

Code Optimization

Code optimization:

- A transformation to a program to make it run faster and/or take up less space
- Code optimizations make improvements in codes by
 - Elimination of **unnecessary operations**
 - Replacing **costly operations** with some other operations
 - **Predicting program behavior**
 - Register allocation – machine dependent
- Optimization should be **safe, preserve the meaning** of a program.
- Code optimizations can be **language dependent or language independent**
 - e.g. stride-one access through array elements may be beneficial for some languages and not for some.

Code Optimization

- Code optimization can either be high level or low level:
 - High level code optimizations are machine independent
 - Example: Loop unrolling, loop fusion, procedure inlining
 - Low level code optimizations are machine dependent
 - Example: Instruction selection, register allocation
- Some optimization can be done in both levels:
 - Example: Common subexpression elimination, strength reduction, etc.
- Flow graph is a common intermediate representation for code optimization.

Basic Block and Control Flow Graph

- A basic block is a:
 - maximal-length sequence of instructions that will execute in its entirety
 - maximal-length straight-line code block
 - maximal-length code block with only one entry and one exit
 - ... in the absence of hardware faults, interrupts, crashes, threading problems, etc.
- To locate basic blocks in flattened code:
 - Starts with: (1) target of a branch (label) or (2) the instruction after a conditional branch
 - Ends with: (1) a branch or (2) the instruction before the target of a branch.
- A control flow graph is a graph whose nodes are basic blocks and whose edges are transitions between blocks.

