Program Analysis

https://www.cse.iitb.ac.in/~karkare/cs618/

Data Flow Analysis

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Recap

- Optimizations
  - Machine Independent
  - Machine Dependent
- Analysis
  - Intraprocedural
    - Local
    - Global
  - Interprocedural

Agenda

- For the next few lectures
- *Intraprocedural* Data Flow analysis
  - Components
  - Classical examples

Assumptions

- Unless otherwise specified
- Intraprocedural: Restrict to a single procedure
- Input in 3–address code format

3 Address Code

- Assignments

  x = y op z

  x = op y

  x = y

- Jump/Control statements

  goto L

  if x relop y goto L

- Statements can have label(s)

  L: …

Arrays, Pointers and Procedures to be added later when needed

Data Flow Analysis

- Class of techniques to derive information about flow of data
  - along program execution paths
- Used to answer questions such as:
  - whether two identical expressions evaluate to same value
    - used in common subexpression elimination
  - whether the result of an assignment is used later
    - used by dead code elimination

Data Flow Abstraction

- Basic Blocks (BB)
  - sequence of 3-address code stmts
  - single entry at the first statement
  - single exit at the last statement
  - Typically we use “maximal” basic block (maximal sequence of such instructions)

Data Flow Abstraction

- *Leader*: First statement of a basic block
  - First instruction of program (procedure)
  - Target of a branch (goto)
  - Instruction immediately following a branch

Special Basic Blocks

- Two special BBs are added to simplify the analysis
  - empty (?) blocks!
- *Entry:* Assumed to be the *first* block to be executed for the procedure analyzed
- *Exit:* Assumed to be the *last* block to be executed

Data Flow Abstraction

- Control Flow Graph (CFG)
- A rooted directed graph G= (N, E)
- N = set of BBs
  - including *entry*, *exit*
- E = set of edges

CFG Edges

- Edge $B1 \rightarrow B2 \in E$ if control can transfer from B1 to B2
  - Fall through
  - Through jump (goto)
  - Edge from *entry* to (all?) real first BB(s)
  - Edge to *exit* from all last BBs
    - BBs containing *return*
    - Last *real* BB

Data Flow Abstraction

- Control Flow graph
  - Graph representation of paths that program may exercise during execution
  - Typically one graph per procedure
  - Graphs for separate procedures have to be combined/connected for interprocedural analysis
    - Later!
    - Single procedure, single flow graph for now.

Data Flow Abstraction

- Input state/Output state for Stmt
  - Program point before/after a stmt
  - Denoted IN[s] and OUT[s]
  - Within a basic block:
    - Program point after a stmt is same as the program point before the next stmt

Data Flow Abstraction

- Input state/Output state for BBs
  - Program point before/after a bb
  - Denoted IN[B] and OUT[B]
  - For B1 and B2:
    - if there is an edge from B1 to B2 in CFG, then the program point *after* the last stmt of B1 *may be* followed immediately by the program point *before* the first stmt of B2.

Data Flow Abstraction

- Execution Path
  - $p_1, p_2, \ldots, p_n$
  - p_i -> p_{i+1} are adjacent program points in the CFG
- Infinite number of possible execution paths.
- No finite upper bound on the length.
- Need to Summarize the information at a program point with a finite set of facts.

Data Flow Schema

- Data flow values associated with each program point
  - Summarize all possible states at that point
- Domain: set of all possible data flow values
- Different domains for different analysis/optimization

Data Flow Problem

- Constraints on data flow values
  - Transfer constraints
  - Control flow constraints
- AIM: To find a solution to the constraints
  - Multiple solutions possible
  - Trivial solutions,…, Exact solutions
- We typically compute approximate solution, close to the exact solution
  - Why not exact solution?

Data Flow Constraints

- Transfer functions
  - relationship between the data flow values before and after a stmt
- forward functions

  $OUT[s] = f_s(IN[s])$

- backward functions

  $IN[s] = f_s(OUT[s])$

Data Flow Constraints

- Control flow constraints
  - relationship between the data flow values of two points that are related by program execution semantics
- For a basic block having n statements:

$$IN[s_{i+1}] = OUT[s_i],\ i = 1,2,\ldots,n\text{-}1$$

$IN[s_1]$, $OUT[s_n]$ to come later

Data Flow Constraints: Basic Block

- Forward
  - For B consisting of $s_1, s_2, \ldots s_n$

    $f_B = f_{s_n} \circ \ldots \circ f_{s_2} \circ f_{s_1}$

    $OUT[B] = f_B(IN[B])$
  - Control flow constraints

    $IN[B] = \cup_{P \text{ a predecessor of } B} OUT[P]$
- Backward

  $IN[B] = f_B(OUT[B])$

  $OUT[B] = \cup_{S \text{ a successor of } B} IN[S]$

Data Flow Equations

- Typical Equation

  out[s] = in[s] – kill[s] U gen[s]

  – gen(s): information generated

  – kill(s) : information killed

- For example:

  a = b * c   // generates expression b*c

  c = 5   // kills expression b*c

  d = b * c   // is b*c redundant here?

