# Dataflow analysis

# Dataflow analysis: what is it?

- A common framework for expressing algorithms that compute information about a program
- Why is such a framework useful?
- It provides a common language, which makes it easier to:
  - communicate your analysis to others
  - compare analyses
  - adapt techniques from one analysis to another
  - reuse implementations (eg: dataflow analysis frameworks)

# Data flow analysis

- Goal :
  - collect information about how a procedure manipulates its data
- This information is used in various optimizations
  - For example, knowledge about what expressions are available at some point helps in common subexpression elimination.
- IMPORTANT!
  - Soundness is a must: Data flow analysis should never tell us that a transformation is safe when in fact it is not.
  - It is better to not perform a valid optimization that to perform one that changes the function of the program.

# Soundness is a must!

- Data flow analysis should never tell us that a transformation is safe when in fact it is not.

- When doing data flow analysis we must be
  - Conservative
    - Do not consider information that may not preserve the behavior of the program
  - Aggressive
    - Try to collect information that is as exact as possible, so we can get the greatest benefit from our optimizations.

# Global Iterative Data Flow Analysis

- Global:
  - Performed on the control flow graph
  - Goal = to collect information at the beginning and end of each basic block
- Iterative:
  - Construct data flow equations that describe how information flows through each basic block and solve them by iteratively converging on a solution.
  - The "ingredients" of the equations:
    - Algebraic representation of the property of interest
    - Labels associated to the control flow diagrams

# Global Iterative Data Flow Analysis

- Components of data flow equations
  - Sets containing collected information
    - **In** (or **entry**) set: information coming into the BB from outside (following flow of dats)
    - **gen** set: information generated/collected within the BB
    - **kill** set: information that, due to action within the BB, will affect what has been collected outside the BB
    - **out** (or **exit**) set: information leaving the BB
  - Functions (operations on these sets)
    - **Transfer functions** describe how information changes as it flows through a basic block
    - **Meet functions** describe how information from multiple paths is combined.

# Global Iterative Data Flow Analysis

- Algorithm sketch
  - Typically, a bit vector is used to store the information.
    - For example, in reaching definitions, each bit position corresponds to one definition.
  - We use an iterative fixed-point algorithm.
  - Depending on the nature of the problem we are solving, we may need to traverse each basic block in a forward (top-down) or backward direction.
    - The order in which we "visit" each BB is not important in terms of algorithm correctness, but is important in terms of efficiency.
  - In & Out sets should be initialized in a conservative and aggressive way.

```
Initialize gen and kill sets
Initialize in or out sets (depending on "direction")
while there are no changes in in and out sets {
    for each BB {
        apply meet function
        apply transfer function
    }
}
```

# Typical problems

- Reaching definitions
  - For each use of a variable, find all definitions that reach it.
- Upward exposed uses
  - For each definition of a variable, find all uses that it reaches.
- Live variables
  - For a point p and a variable v, determine whether v is live at p.
- Available expressions
  - Find all expressions whose value is available at some point p.
- Very Busy expressions
  - Find all expressions whose value will be used in all the next paths

# Reaching definitions

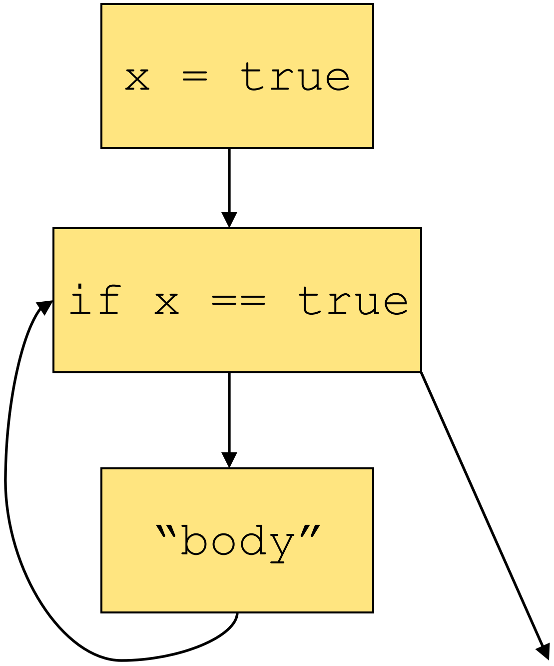
- Determine which definitions of a variable may reach a use of the variable.
  - For each use, list the definitions that reach it. This is also called a ud-chain.
  - In global data flow analysis, we collect such information at the endpoints of a basic block, but we can do additional local analysis within each block.
- Uses of reaching definitions :
  - constant propagation
    - we need to know that all the definitions that reach a variable assign it to the same constant
  - copy propagation
    - we need to know whether a particular copy statement is the only definition that reaches a use.
  - code motion
    - we need to know whether a computation is loop-invariant

# Something obvious

```
boolean x = true;
while (x) {
   . . . // no change to x (and no exit/return stm)
}
```

- The program doesn't terminate.
- Proof: the only assignment to x is at top, so x is always true.

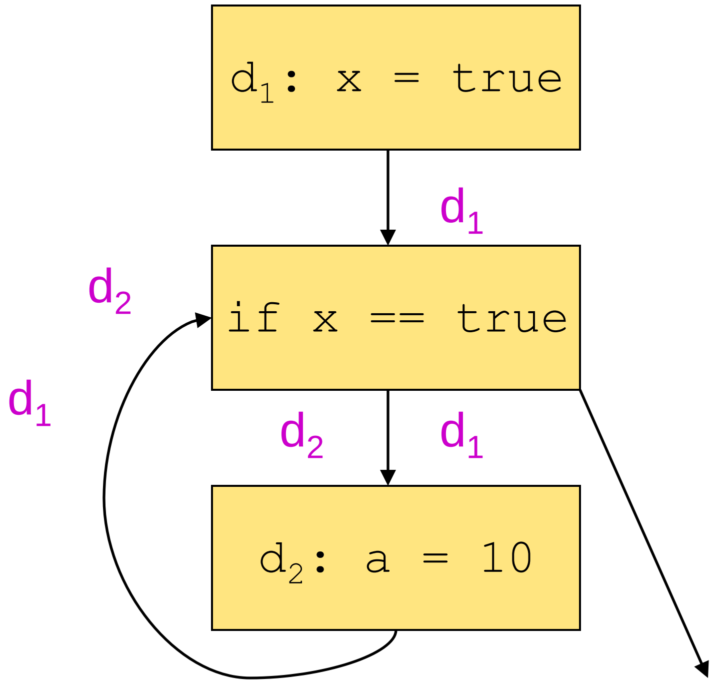
# As a Control Flow Graph



# Formulation: Reaching Definitions

- Each place some variable x is assigned is a *definition*.
- Ask:
  for this use of x, where could x last have been defined?
- In our example:
  only at `x=true`.

