Register Allocation

Register Allocation: Definition

- **Register allocation** assigns registers to values
  - Candidate values:
    - Variables
    - Temporaries
    - Large constants
  - When needed, **spill** registers to memory

- Important low-level optimization
  - Registers are 2x – 7x faster than cache
    - Judicious use **=** big performance improvements

Register Allocation: Complications

- *Explicit names*
  - Unlike all other levels of hierarchy
- *Scarce*
  - Small **register files** (set of all registers)
  - Some reserved by operating system, virtual machine
    - e.g., "FP", "SP"…
- *Complicated*
  - Weird constraints, esp. on CISC architectures
    - For example: Non-orthogonality of instructions

History

- As old as intermediate code
  - Used in the original FORTRAN compiler (1950's)
- No breakthroughs until 1981!
  - Chaitin invented register allocation scheme based on **graph coloring**
  - Simple heuristic, works well in practice

Register Allocation Example

- Consider this program with six variables:

  a := c + d
  e := a + b
  f := e - 1

  with the assumption that a and e die after use
  - Variable a can be "reused" after e := a + b
  - Same with variable e

- Can allocate a, e, and f all to one register (r_1):

  $r_1 := r_2 + r_3$
  $r_1 := r_1 + r_4$
  $r_1 := r_1 - 1$

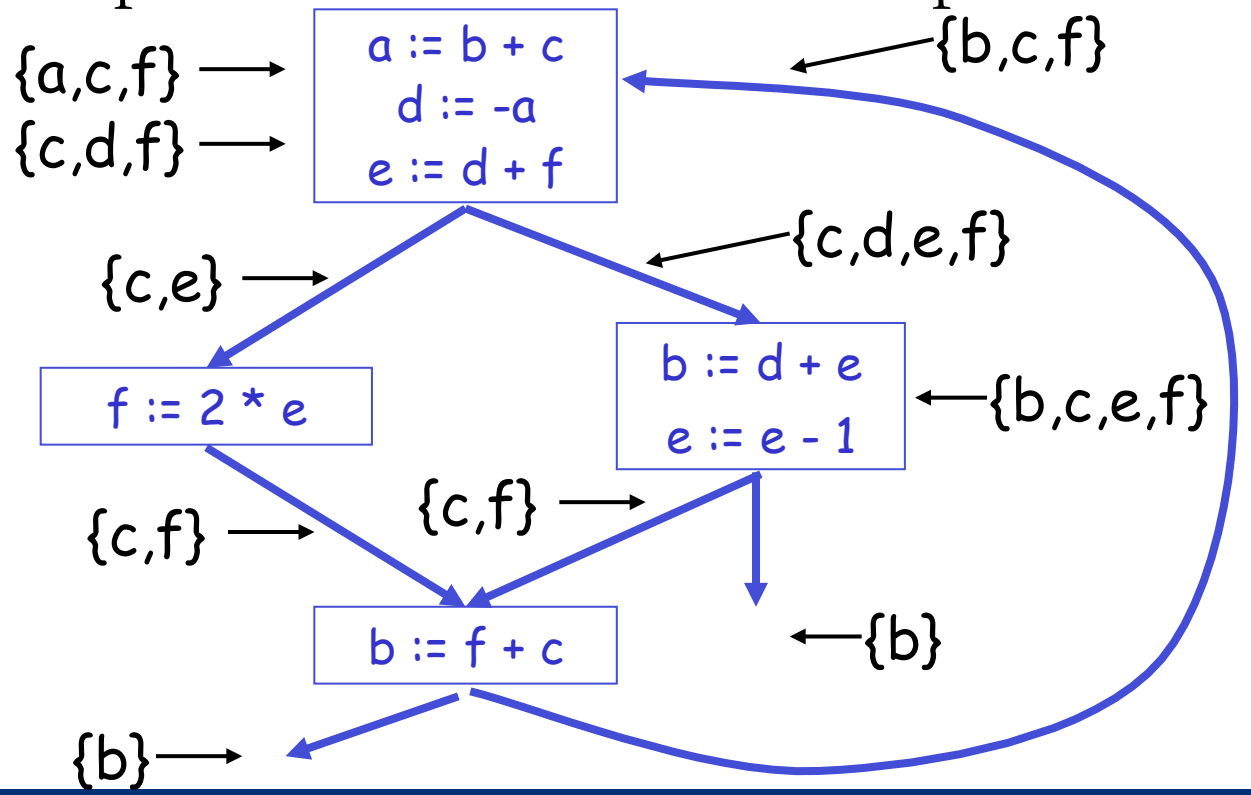
Basic Register Allocation Idea

- Value in dead variable not needed for rest of the computation
  - Register containing dead variable can be reused

