Register Allocation

Compilers for High Performance Architectures

Class Outline

- Live Ranges
- Interference
- Coloring
- LiveRange Splitting
- Rematerialization

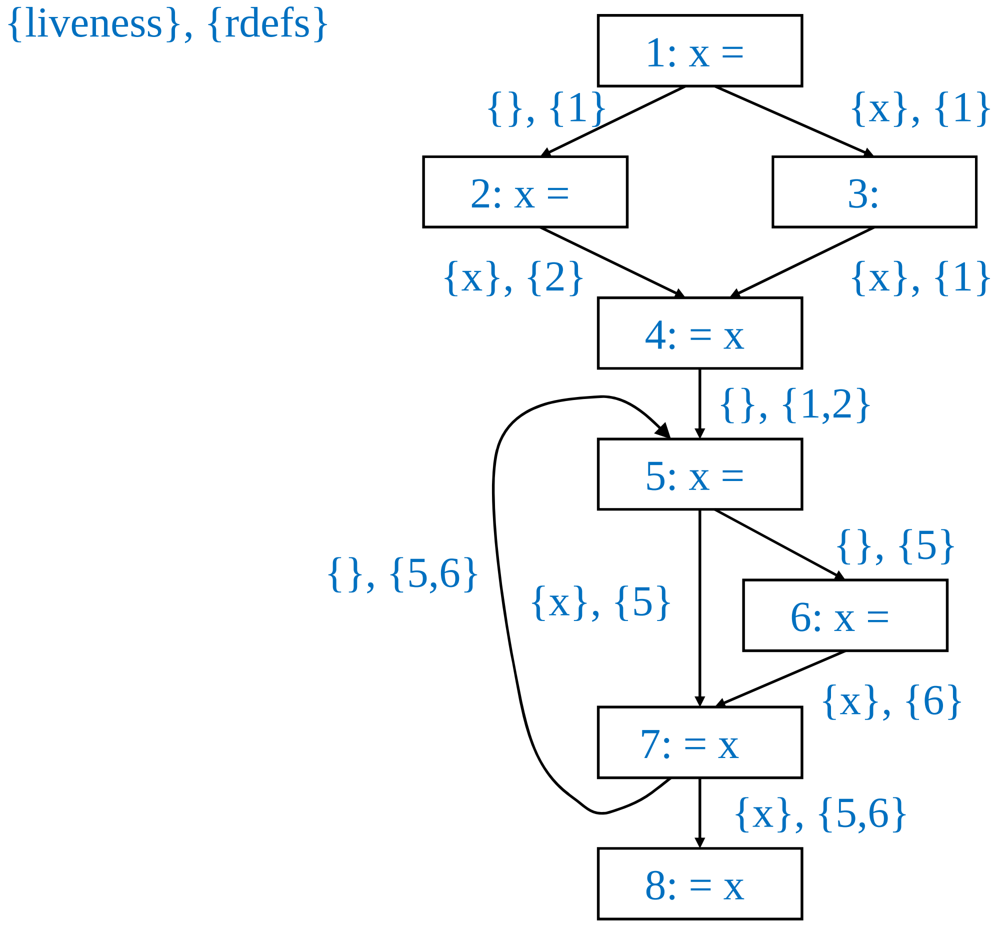
Problem Definition

- Through optimization, assume an infinite number of virtual registers
  - Now, must allocate these infinite virtual registers to a limited supply of hardware registers
  - Want most frequently accessed variables in registers
    - Speed, registers much faster than memory
    - Direct access as an operand
  - Any VR that cannot be mapped into a physical register is said to be spilled
- Questions to answer
  - What is the minimum number of registers needed to avoid spilling?
  - Given n registers, is spilling necessary
  - Find an assignment of virtual registers to physical registers
  - If there are not enough physical registers, which virtual registers get spilled?