B1

```
w = 0;  
x = x + y;  
y = 0;  
if( x > z)
```

B2

```
y = x;  
x++;
```

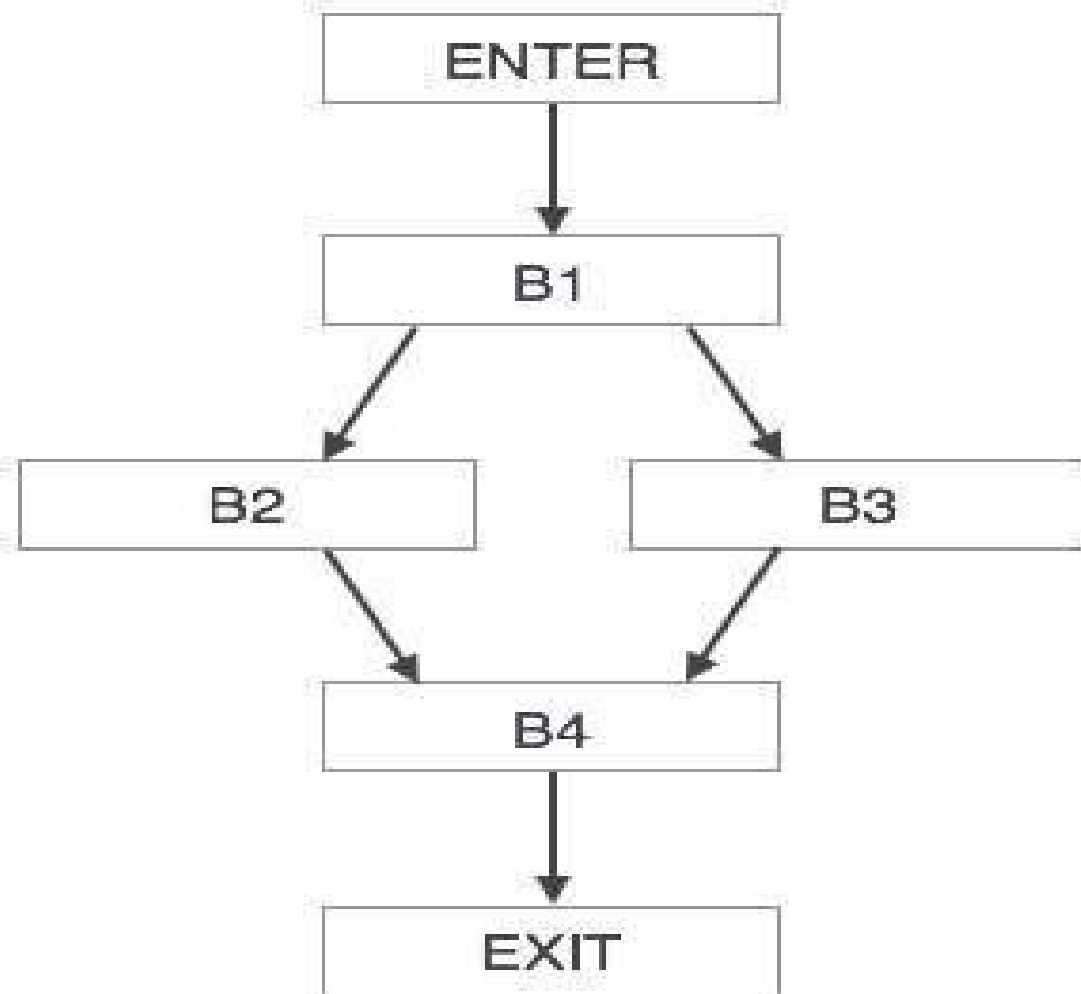
B3

```
y = z;  
z++;
```

B4

```
w = x + z;
```

Basic Blocks



Flow Graph

Scope of Optimization

- Peephole optimization
 - **Examine few instructions** and transform into less expensive others
 - Peephole: a **small moving window** in the instruction sequence
 - Technique: examine a short sequence of target instructions (peephole) and try to replace it with a faster or shorter sequence
 - Example:
 - Redundant instruction elimination
 - Flow of control optimization
 - Algebraic simplifications
 - Instruction selection

Scope of Optimization

- Local optimization
 - Operate on a **single basic block**
 - Basic block: a sequence of consecutive statements with exactly 1 entry and 1 exit
- Loop optimization
 - Act on **a number of basic blocks which made up a loop**
- Global or intra-procedural optimizations
 - Act on the **complete control flow graph of a single procedure**
- Inter-procedural or whole program optimization
 - Most powerful, **optimize interactions between procedures**

Code Optimization

- Constant propagation
 - A transformation that propagates values defined in a statement of the form $x=c$, for a variable x and a constant c , through the entire program.
 - For the constant value, defined by a statement S_i , to be propagated the following conditions have to be satisfied:
 - There should be a statement S_j in which a use of the variable defined in S_i appears.
 - All definitions of the variable reaching the use at S_j must have the same value.
- Constant folding
 - Refers to the evaluation at compile time of expressions whose values are known to be constants. It involves determining that all operands in an expression are constants, performing the **evaluation of the expression and replacing the expression by its value**.
 - May not be always legal.
 - e.g. a) $\text{area} = (22.0 / 7.0) * r ** 2$

Code Optimization

- Useless code elimination
 - A statement is useless if it computes only values that are not used on any executable path leading from the statement
 - Often arises from other code transformations
 - (also known as Dead code eliminations)
- Unreachable code elimination
 - Code that cannot be executed regardless of the input data.
 - Likely to arise as a result of other transformations

Dead code elimination – example

```
int global;  
void f ()  
{  
    int i;  
    i = 1;      /* dead store */  
    global = 1; /* dead store */  
    global = 2;  
    return;  
    global = 3; /* unreachable */  
}
```

After dead code elimination

```
int global;  
void f ()  
{  
    global = 2;  
    return;  
}
```

Code Optimization

- Copy propagation
 - Given an assignment $x=y$ for some variables x and y , replaces later uses of x with uses of y , as long as intervening instructions have not changed the value of either x or y .
 - For a copy statement, $S_i: x=y$, we can replace any later use u of the variable x by the variable y if the following conditions are satisfied:
 - All definitions S_k of x reaching u must be a copy statement with variable y as the source operand (i.e. value of x does not change)
 - On every path from definition S_k to use u , including paths that go through u several times, there are no assignments to the source variable y (i.e. value of y also does not change after defining x)
 - An idea behind this technique is to use g for f whenever possible after the copy of $f := g$

