6.035

Spring 2010

Lecture 1: Introduction

Intro. to Computer Language Engineering

Course Administration info.

Outline

- Course Administration Information
- Introduction to computer language engineering
  - Why do we need a compiler?
  - What are compilers?
  - Anatomy of a compiler

Course Administration

- Staff
- Optional Text
- Course Outline
- The Project
- Project Groups
- Grading

Reference Textbooks

- *Modern Compiler Implementation in Java (Tiger book)*
  A.W. Appel
  Cambridge University Press, 1998
  ISBN 0-52158-388-8

  A textbook tutorial on compiler implementation, including techniques for many language features

- *Advanced Compiler Design and Implementation (Whale book)*
  Steven Muchnick
  Morgan Kaufman Publishers, 1997
  ISBN 1-55860-320-4

  Essentially a recipe book of optimizations; very complete and suited for industrial practitioners and researchers.

- *Compilers: Principles, Techniques and Tools (Dragon book)*
  Aho, Lam, Sethi and Ullman
  Addison-Wesley, 2006
  ISBN 0321486811

  The classic compilers textbook, although its front-end emphasis reflects its age. New edition has more optimization material.

- *Engineering a Compiler (Ark book)*
  Keith D. Cooper, Linda Torczon
  Morgan Kaufman Publishers, 2003
  ISBN 1-55860-698-X

  A modern classroom textbook, with increased emphasis on the back-end and implementation techniques.

- *Optimizing Compilers for Modern Architectures*
  Randy Allen and Ken Kennedy
  Morgan Kaufman Publishers, 2001
  ISBN 1-55860-286-0

  A modern textbook that focuses on optimizations including parallelization and memory hierarchy optimization

The Project: The Five Segments

❶ Lexical and Syntax Analysis

❷ Semantic Analysis

❸ Code Generation

❹ Data-flow Analysis

❺ Optimizations

Each Segment...

- Segment Start
  - Project Description
- Lectures
  - 2 to 5 lectures
- Project Time
  - (Design Document)
  - (Project Checkpoint)
- Project Due

Project Groups

- 1st project is an individual project
- Projects 2 to 5 are group projects consists of 3 to 4 students

- Grading
  - All group members (mostly) get the same grade

Grades

• Compiler project	70%	
• In-class Quizzes	30%	(10% each)
• In-class mini-quizzes	10%	(0.5% each)

Grades for the Project

– Scanner/Parser	5%
– Semantic Checking	7.5%
– Code Generation	10%
– Data-flow Analysis	7.5%
– Optimizations	30%
	60%

Optimization Segment

- Making programs run fast
  - We provide a test set of applications
  - Figure-out what will make them run fast
    Prioritize and implement the optimizations
  - Compiler derby at the end
    - A “similar” application to the test set is provided the day before
    - The compiler that produced the fastest code is the winner
- Do any optimizations you choose
  - Including parallelization for multicores
- Grade is divided into:
  - Documentation 6%
    - Justify your optimizations and the selection process
  - Optimization Implementation 12%
    - Producing correct code
  - Derby performance 12%

30%

The Quiz

- Three Quizzes
- **In-Class Quiz**
  - 50 Minutes (be on time!)
  - Open book, open notes

Mini Quizzes

- You already got one.
- Given at the beginning of the class; Collected at the end
- Collaboration is OK

- This is in lieu of time consuming problem sets

Outline

- Course Administration Information
- Introduction to computer language engineering
  - What are compilers?
  - Why should we learn about them?
  - Anatomy of a compiler

Why Study Compilers?

- Compilers enable programming at a high level language instead of machine instructions.
  - Malleability, Portability, Modularity, Simplicity, Programmer Productivity

    Also Efficiency and Performance

Compilers Construction touches many topics in Computer Science

- Theory
  - Finite State Automata, Grammars and Parsing, data-flow
- Algorithms
  - Graph manipulation, dynamic programming
- Data structures
  - Symbol tables, abstract syntax trees
- Systems
  - Allocation and naming, multi-pass systems, compiler construction
- Computer Architecture
  - Memory hierarchy, instruction selection, interlocks and latencies, parallelism
- Security
  - Detection of and Protection against vulnerabilities
- Software Engineering
  - Software development environments, debugging
- Artificial Intelligence
  - Heuristic based search for best optimizations

Power of a Language

- Can use to describe any action
  - Not tied to a “context”
- Many ways to describe the same action
  - Flexible

How to instruct a computer

- How about natural languages?
  - English??
  - "Open the pod bay doors, Hal."
  - "I am sorry Dave, I am afraid I cannot do that"
  - We are not there yet!!

- Natural Languages:
  - Powerful, but...
  - Ambiguous
    - Same expression describes many possible actions

Programming Languages

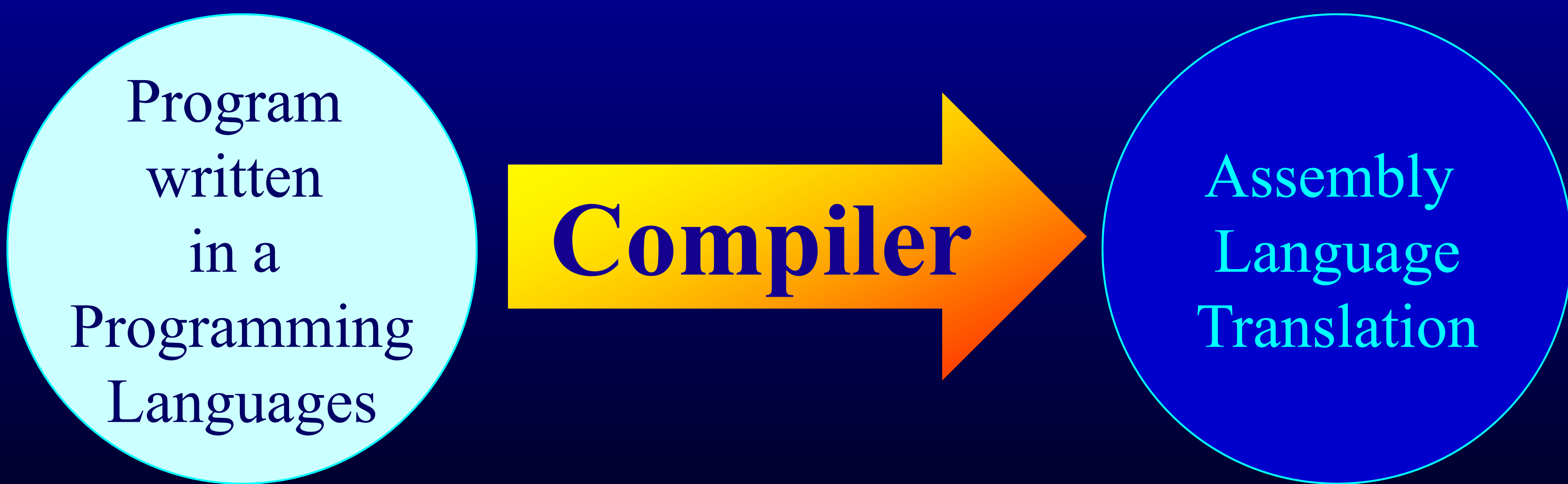
- Properties
  - need to be precise
  - need to be concise
  - need to be expressive
  - need to be at a high-level (lot of abstractions)

High-level Abstract Description to Low-level Implementation Details

Figure by MIT OpenCourseWare.

1. How to instruct the computer

- Write a program using a programming language
  – High-level Abstract Description
- Microprocessors talk in assembly language
  – Low-level Implementation Details



1. How to instruct the computer

- Input: High-level programming language
- Output: Low-level assembly instructions

- Compiler does the translation:
  - Read and understand the program
  - Precisely determine what actions it require
  - Figure-out how to faithfully carry-out those actions
  - Instruct the computer to carry out those actions

Input to the Compiler

- Standard imperative language (Java, C, C++)
  - State
    - Variables,
    - Structures,
    - Arrays
  - Computation
    - Expressions (arithmetic, logical, etc.)
    - Assignment statements
    - Control flow (conditionals, loops)
    - Procedures

Output of the Compiler

- State
  - Registers
  - Memory with Flat Address Space
- Machine code – load/store architecture
  - Load, store instructions
  - Arithmetic, logical operations on registers
  - Branch instructions

Example (input program)

```
int sumcalc(int a, int b, int N)
{
    int i, x, y;
    x = 0;
    y = 0;
    for(i = 0; i <= N; i++) {
        x = x + (4*a/b)*i + (i+1)*(i+1);
        x = x + b*y;
    }
    return x;
}
```

Example (Output assembly code)

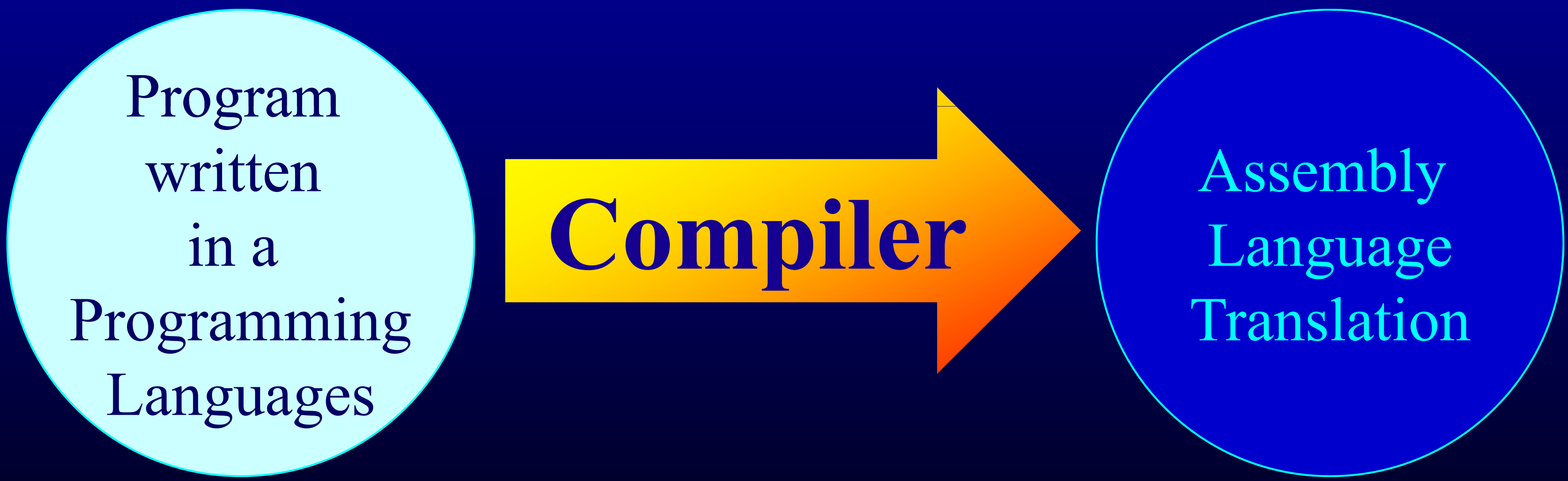
```
sumcalc:
        pushq   %rbp
        movq    %rsp, %rbp
        movl    %edi, -4(%rbp)
        movl    %esi, -8(%rbp)
        movl    %edx, -12(%rbp)
        movl    $0, -20(%rbp)
        movl    $0, -24(%rbp)
        movl    $0, -16(%rbp)
.L2:    movl    -16(%rbp), %eax
        cmpl    -12(%rbp), %eax
        jg      .L3
        movl    -4(%rbp), %eax
        leal    0(,%rax,4), %edx
        leaq    -8(%rbp), %rax
        movq    %rax, -40(%rbp)
        movl    %edx, %eax
        movq    -40(%rbp), %rcx
        cltd
        idivl   (%rcx)
        movl    %eax, -28(%rbp)
        movl    -28(%rbp), %edx
        imull   -16(%rbp), %edx
        movl    -16(%rbp), %eax
        incl    %eax
        imull   %eax, %eax
        addl    %eax, %edx
        leaq    -20(%rbp), %rax
        addl    %edx, (%rax)
        movl    -8(%rbp), %eax
        movl    %eax, %edx
        imull   -24(%rbp), %edx
        leaq    -20(%rbp), %rax
        addl    %edx, (%rax)
        leaq    -16(%rbp), %rax
        incl    (%rax)
        jmp     .L2
.L3:    movl    -20(%rbp), %eax
        leave
        ret
```

```
         .size   sumcalc, .-sumcalc
        .section
.Lframe1:
        .long    .LECIE1-.LSCIE1
.LSCIE1:.long    0x0
        .byte    0x1
        .string  ""
        .uleb128 0x1
        .sleb128 -8
        .byte    0x10
        .byte    0xc
        .uleb128 0x7
        .uleb128 0x8
        .byte    0x90
        .uleb128 0x1
        .align   8
.LECIE1:.long    .LEFDE1-.LASFDE1
        .long    .LASFDE1-.Lframe1
        .quad    .LFB2
        .quad    .LFE2-.LFB2
        .byte    0x4
        .long    .LCFI0-.LFB2
        .byte    0xe
        .uleb128 0x10
        .byte    0x86
        .uleb128 0x2
        .byte    0x4
        .long    .LCFI1-.LCFI0
        .byte    0xd
        .uleb128 0x6
        .align   8
```

Mapping Time Continuum Compilation to Interpretation

- Compile time
  - Ex: C compiler
- Link time
  - Ex: Binary layout optimizer
- Load time
  - Ex: JIT compiler
- Run time
  - Ex: Java Interpreter

Anatomy of a Computer



Anatomy of a Computer

Lexical Analyzer (Scanner)

2	3	4		*		(	1	1		+	-	2	2	)							

Num(234) mul_op lpar_op Num(11) add_op Num(-22) rpar_op

Lexical Analyzer (Scanner)

2	3	4		*		(	1	1		+	-	2	2	)							

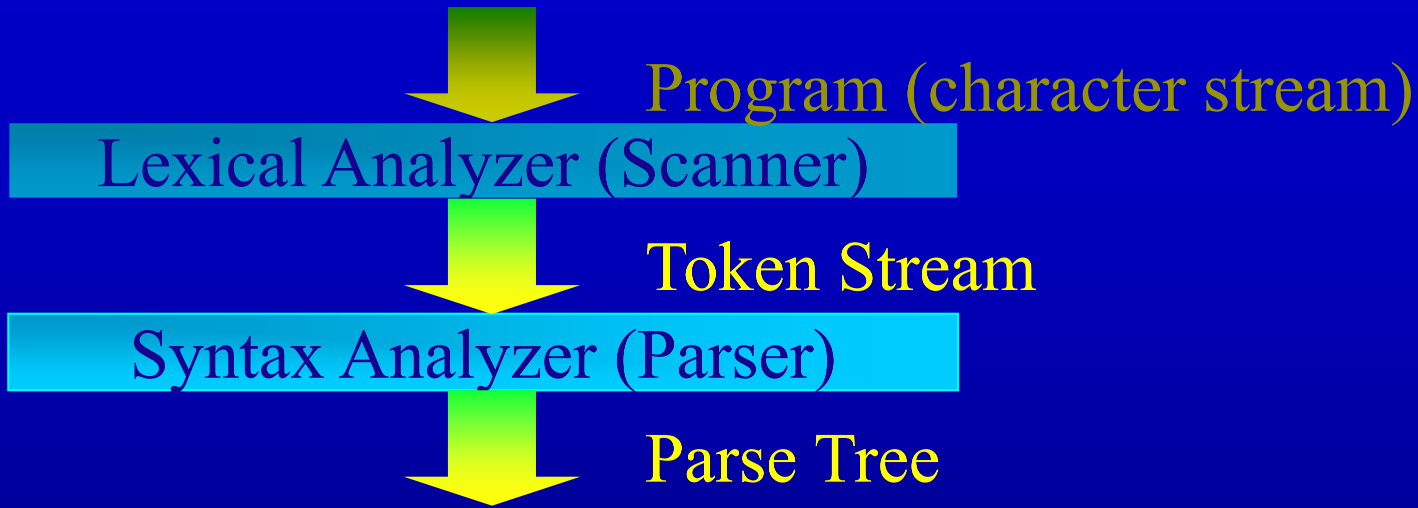
Num(234) mul_op lpar_op Num(11) add_op Num(-22) rpar_op

