Example of Global Data-Flow Analysis

Reaching Definitions

We will illustrate global data-flow analysis with the computation of reaching definition for a very simple and structured programming language.

We want to compute for each block $b$ of the program the set $\text{REACHES}(b)$ of the statements that compute values which are available on entry to $b$.

An assignment statement of the form $x := E$ or a read statement of the form $\text{read } x$ must define $x$.

A call statement $\text{call sub}(x)$ where $x$ is passed by reference or an assignment of the form $*q := y$ where nothing is known about pointer $q$, may define $x$.

We say that a statement $s$ that must or may define a variable $x$ reaches a block $b$ if there is a path from $s$ to $b$ such that there is no statement $t$ in the path that kills $s$, that is there is no statement $t$ that must define $x$. A block may be reached by more than one statement in a path: a must define statement $s$ and one or more may define statements on the same variable that appears after $s$ in a path to $b$.

We must be conservative to guarantee correct transformations. In the case of reaching definitions conservative is to assume that a definition can reach a point even if it might not.
Data-Flow Equations

Consider the following language:

\[ S ::= \text{id:=expression} \mid S;S \mid \text{if expression then } S \text{ else } S \mid \text{do } S \text{ while expression} \]

We define the following equations to compute reaching definitions. In these equations we compute reaching definitions for statements instead of blocks. We use the following terms:

- \( \text{gen}[S] \) is the set of definitions “generated by \( S \)”.
- \( \text{kill}[S] \) is the set of definitions “killed” by \( S \).
- \( \text{in}[S] \) is the set of definitions reaching \( S \) (or the top of \( S \)).
- \( \text{out}[S] \) is the set of definitions that reach the bottom of \( S \).

1. When \( S \) has the form \( \text{id:=expression} \) and label \( d \):
   \[
   \text{gen}[S] = \{ d \} \\
   \text{kill}[S] = D_a - \{ d \}. \ D_a \text{ is the set of all definitions of } a.
   \]
   \[
   \text{out}[S] = \text{gen}[S] + (\text{in}[S]-\text{kill}[S])
   \]

2. When \( S \) is of the form \( S_1; S_2 \):
   \[
   \text{gen}[S] = \text{gen}[S_2]+(\text{gen}[S_1]-\text{kill}[S_2]) \\
   \text{kill}[S] = \text{kill}[S_2]+(\text{kill}[S_1]-\text{gen}[S_2])
   \]
   \[
   \text{in}[S_1] = \text{in}[S] \\
   \text{in}[S_2] = \text{out}[S_1] \\
   \text{out}[S] = \text{out}[S_2]
   \]
3. When $S$ is of the form $\textbf{if}$ ... $\textbf{then} \ S_1 \ \textbf{else} \ S_2$

$$\begin{align*}
gen[S] &= gen[S_1] + gen[S_2] \\
kill[S] &= kill[S_1] \cap \ kill[S_2] \\
\text{in}[S_1] &= \text{in}[S] \\
\text{in}[S_2] &= \text{in}[S] \\
\text{out}[S] &= \text{out}[S_1] + \text{out}[S_2]
\end{align*}$$

4. When $S$ is of the form $\textbf{do} \ S_1 \ \textbf{while}$ ...:

$$\begin{align*}
gen[S] &= gen[S_1] \\
\kill[S] &= \kill[S_1]
\end{align*}$$

$$\begin{align*}
\text{in}[S_1] &= \text{in}[S] + \text{gen}[S_1] \\
\text{out}[S] &= \text{out}[S_1]
\end{align*}$$

For this problem we don’t use a control flow graph. We use an abstract syntax tree for simplicity. Gen$[S]$ and kill$[S]$ are computed bottom up on that tree.

Notice that the real gen$[S]$ is always a subset of the computed gen$[S]$. For example when $S$ is an $\textbf{if}$ statement that always takes the “true” branch, gen$[S_1] + \text{gen}[S_2]$ is bigger than the real gen$[S]$=gen$[S_1]$. At the same time, the real kill$[S]$ is a superset of the computed kill$[S]$.

Notice that out$[S]$ is not the same as gen$[S]$. The former contains all the definitions that reach the bottom of $S$ while the latter includes only those definitions within $S$ that reach the bottom of $S$. 
In[S] and out[S] are computed starting at the statement $S_0$ representing the whole program.

**Algorithm IN-OUT: Compute in[S] and out[S] for all statements S**

*Input:* An abstract syntax tree of program $S_0$ and the gen and kill sets for all the statements within the program.

*Output:* in[S] and out[S] for all statements within the program
compute_out(S):
    case S
    a := ... :
        return(out[S]=gen[S]+(in[S]-kill[S]))
    S_1;S_2 :
        in[S_1]=in[S]
        in[S_2],out[S_1]=compute_out(S_1)
        return(out[S_2]=compute_out(S_2))
    if ...
        then S_1
        else S_2 :
            in[S_1], in[S_2] = in[S]
            return(out[S]=compute_out(S_1)
                    + compute_out(S_2))
    do S_1
    while ...
    return(out[S_1]=compute_out(S_1))
    end case
end

in[S_0] = \emptyset
compute_out(S_0)
The sets of statements can be represented with bit vectors. Then unions and intersections take the form of or and and operations. Only the statements that assign values to program variables have to be taken into account. That is statements (or instructions) assigning to compiler-generated temporaries can be ignored.

In an implementation it is better to do the computations for the basic blocks only. The reaching sets for each statement can be then obtained by applying rule 2 above.
Use-definition chains

Data interconnections may be expressed in a pure form which directly links instructions that produce values to instructions that use them. This may take the following form:

1. For each statement $S$ with input variable $v$,
2. $\text{DEFS}(v,S) = \text{in}(S) \cap D_v$. If $v$ is not input to $S$, $\text{DEFS}(v,S)$ is the empty set.
3. For each definition $S$ with output variable $v$, $\text{USES}(S) = \{T \mid S \text{ is in } \text{DEFS}(v,T)\}$.

Once $\text{DEFS}$ is computed, $\text{USES}$ can be computed by simple inversion

**Algorithm US: USES Computation**

*Input:* $\text{DEFS}$

*Output:* $\text{USES}$

*Method:*

begin

USES($\cdot$):=Ø

for each statement $T$ in the program do

for each input variable $v$ of $T$ do

for each statement $S$ in $\text{DEFS}(v,T)$ do

USES($S$) += $\{T\}$

od

od

od
Three applications of the use-definition chains


Algorithm MK: Mark Useful Definitions

Input:
1. DEFS
2. Set of critical statements, CRIT, which are useful by definition (e.g. writes)

Output: For each definition S, MARK(S) = true iff S is useful

Method:
begin
    MARK(:) = false
    PILE=CRIT
    while PILE ≠ ∅ do
        S from PILE
        MARK(S)=true
        for each T in \( \bigcup_{v}^{DEFS(v, S)} \) do
            if ¬MARK(T) then PILE +=\{T\} fi
        od
    od
end
Algorithm CP: Constant Propagation

**Input:**
1. A program PROG
2. A flag CONST(v,S) for each statement S and input variable v of S. Also, CONST(S) for the output variable of S. Initially, CONST(S) is true only if the rhs of S is a constant. CONST(v,S) is false for all v and S.
3. USES and DEFS

**Output:**
1. The modified CONST flags
2. The mapping VAL(v,S) which provides the run-time constant value of input variable v at statement S. VAL(v,S) is defined only if CONST(v,S) is true. VAL(S) is the value of the output of S. VAL(S) is defined only if CONST(S) is true.
Method:

\begin{verbatim}
begin /*start with the trivially constant statements */
    PILE = \{S in PROG | the rhs of S is a constant\}
    while PILE ≠ ∅ do
        T from PILE
        v = output(T)
        for each S in USES(T) do
            /*check for constant inputs */
            for each U in DEFS(v,S)-\{T\} do
                if ¬CONST(U) or VAL(U) ≠ VAL(T) then next(2)
            od
            /* If it is a constant */
            CONST(v,S)=true
            VAL(v,S)=VAL(T)
            /* is the instruction now constant? */
            if CONST(w,S) true for all inputs w of S then
                CONST(S) = true
                VAL(S) = compute(S)
                PILE += \{S\}
            fi
        od
    od
end
\end{verbatim}
The third example is type analysis. This is important in very high level languages such as SETL where there are no declarations. A statement of the form $x := y + z$ could mean in SETL union of sets or of tuples, integer addition, real addition, etc. A run-time check is needed unless it can be determined at compile time the type of the operands.