# Example: Reaching Definitions



# Clincher

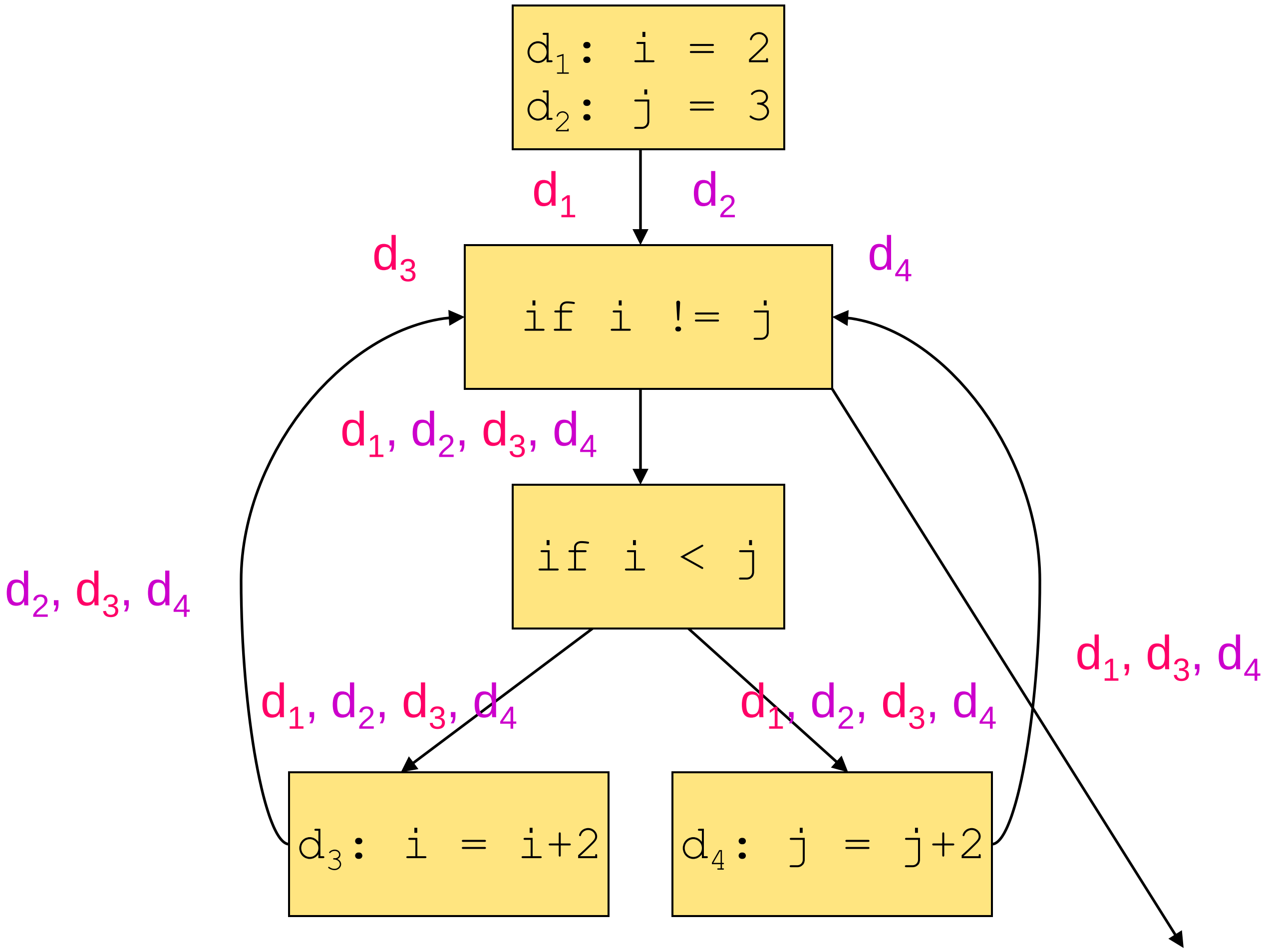
- Since at `x == true`, $d_1$ is the only definition of x that reaches, it must be that x is true at that point.
- The conditional is not really a conditional and can be replaced by a branch.

# Not Always That Easy

```
int i = 2; int j = 3;
while (i != j) {
    if (i < j) i += 2;
    else j += 2;
}
```

- We'll develop techniques for this problem, but later …

# The Control Flow Graph



# DFA is Sufficient Only

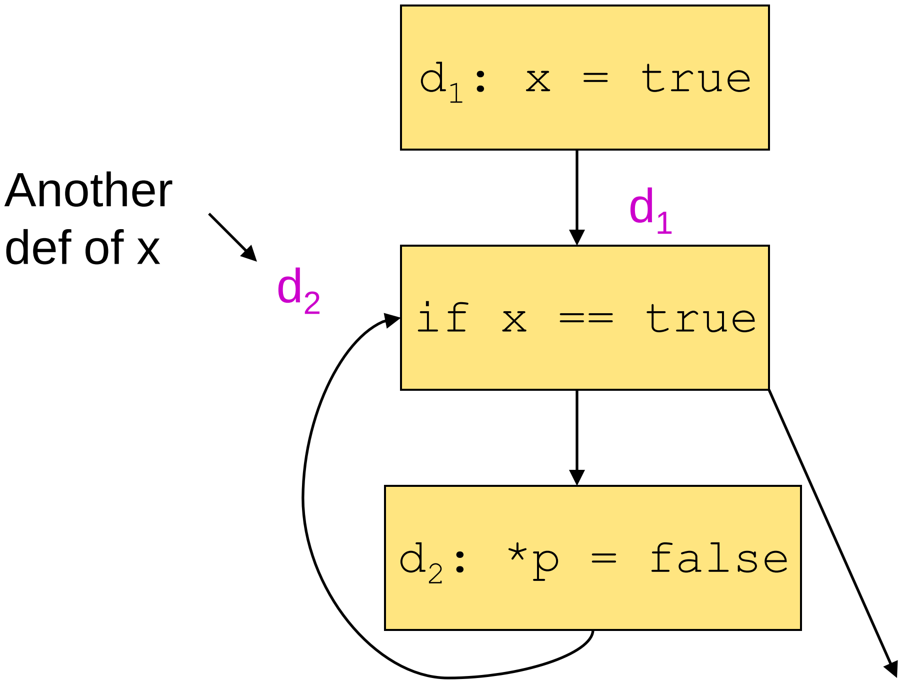
- In this example, i can be defined in two places, and j in two places.
- No obvious way to discover that `i!=j` is always true.
- But OK, because reaching definitions is sufficient to catch most opportunities for *constant folding* (replacement of a variable by its only possible value).

# Example: Be Conservative

```
boolean x = true;
while (x) {
    . . . *p = false; . . .
}
```

- Is it possible that p points to x?

# As a Control Flow Graph



# Possible Resolution

- Just as data-flow analysis of "reaching definitions" can tell what definitions of x might reach a point, another DFA can eliminate cases where p definitely does not point to x.
- Example: the only definition of p is `p = &y` and there is no possibility that y is an alias of x.

# Formalization: Reaching definitions Analysis

- How can we formalize a definition D?
  By a pair (x,n) where x is the variable modified by D, and n identifies the assignment D.

- A definition D reaches a point *p* if there is a path from D to *p* along which D is not killed.

- A definition D of a variable *x* is killed when there is a redefinition of *x.*

- How can we represent the set of definitions reaching a point?

# Reaching definitions

- What is safe?
  - To assume that a definition reaches a point even if it turns out not to.
  - The computed set of definitions reaching a point p will be a superset of the actual set of definitions reaching p
  - It's a "possible", not a "definite" property
  - Goal : make the set of reaching definitions as small as possible (i.e. as close to the actual set as possible)

# Reaching definitions

- How are the **gen** and **kill** sets defined?
  - **gen**[B] = {definitions that appear in B and reach the end of B}
  - **kill**[B] = {all definitions that never reach the end of B}
- What is the direction of the analysis?
  - forward
  - **out**[B] = **gen**[B] $\cup$ (**in**[B] - **kill**[B])

# Reaching definitions

- What is the **confluence** operator?
  - union
  - **in**[P] = ∪ **out**[Q], over the predecessors Q of P

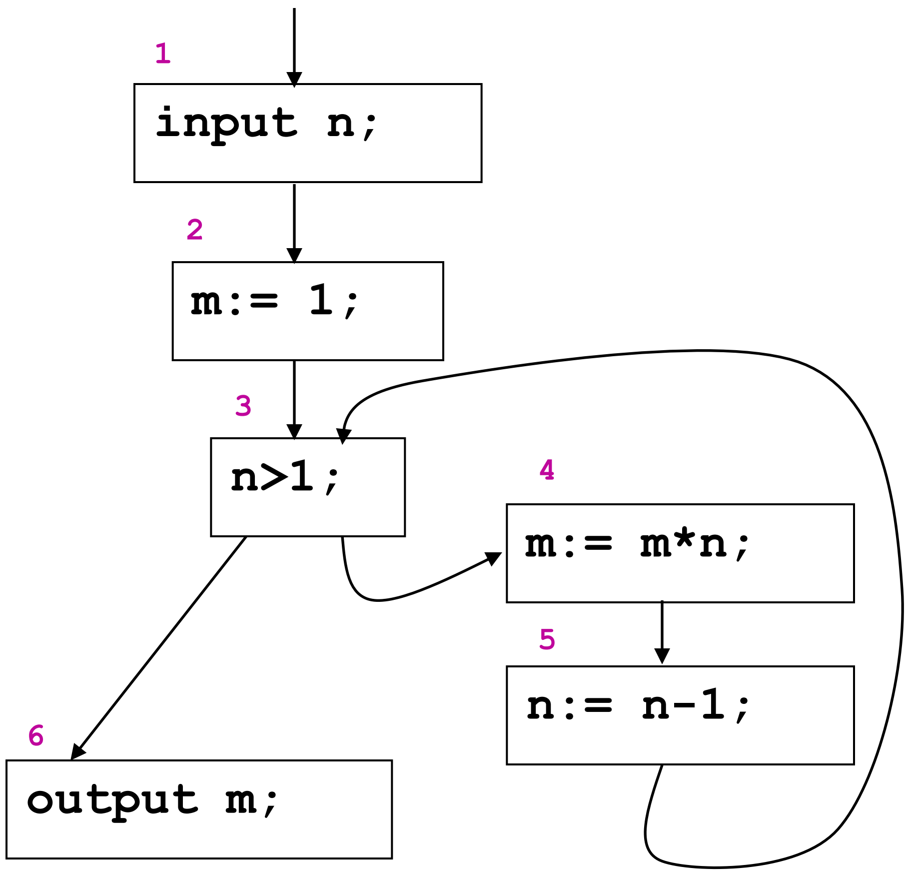
- How do we initialize?
  - start small
    - Why? Because we want the resulting set to be as small as possible
  - for each block B initialize **out**[B] = **gen**[B]