Live Range

- Value = defn of a register
- Live range = Set of operations
  - Values connected by common uses
  - A single VR may have several live ranges
- Live ranges are constructed by taking the intersection of reaching defs and liveness
  - Initially, a live range consists of a single definition and all ops in a function in which that definition is live

Example – Constructing Live Ranges



Each definition is the seed of a live range.
Ops are added to the LR where <u>both the defn reaches and the variable is live</u>

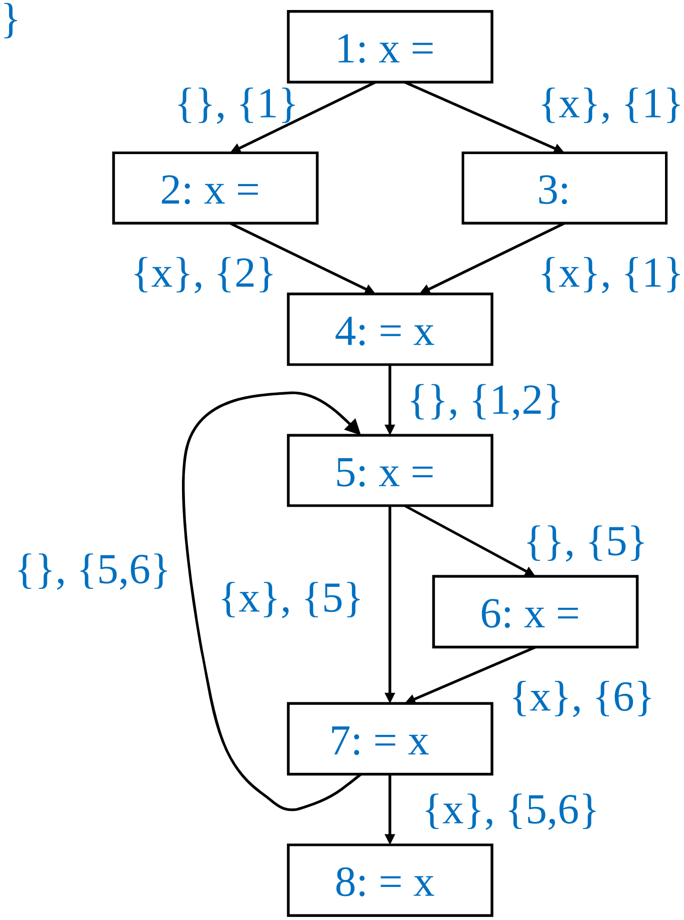
LR1 for def 1 = {1,3,4}
LR2 for def 2 = {2,4}
LR3 for def 5 = {5,7,8}
LR4 for def 6 = {6,7,8}

Merging Live Ranges

- If 2 live ranges for the same VR overlap, they must be merged to ensure correctness
  - LRs replaced by a new LR that is the union of the LRs
  - Multiple defs reaching a common use
  - Conservatively, all LRs for the same VR could be merged
    - Makes LRs larger than need be, but done for simplicity

Example – Merging Live Ranges

{liveness}, {rdefs}

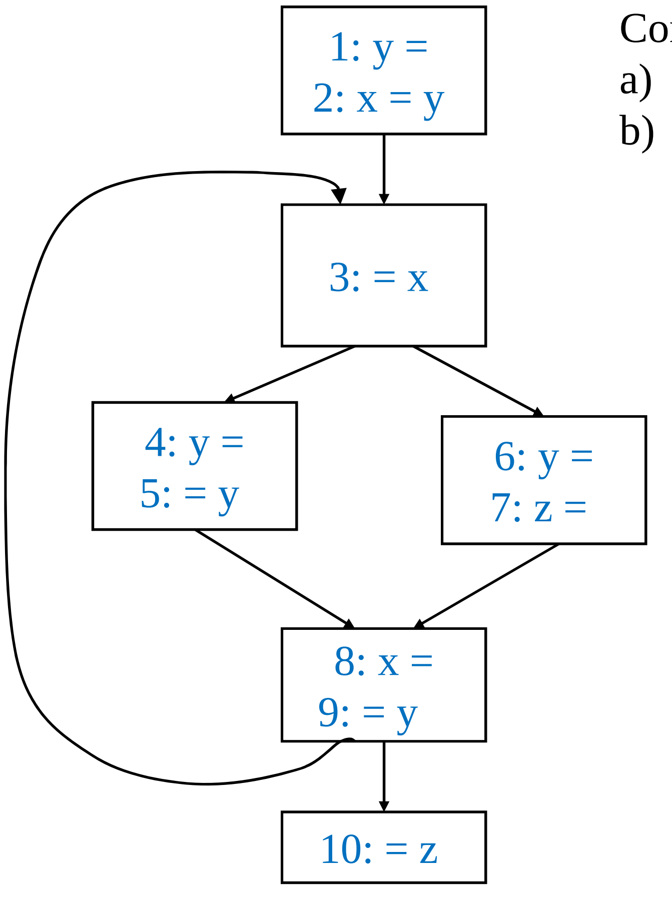


LR1 for def 1 = {1,3,4}
LR2 for def 2 = {2,4}
LR3 for def 5 = {5,7,8}
LR4 for def 6 = {6,7,8}

Merge LR1 and LR2, LR3 and LR4

LR5 = {1,2,3,4}
LR6 = {5,6,7,8}

Class Problem



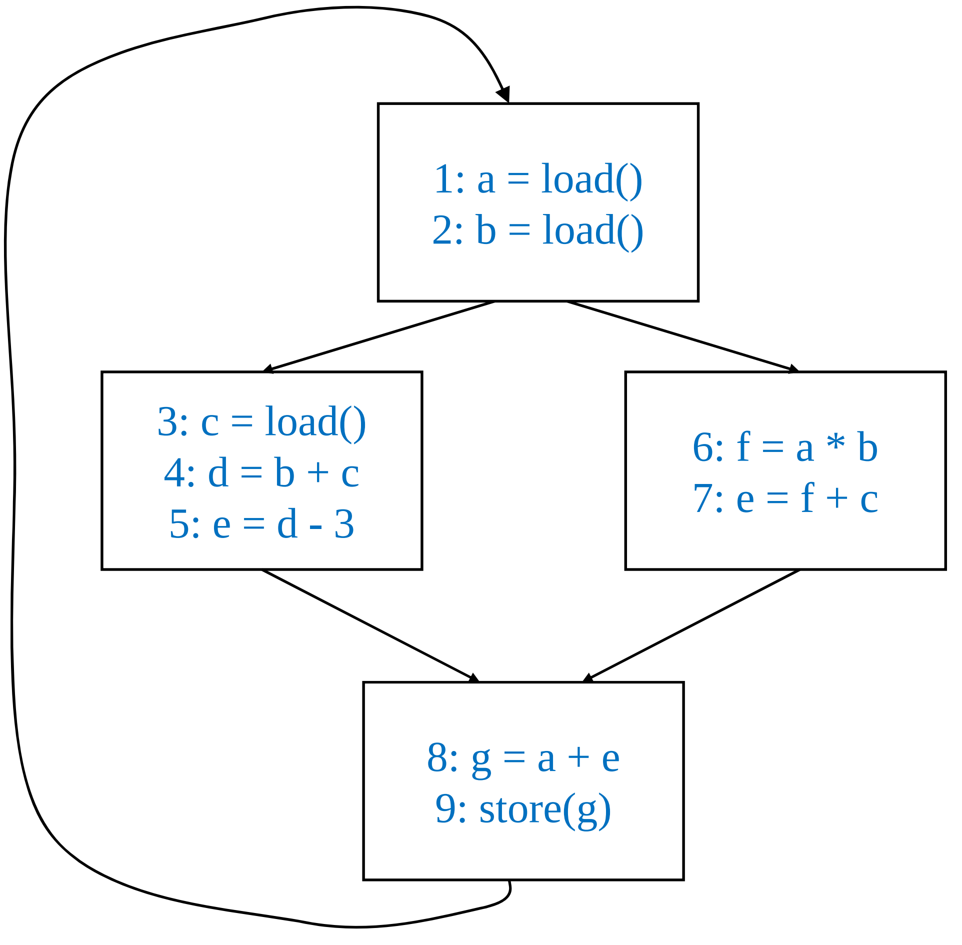
Compute the LRs

a) for each def
b) merge overlapping

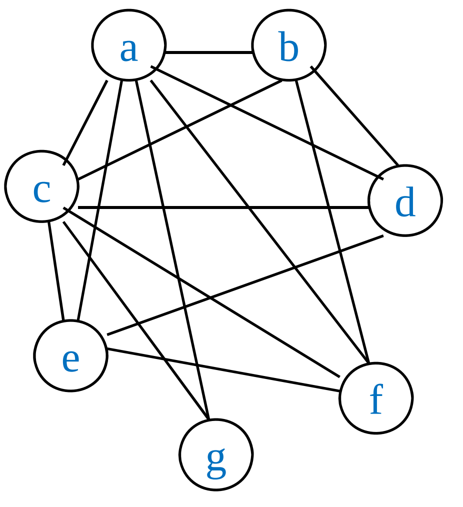
Interference

- Two live ranges interfere if they share one or more ops in common
  - Thus, they cannot occupy the same physical register
  - Or a live value would be lost
- Interference graph
  - Undirected graph where
    - Nodes are live ranges
    - There is an edge between 2 nodes if the live ranges interfere
  - What's not represented by this graph
    - Extent of interference between the LRs
    - Where in the program is the interference

