Code Analysis and Optimization

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COMP 3002

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Outline

- Basic blocks and flow graphs
- Local register allocation
- Global register allocation
- Selected optimization topics

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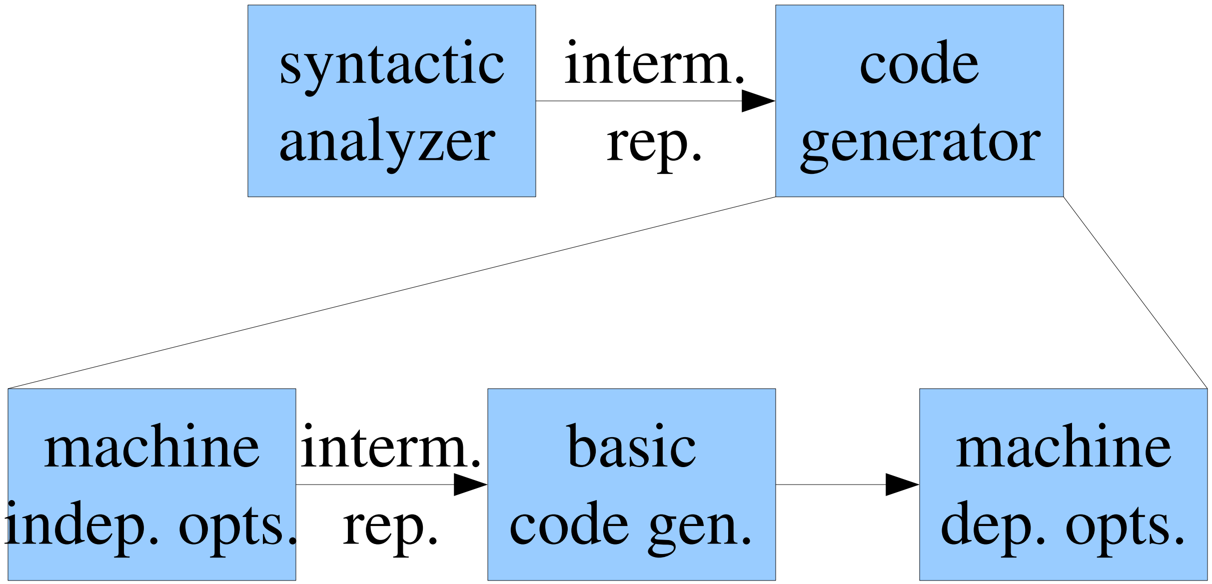
The Big Picture

- By now, we know enough to compile a programming language into machine code
- But the machine code isn't terribly efficient



Today's Lecture

- We will look at different kinds of optimizations a compiler can perform
- Different optimizations apply to different architectures or at different times
  - Virtual stack machines
  - 3-Address instructions
  - Register-based machines

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Basic Blocks

- A basic block is a block of (machine or intermediate) code that always runs straight through without interruption
- A *block head* is
  - the target of a (conditional or unconditional) jump, or
  - the code immediately after a jump or function call, or
  - the first line of code in a function
- A *basic block* starts at a block head and continues to the next block head (or the end of the code/function)

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Basic Block Example

```
   getstatic java/lang/System/out Ljava/io/PrintStream;
   iload 0
   ifeq false_label
```

```
   ldc "true"
   goto print_it
```

```
false_label:
   ldc "false"
```

```
print_it:
   invokevirtual
java/io/PrintStream/println(Ljava/lang/String;)V
```

```
   return
```

Basic Block Example

- Identify the basic blocks in the following

```
    ldc 0.0
    fstore 1
start:
    fload 1     ; load i
    fload 0     ; load n
    fcmpl
    ifge done
    fload 1
    invokestatic SimpleTest/printFloat(F)V
    fload 1
    ldc 1.0
    fadd
    fstore 1
    goto start
done:
    return
```

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Why Basic Blocks?

