Computer Science 160
Translation of Programming Languages

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Overview of Compilers

Compilers

A) **Why do we need a compiler?**

B) What steps do we need to take to realize a compiler?

C) How is a compiler put together?

Compilers

- What is a compiler?
  - A program that translates a program in one language (source language) into an equivalent program in another language (target language), and it reports errors in the source program
- A compiler typically lowers the level of abstraction of the program

  C -> assembly code for Intel x86

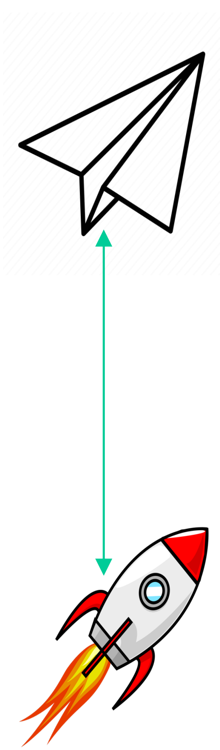
  Java -> Java bytecode
- What is an interpreter?
  - A program that reads an executable program (one instruction at a time) and produces the results of executing these instructions
- C is typically compiled
- Script languages (Python, Javascript) are typically interpreted
- Java is compiled to bytecode, which is then interpreted

Why Build Compilers?

- Compilers provide an essential interface between applications and architectures
- High level programming languages:
  - Increase programmer productivity
  - Better maintenance
  - Portable
- Low level machine details:
  - Instruction selection
  - Addressing modes
  - Pipelines
  - Registers and cache
- Compilers efficiently bridge the gap and shield the application developers from low level machine details

Effectiveness of A Compiler

- Performance of a matrix multiplication kernel (with n = 4,096) on Intel Xeon E5-2666 v3E, with **mostly just** compiler software optimization:



Version	Implementation	Running time (s)	Relative speedup	Absolute Speedup	GFLOPS	Percent of peak
1	Python	21041.67	1.00	1	0.006	0.001
2	Java	2387.32	8.81	9	0.058	0.007
3	C	1155.77	2.07	18	0.118	0.014
4	+ interchange loops	177.68	6.50	118	0.774	0.093
5	+ optimization flags	54.63	3.25	385	2.516	0.301
6	Parallel loops	3.04	17.97	6,921	45.211	5.408
7	+ tiling	1.79	1.70	11,772	76.782	9.184
8	Parallel divide-and-conquer	1.30	1.38	16,197	105.722	12.646
9	+ compiler vectorization	0.70	1.87	30,272	196.341	23.486
10	+ AVX intrinsics	0.39	1.76	53,292	352.408	41.677

[Charles Leiserson, MIT 6.172]

53,292X performance difference!

Desirable Properties of Compilers

- Compiler must generate a correct executable
  - The input program and the output program must be equivalent; the compiler must preserve the meaning (semantics) of the input program
- Output program should run fast
  - We expect the output program to be more efficient than the input program
- Compiler itself should be fast
- Compiler should provide good diagnostics for programming errors
- Compiler should support separate compilation (modules, object files)
- Compiler should work well with debuggers
- Compiled code should be small
- Optimizations should be consistent and predictable
- Compile time should be proportional to code size

Compiler - Example

- Source code
  - Written in a high-level programming language

```
//simple example
while (sum < total)
{
  sum = sum + x*10;
}
```

- Target code
  - Assembly language, which in turn is translated to machine code

```
L1: MOV     total,R0
    CMP     sum,R0
    JL      L2
    GOTO    L3

L2: MOV     #10,R0
    MUL     x,R0
    ADD     sum,R0
    MOV     R0,sum
    GOTO    L1

L3: first instruction
    following the while
    statement
```

Compilers

A) Why do we need a compiler?

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C) How is a compiler put together?

What is the Input?

- Input to the compiler is <u>not</u>

```
//simple example
while (sum < total)
{
  sum = sum + x*10;
}
```

- Input to the compiler is

```
//simple\bexample\nwhile\b(sum\b<\btotal)\b{\n\tsum\b=
\bsum\b+\bx*10;\n}\n
```

- How does the compiler recognize the keywords, identifiers, the structure, etc.?

First Step: Lexical Analysis (Scanning)

- The compiler scans the input file and produces a stream of ***tokens***

```
WHILE,LPAREN,<ID,sum>,LT,<ID,total>,RPAREN,LBRACE,
<ID,sum>,EQ,<ID,sum>,PLUS,<ID,x>,TIMES,<NUM,10>,
SEMICOL,RBRACE
```

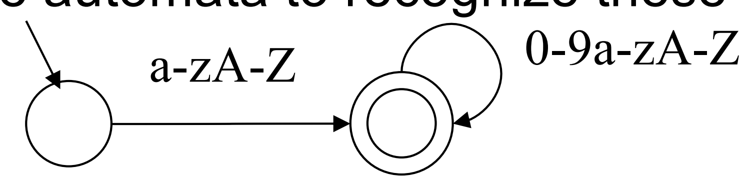
- Each token has a corresponding ***lexeme***, the character string that corresponds to the token
  - For example, "`while`" is the lexeme for token `WHILE`
  - "`sum`", "`x`", "`total`" are lexemes for token `ID`

Lexical Analysis (Scanning)

- Compiler uses a set of patterns to specify valid tokens
  - tokens: LPAREN, ID, NUM, WHILE, etc.

- Each pattern is specified as a regular expression
  - LPAREN should match: `(`
  - WHILE should match: `while`
  - ID should match: [a-zA-Z][0-9a-zA-Z]*

- It uses finite automata to recognize these patterns



ID automaton

Lexical Analysis (Scanning)

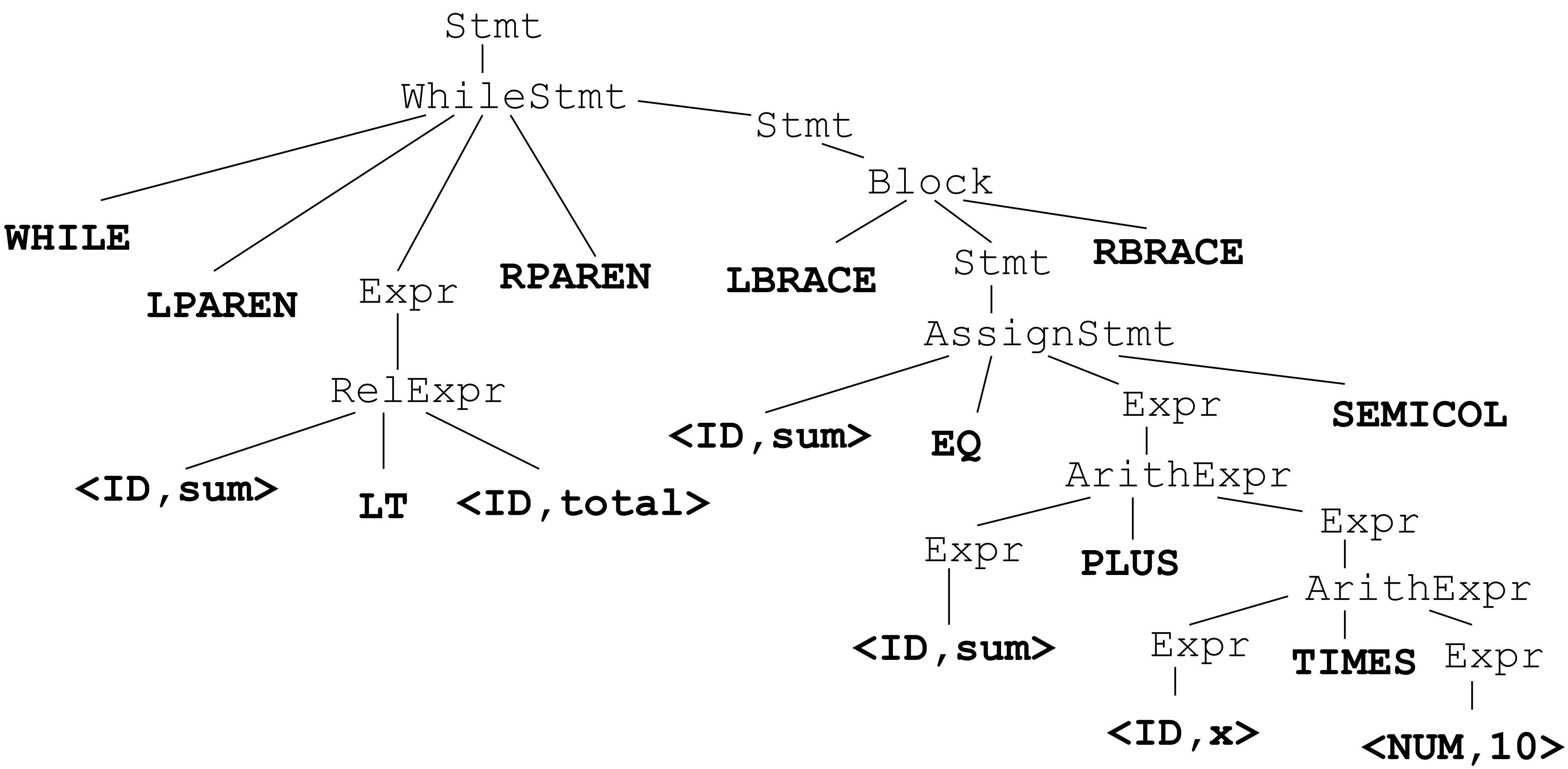
- During the scan the lexical analyzer gets rid of the ***white space*** (`\b`, `\t`, `\n`, etc.) and ***comments***
- Important additional task: Error messages!
  - `Var%1` → Error! Not a token!
  - `whle` → Error? It matches the identifier token.
- Natural language analogy: Tokens correspond to words and punctuation symbols in a natural language

Next Step: Syntax Analysis (Parsing)

- How does the compiler recognize the structure of the program?
  - Loops, blocks, procedures, nesting?

- Parse the stream of tokens -> parse tree
  - program will be on the leaves of the tree

Syntax Analysis (Parsing)



Syntax Analysis (Parsing)

- The syntax of a programming language is defined by a set of recursive rules. These sets of rules are called context free grammars.

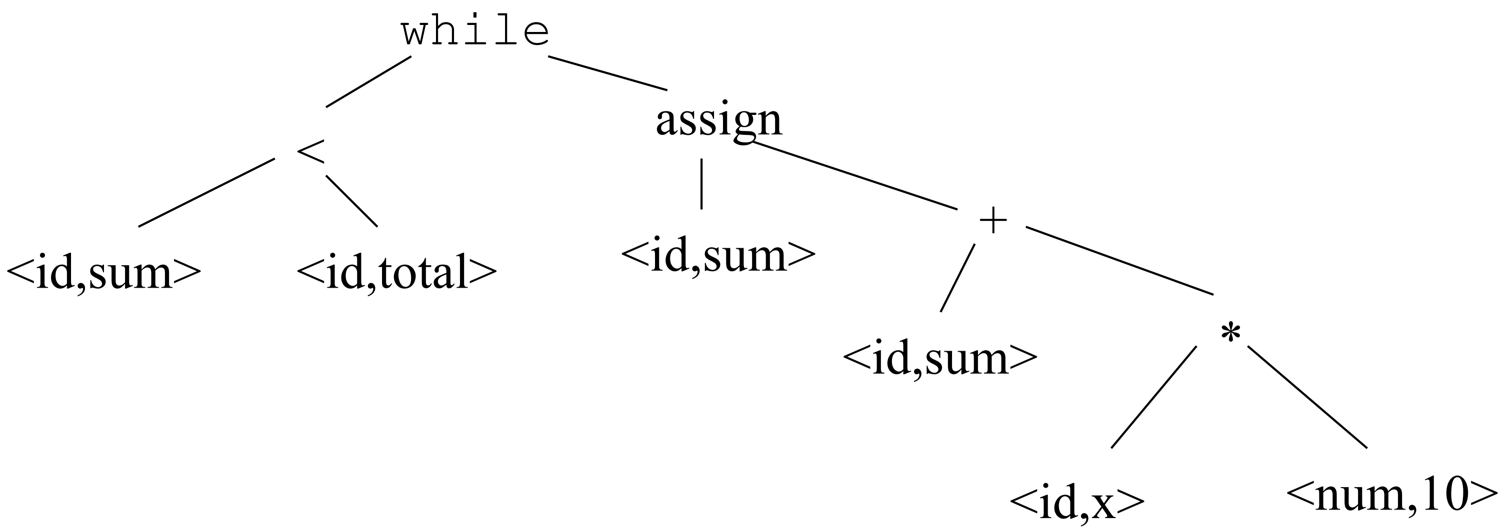
```
Stmt → WhileStmt | Block | ...
WhileStmt → WHILE LPAREN Expr RPAREN Stmt
Expr →  RelExpr | ArithExpr | ...
RelExpr → ...
```

- Compilers apply these rules to produce the parse tree
- Again, important additional task: Error messages!
  - Missing semicolon, missing parenthesis, etc.
- Natural language analogy: It is similar to parsing English text. Paragraphs, sentences, noun-phrases, verb-phrases, verbs, prepositions, articles, nouns, etc.

Intermediate Representations

- The parse tree representation has too many details
  - `LPAREN, LBRACE`, `SEMICOL`, etc.
- Once the compiler understands the structure of the input program, it does not need these details (they prevent ambiguities during parsing)
- Compilers generate a more abstract representation after constructing the parse tree, which does not include the details of the derivation
- Abstract syntax trees (AST): Nodes represent operators, children represent operands

Intermediate Representations



Semantic (Context-Sensitive) Analysis

- Not everything that we care about is related to the *structure* of the program, in some cases we have to check the meaning (or semantics)

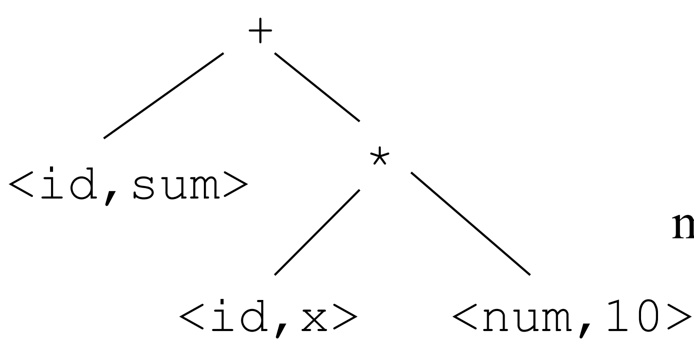
- Are variables declared before they are used?
  - We can find out if "`whle`" is declared by looking at the symbol table

- Do variable types match?

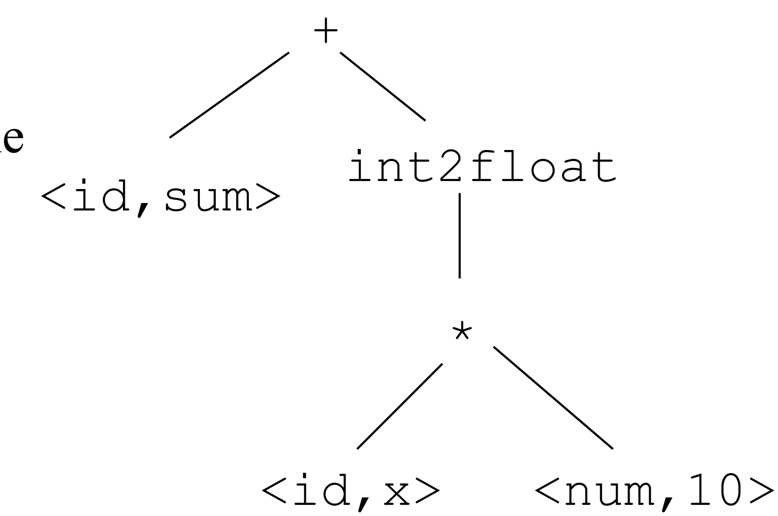
```
sum = sum + x*10;
```

Semantic (Context-Sensitive) Analysis

`sum` can be a floating point number,
`x` can be an integer



may become



Symbol Table

sum	float
x	int

Runtime Environment

- Efficient implementation of programming language abstractions
  - Symbolic names
  - Name spaces
  - Procedures
  - Parameters
  - Control Flow

- Bridge the gap between useful idea and practical application

Code Generation

- Abstract syntax trees are a high-level intermediate representation used in earlier phases of the compilation

- There are lower-level (i.e., closer to the machine code) intermediate representations
  - Three–address code: Every instruction has at most three operands. Very close to (MIPS, x86) assembly
  - Stack based code: Assembly language for JVM (Java Virtual Machine), an abstract stack machine.

