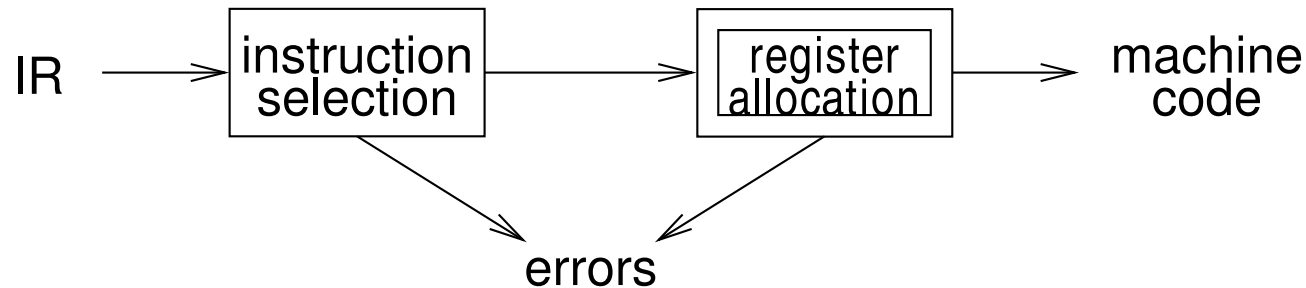


# Register allocation

---



Register allocation:

- have value in a register when used
- limited resources
- changes instruction choices
- can move loads and stores
- optimal allocation is difficult  
⇒ NP-complete for  $k \geq 1$  registers

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# Register allocation by simplification

---

Assume  $K$  registers

1. *Build* interference graph  $G$ : for each program point
  - (a) compute set of temporaries simultaneously live
  - (b) add edge to graph for each pair in set
2. *Simplify*: Color graph using a simple heuristic
  - (a) suppose  $G$  has node  $m$  with degree  $< K$
  - (b) if  $G' = G - \{m\}$  can be colored then so can  $G$ , since nodes adjacent to  $m$  have at most  $K - 1$  colors
  - (c) each such simplification will reduce degree of remaining nodes leading to more opportunity for simplification
  - (d) leads to recursive coloring algorithm
3. *Spill*: suppose  $\nexists m$  of degree  $< K$ 
  - (a) target some node (temporary) for spilling (optimistically, spilling node will allow coloring of remaining nodes)
  - (b) remove and continue simplifying

## Register allocation by simplification (cont.)

---

4. *Select*: assign colors to nodes
  - (a) start with empty graph
  - (b) must be a color for non-spill nodes (basis for removal)
  - (c) if adding spill node and no color available (neighbors already K-colored) then mark as an *actual spill*
  - (d) repeat select
  
5. *Start over*: if select has no actual spills then finished, otherwise
  - (a) rewrite program to fetch actual spills before each use and store after each definition
  - (b) recalculate liveness and repeat