Copy propagation

before

x := t3

a[t7] := t5

a[t10] := x

Goto b2

After

x := t3

a[t7] := t5

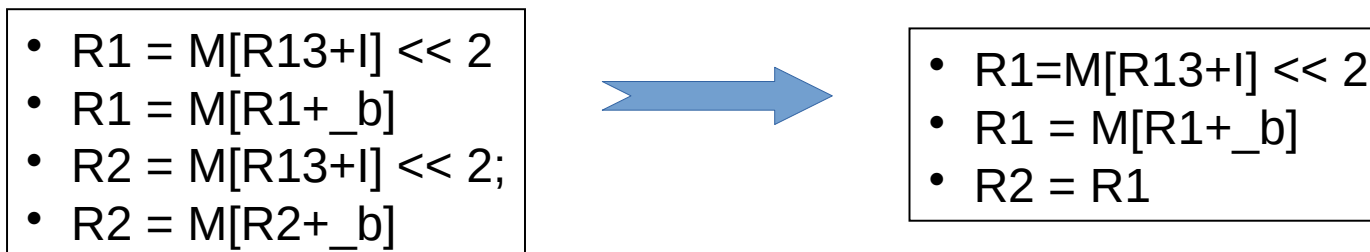
a[t10] := t3

Goto b2

Code Optimization

- Common sub-expression elimination

- An occurrence of an expression in a program is a common subexpression if another occurrence of the expression exists whose evaluation precedes this one in execution order and if the operands of the expression remain unchanged between these two executions.
- Removes re-computations of common subexpressions and replaces them with uses of saved values.
- Identification of common subexpressions:
 - Search for lexically equivalent expressions, i.e. expressions consisting of the same identifiers, operators and appearing in the same order
 - The expressions must also be evaluated to identical values during any course of execution of the program (semantic equivalence)



$a = b * c$

.....

$x = b * c + 5$



$\text{Temp} = b * c$

$a = \text{temp}$

.....

$x = \text{temp} + 5$

Code Optimization

Code space reduction

```
if a < b then
```

```
  z = x ** 2
```

```
  ....
```

```
else
```

```
  y = x ** 2 + 19
```



```
temp = x ** 2
```

```
if a < b then
```

```
  z = temp
```

```
  ....
```

```
else
```

```
  Y = temp + 19
```

- Strength reduction

Replace $2 * x$ with a shift operation or x^3 with $x * x * x$
OR

```
for k = 1 to 10 do
```

```
  ....
```

```
  x = k * 5
```

```
  ....
```

```
end
```



```
temp = 5
```

```
for k = 1 to 10 do
```

```
  ....
```

```
  x = temp
```

```
  ....
```

```
  temp = temp + 5
```

```
end
```

Code Optimization

- Removing procedure calls
 - Procedure inlining – replace the procedure call with the code of the procedure body
 - Tail recursion removal (when the last operation is a call to itself)

```
int gcd (int u, int v)
{
    if (v==0) return u;
    else return gcd ( v, u % v );
}
```



```
int gcd (int u, int v)
{
    begin :
    if ( v == 0) return u;
    else
    {
        int t1 = v, t2 = u % v;
        u = t1; v = t2;
        goto begin;
    }
}
```

Code Optimization

- Loop invariant code motion

- A computation in a loop is invariant if its value does not change within the loop.
- Loop invariant code motion recognizes invariant computations in loops and moves them to the loop preheader.
- For an invariant computation
- $s: x = y + z$ in a loop L , the following three conditions ensure that code motion does not change the semantics of the program
 - The basic block containing s dominates all exit nodes of the loop, where an exit of a loop is a node with successor not in the loop
 - No other statement is in the loop that assigns to x
 - No use of x in the loop is reached by any definition of x from outside the loop.