- Basic rule:
  - Variables t_1 and t_2 can share same register if **at any point** in the program at most one of t_1 or t_2 is live !

Algorithm: Part I

- Compute live variables for each point:



Interference Graph

- Two variables live simultaneously
  - Cannot be allocated in the same register

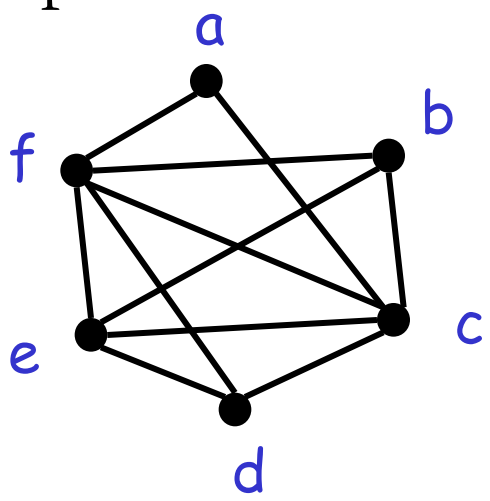
- Construct an **interference graph (IG)**
  - Node for each variable
  - Undirected edge between t_1 and t_2
    - If live simultaneously at some point in the program

- Two variables can be allocated to same register if no edge connects them

Interference Graph: Example

- For our example:

{b,c,f}
{a,c,f}
{c,d,f}
{c,d,e,f}
{c,e}
{b,c,e,f}
{c,f}
{b}



b and c **cannot** be in the same register

b and d **can** be in the same register

Graph Coloring

- **Graph coloring**:
  assignment of colors to nodes
  - Nodes connected by edge have different colors

- Graph **k-colorable** =
  can be colored with k colors

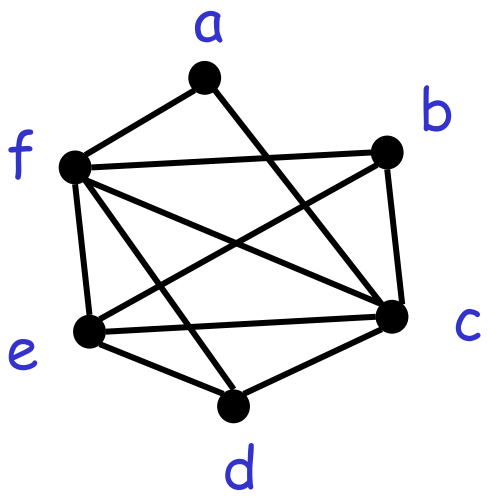
Register Allocation Through Graph Coloring

- In our problem, colors = registers
  - We need to assign colors (registers) to graph nodes (variables)
  - Let k = number of machine registers

- If the IG is k-colorable, there is a register assignment that uses no more than k registers

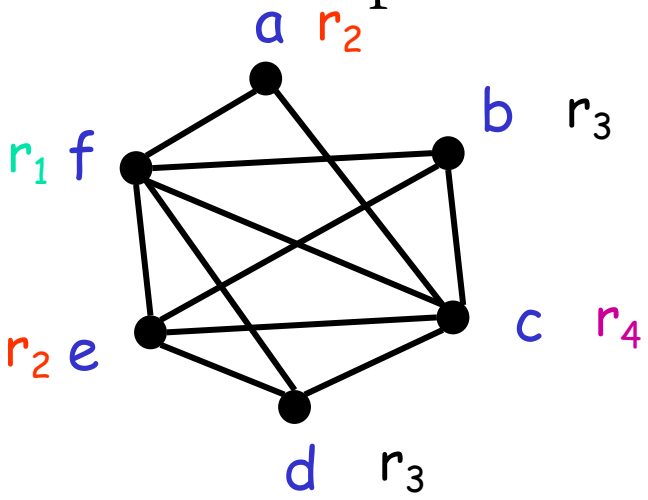
Color the following graph

- What is the smallest k needed to color the graph?



Graph Coloring Example

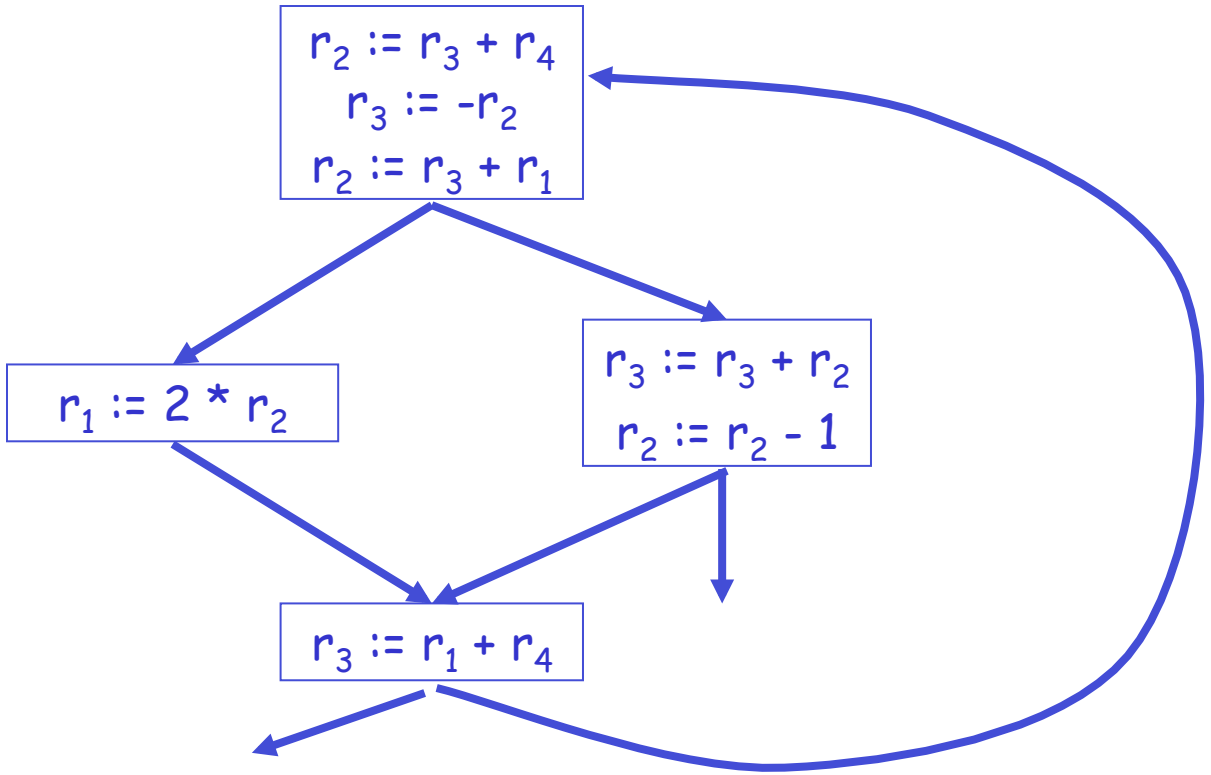
- Consider the example IG



There is no coloring with fewer than 4 colors
There are 4-colorings of this graph

Graph Coloring Example, Continued

- Under this coloring the code becomes:



Computing Graph Colorings

- How do we compute coloring for IG?
  - NP-hard!
  - For given # of registers, coloring may not exist
- Solution
  - Use heuristics

Graph Coloring Algorithm (Chaitin)

while G cannot be **k**-colored
  while graph G has node **N** with degree less than **k**
    Remove **N** and its edges from G and push **N** on a stack S
  end while
  if all nodes removed then graph is **k**-colorable
    while stack S contains node **N**
      Add **N** to graph G and assign it a color from **k** colors
    end while
  else graph G cannot be colored with **k** colors
    Simplify graph G choosing node **N** to spill and remove node
    (spill nodes chosen based number of definitions and uses)
end while