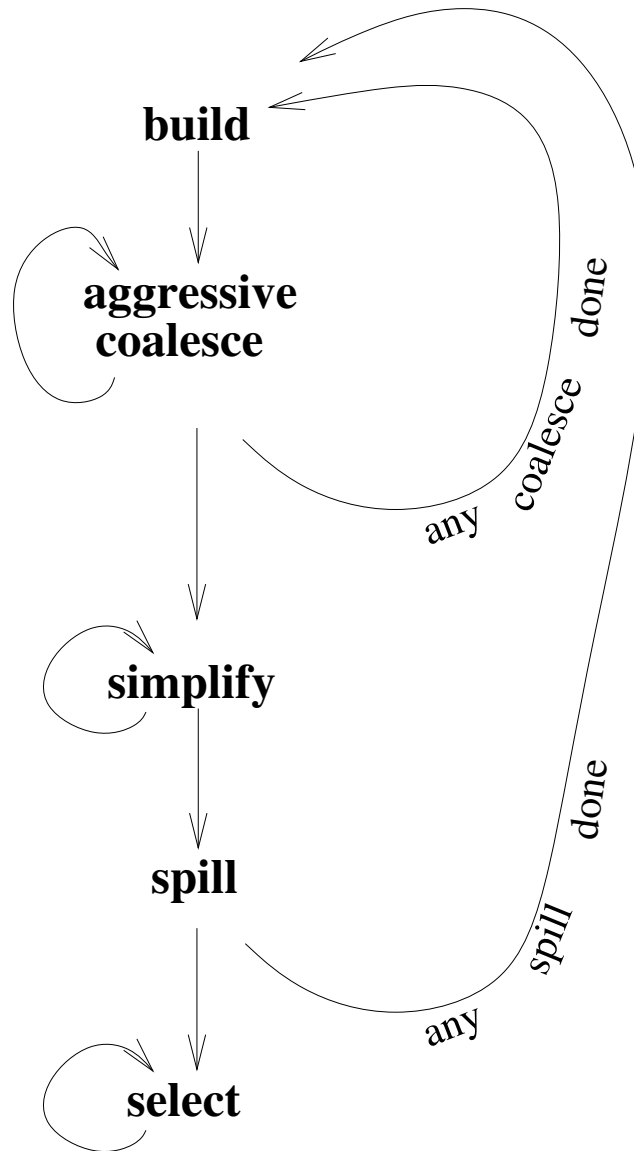
# Coalescing

---

- Can delete a *move* instruction when source  $s$  and destination  $d$  do not interfere:
  - *coalesce* them into a new node whose edges are the union of those of  $s$  and  $d$
- In principle, any pair of non-interfering nodes can be coalesced
  - unfortunately, the union is more constrained and new graph may no longer be  $K$ -colorable
  - overly aggressive

# Simplification with aggressive coalescing

---



# Conservative coalescing

---

Apply tests for coalescing that preserve colorability.

Suppose  $a$  and  $b$  are candidates for coalescing into node  $ab$ .

*Briggs*: coalesce only if  $ab$  has  $< K$  neighbors of *significant* degree  $\geq K$

- *simplify* first removes all insignificant-degree neighbors
- $ab$  will then be adjacent to  $< K$  neighbors
- *simplify* can then remove  $ab$

*George*: coalesce only if all significant-degree neighbors of  $a$  already interfere with  $b$

- *simplify* removes all insignificant-degree neighbors of  $a$
- remaining significant-degree neighbors of  $a$  already interfere with  $b$  so coalescing does not increase the degree of any node

# Iterated register coalescing

---

Interleave simplification with coalescing to eliminate most moves while guaranteeing not to introduce spills:

1. *Build* interference graph  $G$  and distinguish move-related from non-move-related nodes
2. *Simplify*: remove non-move-related nodes of low degree one at a time
3. *Coalesce*: conservatively coalesce move-related nodes
  - remove associated move instruction
  - if resulting node is non-move-related it can now be simplified
  - repeat simplify and coalesce until only significant-degree or uncoalesced moves
4. *Freeze*: if unable to simplify or coalesce
  - (a) look for move-related node of low-degree
  - (b) freeze its associated moves (give up on coalescing)
  - (c) now treat as non-move-related; resume iteration of simplify and coalesce