e.g. while ($i < n$)

do

```
{ A = B + C;  
  Z = A * i;  
  X = f (Z);  
  i = i + 1;  
}
```



$A = B + C$

while ($i < n$)

do

```
{ Z = A * i;  
  X = f (Z);  
  i = i + 1;  
}
```

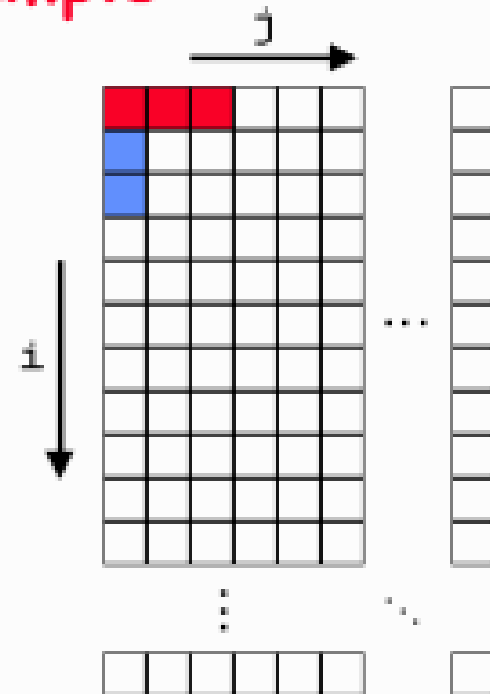

Code Optimization

- Loop interchange
 - Exchanges the position of two loops in a tightly nested loop
 - Requirements for loop interchaging
 - The loops L1 and L2 must be tightly nested
 - The loop limits of L2 are invariant in L1
 - There are no statements S_i and S_j in L2 with specific types of dependences
 - Not always legal
 - Improves locality of reference

Loop Interchange Example

```
/* Before */
for (k = 0; k < 100; k = k+1)
    for (j = 0; j < 100; j = j+1)
        for (i = 0; i < 5000; i = i+1)
            x[i][j] = 2 * x[i][j];

/* After */
for (k = 0; k < 100; k = k+1)
    for (i = 0; i < 5000; i = i+1)
        for (j = 0; j < 100; j = j+1)
            x[i][j] = 2 * x[i][j];
```



Sequential accesses instead of striding
through memory every 100 words; improved
spatial locality



Code Optimization

- Loop fusion

- Fuses two adjacent loops into one
- Reduces the loop overhead, and increases instruction parallelism
- Requirements for fusing two loops L1 and L2 are
 - The two loop control variables should be the same and the loop limits must be identical
 - There should not be any statement S_v in L1 and S_w in L2 with some dependence relation
 - Both loops do not have a conditional branch that exits the loop
 - Loops L1 and L2, both should not have I/O statements

- Loop fission

- Reverse of fusion
- Improves locality of reference

Loop Fusion and Loop Fission

```
for (i = 0; i < 300; i++)  
    a[i] = a[i] + 3;
```

```
for (i = 0; i < 300; i++)  
    b[i] = b[i] + 4;
```

FUSION

```
for (i = 0; i < 300; i++)  
{  
    a[i] = a[i] + 3;  
    b[i] = b[i] + 4;  
}
```

```
for (i = 0; i < 300; i++)  
{  
    a[i] = a[i] + 3;  
    b[i] = b[i] + 4;  
}
```

FISSION

```
for (i = 0; i < 300; i++)  
    a[i] = a[i] + 3;  
  
for (i = 0; i < 300; i++)  
    b[i] = b[i] + 4;
```

Code Optimization

- **Loop reversal**

- Reversal changes the direction in which the loop traverses its iteration space
- It is often used in conjunction with other loop transformations
- Not always legal
- e.g.

```
for (i=0; i<N; i++){  
    a[i]=b[i]+1;  
    c[i]=a[i]/2;  
}
```

may be replaced with

```
for (i=N-1; i<=0; i--){  
    a[i]=b[i]+1;  
    c[i]=a[i]/2;  
}
```

Code Optimization

- **Loop unrolling**

- Decreases number of times the loop condition needs to be tested
- Reduces number of jumps from end to beginning
- Good for instruction pipelining and instruction level parallelism
- However, for complete unrolling, number of instructions to be known at compile time
 - Increases code size significantly

- **Loop unrolling and jam**

- Unroll and jam involves partially unrolling one or more loops
- higher in the nest than the innermost loop, and fusing (“jamming”) the resulting loops back together.