6.035

Fall 2005

Lecture 1: Introduction

Intro. to Computer Language Engineering

Course Administration info.

Outline

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

Course Administration

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

Staff

- Lecturers
  - Prof. Saman Amarasinghe
  - Prof. Martin Rinard

Optional Textbooks

Tiger Book

- Modern Compiler Implementation in Java
  by A.W. Appel
  Cambridge University Press, 1998

Whale Book

- Advanced Compiler Design and Implementation
  by Steven Muchnick
  Morgan Kaufman Publishers, 1997

Dragon Book

- Compilers -- Principles, Techniques and Tools
  by Aho, Sethi and Ullman
  Addison-Wesley, 1988

The Five Segments

1. Lexical and Syntax Analysis
2. Semantic Analysis
3. Code Generation
4. Data-flow Optimizations
5. Instruction Optimizations

Each Segment...

- Segment Start
  - Project Description
- Lectures
  - 2 to 4 lectures
- Project Time
- (Project checkpoint)
- Project Time
- Project Due

Project Groups

- Each project group consists of 3 to 4 students
- Grading
  - All group members (mostly) get the same grade

Weekly Group Meeting with the TA

- TA will schedule a weekly 30 minute slot
- The group will get to:
  - Ask questions about the project
  - Discuss design decisions
  - Describe what each person is doing
  - Answer questions the TA has about the project
- TA will use this to measure individual contribution to the project → be there!

Grades

- Compiler project 58%
- Paper Discussion 12% (3% each)
- In-class Quizzes 30% (10% each)

Grades for the Project

– Scanner/Parser	10%
– Semantic Checking	10%
– Code Generation	14%
– Data-flow Opt.	12%
– Instruction Opt.	12%
	58%

The Quiz

- Three Quizzes

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

Paper Discussions

- Will be giving out 3 papers
- Read the paper, think about…
  - Do you like the research?
  - What is the context of the research?
  - Did anything surprise you about the paper?
  - Do the results allow you to evaluate the proposed technique?
  - Do the authors understand the wider ramifications of their research?
  - How have things changed since the paper was written?
  - How important will the research be in the future?
- Write a 150 to 200 word summary of the paper.
- Will schedule a one-on-one (15 or 20 minute) meeting with a professor or a TA to talk about the paper.

Outline

- Course Administration Information

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

What is Computer Language Engineering

1. How to give instructions to a computer

2. How to make the computer carryout the instructions efficiently

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:
  - Same expression describes many possible actions
  - Ambiguous

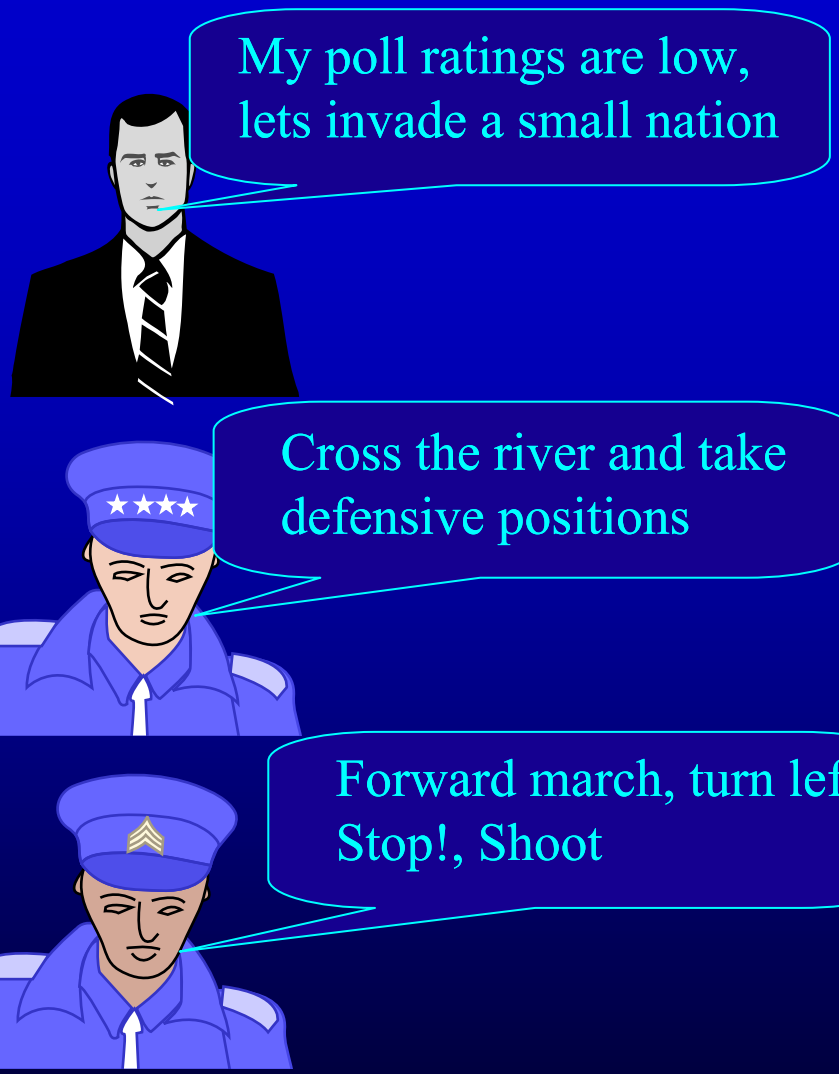
How to instruct a computer

- 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!!
- Use a programming language
  - Examples: Java, C, C++, Pascal, BASIC, Scheme