Analysis of Structured Programs

- Reaching Definitions Analysis

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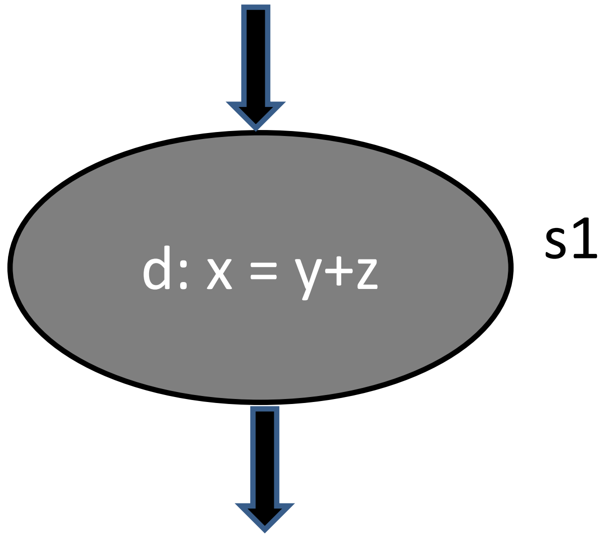
    - there is a path from the point immediately following *d* to *p*
    - d is not “killed” along that path
    - “Kill” means redefinition of the left hand side (*x* in the above case)

Analysis of Structured Programs



out(s1) = in(s1) - kill(s1) U gen(s1)

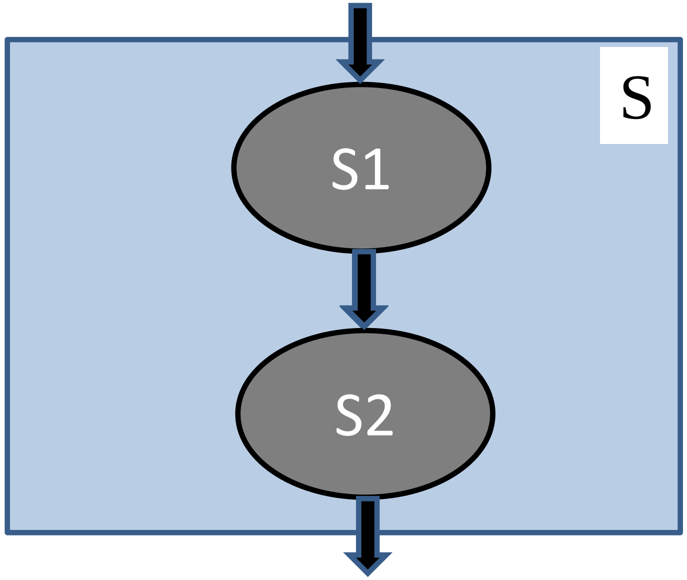
gen(s1) = {d}

kill(s1) = D_x – {d}   // D_x : set of all defs of x

kill(s1) = D_x will also work here!

But may not work in general!

Analysis of Structured Programs



gen(s) = gen(s2) U (gen(s1) – kill(s2))

kill(s) = kill(s2) U (kill(s1) – gen(s2))

in(s1) = in(s)

in(s2) = out(s1)

out(s) = out(s2)

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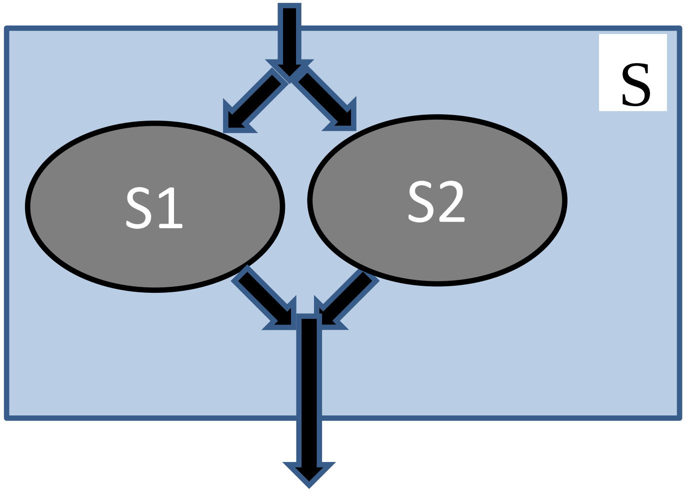


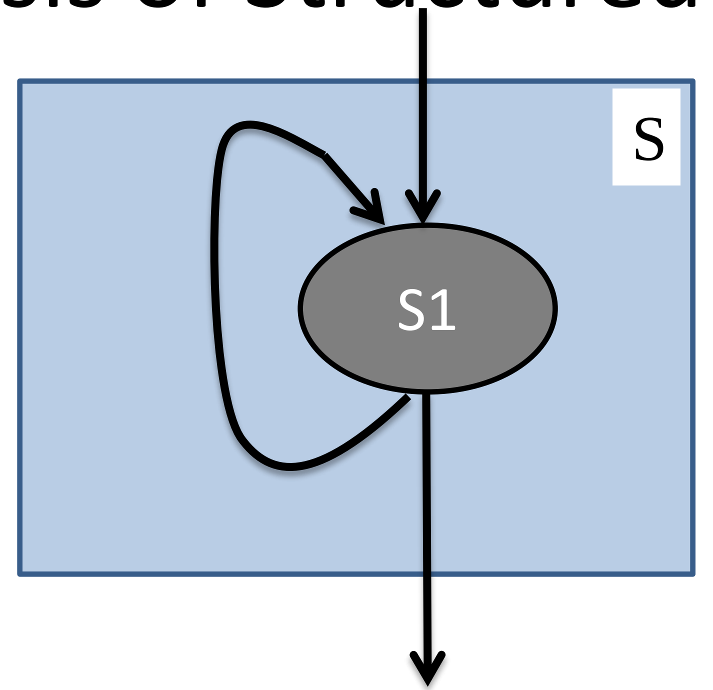
gen(s) = gen(s1) U gen(s2)

kill(s) = kill(s1) ∩ kill(s2)

in(s1) = in(s2) = in(s)

out(s) = out(s1) U out(s2)

Analysis of Structured Programs



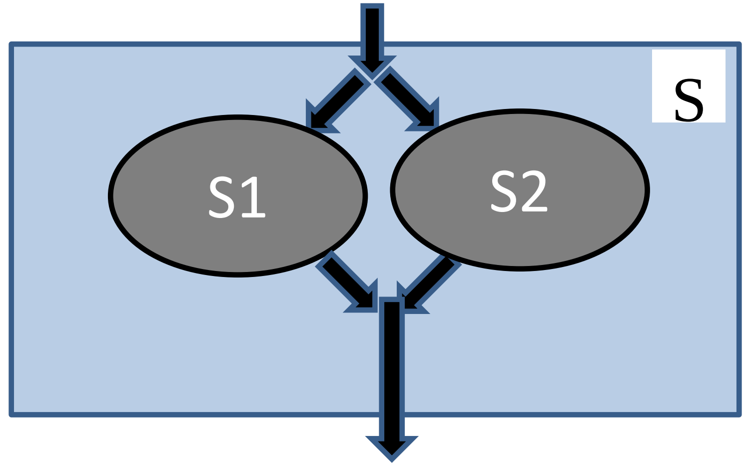
gen(s) = gen(s1)

kill(s) = kill(s1)

in(s1) = in(s) U gen(s1)

out(s) = out(s1)

Conservative Analysis

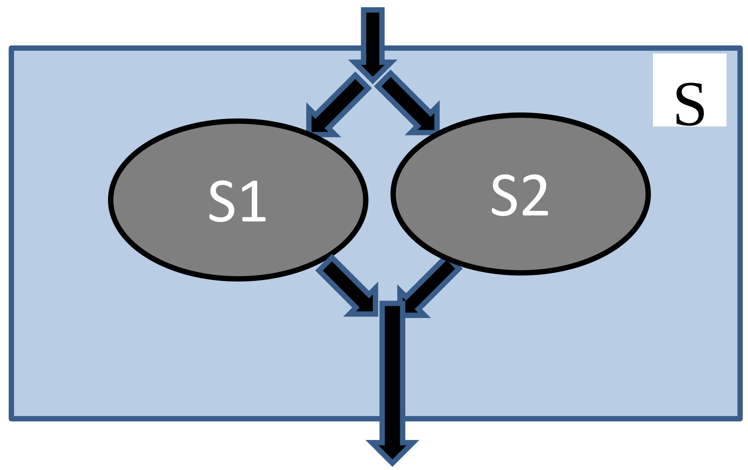


- Assumption: All paths are feasible.
  - Consider: if (true) s1; else s2
  - s2 is never executed

  gen(s) = gen(s1) $\subseteq$ gen(s1) $\cup$ gen(s2)

  kill(s) = kill(s1) $\supseteq$ kill(s1) $\cap$ kill(s2)

Conservative Analysis



- Thus: true gen (s) $\subseteq$ analysis gen(s)
  true kill (s) $\supseteq$ analysis kill(s)
- True is what is computed at run time
- This is SAFE estimate
  - prevents optimization
  - but no wrong optimization