Introduction to Machine-Independent Optimizations - 1

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NPTEL Course on Principles of Compiler Design

Outline of the Lecture

- What is code optimization?
- Illustrations of code optimizations
- Examples of data-flow analysis
- Fundamentals of control-flow analysis
- Algorithms for two machine-independent optimizations
- SSA form and optimizations

Machine-independent Code Optimization

- Intermediate code generation process introduces many inefficiencies
  - Extra copies of variables, using variables instead of constants, repeated evaluation of expressions, etc.
- Code optimization removes such inefficiencies and improves code
- Improvement may be time, space, or power consumption
- It changes the structure of programs, sometimes of beyond recognition
  - Inlines functions, unrolls loops, eliminates some programmer-defined variables, etc.
- Code optimization consists of a bunch of heuristics and percentage of improvement depends on programs (may be zero also)

Examples of Machine-Independant Optimizations

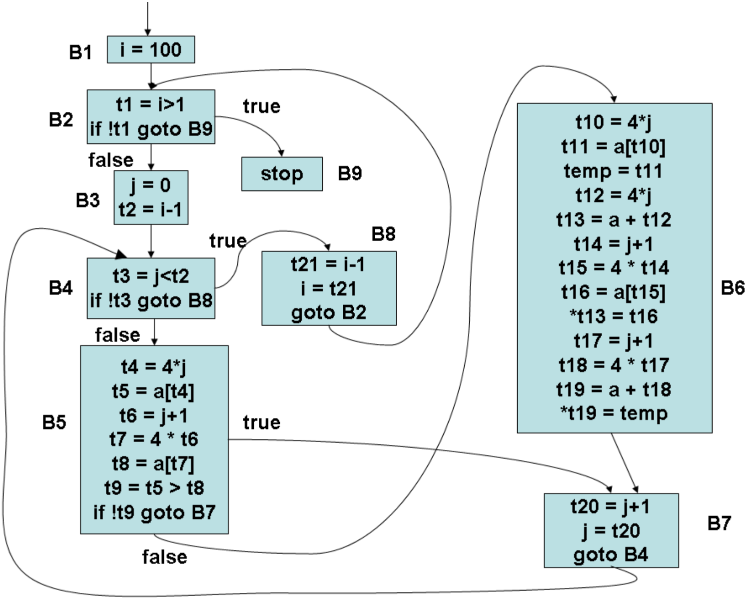
- Global common sub-expression elimination
- Copy propagation
- Constant propagation and constant folding
- Loop invariant code motion
- Induction variable elimination and strength reduction
- Partial redundancy elimination
- Loop unrolling
- Function inlining
- Tail recursion removal
- Vectorization and Concurrentization
- Loop interchange, and loop blocking

Bubble Sort

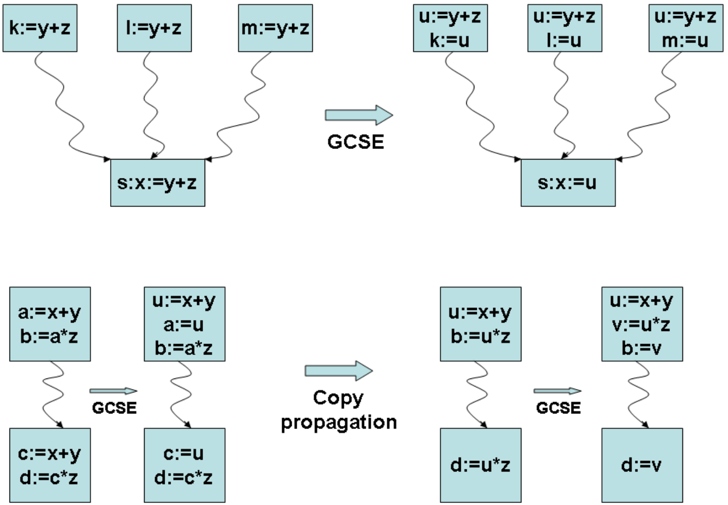
```
for (i=100; i>1; i--) {
    for (j=0; j<i-1; j++) {
        if (a[j] > a[j+1]) {
            temp = a[j];
            a[j+1] = a[j];
            a[j] = temp;
        }
    }
}
```

- int a[100]
- array a runs from 0 to 99
- No special jump out if array is already sorted

Control Flow Graph of Bubble Sort

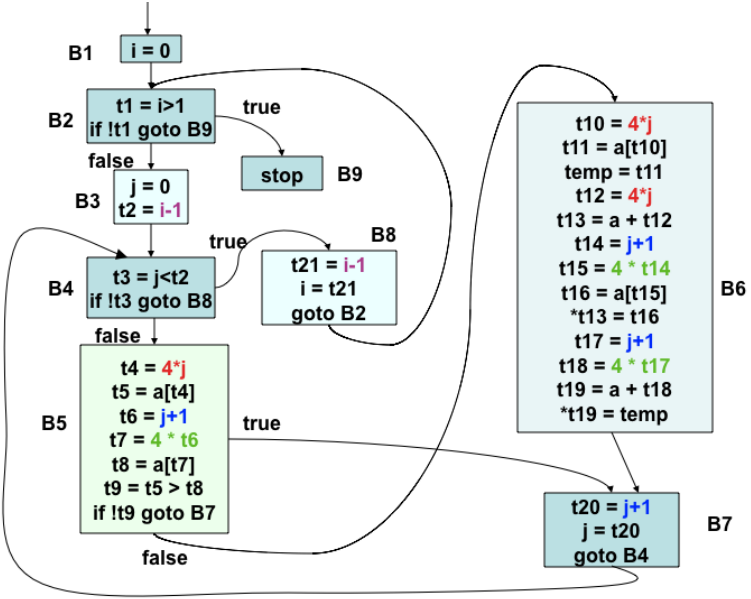


GCSE Conceptual Example

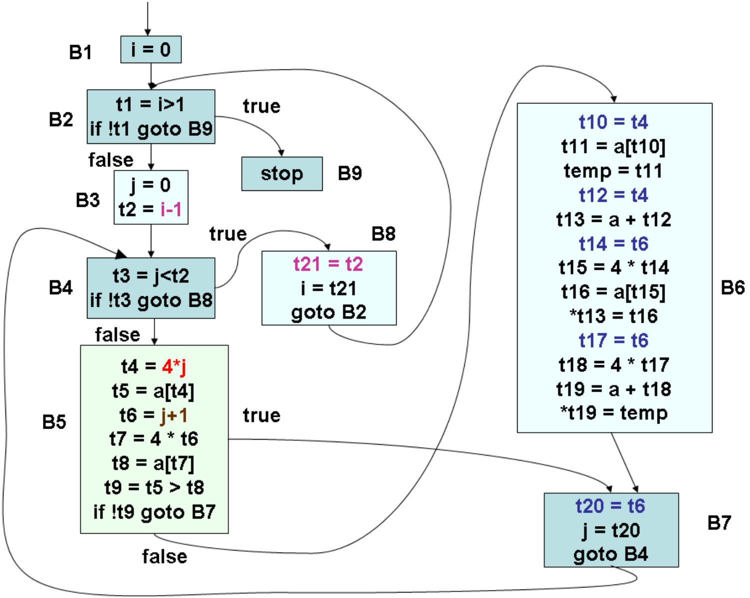


Demonstrating the need for repeated application of GCSE

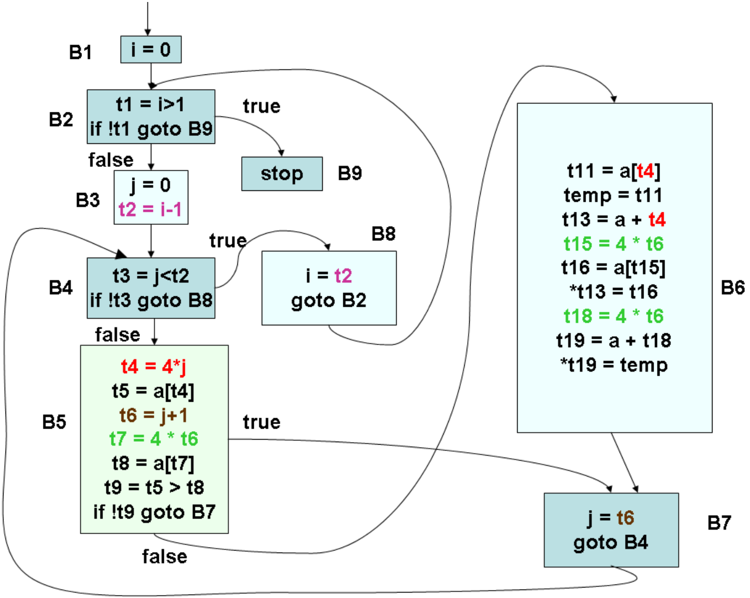
GCSE on Running Example - 1



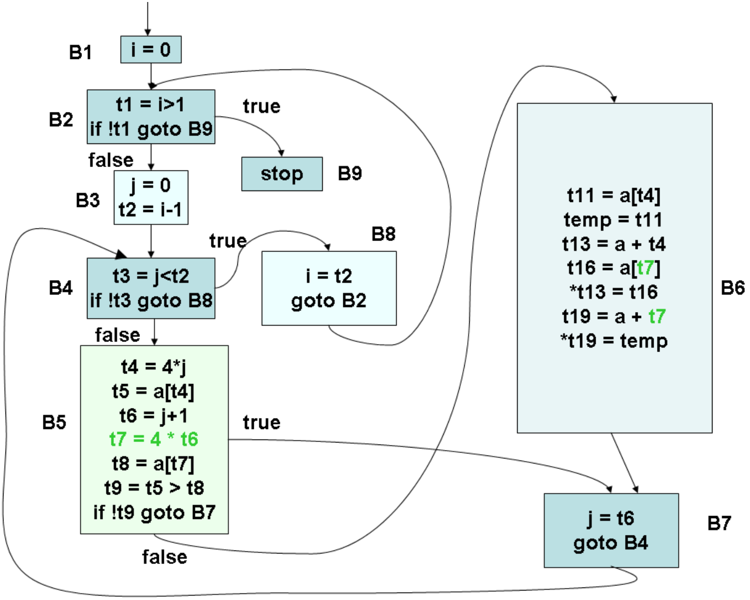
GCSE on Running Example - 2



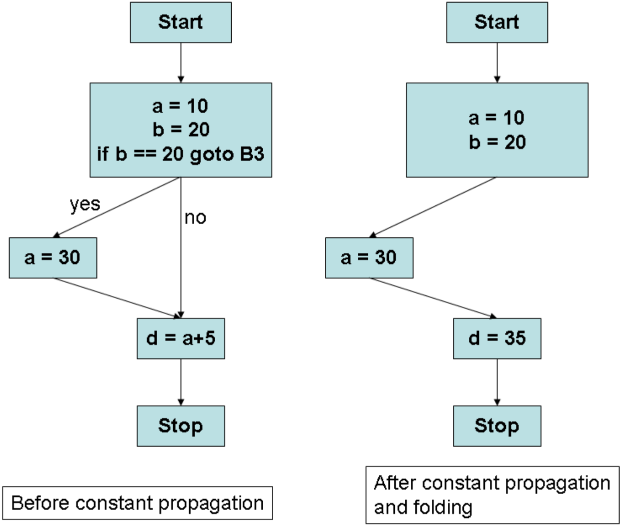
Copy Propagation on Running Example



GCSE and Copy Propagation on Running Example



Constant Propagation and Folding Example



Loop Invariant Code motion Example

```
      t1 = 202
      i = 1
L1:   t2 = i>100
      if t2 goto L2
      t1 = t1-2
      t3 = addr(a)
      t4 = t3 - 4
      t5 = 4*i
      t6 = t4+t5
      *t6 = t1
      i = i+1
      goto L1
L2:
```

Before LIV code motion

```
      t1 = 202
      i = 1
      t3 = addr(a)
      t4 = t3 - 4
L1:   t2 = i>100
      if t2 goto L2
      t1 = t1-2
      t5 = 4*i
      t6 = t4+t5
      *t6 = t1
      i = i+1
      goto L1
L2:
```

After LIV code motion

Strength Reduction

```
      t1 = 202
      i = 1
      t3 = addr(a)
      t4 = t3 - 4
L1:   t2 = i>100
      if t2 goto L2
      t1 = t1-2
      t5 = 4*i
      t6 = t4+t5
      *t6 = t1
      i = i+1
      goto L1
L2:
```

Before strength reduction for t5

```
      t1 = 202
      i = 1
      t3 = addr(a)
      t4 = t3 – 4
      t7 = 4
L1:   t2 = i>100
      if t2 goto L2
      t1 = t1-2
      t6 = t4+t7
      *t6 = t1
      i = i+1
      t7 = t7 + 4
      goto L1
L2:
```

After strength reduction for t5 and copy propagation

Induction Variable Elimination

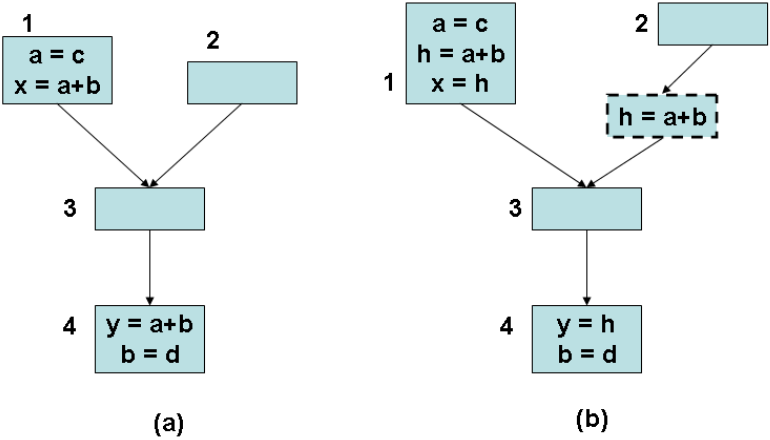
```
      t1 = 202
      i = 1
      t3 = addr(a)
      t4 = t3 – 4
      t7 = 4
L1:   t2 = i>100
      if t2 goto L2
      t1 = t1-2
      t6 = t4+t7
      *t6 = t1
      i = i+1
      t7 = t7 + 4
      goto L1
L2:
```

Before induction variable elimination (i)

```
      t1 = 202
      t3 = addr(a)
      t4 = t3 – 4
      t7 = 4
L1:   t2 = t7 >400
      if t2 goto L2
      t1 = t1-2
      t6 = t4+t7
      *t6 = t1
      t7 = t7 + 4
      goto L1
L2:
```

After eliminating i and replacing it with t7

Partial Redundancy Elimination



Unrolling a For-loop

```
for (i = 0; i<N; i++) { S1(i); S2(i); }

for (i = 0; i+3 < N; i+=3) {
    S1(i); S2(i);
    S1(i+1); S2(i+1);
    S1(i+2); S2(i+2);
}
// remaining few iterations, 1,2, or 3:
// (((N-1) mod 3)+1)
for (k=i; k<N; k++) { S1(k); S2(k); }
```

Unrolling While and Repeat loops

```
while (C) { S1; S2; }

while (C) {
   S1; S2;
   if (!C) break;
   S1; S2;
   if (!C) break;
   S1; S2;
}
```

```
repeat { S1; S2; } until C;

repeat {
   S1; S2;
   if (C) break;
   S1; S2;
   if (C) break;
   S1; S2;
} until C;
```