Example – Interference Graph



lr(a) = {1,2,3,4,5,6,7,8}
lr(b) = {2,3,4,6}
lr(c) = {1,2,3,4,5,6,7,8,9}
lr(d) = {4,5}
lr(e) = {5,7,8}
lr(f) = {6,7}
lr{g} = {8,9}



Graph Coloring

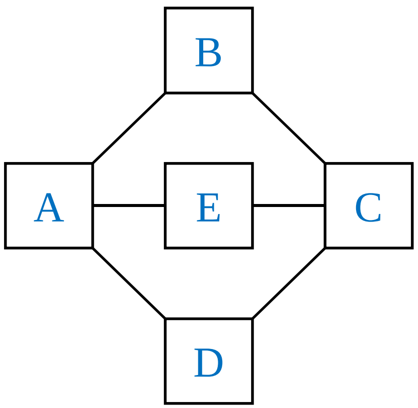
- A graph is n-colorable if every node in the graph can be colored with one of the n colors such that 2 adjacent nodes do not have the same color
  - Model register allocation as graph coloring
  - Use the fewest colors (physical registers)
  - Spilling is necessary if the graph is not n-colorable where n is the number of physical registers
- Optimal graph coloring is NP-complete for n > 2
  - Use heuristics proposed by compiler developers
    - "Register Allocation Via Coloring", G. Chaitin et al, 1981
    - "Improvement to Graph Coloring Register Allocation", P. Briggs et al, 1989
  - Observation – a node with degree < n in the interference can always be successfully colored given its neighbors colors

Coloring Algorithm

- 1. While any node, x, has < n neighbors
  - Remove x and its edges from the graph
  - Push x onto a stack
- 2. If the remaining graph is non-empty
  - Compute cost of spilling each node (live range)
    - For each reference to the register in the live range
      - Cost += (execution frequency * spill cost)
  - Let NB(x) = number of neighbors of x
  - Remove node x that has the smallest cost(x) / NB(x)
    - Push x onto a stack (mark as spilled)
  - Go back to step 1
- While stack is non-empty
  - Pop x from the stack
  - If x's neighbors are assigned fewer than R colors, then assign x any unsigned color, else leave x uncolored

Example – Finding Number of Needed Colors

How many colors are needed to color this graph?



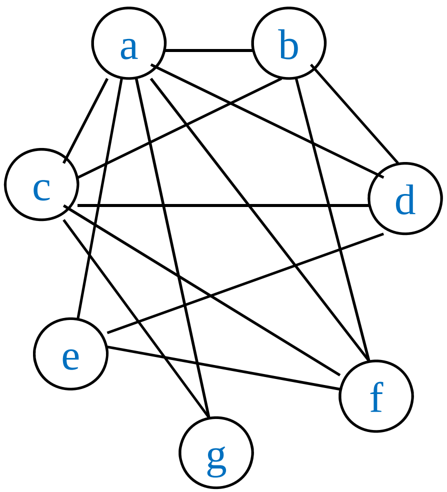
Try n=1, no, cannot remove any nodes

Try n=2, no again, cannot remove any nodes

Try n=3,

Remove B, D
Then can remove A, E, C
Thus it is 3-colorable

Example – Do a 3-Coloring



lr(a) = {1,2,3,4,5,6,7,8}
refs(a) = {1,6,8}
lr(b) = {2,3,4,6}
refs(b) = {2,4,6}
lr(c) = {1,2,3,4,5,6,7,8,9}
refs(c) = {3,4,7}
lr(d) = {4,5}
refs(d) = {4,5}
lr(e) = {5,7,8}
refs(e) = {5,7,8}
lr(f) = {6,7}
refs(f) = {6,7}
lr{g} = {8,9}
refs(g) = {8,9}

Profile freqs
1,2 = 100
3,4,5 = 75
6,7 = 25
8,9 = 100

Assume each spill requires 1 operation

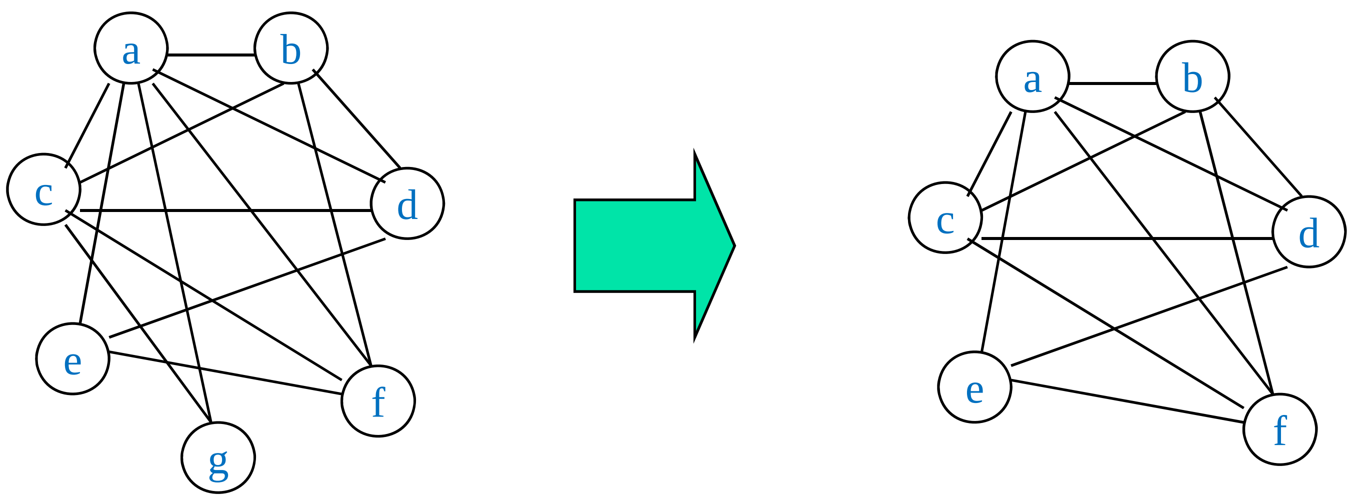
	a	b	c	d	e	f	g
cost	225	200	175	150	200	50	200
neighbors	6	4	5	4	3	4	2
cost/n	37.5	50	35	37.5	66.7	12.5	100

Example – Do a 3-Coloring (2)

Remove all nodes < 3 neighbors

So, g can be removed

<u>Stack</u>
g

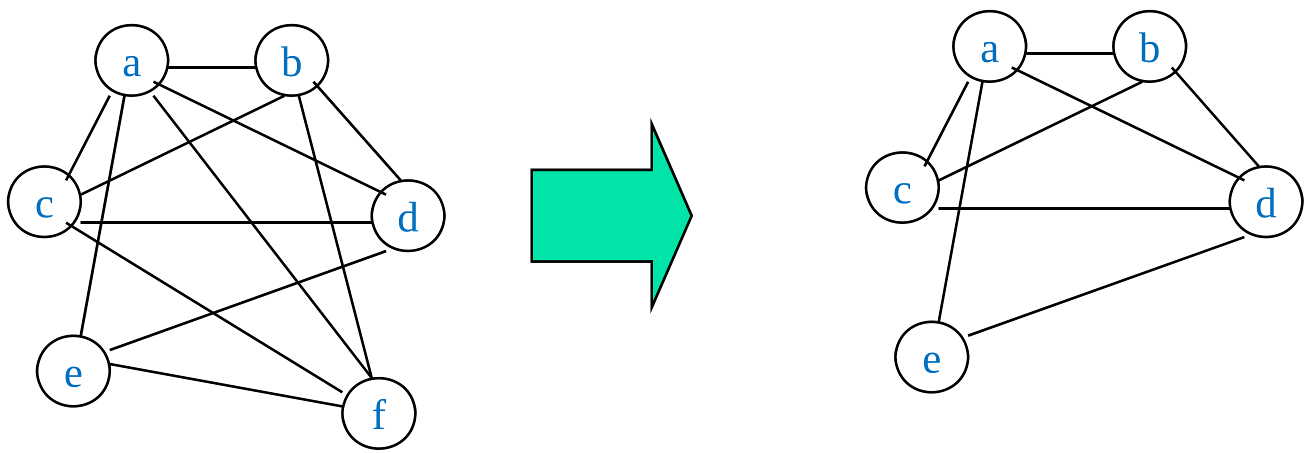


Example – Do a 3-Coloring (3)

Now must spill a node

Choose one with the smallest cost/NB → f is chosen

<u>Stack</u>
f (spilled)
g

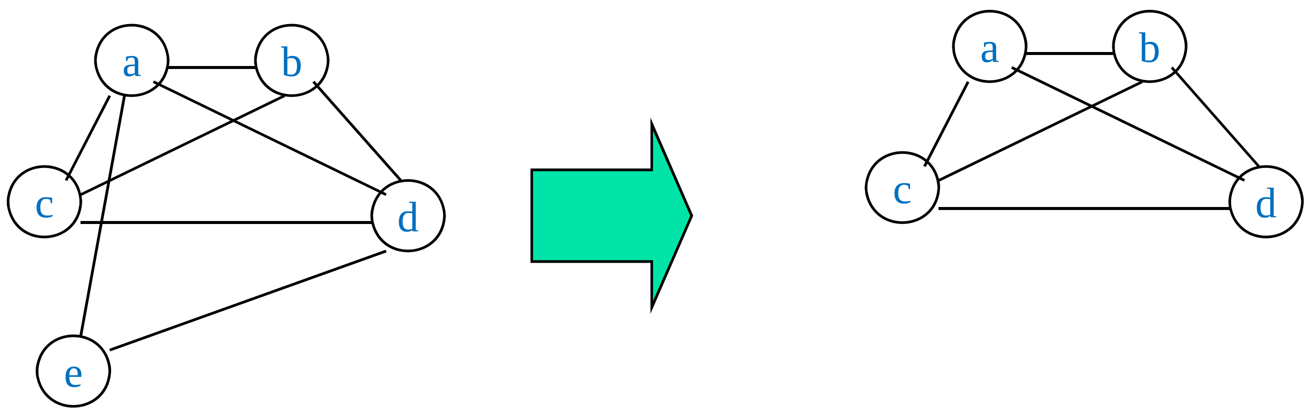


Example – Do a 3-Coloring (4)

Remove all nodes < 3 neighbors

So, e can be removed

Stack
e
f (spilled)
g

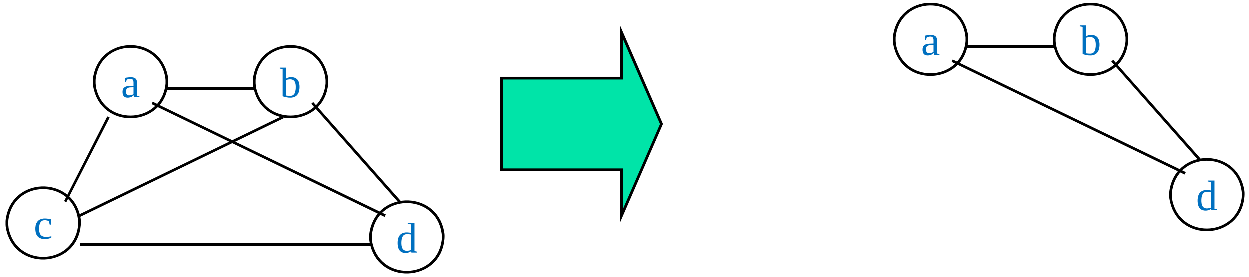


Example – Do a 3-Coloring (5)

Now must spill another node

Choose one with the smallest cost/NB → c is chosen

Stack
c (spilled)
e
f (spilled)
g

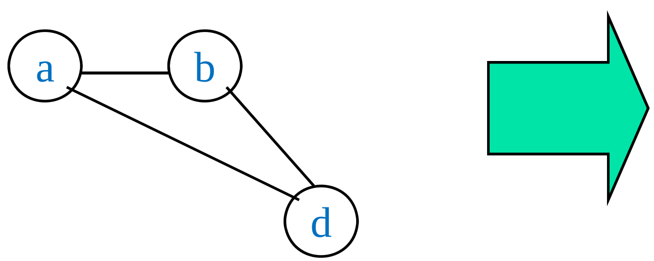


Example – Do a 3-Coloring (6)

Remove all nodes < 3 neighbors

So, a, b, d can be removed

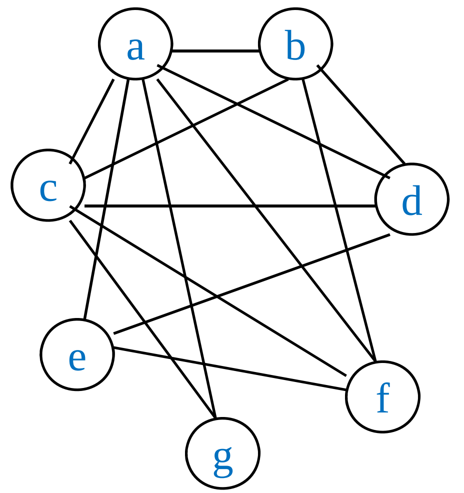
<u>Stack</u>
d
b
a
c (spilled)
e
f (spilled)
g



Null

Example – Do a 3-Coloring (7)

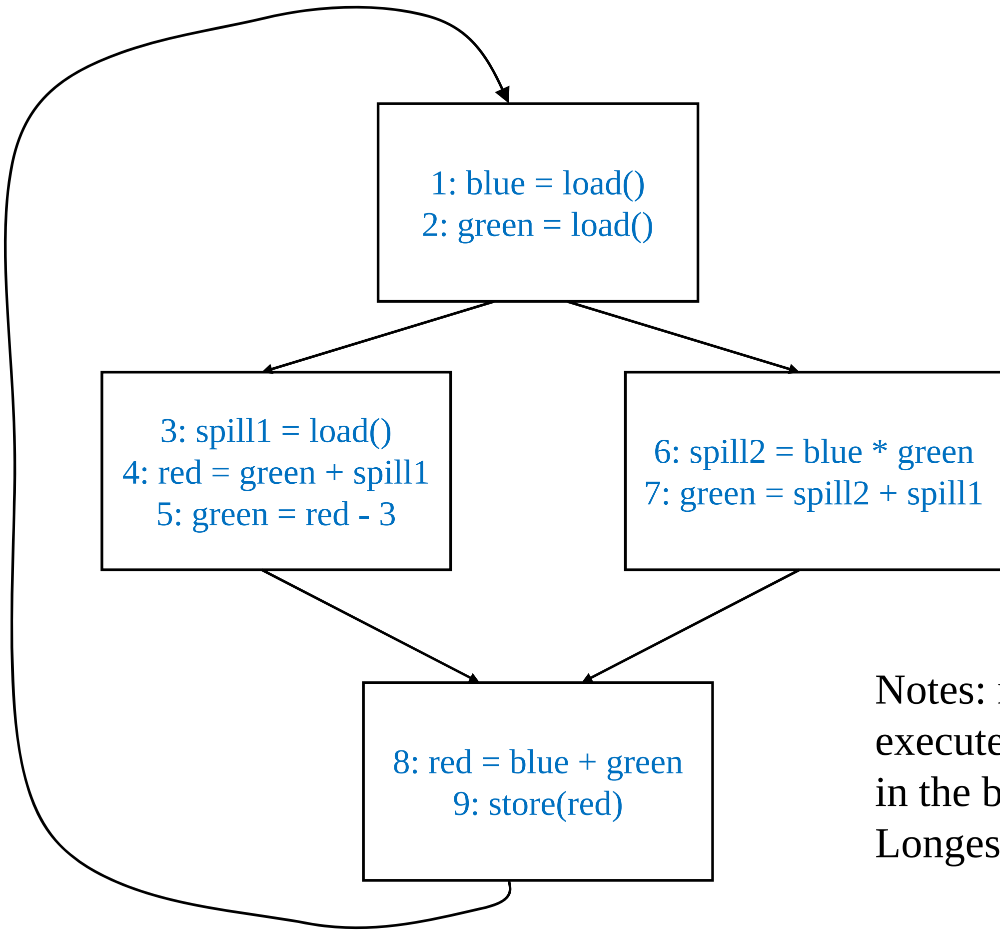
Stack
d
b
a
c (spilled)
e
f (spilled)
g



Have 3 colors: red, green, blue, pop off the stack assigning colors
only consider conflicts with non-spilled nodes already popped off stack

d → red
b → green (cannot choose red)
a → blue (cannot choose red or green)
c → no color (spilled)
e → green (cannot choose red or blue)
f → no color (spilled)
g → red (cannot choose blue)

