Using Program Analysis for Optimization

Advanced Compiler Techniques

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Reaching Definitions

- Concept of *definition* and *use*
  - `a=x+y`
    - is a definition of a.
    - is a use of x and y.
- A definition reaches a use if value written by definition may be read by use.

Reaching Definitions and Constant Propagation

- Is a use of a variable a constant?
  - Check all reaching definitions.
  - If all assign variable to same constant.
  - Then use is in fact a constant.
- Can replace variable with constant.

Computing Reaching Definitions

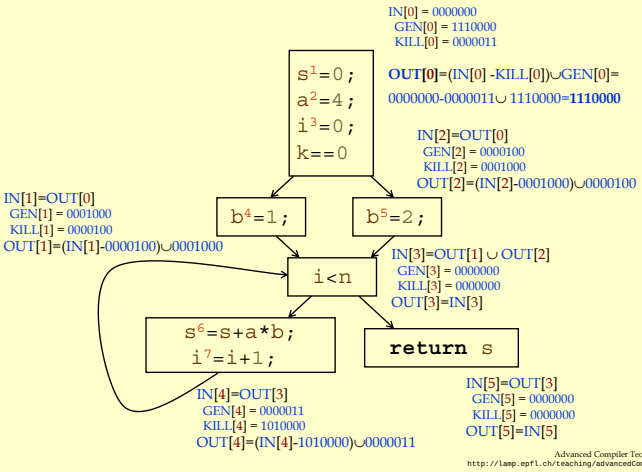
- Compute with sets of definitions:
  - Represent sets using bit vectors.
  - Each definition has a position in bit vector.
- At each basic block, compute:
  - Definitions that reach start of block.
  - Definitions that reach end of block.
- Do computation by simulating execution of program until the fixed point is reached.

Formalizing Analysis

- Each basic block has
  - IN - set of definitions that reach beginning of block
  - OUT - set of definitions that reach end of block
  - GEN - set of definitions generated in block
  - KILL - set of definitions killed in the block
- Compiler scans each basic block to derive GEN and KILL sets.

Dataflow Equations

- $IN[b_i] = OUT[b_1] \cup ... \cup OUT[b_n]$
  where b_1, ..., b_n are predecessors of b_i
- $OUT[b_i] = (IN[b_i] - KILL[b_i]) \cup GEN[b_i]$
- $IN[entry] = 0000000$
- Result: system of equations.



Solving Equations

- Use fix point algorithm.
- Initialize with solution of $OUT[b_i] = 0000000$
- Repeatedly apply equations:
  - $IN[b_i] = OUT[b_1] \cup ... \cup OUT[b_n]$
  - $OUT[b_i] = (IN[b_i] - KILL[b_i]) \cup GEN[b_i]$
- Until reach fixed point, i.e., until equation application has no further effect.
- Use a worklist to track which equation applications may have further effect.

Reaching Definitions Algorithm

```
for all nodes n2N
  OUT[n] = ;;                          // Or OUT[n] = GEN[n];
Changed = N;                           // N = all nodes in graph
while (Changed != ;)                   // Until fixed point reached.
  choose n2Changed;                    // Node from worklist
  Changed=Changed-{n};                 // Remove from worklist
  OldOut = OUT[n]                      // Remember old result
  IN[n] = ;;                           // Calculate IN as join
  for all nodes p2predecessors(n)      //   of predecessors.
      IN[n]=IN[n]∪OUT[p];
  OUT[n]=(IN[n]-KILL[n])∪GEN[n];       // Recalculate OUT
  if (OUT[n] != OldOut)                // If OUT[n] changed
    for all nodes s2successors(n)
      Changed=Changed∪{s};             //Add succs to worklist
```


Questions

- Does the algorithm halt?
  - yes, because transfer function is monotonic.
  - if increase IN, increase OUT.
  - in limit, all bits are 1.
- If bit is 1, is there always an execution in which corresponding definition reaches basic block?
- If bit is 0, does the corresponding definition ever reach basic block?
- Concept of conservative analysis.

