Introduction to Machine-Independent Optimizations

Y.N. Srikant

Department of Computer Science and Automation
Indian Institute of Science
Bangalore 560 012

NPTEL Course on Compiler Design

Outline of the Lecture

- What is code optimization?
- Types of code optimizations
- Illustrations of code 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

Data-flow Analysis

- Code optimization needs information about the program
  - which expressions are being recomputed in a function?
  - Which expressions are partially redundant?
  - which definitions reach a point?
  - Which copies and constants can be propagated? Etc.
- All such information is gathered through data-flow analysis

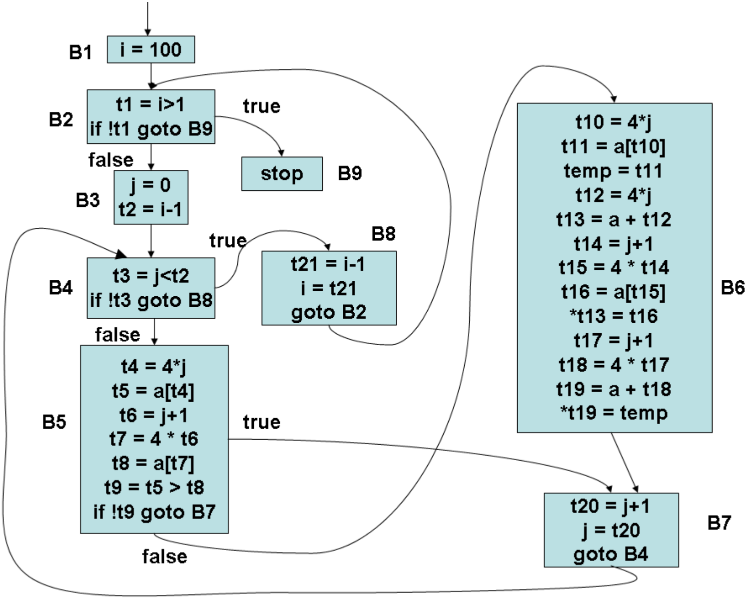
Bubble Sort Running Example

Bubble Sort

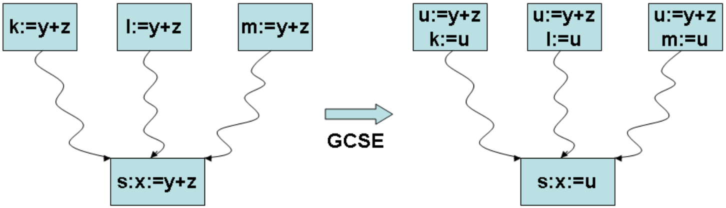
```
for (i=100; i>1; i--) {
    for (j=0; j<i-1; j++) {
        if (a[j] > a[j+1]) {
            temp = a[j];
            a[j+1] = a[j];
            a[j] = temp;
        }
    }
}
```

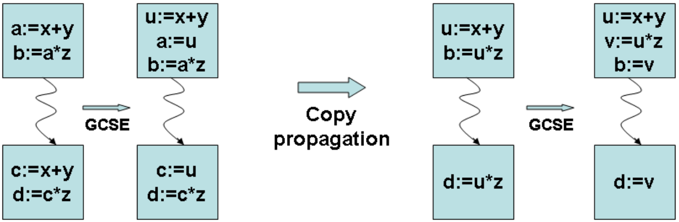
- int a[100]
- array a runs from 0 to 99
- No special jump out if array is already sorted