18..23 + val#ue

Variable names cannot have '#' character

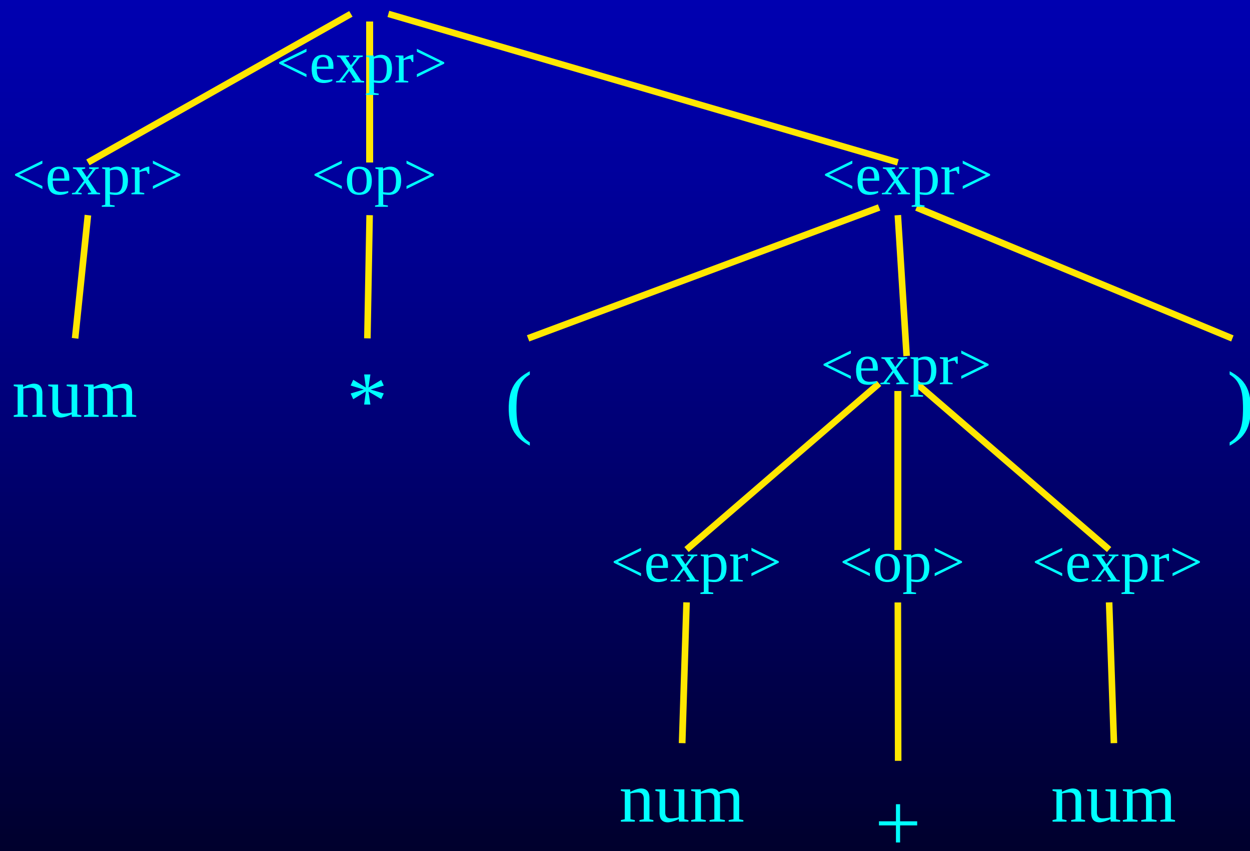
Not a number

Anatomy of a Computer



Syntax Analyzer (Parser)

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



Syntax Analyzer (Parser)

```
int * foo(i, j, k))
   int i;
   int j;
{
   for(i=0; i j) {
   fi(i>j)
      return j;
}
```

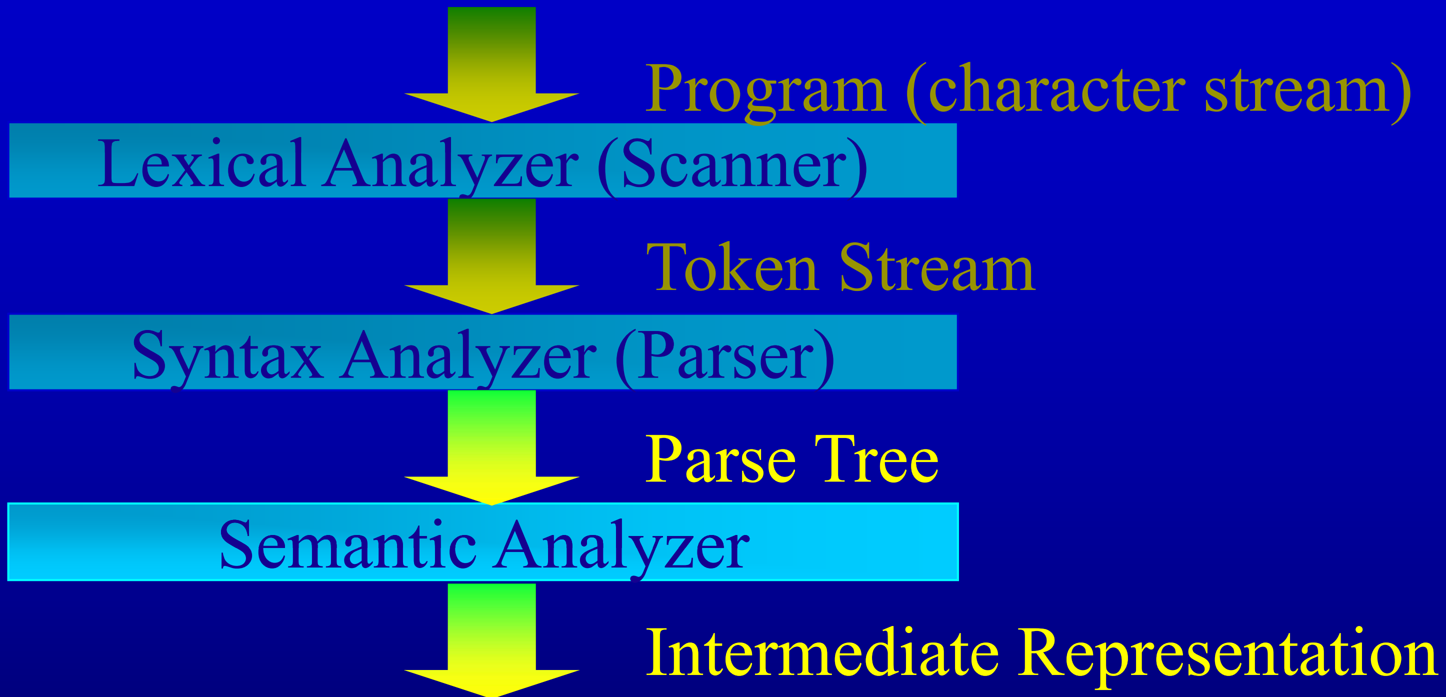
Extra parentheses

Missing increment

Not an expression

Not a keyword

Anatomy of a Computer



Semantic Analyzer

```
int * foo(i, j, k)
    int i;
    int j;
{
    int x;
    x = x + j + N;
    return j;
}
```

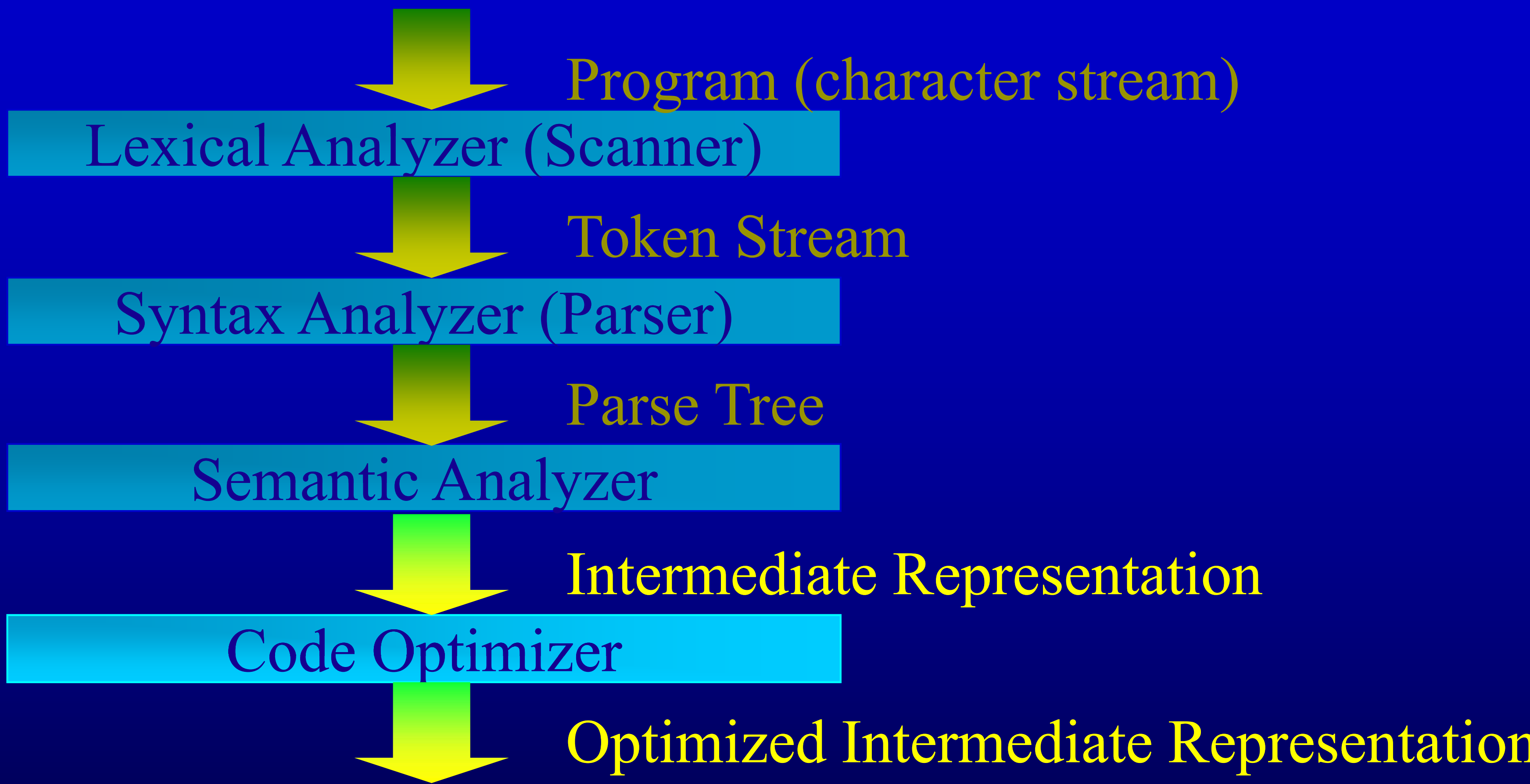
Type not declared

Mismatched return type

Uninitialized variable used

Undeclared variable

Anatomy of a Computer

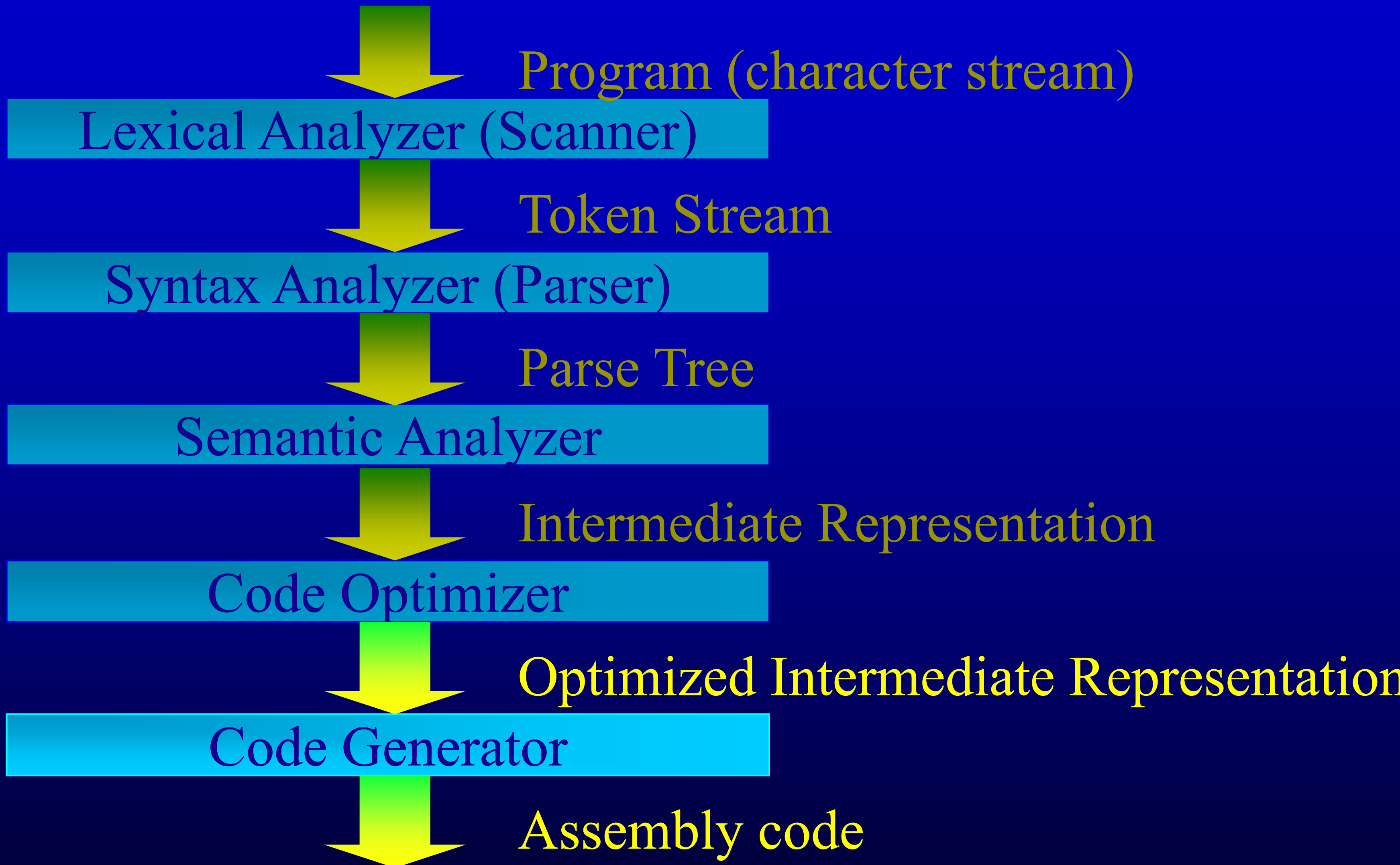


Optimizer

```
int sumcalc(int a, int b, int N)
{
    int i;
    int x, y;
    x = 0;
    y = 0;
    for(i = 0; i <= N; i++) {
        x = x+4*a/b*i+(i+1)*(i+1);
        x = x + b*y;
    }
    return x;
}
```

```
int sumcalc(int a, int b, int N)
{
    int i;
    int x, t, u, v;
    x = 0;
    u = ((a<<2)/b);
    v = 0;
    for(i = 0; i <= N; i++) {
        t = i+1;
        x = x + v + t*t;
        v = v + u;
    }
    return x;
}
```

Anatomy of a Computer



Code Generator

```
int sumcalc(int a, int b, int N)
{
    int i;
    int x, t, u, v;
    x = 0;
    u = ((a<<2)/b);
    v = 0;
    for(i = 0; i <= N; i++) {
        t = i+1;
        x = x + v + t*t;
        v = v + u;
    }
    return x;
}
```

```
sumcalc:
        xorl    %r8d, %r8d
        xorl    %ecx, %ecx
        movl    %edx, %r9d
        cmpl    %edx, %r8d
        jg      .L7
        sall    $2, %edi
.L5:    movl    %edi, %eax
        cltd
        idivl   %esi
        leal    1(%rcx), %edx
        movl    %eax, %r10d
        imull   %ecx, %r10d
        movl    %edx, %ecx
        imull   %edx, %ecx
        leal    (%r10,%rcx), %eax
        movl    %edx, %ecx
        addl    %eax, %r8d
        cmpl    %r9d, %edx
        jle     .L5
.L7:    movl    %r8d, %eax
        ret
```

Program Translation

- Correct
  - The actions requested by the program has to be faithfully executed
- Efficient
  - Intelligently and efficiently use the available resources to carry out the requests
  - (the word optimization is used loosely in the compiler community – Optimizing compilers are never optimal)

Efficient Execution

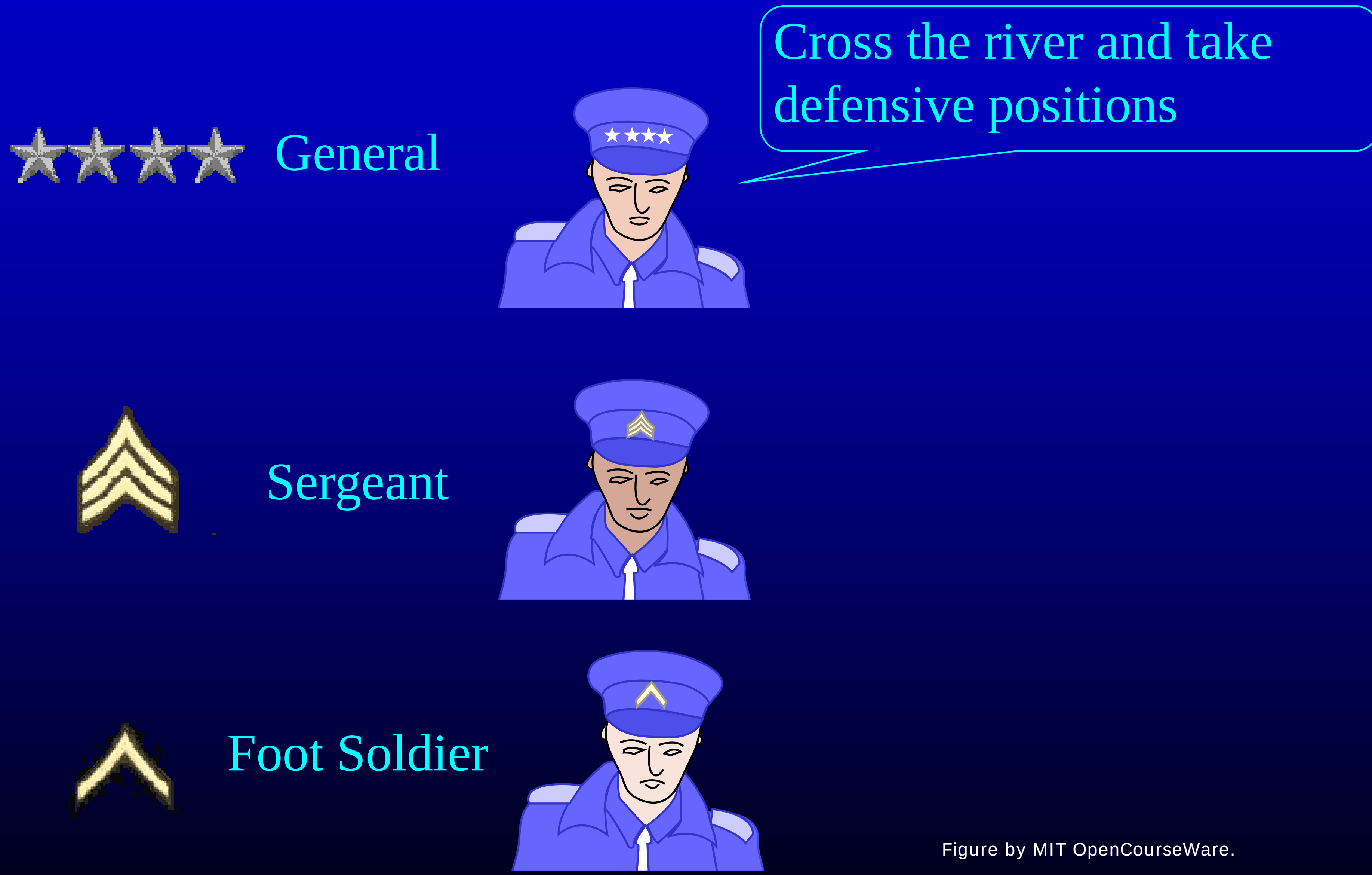


Figure by MIT OpenCourseWare.

Efficient Execution

Cross the river and take defensive positions

General

Where to cross the river? Use the bridge upstream or surprise the enemy by crossing downstream?
How do I minimize the casualties??

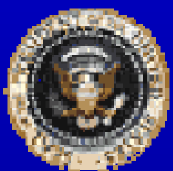
Sergeant

Foot Soldier

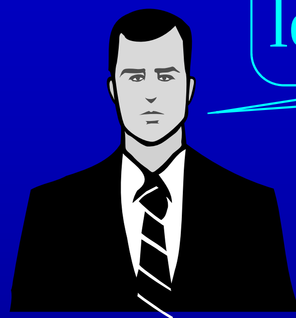
Figure by MIT OpenCourseWare.

Efficient Execution

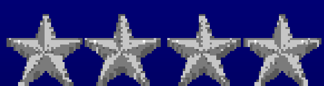
My poll ratings are low,
lets invade a small nation



President



Russia or Bermuda?
Or just stall for his poll
numbers to go up?



General

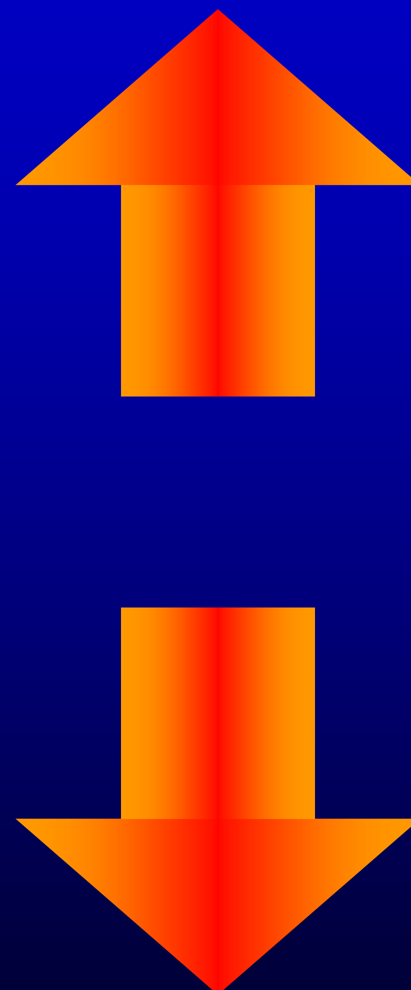
Figure by MIT OpenCourseWare.

Efficient Execution

- Mapping from High to Low
  - Simple mapping of a program to assembly language produces inefficient execution
  - Higher the level of abstraction $\Rightarrow$ more inefficiency
- If not efficient
  - High-level abstractions are useless
- Need to:
  - provide a high level abstraction
  - with performance of giving low-level instructions

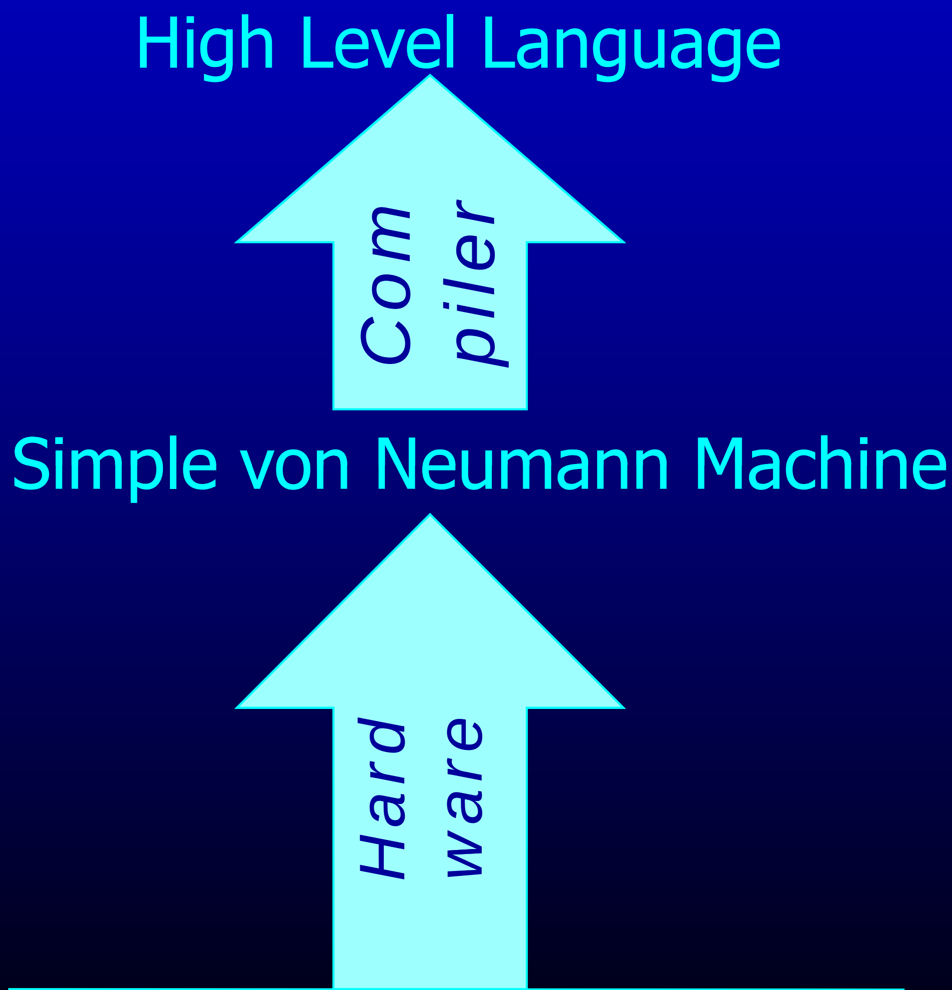
Efficient Execution help increase the level of abstraction

- Programming languages
  - From C to OO-languages with garbage collection
  - Even more abstract definitions
- Microprocessor
  - From simple CISC to RISC to VLIW to ....

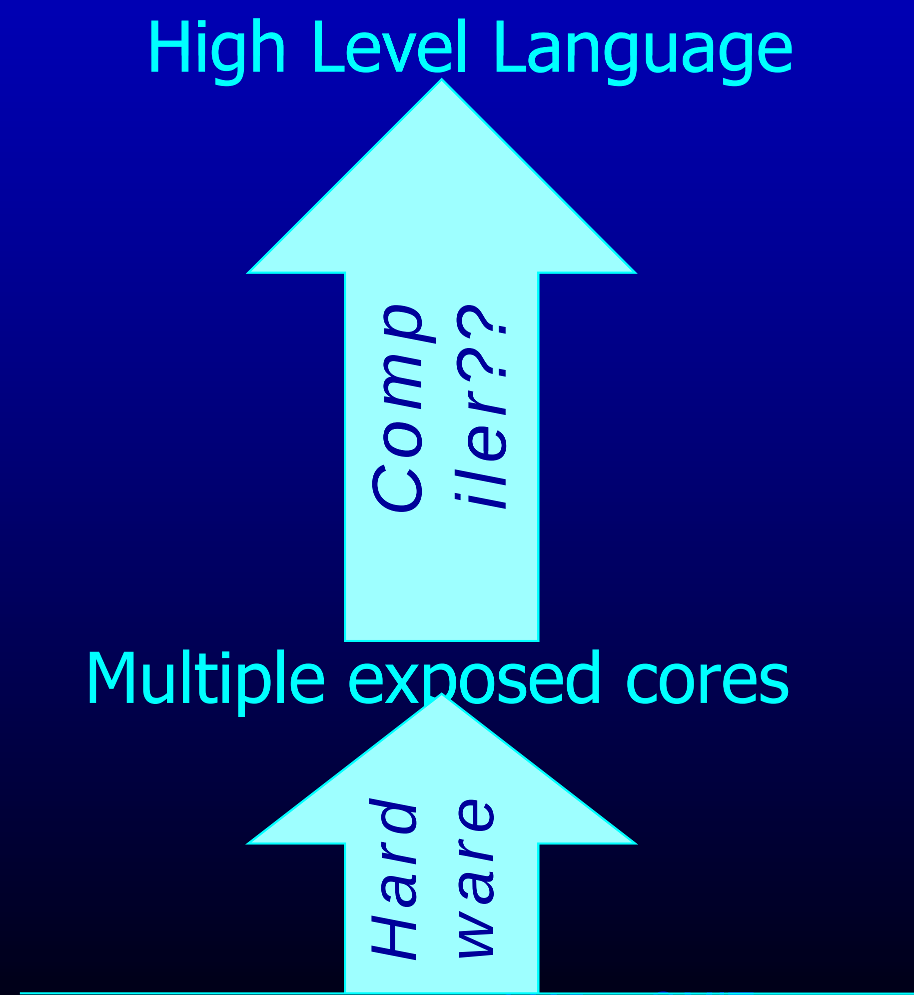


The Multicore Dilemma

- Superscalars

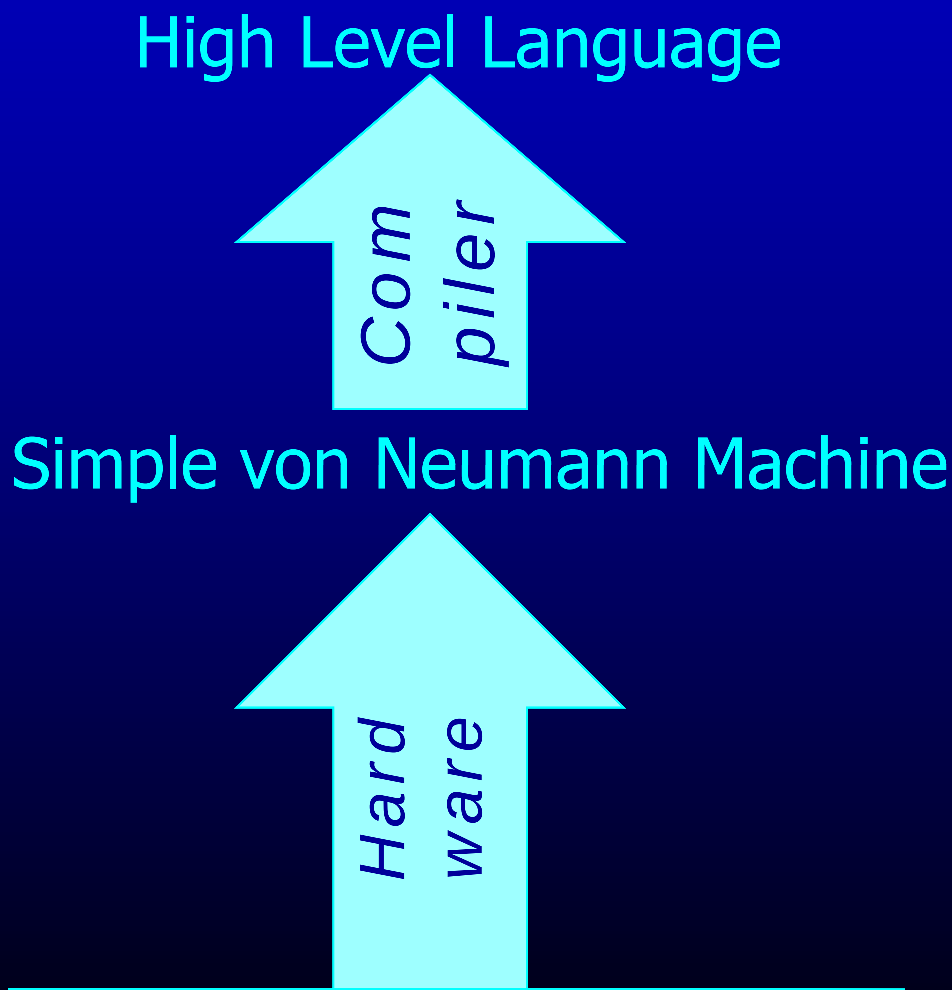


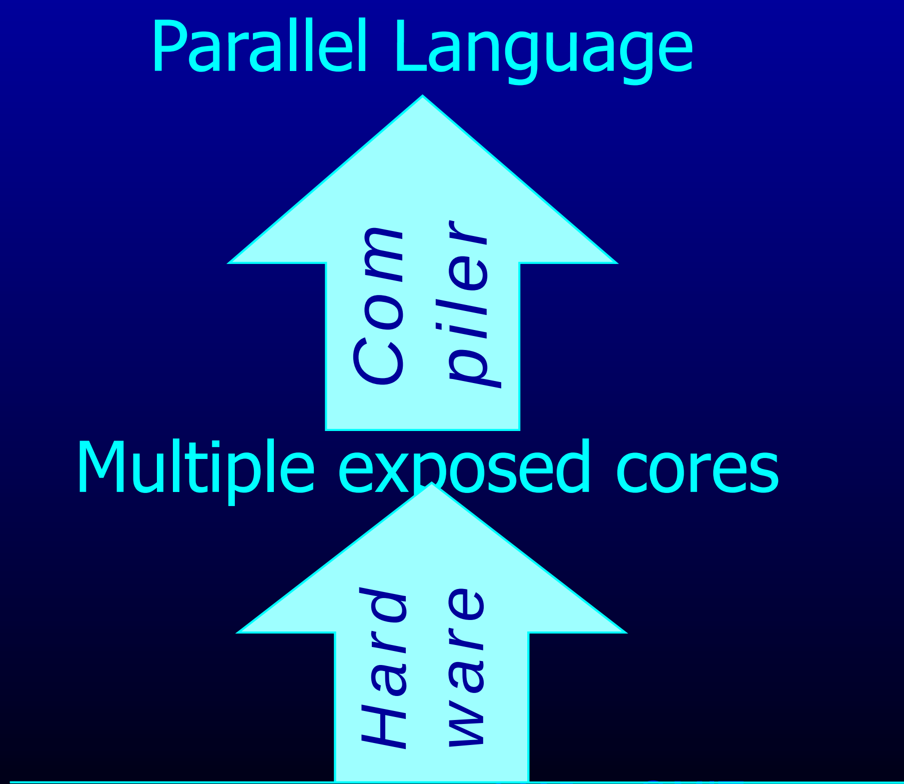
- Multicores



The Multicore Dilemma

- Superscalars
- Multicores





Optimization Example

```
int sumcalc(int a, int b, int N)
{
    int i;
    int x, y;
    x = 0;
    y = 0;
    for(i - 0; i <= N; i++) {
       x = x + (4*a/b)*i + (i+1)*(i+1);
        x = x + b*y;
    }
    return x;
}
```

```
        pushq   %rbp
        movq    %rsp, %rbp
        movl    %edi, -4(%rbp)
        movl    %esi, -8(%rbp)
        movl    %edx, -12(%rbp)
        movl    $0, -20(%rbp)
        movl    $0, -24(%rbp)
        movl    $0, -16(%rbp)
.L2:    movl    -16(%rbp), %eax
        cmpl     12(%rbp), %eax
        jg      .L3
        movl    -4(%rbp), %eax
        leal    0(,%rax,4), %edx
        leaq    -8(%rbp), %rax
        movq    %rax, -40(%rbp)
        movl    %edx, %eax
        movq    -40(%rbp), %rcx
        cltd
        idivl   (%rcx)
        movl    %eax, -28(%rbp)
        movl    -28(%rbp), %edx
        imull   -16(%rbp), %edx
        movl    -16(%rbp), %eax
        incl    %eax
        imull   %eax, %eax
        addl    %eax, %edx
        leaq    -20(%rbp), %rax
        addl    %edx, (%rax)
        movl    -8(%rbp), %eax
        movl    %eax, %edx
        imull    24(%rbp), %edx
        leaq    -20(%rbp), %rax
        addl    %edx, (%rax)
        leaq    -16(%rbp), %rax
        incl    (%rax)
        jmp      L2
.L3:    movl    -20(%rbp), %eax
        leave
        ret
```

Lets Optimize...

```
int sumcalc(int a, int b, int N)
{
    int i, x, y;
    x = 0;
    y = 0;
    for(i = 0; i <= N; i++) {
       x = x + (4*a/b)*i + (i+1)*(i+1);
       x = x + b*y;
    }
    return x;
}
```

Constant Propagation

```
int i, x, y;
x = 0;
y = 0;
for(i = 0; i <= N; i++) {
    x = x + (4*a/b)*i + (i+1)*(i+1);
    x = x + b*y;
}
return x;
```

Constant Propagation

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int i, x, y;
x = 0;
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for(i = 0; i <= N; i++) {
  x = x + (4*a/b)*i + (i+1)*(i+1);
  x = x + b*y;
}
return x;
```

Constant Propagation

```
int i, x, y;
x = 0;
y = 0;
for(i = 0; i <= N; i++) {
  x = x + (4*a/b)*i + (i+1)*(i+1);
  x = x + b*0;
}
return x;
```

Algebraic Simplification

```
int i, x, y;
x = 0;
y = 0;
for(i = 0; i <= N; i++) {
  x = x + (4*a/b)*i + (i+1)*(i+1);
  x = x + b*0;
}
return x;
```

Algebraic Simplification

```
int i, x, y;
x = 0;
y = 0;
for(i = 0; i <= N; i++) {
  x = x + (4*a/b)*i + (i+1)*(i+1);
  x = x + b*0;
}
return x;
```

Algebraic Simplification

```
int i, x, y;
x = 0;
y = 0;
for(i = 0; i <= N; i++) {
  x = x + (4*a/b)*i + (i+1)*(i+1);
  x = x;
}
return x;
```

Copy Propagation

```
int i, x, y;
x = 0;
y = 0;
for(i = 0; i <= N; i++) {
  x = x + (4*a/b)*i + (i+1)*(i+1);
  x = x;
}
return x;
```

Copy Propagation

```
int i, x, y;
x = 0;
y = 0;
for(i = 0; i <= N; i++) {
  x = x + (4*a/b)*i + (i+1)*(i+1);
  x = x;
}
return x;
```

Copy Propagation

```
int i, x, y;
x = 0;
y = 0;
for(i = 0; i <= N; i++) {
  x = x + (4*a/b)*i + (i+1)*(i+1);

}
return x;
```

Common Subexpression Elimination

```
int i, x, y;
x = 0;
y = 0;
for(i = 0; i <= N; i++) {

   x = x + (4*a/b)*i + (i+1)*(i+1);
}
return x;
```

Common Subexpression Elimination

```
int i, x, y;
x = 0;
y = 0;
for(i = 0; i <= N; i++) {

   x = x + (4*a/b)*i + (i+1)*(i+1);
}
return x;
```

Common Subexpression Elimination

```
int i, x, y, t;
x = 0;
y = 0;
for(i = 0; i <= N; i++) {
    t = i+1;
    x = x + (4*a/b)*i + t*t;
}
return x;
```

Dead Code Elimination

```
int i, x, y, t;
x = 0;
y = 0;
for(i = 0; i <= N; i++) {
   t = i+1;
   x = x + (4*a/b)*i + t*t;
}
return x;
```

Dead Code Elimination

```
int i, x, y, t;
x = 0;
y = 0;
for(i = 0; i <= N; i++) {
   t = i+1;
   x = x + (4*a/b)*i + t*t;
}
return x;
```

Dead Code Elimination

```
int i, x, t;
x = 0;

for(i = 0; i <= N; i++) {
    t = i+1;
    x = x + (4*a/b)*i + t*t;
}
return x;
```

Loop Invariant Removal

```
int i, x, t;
x = 0;

for(i = 0; i <= N; i++) {
    t = i+1;
    x = x + (4*a/b)*i + t*t;
}
return x;
```

Loop Invariant Removal

```
int i, x, t;
x = 0;

for(i = 0; i <= N; i++) {
   t = i+1;
   x = x + (4*a/b)*i + t*t;
}
return x;
```

Loop Invariant Removal

```
int i, x, t, u;
x = 0;
u = (4*a/b);
for(i = 0; i <= N; i++) {
   t = i+1;
   x = x + u*i + t*t;
}
return x;
```

Strength Reduction

```
int i, x, t, u;
x = 0;
          /b);

for(i = 0; i <= N; i++) {
   t = i+1;
   x = x + u*i + t*t;

}
return x;
```

Strength Reduction

```
int i, x, t, u;
x = 0;
u = (4*a/b);

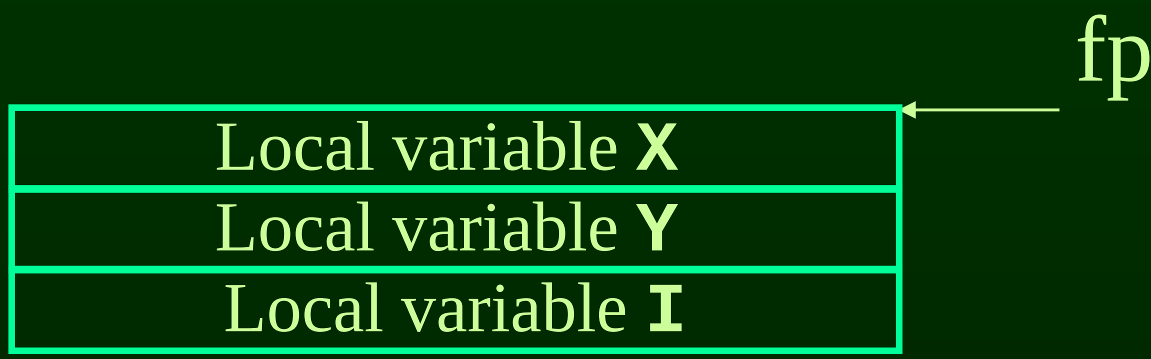
for(i = 0; i <= N; i++) {
   t = i+1;
   x = x + u*i + t*t;

}
return x;
```

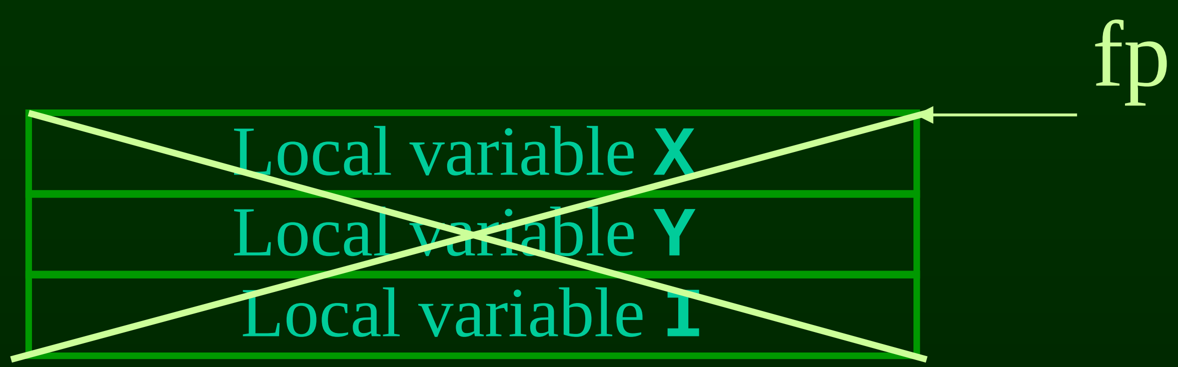
Strength Reduction

```
int i, x, t, u, v;
x = 0;
u = ((a<<2)/b);
v = 0;
for(i = 0; i <= N; i++) {
    t = i+1;
    x = x + v + t*t;
    v = v + u;
}
return x;
```

Register Allocation



Register Allocation




```
$r8d  = X
$r9d  = t
$r10d = u
$ebx  = v
$ecx  = i
```

Optimized Example

```
int sumcalc(int a, int b, int N)
{
    int i, x, t, u, v;
    x = 0;
    u = ((a<<2)/b);
    v = 0;
    for(i - 0; i <= N; i++) {
        t = i+1;
        x = x + v + t*t;
        v = v + u;
    }
    return x;
}
```

Unoptimized Code

```
        pushq   %rbp
        movq    %rsp, %rbp
        movl    %edi, -4(%rbp)
        movl    %esi, -8(%rbp)
        movl    %edx, -12(%rbp)
        movl    $0, -20(%rbp)
        movl    $0, -24(%rbp)
        movl    $0, -16(%rbp)
.L2:    movl    -16(%rbp), %eax
        cmpl    -12(%rbp), %eax
        jg      .L3
        movl    -4(%rbp), %eax
        leal    0(,%rax,4), %edx
        leaq    -8(%rbp), %rax
        movq    %rax, -40(%rbp)
        movl    %edx, %eax
        movq    -40(%rbp), %rcx
        cltd
        idivl   (%rcx)
        movl    %eax, -28(%rbp)
        movl    -28(%rbp), %edx
        imull   -16(%rbp), %edx
        movl    -16(%rbp), %eax
        incl    %eax
        imull   %eax, %eax
        addl    %eax, %edx
        leaq    -20(%rbp), %rax
        addl    %edx, (%rax)
        movl    -8(%rbp), %eax
        movl    %eax, %edx
        imull   -24(%rbp), %edx
        leaq    -20(%rbp), %rax
        addl    %edx, (%rax)
        leaq    -16(%rbp), %rax
        incl    (%rax)
        jmp     .L2
.L3:    movl    -20(%rbp), %eax
        leave
        ret
```

Optimized Code

```
        xorl    %r8d, %r8d
        xorl    %ecx, %ecx
        movl    %edx, %r9d
        cmpl    %edx, %r8d
        jg      .L7
        sall    $2, %edi
.L5:    movl    %edi, %eax
        cltd
        idivl   %esi
        leal    1(%rcx), %edx
        movl    %eax, %r10d
        imull   %ecx, %r10d
        movl    %edx, %ecx
        imull   %edx, %ecx
        leal    (%r10,%rcx), %eax
        movl    %edx, %ecx
        addl    %eax, %r8d
        cmpl    %r9d, %edx
        jle     .L5
.L7:    movl    %r8d, %eax
        ret
```

Inner Loop:

10*mov + 5*lea + 5*add/inc
+ 4*div/mul + 5*cmp/br/jmp
= 29 instructions

Execution time = 43 sec

4*mov + 2*lea + 1*add/inc+
3*div/mul + 2*cmp/br/jmp
= 12 instructions

Execution time = 17 sec

Compilers Optimize Programs for…

- Performance/Speed
- Code Size
- Power Consumption
- Fast/Efficient Compilation
- Security/Reliability
- Debugging