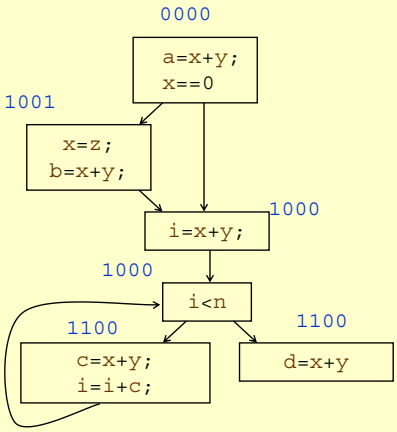
Available Expressions

- An expression x+y is available at a point p if
  - **every** path from the initial node to p evaluates x+y before reaching p,
  - and there are **no assignments** to x or y after the evaluation but before p.
- Available Expression information can be used to do global (across basic blocks) CSE.
- If an expression is available at use, there is no need to re-evaluate it.

Computing Available Expressions

- Represent sets of expressions using bit vectors.
- Each expression corresponds to a bit.
- Run dataflow algorithm similar to reaching definitions.
- Big difference:
  - Definition reaches a basic block if it comes from **ANY** predecessor in CFG.
  - Expression is available at a basic block only if it is available from **ALL** predecessors in CFG.

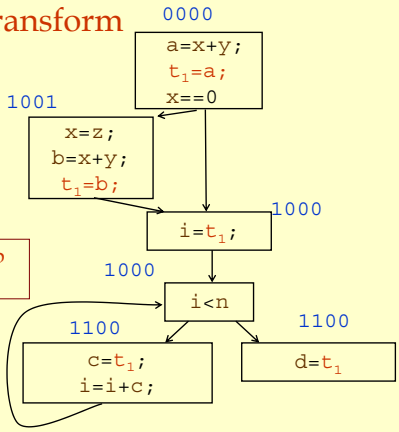
Expressions
1: x+y
2: i<n
3: i+c
4: x==0



Global CSE Transform

Expressions
1: x+y
2: i<n
3: i+c
4: x==0

Must use same temp for CSE in all blocks



Formalizing Analysis

- Each basic block has
  - IN - set of expressions that reach beginning of block.
  - OUT - set of expressions that reach end of block.
  - GEN - set of expressions generated in block.
  - KILL - set of expressions killed in the block.
- GEN[x=z; b=x+y] = 1000
- KILL[x=z; b=x+y] = 1001
- Compiler scans each basic block to derive GEN and KILL sets.

Dataflow Equations

- $IN[b_i] = OUT[b_1] \cap ... \cap OUT[b_n]$
  - where b_1, ..., b_n are predecessors of b_i
- $OUT[b_i] = (IN[b_i] - KILL[b_i]) \cup GEN[b_i]$
- $IN[entry] = 0000$
- Result: system of equations.

Solving Equations

- Use fix point algorithm.
- $IN[entry]=0000$
- Initialize with solution of $OUT[b_i] = 1111$
- Repeatedly apply equations:
  - $IN[b_i] = OUT[b_1] \cap ... \cap OUT[b_n]$
  - $OUT[b_i] = (IN[b_i] - KILL[b_i]) \cup GEN[b_i]$
- Use a worklist to track which equation applications may have further effect.

Available Expressions Algorithm

```
for all nodes n2N                 // E is set of all expressions.
   OUT[n] = E;                    // OUT[n] =E -KILL[n];
Changed = N;                      // N = all nodes in graph
while (Changed != ;)
   choose n2Changed;
   Changed=Changed-{n};
   IN[n] = E ;
   OldOut = OUT[n]
   for all nodes p2predecessors(n)
        IN[n]=IN[n]∩OUT[p];
  OUT[n]=(IN[n]-KILL[n])∪GEN[n];
  if (OUT[n] != OldOut)
    for all nodes s2successors(n) Changed=Changed∪{s};
```

Questions

- Does algorithm always halt?
- If expression is available in some execution, is it always marked as available in analysis?
- If expression is not available in some execution, can it be marked as available in analysis?
- In what sense is the algorithm conservative?