We assume that there is a number of atomic type symbols such as I (integer), R (real), N (number, i.e. real or integer), UD (undefined), NS (set of arbitrary elements), S (sets), Z (error), etc.

We also assume an algebra of types encoded in a transition function $F$ which, for each operation $op$ and input types $t_1, t_2, ..., t_n$ of the operands, produces $t_0 = F_{op}(t_1, t_2, ..., t_n)$. e.g. real + real is real, real + integer is also real, integer + integer is integer.

**Algorithm TA: Type Analysis**

**Input:**
1. A program PROG
2. A mapping TYPE, such that $\text{TYPE}(v, S)$ is the best initial estimate of the type of the variable $v$ at the input of $S$ (for most variables this is ‘UD’). Also, $\text{TYPE}(S)$ is the type of the output (lhs) of $S$.
3. DEFS and USES

**Output:** For each instruction $S$ and input or output variable $v$, $\text{Type}(v, S)$, a conservative approximation to the most specific type information provably true at $S$. 
begin
  PILE = \{ S \in \text{PROG} \mid \text{no variable in the rhs is of type 'UD'} \}
  \textbf{while } PILE \neq \emptyset \textbf{ do}
  \hspace{1em} S \textbf{ from } PILE
  \hspace{1em} v = \text{output} (S)
  \hspace{1em} \textbf{for each } T \text{ in } \text{USES}(S) \textbf{ do}
  \hspace{2em} /* \text{recompute type } */
  \hspace{2em} \text{oldtype} = \text{TYPE}(v, T)
  \hspace{2em} \text{TYPE}(v, T) = \bigcup_{U \in \text{DEFS}(v, T)} \text{TYPE}(U)
  \hspace{2em} \textbf{if } \text{TYPE}(v, T) \neq \text{oldtype} \textbf{ then}
  \hspace{3em} /* \text{a type refinement } */
  \hspace{3em} \text{TYPE}(T) = F_{op}(T) \text{ (input types of } T)
  \hspace{3em} \text{PILE} += \{ T \}
  \hspace{2em} \textbf{fi}
  \hspace{1em} \textbf{od}
end
Some simple iterative algorithms for data flow analysis

The data flow analysis above was done assuming a structured program and operated on an abstract syntax tree.

One simple approach that works even when the flow graph is not reducible is to use iterative algorithms.

These algorithms try to find a solution to a system of equations. For example, for the reaching definitions problem, we have the following equations defined on each node B (a basic block) of the flow graph:

\[
\text{in}[B] = \bigcup_{C \in \text{PREDECESSOR}(B)} \text{out}[C]
\]

\[
\text{out}[B] = \text{gen}[B] \cup (\text{in}[B] - \text{kill}[B])
\]

or, in terms of in alone:

\[
\text{in}[B] = \bigcup_{C \in \text{PRED}(B)} \text{gen}[C] \cup (\text{in}[C] - \text{kill}[C])
\]

Notice that gen and kill are defined for basic blocks. Also, in[S] is assumed to be the empty set. S is the source node of the flow graph.

These equations do not have a unique solution. What we want is the smallest solution. Otherwise the result would not be as accurate as possible.
There are other important problems that can also be expressed as systems of equations.

The available expressions problem is used to do global common subexpression elimination. An expression \( x+y \) is available at a point \( p \) if every path from the initial node to \( p \) evaluates \( x+y \) and after the last such evaluation before reaching \( p \), there are no subsequent assignments to either operand.

A block \( \textit{kills} \) expression \( x+y \) if it assigns (or may assign) \( x \) or \( y \) and does not subsequently recompute \( x+y \). A block \( \textit{generates} \) expression \( x+y \) if it definitely evaluates \( x+y \) and does not subsequently redefine \( x \) or \( y \).

