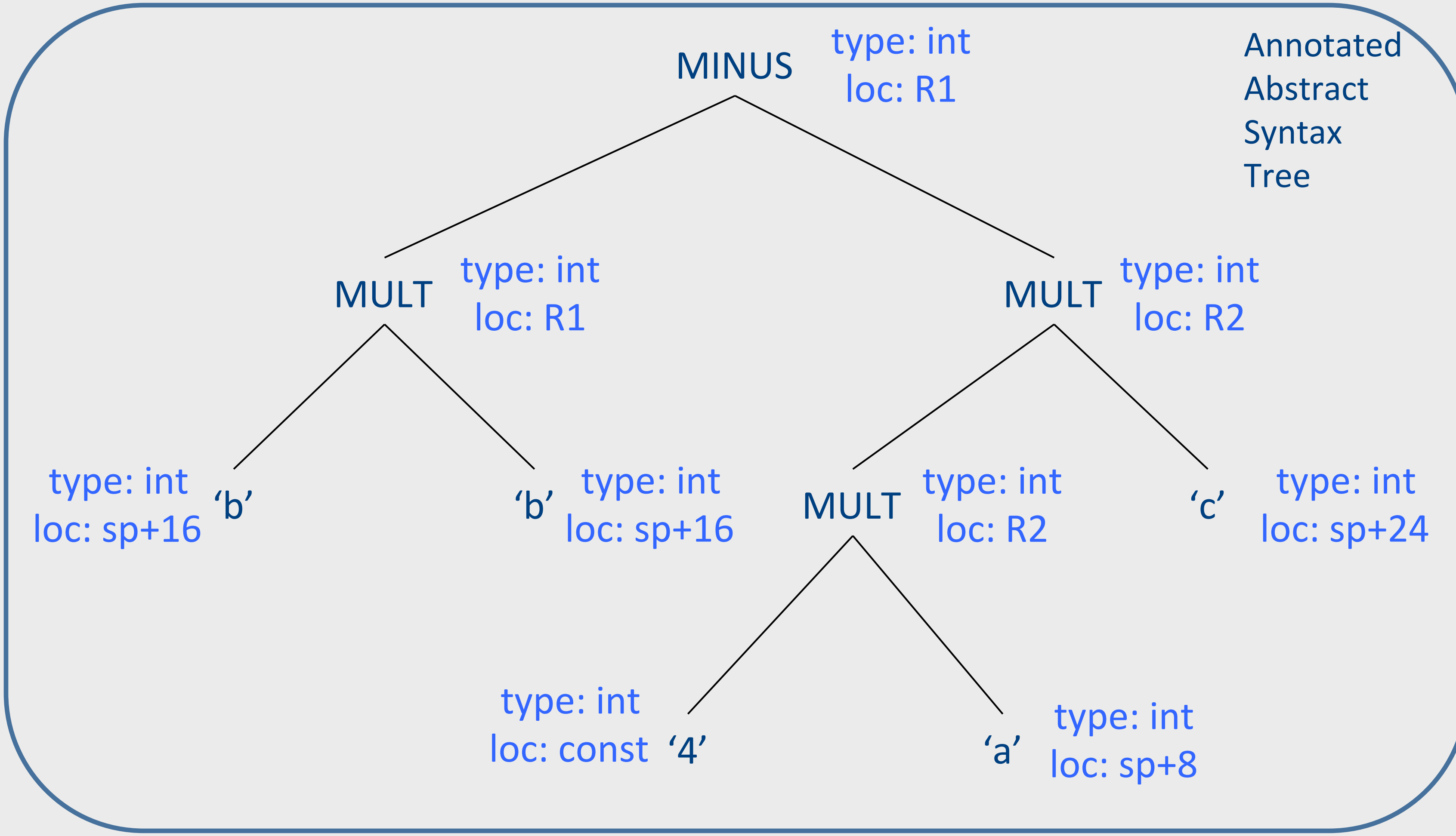


Lexical Analysis | Syntax Analysis | Sem. Analysis | Inter. Rep. | Code Gen.

Summary: Journey inside a compiler

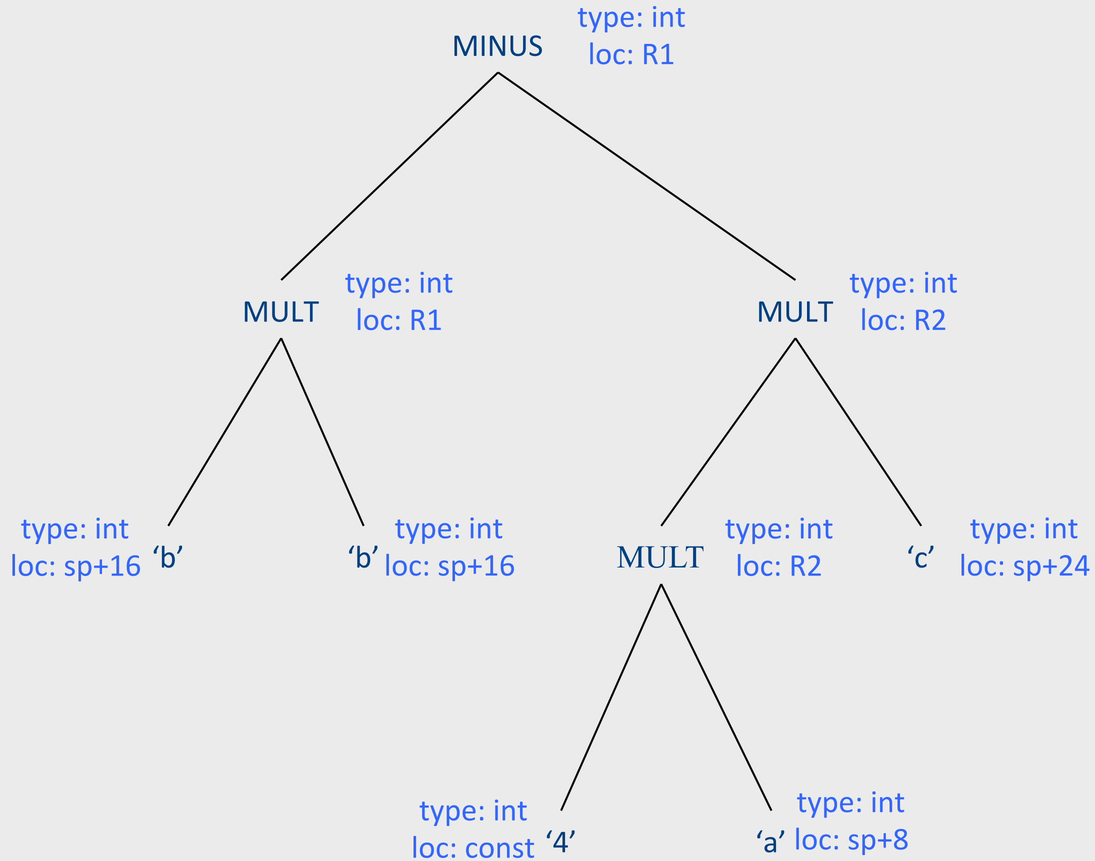


Summary: Journey inside a compiler



Lexical Analysis	Syntax Analysis	Sem. Analysis	Inter. Rep.	Code Gen.