## Iterated register coalescing (cont.)

---

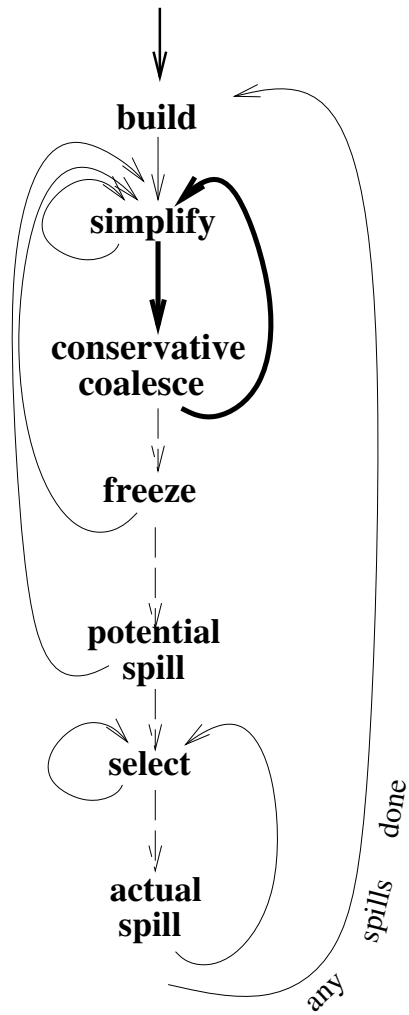
5. *Spill*: if no low-degree nodes
  - (a) select candidate for spilling
  - (b) remove to stack and continue simplifying
6. *Select*: pop stack assigning colors (including actual spills)
7. *Start over*: if select has no actual spills then finished, otherwise
  - (a) rewrite code to fetch actual spills before each use and store after each definition
  - (b) recalculate liveness and repeat



# Iterated register coalescing

---

SSA constant propagation  
(optional)



# Spilling

---

- Spills require repeating *build* and *simplify* on the whole program
- To avoid increasing number of spills in future rounds of *build* can simply discard coalescences
- Alternatively, preserve coalescences from before first *potential* spill, discard those after that point
- Move-related spilled temporaries can be aggressively coalesced, since (unlike registers) there is no limit on the number of stack-frame locations

# Precolored nodes

---

*Precolored nodes* correspond to machine registers (e.g., stack pointer, arguments, return address, return value)

- *select* and *coalesce* can give an ordinary temporary the same color as a precolored register, if they don't interfere
- e.g., argument registers can be reused inside procedures for a temporary
- *simplify*, *freeze* and *spill* cannot be performed on them
- also, precolored nodes interfere with other precolored nodes

So, treat precolored nodes as having infinite degree

This also avoids needing to store large adjacency lists for precolored nodes; coalescing can use the George criterion

# Temporary copies of machine registers

---

Since precolored nodes don't spill, their live ranges must be kept short:

1. use *move* instructions
2. move callee-save registers to fresh temporaries on procedure entry, and back on exit, spilling between as necessary
3. *register pressure* will spill the fresh temporaries as necessary, otherwise they can be coalesced with their precolored counterpart and the moves deleted

# Caller-save and callee-save registers

---

Variables whose live ranges span calls should go to callee-save registers, otherwise to caller-save

This is easy for graph coloring allocation with spilling

- calls interfere with caller-save registers
- a cross-call variable interferes with all precolored caller-save registers, as well as with the fresh temporaries created for callee-save copies, forcing a spill
- choose nodes with high degree but few uses, to spill the fresh callee-save temporary instead of the cross-call variable
- this makes the original callee-save register available for coloring the cross-call variable

# Example

---

enter:

c := r3

a := r1

b := r2

d := 0

e := a

loop:

d := d + b

e := e - 1

if e > 0 goto loop

r1 := d

r3 := c

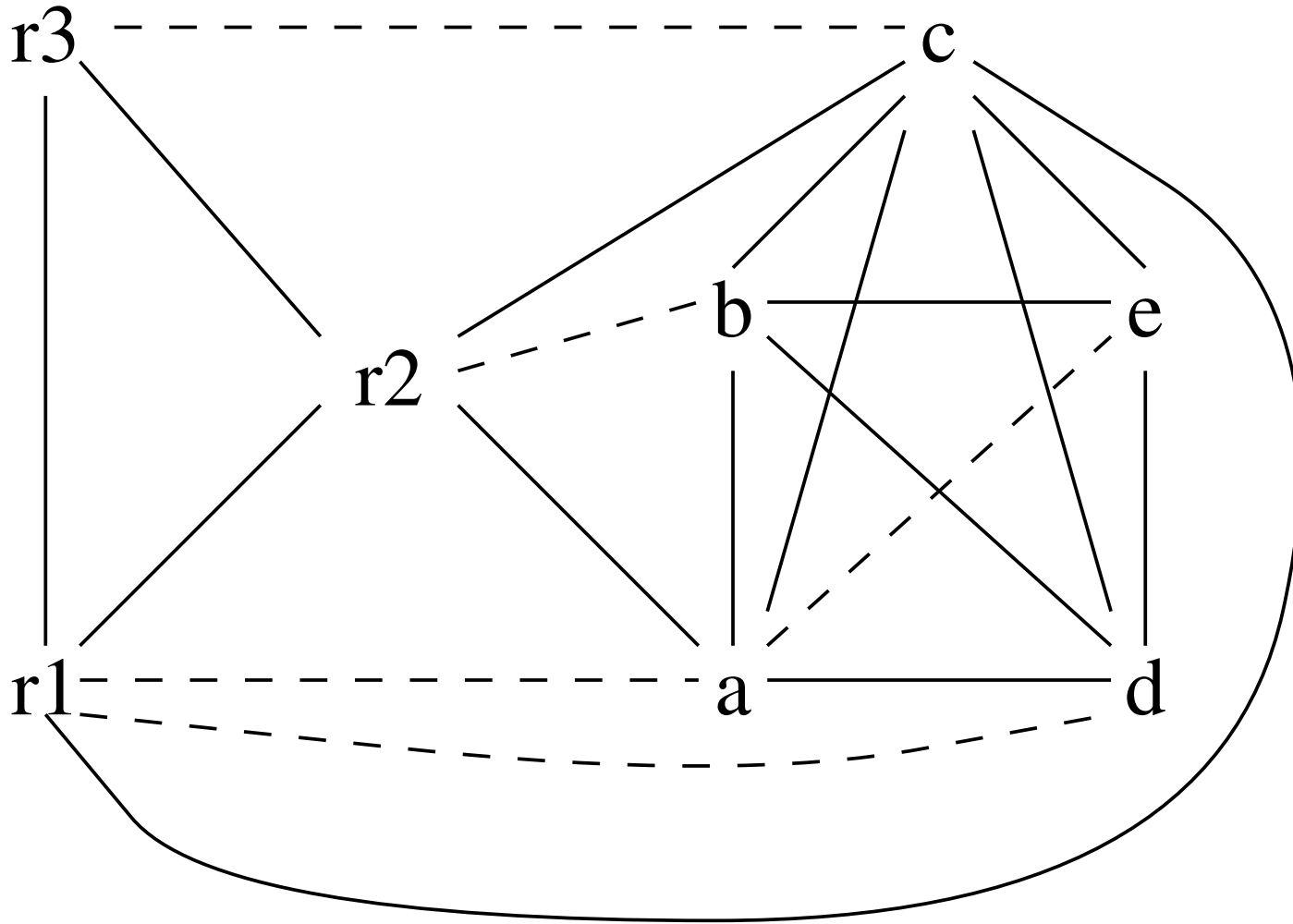
return [ r1, r3 live out ]

- Temporaries are a, b, c, d, e
- Assume target machine with  $K = 3$  registers: r1, r2 (caller-save/argument/result), r3 (callee-save)
- The code generator has already made arrangements to save r3 explicitly by copying into temporary a and back again

## Example (cont.)

---

Interference graph:



## Example (cont.)

---

- No opportunity for *simplify* or *freeze* (all non-precolored nodes have significant degree  $\geq K$ )
- Any *coalesce* will produce a new node adjacent to  $\geq K$  significant-degree nodes

- Must *spill* based on priorities:

Node	uses + defs outside loop	uses + defs inside loop	degree	priority
a	{ 2 +10×	{ 0	4	= 0.50
b	{ 1 +10×	{ 1	4	= 2.75
c	{ 2 +10×	{ 0	6	= 0.33
d	{ 2 +10×	{ 2	4	= 5.50
e	{ 1 +10×	{ 3	3	= 10.30

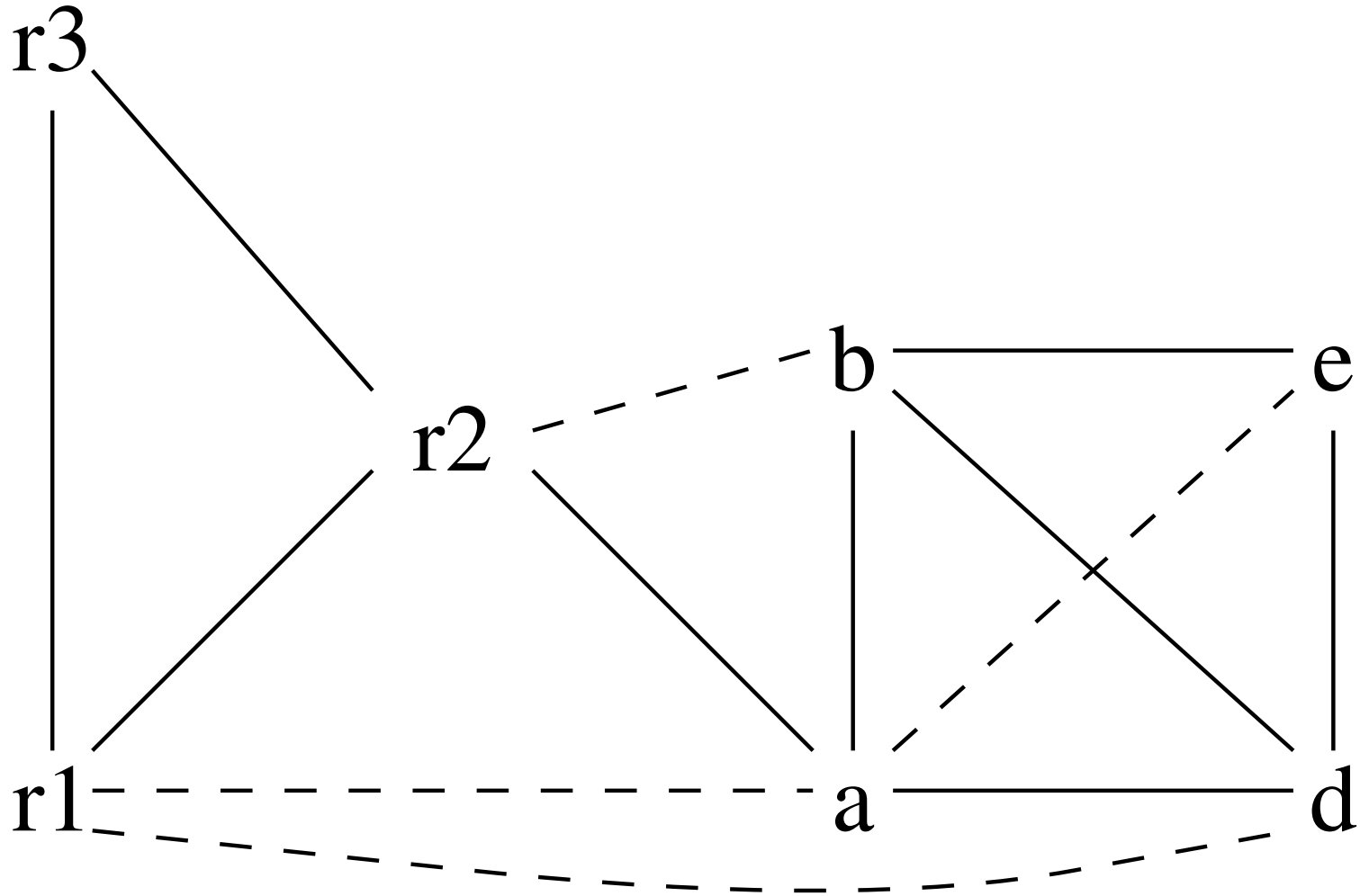
- Node c has lowest priority so spill it



## Example (cont.)

---

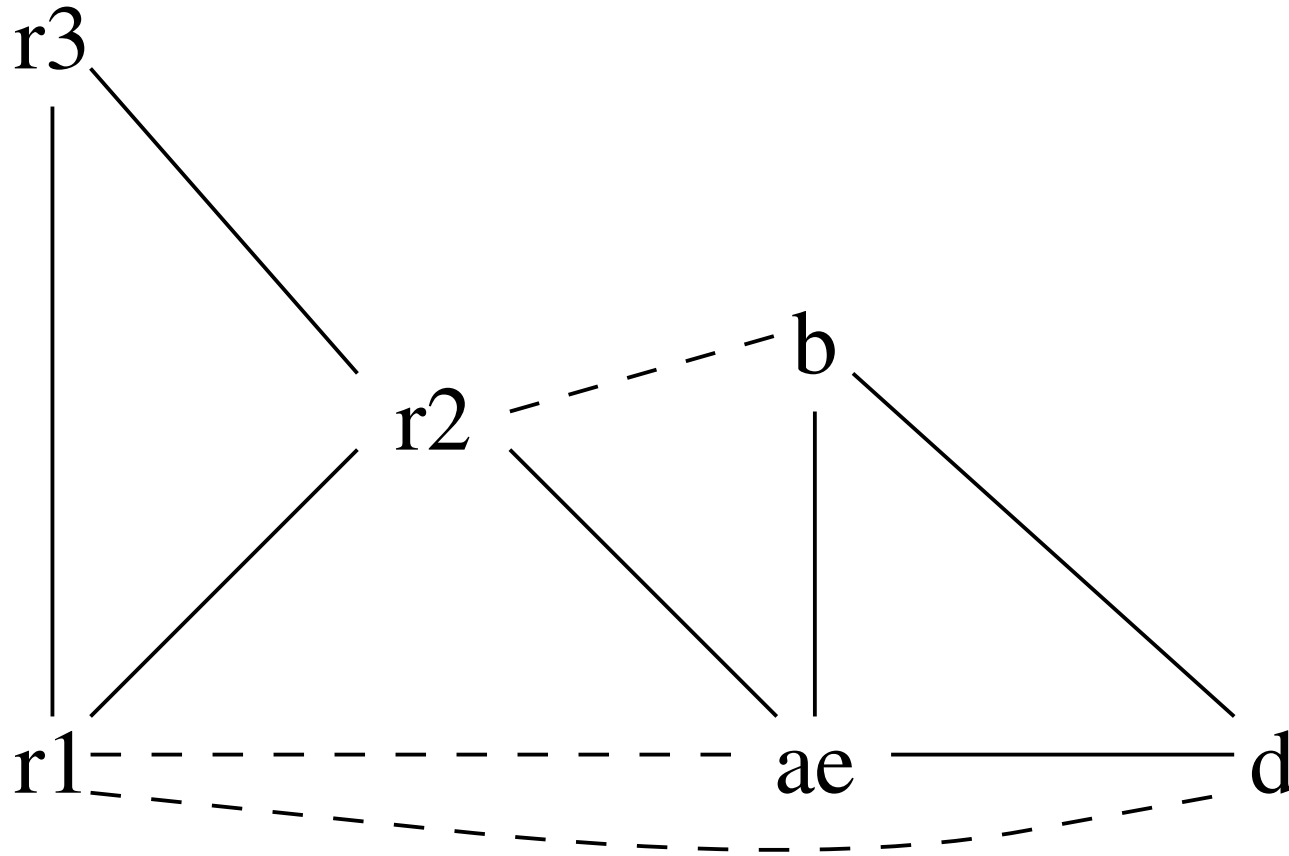
Interference graph with  $c$  removed:



