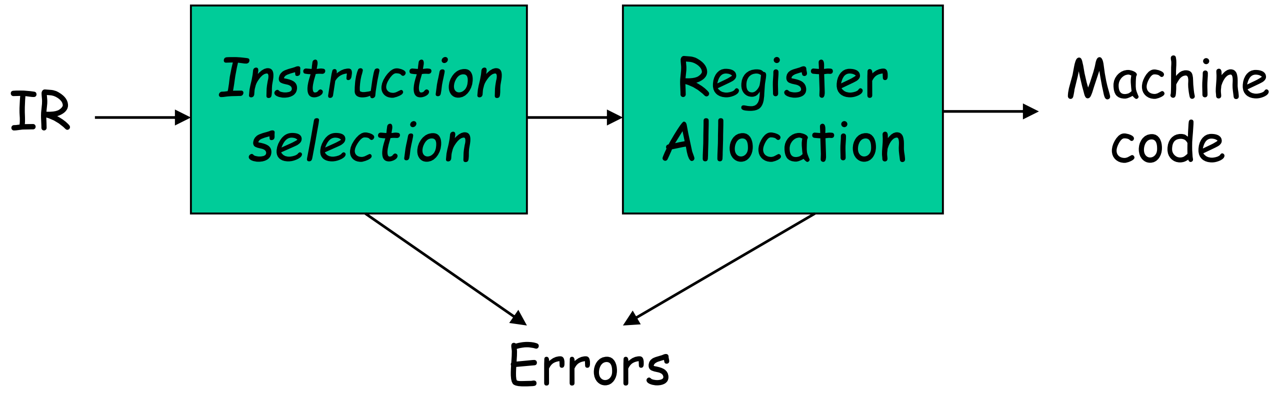
40-414 Compiler Design

Register Allocation

Lecture 13

Back-End (Revisited)



Back-End:

- Translate IR into machine code
- Choose instructions for each IR operation
- Decide what to keep in registers at each point

The Register Allocation Problem

- Intermediate code uses unlimited temporaries
  - Simplifies code generation and optimization
  - Complicates final translation to assembly

- Typical intermediate code uses too many temporaries

The Register Allocation Problem (Cont.)

- The problem:

  Rewrite the intermediate code to use no more temporaries than there are machine registers

- Method:
  - Assign multiple temporaries to each register
  - But without changing the program behavior

Many temps to one →

An Example

- Consider the program

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

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

Many to one mapping →

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

- Assume a and e dead after use
  - Temporary a can be "reused" after $e := a + b$
  - So can temporary e

- A dead temporary is not needed
  - A dead temporary can be reused

History

- Register allocation is as old as compilers
  - Register allocation was used in the original FORTRAN compiler in the '50s
  - Very crude algorithms

- A breakthrough came in 1980
  - Register allocation scheme based on graph coloring
  - Relatively simple, global and works well in practice

The Idea

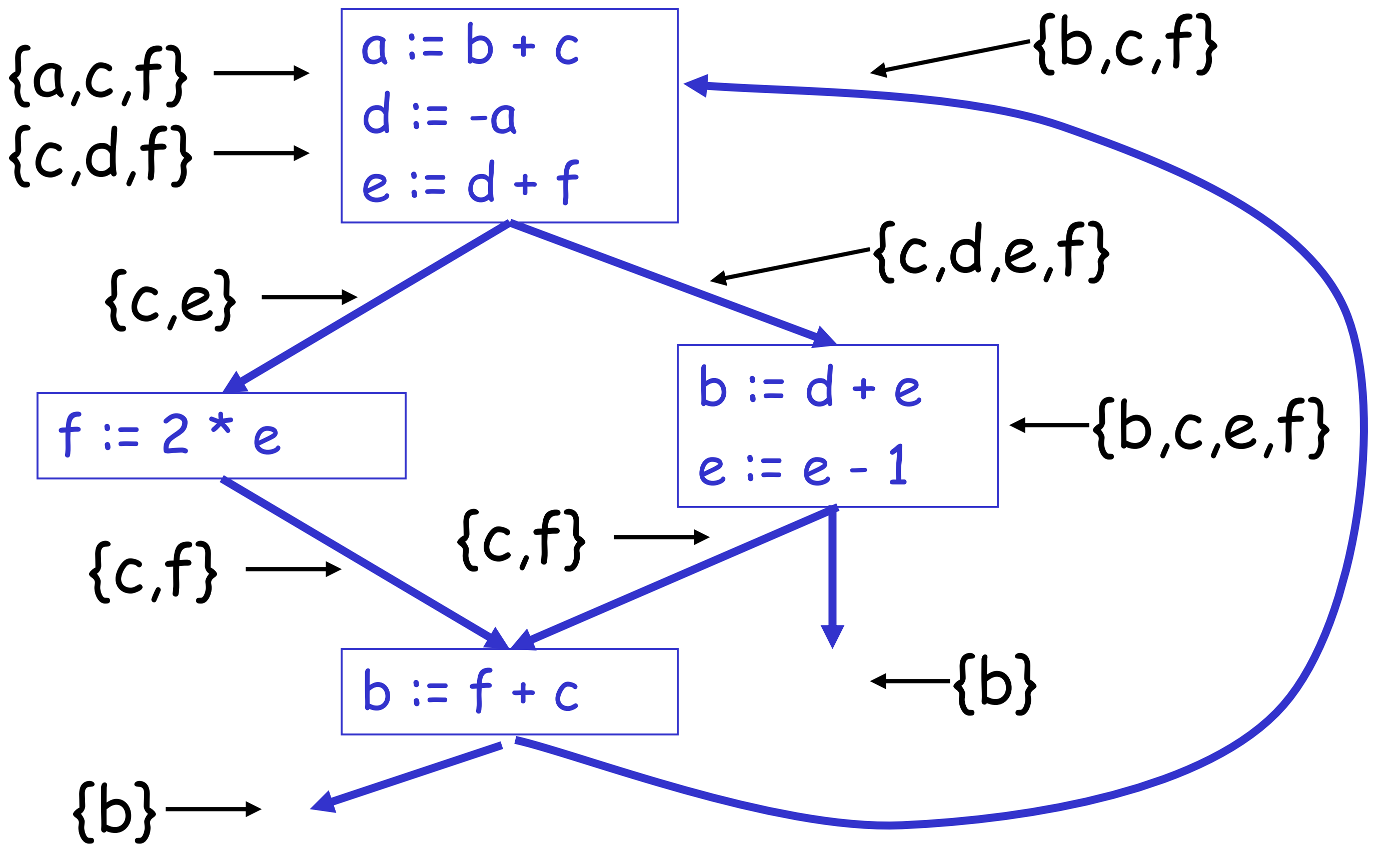
Temporaries t_1 and t_2 can share the same register if <u>at any point in the program at most one</u> of t_1 or t_2 is live .

Or

If t_1 and t_2 are live at the same time, they cannot share a register

Algorithm: Part I

- Compute live variables for each point:



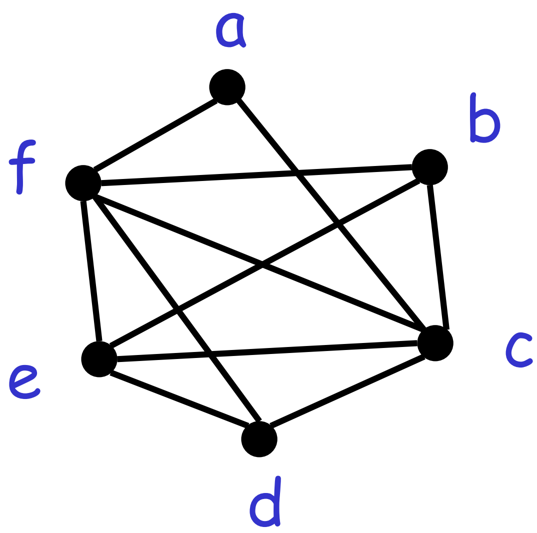
The Register Interference Graph

- Construct an undirected graph
  - A node for each temporary
  - An edge between t_1 and t_2 if they are live simultaneously at some point in the program

- This is the *register interference graph* (RIG)
  - Two temporaries can be allocated to the same register if there is no edge connecting them

Example

- For our example:



- E.g., b and c cannot be in the same register
- E.g., b and d could be in the same register

Notes on Register Interference Graphs

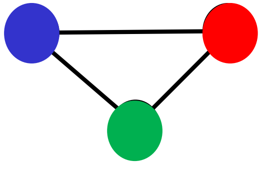
- Extracts exactly the information needed to characterize legal register assignments

- Gives a global (i.e., over the entire flow graph) picture of the register requirements

- After RIG construction the register allocation algorithm is architecture independent
  - It does not depend on any property of the machine except for the number of registers

Definitions

- A coloring of a graph is an assignment of colors to nodes, such that nodes connected by an edge have different colors



- A graph is k-colorable if it has a coloring with k colors

Register Allocation Through Graph Coloring

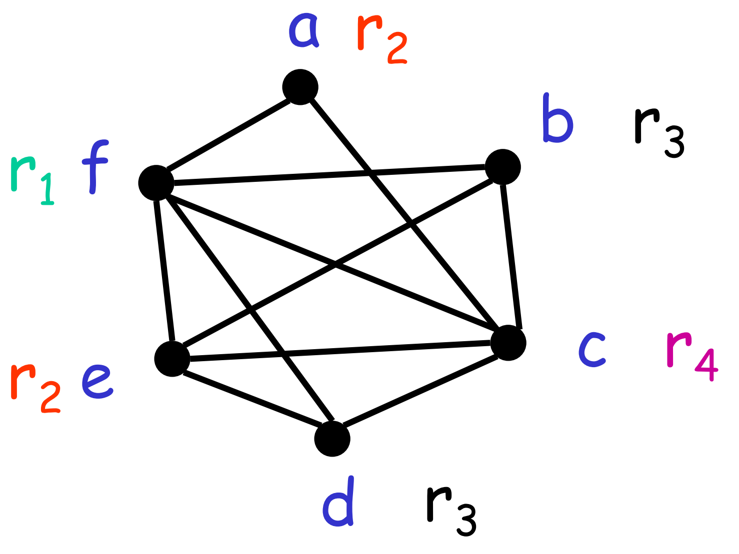
- In our problem, colors = registers
  - We need to assign colors (registers) to graph nodes (temporaries)

