

6.035

Lecture 1: Introduction

Staff

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- Web Site

- <https://github.com/6035/sp21>

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

- ① Lexical and Syntax Analysis
- ② Semantic Analysis
- ③ Code Generation
- ④ Dataflow Analysis
- ⑤ Optimizations

Each Segment...

- Segment Start
 - Project Description
- Lectures
- Project Time – No Class
 - (Design Document)
 - (Project Checkpoint)
- Project Due

Project Groups

- 1st project is an individual project
- Projects 2 to 5 are group projects
- Each group consists of 3 to 4 students
- Projects are designed to produce a compiler by the end of class
- Grading
 - All group members (mostly) get the same grade
 - Scanner/parser ungraded
(you can use this to evaluate potential group members)
 - Semantic Checker/Code Generator graded together
 - Dataflow Analyzer/Optimizer graded together
 - 5 turnins total, 2 turnins are graded

Project Collaboration Policy

- Talk about anything you want with anybody
- Write all the code yourself
- Check with TAs before using specialized libraries designed to support compiler construction
- See the website for specifics

Quizzes

- Two Quizzes
- Unless we have another remote semester, in which case we may do problem sets or some combination instead

Mini Quizzes

- Given at the beginning of the class
- Collected at the end
- Collaboration of any kind is OK

More Course Stuff

- Blank page project – all the rope you want!
- Challenging project
- You are on your own!

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
- Indispensible programmer productivity tool
- One of most complex software systems to build

What a Compiler Does

- Input: High-level programming language
- Output: Low-level assembly instructions
- Compiler does the translation:
 - Read and understand the program
 - Precisely determine what actions it requires
 - 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;
}
```

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

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
```

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

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

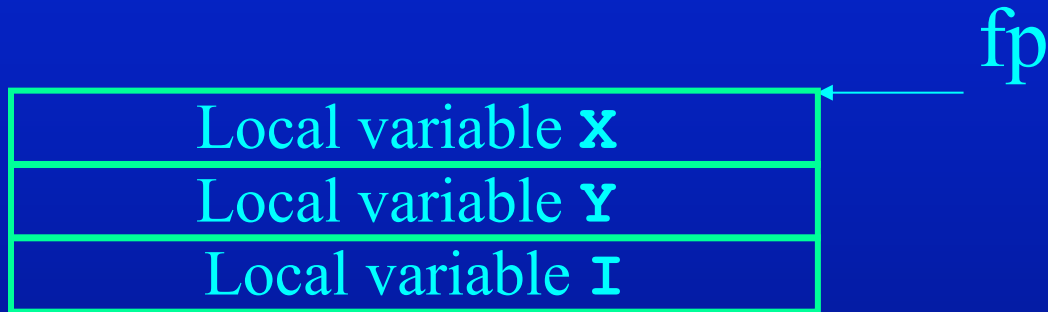

Strength Reduction

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

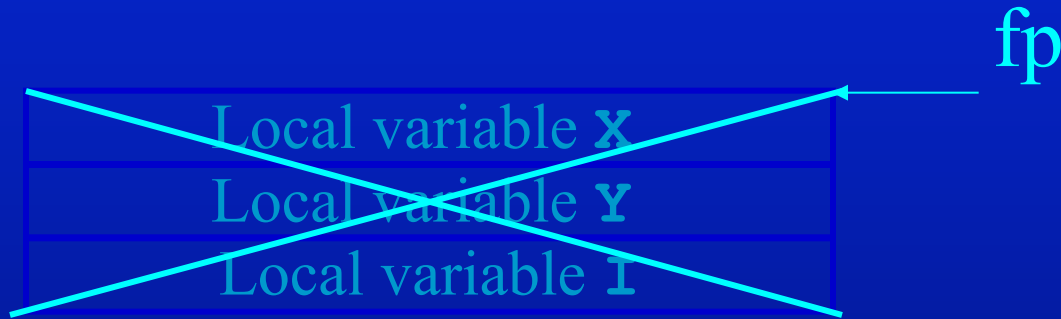
Strength Reduction

```
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