Graph Coloring Heuristic

- Observation: "degree < k rule"
  - Reduce graph:
    - Pick node N with < k neighbors in IG
    - Eliminate N and its edges from IG
  - If the resulting graph has k-coloring, so does the original graph

- Why?
  - Let $c_1,\ldots,c_n$ be colors assigned to neighbors of t in reduced graph
  - Since n < k, we can pick some color for t different from those of its neighbors

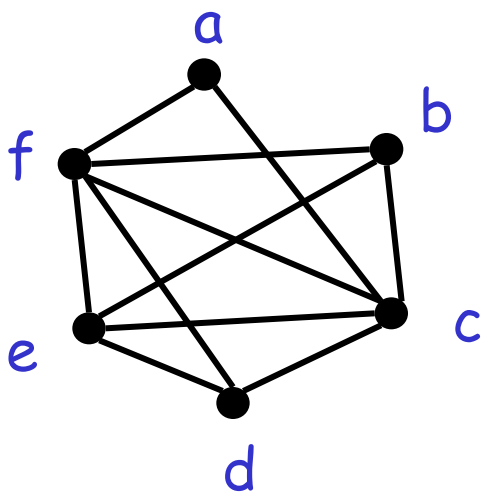
Graph Coloring Heuristic (cont'd)

- Heuristic:
  - Pick node t with fewer than k neighbors
  - Put t on a stack and remove it from the IG
  - Repeat until all nodes have been removed

- Start assigning colors to nodes on the stack (starting with the last node added)
  - At each step, pick color different from those assigned to already-colored neighbors

Graph Coloring Example (1)

- Start with the IG and with **k = 4**
- Try 4-coloring the graph

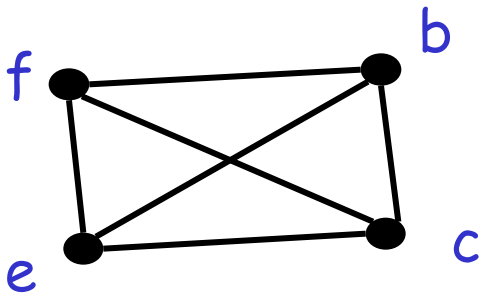


Stack: {}

- Remove a and then d

Graph Coloring Example (2)

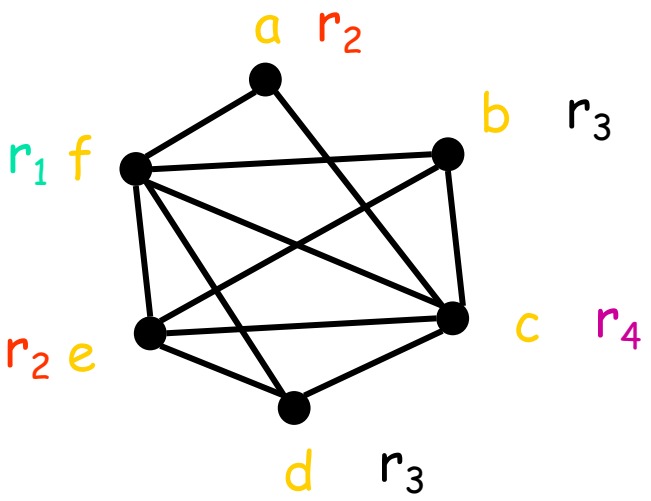
- Now all nodes have fewer than 4 neighbors and can be removed: c, b, e, f



Stack: {d, a}

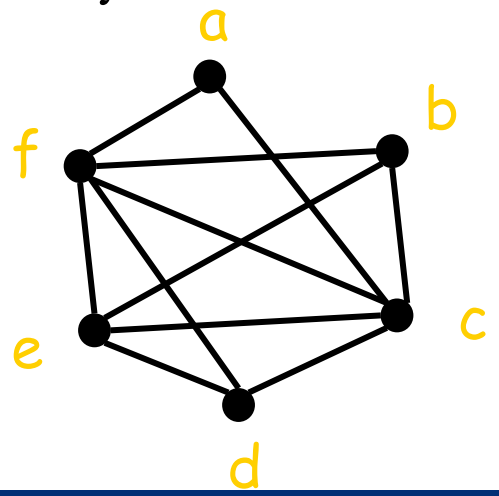
Graph Coloring Example (2)