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)

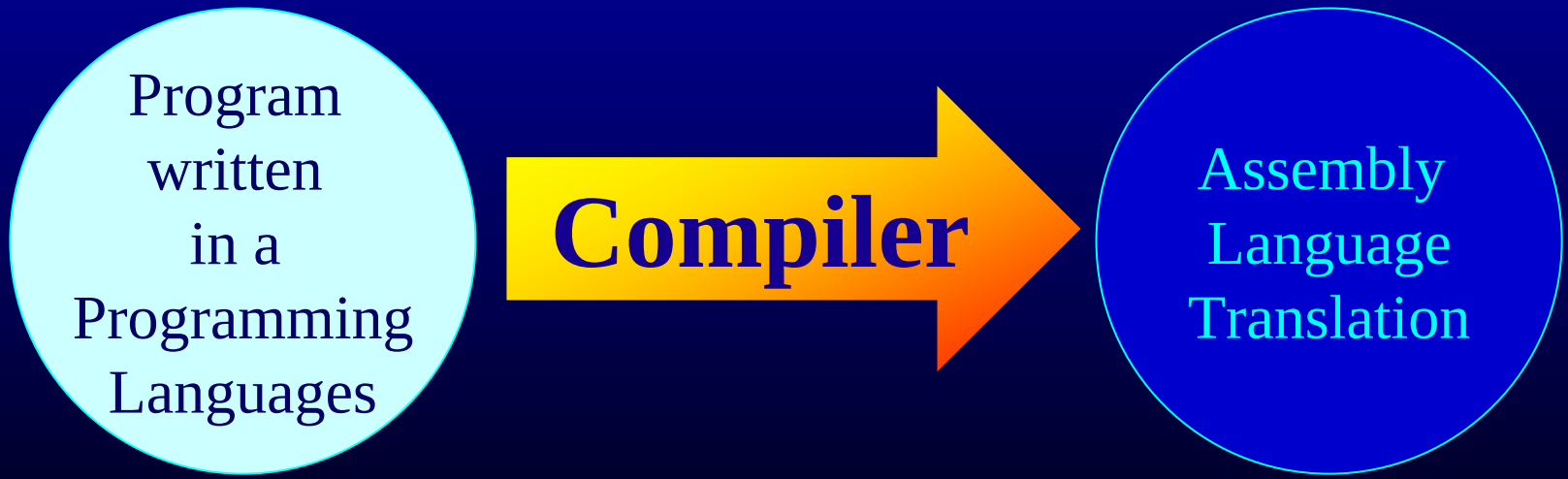
High-level Abstract Description to Low-level Implementation Details



Figures by MIT OCW.

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

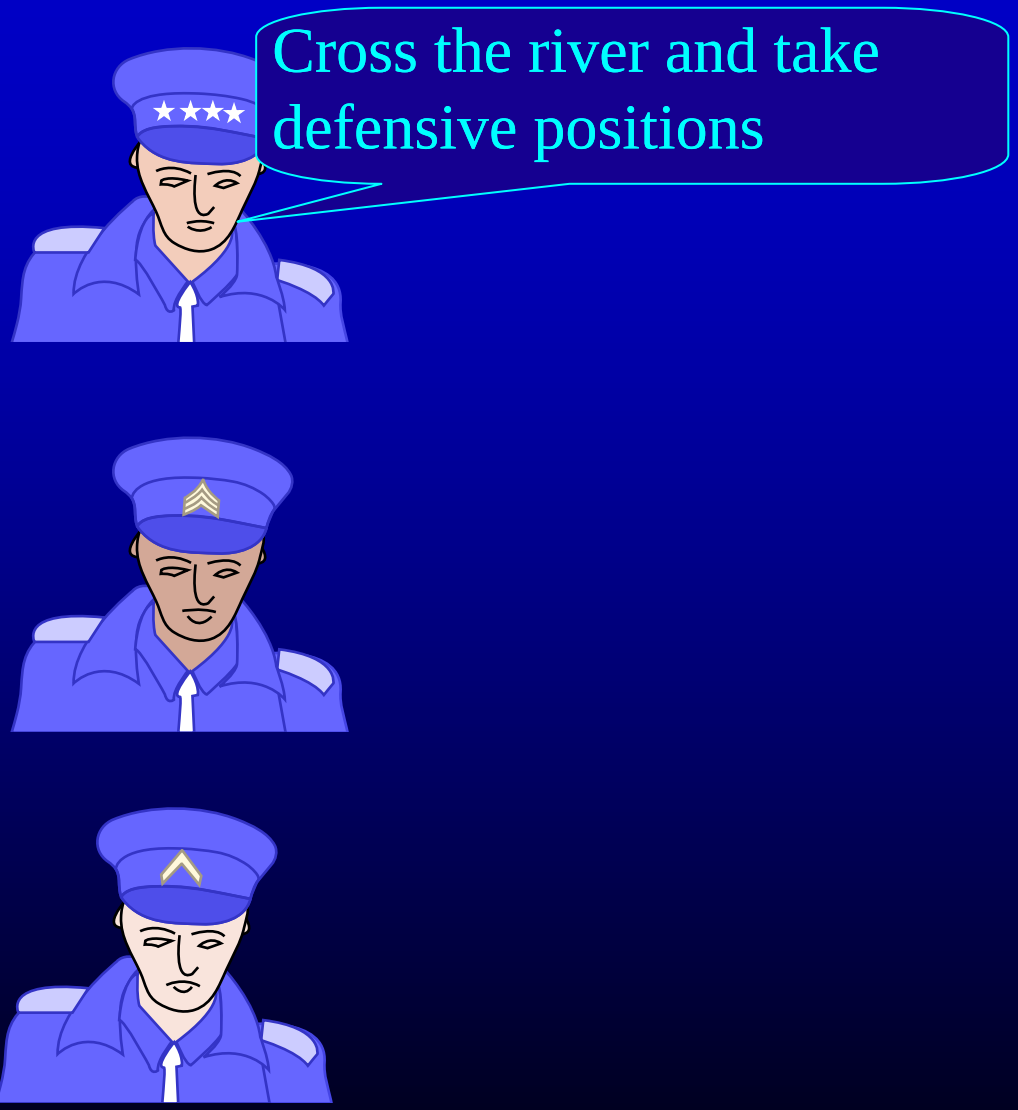
Example (input program)

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

Example (Output assembly code)

```
        lda $30,-32($30)
        stq $26,0($30)
        stq $15,8($30)
        bis $30,$30,$15
        bis $16,$16,$1
        stl $1,16($15)
        lds $f1,16($15)
        sts $f1,24($15)
        ldl $5,24($15)
        bis $5,$5,$2
        s4addq $2,0,$3
        ldl $4,16($15)
        mull $4,$3,$2
        ldl $3,16($15)
        addq $3,1,$4
        mull $2,$4,$2
        ldl $3,16($15)
        addq $3,1,$4
        mull $2,$4,$2
        stl $2,20($15)
        ldl $0,20($15)
        br $31,$33
$33:
        bis $15,$15,$30
        ldq $26,0($30)
        ldq $15,8($30)
        addq $30,32,$30
        ret $31,($26),1
```

Efficient Execution of the Actions



Figures by MIT OCW.

Efficient Execution of the Actions

General

Cross the river and take defensive positions

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

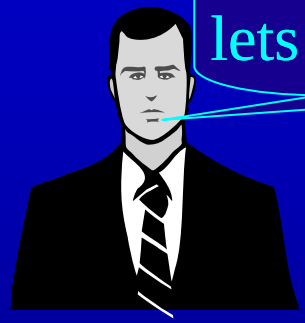
Sergeant

Foot Soldier

Figures by MIT OCW.

Efficient Execution of the Actions

President



My poll ratings are low,
lets invade a small nation

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

General

Figures by MIT OCW.

Efficient Execution of the Actions

- 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

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;
}
```

```
test:
    subu   $fp, 16
    sw     zero, 0($fp)              # x = 0
    sw     zero, 4($fp)              # y = 0
    sw     zero, 8($fp)              # i = 0
lab1:                                # for(i=0;i<N; i++)
    mul    $t0, $a0, 4               # a*4
    div    $t1, $t0, $a1             # a*4/b
    lw     $t2, 8($fp)               # i
    mul    $t3, $t1, $t2             # a*4/b*i
    lw     $t4, 8($fp)               # i
    addui$t4, $t4, 1                 # i+1
    lw     $t5, 8($fp)               # i
    addui$t5, $t5, 1                 # i+1
    mul    $t6, $t4, $t5             # (i+1)*(i+1)
    addu $t7, $t3, $t6               # a*4/b*i + (i+1)*(i+1)
    lw   $t8, 0($fp)                 # x
    add  $t8, $t7, $t8               # x = x + a*4/b*i + (i+1)*(i+1)
    sw     $t8, 0($fp)
    lw     $t0, 4($fp)               # y
    mul    $t1, $t0, a1              # b*y
    lw     $t2, 0($fp)               # x
    add    $t2, $t2, $t1             # x = x + b*y
    sw     $t2, 0($fp)
    lw     $t0, 8($fp)               # i
    addui $t0, $t0, 1                # i+1
    sw    $t0, 8($fp)
    ble    $t0, $a3, lab1
    lw     $v0, 0($fp)
    addu   $fp, 16
    b      $ra
```

Lets Optimize...

```
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;
}
```

Constant Propagation

```
int sumcalc(int a, int b, int N)
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Algebraic Simplification

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int sumcalc(int a, int b, int N)
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Common Subexpression Elimination

```
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}
```

Common Subexpression Elimination

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

Dead Code Elimination

```
int sumcalc(int a, int b, int N)
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    y = 0;
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Loop Invariant Removal

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```

Strength Reduction

```
int sumcalc(int a, int b, int N)
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       t = i+1;
       x = x + u*i + t*t;
    }
    return x;
}
```

```
u*0,  v=0,
u*1,  v=v+u,
u*2,  v=v+u,
u*3,  v=v+u,
u*4,  v=v+u,
...   ...
```

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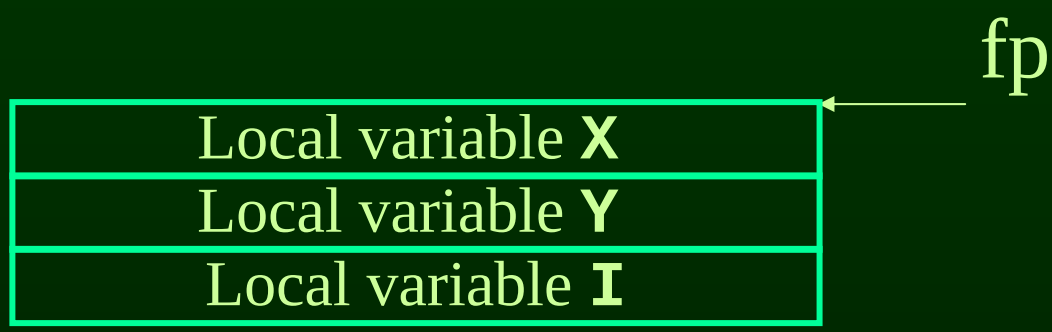
       x = x + v + t*t;
       v = v + u;
    }
    return x;
}
```

Strength Reduction

```
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;
}
```

Register Allocation



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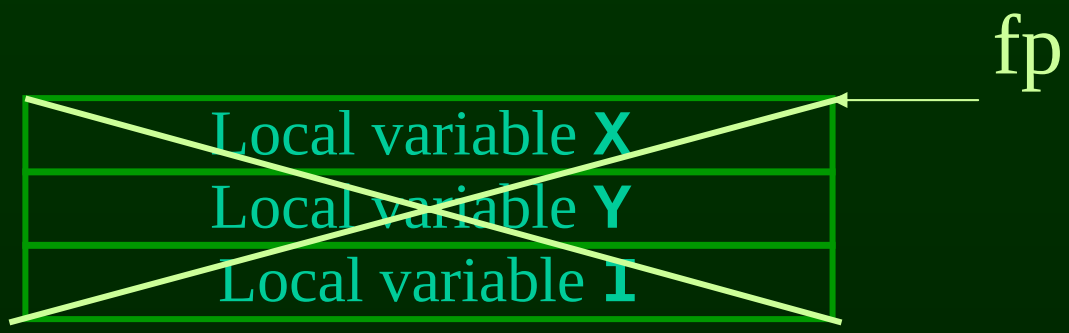



```
$t9 = X
$t8 = t
$t7 = u
$t6 = v
$t5 = i
```

Optimized Example

```
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;
}
```

```
test:
   subu $fp, 16
   add  $t9, zero, zero     # x = 0
   sll  $t0, $a0, 2         # a<<2
   div  $t7, $t0, $a1       # u = (a<<2)/b
   add  $t6, zero, zero     # v = 0
   add  $t5, zero, zero     # i = 0

lab1:                       # for(i=0;i<N; i++)
   addui$t8, $t5, 1         # t = i+1
   mul  $t0, $t8, $t8       # t*t
   addu $t1, $t0, $t6       # v + t*t
   addu $t9, t9, $t1        # x = x + v + t*t

   addu $6, $6, $7          # v = v + u

   addui$t5, $t5, 1         # i = i+1
   ble  $t5, $a3, lab1

   addu $v0, $t9, zero
   addu $fp, 16
   b    $ra
```

Unoptimized Code

```
test:
     subu      $fp, 16
     sw        zero, 0($fp)
     sw        zero, 4($fp)
     sw        zero, 8($fp)
lab1:
     mul       $t0, $a0, 4
     div       $t1, $t0, $a1
     lw        $t2, 8($fp)
     mul       $t3, $t1, $t2
     lw        $t4, 8($fp)
     addui     $t4, $t4, 1
     lw        $t5, 8($fp)
     addui     $t5, $t5, 1
     mul       $t6, $t4, $t5
     addu      $t7, $t3, $t6
     lw        $t8, 0($fp)
     add       $t8, $t7, $t8
     sw        $t8, 0($fp)
     lw        $t0, 4($fp)
     mul       $t1, $t0, a1
     lw        $t2, 0($fp)
     add       $t2, $t2, $t1
     sw        $t2, 0($fp)
     lw        $t0, 8($fp)
     addui     $t0, $t0, 1
     sw        $t0, 8($fp)
     ble       $t0, $a3, lab1

     lw        $v0, 0($fp)
     addu      $fp, 16
     b         $ra
```

4*ld/st + 2*add/sub + br +
N*(9*ld/st + 6*add/sub + 4* mul + div + br)
= 7 + N*21

Execution time = 43 sec

Optimized Code

```
test:
     subu      $fp, 16
     add       $t9, zero, zero
     sll       $t0, $a0, 2
     div       $t7, $t0, $a1
     add       $t6, zero, zero
     add       $t5, zero, zero
lab1:
     addui     $t8, $t5, 1
     mul       $t0, $t8, $t8
     addu      $t1, $t0, $t6
     addu      $t9, t9, $t1
     addu      $6, $6, $7
     addui     $t5, $t5, 1
     ble       $t5, $a3, lab1

     addu      $v0, $t9, zero
     addu      $fp, 16
     b         $ra
```

6*add/sub + shift + div + br +
N*(5*add/sub + mul + br)
= 9 + N*7

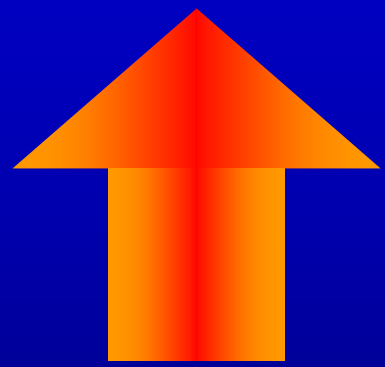
Execution time = 17 sec

Compilers Optimize Programs for…

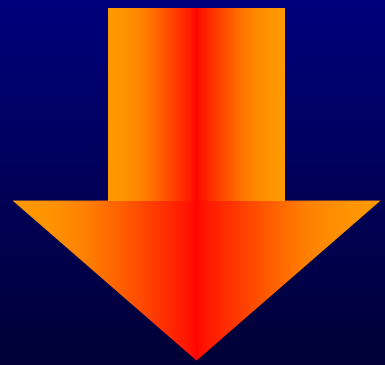
- Performance/Speed
- Code Size
- Power Consumption
- Fast/Efficient Compilation
- Security/Reliability
- Debugging

Compilers help increase the level of abstraction

- Programming languages
  - From C to OO-languages with garbage collection
  - Even more abstract definitions



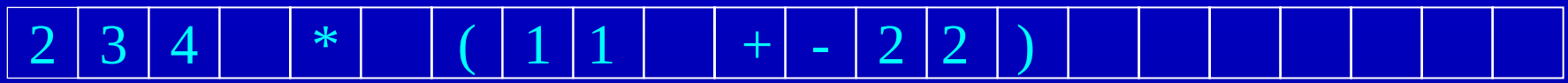
- Microprocessor
  - From simple CISC to RISC to VLIW to ….



Anatomy of a Computer

Anatomy of a Computer

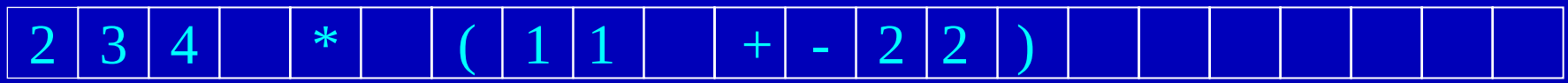
Lexical Analyzer (Scanner)



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

18..23 + val#ue

Lexical Analyzer (Scanner)



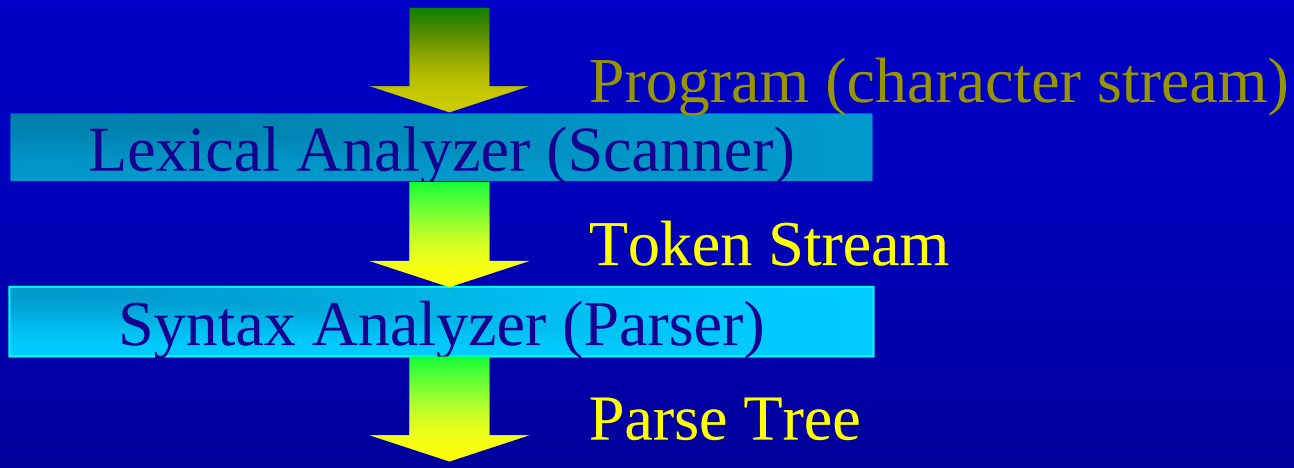
Num(234) mul_op lpar_op Num(11) add_op Num(-22) rpar_op

18..23 + val#ue

Variable names cannot have ‘#’ character

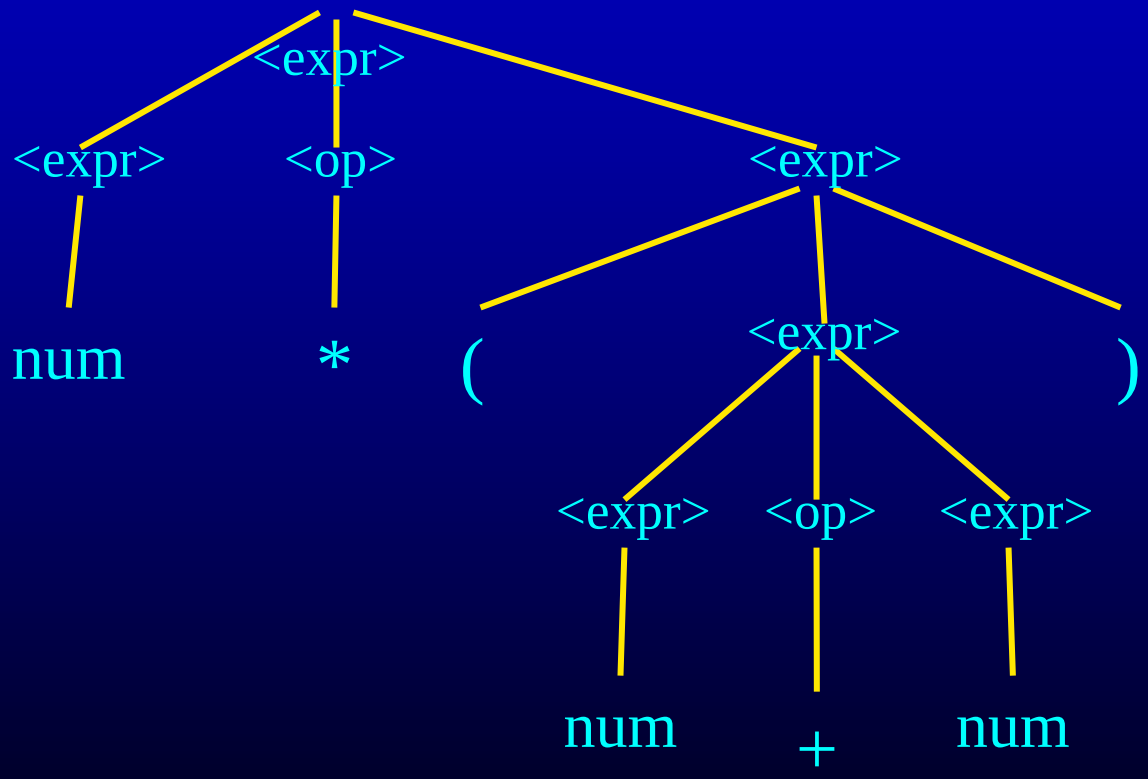
Not a number

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;
}
```

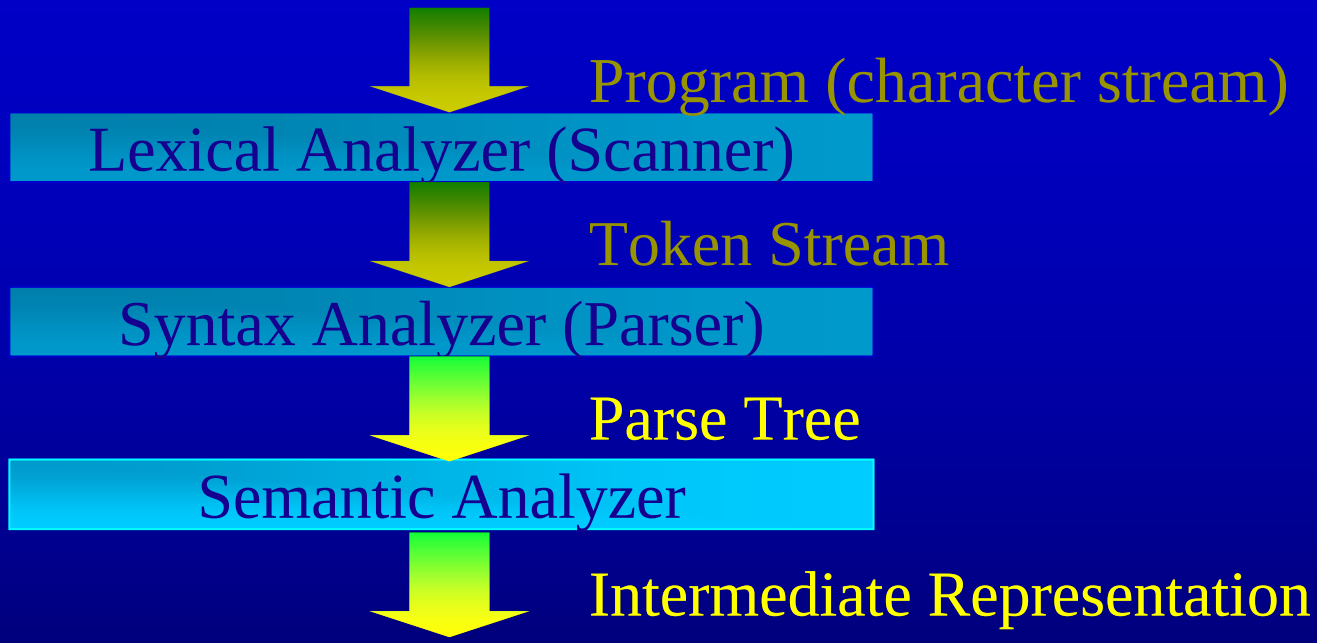
Extra parentheses

Missing increment

Not an expression

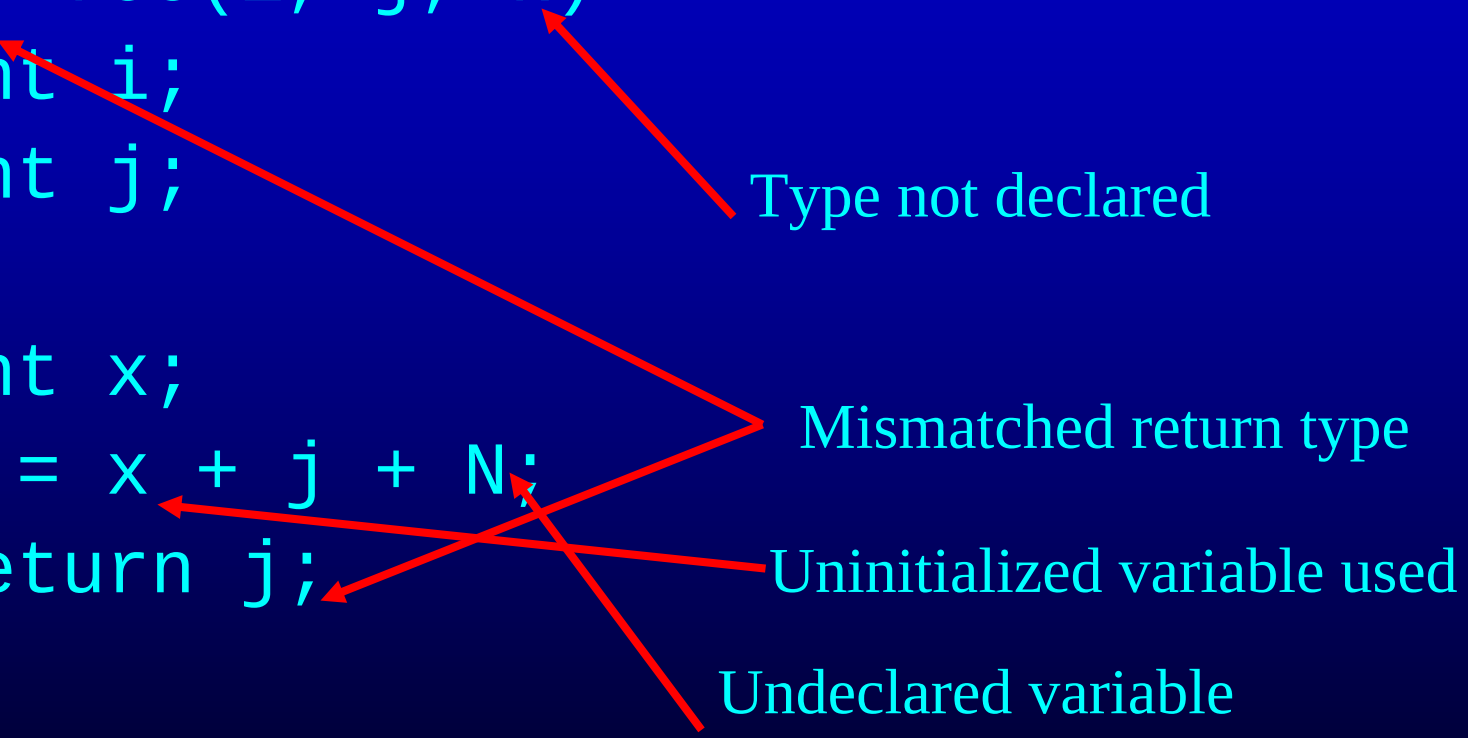
Not a keyword

Anatomy of a Computer

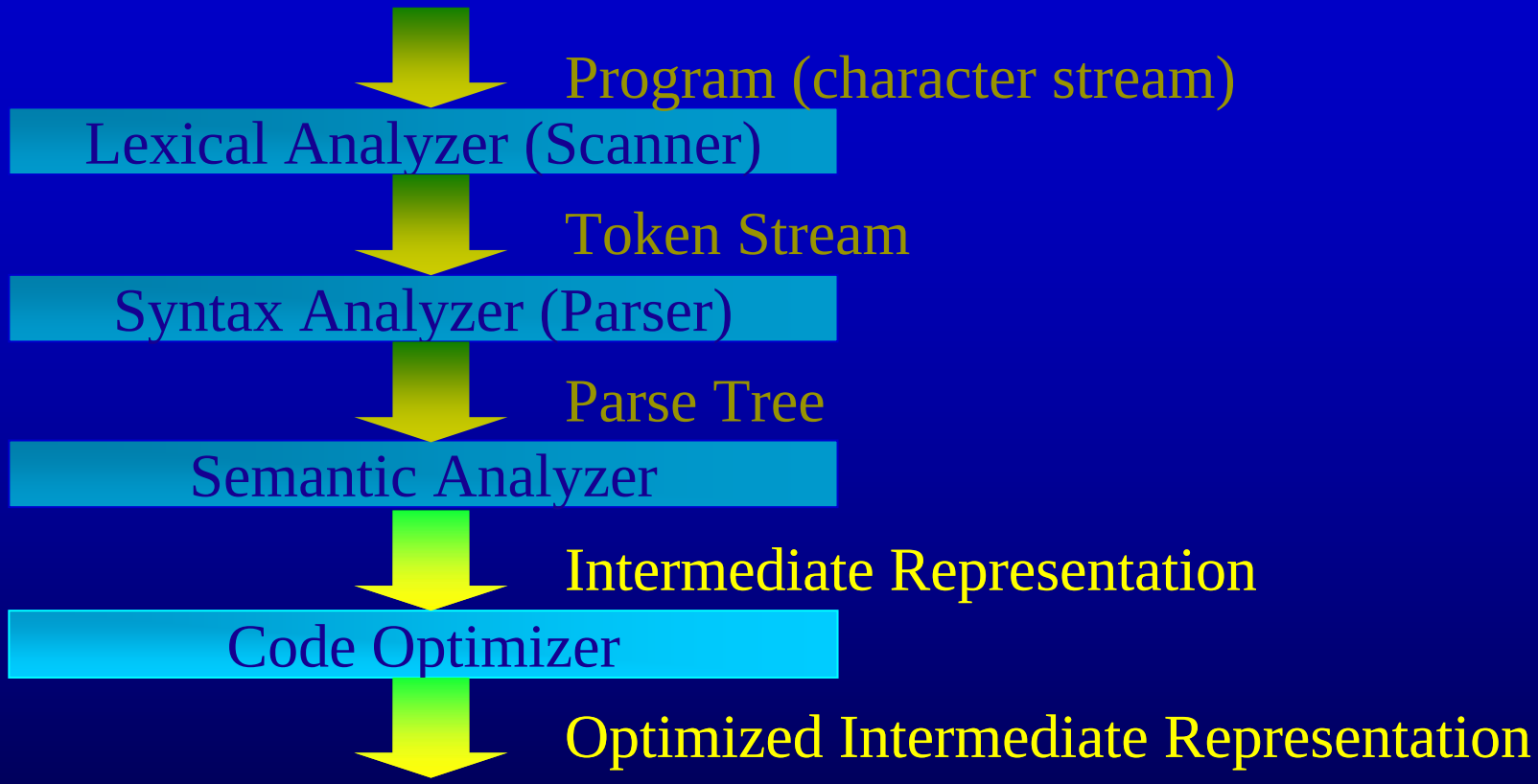


Semantic Analyzer

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

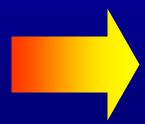


Anatomy of a Computer



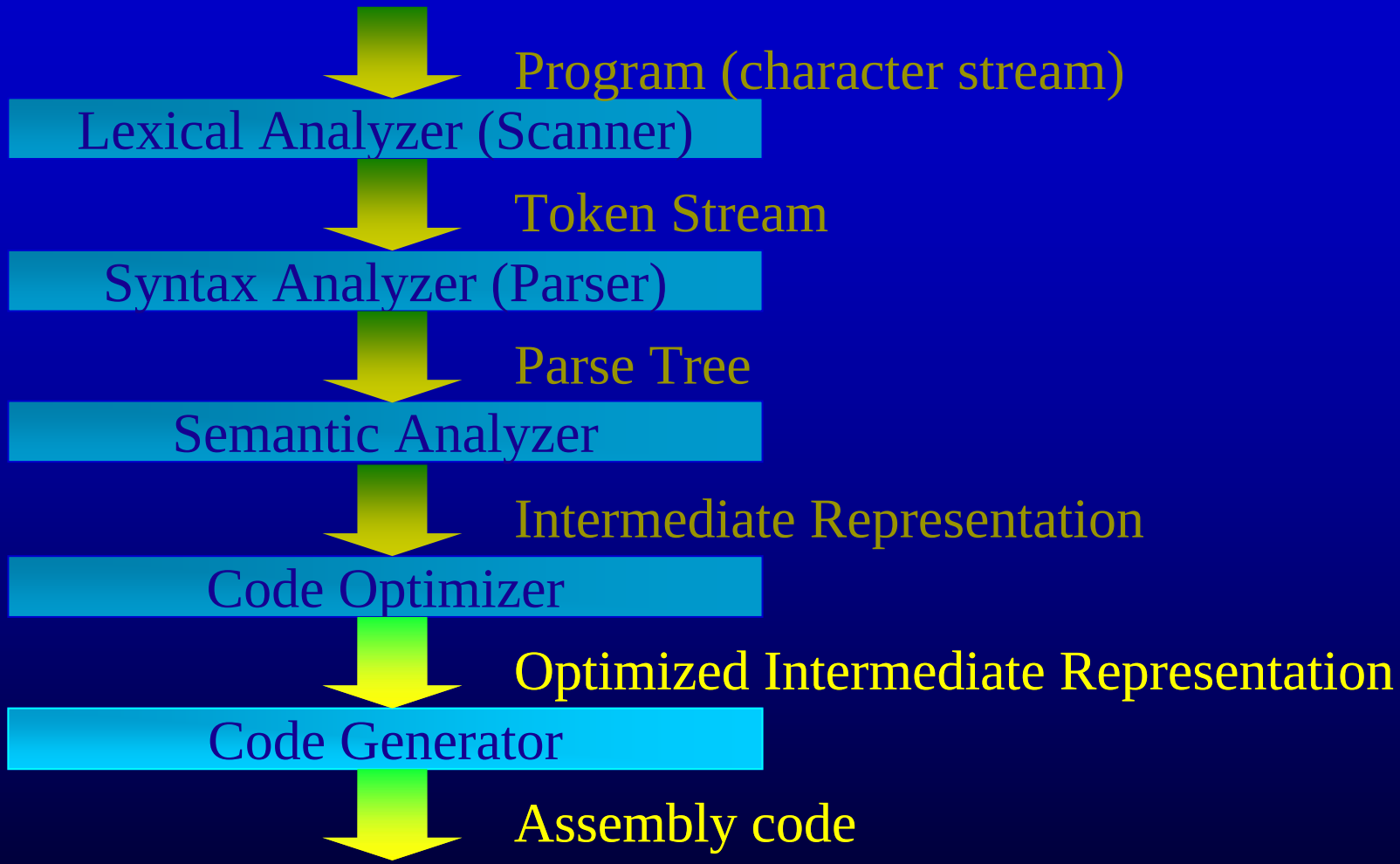
Optimizer

```
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;
}
```



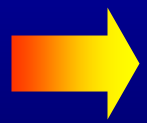
```
int sumcalc(int a, int b, int N)
{
    int i;
    int x, t, u, v;
    x = 0;
     u = ((a<<2)/b);
     v = 0;
    for(i = 0; i <= N; i++) {
         t = i+1;
          x = x + v + t*t;
         v = v + u;
     }
    return x;
}
```

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;
}
```



```
test:
    subu    $fp, 16
    add     $t9, zero, zero
    sll     $t0, $a0, 2
    div     $t7, $t0, $a1
    add     $t6, zero, zero
    add     $t5, zero, zero
lab1:
    addui   $t8, $t5, 1

    mul     $t0, $t8, $t8
    addu    $t1, $t0, $t6
    addu    $t9, t9, $t1

    addu    $6, $6, $7

    addui   $t5, $t5, 1

    ble     $t5, $a3, lab1

    addu    $v0, $t9, zero
    addu    $fp, 16
    b       $ra
```