Journey inside a compiler

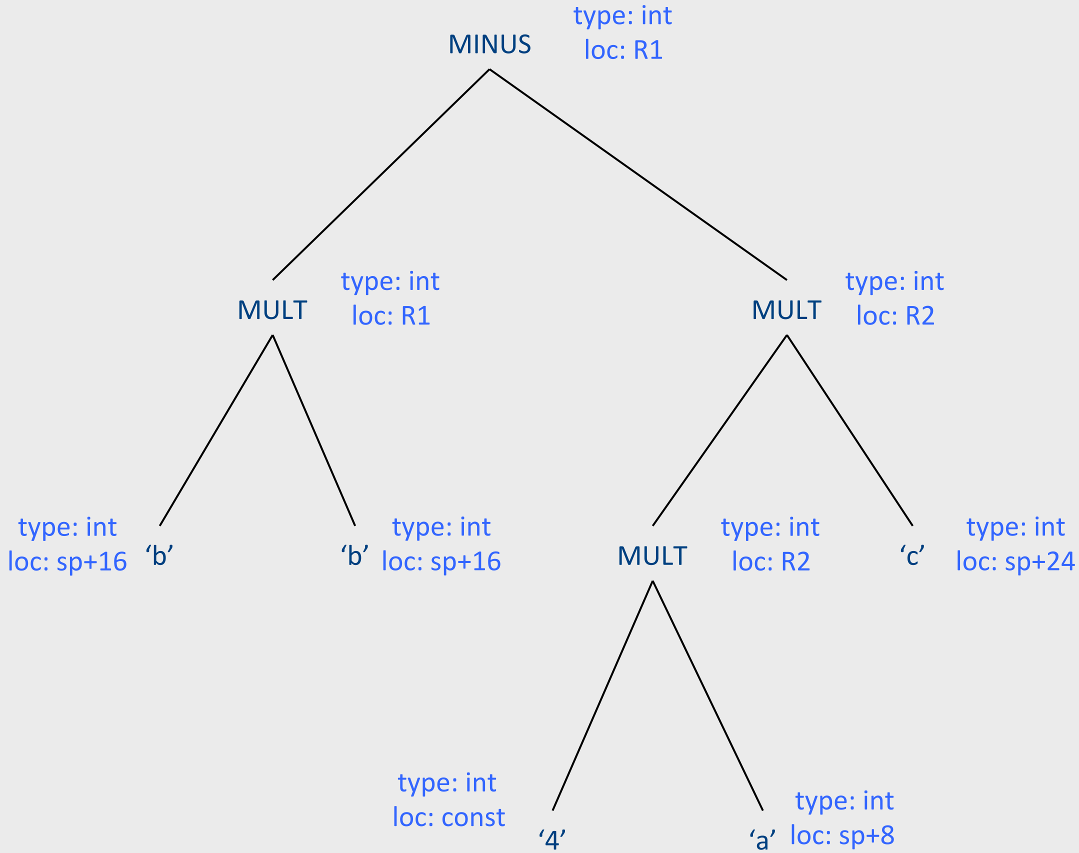


Intermediate Representation

R2 = 4*a
R1=b*b
R2= R2*c
R1=R1-R2

Lexical Analysis | Syntax Analysis | Sem. Analysis | Inter. Rep. | Code Gen.

Journey inside a compiler



Intermediate Representation

R2 = 4*a
R1=b*b
R2= R2*c
R1=R1-R2

Assembly Code

```
MOV R2,(sp+8)
SAL R2,2
MOV R1,(sp+16)
MUL R1,(sp+16)
MUL R2,(sp+24)
SUB R1,R2
```

Lexical Analysis | Syntax Analysis | Sem. Analysis | Inter. Rep. | Code Gen.