- Let k = number of machine registers

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

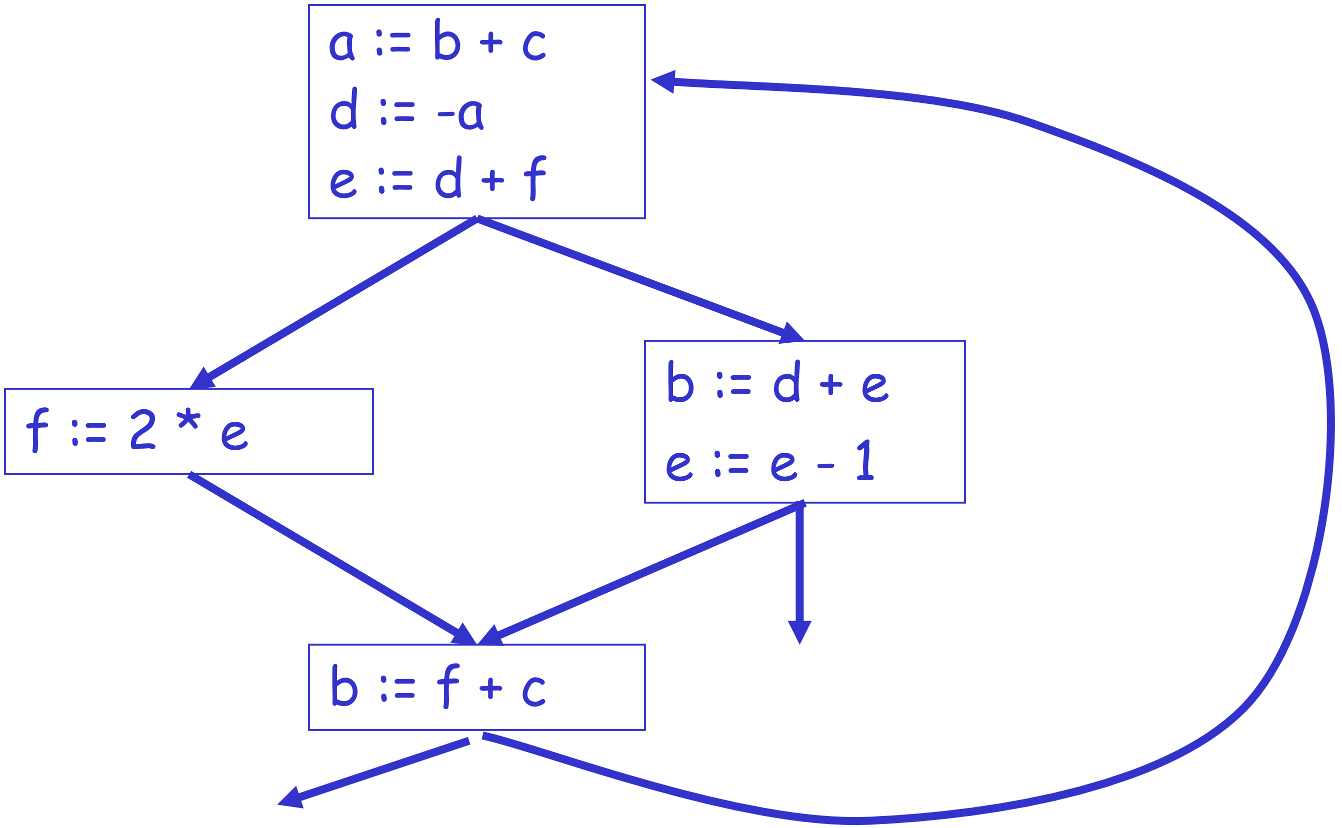
Graph Coloring Example

- Consider the example RIG



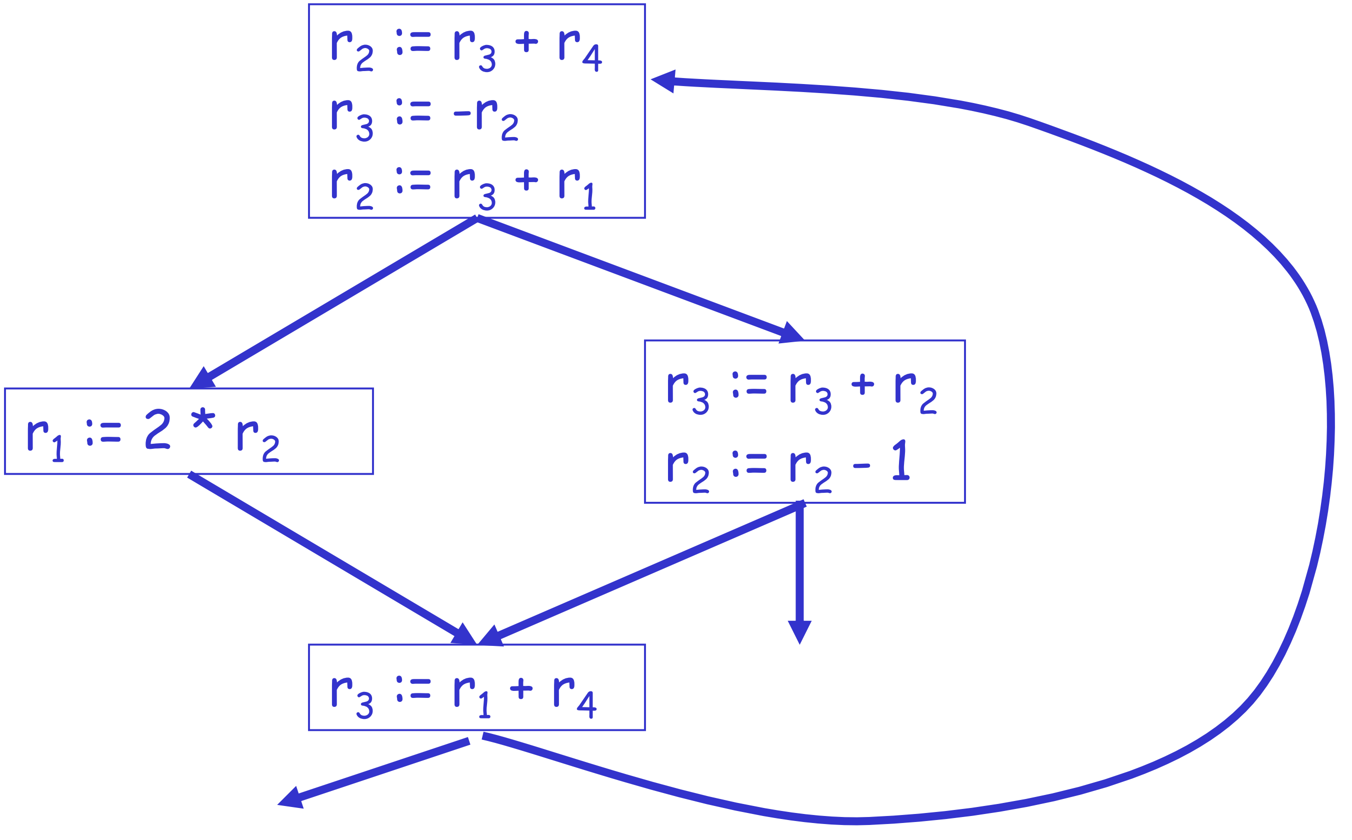
- There is no coloring with less than 4 colors
- There are 4-colorings of this graph

Example Review



Example After Register Allocation

- Under this coloring the code becomes:



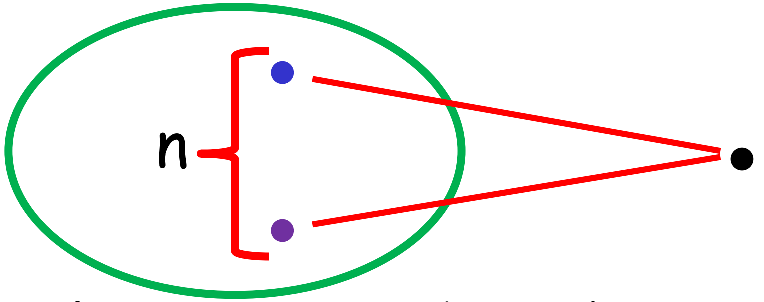
Computing Graph Colorings

- How do we compute graph colorings?

- It isn't easy:
  1. This problem is very hard (NP-hard). No efficient algorithms are known.
     - *Solution: use heuristics*
  2. A coloring might not exist for a given number of registers
     - *Solution: later*

Graph Coloring Heuristic

- Observation:
  - Pick a node t with fewer than k neighbors in RIG
  - Eliminate t and its edges from RIG
  - If resulting graph is k-colorable, then so is the original graph



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

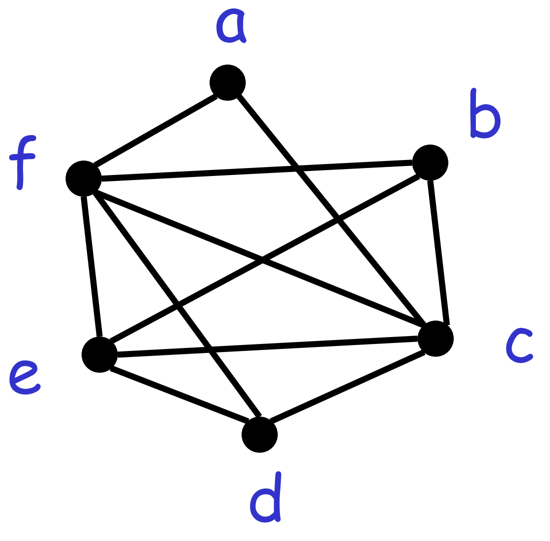
Graph Coloring Heuristic

1. The following works well in practice:
   - Pick a node t with fewer than k neighbors
   - Put t on a stack and remove it from the RIG
   - Repeat until the graph has one node

2. Assign colors to nodes on the stack
   - Start with the last node added
   - At each step pick a color different from those assigned to already colored neighbors

Graph Coloring Example (1)

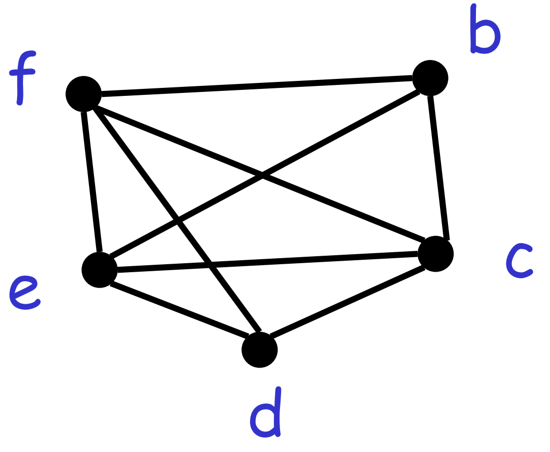
- Start with the RIG and with k = 4:



