Course Overview

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http://www.cs.tau.ac.il/~msagiv/courses/wcc20.html

Course Goals

- Understand basic compilation techniques and tools
- Moderate programming project with well defined interfaces
- Become a better programmer
  - Critical thinking of performance, software productivity, software security

Outline

- Course Requirements
- High Level Programming Languages
- Interpreters vs. Compilers
- Why study compilers (1.1)
- A simple traditional modern compiler/interpreter (1.2)
- Subjects Covered
- Summary

Course Requirements

- Compiler Project 50%
  - Translate Java Subset into LLVM
  - A lot of work
- Final exam 50% (must pass)

Lecture Goals

- Understand the basic structure of a compiler
- Compiler vs. Interpreter
- Techniques used in compilers

High Level Programming Languages

- Imperative
  - Algol, PL1, Fortran, Pascal, Ada, Modula, and 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
    - Fields Data (structure fields)
    - Methods Code (procedures/functions with overloading)
    - Inheritance Refining the functionality of a class with different fields and methods
- Functional
  - Lisp, Scheme, ML, Miranda, Hope, Haskel, OCaml, F#
- Functional/Imperative
  - Rubby
- Logic Programming
  - Prolog

New PL in Industry

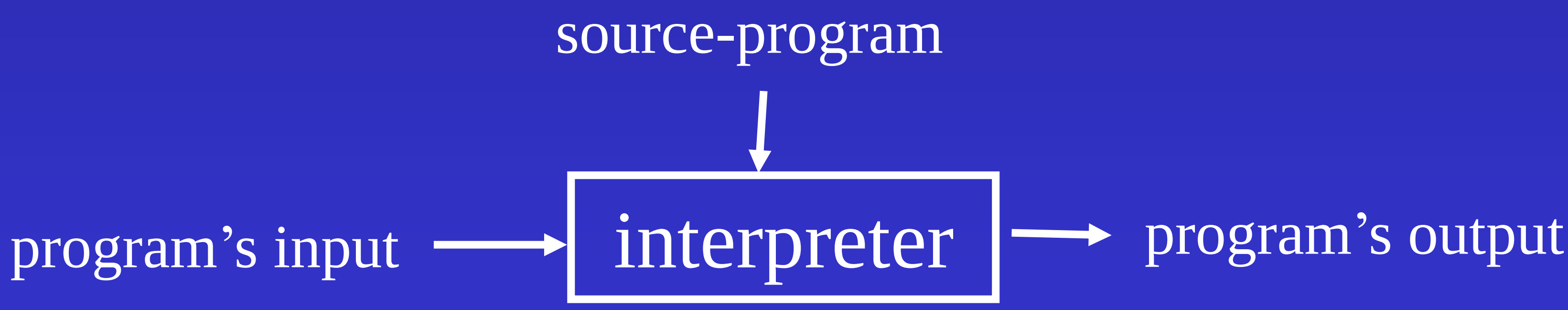
PL	**Company**	**Predecessor**	**Domain**	**Concepts**
Go	Google	C	Systems	Channels Type Inference ML modules GC
Dart	Google	Javascript	Web	Types
Rust		C++	System Browser	Type Inference Ownership Linear Types
Hack	facebook	PHP	Social Network	Gradual Types

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, CLR

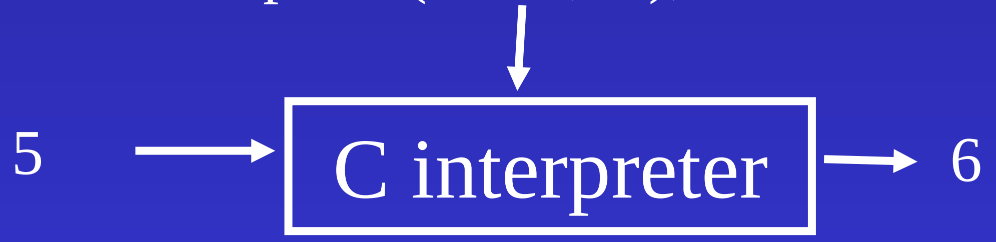
Interpreter

- A program which interprets instructions
- Input
  - A program
  - An input for the program
- Output
  - The required output



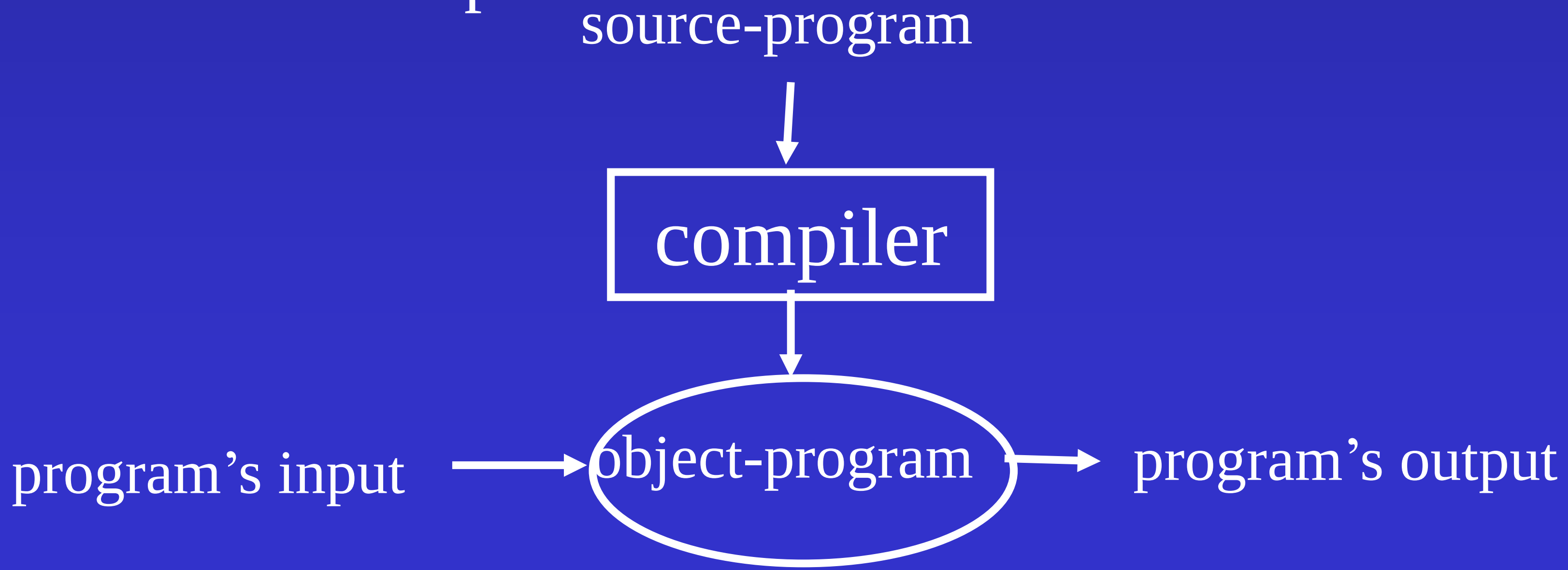
Example

```
int x;
scanf("%d",  &x);
x = x + 1 ;
printf("%d",  x);
```



Compiler

- A program which compiles instructions
- Input
  - A program
- Output
  - An object program that reads the input and writes the output