- Intermediate code generation for these lower level representations and machine code generation are similar

Improving the Code: Code Optimization

- Compilers can improve the quality of code by static analysis
  - Data flow analysis, dependence analysis, code transformations, dead code elimination, etc.

```
while (sum < total)
{
  sum = sum + x*10;
}
```

transformation to more efficient code

We do not need to recompute `x*10` in each iteration of the loop

```
temp = x*10;
while (sum < total)
{
  sum = sum + temp;
}
```

Code Generation: Instruction Selection

- Source code

```
a = b + c;
d = a + e;
```

- Target code

If we generate code for each statement separately we will not generate efficient code

code for the first statement:

```
MOV  b,R0
ADD  c,R0
MOV  R0,a
```

code for the second statement:

```
MOV  a,R0      <- This instruction is redundant
ADD  e,R0
MOV  R0,d
```

Code Generation: Register Allocation

- There are a limited number of registers available on real machines
- Registers are valuable resources (keeping the values in registers prevents memory access), the compiler has to use them efficiently

source code	three-address code	assembly code
d = (a-b)+(a-c)+(a-c);	t = a - b;	MOV a,R0
	u = a - c;	SUB b,R0
	v = t + u;	MOV a,R1
	d = v + u;	SUB c,R1
		ADD R1,R0
		ADD R1,R0
		MOV R0,d

Compilers

A) Why do we need a compiler?

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History of Compiler Development

Source program

↓

Compiler

↓

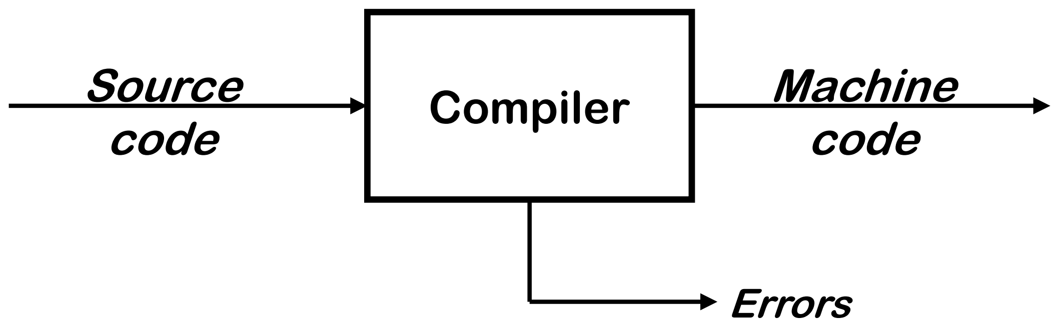
Target program

+ Error Diagnosis
+ Code Optimization

Monolithic Compiler	Two-pass Compiler	Modular Optimizing Compiler	Multicore/GPU Compiler	Autotuning Compiler	ML/Quantum Compiler
1950s	1980s	2004 LLVM	2002 OpenMP 2007 NVCC	2009 Petabricks 2014 Opentuner	2018 TVM

Our observation: From **Monolithic** to **Modular** to **Architecture(input)-aware** to **Domain-Specific.**

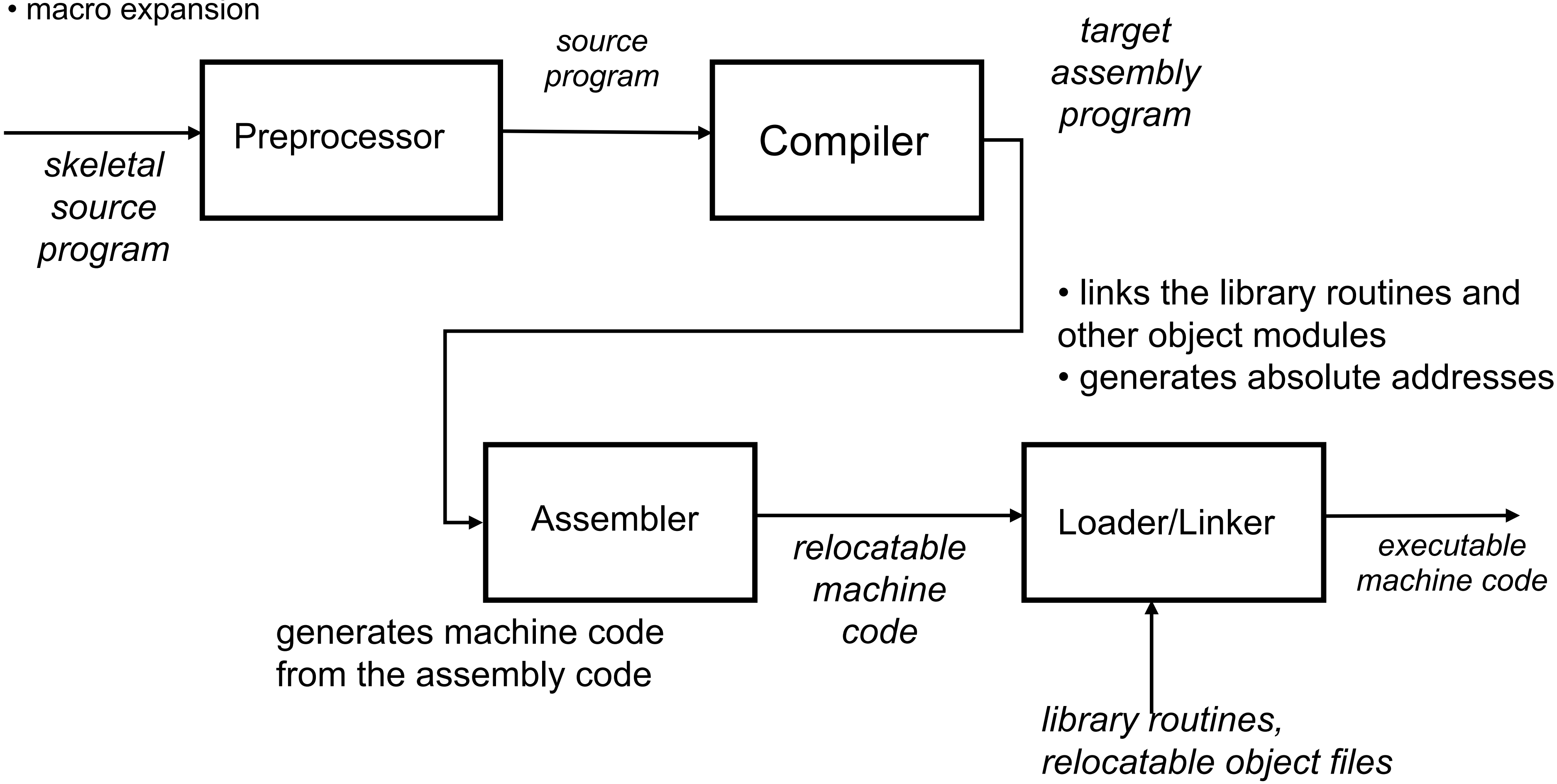
High-level View of a Compiler



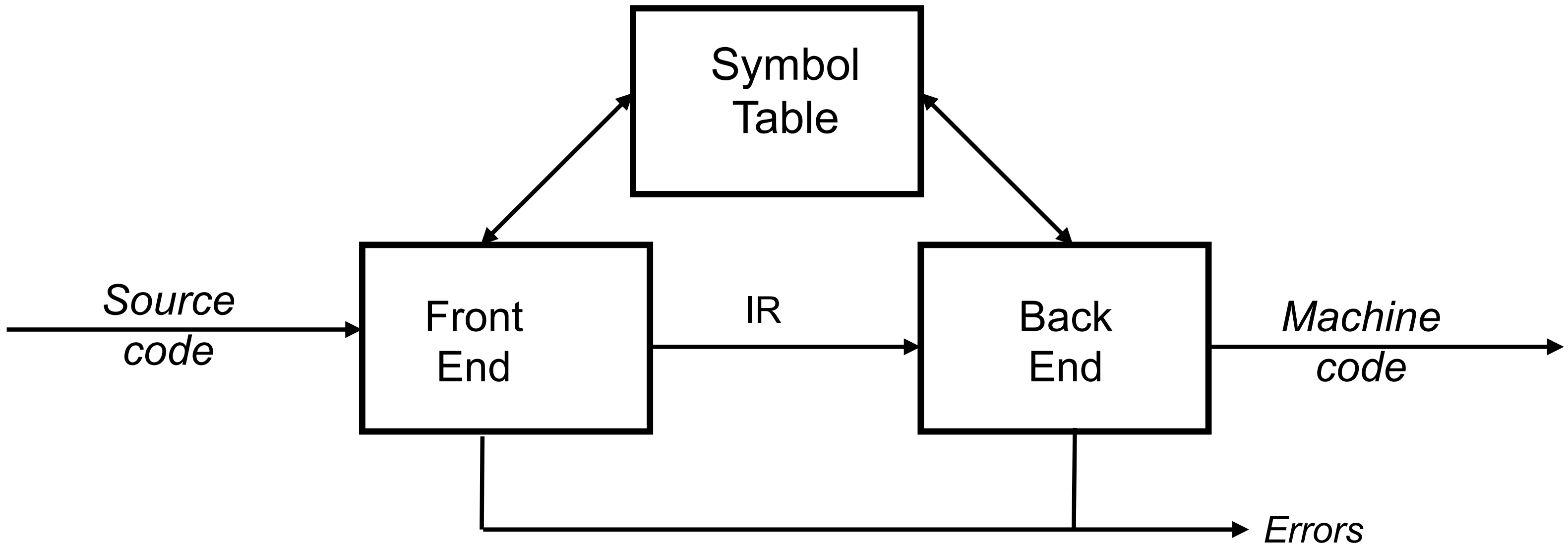
- Must recognize legal (and illegal) programs
- Must generate correct code
- Must manage storage of all variables (and code)
- Must agree with OS and linker on format for object code

A Higher Level View: How Does the Compiler Fit In?

• collects the source program that is divided into separate files
• macro expansion

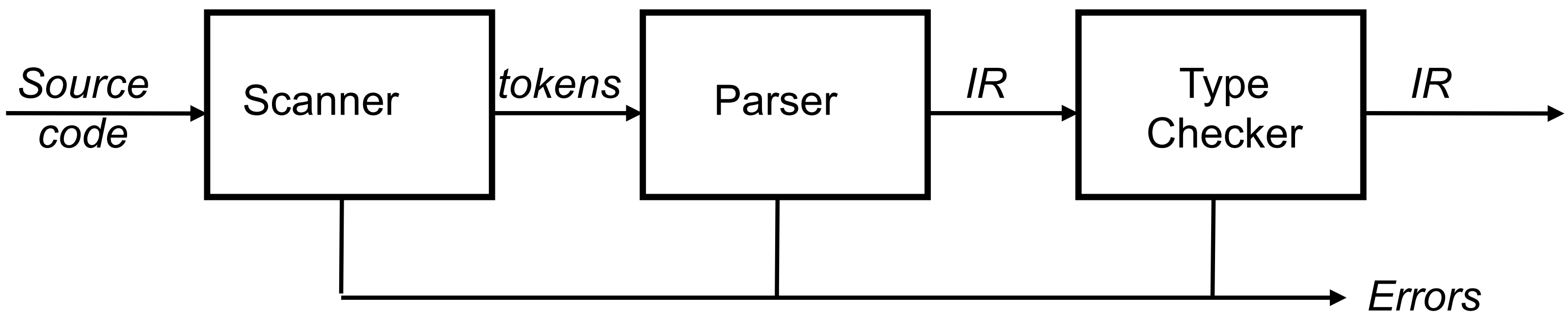


Traditional Two-pass Compiler



- Use an intermediate representation (IR)
- Front end maps legal source code into IR
- Back end maps IR into target machine code
- Admits multiple front ends and multiple passes
  - Typically, front end is O(n) or O(n log n), back end is NP-complete
- Different phases of compiler also interact through the symbol table

