Loop-invariant code motion

Two steps: analysis & transformation

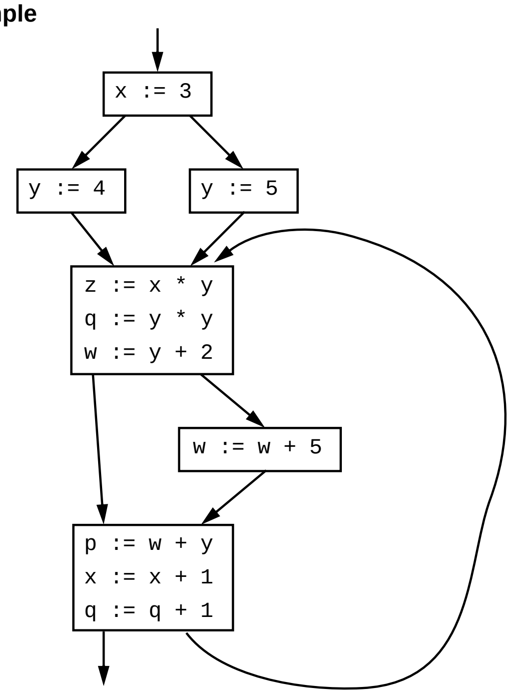
Step 1: find invariant computations in loop

- invariant: computes same result each time evaluated

Step 2: move them outside loop

- to top: **code hoisting**
  - if used within loop
- to bottom: **code sinking**
  - if only used after loop

Example



Detecting loop-invariant expressions

An expression is invariant w.r.t. a loop *L* iff:

base cases:

- it's a constant
- it's a variable use, **all of whose defs are outside *L***

inductive cases:

- it's an idempotent computation
  all of whose args are loop-invariant
- it's a variable use **with only one reaching def**,
  and the rhs of that def is loop-invariant

Computing loop-invariant expressions

Option 1:

- repeat iterative dfa
  until no more invariant expressions found
  - to start, optimistically assume all expressions loop-invariant

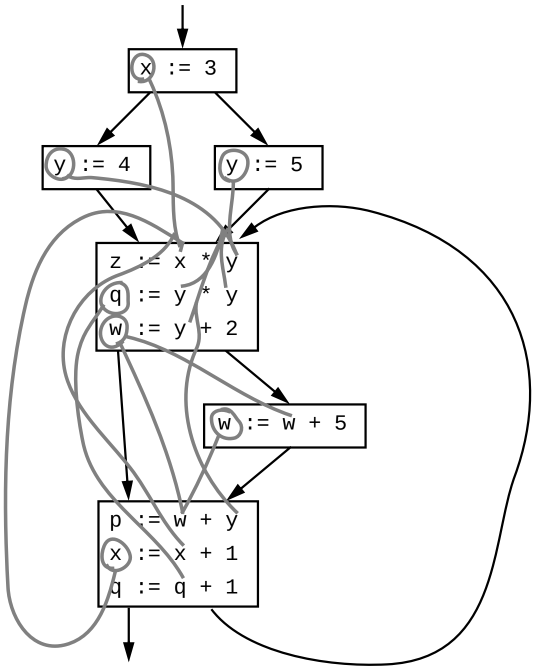
Option 2:

- build def/use chains,
  follow chains to identify & propagate
  invariant expressions

Option 3:

- convert to SSA form,
  then similar to def/use form

Example using def/use chains



Loop-invariant expression detection for SSA form

SSA form simplifies detection of loop invariants,
since each use has only one reaching definition

An expression is invariant w.r.t. a loop *L* iff:

base cases:

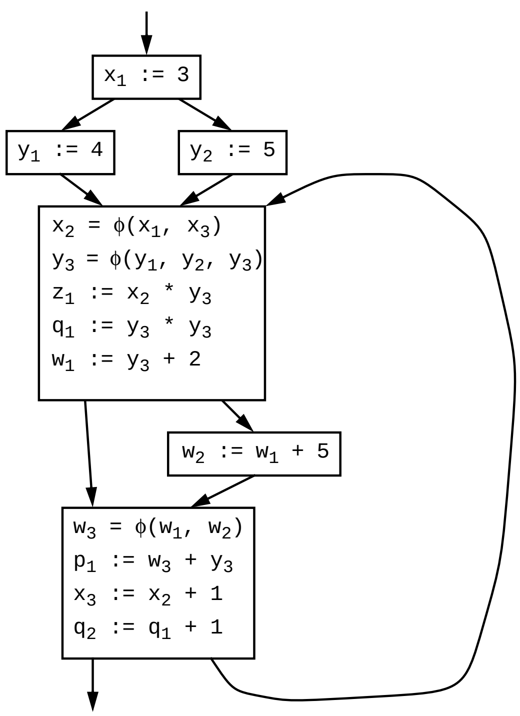
- it's a constant
- it's a variable use **whose single def is outside *L***

inductive cases:

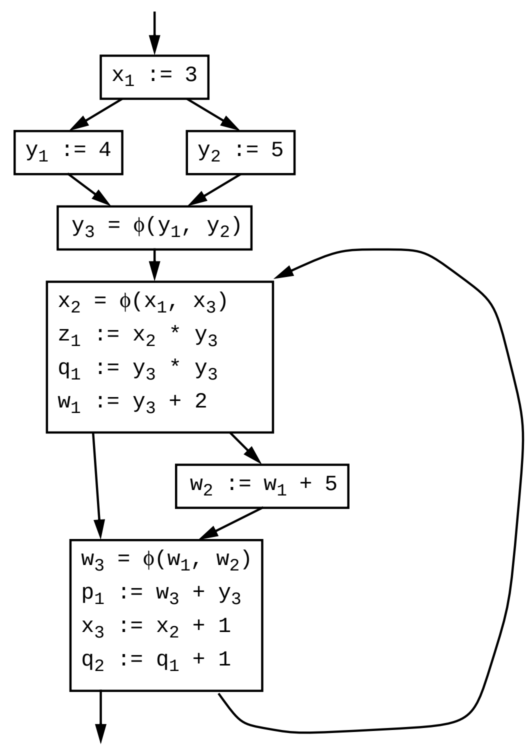
- it's an idempotent computation
  all of whose args are loop-invariant
- it's a variable use
  whose single def's rhs is loop-invariant

ϕ functions are *not* idempotent

Example using SSA form



Example using SSA form & preheader



Code motion

When find invariant computation *S:* `z := x op y`,
want to move it out of loop (to loop preheader)

When is this legal?

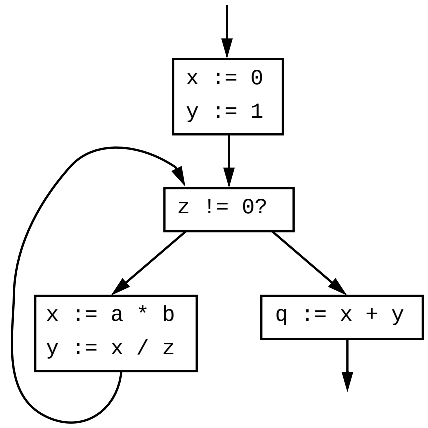
Sufficient conditions:

- *S* **dominates** all loop exits
  [*A* dominates *B* when
  all paths to *B* must first pass through *A*]
  - otherwise may execute *S* when never executed otherwise
  - can relax this condition, if *S* has no side-effects or traps, at cost of possibly slowing down program
- *S* is only assignment to `z` in loop, &
  no use of `z` in loop is reached by any def other than *S*
  - otherwise may reorder defs/uses and change outcome
  - unnecessary in SSA form!

If met, then can move *S* to loop preheader

- but preserve relative order of invariant computations, to preserve data flow among moved statements

Example of need for domination requirement



Avoiding domination restriction

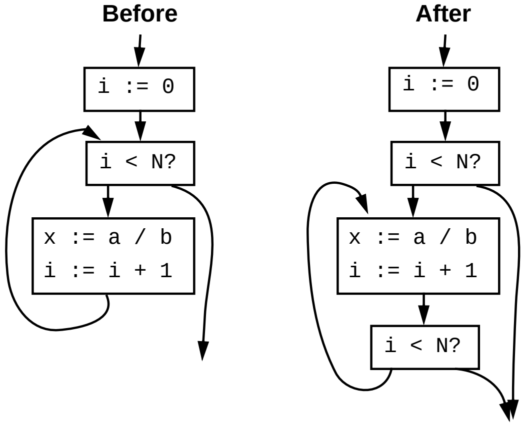
Requirement that invariant computation dominates exit is strict

- nothing in conditional branch can be moved
- nothing after loop exit test can be moved

Can be circumvented through other transformations
such as **loop normalization**

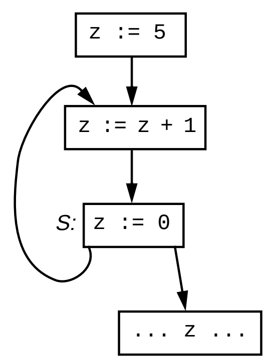
- move loop exit test to bottom of loop
  (while-do ⇒ do-while)

Before **After**



Example of data dependence restrictions

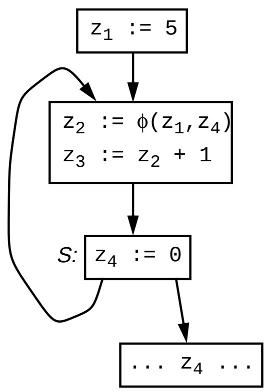
"*S* is only assignment to `z` in loop, &
no use of `z` in loop is reached by any def other than *S*"



Example in SSA form

Restrictions unnecessary if in SSA form

- if reorder defs/uses, generate code along merging arcs to implement ϕ functions



Loop-invariant code copying

Alternative to code motion:
copy instruction to loop header, assigning to new temp, then do CSE & copy propagation to simplify in-loop version

- more modular design, leverage off of existing optimizations

Can always copy, unless instruction has side-effects

CSE & copy propagation will eliminate in-loop instruction exactly when (non-SSA) loop-invariant code motion would have, PLUS can replace invariant but unmovable instructions with copies

SSA-based code motion gets same effect

- copies correspond to reified ϕ functions

Example