- Start assigning colors to: f, e, b, c, d, a



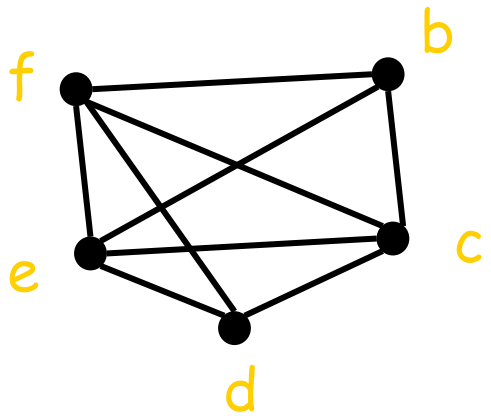
What if the Heuristic Fails?

- What if during simplification we get to a state where all nodes have k or more neighbors?
- Example: try to find a 3-coloring of the IG:



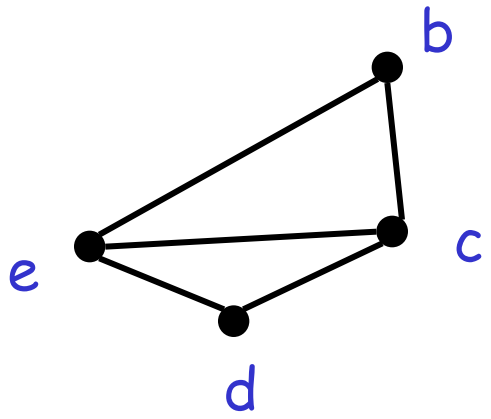
What if the Heuristic Fails?

- Remove a and get stuck (as shown below)
  - Pick a node as a candidate for spilling
  - Assume that f is picked



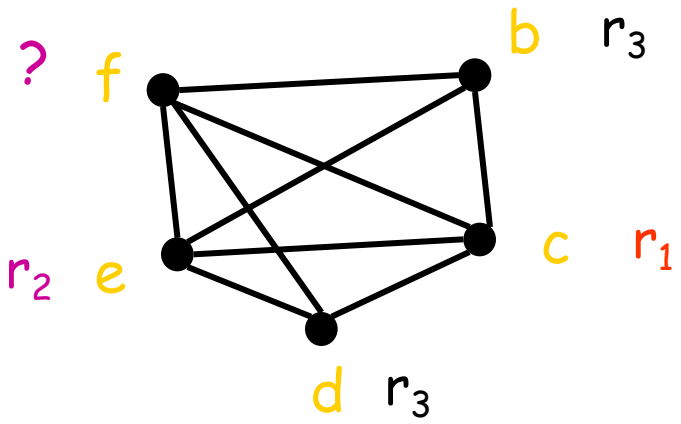
What if the Heuristic Fails?

- Remove f and continue the simplification
  - Simplification now succeeds: b, d, e, c



What if the Heuristic Fails?

- During assignment phase, we get to the point when we have to assign a color to f
- Hope: among the 4 neighbors of f,
  we use less than 3 colors ⇒ **optimistic coloring**



Spilling

- Optimistic coloring failed = must spill variable f
- Allocate memory location as home of f
  - Typically in current stack frame
  - Call this address fa