The equations are (Here \( in \) is the set of expressions available at the top of a basic block):

\[
out[B] = egen[B] \cup (in[B] - ekill[B])
\]

\[
in[B] = \bigcap_{C \in \textit{PRED}[B]} out[C]
\]

or in terms of \( in \) alone:

\[
in[B] = \bigcap_{C \in \textit{PRED}[B]} egen[C] \cup (in[C] - ekill[C])
\]
In this case, we want the largest solution to the system of equations. Consider for example, the following flow graph:

![Flow Graph]

where \( ekill[B2] = \emptyset \) and \( egen[B2] = \emptyset \). Also, \( out[B1] \) is \{\( x+y \)\}. By applying the previous equations we can see that \{\( x+y \)\} and \( \emptyset \) are both solutions to the system of equations. Clearly \{\( x+y \)\} is more accurate.

Again in this case we assume that \( in[S] \) is the empty set.

Another interesting problem is **live variable analysis**. This is computed in the direction opposite to the flow of control. In live variable analysis we wish to know for variable \( x \) and point \( p \) whether the value of \( x \) at \( p \) could be used along some path in the flow graph starting at \( p \). If so, \( x \) is live at \( p \); otherwise is dead at \( p \).

After a value is computed in a register within a block, it is not necessary to store that value if it is dead at the end of the block. Also, if all registers are full and we need another register, we should favor using a register with a dead value, since that value does not have to be stored.
Let $def[B]$ be the set of variables definitively assigned values in $B$ prior to any use of the variable in $B$, and let $use[B]$ be the set of variables whose values may be used in $B$ prior to any definition of the variable.

The equations are (Here $out[B]$ are the variables live at the end of the block, and $in[B]$, the variables live just before block $B$.

\[ in[B] = use[B] \cup (out[B] - def[B]) \]
\[ out[B] = \bigcup_{C \in SUCCESSOR(B)} in[C] \]

or in terms of $out$ alone:

\[ out[B] = \bigcup_{C \in SUC(B)} use[C] \cup (out[C] - def[C]) \]

The final problem we will mention is very busy expressions. An expression that is evaluated regardless of the path taken from a given point is said to be very busy at that point. Such expressions could be moved to the earliest point beyond which they would always be evaluated. It is a transformation that almost always reduces the space occupied by a program but that may affect its execution positively, negatively, or not at all. We define $eval[B]$ as the set of expressions that are evaluated in basic block $B$ before any of the operands are assigned to it in the block. We define $kill[B]$ to be the set of expressions killed by
block B. An expression is killed by a basis block if one of its operands is assigned to in the block.

\[ \text{in}[B] = \text{eval}[B] \cup (\text{out}[B] - \text{kill}[B]) \]

\[ \text{out}[B] = \bigcap_{C \in \text{SUCCESSOR}(B)} \text{in}[B] \]

**The four types of bit vector frameworks**

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**Observation 1.** A top-down (respectively bottom-up) problem defined on a single-exit flow graph G can be transformed into a bottom-up (respectively top-down) problem on the reverse graph of G (reverse the arcs) such that a solution to the modified problem gives an almost immediate solution to the original problem.

**Observation 2.** A set intersection (respectively set union) problem can be transformed into a set union (respectively set intersection) problem such that a solution to the modified problem gives a solution to the original problem. (By DeMorgan’s Laws).
Two simple iterative algorithms for the available expressions problem

We will now use the available expressions problem to illustrate two simple iterative algorithms to compute the \( \text{in}[B] \) sets. We will use a matrix \( \text{in}[B,e] \), that will be one iff an expression \( e \) is in \( \text{in}[B] \). Similar matrices for \text{egen} and \text{ekill} will be used (but not necessarily implemented). To understand the algorithm, consider again the equation:

\[
\text{in}[B] = \bigcap_{C \in PRED[B]} \text{egen}[C] \cup (\text{in}[C] - \text{ekill}[C])
\]

We can rewrite it as a boolean equation:

\[
\text{in}[B,e] = \prod_{C \in PRED[B]} \text{egen}[C,e] \lor (\text{in}[C,e] \land \overline{\text{ekill}[C,e]})
\]

or

\[
\overline{\text{in}[B,e]} = \sum_{C \in PRED[B]} ((\text{in}[C,e] \land \overline{\text{egen}[C,e]}) \lor (\text{ekill}[C,e] \land \overline{\text{egen}[C,e]}))
\]

Note here the \( \sum \) and the \( \prod \) symbols stand for logical OR and AND respectively.
begin
  PILE = ∅
  for each expression e in PROG do
    for each basic block B of PROG do
      if B is S or there is C in PRED(B) such that
        \( ekill[C, e] \land (\neg egen[C, e]) \) then
        /* By second term of equation */
        \( in[B, e] = 0 \)
        PILE += \{ B \}
      else
        \( in[B, e] = 1 \)
      fi
    od
  while PILE ≠ ∅ do
    C from PILE
    if \( \neg egen[C, e] \) then
      for each B in SUC(C) do
        if \( in[B, e] = 1 \) then
          /* By first term */
          \( in[B, e] = 0 \)
          PILE += \{ B \}
        fi
      od
    fi
  od
**Theorem.** The previous algorithm terminates and is correct.

**Proof**

*Termination.* For each expression $e$, no node is placed in PILE more than once and each iteration of the **while** loop removes an entry from PILE.

*Correctness.* $in[B,e]$ should be 0 iff either:
1. There is a path from $S$ to $B$ such that $e$ is not generated in any node preceding $B$ on this path or
2. there is a path to $B$ such that $e$ is killed in the first node of this path and not subsequently generated.

If $in[B,e]$ is set to zero because of the second term of the equation clearly either 1 or 2 hold. A straightforward induction on the number of iterations of the **while** loop shows that if $in[B,e]$ is set to zero because of the first term of the equation, then 1 or 2 must hold.

Conversely if 1 or 2 hold, then a straightforward induction shows that $in[B,e]$ is eventually set to 0.

**Theorem** The algorithm requires at most $O(mr)$ elementary steps, where $m$ is the number of expressions and $r$ is the number of arcs.

**Proof** The “for each” basic block” loop takes $O(n)$ steps. The **while** loop considers each arc once. Therefore $O(r)$. Outermost loop is $m$ iterations and $r \geq n-1$. Therefore $O(mr)$. 
Here is another algorithm (Kildall’s):

begin
\[\text{in}[1]=0^m\]
\[\text{in}[2:n]=1^m\]
for each C in SUC(1) do
  \text{PILE} += \{(C,\text{egen}[1,:])\}
od
for each node C do
  \text{T}(:) = \text{egen}[C,:] or \neg \text{ekill}[C,:]
  for each B in SUC(C) do
    \text{PILE} += \{B,T\}
  od
od
while \text{PILE} \neq \emptyset do
  (C,T) from \text{PILE}
  if (\neg T \text{ and } \text{in}[C]) \neq 0^m \text{ then}
    \text{in}[C,:] = \text{in}[C,:] and \text{T}(:)
    \text{T}(:) = (\text{in}[C,:] and \neg \text{ekill}[C,:]) or \text{egen}[C,:]
    \text{PILE} += \{(D,T) | D \text{ in SUC}(C)\}
  fi
od
end
Round-Robin Version of the Algorithm

This is the most straightforward version:

begin
  \(in[S] = \emptyset\)
  \(out[S] = egen[S]\)
  for each block \(B \neq S\) do
    \(out[B] = U - ekill[B]\)
  od
  change = true
while change do
  change = false
  for each block \(B \neq S\) /* in rPOSTORDER */
    \(in[B] = \bigcap_{C \in \text{PRED}[B]} out[C]\)
    oldout = out[B]
    out[B] = egen[B] \cup (in[B] - ekill[B])
    if out[B] \neq oldout then
      change = true
    fi
  od
  od
end
In bit notation

\[ \text{begin} \]
\[
in[S, :] = 0^m
\]
\[ \text{for each block } B \neq S \text{ do} \]
\[
in[B, :] = 1^m
\]
\[ \text{od} \]
\[ \text{change} = \text{true} \]
\[ \text{while} \text{ change do} \]
\[ \text{change} = \text{false} \]
\[ \text{for each block } B \neq S \text{ in rPOSTORDER do} \]
\[
\text{new} = \bigwedge \text{egen}[C, :] \lor (\text{in}[C, :] \land \neg \text{ekill}[C, :])
\]
\[
C \in \text{PRED}[B]
\]
\[ \text{if } \text{new} \neq \text{in}[B, :] \text{ then} \]
\[
in[B, :] = \text{new}
\]
\[ \text{change} = \text{true} \]
\[ \text{fi} \]
\[ \text{od} \]
\[ \text{od} \]
\[ \text{end} \]
To study the complexity of the above algorithm we need the following definition.

**Definition** Loop-connectedness of a reducible flow graph is the largest number of back arcs on any cycle-free path of the graph.

**Lemma** Any cycle-free path in a reducible flow graph beginning with the initial node is monotonically increasing in rPOSTORDER.

**Lemma** The while loop in the above algorithm is executed at most $d+2$ times for a reducible flow graph, where $d$ is the loop connectedness of the graph.

**Proof** A 0 propagates from its point of origin (either from the initial node or from a “kill”) to the place where it is needed in $d+1$ iterations if it must propagate along a path $P$ of $d$ back arcs. One more iteration is needed to detect that there are no further changes.

**Theorem** If we ignore initialization, the previous algorithm takes at most $(d+2)(r+n)$ bit vector steps; that is $O(dr)$ or $O(r^2)$ bit vector steps.
Global Common Subexpression Elimination

A very simple algorithm is presented in the book by Aho Sethi and Ullman:

Algorithm GCSE: Global Common Subexpression Elimination

Input: A flow Graph with available expression information.

Output: A revised Flow graph

Method:

```
begin
for each block B do
    for each statement r in B of the form x = y op z
    with y op z available at the beginning of B and
    neither y nor z defined before r in B do
        for each block C computing the expression
        y op z reaching B do
            let t be the last statement in C of the
            form w = y op z
            replace t with the pair
            u = y op z
            w = u
            od
        Replace t with x = u
    od
od
end
```
To find the statements $t$, the algorithm searches backwards in the flow graph. We could compute something equivalent to use-definitions chains for expressions, but this may produce too much useless information.

Copy propagation can be applied to the program to eliminate the $w = u$ statement.

The algorithm can be applied several times to remove complex redundant expressions.
Copy propagation

To eliminate copy statements introduced by the previous algorithm we first need to solve a data flow analysis problem.

Let \( cin[B] \) be the set of copy statements that (1) dominate \( B \), and (2) their rats are not rewritten before \( B \).

\( out[B] \) is the same, but with respect to the end of \( B \).

\( cgen[B] \) is the set of copy statements whose rats are not rewritten before the end of \( B \).

\(ckill[B] \) is the set of copy statements not in \( B \) whose rhs or lhs are rewritten in \( B \).

We have the following equation:

\[
cin[B] = \bigcap_{C \in PRED[B]} (cgen[C] \cup (cin[C] \setminus ckill[C]))
\]

Here we assume that \( cin[S] = \emptyset \)

Using the solution to this system of equations we can do copy propagation as follows:
Algorithm CP: Copy Propagation

Input: A flow Graph with use-definition chains, and cin[B] computed as just discussed above.

Output: A revised Flow graph

Method:

begin
    for each copy statement $t: x=y$ do
        if for every use of $x$, $B$:
            $t$ is in cin[B] and
            neither $x$ nor $y$ are redefined within $B$ before the use
        then
            remove $t$ and
            replace all uses of $x$ by $y$.
        fi
    od
end
Detection of Loop-Invariant Computation

*Input.* A loop L. Use-definition chains

*Output.* The set of statements in L that compute the same value every time they are executed

*Method*

```
begin
  Mark “invariant” those statements whose operands are all either constant or have their reaching definitions outside L
  while at least one statement is marked invariant do
    mark invariant those statements with the following property: *Each operand* is either (1) constant, or (2) have all their reaching definitions outside L, or (3) have exactly one reaching definition, and that definition is a statement in L marked invariant.
  od
end
```

Once the “invariant” marking is completed statements can be moved out of the loop. The statements should be moved in the order in which they were marked by the previous algorithm. These statements should satisfy the following conditions:

1. All their definition statements that were within L should have been moved outside L.
2. The statement should dominate all exits of L.
3. The lhs of the statement is not defined elsewhere in L, and
4. All uses in L of the lhs of the statement can only be reached by the statement.