- Because basic blocks always run straight through, without interruption
  - We are free to modify a lot of the code within a basic block
  - If a variable is set within a basic block then we know the value of that variable for the remainder of the block

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Transformations on Basic Blocks

- Common subexpression elimination
  - Works because we know the values of all variables that have been set within that block

```
a := b+c
b := a-d
c := b+c
d := a-d   ; replace with d := b
```

Transformations on Basic Blocks

- Useless code elimination
  - We can determine that some statements have no effect outside the basic block and can be eliminated

```
iload 0
ldc 1
iadd
istore 0
iload 0          ; eliminate
pop              ; eliminate
```

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Transformation on Basic Blocks

- Renaming temporary variables (3-address codes) and reordering instructions can be useful

```
t1 := b+c
t2 := x+y  ; can reorder if b,c!=t2 and x,y!=t1
```

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Transformations on Basic Blocks

- We can use algebraic identities to simplify code or use less expensive instructions
  - Usually applies when one of the operands is a constant

```
x := x + 0    ; eliminate
x := x * 1    ; eliminate

x := y + 0    ; x := y
x := y * 1    ; x := y

x := y * 2    ; x := y + y  might be faster
```

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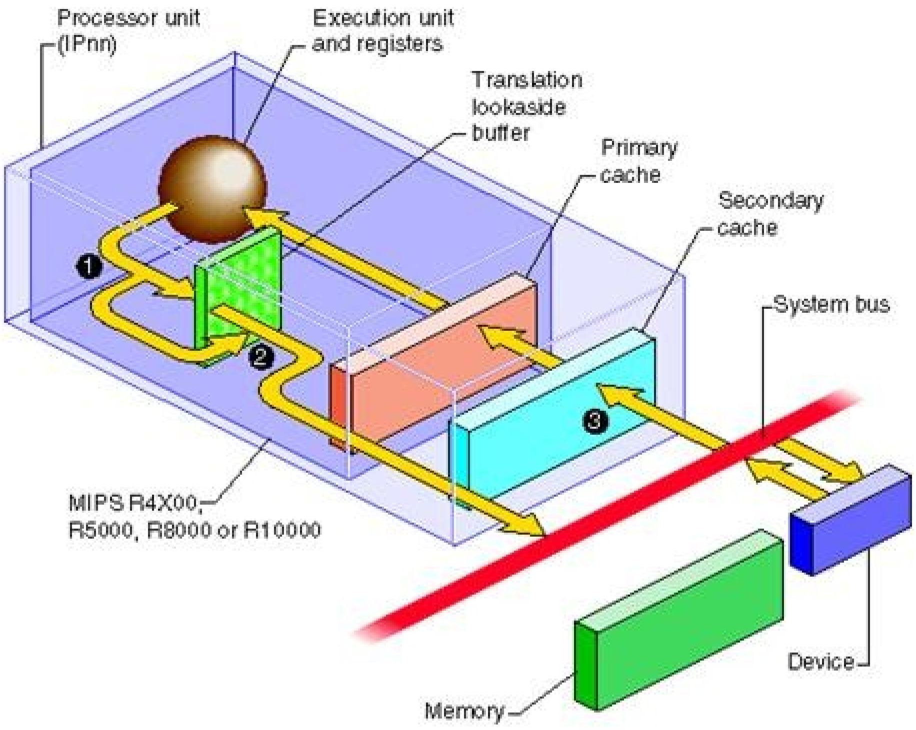
Register Machines



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Register Machines

- A typical computer has a fixed number of registers
- All operations require that the operands be contained in these registers
- Reading data from memory into registers (load) and writing it back (store) is slow
- We want to minimize the number of loads and stores
- Problem: Many functions will have more variables than available registers

Next-Use Information

- When inspecting a basic block, it can be helpful to know when each variable will be used next

```
; code for x := y + z
mov y, R0       ; put y into register 0
mov z, R1       ; put z into register 1
add R0, R1      ; store result of add in R0
mov R0, x       ; store x

; code for p := y * 2
mov y, R0       ; put y into register 0
ld  2, R1       ; put 2 into register 1
add R0, R1      ; store result of add in R0
mov R0, p       ; store p
```

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Next-Use Information (Cont'd)

- An improved use of registers

```
; code for x := y + z
mov y, R0       ; put y into register 0
mov z, R1       ; put z into register 1
add R1, R0      ; store result of add in R1
mov R1, x       ; store x

; code for p := y * 2
                ; y is still in R0
ld  2, R1       ; put 2 into register 1
add R0, R1      ; store result of add in R0
mov R0, p       ; store p
```

Computing Next Use Information

- By scanning backwards we can compute next-use information for each variable used in each line of a basic block
- With each variable, we know
  - the next time it is used in an expression
  - the next time its value is changed
- Aliasing (pointers and references) can complicate matters

Next-Use Information – Example

```
1. t1 := b * b     ; t1(5) b(never)
2. t2 := 4 * a     ; t2(3) a(6)
3. t3 := t2 * c    ; t3(4) t2(never) c(never)
4. t4 := sqrt(t3) ; t4(5) t3(never)
5. t5 := t1 – t4   ; t5(7) t1(never) t4(never)
6. t6 := 2 * a     ; t6(6) a(never)
7. t7 := t5 / t6   ; t7(8) t5(never) t6(never)
```

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Generating Code From Next-Use

- Scan the block from beginning to end, keeping track of where each variable is stored (in which register or in memory)
- To generate code for `x := y + z`
  - Assume x, y, and z are *distinct*
  - if x is in a register Ri then mark Ri as free
  - If y and z are not in registers, then bring them into registers
  - Do the addition (now x is stored in a register)

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Bringing a Variable into a Register

- To load a variable y into a register
  - If some register is free then use that register
  - Otherwise, consider registers that store values also stored in memory and use one of those
  - Otherwise, write a register into memory and use it
- In the case of ties, write the register holding the variable whose next use information is farthest into the future
- At the end of the basic block, generate code to write all registers back to memory

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Code Generation - Example

- Generate code for this on a 2-register machine

```
1. t1 := b * b     ; t1(5) b(never)
2. t2 := 4 * a     ; t2(3) a(6)
3. t3 := t2 * c    ; t3(4) t2(never) c(never)
4. t4 := sqrt(t3)  ; t4(5) t3(never)
5. t5 := t1 – t4   ; t5(7) t1(never) t4(never)
6. t6 := 2 * a     ; t6(6) a(never)
7. t7 := t5 / t6   ; t7(8) t5(never) t6(never)
```

The Pains of Pointers

- In languages with pointers, basic register allocation becomes much more difficult
  - This is especially true in languages, like C and C++ with very flexible pointers
- For this reason, many languages outperform even the best optimizing C compilers

```
int *a;
int x, y, z, w;

...
*a = 23; // this may have modified x, y, z, or w
         // a C compiler has to work hard to
         // know that it doesn't
```

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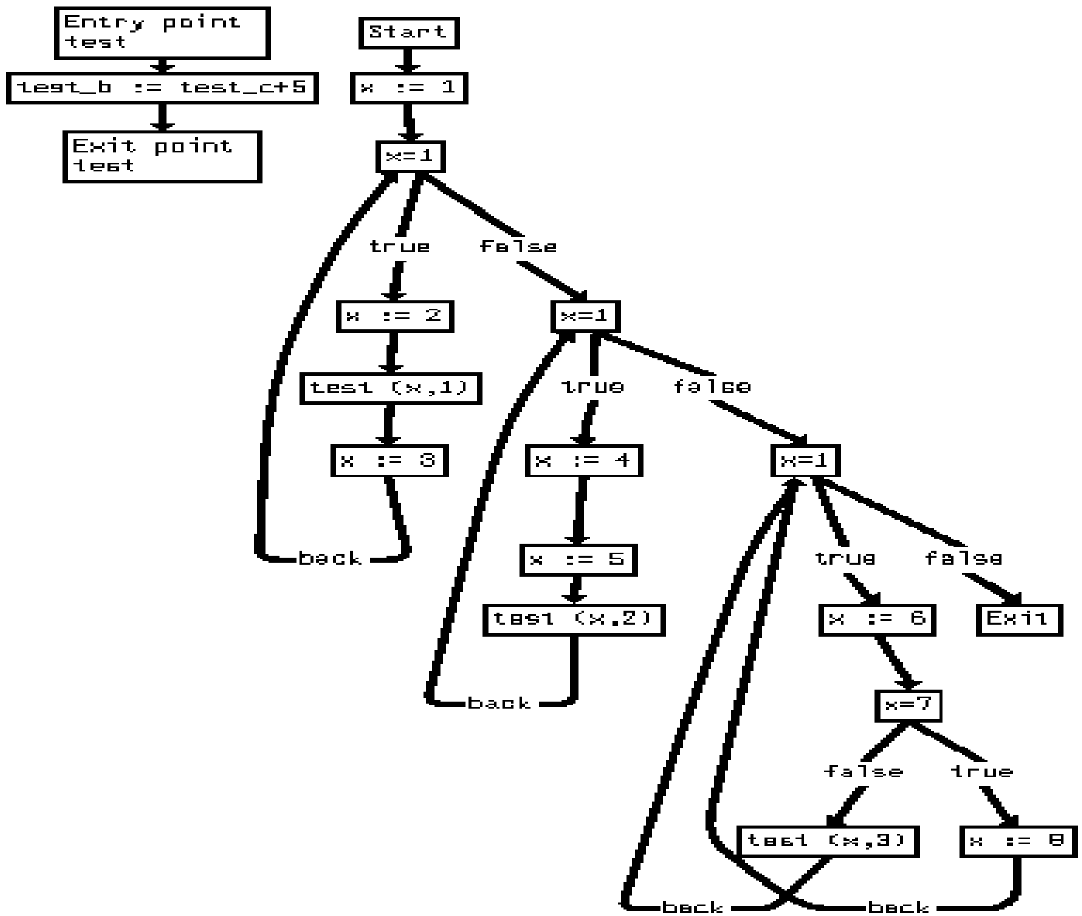
The Control Flow Graph



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The Control Flow Graph

- The (control) flow graph is a directed graph whose vertices are the basic blocks
- An edge goes from block A to block B if
  - A terminates with a (conditional) jump to B, or
  - B comes after A and A's last statement is anything other than a goto or return (unconditional jump)
- The flow graph tells us, for every block, which blocks we might visit next

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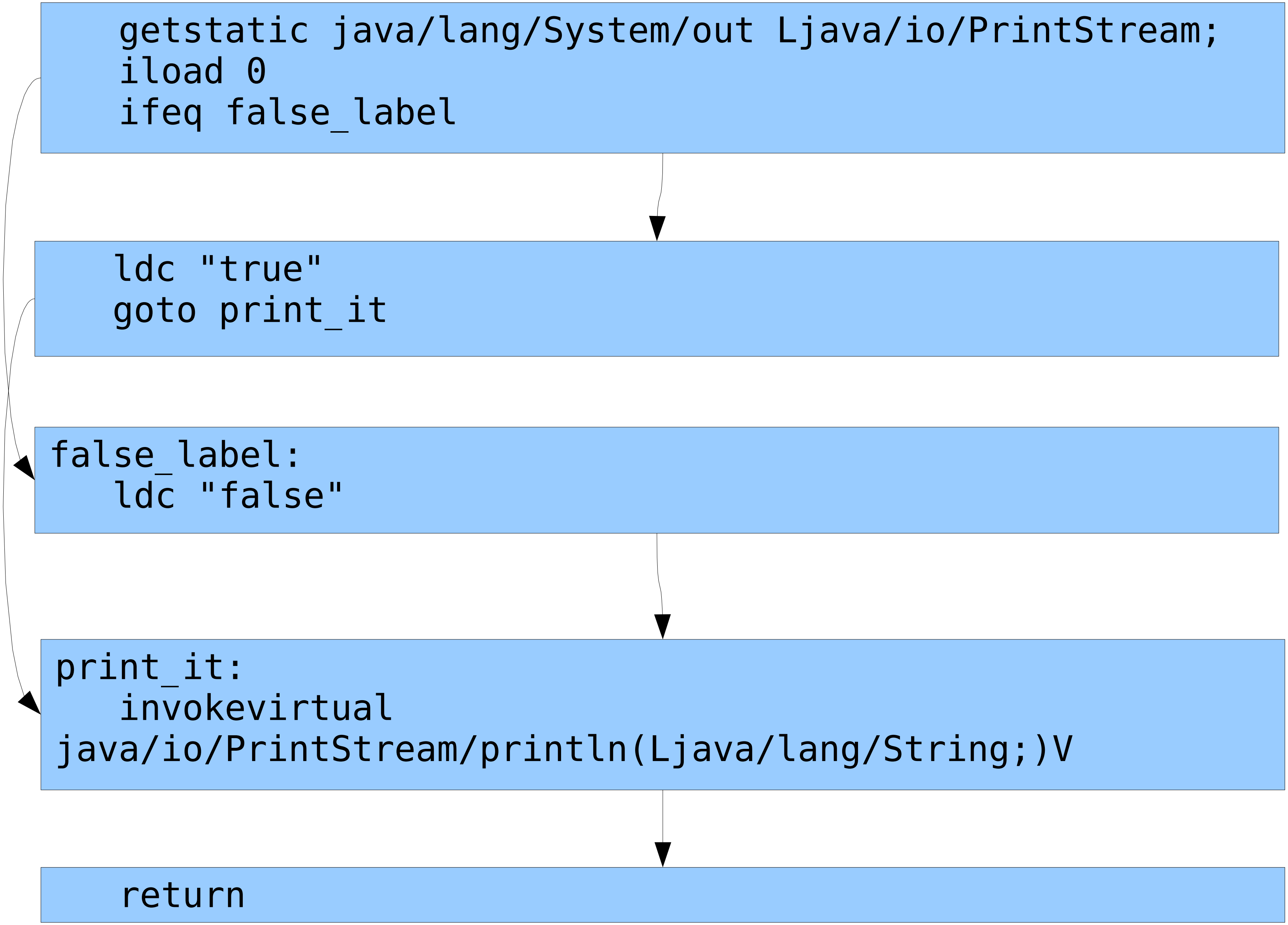
getstatic java/lang/System/out Ljava/io/PrintStream;
iload 0
ifeq false_label
ldc "true"
goto print_it
false_label:
ldc "false"
print_it:
invokevirtual
java/io/PrintStream/println(Ljava/lang/String;)V
return

Flow Graph Example

- Construct the control flow graph:

```
    ldc 0.0
    fstore 1
start:
    fload 1      ; load i
    fload 0      ; load n
    fcmpl
    ifge done
    fload 1
    invokestatic SimpleTest/printFloat(F)V
    fload 1
    ldc 1.0
    fadd
    fstore 1
    goto start
done:
    return
```

Global Register Allocation

- We have seen an efficient algorithm for managing registers within a block
  - Summary:
    - Keep track of which values are in which registers
    - Only store a register when necessary
    - Store all “dirty” registers at the end of a block
- Problem:
  - It's often worth keeping registers in variables across blocks
    - loop indices are a common example

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Example

```
       i := 0
start: i := i + 1
       ...
       if i < 1000 goto start
```

```
       ldc R0, 0
start: inc R0
       ...
       ldc R1, 1000
       sub R1,R0
       jmplt R1, start
```

```
       ldc R0, 0
       mov R0, o      ; store i
start: mov i, R0      ; load i
       inc R0
       ...
       ldc R1, 1000
       sub R1, R0
       mov R0, i      ; store i
       jmplt R1, start
```

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Global Register Allocation

- Designate one or more registers as "variable registers" that will be used to store local variables
- Analyze loops and decide which variables get to become "register" variables

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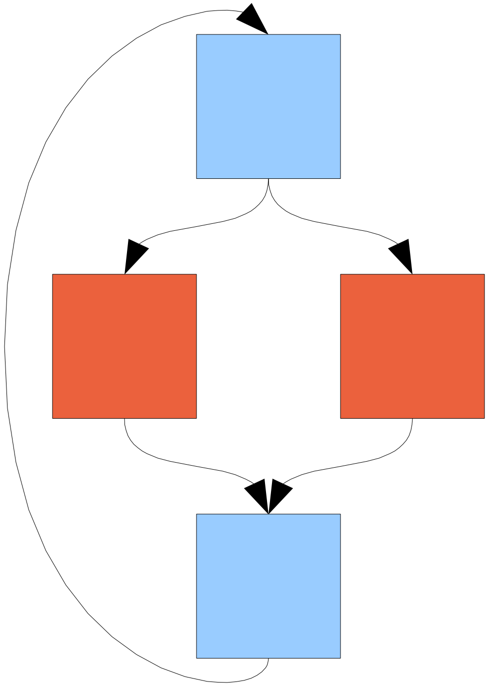
Assigning "Register" Variables

- Easy case: 1 block in a loop
  - Calculate the *savings* for each variable
    - save 1 load if the variable is accessed
    - save 1 store if the variable is modified
- Example:
  - i used and modified (1 load + 1 store)
  - a is modified but not used (1 store)
  - b and c are used but not modified (1 load)
  - putting i in a register yields the greatest savings

```
start: i := i + 1
       a := b + c
       ...
       if i < 1000 goto start
```

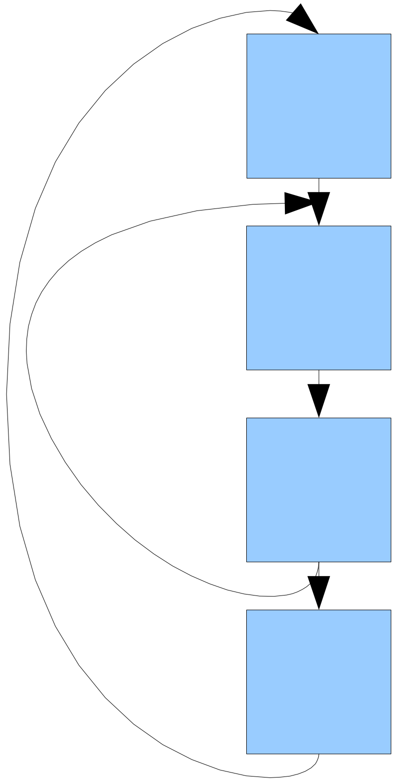
More Complicated Variants

- A cycle with an if statement
  - Only count savings by half as much in the red boxes



More Complicated Variants

- Nested Cycles
  - Pay a penalty for choosing a different variable to use in the inner cycle



Other Control Flow Graph Tricks

- The control flow graph allows several other useful optimizations based on reachability analysis
- Can we get to a basic block B from a basic block A?
- This question is answered by computing the *transitive closure* of the control flow graph

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Dead Code Elimination

- A piece of code is *dead* if it can not be reached in any execution path
- For a function
  - look at the first basic block of the function (A)
  - code B is dead if A->B is not in the transitive closure
- Dead code never executes and can therefore be eliminated

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No Longer Used Variables

- At some point during the execution of a function, a local variable may never be used again
  - We can avoid unnecessarily storing this variable
- If variable i is modified in basic block A
  - Check if there is any block B such that
    - i is used in block B, and
    - A -> B in the transitive closure
  - If not, then i is never used again after visiting A

When to Construct the Flow Graph

- The best time to construct the control flow graph is after some optimizations have been done on the basic blocks
- This may reduce the number of edges in the graph

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```
start:
        ...
        t0 = 1 < 3
        if t0 goto start
```

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Summary

- Basic blocks and control flow graphs represent a compiler's understanding of how a program executes
- Basic blocks always run right through
  - We understand enough about values in basic blocks to optimize agressively
- Flow graphs represent execution paths
  - Give more information about data in basic blocks
  - Allow for reachability analysis