Advanced program representations

Goal:

- more effective analysis
- faster analysis
- easier transformations

Approach:

more directly capture important program properties

- e.g. data flow, independence

Examples

CFG:

+ simple to build
+ complete
+ no derived info to keep up to date during transformations

– computing info is slow and/or ineffective
  - lots of propagation of big sets/maps

Def/use chains

Def/use chains directly linking defs to uses & vice versa

+ directly captures data flow for analysis
  - e.g. constant propagation, live variables easy

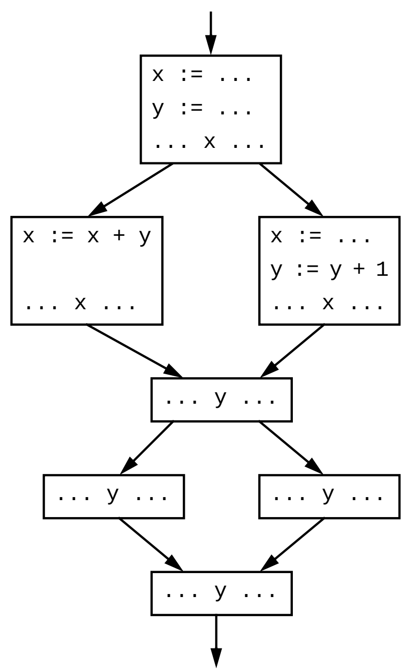
– ignores control flow
  - misses some optimization opportunities, since it assumes all paths taken
  - not executable by itself, since it doesn't include control dependence links
  - not appropriate for some optimizations, such as CSE and code motion

– must update after transformations
  - not too hard (just remove edges)

– space-consuming, in worst case: $O(E^2V)$

– can have multiple defs of same variable in program, multiple defs can reach a use
  - complicates analysis

Example



Static Single Assignment (SSA) form

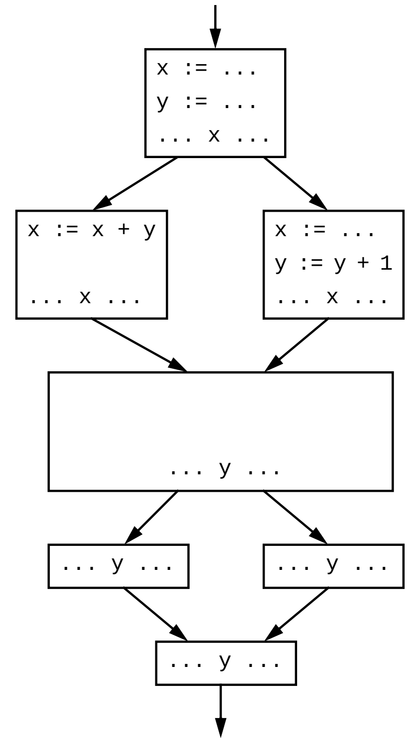
[Alpern, Rosen, Wegman, & Zadeck, two POPL 88 papers]

Invariant: at most one definition reaches each use

Constructing equivalent SSA form of program:

1. Create new target names for all definitions
2. Insert **pseudo-assignments** at merge points
   reached by multiple definitions of same source variable:
   $x_n := \phi(x_1, ..., x_n)$
3. Adjust uses to refer to appropriate new names

Example



Comparison

+ lower worst-case space cost than def/use chains: O(*EV*)

+ algorithms simplified by exploiting
  single assignment property:
  - variable has a unique meaning independent of program point
  - can treat variable & its contents synonymously
  - can have single global table mapping var to info,
    not one per program pt.

+ transformations not limited by reuse of variable names
  - can reorder assignments to same source variable, without
    affecting dependences of SSA version

– still not executable by itself

– still must update/reconstruct after transformations

– inverse property (static single use) not provided
  - **dependence flow graphs** [Pingali *et al.*] and
    value dependence graphs [Weise *et al.*] fix this,
    with single-entry, single-exit (SESE) region analysis

Very popular in research compilers, analysis descriptions

Common subexpression elimination

At each program point, compute set of **available expressions**:
map from expression to variable holding that expression

- e.g. `{a+b → x, -c → y, *p → z}`

(More generally, can have map from
expensive expression to equivalent but cheaper expression

- subsumes CSE, constant prop, copy prop.)

CSE transformation using AE analysis results:
if a+b→x available before `y :=` a+b, transform to `y :=` x

Specification

All possible available expressions:

AvailableExprs = {*expr*→*var* | ∀*expr* ∈ Exprs, ∀*var* ∈ Vars}
= Exprs × Vars

- Exprs = set of all right-hand-side expressions in procedure
- Vars = set of all variables in procedure

[is this a function from Exprs to Vars, or just a relation?]

Domain AV = < Pow(AvailableExprs), $\leq_{AV}$ >

$ae_1 \leq_{AV} ae_2 \quad \Leftrightarrow$

- top:
- bottom:
- meet:
- lattice height:

Constraints

$AE_{\texttt{x := y } op \texttt{ z}}$:

$AE_{\texttt{x := y}}$:

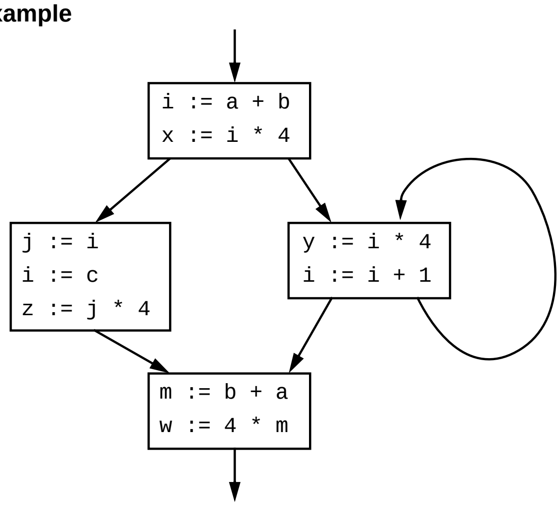
Initial conditions at program points?

What direction to do analysis?

Can use bit vectors?

Can summarize sequences of flow functions?

Example



Exploiting SSA form

Problem: previous available expressions overly sensitive to name choices, operand orderings, renamings, assignments, ...

A solution:

Step 1: convert to SSA form

- distinct values have distinct names
  ⇒ can simplify flow functions to ignore assignments

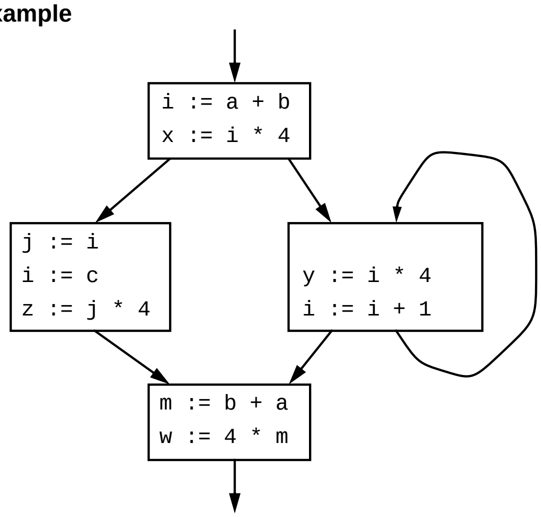
$AE^{SSA}_{\texttt{x := y } op \texttt{ z}}$:

Step 2: do **copy propagation**

- same values (usually) have same names
  ⇒ avoid missed opportunities

Step 3: adopt canonical ordering for commutative operators
⇒ avoid missed opportunities

Example



After SSA conversion, copy propagation, & operand order canonicalization: