Optimization Techniques

- The most complex component of modern compilers
- Must always be *sound,* i.e., semantics-preserving
  - Need to pay attention to exception cases as well
  - Use a conservative approach: risk missing out optimization rather than changing semantics
- Reduce runtime resource requirements (most of the time)
  - Usually, runtime, but there are memory optimizations as well
  - Runtime optimizations focus on frequently executed code
    - How to determine what parts are frequently executed?
      - Assume: loops are executed frequently
      - Alternative: profile-based optimizations
  - Some optimizations involve trade-offs, e.g., more memory for faster execution
- Cost-effective, i.e., benefits of optimization must be worth the effort of its implementation

Code Optimizations

- High-level optimizations
  - Operate at a level close to that of source-code
  - Often language-dependent
- Intermediate code optimizations
  - Most optimizations fall here
  - Typically, language-independent
- Low-level optimizations
  - Usually specific to each architecture

High-level optimizations

- **Inlining**

•Replace function call with the function body

- **Partial evaluation**

•Statically evaluate those components of a program that can be evaluated

- Tail recursion elimination
- Loop reordering
- Array alignment, padding, layout

Intermediate code optimizations

- Common subexpression elimination
- Constant propagation
- Jump-threading
- Loop-invariant code motion
- Dead-code elimination
- Strength reduction

Constant Propagation

- Identify expressions that can be evaluated at compile time, and replace them with their values.
-
```
x = 5;          =>  x =   5;        =>  x =   5;
y = 2;              y = 2;              y = 2;
v = u + y;          v = u + y;          v = u + 2;
z = x * y;          z = x * y;          z = 10;
w = v + z + 2;      w = v + z + 2;      w = v + 12;
...                 ...                 ...
```


Strength Reduction

- Replace expensive operations with equivalent cheaper (more efficient) ones.

```
y = 2;       =>     y = 2;
z = x^y;            z = x*x;
 ...                 ...
```

- The underlying architecture may determine which operations are cheaper and which ones are more expensive.

Loop-Invariant Code Motion

- Move code whose effect is independent of the loop's iteration outside the loop.

```
for (i=0; i<N; i++) {     =>     for (i=0; i<N; i++) {
  for (j=0; j<N; i++) {            base = a + (i * dim1);
    ... a[i][j] ...                for (j=0; j<N; i++) {
                                     ... (base + j) ...
```


Low-level Optimizations

- Register allocation
- Instruction Scheduling for pipelined machines.
- loop unrolling
- instruction reordering
- delay slot filling
- Utilizing features of specialized components, e.g., floating-point units.
- Branch Prediction

Peephole Optimization

- Optimizations that examine small code sections at a time, and transform them
- Peephole: a small, moving window in the target program
- Much simpler to implement than global optimizations
- Typically applied at machine code, and some times at intermediate code level as well
- Any optimization can be a peephole optimization, provided it operates on the code within the peephole.
- redundant instruction elimination
- flow-of control optimizations
- algebraic simplifications
- ...

Profile-based Optimization

- A compiler has difficulty in predicting:
- likely outcome of branches
- functions and/or loops that are most frequently executed
- sizes of arrays
- or more generally, any thing that depends on dynamic rogram behavior.
- Runtime profiles can provide this missing information, making it easier for compilers to decide when certain

Example Program: *Quicksort*

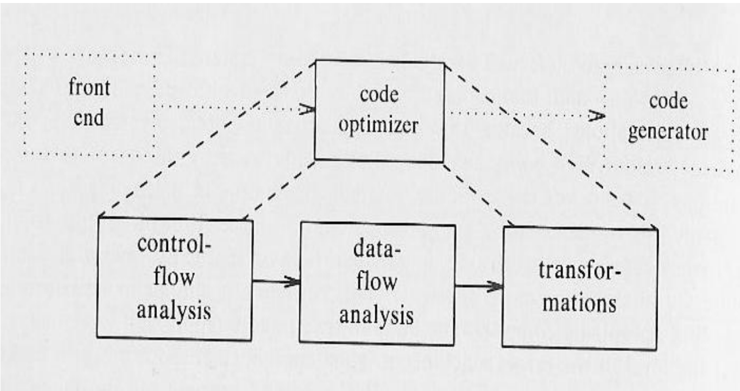
```
void quicksort(m,n)
int m,n;
{
    int i,j;
    int v,x;
    if ( n <= m ) return;
    /* fragment begins here */
    i = m-1; j = n; v = a[n];
    while(1) {
        do i = i+1; while ( a[i] < v );
        do j = j-1; while ( a[j] > v );
        if (i >= j ) break;
        x = a[i]; a[i] = a[j]; a[j] = x;
    }
    x = a[i]; a[i] = a[n]; a[n] = x;
    /* fragment ends here */
    quicksort(m,j); quicksort(i+1,n);
}
```