Control Flow Graph of Bubble Sort



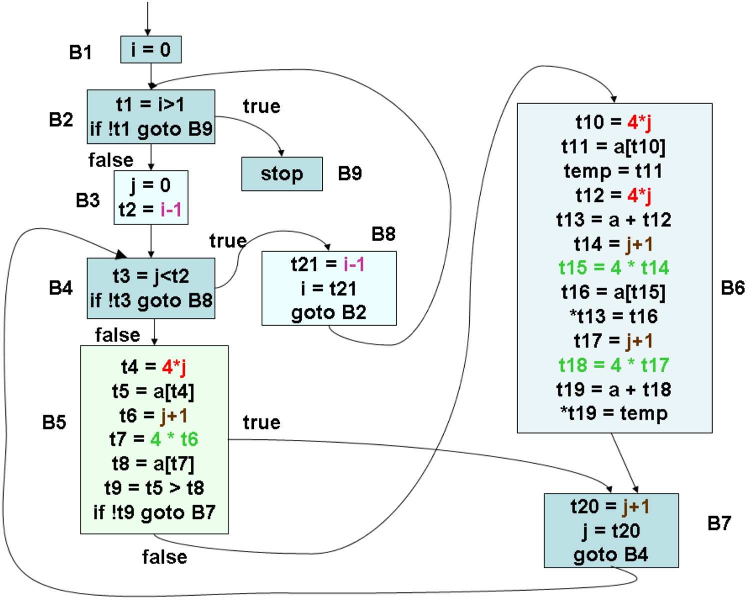
GCSE Conceptual Example



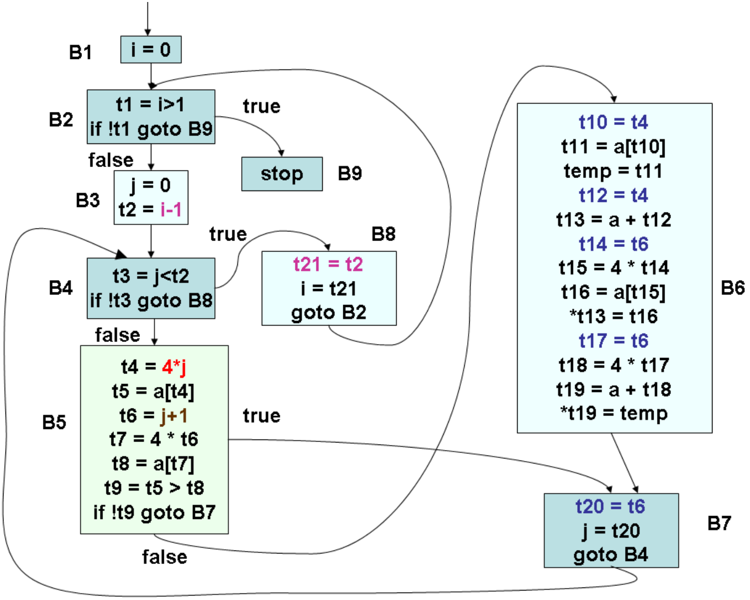


Demonstrating the need for repeated application of GCSE

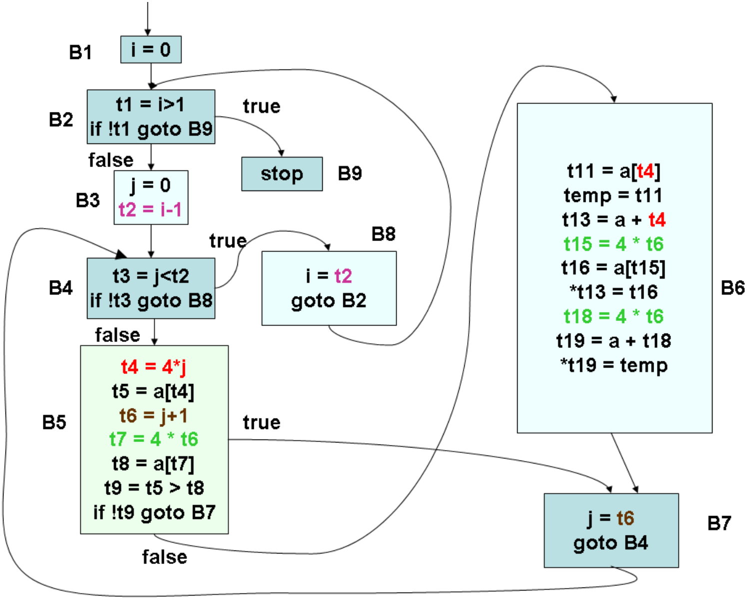
GCSE on Running Example - 1



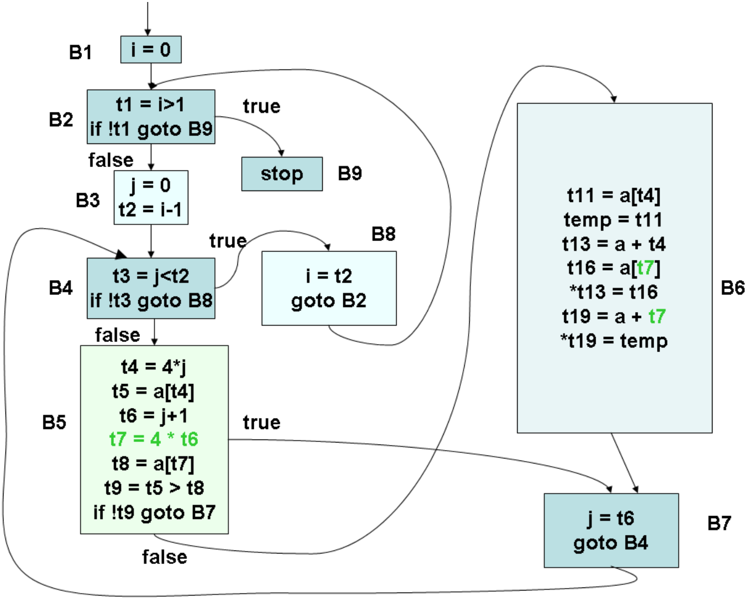
GCSE on Running Example - 2



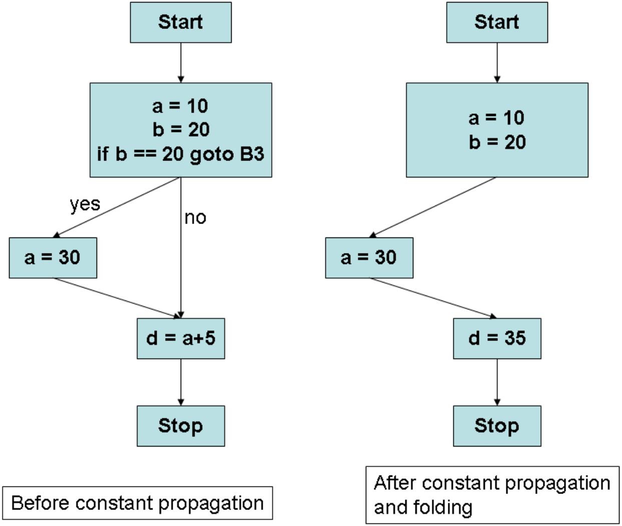
Copy Propagation on Running Example



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

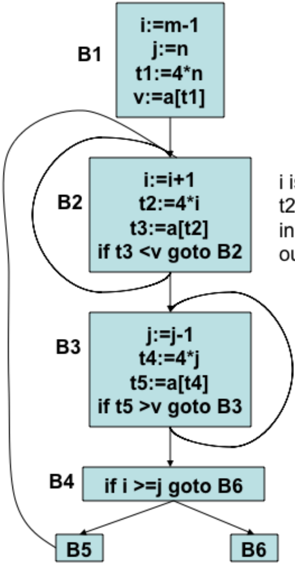
Induction Variable Elimination

```
      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)

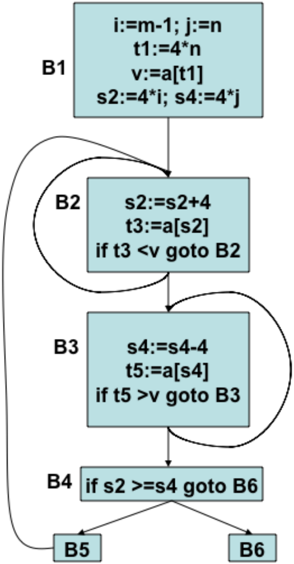
```
      t1 = 202
      t3 = addr(a)
      t4 = t3 – 4
      t7 = 4
L1:   t2 = t7 >400
      if t2 goto L2
      t1 = t1-2
      t6 = t4+t7
      *t6 = t1
      t7 = t7 + 4
      goto L1
L2:
```

After eliminating i and replacing it with t7

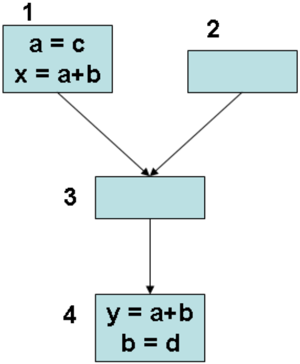


i is basic i.v
t2 is derived i.v
in both inner and
outer loops

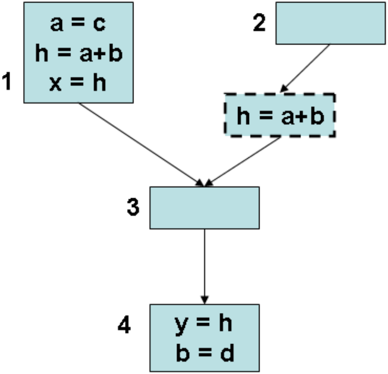
j is basic i.v
t4 is derived i.v
in both inner
and outer loops



Partial Redundancy Elimination



(a)



(b)

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];
}
```