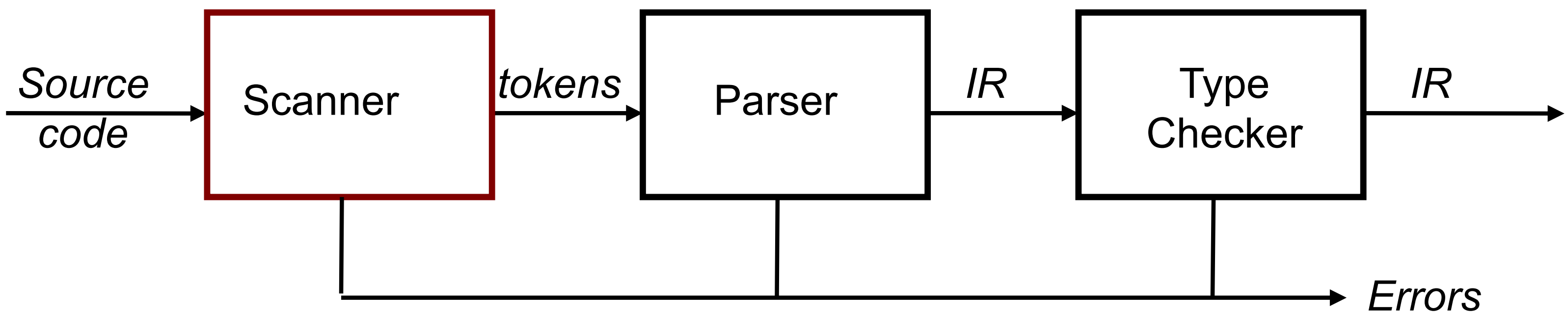
The Front End



Responsibilities

- Recognize legal programs
- Report errors for the illegal programs in a useful way
- Produce IR and construct the symbol table
- Much of front end construction can be automated

The Front End

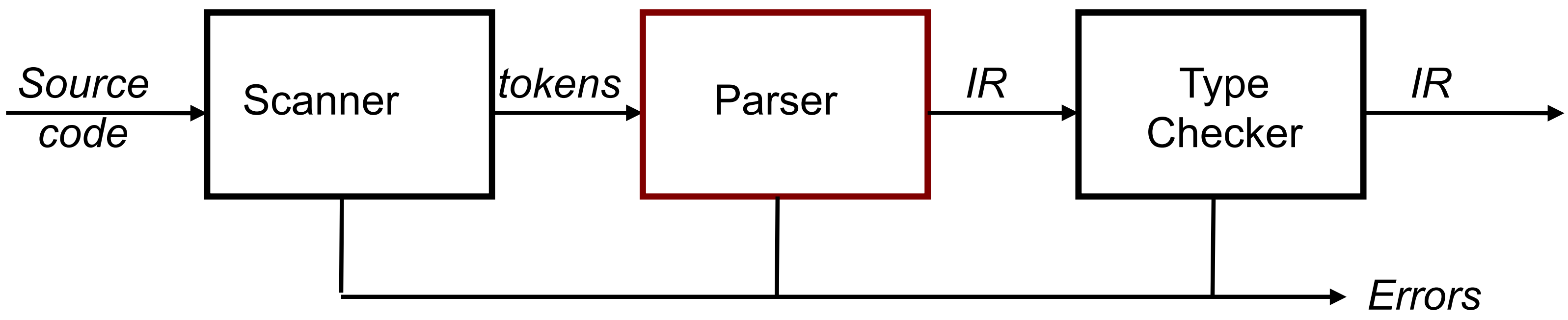


Scanner

- Maps character stream into words—the basic unit of syntax
- Produces tokens and stores lexemes when it is necessary
  - `x = x + y ;` becomes

    <id,x> EQ <id,x> PLUS <id,y> SEMICOLON
  - Typical tokens include *number, identifier,* +, -, *while, if*
- Scanner eliminates white space and comments

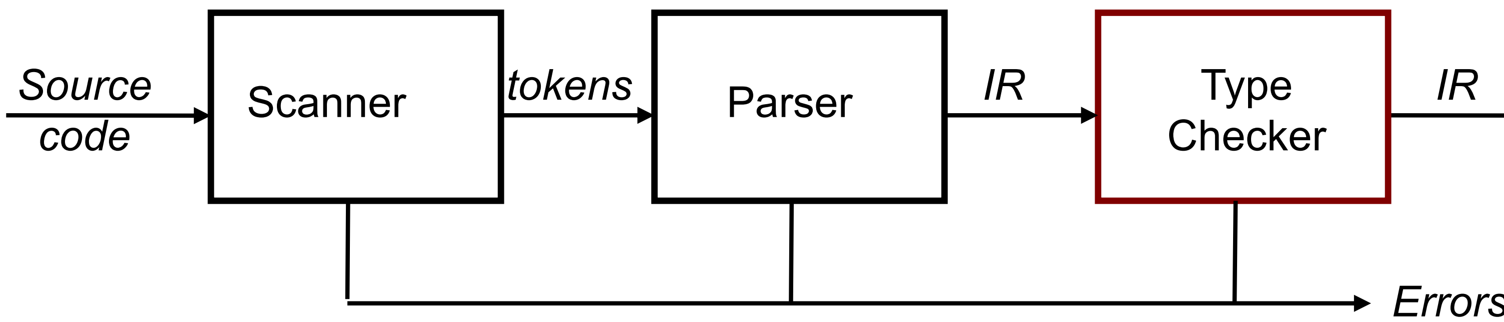
The Front End



Parser

- Uses scanner as a subroutine
- Recognizes context-free syntax and reports errors
- Guides context-sensitive analysis (type checking)
- Builds IR for source program
- Scanning and parsing can be grouped into one pass

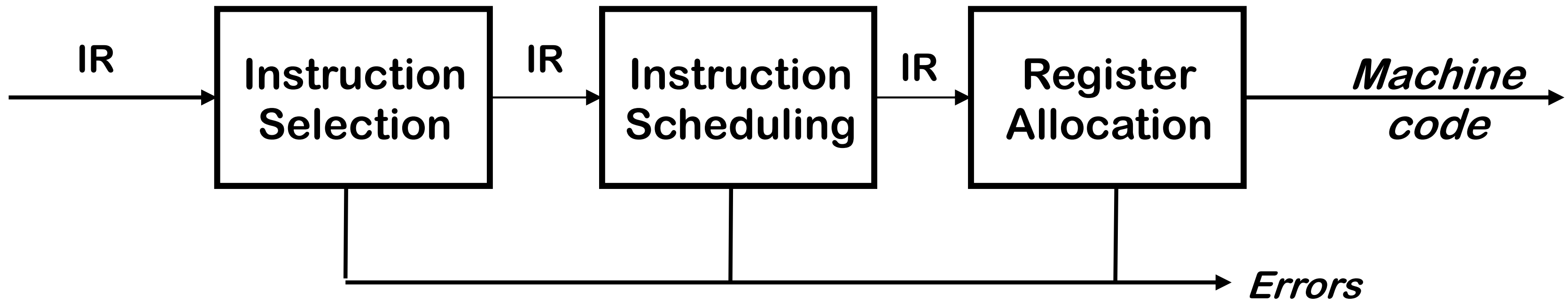
The Front End



<u>Context Sensitive Analysis</u>

- Check if all the variables are declared before they are used
- Type checking
  - Check type errors such as adding a procedure and an array
- Add the necessary type conversions
  - int-to-float, float-to-double, etc.

The Back End

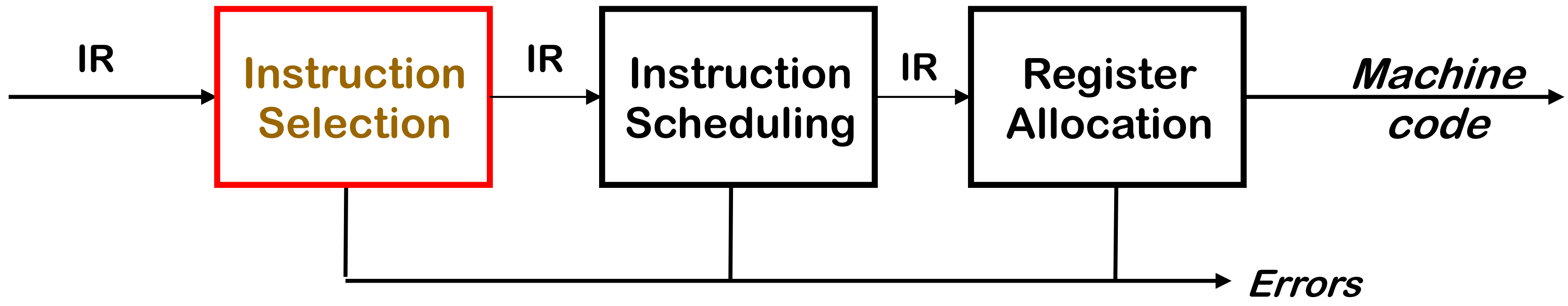


Responsibilities

- Translate IR into target machine code
- Choose instructions to implement each IR operation
- Decide which values to keep in registers
- Schedule the instructions for instruction pipeline

Automation has been *much less* successful in the back end

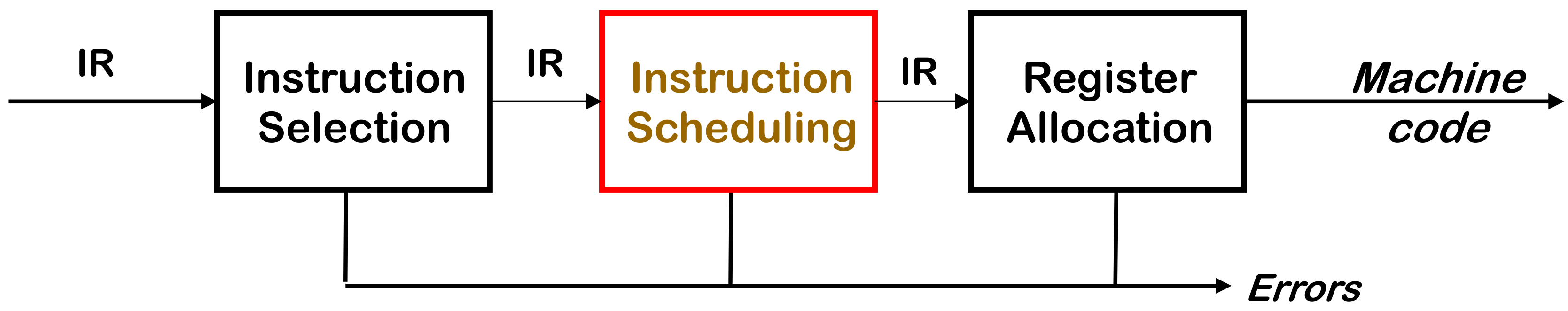
The Back End



Instruction Selection

- Produce fast, compact code
- Take advantage of target language features
  - E.g., addressing modes
- Usually viewed as a pattern matching problem
  - *Ad hoc* methods, pattern matching, dynamic programming
- Especially problematic when instruction sets are complex
  - RISC architectures simplified this problem

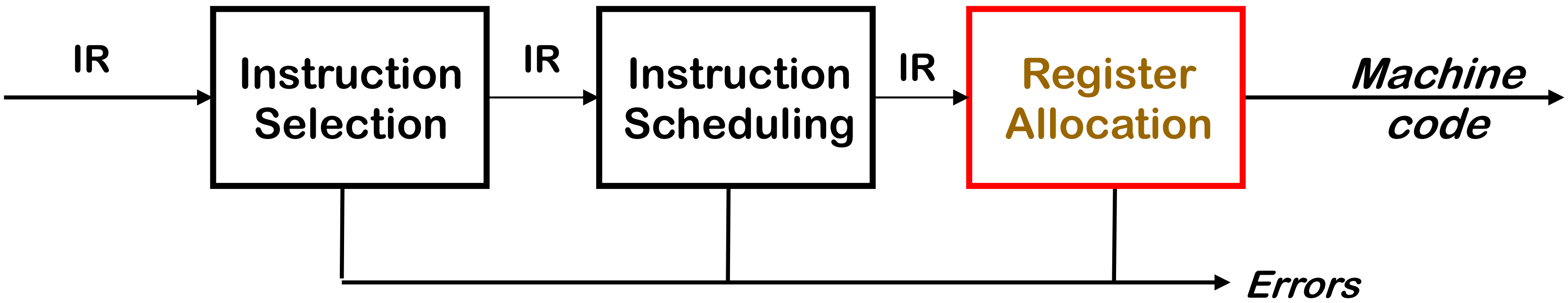
The Back End



Instruction Scheduling

- Avoid hardware stalls (keep pipeline moving)
- Use all functional units productively
- Optimal scheduling is NP-Complete

The Back End

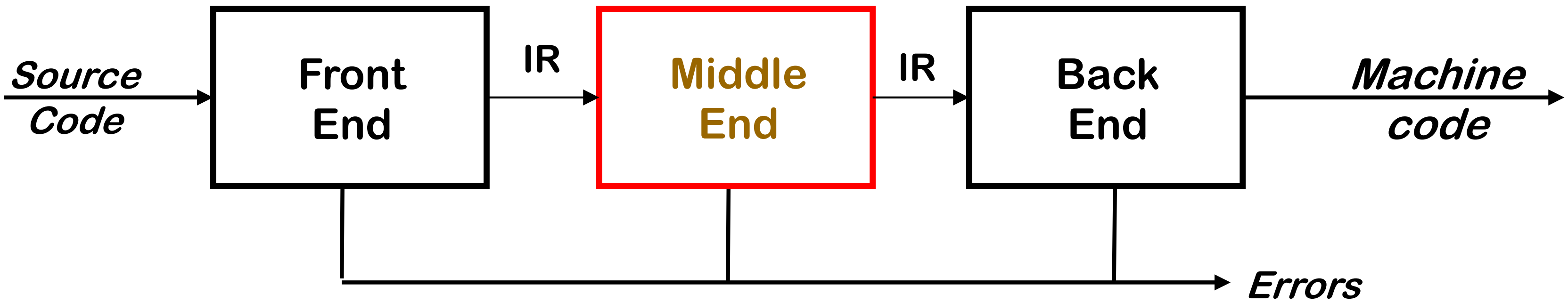


<u>Register Allocation</u>

- Have each value in a register when it is used
- Manage a limited set of registers
- Can change instruction choices and insert LOADs and STOREs
- Optimal allocation is NP-Complete

Compilers approximate solutions to NP-Complete problems

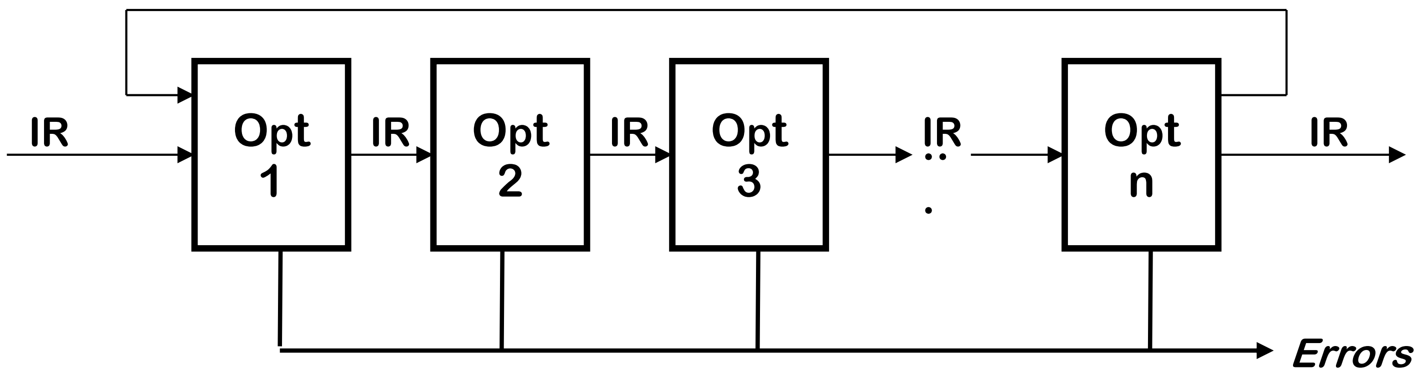
Traditional Three-pass (Optimizing) Compiler



Code Optimization

- Analyzes IR and transforms IR
- Primary goal is to reduce running time of the compiled code
  - May also improve space, power consumption (mobile computing)
- Must preserve "meaning" of the code

The Optimizer (or Middle End)



Modern optimizers are structured as a series of passes

<u>Typical Transformations</u>

- Discover and propagate constant values (constant propagation)
- Move a computation to a less frequently executed place
- Discover a redundant computation and remove it
- Remove unreachable code