Function Inlining

```
int find_greater(int A[10], int n) {  int i;
    for (i=0; i<10; i++){ if (A[i] > n) return i; }
}
// inlined call: x = find_greater(Y, 250);
int new_i, new_A[10];
new_A = Y;
for (new_i=0; new_i<10; new_i++) {
    if (new_A[new_i] > 250)
      { x = new_i; goto exit;}
}
exit:
```

Tail Recursion Removal

```
void sum (int A[], int n, int* x) {
    if (n==0) *x = *x+ A[0]; else {
        *x = *x+A[n];  sum(A, n-1, x);
    }
}
// after removal of tail recursion
void sum (int A[], int n, int* x) {
  while (true) { if (n==0) {*x=*x+A[0]; break;}
                 else{ *x=*x + A[n]; n=n-1; continue;}
  }
}
```

Vectorization and Concurrentization Example 1

```
for I = 1 to 100 do {
   X(I) = X(I) + Y(I)
}

can be converted to

X(1:100) = X(1:100) + Y(1:100)

or

forall I = 1 to 100 do X(I) = X(I) + Y(I)
```

Vectorization Example 2

```
for I = 1 to 100 do {
   X(I+1) = X(I) + Y(I)
}

cannot be converted to

X(2:101) = X(1:100) + Y(1:100)
or equivalent concurrent code

because of dependence as shown below

X(2) = X(1) + Y(1)
X(3) = X(2) + Y(2)
X(4) = X(3) + Y(3)
...
```

Loop Interchange for parallelizability

```
for I = 1 to N do {
   for J = 1 to N do {
S:      A(I+1,J) = A(I,J) * B(I,J) + C(I,J)
   }
}
```

Outer loop is not parallelizable, but inner loop is

Less work per thread

```
for J = 1 to N do {
   for I = 1 to N do {
S:      A(I+1,J) = A(I,J) * B(I,J) + C(I,J)
   }
}
```

Outer loop is parallelizable but inner loop is not

More work per thread

```
forall J = 1 to N do {
   for I = 1 to N do {
S:      A(I+1,J) = A(I,J) * B(I,J) + C(I,J)
   }
}
```

Loop Blocking

```
{ for (i = 0; i < N; i++)
    for (j=0; j < M; j++)
      A[j,I] = B[i] + C[j];
}
// Loop after blocking
{ for (ii = 0; ii < N; ii = ii+64)
    for (jj = 0; jj < M; jj = jj+64)
      for (i = ii; i < ii+64; i++)
        for (j=jj; j < jj+64; j++)
          A[j,I] = B[i] + C[j];
}
```

Fundamentals of Data-flow Analysis

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Data-flow analysis

- These are techniques that derive information about the flow of data along program execution paths
- An *execution path* (or *path*) from point p_1 to point p_n is a sequence of points $p_1, p_2, ..., p_n$ such that for each $i = 1, 2, ..., n-1$, either
  1. p_i is the point immediately preceding a statement and p_{i+1} is the point immediately following that same statement, or
  2. p_i is the end of some block and p_{i+1} is the beginning of a successor block
- In general, there is an infinite number of paths through a program and there is no bound on the length of a path
- Program analyses summarize all possible program states that can occur at a point in the program with a finite set of facts
- No analysis is necessarily a perfect representation of the state

Uses of Data-flow Analysis

- Program debugging
  - Which are the definitions (of variables) that *may* reach a program point? These are the *reaching definitions*
- Program optimizations
  - Constant folding
  - Copy propagation
  - Common sub-expression elimination etc.

Data-Flow Analysis Schema

- A *data-flow value* for a program point represents an abstraction of the set of all possible program states that can be observed for that point
- The set of all possible data-flow values is the *domain* for the application under consideration
  - Example: for the *reaching definitions* problem, the domain of data-flow values is the set of all subsets of of definitions in the program
  - A particular data-flow value is a set of definitions
- $IN[s]$ and $OUT[s]$: data-flow values *before* and *after* each statement s
- The *data-flow problem* is to find a solution to a set of constraints on $IN[s]$ and $OUT[s]$, for all statements s