- Most optimizations opportunities arise in intermediate code
  - Several aspects of execution (e.g., address calculation for array access) aren't exposed in source code
- Explicit representations provide most opportunities for optimization
- It is best for programmers to focus on writing readable code, leaving simple optimizations to a compiler

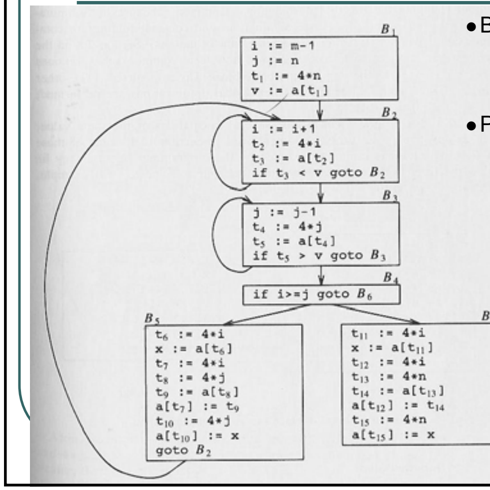
3-address code for *Quicksort*

```
(1)  i := m-1              (16)  t7 := 4*i
(2)  j := n                (17)  t8 := 4*j
(3)  t1 := 4*n             (18)  t9 := a[t8]
(4)  v := a[t1]            (19)  a[t7] := t9
(5)  i := i+1              (20)  t10 := 4*j
(6)  t2 := 4*i             (21)  a[t10] := x
(7)  t3 := a[t2]           (22)  goto (5)
(8)  if t3 < v goto (5)    (23)  t11 := 4*i
(9)  j := j-1              (24)  x := a[t11]
(10) t4 := 4*j             (25)  t12 := 4*i
(11) t5 := a[t4]           (26)  t13 := 4*n
(12) if t5 > v goto (9)    (27)  t14 := a[t13]
(13) if i >= j goto (23)   (28)  a[t12] := t14
(14) t6 := 4*i             (29)  t15 := 4*n
(15) x := a[t6]            (30)  a[t15] := x
```

Organization of Optimizer

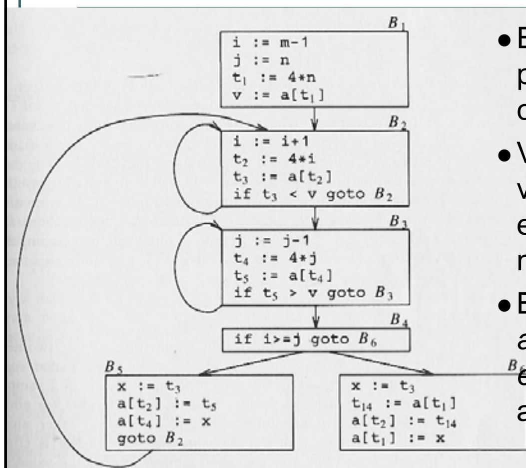


Flow Graph for *Quicksort*



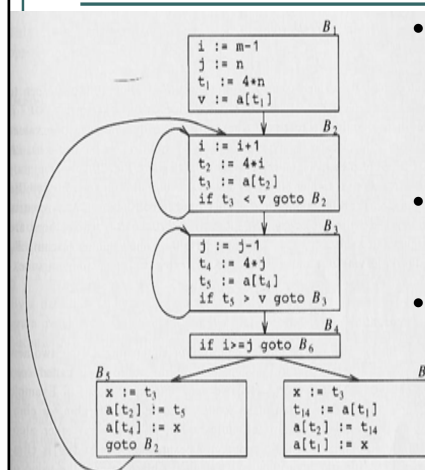
- B1,…,B6 are *basic blocks*
  - sequence of statements where control enters at beginning, with no branches in the middle
- Possible optimizations
  - Common subexpression elimination (CSE)
  - Copy propagation
    - Generalization of constant folding to handle assignments of the form x = y
  - Dead code elimination
  - Loop optimizations
    - Code motion
    - Strength reduction
    - Induction variable elimination

Common Subexpression Elimination



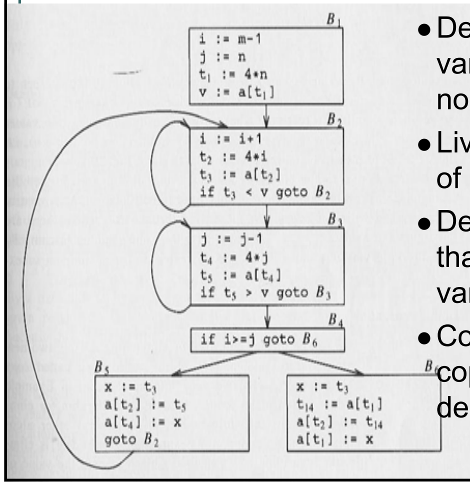
- Expression previously computed
- Values of all variables in expression have not changed.
- Based on *available expressions* analysis

Copy Propagation



- Consider
  x = y;
  z = x*u;
  w = y*u;
  Clearly, we can replace assignment on w by
  w = z
- This requires recognition of cases where multiple variables have same value (i.e., they are copies of each other)
- One optimization may expose opportunities for another
  - Even the simplest optimizations can pay off
  - Need to iterate optimizations a few times

Dead Code Elimination

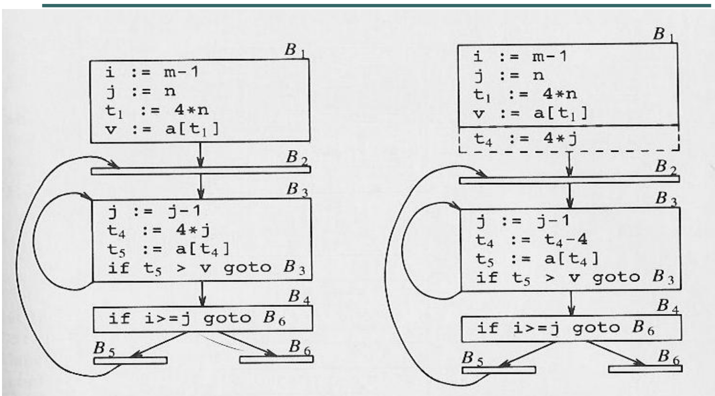


- Dead variable: a variable whose value is no longer used
- Live variable: opposite of dead variable
- Dead code: a statement that assigns to a dead variable
- Copy propagation turns copy statement into dead code.

Induction Vars, Strength Reduction and IV Elimination

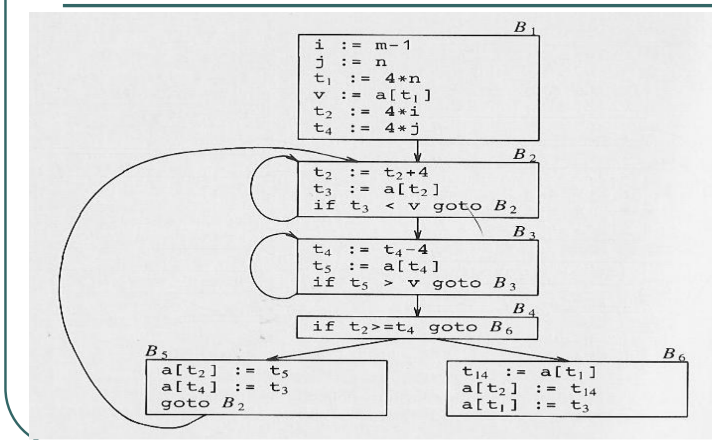
- Induction Var: a variable whose value changes in lock-step with a loop index
- If expensive operations are used for computing IV values, they can be replaced by less expensive operations
- When there are multiple IVs, some can be eliminated

Strength Reduction on IVs



(a) Before (b) After

After IV Elimination …



Program Analysis

- Optimization is usually expressed as a program transformation
  $C_1 \Leftrightarrow C_2$ when property P holds
- Whether property P holds is determined by a *program analysis*
- Most program properties are undecidable in general
  - Solution: Relax the problem so that the answer is an "yes" or "don't know"

Applications of Program Analysis

- Compiler optimization
- Debugging/Bug-finding
  - "Enhanced" type checking
    - Use before assign
    - Null pointer dereference
    - Returning pointer to stack-allocated data
- Vulnerability analysis/mitigation
  - Information flow analysis
    - Detect propagation of sensitive data, e.g., passwords
    - Detect use of untrustworthy data in security-critical context
  - Find potential buffer overflows
- Testing – automatic generation of test cases
- Verification: Show that program satisfies a specified property, e.g., no deadlocks
  - model-checking

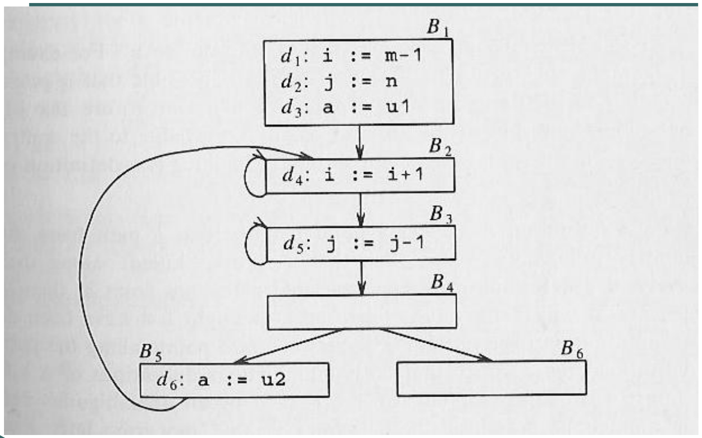
Dataflow Analysis

- Answers questions relating to how data flows through a program
  - What can be asserted about the value of a variable (or more generally, an expression) at a program point
- Examples
  - Reaching definitions: which assignments reach a program statement
  - Available expressions
  - Live variables
  - Dead code
  - …

Dataflow Analysis

- Equations typically of the form
  $out[S] = gen[S] \cup (in[S] - kill[S])$
  where the definitions of *out, gen, in* and *kill* differ for different analysis
- When statements have multiple predecessors, the equations have to be modified accordingly
- Procedure calls, pointers and arrays require careful treatment

Points and Paths



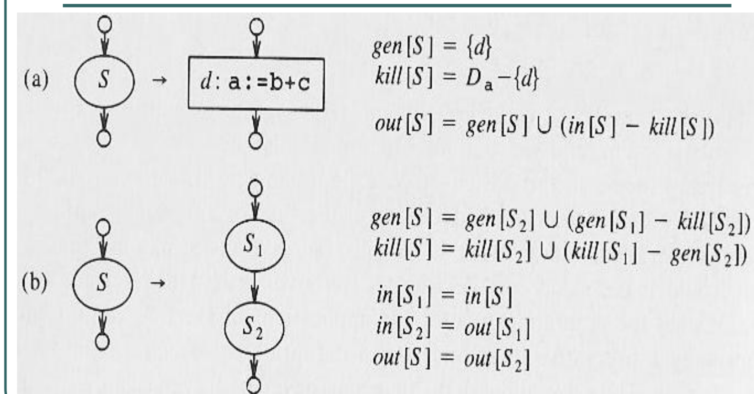
Reaching Definitions

- A *definition* of a variable *x* is a statement that assigns to *x*
  - *Ambiguous definition:* In the presence of aliasing, a statement may define a variable, but it may be impossible to determine this for sure.
- A definition *d* reaches a point *p* provided:
  - There is a path from *d* to *p,* and this definition is not "killed" along *p*
    - "Kill" means an unambiguous redefinition
- Ambiguity ➔ approximation
  - Need to ensure that approximation is in the right direction, so that the analysis will be *sound*

DFA of Structured Programs

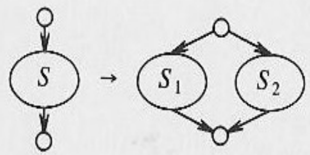
- *S* → **id** := *E*
  | *S*;*S*
  | **if** *E* **then** *S* **else** *S*
  | **do** *S* **while** *E*
- *E* → ***E* + *E***
  | **id**

DF Equations for Reaching Defns



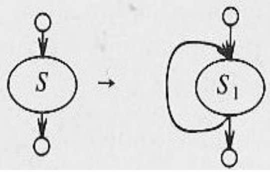
DF Equations for Reaching Defns

(c)



$$gen[S] = gen[S_1] \cup gen[S_2]$$
$$kill[S] = kill[S_1] \cap kill[S_2]$$
$$in[S_1] = in[S]$$
$$in[S_2] = in[S]$$
$$out[S] = out[S_1] \cup out[S_2]$$

(d)



$$gen[S] = gen[S_1]$$
$$kill[S] = kill[S_1]$$
$$in[S_1] = in[S] \cup gen[S_1]$$
$$out[S] = out[S_1]$$

Direction of Approximation

- Actual *kill* is a superset of the set computed by the dataflow equations
- Actual *gen* is a subset of the set computed by these equations
- Are other choices possible?
  - Subset approximation of kill, superset approximation of gen
  - Subset approximation of both
  - Superset approximation of both
- Which approximation is suitable depends on the intended use of analysis results

Solving Dataflow Equations

- Dataflow equations are recursive
- Need to compute so-called *fixpoints,* to solve these equations
- Fixpoint computations uses an interative procedure
  - $out^0 = \phi$
  - out^i is computed using the equations by substituting out^{i-1} for occurrences of *out* on the rhs
  - Fixpoint is a solution, i.e., $out^i = out^{i-1}$

Computing Fixpoints: Equation for Loop

- Rewrite equations using more compact notation, with:
  J standing for in[S] and
  I, G, K, and O for in[S1], gen[S1], kill[S1] and out[S1]:
  $$I = J \cup O,$$
  $$O = G \cup (I - K)$$
- Letting $I^0 = O^0 = \phi$, we have:

$I^1 = \mathbf{J}$ $\qquad$ $O^1 = G \cup (I^0 - K) = \mathbf{G}$
$I^2 = J \cup O^1 = \mathbf{J \cup G}$ $\qquad$ $O^2 = G \cup (I^1 - K) = \mathbf{G \cup (J - K)}$
$I^3 = J \cup O^2$ $\qquad$ $O^3 = G \cup (I^2 - K)$
$= J \cup G \cup (J - K)$ $\qquad$ $= G \cup (J \cup G - K)$
$= J \cup G = I^2$ $\qquad$ $= G \cup (J - K) = O^2$

(Note that for all sets A and B, A U (A-B) = A, and
for all sets A, B and C, A U (A U C –B) = A U (C-B).)

Thus, we have a fixpoint.

Use-Definition Chains

- Convenient way to represent reaching definition information
- ud-chain for a variable links each use of the variable to its reaching definitions
  - One list for each use of a variable

Available Expressions

- An expression ***e*** is available at point ***p*** if
  - every path to ***p*** evaluates ***e***
  - none of the variables in ***e*** are assigned after last computation of ***e***
- A block *kills* ***e*** if it assigns to some variable in ***e*** and does not recompute ***e.***
- A block *generates* ***e*** if it computes ***e*** and doesn't subsequently assign to variables in ***e***
- ***Exercise:*** Set up data-flow equations for available expressions. Give an example use for which your equations are sound, and another example for which they aren't

Available expressions -- Example

a := b+c

b := a-d

c := b+c

d := a-d

Live Variable Analysis

- A variable ***x*** is *live* at a program point ***p*** if the value of ***x*** is used in some path from ***p***
- Otherwise, ***x*** is *dead.*
- Storage allocated for dead variables can be freed or reused for other purposes.
- in[B] = use[B] ∪ (out[B] – def[B])
- out[B] = ⋃ in[S], for S a successor of B
- Equation similar to reaching definitions, but the role of in and out are interchanged

Def-Use Chains

- du-chain links the definition of a variable with all its uses
  - Use of a definition of a variable ***x*** at a point ***p*** implies that there is a path from this definition to ***p*** in which there are no assignments to ***x***
- du-chains can be computed using a dataflow analysis similar to that for live variables

Optimizations and Related Analyses

- Common subexpression elimination
  - Available expressions
- Copy propagation
  - In every path that reaches a program point ***p***, the variables ***x*** and ***y*** have identical values
- Detection of loop-invariant computation
  - Any assignment ***x := e*** where the definition of every variable in ***e*** occurs outside the loop.
- Code reordering: A statement ***x := e*** can be moved
  - earlier before statements that (a) do not use ***x***, (b) do not assign to variables in ***e***
  - later after statements that (a) do not use , (b) do not assign to variables in ***e***

Difficulties in Analysis

- Procedure calls
- Aliasing

Difficulties in Analysis

- Procedure calls
  - may modify global variables
    - potentially kill all available expressions involving global variables
    - modify reaching definitions on global variables
- Aliasing
  - Create ambiguous definitions
  - a[i] = a[j] --- here, i and j may have same value, so assignment to a[i] can potentially kill a[j]
  - *p = q + r --- here, p could potentially point to q, r or any other variable
    - creates ambiguous redefinition for all variables in the program!