More Dataflow Analyses

Steps to building analysis

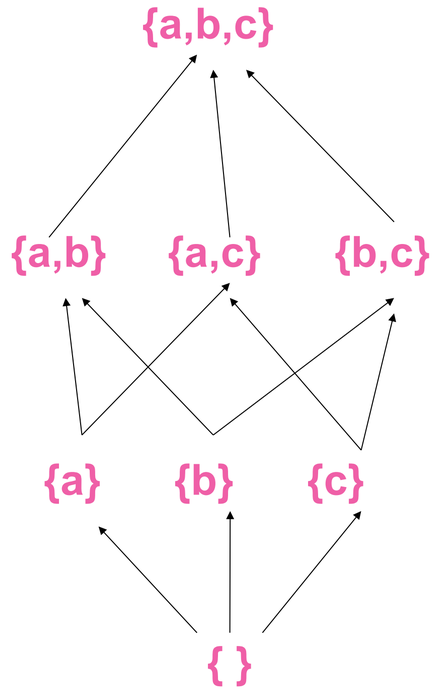
- Step 1: Choose lattice
- Step 2: Choose direction of dataflow (forward or backward)
- Step 3: Create transfer function
- Step 4: Choose *confluence* operator (*i.e.*, what to do at merges)
  - Either join or meet in the lattice
- Let's walk through these steps for a new (old) analysis

Liveness analysis

- Which variables are live at a particular program point?
- Used all over the place in compilers
  - Register allocation
  - Loop optimizations
- We've done this for single basic blocks, but what about across basic blocks?

Choose lattice

- What do we want to know?
  - At each program point, want to maintain the set of variables that are live
  - Lattice elements: sets of variables
  - Natural choice for lattice: powerset of variables!



Choose dataflow direction

- A variable is *live* if it is used later in the program without being redefined
  - At a given program point, we want to know information about what happens later in the program
  - This is information about the future of the program
- This means that liveness is a *backwards* analysis
  - No reason to run the program forward!
  - Recall that we did liveness backwards when we looked at single basic blocks
- Rule of thumb: if symbolic information you are tracking is about what happens in the future, run the analysis backwards

symbolically executing a statement

- What do we do for a statement like:
- x = y + z
- If x was live “before” (i.e., live after the statement), it isn’t now (i.e., is not live before the statement)
- If y and z were not live “before,” they are now
- What about:
- x = x

symbolically executing a statement

- Let's generalize
- For any statement s, we can look at which live variables are *killed*, and which new variables are made live (*generated*)
- Which variables are killed in s?
  - The variables that are *defined* in s: DEF(s)
- Which variables are made live in s?
  - The variables that are *used* in s: USE(s)
- If the set of variables that are live after s is X, what is the set of variables live before s?

$$T_s(X) = \mathbf{use}(s) \cup (X - \mathbf{def}(s))$$

Dealing with aliases

- Aliases, as usual, cause problems
- Consider

```
int x, y, r, s
int *z, *w;
if (...) z = &y else z = &x
if (...) w = &r else w = &s
*z = *w; //which variable is defined? which is used?
```

- What should USE(*z = *w) and DEF(*z = *w) be?
  - Keep in mind: the goal is to get a list of variables that *may* be live at a program point
- For now, assume there is no aliasing

Dealing with function calls

- Similar problem as aliases:

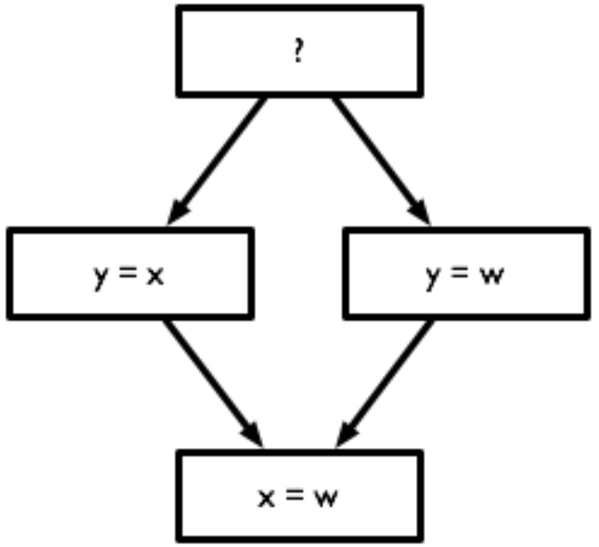
```
int foo(int &x, int &y); //pass by reference!

void main() {
 int x, y, z;
 z = foo(x, y);
}
```

- Simple solution: functions can do *anything* – redefine variables, use variables
  - So DEF(foo()) is { } and USE(foo()) is V
- Real solution: *interprocedural* analysis, which determines what variables are used and defined in foo

What about merges?

- What happens at a merge point?
  - The variables live into a merge point are the variables that are live along *either* branch
  - Confluence operator: Set union (⊔) of all live sets of outgoing edges



$$T_{merge} = \bigsqcup_{X \in succ(merge)} X$$

How to initialize analysis?

- At the end of the program, we know no variables are live → value at exit point is { }
  - What about if we're analyzing a single function?
  - Need to make conservative assumption about what may be live
- What about elsewhere in the program?
  - We should initialize other sets to { }

liveness example