Example

```
int x;
scanf("%d",  &x);
x = x + 1 ;
printf("%d",  x);
```

↓

Sparc-cc-compiler

↓

```
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
```

↓

assembler/linker

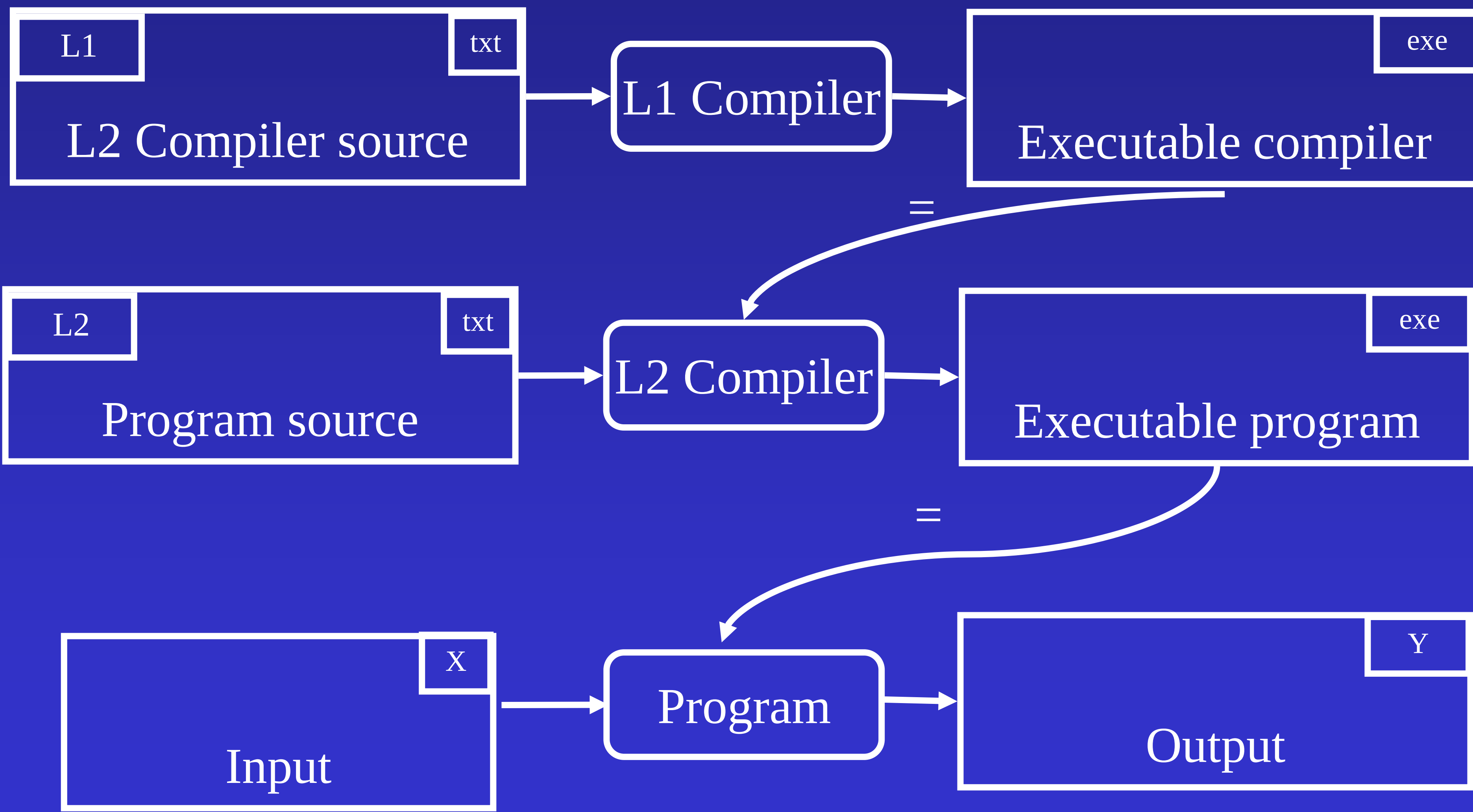
↓

object-program

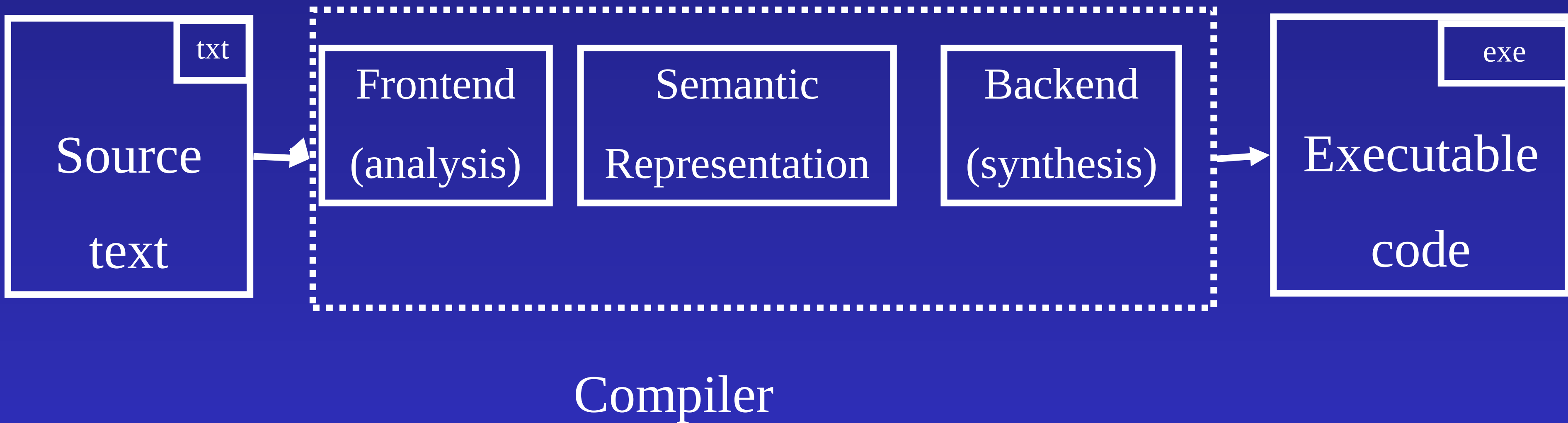
Remarks

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

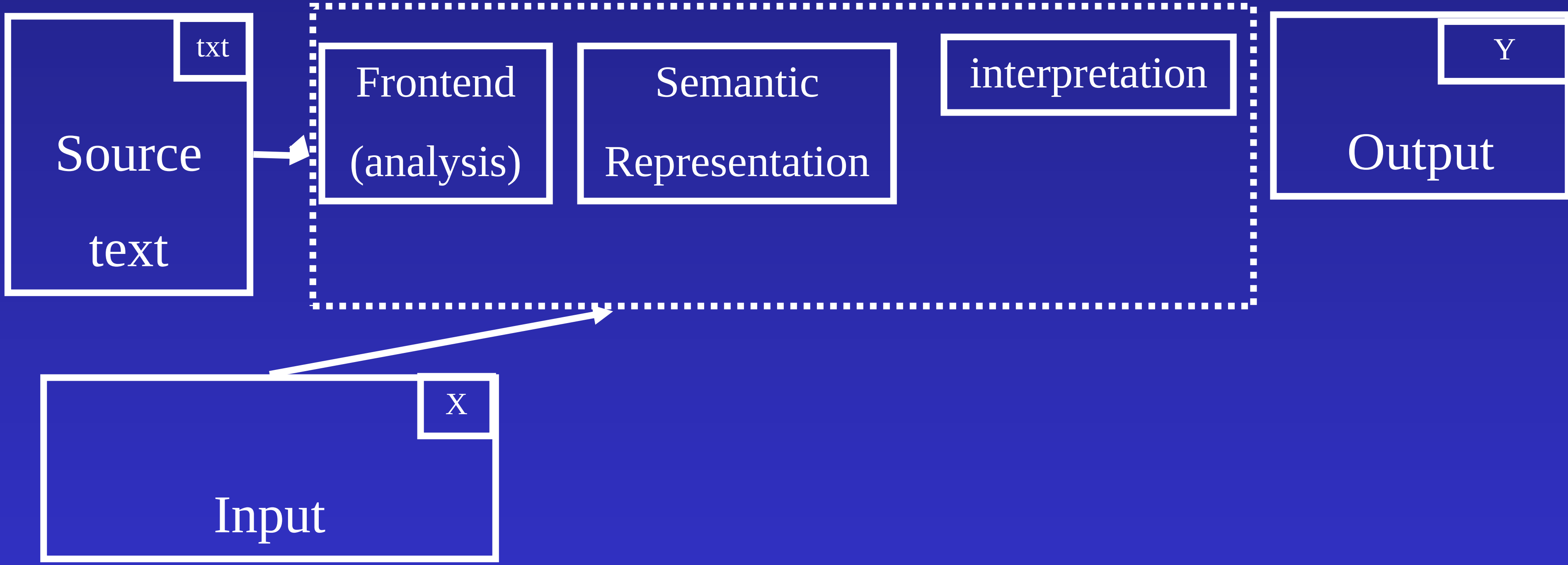
Bootstrapping a compiler



Conceptual structure of a compiler



Conceptual structure of an interpreter



Interpreter vs. Compiler

- Conceptually simpler (the definition of the programming language)
- Easier to port
- Can provide more specific error report
- Normally faster
- [More secure]

- Can report errors before input is given
- More efficient
  - Compilation is done once for all the inputs --- many computations can be performed at compile-time
  - Sometimes even *compile-time + execution-time < interpretation-time*

Interpreters provide specific error report

- Input-program

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

- Input data y=0

Compilers can provide errors before actual input is given

- Input-program

```
scanf("%", &y);
if (y < 0)
        x = 5;
...
 if  (y <= 0)
/* line 88 */      z = x + 1;
```

- Compiler-Output

  "line 88: x may be used before set"

Compilers can provide errors before actual input is given

- Input-program

```
        int a[100], x, y ;
        scanf("%d", &y) ;
        if (y < 0)
/* line 4*/    y = a ;
```

- Compiler-Output

“line 4: improper pointer/integer combination: op ="

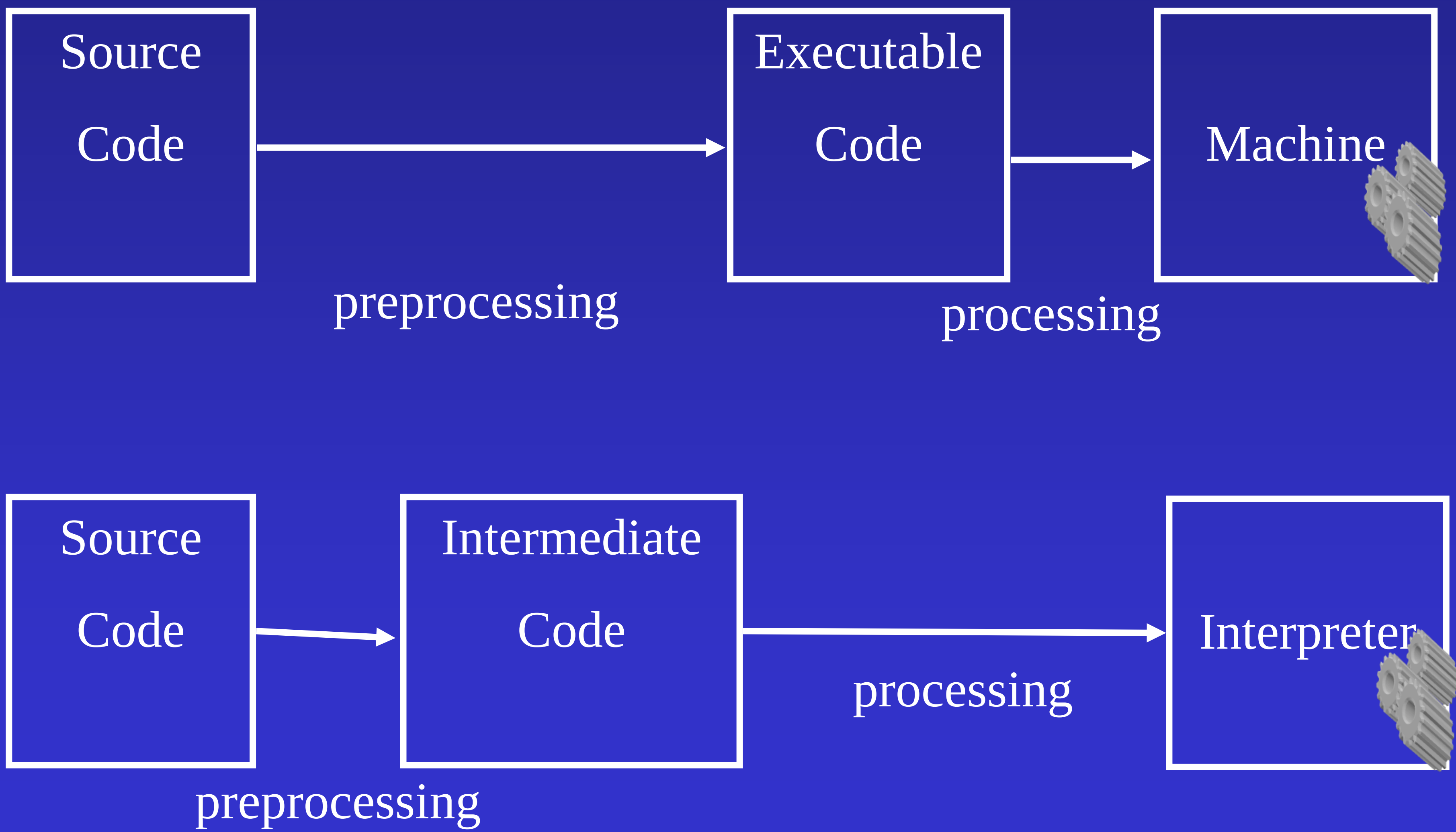
Compilers are usually more efficient

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

Sparc-cc-compiler

```
 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



Why Study Compilers?

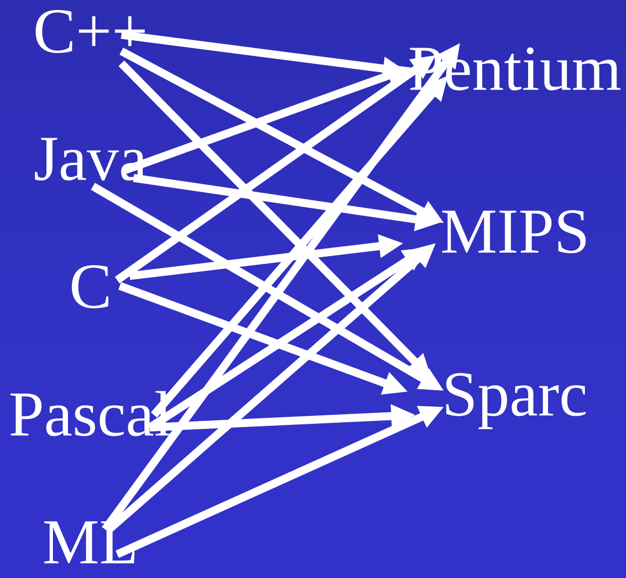
- Become a compiler writer
  - New programming languages
  - New machines
  - New compilation modes: “just-in-time”
- Using some of the techniques in other contexts
- Design a very big software program using a reasonable effort
- Learn applications of many CS results (formal languages, decidability, graph algorithms, dynamic programming, ...
- Better understating of programming languages and machine architectures
- Become a better programmer

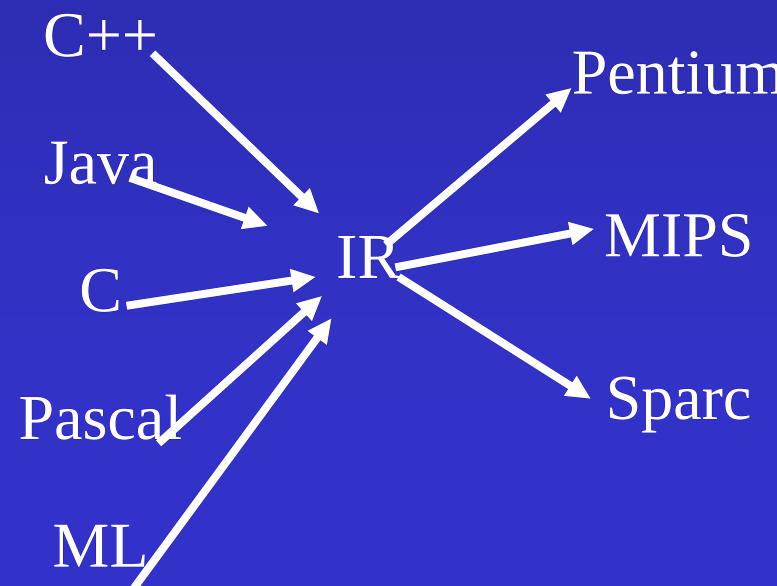
Why study compilers?

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

Proper Problem Structure

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



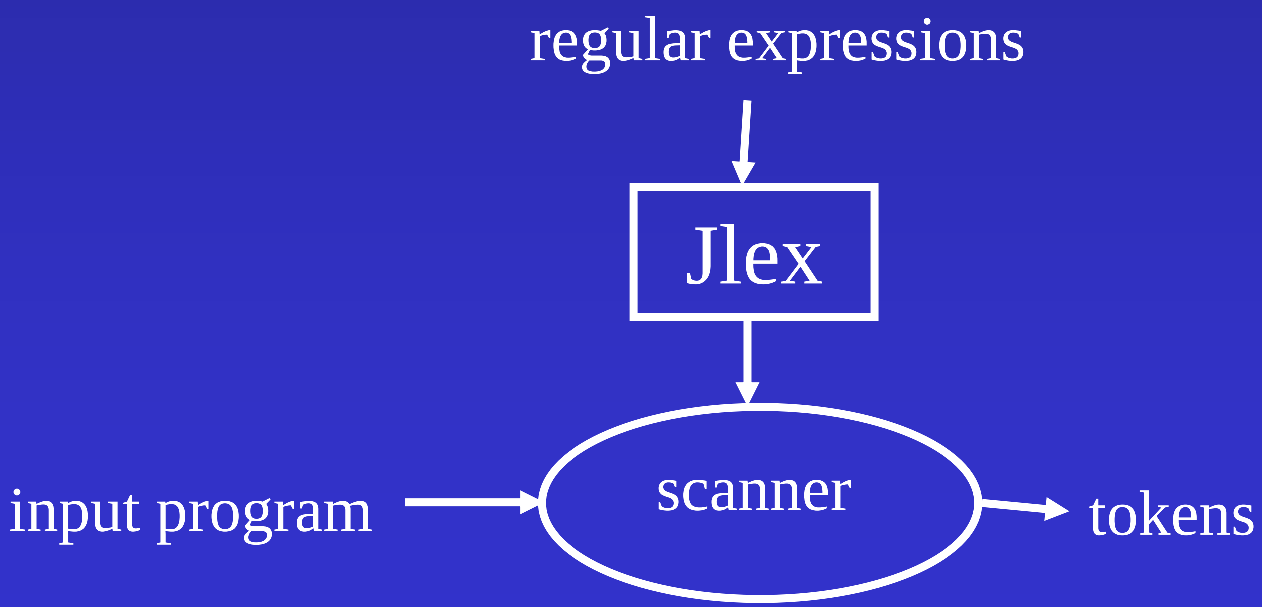


Judicious use of formalisms

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

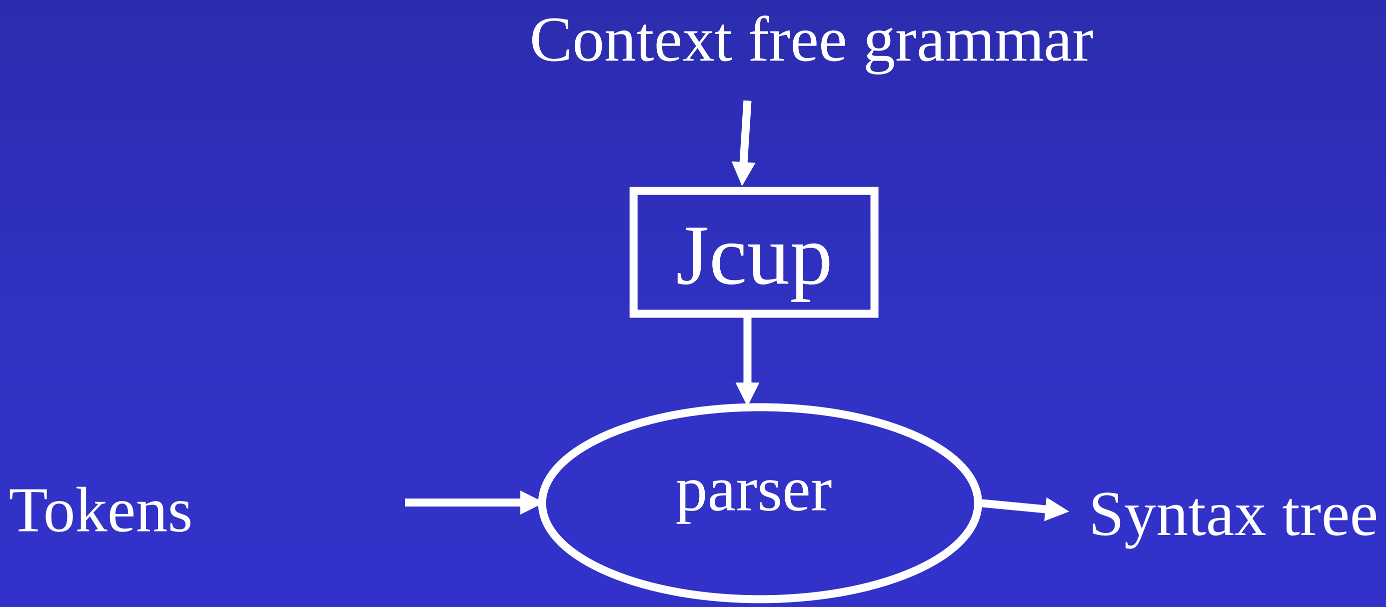
Use of program-generating tools

- Parts of the compiler are automatically generated from specification

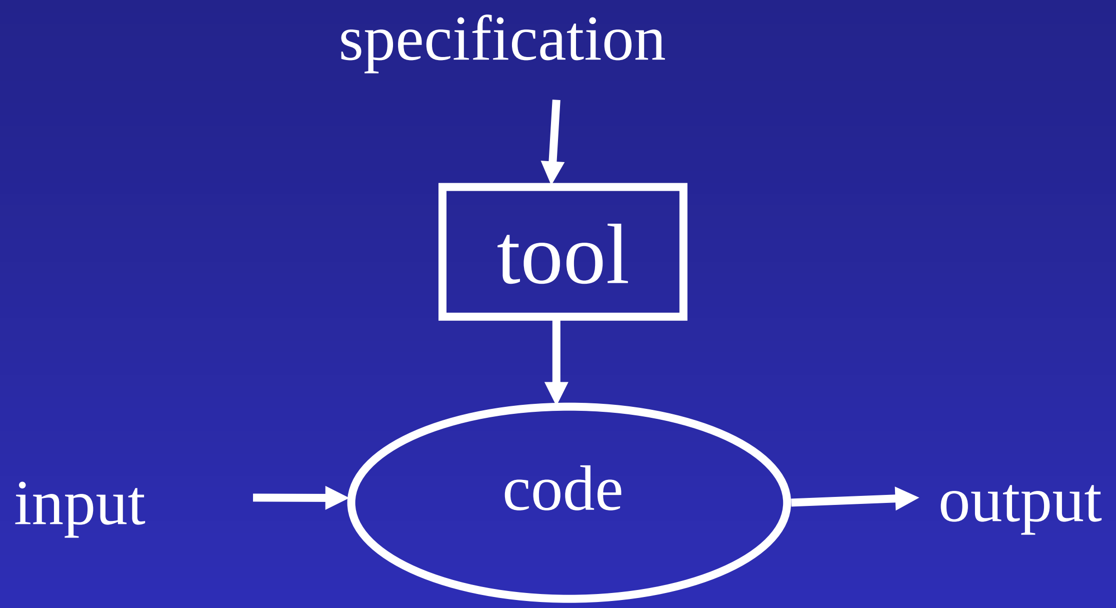


Use of program-generating tools

- 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

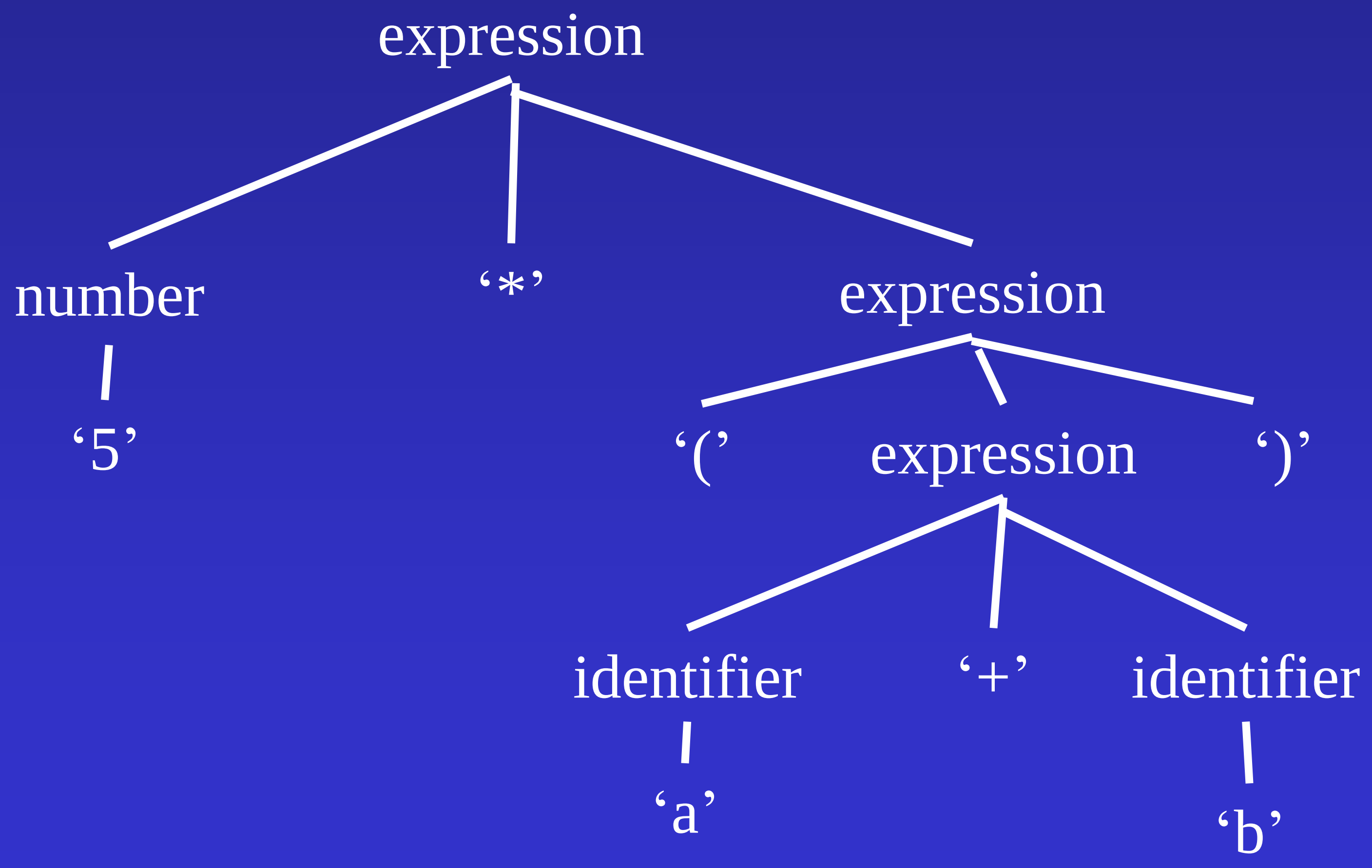
A simple traditional modular compiler/interpreter (1.2)

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

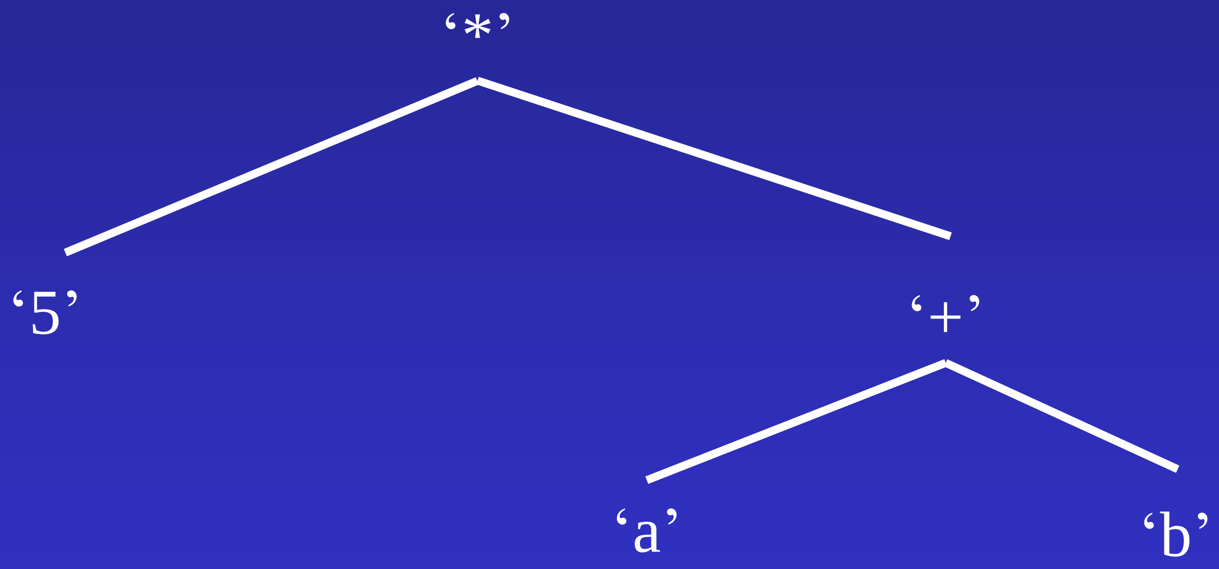
The abstract syntax tree (AST)

- 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)

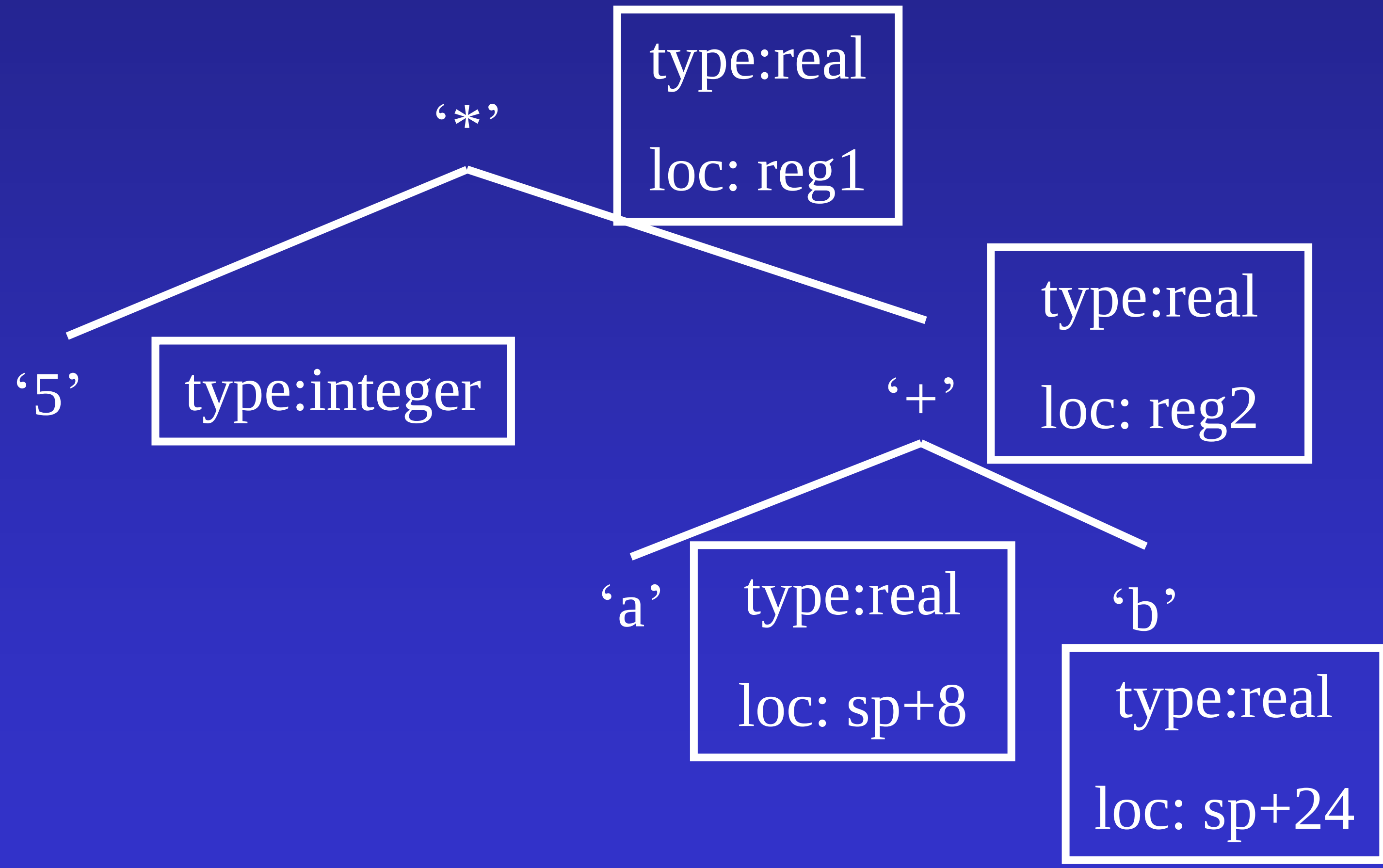
Syntax tree


expression
number
‘*’
expression
‘5’
‘(’
expression
‘)’
identifier
‘+’
identifier
‘a’
‘b’

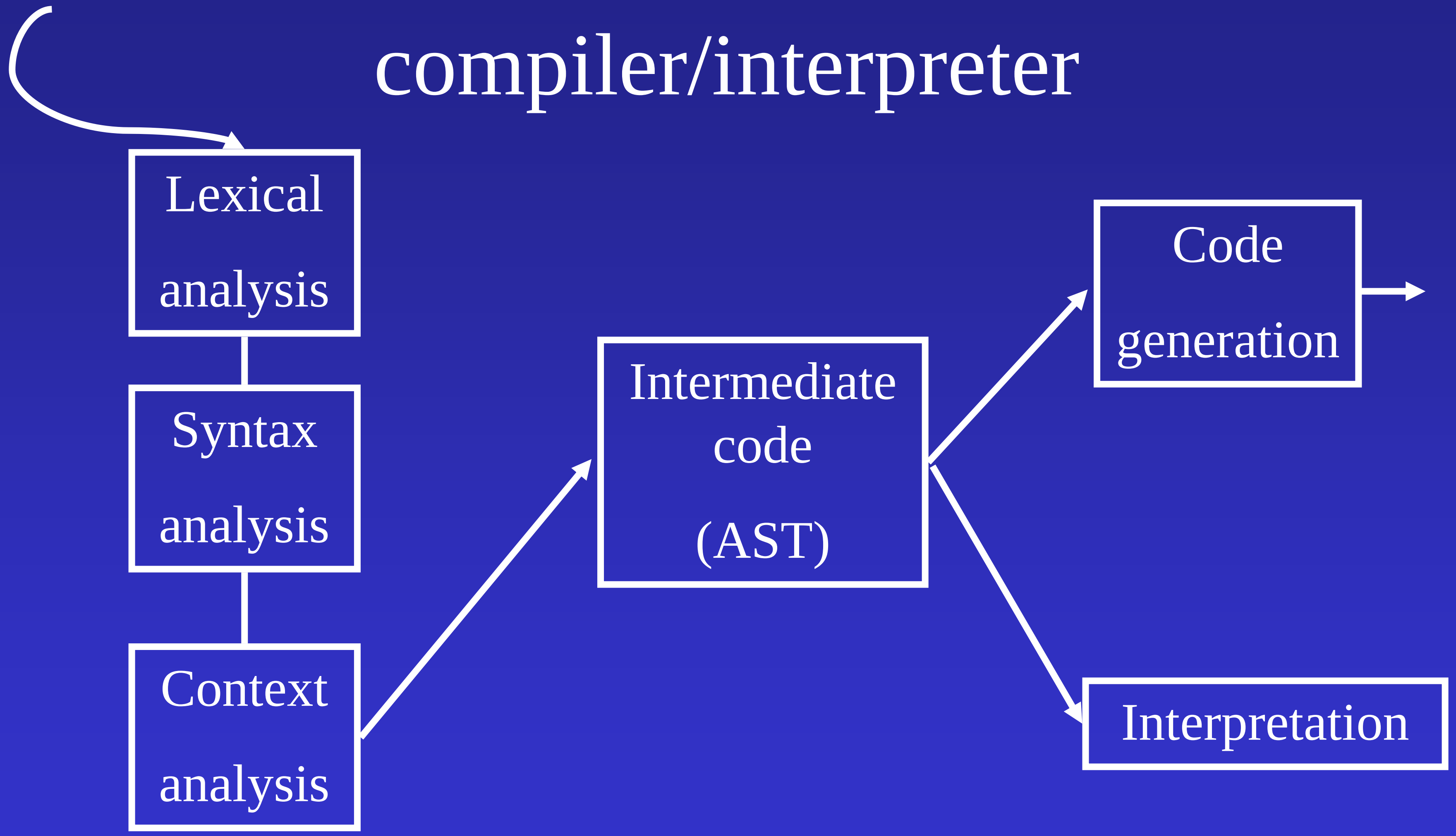
Abstract Syntax tree



Annotated Abstract Syntax tree



Structure of a demo compiler/interpreter



Input language

- Fully parameterized expressions
- Arguments can be a single digit

expression → digit | '(' expression operator expression ')'

operator → '+' | '*'

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

Driver for the demo 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

Header file lex.h 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);
```

```
#include    "lex.h"
static int Layout_char(int ch) {
    switch (ch) {
    case ' ': case '\t': case '\n': return 1;
    default:                        return 0;
    }
}
token_type Token;
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;
}
```

Parser

- Invokes lexical analyzer
- Reports syntax errors
- Constructs AST

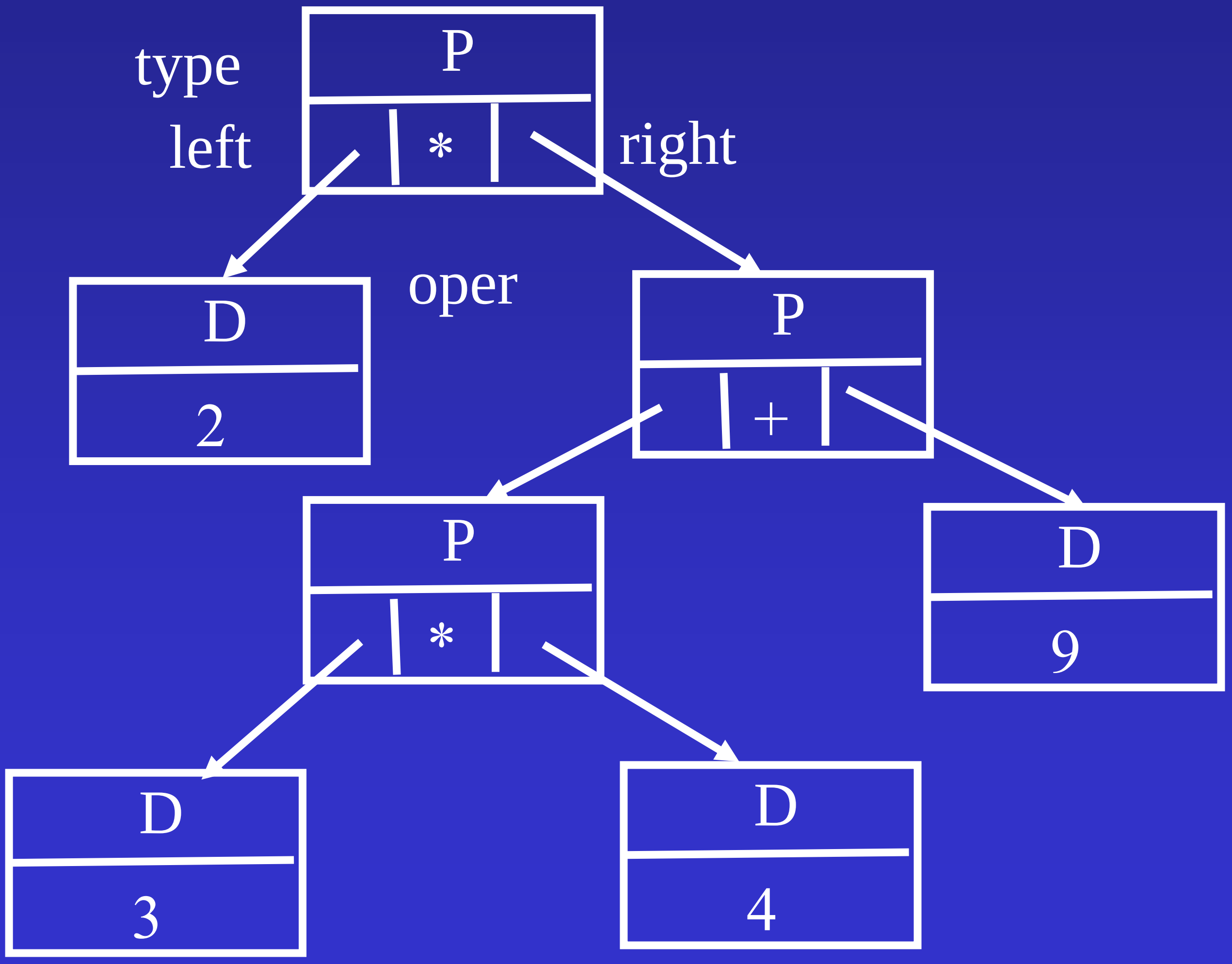
Parser Environment

```
#include    "lex.h"
#include    "error.h"
#include    "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' */
                               struct _expression *left, *right; /* for 'P' */
                               Operator oper;                /* for 'P' */
                           } 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

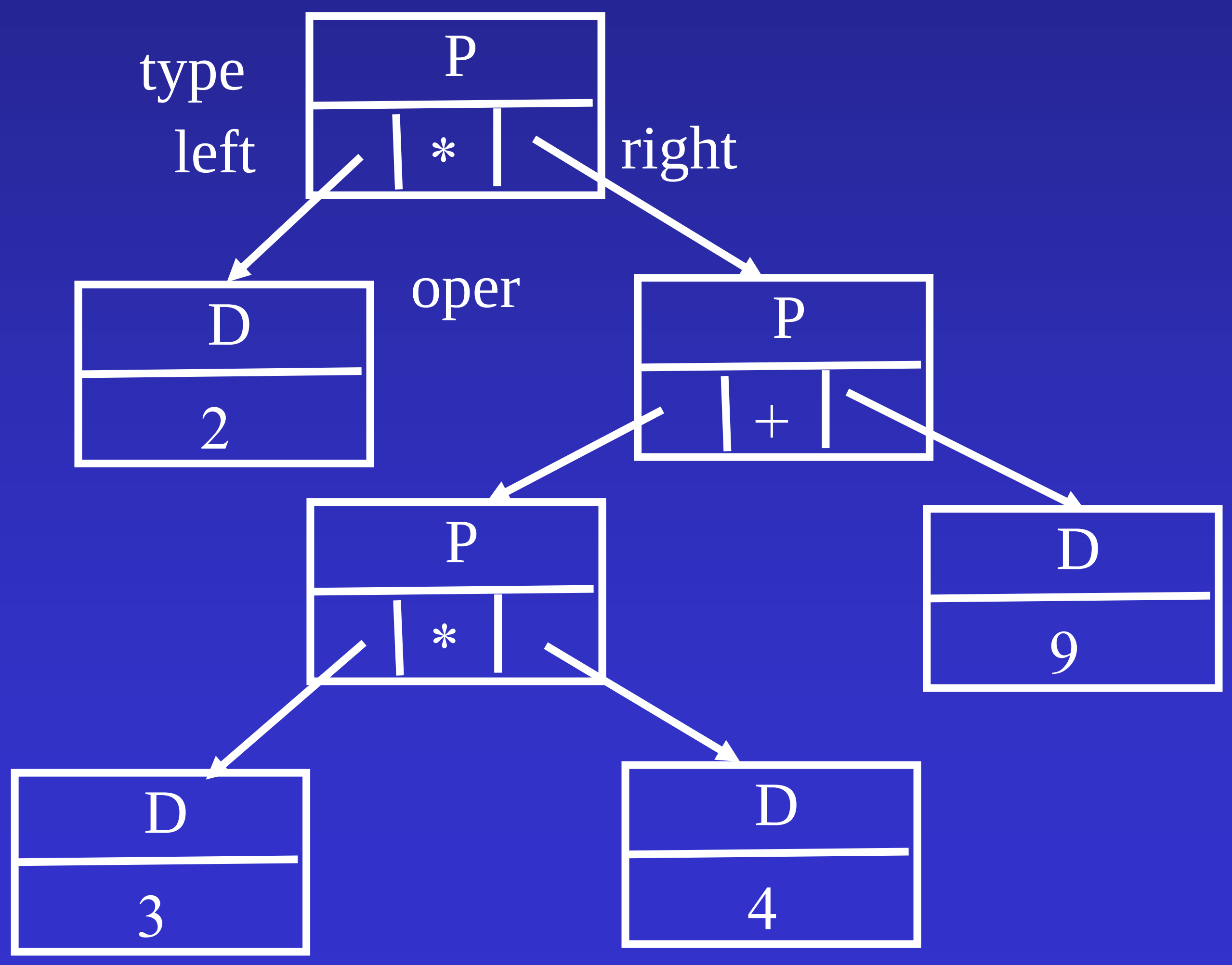
- Optimistically build the tree from the root to leaves
- Try every alternative production
  - For $P \rightarrow A_1\ A_2\ \ldots\ A_n \mid B_1\ B_2\ \ldots\ B_m$
  - If A_1 succeeds
    - If A_2 succeeds
      - if A_3 succeeds
        - » ...
      - Otherwise fail
    - Otherwise fail
  - If B_1 succeeds
    - If B_2 succeeds
      - ...
  - No backtracking
- Recursive descent parsing
- Can be applied for certain grammars

Parse_Operator

```
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;
}
```

```
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;
}
```

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



Context handling

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

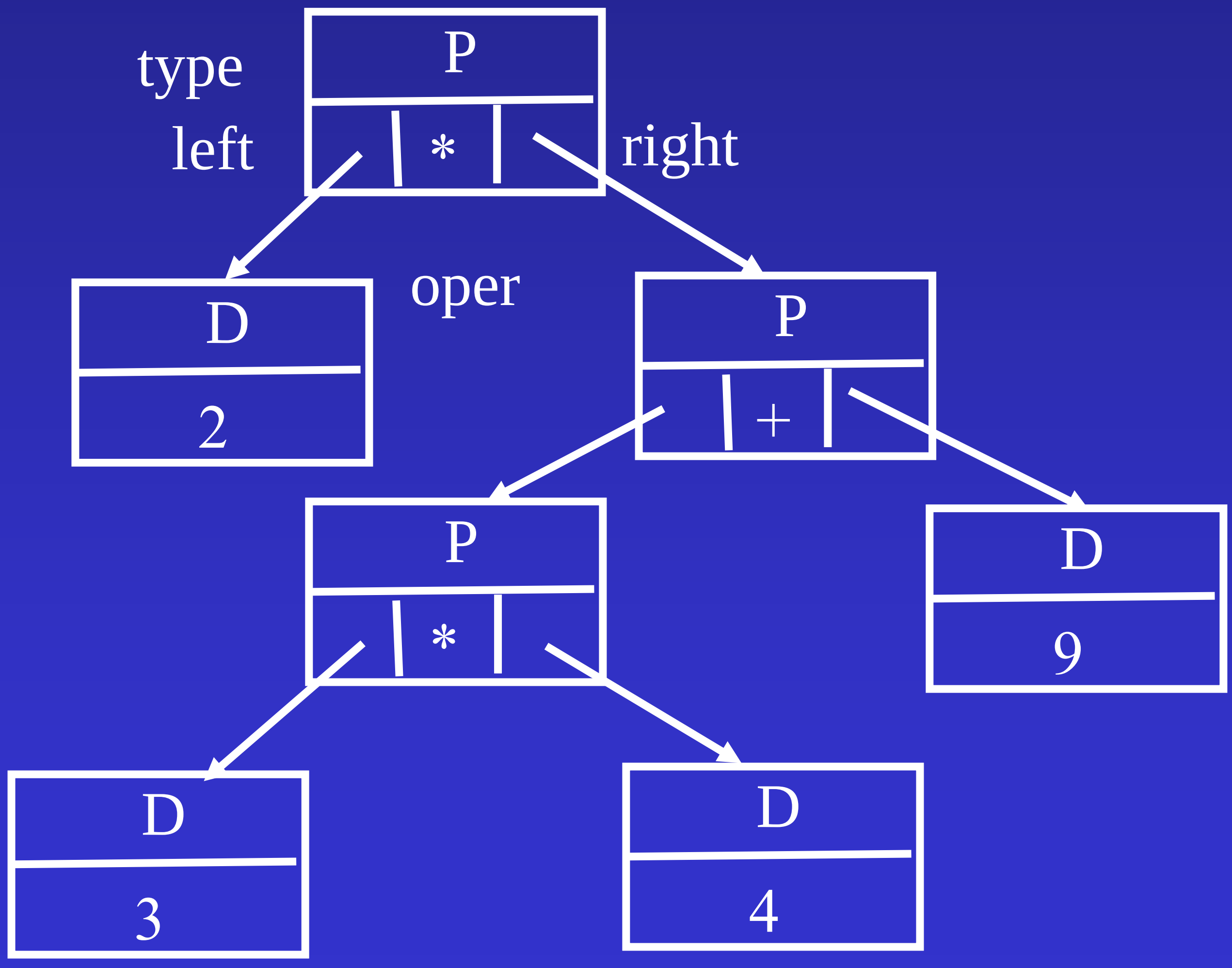
Code generation

- 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

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

Generated Code Execution

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

Generated Code Execution

PUSH 2

PUSH 3

PUSH 4

MULT

PUSH 9

ADD

MULT

PRINT

Stack	Stack
4	12
3	2
2	

Generated Code Execution

PUSH 2

PUSH 3

PUSH 4

MULT

PUSH 9

ADD

MULT

PRINT

Stack	Stack
12	9
2	12
	2

Generated Code Execution

	Stack	Stack
PUSH 2		
PUSH 3	9	21
PUSH 4	12	2
MULT	2	
PUSH 9		
ADD		
MULT		
PRINT		

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

42

PUSH 2

PUSH 3

PUSH 4

MULT

PUSH 9

ADD

MULT

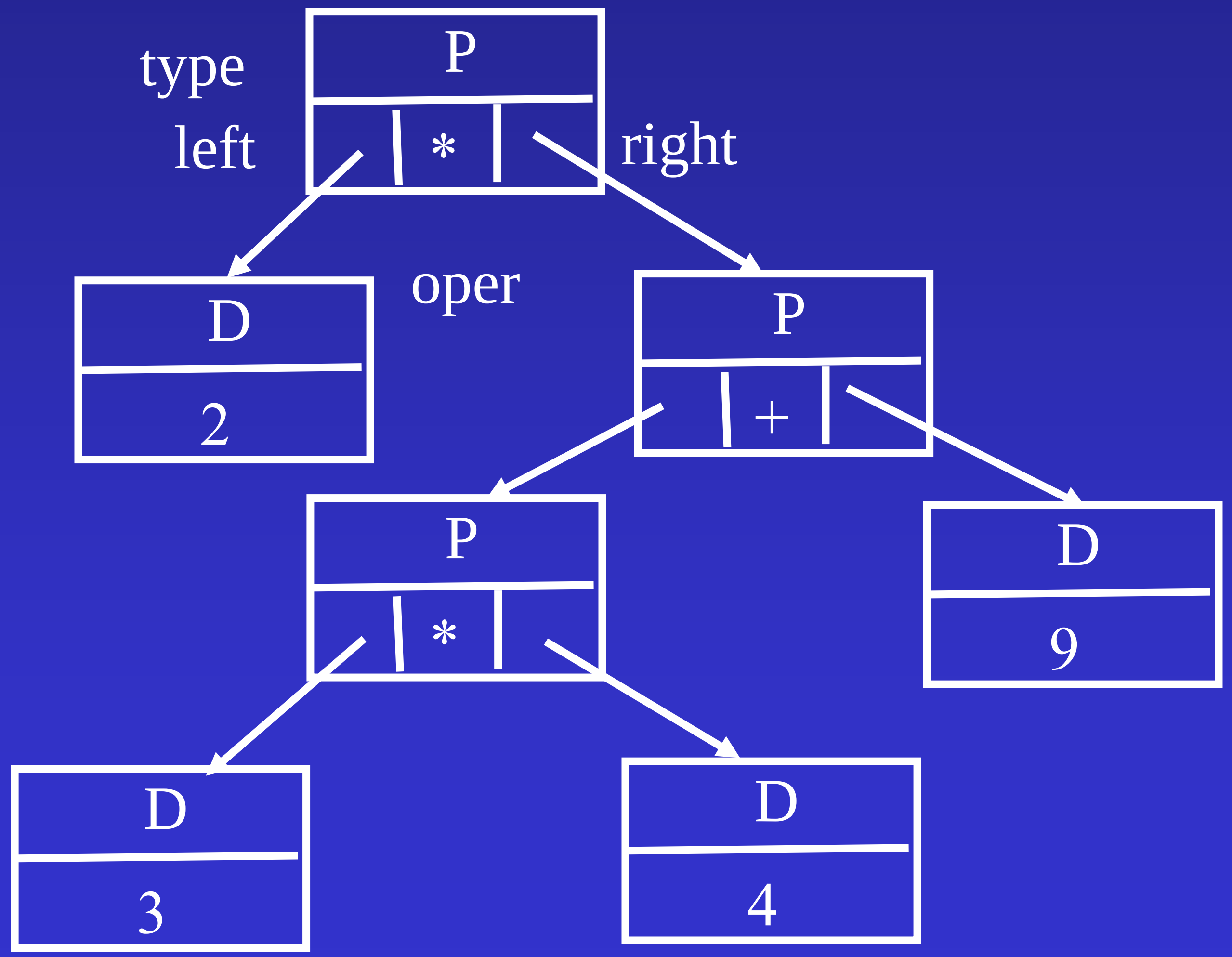
PRINT

Interpretation

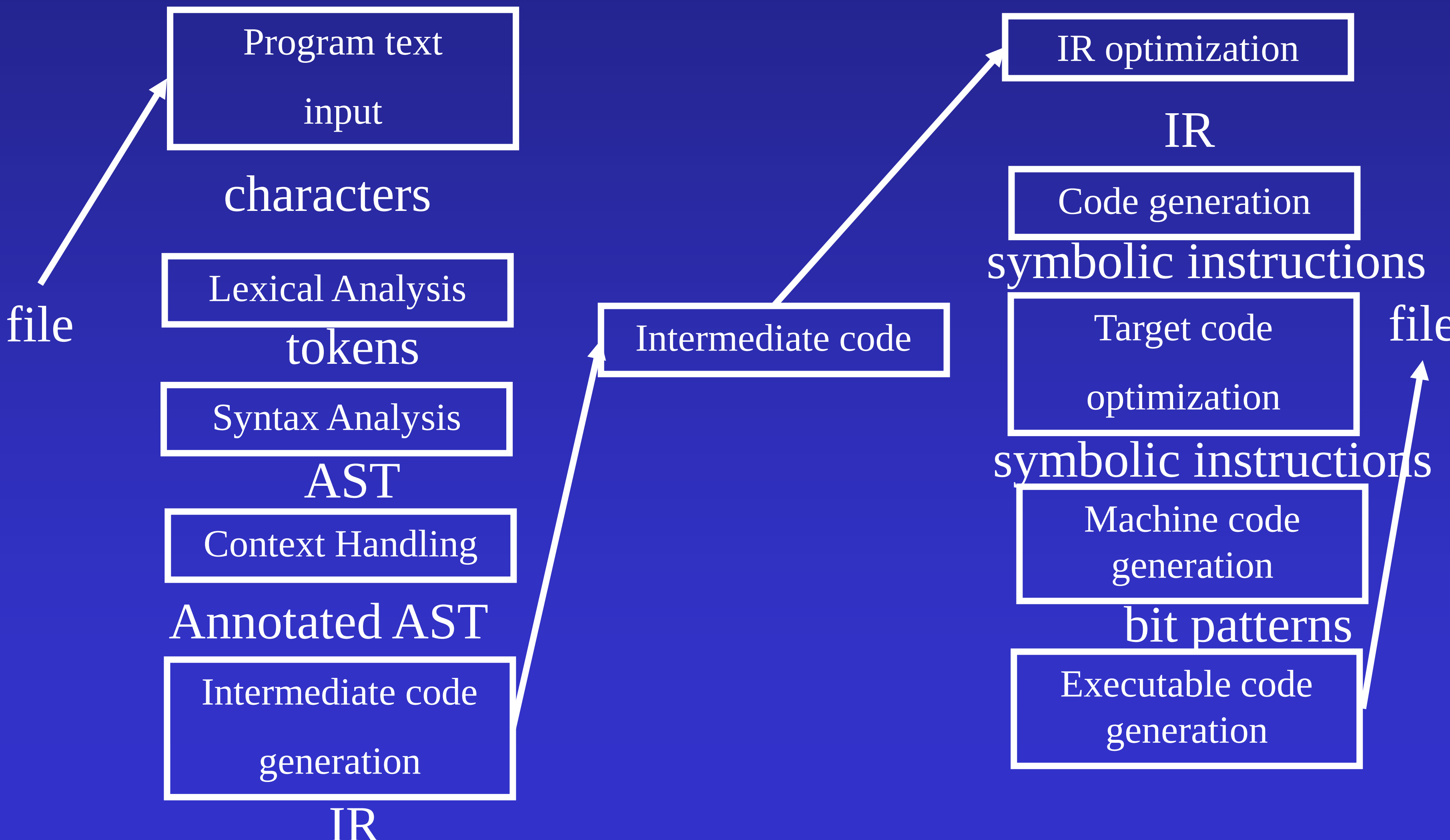
- Bottom-up evaluation of expressions
- The same interface of the compiler

```
#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))



A More Realistic Compiler



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

Shortcuts

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

Tentative Syllabus

Date	Lecture	Recitation	Assignment
20/10	Overview & AST	MiniJava	
27/10	Assembler	Visitor patterns	Variable&method renaming (19/11)
3/11	Intermediate Representation	Symbol Tables	
10/11	LLVM	LLVM	
17/11	Code Generation	LLVM Code Generation	Code generation (10/12)
26/11	Object Oriented Code Generation	LLVM Object Oriented Code Generation	
1/12	Semantic Analysis	Semantic Analysis and Type Checking	
8/12	Static Analysis	Static Analysis	Semantic Analysis (30/12)
15/12	Lexical Analysis	Lexical Analysis	
22/12	Top-Down Parsing	Top-Down Parsing	Lexing & Parsing (14/1)
29/12	Bottom-Up Parsing	Bottom-Up Parsing	
5/1	X86 Code Generation	X86 Code Generation & AR	
12/1	Advanced Topics	Rehearsal	

Summary

- Phases drastically simplifies the problem of writing a good compiler
- The frontend is shared between compiler/interpreter
- In the course we will learn this backwards