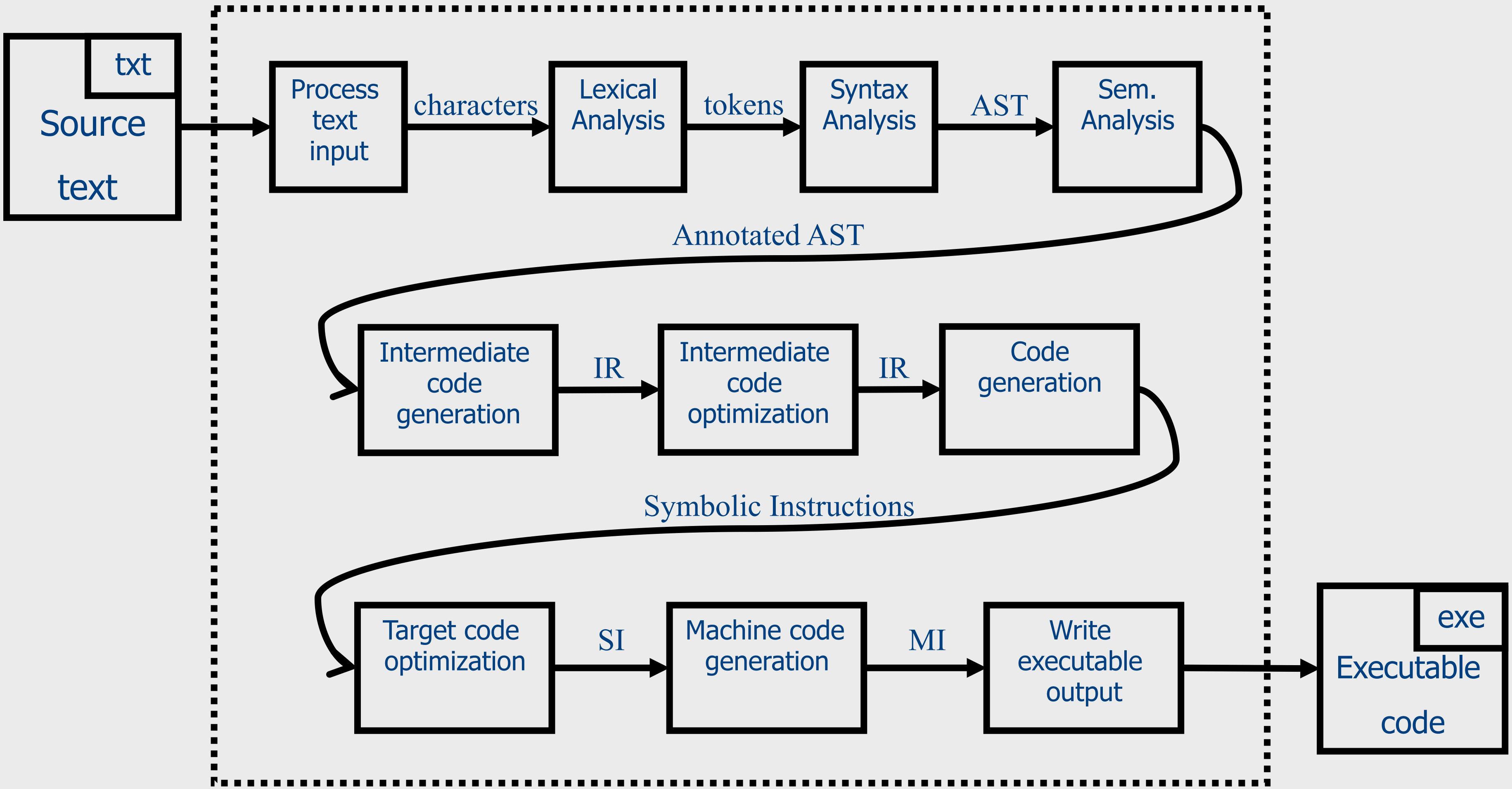
Error Checking

- In every stage…

- Lexical analysis: illegal tokens
- Syntax analysis: illegal syntax
- Semantic analysis: incompatible types, undefined variables, …

- Every phase tries to recover and proceed with compilation (why?)
  - Divergence is a challenge

The Real Anatomy of a Compiler



Optimizations

- "Optimal code" is out of reach
  - many problems are undecidable or too expensive (NP-complete)
  - Use approximation and/or heuristics

- Loop optimizations: hoisting, unrolling, …
- Peephole optimizations
- Constant propagation
  - Leverage compile-time information to save work at runtime (pre-computation)
- Dead code elimination
  - space
- …

Machine code generation

- Register allocation
  - Optimal register assignment is NP-Complete
  - In practice, known heuristics perform well
- assign variables to memory locations
- Instruction selection
  - Convert IR to actual machine instructions

- Modern architectures
  - Multicores
  - Challenging memory hierarchies

Compiler Construction Toolset

- Lexical analysis generators
  - Lex, JLex
- Parser generators
  - Yacc, Jcup
- Syntax-directed translators
- Dataflow analysis engines

Shortcuts

- Avoid generating machine code
- Use local assembler
- Generate C code

One More Thing: Runtime systems

- Responsible for language dependent dynamic resource allocation
- Memory allocation
  - Stack frames
  - Heap
- Garbage collection
- I/O
- Interacts with operating system/architecture
- Important part of the compiler

Summary (for Real)

- Compiler is a program that translates code from source language to target language
- Compilers play a critical role
  - Bridge from programming languages to the machine
  - Many useful techniques and algorithms
  - Many useful tools (e.g., lexer/parser generators)
- Compiler constructed from modular phases
  - Reusable
  - Different front/back ends