Stack: {}

- Remove a

Graph Coloring Example (2)

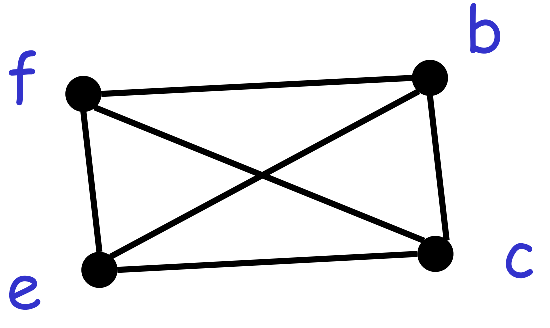


Stack: {a}

- Remove d

Graph Coloring Example (3)

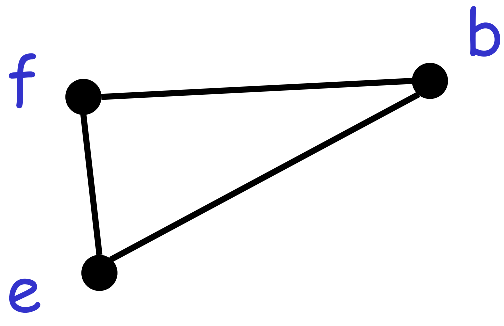
- Note: all nodes now have fewer than 4 neighbors



Stack: {d, a}

- Remove c

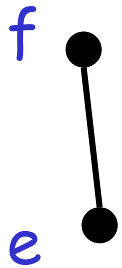
Graph Coloring Example (4)



Stack: {c, d, a}

- Remove b

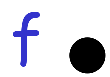
Graph Coloring Example (5)



Stack: {b, c, d, a}

- Remove e

Graph Coloring Example (6)



Stack: {e, b, c, d, a}

- Remove f

Graph Coloring Example (7)

- Empty graph - done with the first part!

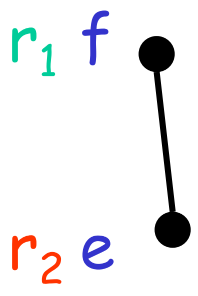
Stack: {f, e, b, c, d, a}

- Now start assigning colors to nodes, starting with the top of the stack

Graph Coloring Example (8)

Stack: {e, b, c, d, a}

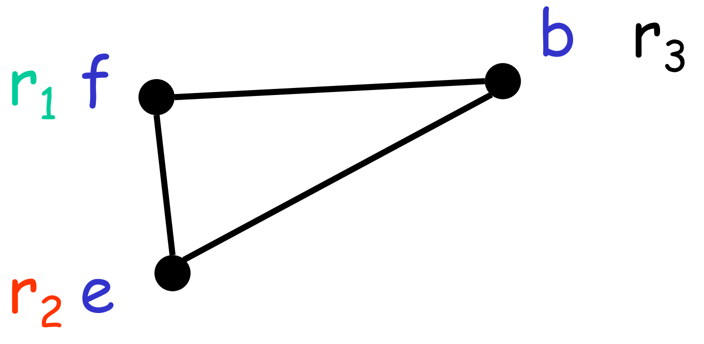
Graph Coloring Example (9)



Stack: {b, c, d, a}

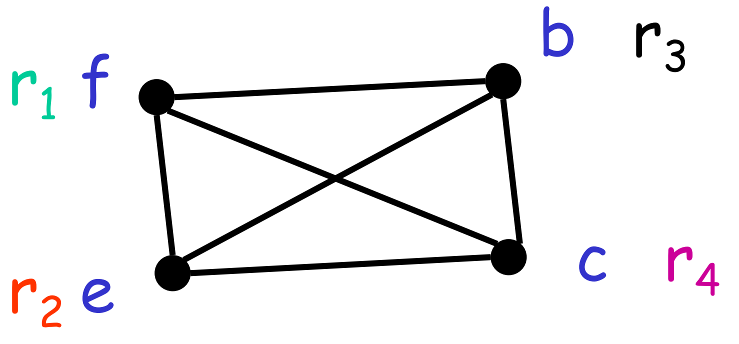
- e must be in a different register from f

Graph Coloring Example (10)



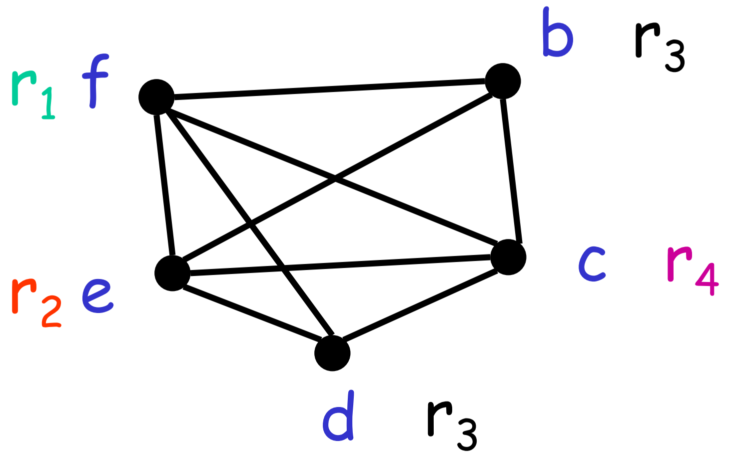
Stack: {c, d, a}

Graph Coloring Example (11)



Stack: {d, a}

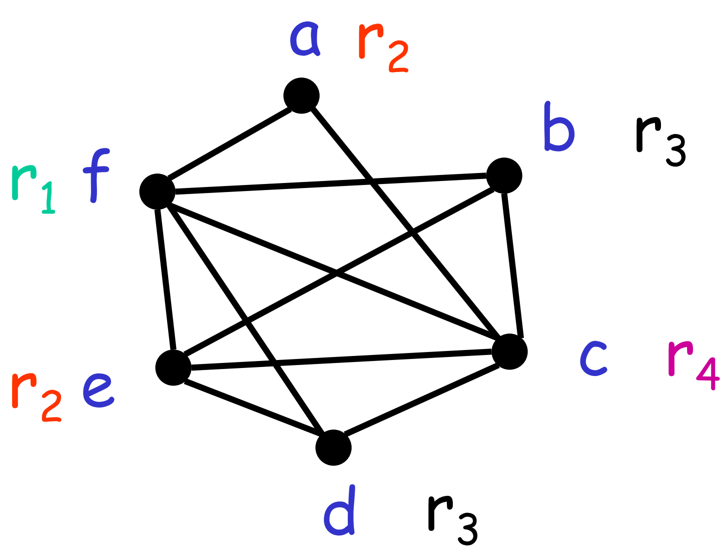
Graph Coloring Example (12)



Stack: {a}

- d can be in the same register as b

Graph Coloring Example (13)



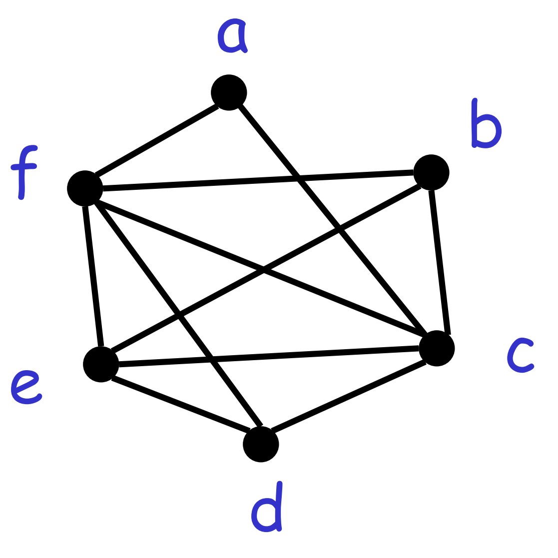
What if the Heuristic Fails?

- *What happens if the graph coloring heuristic fails to find a coloring?*

- *In this case, we can't hold all values in registers.*
  - *Some values are spilled to memory*

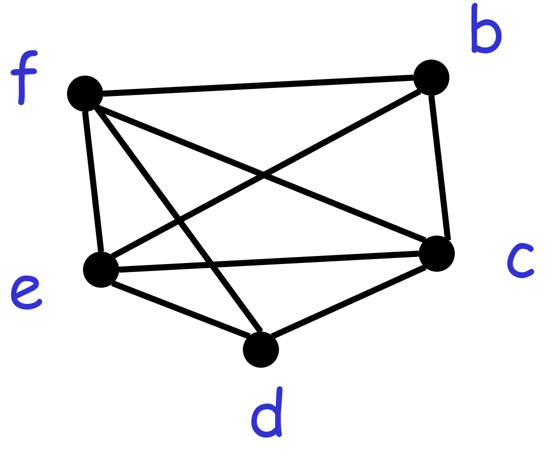
What if the Heuristic Fails?

- What if all nodes have k or more neighbors ?
- Example: Try to find a 3-coloring of the RIG:



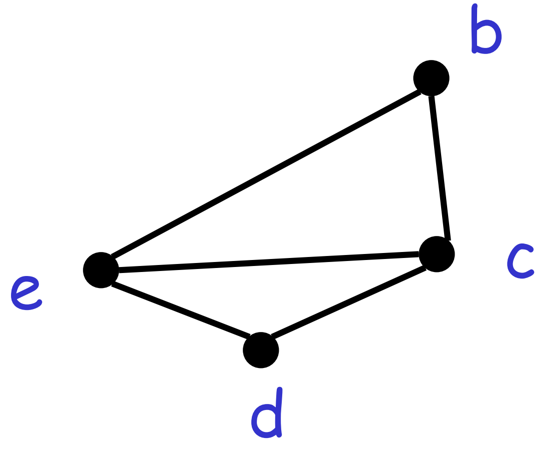
What if the Heuristic Fails?

- Remove a and *get* stuck (as shown below)
  - There is no node with fewer than 3 neighbors
- Pick a node as a candidate for *spilling*
  - A spilled temporary "lives" in memory
  - Assume that f is picked as a candidate



What if the Heuristic Fails?

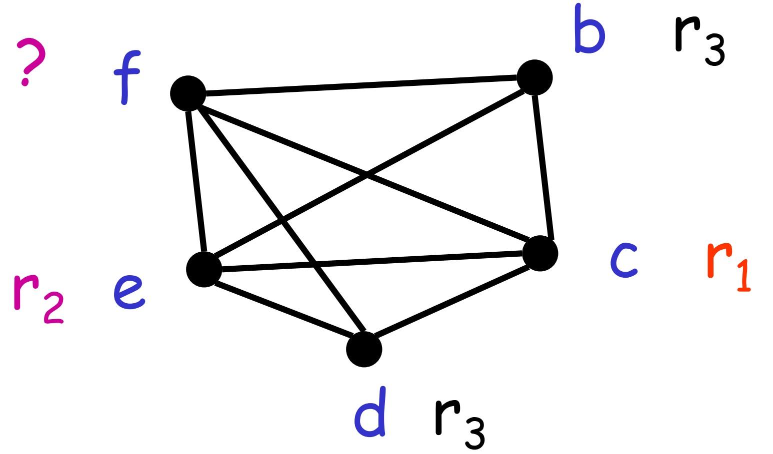
- Remove f and continue the simplification
  - Simplification now succeeds: b, d, e, c



What if the Heuristic Fails?

- Eventually we must assign a color to f
- We hope that among the 4 neighbors of f we use less than 3 colors ⇒ optimistic coloring

In this ex., it doesn't work



Spilling

- If optimistic coloring fails, we spill f
  - Allocate a memory location for f
    - Typically in the current stack frame
    - Call this address fa

- Before each operation that reads f, insert

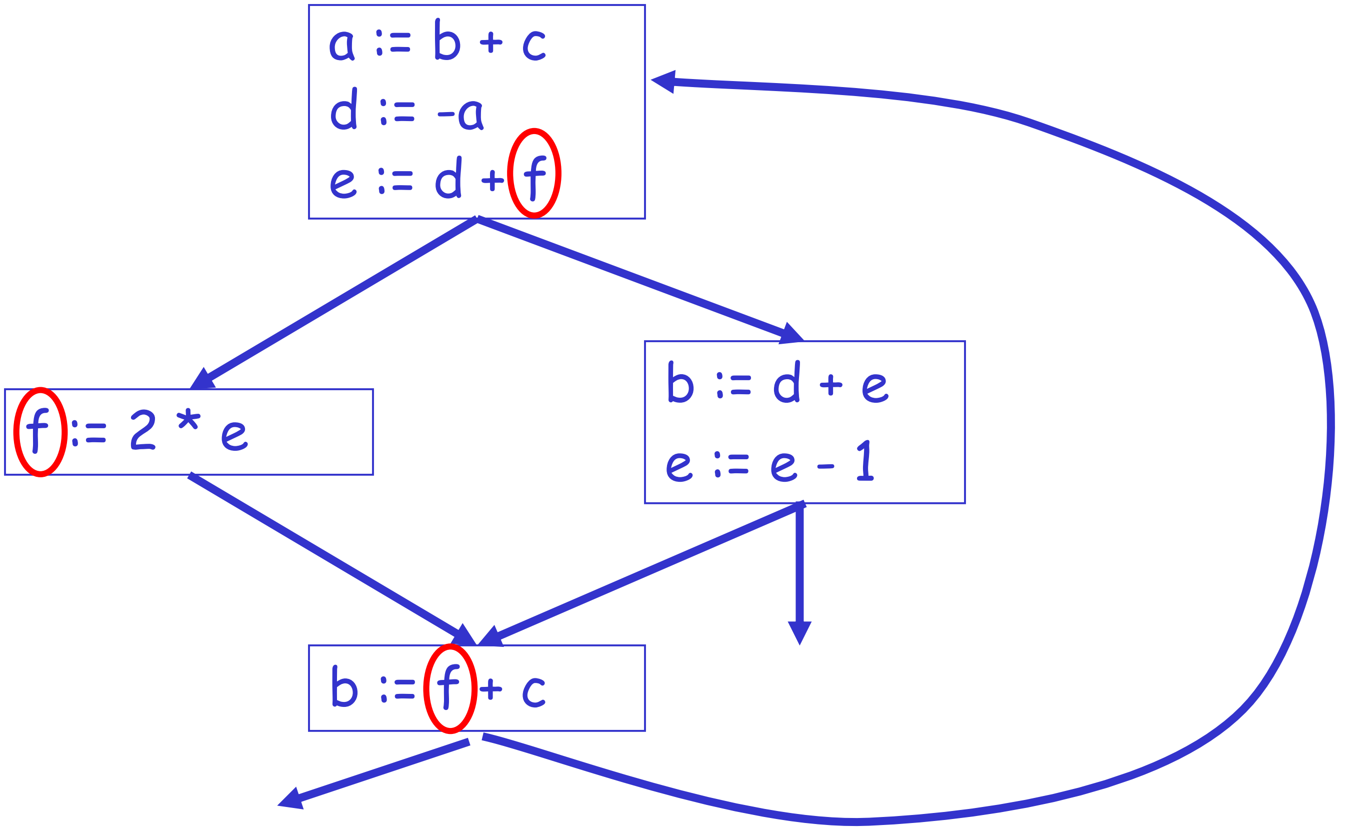
  f := load fa

- After each operation that writes f, insert

  store f, fa

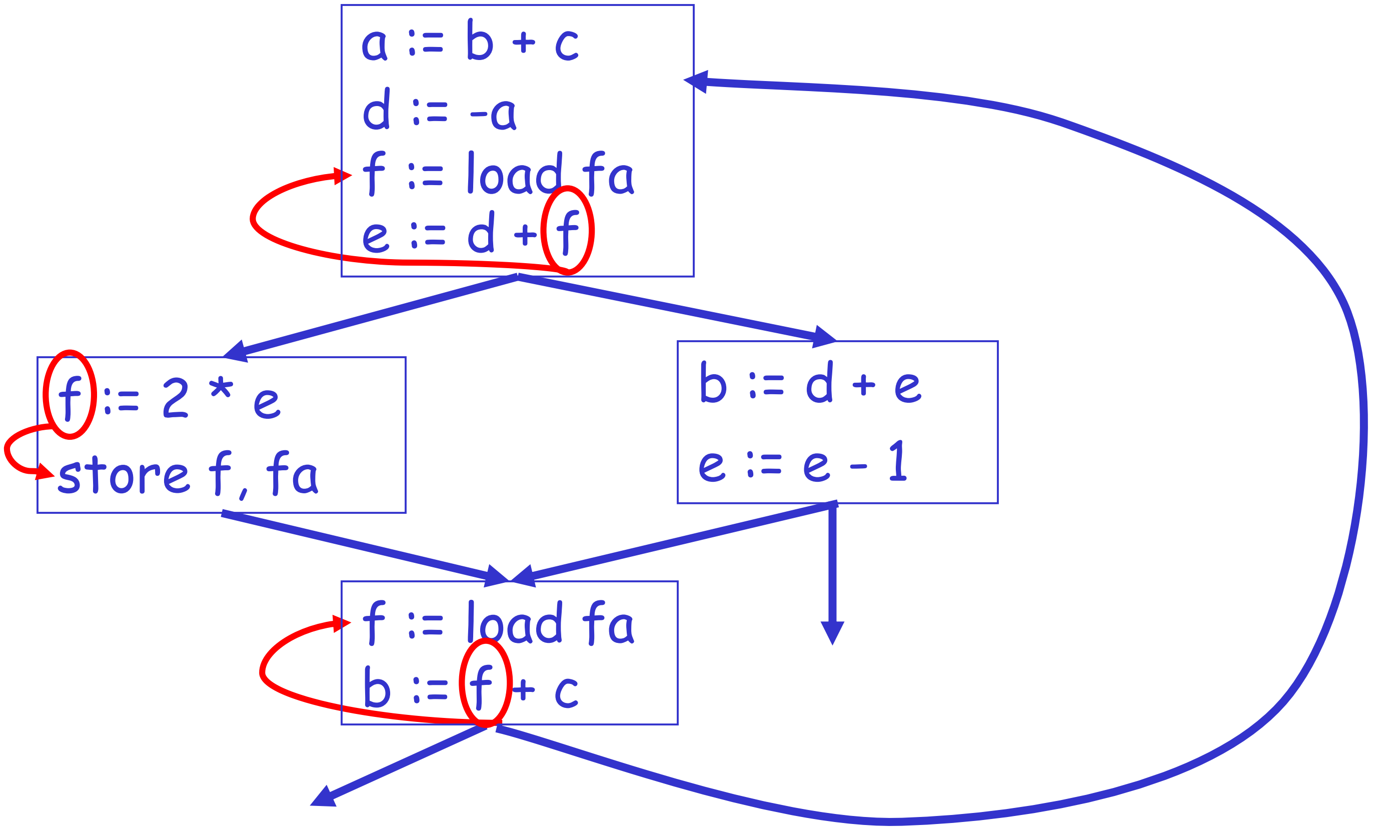
Spilling Example

- Original code



Spilling Example

- This is the new code after spilling f

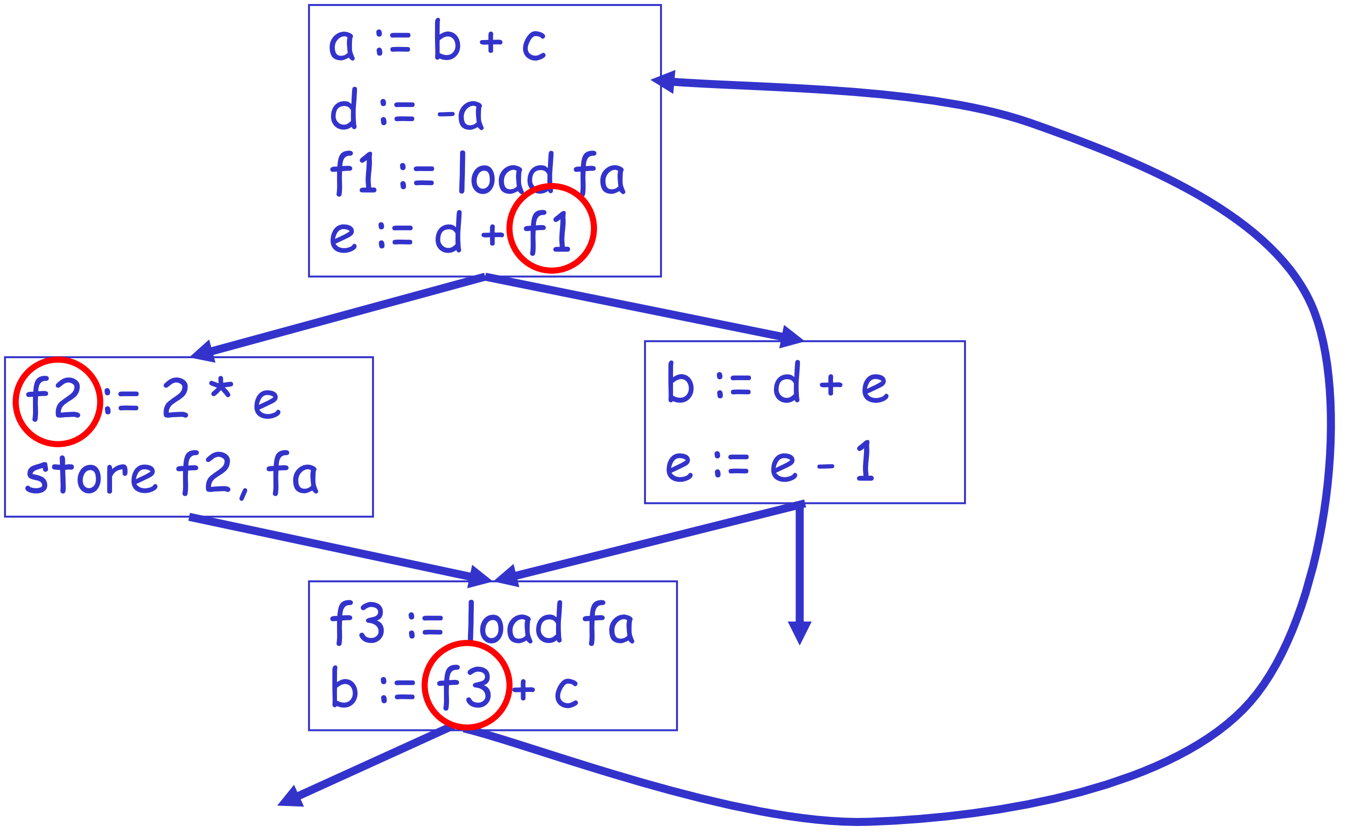


A Problem

- This code reuses the register name f
- Correct, but suboptimal
  - Should use distinct register names whenever possible
  - Allows different uses to have different colors

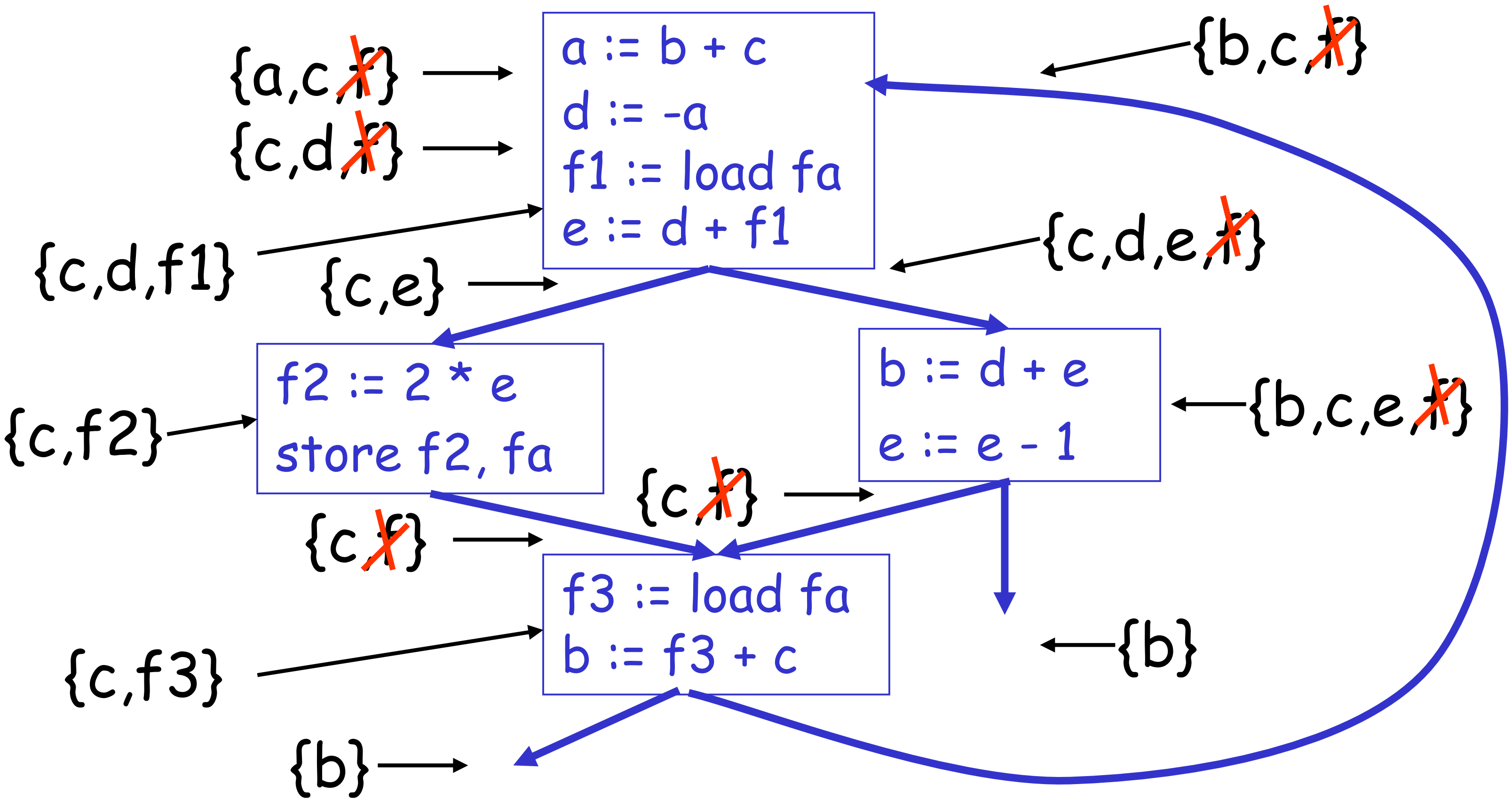
Spilling Example

- This is the new code after spilling f



Recomputing Liveness Information

- The new liveness information after spilling:



Recomputing Liveness Information

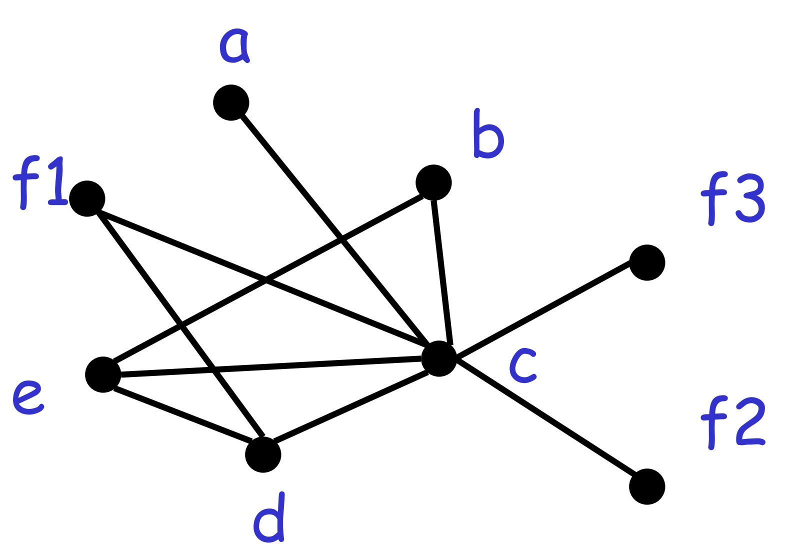
- New liveness information is almost as before
  - Note f has been split into three temporaries

- fi is live only
  - Between a fi := load fa and the next instruction
  - Between a store fi, fa and the preceding instr.

