6.035

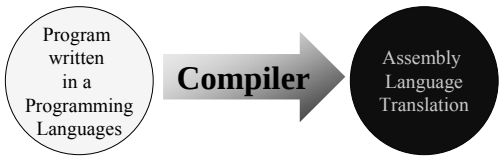
Fall 2005

Lecture 15: Putting it all together

From parsing to code generation

How to make the computer understand?

- Write a program using a programming language
- Microprocessors talk in assembly language



Example (input program)

```
int expr(int n)
{
    int d;
    d = 4 * n * n * (n + 1) * (n + 1);
    return d;
}
```


Example (Output assembly code)

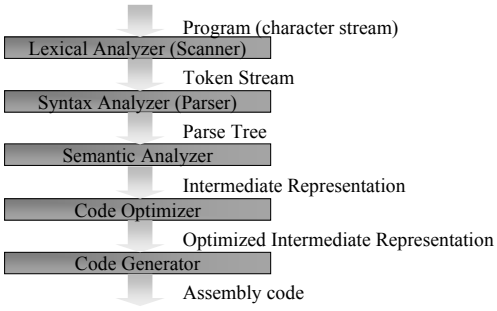
Unoptimized Code

```
   expr:
.LFB2:
        pushq   %rbp
.LCFI0:
        movq    %rsp, %rbp
.LCFI1:
        movl    %edi, -4(%rbp)
        movl    -4(%rbp), %eax
        movl    %eax, %edx
        imull   -4(%rbp), %edx
        movl    -4(%rbp), %eax
        incl    %eax
        imull   %eax, %edx
        movl    -4(%rbp), %eax
        incl    %eax
        imull   %edx, %eax
        sall    $2, %eax
        movl    %eax, -8(%rbp)
        movl    -8(%rbp), %eax
        leave
        ret
```

Optimized Code

```
   expr:
.LFB2:
        movl    %edi, %eax
        imull   %edi, %eax
        incl    %edi
        imull   %edi, %eax
        imull   %edi, %eax
        sall    $2, %eax
        ret
```


Anatomy of a Computer



Lexical Analysis

- Lexical analyzer create tokens out of a text stream
- Tokens are defined using regular expressions

Examples of Regular Expressions

Regular Expression	Strings matched
a	"a"
a · b	"ab"
a | b	"a" "b"
ε	""
a*	"" "a" "aa" "aaa" …
(a | ε) · b	"ab" "b"
num = 0|1|2|3|4|5|6|7|8|9	"0" "1" "2" "3" …
posint = *num* · *num**	"8" "6035" …
int = (ε | -) · *posint*	"-42" "1024" …
real = *int* · (ε | (. · *posint*))	"-12.56" "12" "1.414"...

Lexical Analysis

- Lexical analyzer create tokens out of a text stream
- Tokens are defined using regular expressions
- Regular expressions can be mapped to Nondeterministic Finite Automatons (NFA)
  - by simple construction
- NFA is transformed to a DFA
  - Transformation algorithm
  - Executing a DFA is straightforward

Syntax Analysis (parsing)

- Defining a language using context-free grammars

Example: A CFG for expressions

<expr> → <expr> <op> <expr>

<expr> → (<expr>)

<expr> → - <expr>

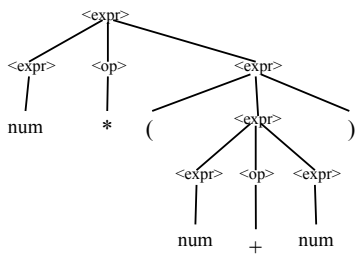
<expr> → **num**

<op> → +

<op> → *

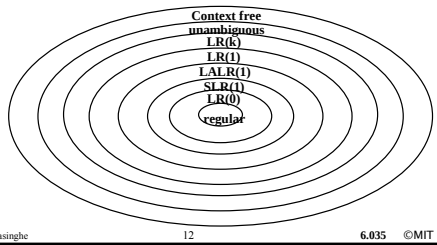
Parse Tree Example

num '*' '(' num '+' num ')'



Syntax Analysis (parsing)

- Defining a language using context-free grammars
- Classification of Grammars



LR(k) Parser Engine

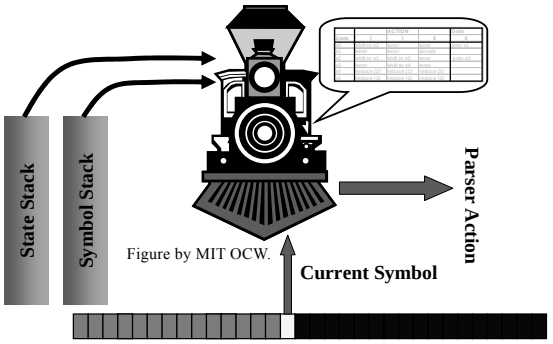
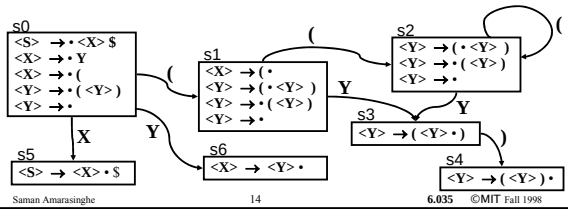


Figure by MIT OCW.

		ACTION		Goto	
State	(	)	$	X	Y
s0	shift to s2	reduce (5)	reduce (5)	goto s5	goto s6
s1	shift to s2	reduce (5)	reduce(3 or 5)		goto s3
s2	shift to s2	reduce (5)	reduce (5)		goto s3
s3	error	shift to s4	error		
s4	error	reduce (4)	reduce (4)		
s5	error	error	accept		
s6	error	error	reduce (2)		



Semantic Analysis

- Building a symbol table
- Static Checking
  - Flow-of-control checks
  - Uniqueness checks
  - Type checking
- Dynamic Checking
  - Array bounds check
  - Null pointer dereference check

Translation to Intermediate Format

- Goal: Remain Largely Machine Independent But Move Closer to Standard Machine Model
  - From high-level IR to a low-level IR
- Eliminate Structured Flow of Control
- Convert to a Flat Address Space

Code Optimizations

- Generate code as good as hand-crafted by a good assembly programmer
- Have stable, robust performance
- Abstract the architecture away from the programmer
  - Exploit architectural strengths
  - Hide architectural weaknesses

Code Optimizations

- Algebraic simplification
- Common subexpression elimination
- Copy propagation
- Constant propagation
- Dead-code elimination
- Register allocation
- Instruction Scheduling

Compiler Project!

- You guys build a full-blown compiler from the ground up!!!
- From decaf to working code

Compiler Derby

- Who has the fastest compiler in the east???
- Will give you the program 12 hours in advance
  - Test and make all the optimizations work
  - DO NOT ADD PROGRAM SPECIFIC HACKS!
- Wednesday, December 14th at 11:00AM location TBA
  - refreshments provided

How will you use 6.035 knowledge?

- As an informed programmer
- As a designer of simple languages to aid other programming tasks
- As an engineer dealing with new computer architectures
- As a true compiler hacker

1. Informed Programmer

- Now you know what the compiler is doing
  - don't treat it as a black box
  - don't trust it to do the right thing!
- Implications
  - performance
  - debugging
  - correctness

1. Informed Programmer

- What did you learned in 6.035?
  - How optimizations work
    or why they did not work
  - How to read and understand optimized code

2. Language Extensions

- In many applications and systems, you may need to:
  - implement a simple language
    - handle input
    - define an interface
    - command and control
  - extend a language
    - add new functionality
    - modify semantics
    - help with optimizations

2. Language Extensions

- What you learned in 6.035
  - define tokens and languages using regular expressions and CFGs
  - use tools such as jlex, lex, javacup, yacc
  - build intermediate representations
  - perform simple transformations on the IR

3. Computer Architectures

- Many special purpose processors
  - in your cell phone, car engine, watch, etc. etc.
- Designing new architectures
- Adapting compiler back-ends for new architectures

3. Designing New Architectures

- Great advances in VLSI technology
  - very fast and small transistors
  - scaling up to billion transistors
  - but, slow and limited wires and I/O
- A computer architecture is a combination of hardware and compiler
  - need to know what a compiler can do and what hardware need to do
  - If compiler can do it don't waste hardware resources.

3. Designing New Architectures

- What did you learned in 6.035
  - Capabilities of a compiler: what is simple and what is hard to do
  - How to think like a compiler writer

3. Back-end support

- Every new architecture need a new backend
- Instruction scheduling
  - Even if the ISA is the same, different resource constrains
  - How to handle new features

3. Back-end support

- What do you learned in 6.035
  - Intermediate representations
  - Transforming/optimizing the IR
  - Process of generating assembly from a high-level IR
  - Assembly interface issues (eg: calling conventions)
  - Register allocation issues
  - Code scheduling issues

4. Compiler Hacking

- Theory
- Algorithms
- Implementation

4. Compiler Hacking

- Theory:
  - Develop general, abstract concepts
  - Prove correctness, optimality etc.
- Examples
  - parse theory
  - lattices and data-flow
  - abstract interpretation
  - The language ML

4. Compiler Hacking

- Algorithms:
  - Design a solution to a given problem (Mostly new optimizations)
  - Use many techniques such as graph theory, number theory, etc.
  - May have to limit the scope and find good heuristics
- Examples
  - partial redundancy elimination
  - register allocation by graph coloring
  - using multi-granular (MMX) operations

4. Compiler Hacking

- Implementation:
  - Develop a new compiler
  - Issues of designing a very complex software
  - Putting theory and algorithms into practice
- Examples
  - A JIT for Java
  - A query optimization engine for SQL
  - A rasterizer for postscript

4. Compiler Hacking

- What did you learned in 6.035?

Everything!!!!

Where to Look for Current Research?

- PLDI – Programming Languages Design and Implementation Conference
- Code Generation / Machine specific
  - Micro Conference
  - ASPLOS – Architecture Support for Programming Languages and Operating Systems
  - CGO – Code Generation and Optimization
- Language Theory
  - POPL – Principles of Programming Languages
  - OOPSLA – Object Oriented Programming Systems Languages and Applications
- Program Analysis
  - SAS – Static Analysis Symposium
  - PPoPP – Principles and Practice of Parallel Programming