- Before each operation that uses f, insert

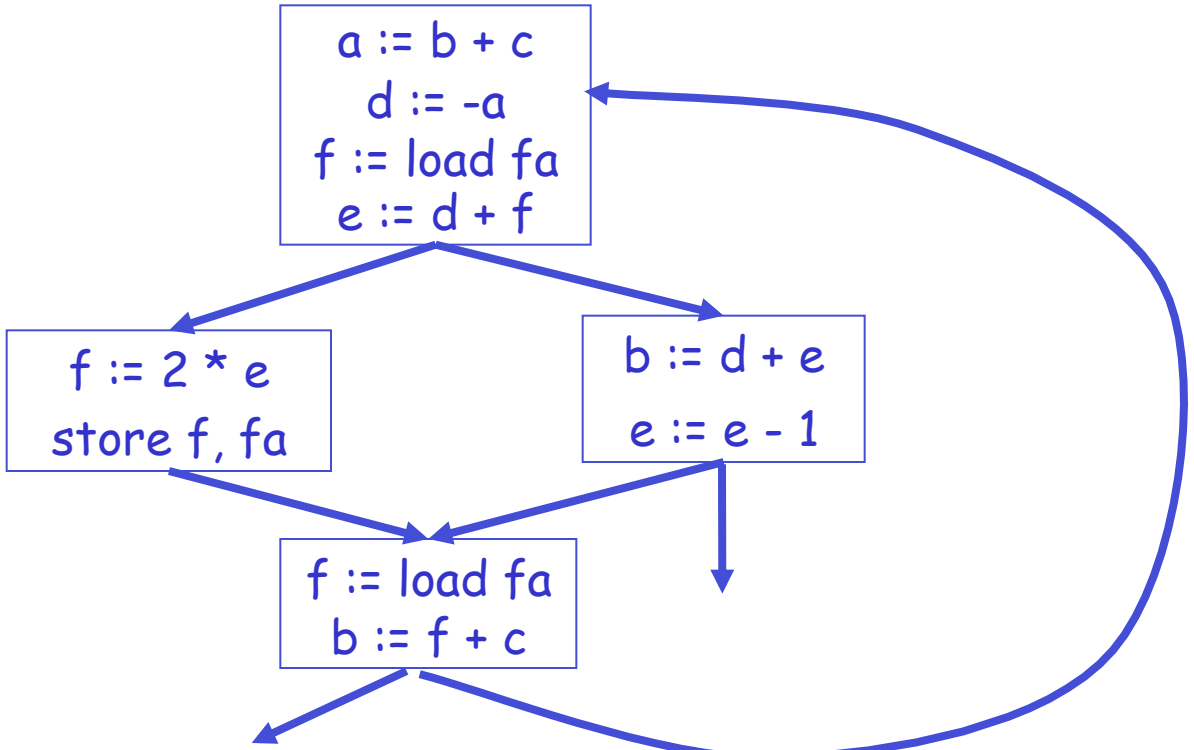
  f := load fa

- After each operation that defines f, insert

  store f, fa

Spilling Example

- New code after spilling f



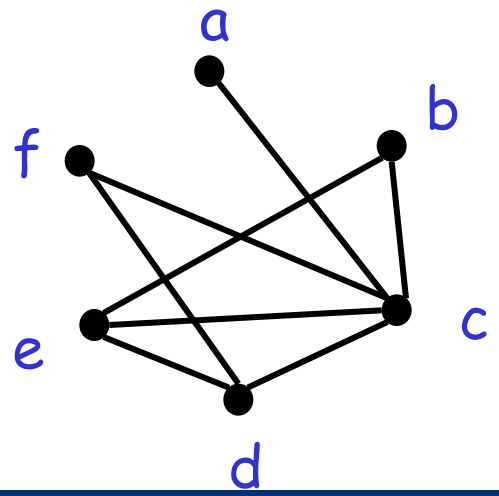
Recomputing Liveness Information

- New liveness info almost as before, but:
  f is live only
  - Between f := load fa and the next instruction
  - Between store f, fa and the preceding instruction

- Spilling reduces the live range of f
  - Reduces its interferences
  - Results in fewer neighbors in IG for f

Recompute IG After Spilling

- Remove some edges of spilled node
- Here, f still interferes only with c and d
  - Resulting IG is 3-colorable



Spilling, Continued

- Additional spills might be required before coloring is found

- Tricky part: deciding what to spill
  - Possible heuristics:
    - Spill variables with most conflicts
    - Spill variables with few definitions and uses
    - Avoid spilling in inner loops
  - All are "correct"

Conclusion

- Register allocation: "must have" optimization in most compilers:
  - Intermediate code uses too many temporaries
  - Makes a big difference in performance
- Graph coloring:
  - Powerful register allocation scheme

Recomputing Liveness Information

- New liveness information after spilling: