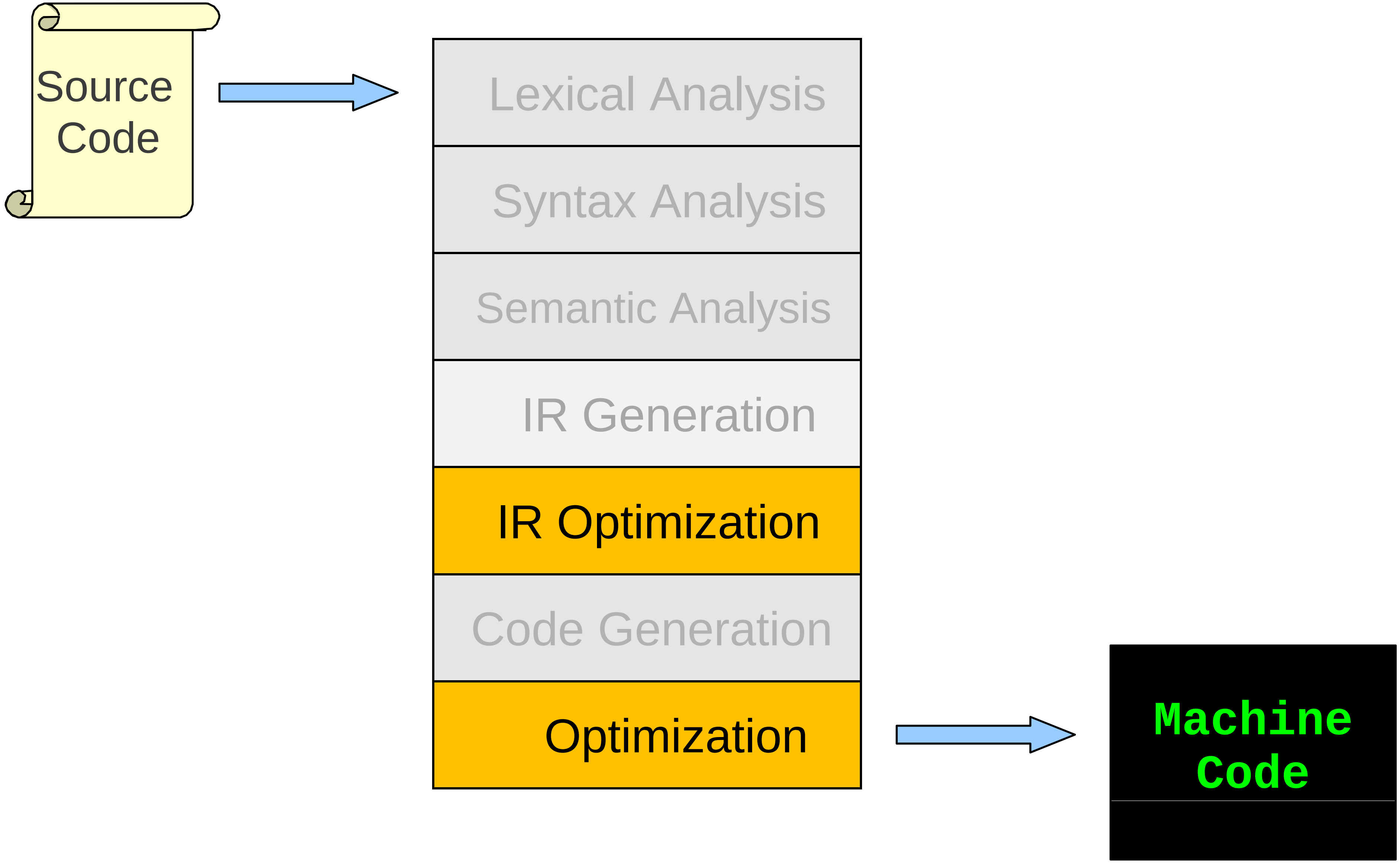
Compilers and Interpreters

Optimization

Where We Are


Source Code
Lexical Analysis
Syntax Analysis
Semantic Analysis
IR Generation
IR Optimization
Code Generation
Optimization
Machine Code

Optimization

- Code produced by standard algorithms can often be made to run faster, take less space or both
- These improvements are achieved through transformations called optimization
- Compilers that apply these transformations are called optimizing compilers
- It is especially important to optimize frequently executed parts of a program

Criteria for Transformations

- A transformation must preserve the meaning of a program
  - Can not change the output produced for any input
  - Can not introduce an error
- Transformations should, on average, speed up programs
- Transformations should be worth the effort

Beyond Optimizing Compilers

- Really improvements can be made at various phases
- Source code:
  - –Algorithmic transformations can produce spectacular improvements
  - –Profiling can be helpful to focus a programmer's attention on important code
- Intermediate code:
  - –Compiler can improve loops, procedure calls, and address calculations
  - –Typically only optimizing compilers include this phase
- Target code:
  - –Compilers can use registers efficiently
  - –Peephole transformation can be applied

Peephole Optimizations

- A simple technique for locally improving target code (can also be applied to intermediate code)
- The peephole is a small, moving window on the target program
- Each improvement replaces the instructions of the peephole with a shorter or faster sequence
- Each improvement may create opportunities for additional improvements
- Repeated passes may be necessary

Redundant-Instruction Elimination

- Redundant loads and stores:

```
(1)MOV R0, a
(2)MOV a, R0
```

- Unreachable code:

```
#define debug 0
if (debug) {
  /* print debugging information */
}
```

Flow-of-Control Optimizations

- Jumps to jumps, jumps to conditional jumps, and conditional jumps to jumps are not necessary
- Jumps to jumps example:
  - The following replacement is valid:

```
    goto L1
    …
L1: goto L2
```

$\Longrightarrow$

```
    goto L2
    …
L1: goto L2
```

  - If there are no other jumps to `L1` and `L1` is preceded by an unconditional jump, the statement at `L1` can be eliminated
- Jumps to conditional jumps and conditional jumps to jumps lead to similar transformations

Other Peephole Optimizations

- A few algebraic identities that occur frequently (such as `x := x + 0` or `x := x * 1`) can be eliminated
- Reduction in strength replaces expensive operations with cheaper ones
  - –Calculating `x * x` is likely much cheaper than `x^2` using an exponentiation routine
  - –It may be cheaper to implement `x * 5` as `x * 4 + x`
- Some machines may have hardware instructions to implement certain specific operations efficiently
  - –For example, auto-increment may be cheaper than a straight-forward `x := x + 1`
  - –Auto-increment and auto-decrement are also useful when pushing into or popping off of a stack

Optimizing Intermediate Code

- This phase is generally only included in optimizing compilers
- Offers the following advantages:
  - –Operations needed to implement high-level constructs are made explicit (i.e. address calculations)
  - –Intermediate code is independent of target machine; code generator can be replaced for different machine
- We are assuming intermediate code uses three-address instructions

Local vs. Global Transformations

- Local transformations involve statements within a single basic block
- All other transformations are called global transformations
- Local transformations are generally performed first
- Many types of transformations can be performed either locally or globally

Common Subexpressions

- **E** is a common subexpression if:
  - –**E** was previously computed
  - –Variables in E have not changed since previous computation
- Can avoid recomputing E if previously computed value is still available
- Dags are useful to detect common subexpressions

Copy Propagation

- Assignments of the form `f := g` are called copy statements (or copies)
- The idea behind copy propagation is to use `g` for `f` whenever possible after such a statement
- For example, applied to block B5 of the previous flow graph, we obtain:

```
x := t3
a[t2] := t5
a[t4] := t3
goto B2
```

- Copy propagation often turns the copy statement into "dead code"

Dead-Code Elimination

- Dead code includes code that can never be reached and code that computes a value that never gets used
- Consider: `if (debug) print …`
  - –It can sometimes be deduced at compile time that the value of an expression is constant
  - –Then the constant can be used in place of the expression (constant folding)
  - –Let's assume a previous statement assigns `debug := false` and value never changes
  - –Then the print statement becomes unreachable and can be eliminated
- Consider the example from the previous slide
  - –The value of `x` computed by the copy statement never gets used after the copy propagation
  - –The copy statement is now dead code and can be eliminated

Loop Optimizations (1)

- The running time of a program may be improved if we do both of the following:
  - Decrease the number of statements in an inner loop
  - Increase the number of statements in the outer loop
- Code motion moves code outside of a loop
  - For example, consider:

    ```
    while (i <= limit-2) …
    ```

  - The result of code motion would be:

    ```
    t = limit - 2
    while (i <= t) …
    ```

Loop Optimizations (2)

- Induction variables: variables that remain in "lock-step"
  - –For example, in block B3 of previous flow graph, `j` and `t4` are induction variables
  - –Induction-variable elimination can sometimes eliminate all but one of a set of induction variables
- Reduction in strength replaces a more expensive operation with a less expensive one
  - –For example, in block B3, `t4` decreases by four with every iteration
  - –If initialized correctly, can replace multiplication with subtraction
  - –Often application of reduction in strength leads to induction-variable elimination
- Methods exist to recognize induction variables and apply appropriate transformations automatically

Example

```
P:=0
    for  I:=1 to 20 do
      P:=P+A[I]*B[I]
```

B1

```
(1)P:=0
(2)I:=1
```

B2

```
(3)   T1:=4*I
(4)   T2:=addr(A)-4
(5)   T3:=T2[T1]
(6)   T4:=4*I
(7)   T5:=addr(B)-4
(8)   T6:=T5[T4]
(9)   T7:=T3*T6
(10) P:=P+T7
(11) I:=I+1
(12) if  I<=20 goto(3)
```

Local Common Subexpressions

```
P:=0
   for  I:=1 to 20 do
     P:=P+A[I]*B[I]
```

B1

```
(1)P:=0
(2)I:=1
```

B2

```
(3)   T1:=4*I
(4)   T2:=addr(A)-4
(5)   T3:=T2[T1]
(6)   T4:=T1
(7)   T5:=addr(B)-4
(8)   T6:=T5[T4]
(9)   T7:=T3*T6
(10) P:=P+T7
(11) I:=I+1
(12) if  I<=20 goto(3)
```

Code motion moves code outside of a loop

B1

```
(1)  P:=0
(2)  I:=1
(4)  T2:=addr(A)-4
(7)  T5:=addr(B)-4
```

B2

```
(3)   T1:=4*I
(5)   T3:=T2[T1]
(6)   T4:=T1
(8)   T6:=T5[T4]
(9)   T7:=T3*T6
(10) P:=P+T7
(11) I:=I+1
(12) if  I<=20 goto(3)
```

Using Cheaper operations

B1

```
(1)  P:=0
(2)  I:=1
(4)  T2:=addr(A)-4
(7)  T5:=addr(B)-4
(3)  T1:=4*I
```

B2

```
(5)   T3:=T2[T1]
(6)   T4:=T1
(8)   T6:=T5[T4]
(9)   T7:=T3*T6
(10) P:=P+T7
(11) I:=I+1
(3’)  T1:=T1+4
(12) if  I<=20 goto(5)
```

Copy Propagation

B1

(1) P:=0
(2) I:=1
(4) T2:=addr(A)-4
(7) T5:=addr(B)-4
(3) T1:=4*I

B2

(5) T3:=T2[T1]
(6) T4:=T1
(8) T6:=T5[T4]
(9) T7:=T3*T6
(10) P:=P+T7
(11) I:=I+1
(12) if I<=20 goto(5

B1

(1) P:=0
(2) I:=1
(4) T2:=addr(A)-4
(7) T5:=addr(B)-4
(3) T1:=4

B2

(5) T3:=T2[T1]
(6) T4:=T1
(8) T6:=T5[T1]
(9) T7:=T3*T6
(10) P:=P+T7
(11) I:=I+1
(3’) T1:=T1+4
(12) if T1<=80 goto(3)

Dead-Code Elimination

B1

(1) P:=0
(2) I:=1
(4) T2:=addr(A)-4
(7) T5:=addr(B)-4
(3) T1:=4

B2

(5) T3:=T2[T1]
(6) T4:=T1
(8) T6:=T5[T1]
(9) T7:=T3*T6
(10) P:=P+T7
(11) I:=I+1
(3’) T1:=T1+4
(12) if T1<=80 goto(5)

B1

(1) P:=0
~~(2) I:=1~~
(4) T2:=addr(A)-4
(7) T5:=addr(B)-4
(3) T1:=4

B2

(5) T3:=T2[T1]
~~(6) T4:=T1~~
(8) T6:=T5[T1]
(9) T7:=T3*T6
(10) P:=P+T7
~~(11) I:=I+1~~
(3’) T1:=T1+4
(12) if T1<=80 goto(5)

Quicksort in C

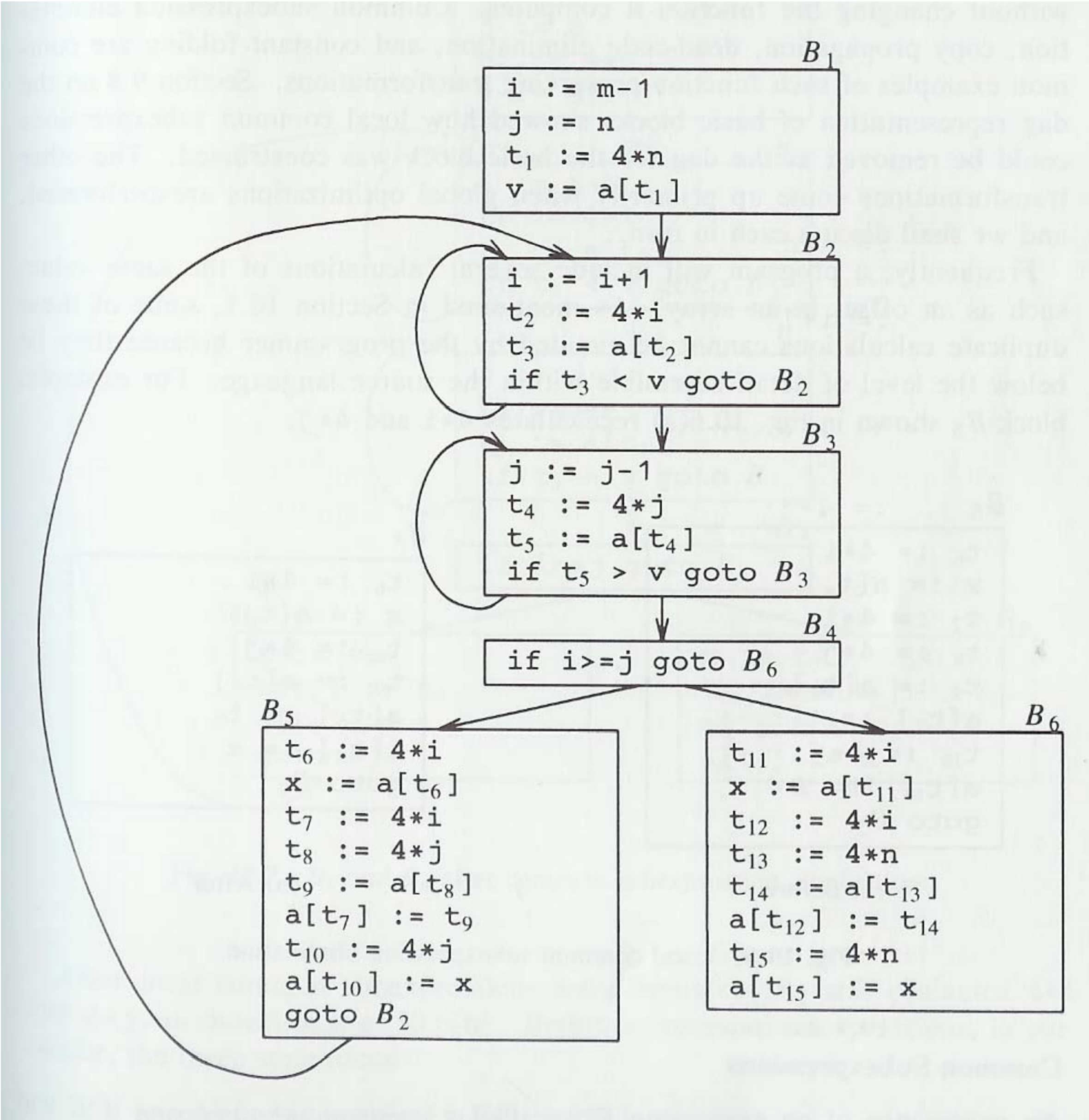
```
void quicksort(int m, int n) {
  int i, j, v, x;

  if (n <= m) return;

  /* Start of partition code */
  i = m-1; j = n; v =a[n];
  while (1) {
    do i = i+1; while (a[i] < v);
    do j = j-1; while (a[j] > v);
    if (i >= j) break;
    x = a[i]; a[i] = a[j]; a[j] = x;
  }
  x = a[i]; a[i] = a[n]; a[n] = x;
  /* End of partition code */

  quicksort(m, j); quicksort(i+1, n);
}
```