Duality In Two Algorithms

- Reaching definitions
  - Confluence operation is set **union.**
  - OUT[b] initialized to **empty set**.
- Available expressions
  - Confluence operation is set **intersection.**
  - OUT[b] initialized to **set of available expressions.**
- General framework for dataflow algorithms.
- Build parameterized dataflow analyzer once, use for all dataflow problems.

Liveness Analysis

- A variable v is live at point p if
  - v is used along some path starting at p, and
  - no definition of v along the path before the use.
- When is a variable v dead at point p?
  - No use of v on any path from p to exit node, or
  - If all paths from p, redefine v before using v.

What Use is Liveness Information?

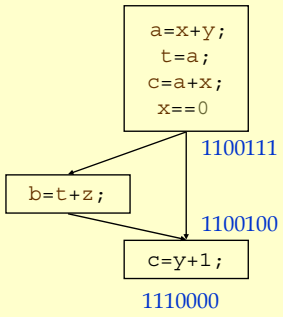
- Register allocation.
  - If a variable is dead, we can reassign its register.
- Dead code elimination.
  - Eliminate assignments to variables not read later.
  - But must not eliminate last assignment to variable (such as instance variable) visible outside CFG.
  - Can eliminate other dead assignments.
  - Handle by making all externally visible variables live on exit from CFG.

Conceptual Idea of Analysis

- Simulate execution.
- But start from exit and go **backwards** in CFG.
- Compute liveness information from end to beginning of basic blocks.

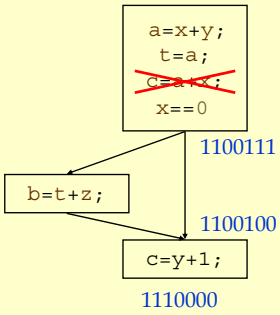
Liveness Example

- Assume `a,b,c` visible outside function. They are live on exit.
- Assume `x,y,z,t` are not visible.
- Represent liveness using a bit vector:
  order is `abcxyzt`.



Using Liveness Information for Dead Code Elimination

- Assume `a,b,c` visible outside function. They are live on exit.
- Assume `x,y,z,t` are not visible.
- Represent liveness using a bit vector: order is `abcxyzt`.



Formalizing Analysis

- Each basic block has
  - IN - set of variables live at start of block.
  - OUT - set of variables live at end of block.
  - USE - set of variables with upwards exposed uses in block. (**GEN**)
  - DEF - set of variables defined in block. (**KILL**)
- USE[`x=z;x=x+1;y=1;`] = {z} (x not in USE)
- DEF[`x=z;x=x+1;y=1;`] = {x, y}
- Compiler scans each basic block to derive USE and DEF sets.

Algorithm

```
OUT[Exit] = ;
IN[Exit] = USE[n];
for all nodes n2N-{Exit}
  IN[n] = ;
Changed = N-{Exit};
while (Changed != ;)
  choose n 2 Changed;
  Changed = Changed-{n};
  OldIn=IN[n]
  OUT[n] = ;
  for all nodes s 2 successors(n) OUT[n] = OUT[n] ∪ IN[p];
  IN[n] = USE[n] ∪ (OUT[n] - DEF[n]);
  if (IN[n] != OldIn)
    for all nodes p 2 predecessors(n) Changed=Changed∪{p};
```


Similar to Other Dataflow Algorithms

- Backwards analysis, not forwards.
- Still have transfer functions.
- Still have confluence operators.
- Can generalize framework to work for both forwards and backwards analyses.

Analysis Information Inside Basic Blocks

- One detail:
  - Given dataflow information at IN and OUT of node.
  - Also need to compute information at each statement of basic block.
  - Simple propagation algorithm usually works fine.
  - Can be viewed as restricted case of dataflow analysis.

Summary

- Dataflow Analysis
  - Control flow graph.
  - IN[b], OUT[b], transfer functions, join points.
- Pairs of analyses and transformations:
  - Reaching definitions/constant propagation.
  - Available expressions/common sub-expression elimination.
  - Liveness analysis/Dead code elimination.