An Overview of a Compiler

Y.N. Srikant

Department of Computer Science and Automation
Indian Institute of Science
Bangalore 560 012

NPTEL Course on Principles of Compiler Design

Outline of the Lecture

- About the course
- Why should we study compiler design?
- Compiler overview with block diagrams

About the Course

- A detailed look at the internals of a compiler
- Does not assume any background but is intensive
- Doing programming assignments and solving theoretical problems are both essential
- A compiler is an excellent example of theory translated into practice in a remarkable way

Why Should We Study Compiler Design?

- Compilers are everywhere!
- Many applications for compiler technology
  - Parsers for HTML in web browser
  - Interpreters for javascript/flash
  - Machine code generation for high level languages
  - Software testing
  - Program optimization
  - Malicious code detection
  - Design of new computer architectures
    - Compiler-in-the-loop hardware development
  - Hardware synthesis: VHDL to RTL translation
  - Compiled simulation
    - Used to simulate designs written in VHDL
    - No interpretation of design, hence faster

About the Complexity of Compiler Technology

- A compiler is possibly the most complex system software and writing it is a substantial exercise in software engineering
- The complexity arises from the fact that it is required to map a programmer's requirements (in a HLL program) to architectural details
- It uses algorithms and techniques from a very large number of areas in computer science
- Translates intricate theory into practice - enables tool building

About the Nature of Compiler Algorithms

- Draws results from mathematical logic, lattice theory, linear algebra, probability, etc.
  - type checking, static analysis, dependence analysis and loop parallelization, cache analysis, etc.
- Makes practical application of
  - Greedy algorithms - register allocation
  - Heuristic search - list scheduling
  - Graph algorithms - dead code elimination, register allocation
  - Dynamic programming - instruction selection
  - Optimization techniques - instruction scheduling
  - Finite automata - lexical analysis
  - Pushdown automata - parsing
  - Fixed point algorithms - data-flow analysis
  - Complex data structures - symbol tables, parse trees, data dependence graphs
  - Computer architecture - machine code generation

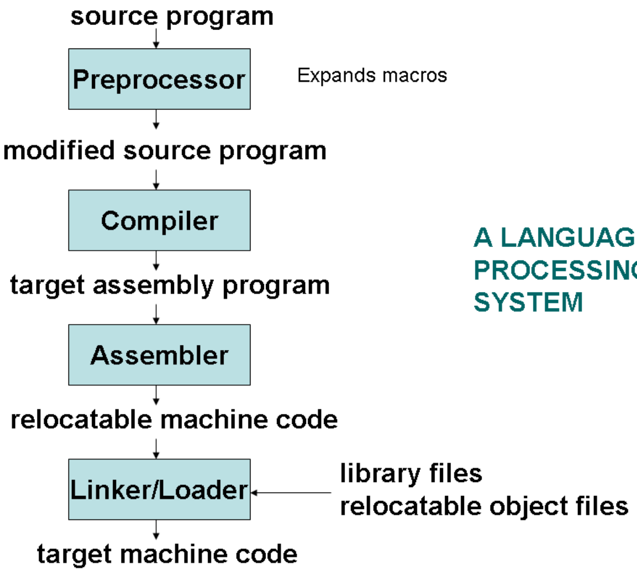
Other Uses of Scanning and Parsing Techniques

- Assembler implementation
- Online text searching (GREP, AWK) and word processing
- Website filtering
- Command language interpreters
- Scripting language interpretation (Unix shell, Perl, Python)
- XML parsing and document tree construction
- Database query interpreters

Other Uses of Program Analysis Techniques

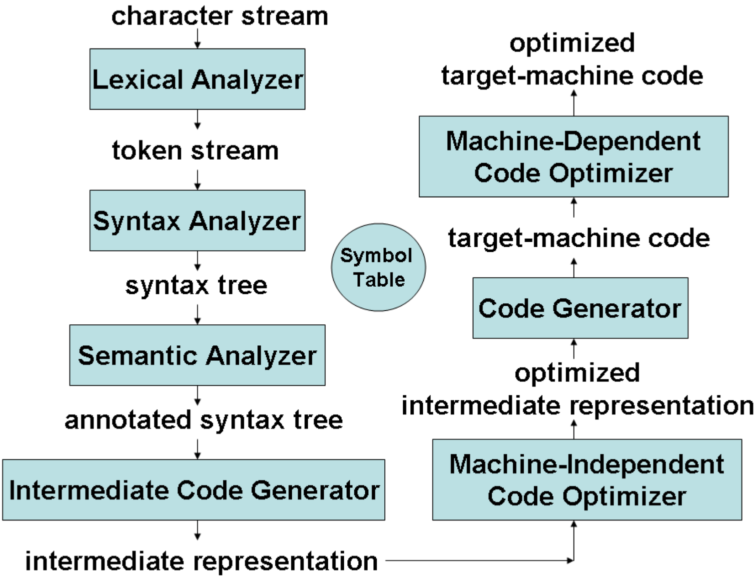
- Converting a sequential loop to a parallel loop
- Program analysis to determine if programs are data-race free
- Profiling programs to determine busy regions
- Program slicing
- Data-flow analysis approach to software testing
  - Uncovering errors along all paths
  - Dereferencing null pointers
  - Buffer overflows and memory leaks
- Worst Case Execution Time (WCET) estimation and energy analysis

Language Processing System



A LANGUAGE PROCESSING SYSTEM

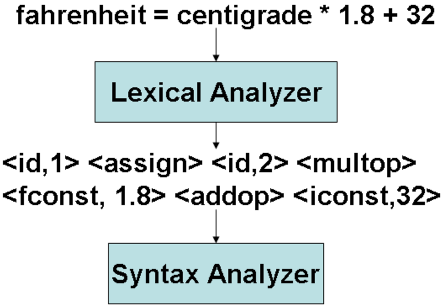
Compiler Overview



Compilers and Interpreters

- Compilers generate machine code, whereas interpreters interpret intermediate code
- Interpreters are easier to write and can provide better error messages (symbol table is still available)
- Interpreters are at least 5 times slower than machine code generated by compilers
- Interpreters also require much more memory than machine code generated by compilers
- Examples: Perl, Python, Unix Shell, Java, BASIC, LISP

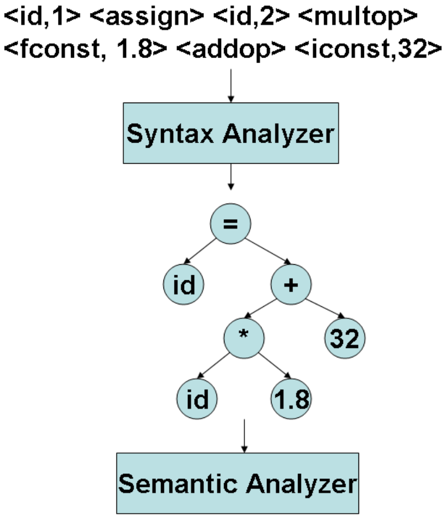
Translation Overview - Lexical Analysis



Lexical Analysis

- LA can be generated automatically from regular expression specifications
  - LEX and Flex are two such tools
- LA is a deterministic finite state automaton
- Why is LA separate from parsing?
  - Simplification of design - software engineering reason
  - I/O issues are limited LA alone
  - LA based on finite automata are more efficient to implement than pushdown automata used for parsing (due to stack)

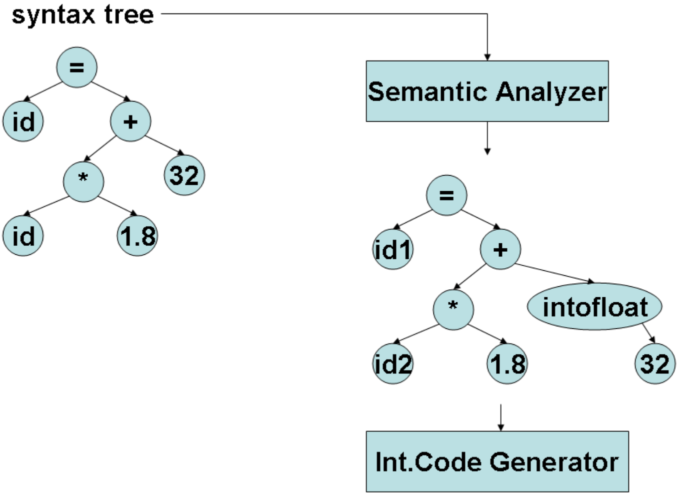
Translation Overview - Syntax Analysis



Parsing or Syntax Analysis

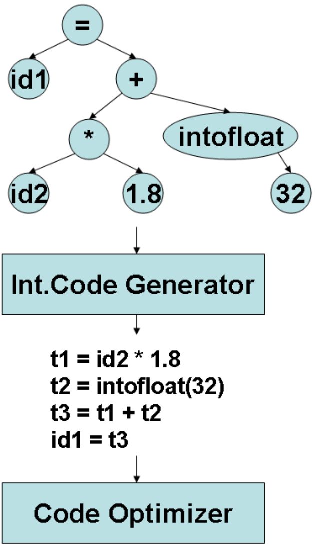
- Syntax analyzers (parsers) can be generated automatically from several variants of context-free grammar specifications
  - LL(1), and LALR(1) are the most popular ones
  - ANTLR (for LL(1)), YACC and Bison (for LALR(1)) are such tools
- Parsers are deterministic push-down automata
- Parsers cannot handle context-sensitive features of programming languages; e.g.,
  - Variables are declared before use
  - Types match on both sides of assignments
  - Parameter types and number match in declaration and use

Translation Overview - Semantic Analysis



Semantic Analysis

- Semantic consistency that cannot be handled at the parsing stage is handled here
- Type checking of various programming language constructs is one of the most important tasks
- Stores type information in the symbol table or the syntax tree
  - Types of variables, function parameters, array dimensions, etc.
  - Used not only for semantic validation but also for subsequent phases of compilation
- Static semantics of programming languages can be specified using attribute grammars


=
id1
+
*
intofloat
id2
1.8
32
Int.Code Generator
t1 = id2 * 1.8
t2 = intofloat(32)
t3 = t1 + t2
id1 = t3
Code Optimizer

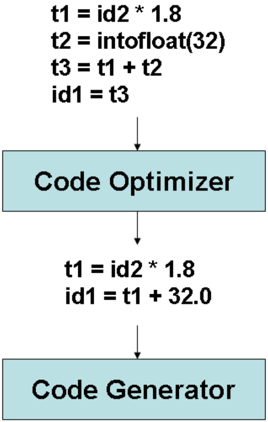
Intermediate Code Generation

- While generating machine code directly from source code is possible, it entails two problems
  - With m languages and n target machines, we need to write $m \times n$ compilers
  - The code optimizer which is one of the largest and very-difficult-to-write components of any compiler cannot be reused
- By converting source code to an intermediate code, a machine-independent code optimizer may be written
- Intermediate code must be easy to produce and easy to translate to machine code
  - A sort of universal assembly language
  - Should not contain any machine-specific parameters (registers, addresses, etc.)

Different Types of Intermediate Code

- The type of intermediate code deployed is based on the application
- Quadruples, triples, indirect triples, abstract syntax trees are the classical forms used for machine-independent optimizations and machine code generation
- Static Single Assignment form (SSA) is a recent form and enables more effective optimizations
    - Conditional constant propagation and global value numbering are more effective on SSA
- Program Dependence Graph (PDG) is useful in automatic parallelization, instruction scheduling, and software pipelining

Translation Overview - Code Optimization



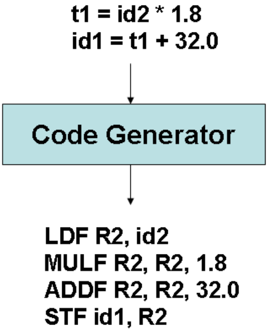
Machine-independent Code Optimization

- Intermediate code generation process introduces many inefficiencies
  - Extra copies of variables, using variables instead of constants, repeated evaluation of expressions, etc.
- Code optimization removes such inefficiencies and improves code
- Improvement may be time, space, or power consumption
- It changes the structure of programs, sometimes of beyond recognition
  - Inlines functions, unrolls loops, eliminates some programmer-defined variables, etc.
- Code optimization consists of a bunch of heuristics and percentage of improvement depends on programs (may be zero also)

Examples of Machine-Independant Optimizations

- Common sub-expression elimination
- Copy propagation
- Loop invariant code motion
- Partial redundancy elimination
- Induction variable elimination and strength reduction
- Code opimization needs information about the program
  - which expressions are being recomputed in a function?
  - which definitions reach a point?
- All such information is gathered through data-flow analysis

Translation Overview - Code Generation



Code Generation

- Converts intermediate code to machine code
- Each intermediate code instruction may result in many machine instructions or vice-cersa
- Must handle all aspects of machine architecture
  - Registers, pipelining, cache, multiple function units, etc.
- Generating efficient code is an NP-complete problem
  - Tree pattern matching-based strategies are among the best
  - Needs tree intermediate code
- Storage allocation decisions are made here
  - Register allocation and assignment are the most important problems

Machine-Dependent Optimizations

- Peephole optimizations
  - Analyze sequence of instructions in a small window (*peephole*) and using preset patterns, replace them with a more efficient sequence
  - Redundant instruction elimination
    e.g., replace the sequence [LD A,R1][ST R1,A] by [LD A,R1]
  - Eliminate “jump to jump” instructions
  - Use machine idioms (use INC instead of LD and ADD)
- Instruction scheduling (reordering) to eliminate pipeline interlocks and to increase parallelism
- Trace scheduling to increase the size of basic blocks and increase parallelism
- Software pipelining to increase parallelism in loops