- Spilling reduces the live range of f
  - And thus reduces its interferences
  - Which results in fewer RIG neighbors

Recompute RIG After Spilling

- Some edges of the spilled node are removed
- In our case f still interferes only with c and d
- And the resulting RIG is 3-colorable



Spilling Notes

- Additional spills might be required before a coloring is found

- The tricky part is deciding what to spill
  - But any choice is correct

- Possible heuristics:
  - Spill temporaries with most conflicts
  - Spill temporaries with few definitions and uses
  - Avoid spilling in inner loops

Conclusions

- Register allocation is a "must have" in compilers:
  - Because intermediate code uses too many temporaries
  - Because it makes a big difference in performance

- Register allocation is more complicated for CISC machines

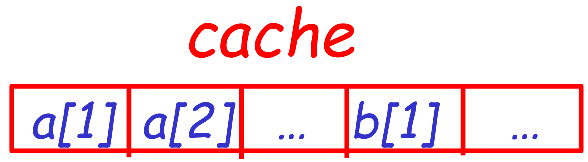
Caches

- Compilers are very good at managing registers
  - Much better than a programmer could be
- Compilers are not good at managing caches
  - This problem is still left to programmers
  - It is still an open question how much a compiler can do to improve cache performance
- Compilers can, and a few do, perform some cache optimizations

Cache Optimization

- Consider the loop

```
for(j := 1; j < 10; j++)
    for(i=1; i<1000; i++)
        a[i] *= b[i]
```



*a[1] *= b[1]*
*a[2] *= b[2]*
...

- This program has terrible cache performance
  - Because each iteration of the inner loop refers to a new element of arrays (i.e., fresh data) = [a cache miss]

Cache Optimization (Cont.)

- Consider the program:

```
for(i=1; i<1000; i++)
    for(j := 1; j < 10; j++)
        a[i] *= b[i]
```

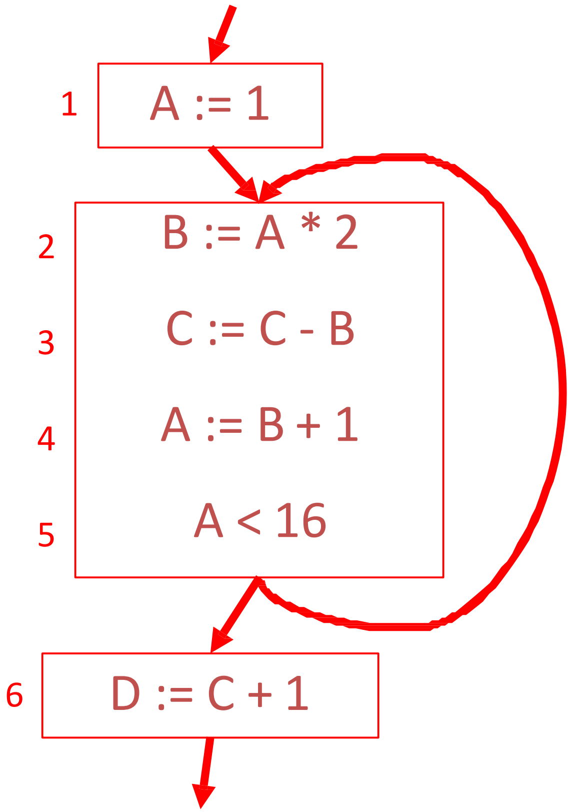
  - Computes the same thing
  - But with much better cache behavior
  - Might actually be more than 10x faster

- A compiler can perform this optimization
  - called loop interchange

Question?

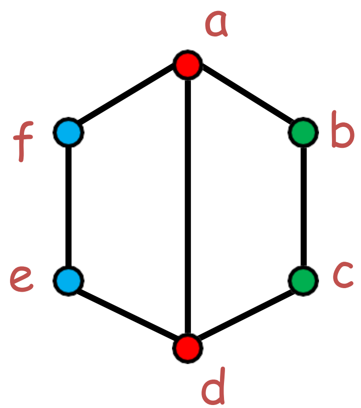
Which of the following pairs of temporaries interfere in the code fragment given at right?

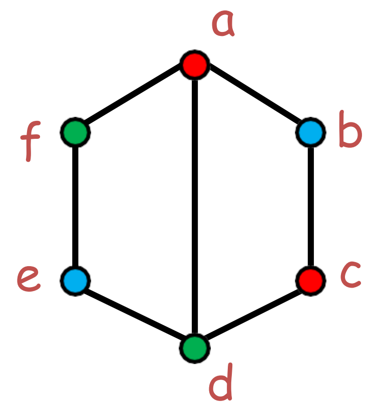
- ☐ A and B
- ☐ A and C
- ☐ B and C
- ☐ C and D

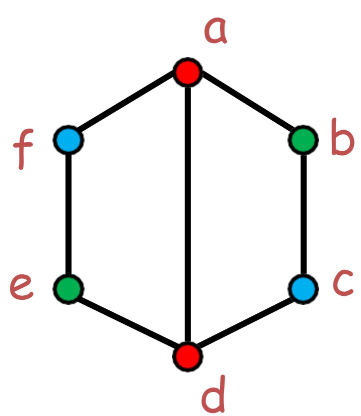


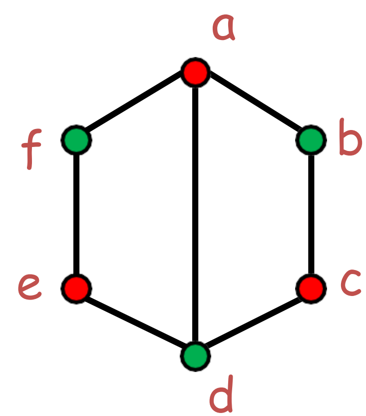
Question?

Which of the following colorings is a valid minimal coloring of the given RIG?





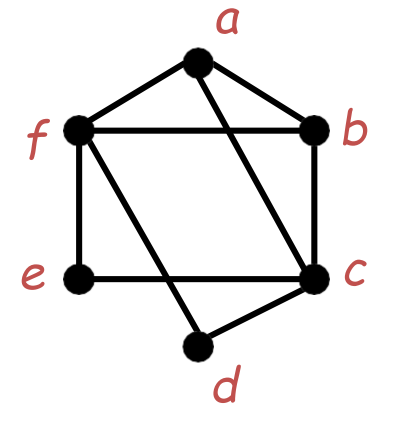




Question?

For the given RIG and k = 3, which of the following are valid deletion orders for the nodes of the RIG?

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



Question?

For the given code fragment and RIG, find the minimum cost spill. In this example, the cost of spilling a node is given by:

# of occurrences (use or definition)
- # of conflicts
+ 5 if the node corresponds to a variable used in a loop

- ☐ A
- ☐ B
- ☐ C
- ☐ D