# Formal specification

- The reaching Definition Analysis is specified by the folllowing equations:
- For each program point,

$$RD_{in}(p) = \begin{cases} \iota & \text{if p is the initial point in the control graph} \\ \bigcup \{ RD_{out}(q) \mid \text{there is an arrow from q to p in the CFD} \} & \end{cases}$$

$$RD_{out}(p) = gen_{RD}(p) \cup (RD_{in}(p) \setminus kill_{RD}(p))$$




- $RD_{in}(1) = \{(n,?),(m,?)\}$
  $RD_{out}(1) = \{(n,?),(m,?)\}$

- $RD_{in}(2) = \{(n,?),(m,?)\}$
  $RD_{out}(2) = \{(n,?),(m,2)\}$

- $RD_{in}(3) = RD_{out}(2) \cup RD_{out}(5)$
  $= \{(n,?),(n,5),(m,2),(m,4)\}$
  $RD_{out}(3) = \{(n,?),(n,5),(m,2),(m,4)\}$

- $RD_{in}(4) = \{(n,?),(n,5),(m,2),(m,4)\}$
  $RD_{out}(4) = \{(n,?),(n,5),(m,4)\}$

- $RD_{in}(5) = \{(n,?),(n,5),(m,4)\}$
  $RD_{out}(5) = \{(n,5),(m,4)\}$

- $RD_{in}(6) = \{(n,?),(n,5),(m,2),(m,4)\}$
  $RD_{out}(6) = \{(n,?),(n,5),(m,2),(m,4)\}$

# Algorithm

- Input: Control Graph Diagram
- Output : RD

- Steps:
  – step 1 (inizialization):
    - $RD_{in}(p)$ is the emptyset for each p
    - $RD_{in}(1) = \iota = \{(x,?) \mid x \text{ is a program variable}\}$

- Step 2 (iteration)
  - Flag =TRUE;
    while Flag
    Flag = FALSE;
    for each program point p
    new = U{f(RD,q) | (q,p) is an edge of the graph}
    if $RD_{in}(p)$ != new
    Flag = TRUE;
    $RD_{in}(p)$ = new;

where $f(RD,q) = gen_{RD}(q) \cup (RD_{in}(q) \setminus kill_{RD}(q))$

# Example

```
[ input n; ]1
[ m:= 1; ]2
  [ while n>1 do ]3
     [ m:= m * n; ]4
     [ n:= n - 1; ]5
[ output m; ]6
```

- $RD_{in}(1)= \{(n,?), (m,?)\}$
- $RD_{in}(2)= \{(n,?), (m,?)\}$
- $RD_{in}(3)= \{(n,?), (n,5), (m,2), (m,4)\}$
- $RD_{in}(4)= \{(n,?), (n,5), (m,4)\}$
- $RD_{in}(5)= \{(n,5), (m,4)\}$
- $RD_{in}(6)= \{(n,?), (n,5), (m,2), (m,4)\}$