CMSC 430
Theory of Language Translation

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These slides are based on slides copyrighted by Keith Cooper, Linda Torczon & Ken Kennedy at Rice University, with modifications by Uli Kremer at Rutgers University

CMSC 430 — a.k.a. Compilers

- Catalog Description
  - → Introduction to compiler construction (emphasis on compiler front ends). Course contents include the following: Formal translation of programming languages, program syntax and semantics. Finite state recognizers and regular grammars. Context-free parsing techniques such as LL(k) and LR(k). Code generation, improvement, syntax-directed translation schema.
- Course Objectives
  - → This course focuses on compilation techniques needed to translate programs written in a standard programming language into executable code on microprocessor architectures. Program analysis and optimization techniques are presented in class lectures. Programming projects provide experience with implementation issues and allow students to develop programming and software engineering skills.

Basis for Grading

- Tests
  - → 2 Midterms 15%
  - → Final 20%
- Projects
  - → Scanner 10%
  - → Parser 10%
  - → Type Checker 10%
  - → Code Generator 10%
  - → Optimizer 10%

Notice: *This grading scheme is tentative and subject to change.*

Basis for Grading

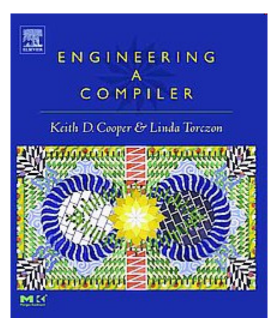
• Exams → Midterms → Final	☞ Closed-notes, closed-book ☞ Final is cumulative
• Practice problems	☞ Reinforce concepts, provide practice
• Projects	☞ Cumulative ☞ Don't fall behind!

Syllabus

- Scanning
- Parsing
- Context Sensitive Analysis
- Runtime Environment
- Intermediate Representations
- Code Generation
- Optimizations
- Dataflow Analysis
- Register Allocation
- Instruction Scheduling

Recommended Textbook

- Engineering A Compiler
  - → Keith Cooper & Linda Torczon



Class-taking technique for CMSC 430

- I will use slides extensively
  - → I will moderate my speed, *you* sometimes need to say "STOP"
- You should read books for details
  - → Not all material will be covered in class
  - → Book complements the lectures
- CMSC 430 is not a programming course
  - → Projects are graded on functionality, documentation, and project reports more than style. However, things should be reasonable
- Use the resources provided to you
  - → See me in office hours if you have questions
  - → Post questions regarding projects on Forum

Compilers

- What is a compiler?
  - → A program that translates an *executable* program in one language into an *executable* program in another language
  - → A good compiler should improve the program, *in some way*
- What is an interpreter?
  - → A program that reads an *executable* program and produces the results of executing that program
- C is typically compiled, Scheme is typically interpreted
- Java is compiled to bytecodes (code for the Java VM)
  - → which are then interpreted
  - → Or a hybrid strategy is used
    - Just-in-time compilation
    - Dynamic optimization (hot paths)

Why Study Compilation?

- Compilers are important system software components
  - → They are intimately interconnected with architecture, systems, programming methodology, and language design
- Compilers include many applications of theory to practice
  - → Scanning, parsing, static analysis, instruction selection
- Many practical applications have embedded languages
  - → Commands, macros, …
- Many applications have input formats that look like languages,
  - → Matlab, Mathematica
- Writing a compiler exposes practical algorithmic & engineering issues
  - → Approximating hard problems; efficiency & scalability

Intrinsic interest

- Compiler construction involves ideas from many different parts of computer science

Artificial intelligence	Greedy algorithms Heuristic search techniques
Algorithms	Graph algorithms, union-find Dynamic programming
Theory	DFAs & PDAs, pattern matching Fixed-point algorithms
Systems	Allocation & naming, Synchronization, locality
Architecture	Pipeline & hierarchy management Instruction set use

Intrinsic merit

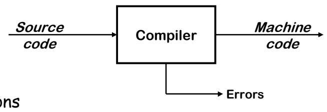
- Compiler construction poses challenging and interesting problems:
  - → Compilers must do a lot but also run fast
  - → Compilers have primary responsibility for run-time performance
  - → Compilers are responsible for making it acceptable to use the full power of the programming language
  - → Computer architects perpetually create new challenges for the compiler by building more complex machines
  - → Compilers must hide that complexity from the programmer
  - → Success requires mastery of complex interactions

Making Languages Usable

It was our belief that if FORTRAN, during its first months, were to translate any reasonable "scientific" source program into an object program only half as fast as its hand-coded counterpart, then acceptance of our system would be in serious danger... I believe that had we failed to produce efficient programs, the widespread use of languages like FORTRAN would have been seriously delayed.

— John Backus

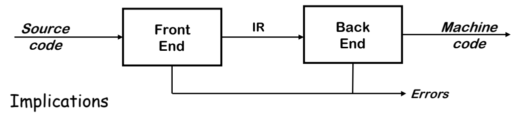
High-level View of a Compiler



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

Big step up from assembly language—use higher level notations

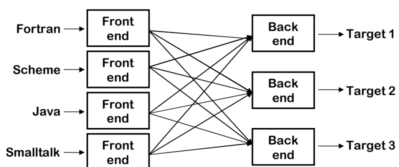
Traditional Two-pass Compiler



Implications
- Use an intermediate representation (IR)
- Front end maps legal source code into IR
- Back end maps IR into target machine code
- Extension: multiple front ends & multiple passes (*better code*)

Typically, front end is O(n) or O(n log n), while back end is NPC

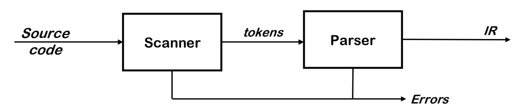
A Common Fallacy



Can we build *n x m* compilers with *n+m* components?
- Must encode all language specific knowledge in each front end
- Must encode all features in a single IR
- Must encode all target specific knowledge in each back end

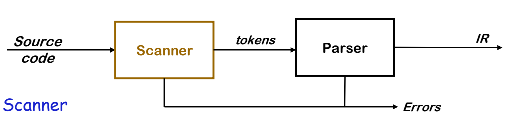
Limited success in systems with very low-level IRs

The Front End



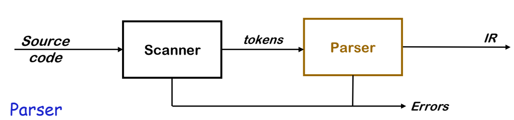
Responsibilities
- Recognize legal (& illegal) programs
- Report errors in a useful way
- Produce IR & preliminary storage map
- Shape the code for the back end
- Much of front end construction can be automated

The Front End



Scanner
- Maps character stream into words—the basic unit of syntax
- Produces pairs — a word & its part of speech
  - x = x + y ; *becomes* <id,x> = <id,x> + <id,y> ;
  - → *word ≅ lexeme, part of speech ≅ token type*
  - → In casual speech, we call the pair a *token*
- Typical tokens include *number*, *identifier*, +, –, new, *while*, *if*
- Scanner eliminates white space (*including comments*)
- Speed is important

The Front End



Parser
- Recognizes context-free syntax & reports errors
- Guides context-sensitive ("semantic") analysis (*type checking*)
- Builds IR for source program

Hand-coded parsers are fairly easy to build
Most books advocate using automatic parser generators

The Front End

Context-free syntax is specified with a grammar

SheepNoise → *SheepNoise* baa
  | baa

This grammar defines the set of noises that a sheep makes under normal circumstances

It is written in a variant of Backus–Naur Form (BNF)

Formally, a grammar *G = (S,N,T,P)*

- *S* is the *start symbol*
- *N* is a set of *non-terminal symbols*
- *T* is a set of *terminal symbols* or *words*
- *P* is a set of *productions* or *rewrite rules* (*P : N* → *N* ∪ *T*)

The Front End

Context-free syntax can be put to better use

1. *goal* → *expr*
2. *expr* → *expr op term*
3. | *term*
4. *term* → number
5. | id
6. *op* → +
7. | -

S = *goal*

T = { number, id, +, - }

N = { *goal, expr, term, op* }

P = { 1, 2, 3, 4, 5, 6, 7}

- This grammar defines simple expressions with addition & subtraction over "number" and "id"
- This grammar, like many, falls in a class called "context-free grammars", abbreviated CFG

The Front End

Given a CFG, we can *derive* sentences by repeated substitution

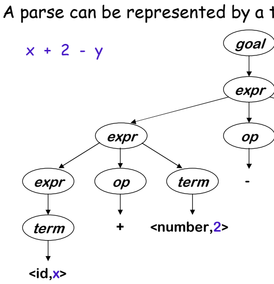
Production	Result
	goal
1	*expr*
2	*expr op term*
5	*expr op* y
7	*expr* - y
2	*expr op term* - y
4	*expr op* 2 - y
6	*expr* + 2 - y
3	*term* + 2 - y
5	x + 2 - y

To recognize a valid sentence in some CFG, we reverse this process and build up a *parse*

The Front End

A parse can be represented by a tree (*parse tree* or *syntax tree*)

x + 2 - y



1. *goal* → *expr*
2. *expr* → *expr op term*
3. | *term*
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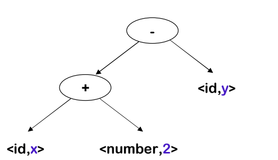
7. | -

This contains a lot of unneeded information.

The Front End

Compilers often use an *abstract syntax tree*

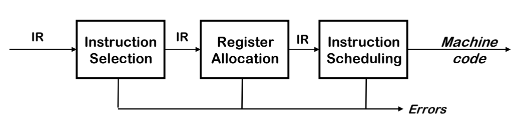


The AST summarizes grammatical structure, without including detail about the derivation

This is much more concise

ASTs are one kind of *intermediate representation (IR)*

The Back End

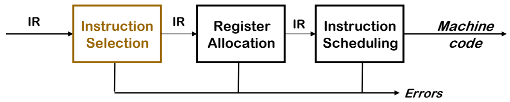


Responsibilities

- Translate IR into target machine code
- Choose instructions to implement each IR operation
- Decide which value to keep in registers
- Ensure conformance with system interfaces

Automation has been *less* successful in the back end

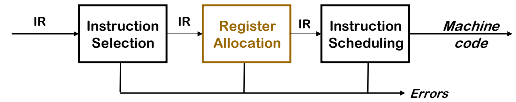
The Back End



Instruction Selection
- Produce fast, compact code
- Take advantage of target features such as addressing modes
- Usually viewed as a pattern matching problem
  - → *ad hoc* methods, pattern matching, dynamic programming

This was the problem of the future in 1978
- → Spurred by transition from PDP-11 to VAX-11
- → Orthogonality of RISC simplified this problem

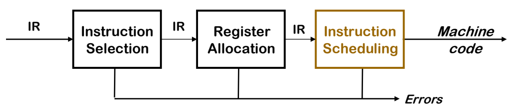
The Back End



Register Allocation
- Have each value in a register when it is used
- Manage a limited set of resources
- Can change instruction choices & insert LOADs & STOREs
- Optimal allocation is NP-Complete (1 or *k* registers)

Typically, compilers approximate solutions to NP-Complete problems

The Back End

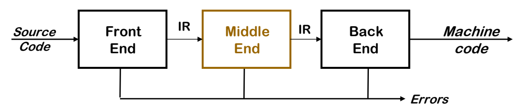


Instruction Scheduling
- Avoid hardware stalls and interlocks
- Use all functional units productively
- Can increase lifetime of variables (changing the allocation)

Optimal scheduling is NP-Complete in nearly all cases

Heuristic techniques are well developed

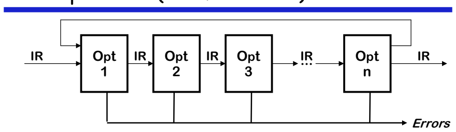
Traditional Three-pass Compiler



Code Improvement (or *Optimization*)
- Analyzes IR and rewrites (or *transforms*) IR
- Primary goal is to reduce running time of the compiled code
  - → May also improve space, power consumption, …
- Must preserve "meaning" of the code
  - → Measured by values of named variables

Subject of CS515, and CS516, maybe final weeks of 415

The Optimizer (or Middle End)



Modern optimizers are structured as a series of passes

Typical Transformations
- Discover & propagate some constant value
- Move a computation to a less frequently executed place
- Specialize some computation based on context
- Discover a redundant computation & remove it
- Remove useless or unreachable code
- Encode an idiom in some particularly efficient form

Example

- Optimization of Subscript Expressions in Fortran

Address(A(I,J)) = address(A(0,0)) + J * (column size) + I

Does the user realize a multiplication is generated here?

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```
DO I = 1, M
    A(I,J) = A(I,J) + C
ENDDO
```


Example

- Optimization of Subscript Expressions in Fortran

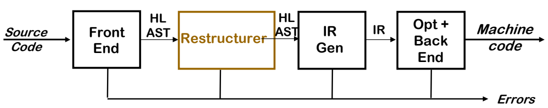
Address(A(I,J)) = address(A(0,0)) + J * (column size) + I

Does the user realize a multiplication is generated here?

```
DO I = 1, M
    A(I,J) = A(I,J) + C
ENDDO
```

```
compute addr(A(0,J)
DO I = 1, M
    add 1 to get addr(A(I,J))
    A(I,J) = A(I,J) + C
ENDDO
```


Modern Restructuring Compiler



Typical Restructuring (source-to-source) Transformations:

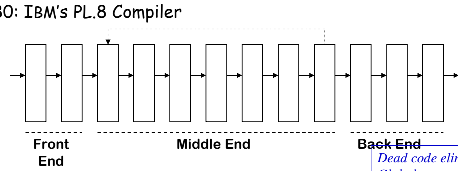
- Blocking for memory hierarchy and register reuse
- Vectorization
- Parallelization
- All based on dependence
- Also full and partial inlining

Role of the Run-time System

- Memory management services
  - Allocate
    - In the heap or in an activation record (*stack frame*)
  - Deallocate
  - Collect garbage
- Run-time type checking
- Error processing (exception handling)
- Interface to the operating system
  - Input and output
- Support of parallelism
  - Parallel thread initiation
  - Communication and synchronization

Classic Compilers

1980: IBM's PL.8 Compiler



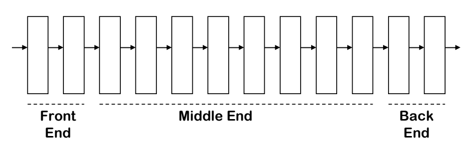
- Many passes, one front end, several back ends
- Collection of 10 or more passes
  - Repeat some passes and analyses
  - Represent complex operations at 2 levels
  - Below machine-level IR

Dead code elimination
Global cse
Code motion
Constant folding
Strength reduction
Value numbering
Dead store elimination
Code straightening
Trap elimination
Algebraic reassociation

Multi-level IR has become common wisdom

Classic Compilers

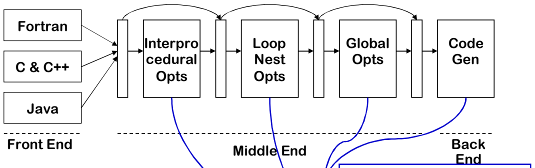
1986: HP's PA-RISC Compiler



- Several front ends, an optimizer, and a back end
- Four fixed-order choices for optimization (9 passes)
- Coloring allocator, instruction scheduler, peephole optimizer

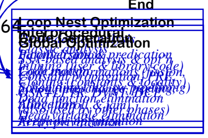
Classic Compilers

2000: The SGI Pro64 Compiler (now Open64 from Intel)



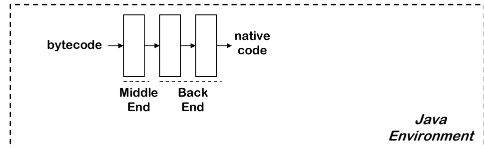
Open source optimizing compiler for IA 64

- 3 front ends, 1 back end
- Five-levels of IR
- Gradual lowering of abstraction level



Classic Compilers

Even a 2000 JIT fits the mold, albeit with fewer passes



- Front end tasks are handled elsewhere
- Few (if any) optimizations
  - Avoid expensive analysis
  - Emphasis on generating native code
  - Compilation must be profitable