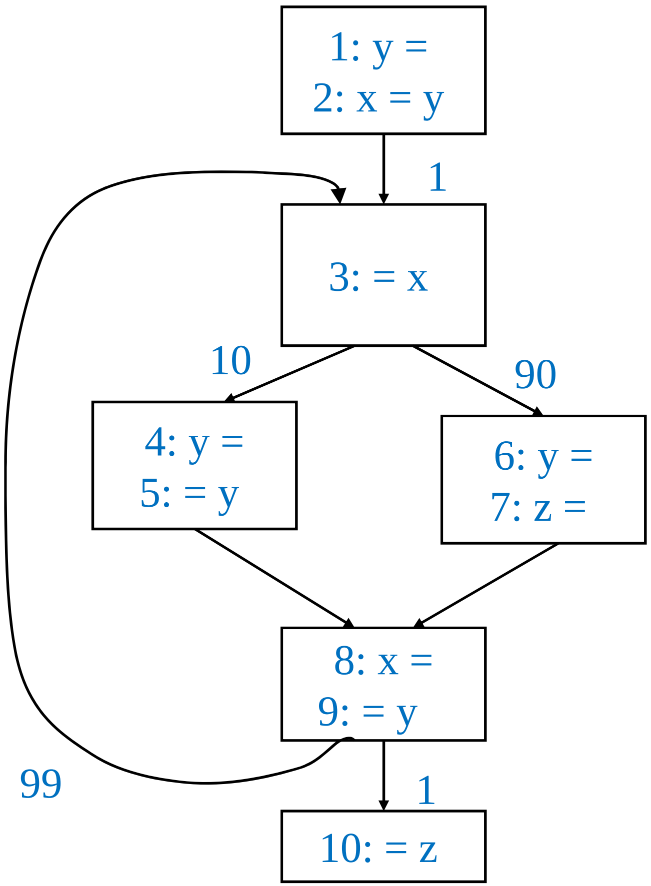
Example – Do a 3-Coloring (8)



d → red
b → green
a → blue
c → no color
e → green
f → no color
g → red

Notes: no spills in the blocks executed 100 times. Most spills in the block executed 25 times. Longest lifetime (c) also spilled

Class Problem



do a 2-coloring

- compute cost matrix
- draw interference graph
- color graph

Caller/Callee Save Preference

- Processors generally divide regs, ½ caller, ½ callee
  - Caller/callee save is a programming convention
  - Not part of architecture or microarchitecture
- When you are assigning colors, need to choose caller/callee
- Using a register may have save/restore overhead
  - Caller save/restore cost
    - For each BRL a live range spans
      - Cost += (save_cost + restore_cost) * brl_frequency
    - Variable not live across a BRL, has 0 caller cost
      - Leaf routines are ideal
  - Callee save/restore cost
    - Cost += (save_cost + restore_cost) * procedure_entry_freq
    - When BRLs are in the live range, callee usually better
  - Compare these costs with just spilling the variable
    - If cheaper to spill, then just spill it

Alternative Priority Schemes

- Chaitin priority
  - priority = spill cost / number of neighbors
- Hennessy and Chow
  - “The priority-based coloring approach to register allocation”, ACM TOPLAS 1990
  - priority = spill cost / size of live range
  - Intuition
    - Small live ranges with high spill cost are ideal candidates to be allocated a register
    - As the size of a live range grows, it becomes less attractive for register allocation
      - Ties up a register for a long time!

Live Range Splitting

- Rather than spill an entire live range that can't be colored
  - Split the live range into 2 or more smaller live ranges
  - Then recolor
  - Spill a subset of a live range
- Splitting a live range is a challenge
  - Many possibilities
  - Don't make the problem worse!
- Live range splitting (simple heuristic)
  - Given a live range, LR, that cannot be colored
  - Remove the first op in LR, put in new live range, LR'
  - Move successor ops from LR into LR' as long as LR' remains colorable
  - Single ops that cannot be colored are spilled

Rematerialization

- Some expressions are simple to recompute
  - Operands are constant
  - Operands available globally
    - sp/fp
  - Chaitin called these "never killed expressions"
- If registers holding these expressions are selected for spill
  - Rematerialize instead of spilling/reloading
  - Cheaper to just recompute

original	conventional	rematerialize
r1 = sp + 24 store(r1)	r1 = sp + 24 store(r1) spill r1	r1 = sp + 24 store(r1)
load(r1)	reload r1 load(r1)	r1 = sp + 24 load(r1)
store(r1)	reload r1 store(r1)	r1 = sp + 24 store(r1)
load(r1)	reload r1 load(r1)	r1 = sp + 24 load(r1)