Partition in Three-Address Code

```
 (1) i := m-1
 (2) j := n
 (3) t1 := 4*n
 (4) v := a[t1]
 (5) i := i+1
 (6) t2 := 4*i
 (7) t3 := a[t2]
 (8) if t3 < v goto (5)
 (9) j := j-1
(10) t4 := 4*j
(11) t5 := a[t4]
(12) if t5 > v goto (9)
(13) if i >= j goto (23)
(14) t6 := 4*i
(15) x := a[t6]
```

```
(16) t7 := 4*i
(17) t8 := 4*j
(18) t9 := a[t8]
(19) a[t7] := t9
(20) t10 := 4*j
(21) a[t10] := x
(22) goto (5)
(23) t11 := 4*i
(24) x := a[t11]
(25) t12 := 4*i
(26) t13 := 4*n
(27) t14 := a[t13]
(28) a[t12] := t14
(29) t15 := 4*n
(30) a[t15] := x
```

Partition Flow Graph

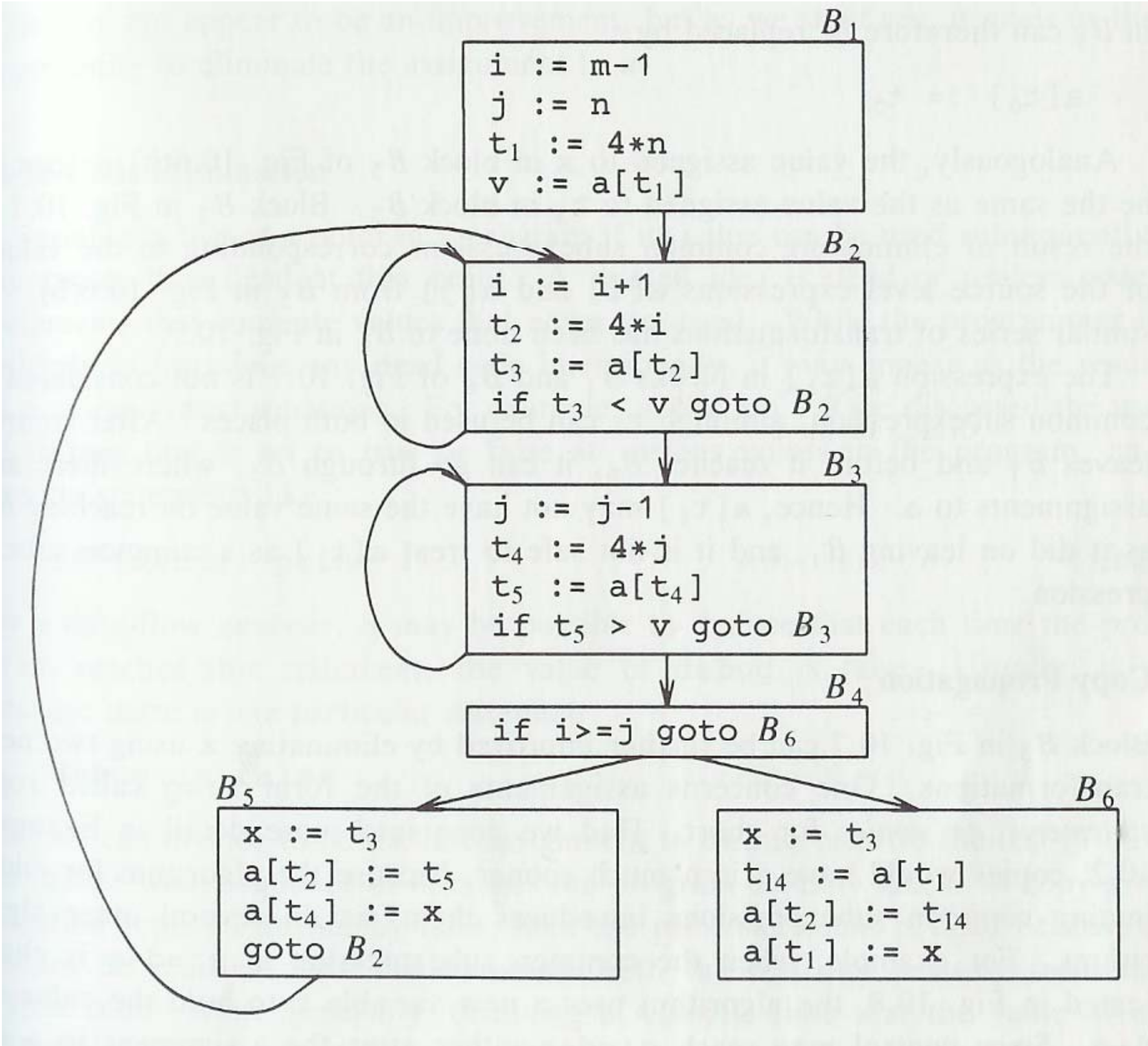


Local Common Subexpressions

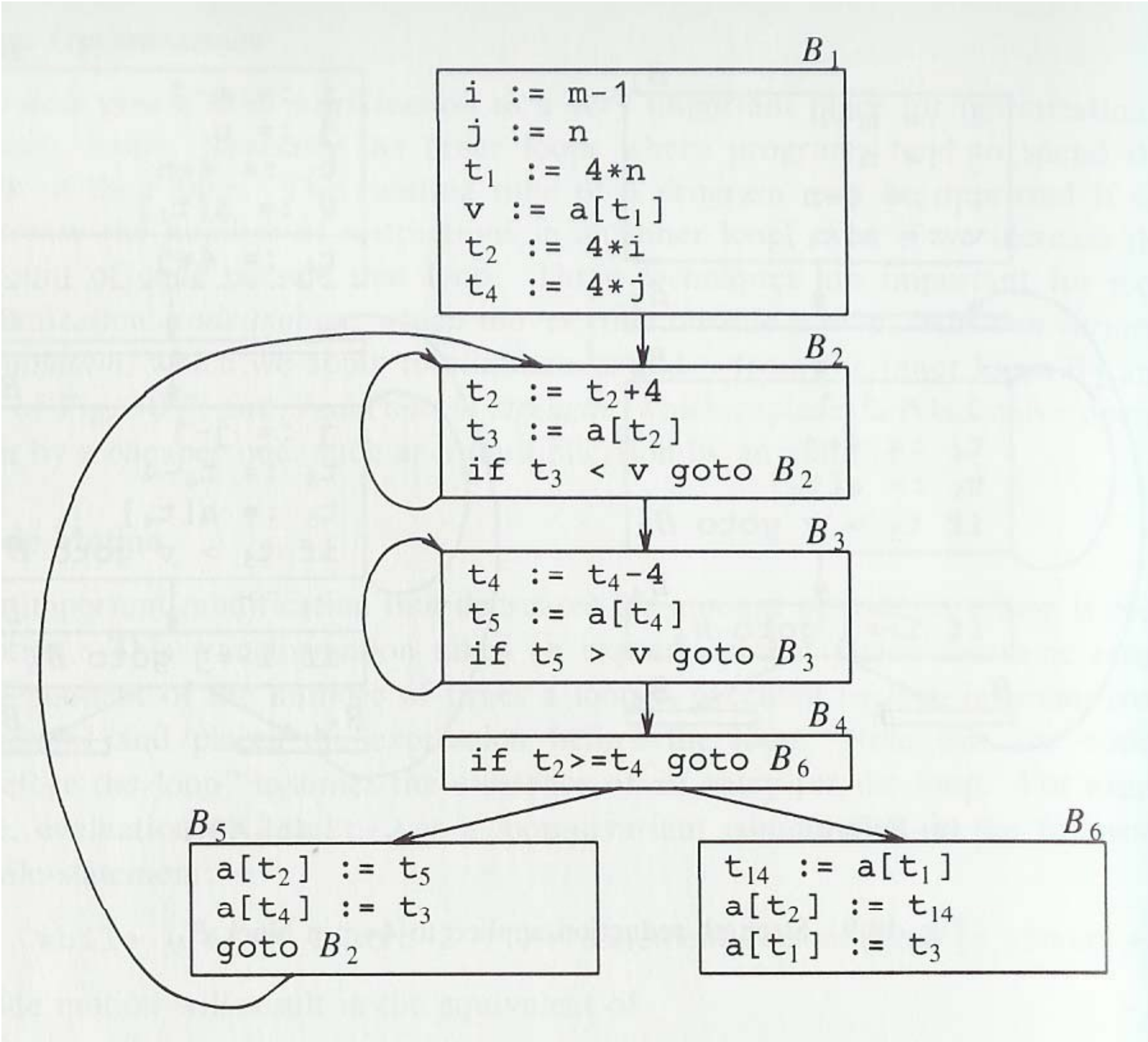
```
t6 := 4*i
x := a[t6]
t7 := 4*i
t8 := 4*j
t9 := a[t8]
a[t7] := t9
t10 := 4*j
a[t10] := x
goto B2
```

```
t6 := 4*i
x := a[t6]
t8 := 4*j
t9 := a[t8]
a[t6] := t9
a[t8] := x
goto B2
```

Global Common Subexpressions

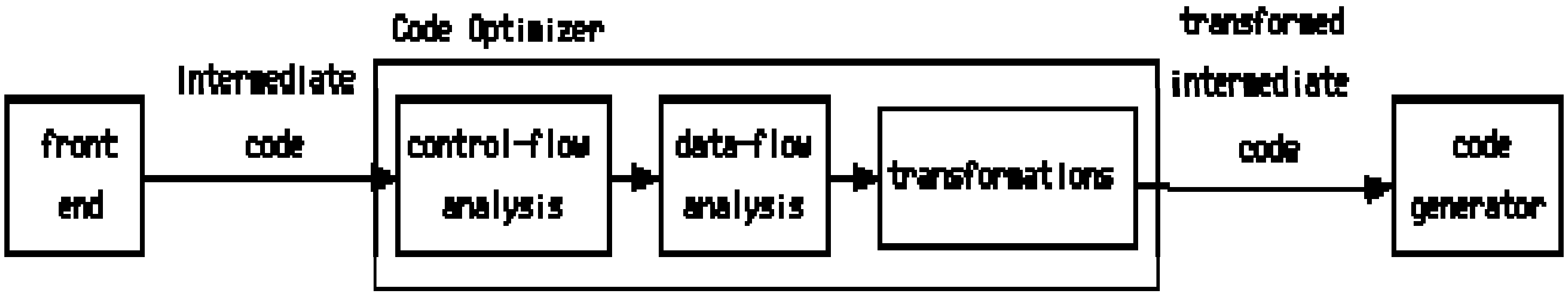


Loop Optimization Example



Implementing a Code Optimizer

- Organization consists of control-flow analysis, then data-flow analysis, and then transformations
- The code generator is applied to the transformed intermediate code
- Details of code optimization are beyond the scope of this course



Reference

- Compilers Principles, Techniques & Tools (Second Edition) Alfred Aho., Monica S. Lam, Ravi Sethi, Jeffrey D. Ullman, Addison-Wesley, 2007
    - Chapter 9.1, 9.2

- Coursera Course – Compiler, http://www. Coursera.org
- Stanford Course CS143 by Keith Schwarz, http://cs143.stanford.edu