## Example (cont.)

---

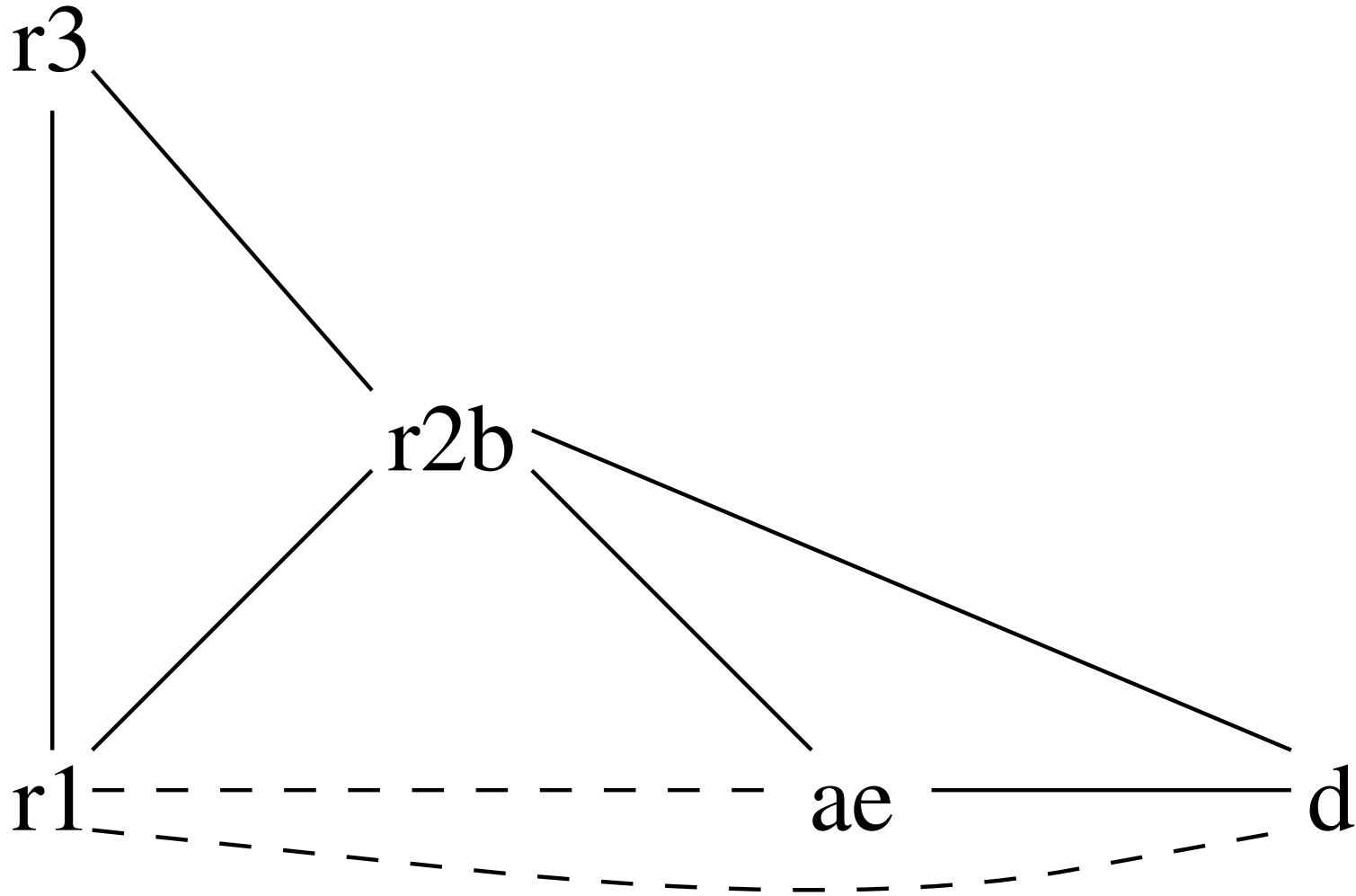
Only possibility is to *coalesce* a and e: ae will have  $< K$  significant-degree neighbors (after coalescing d will be low-degree, though high-degree before)



## Example (cont.)

---

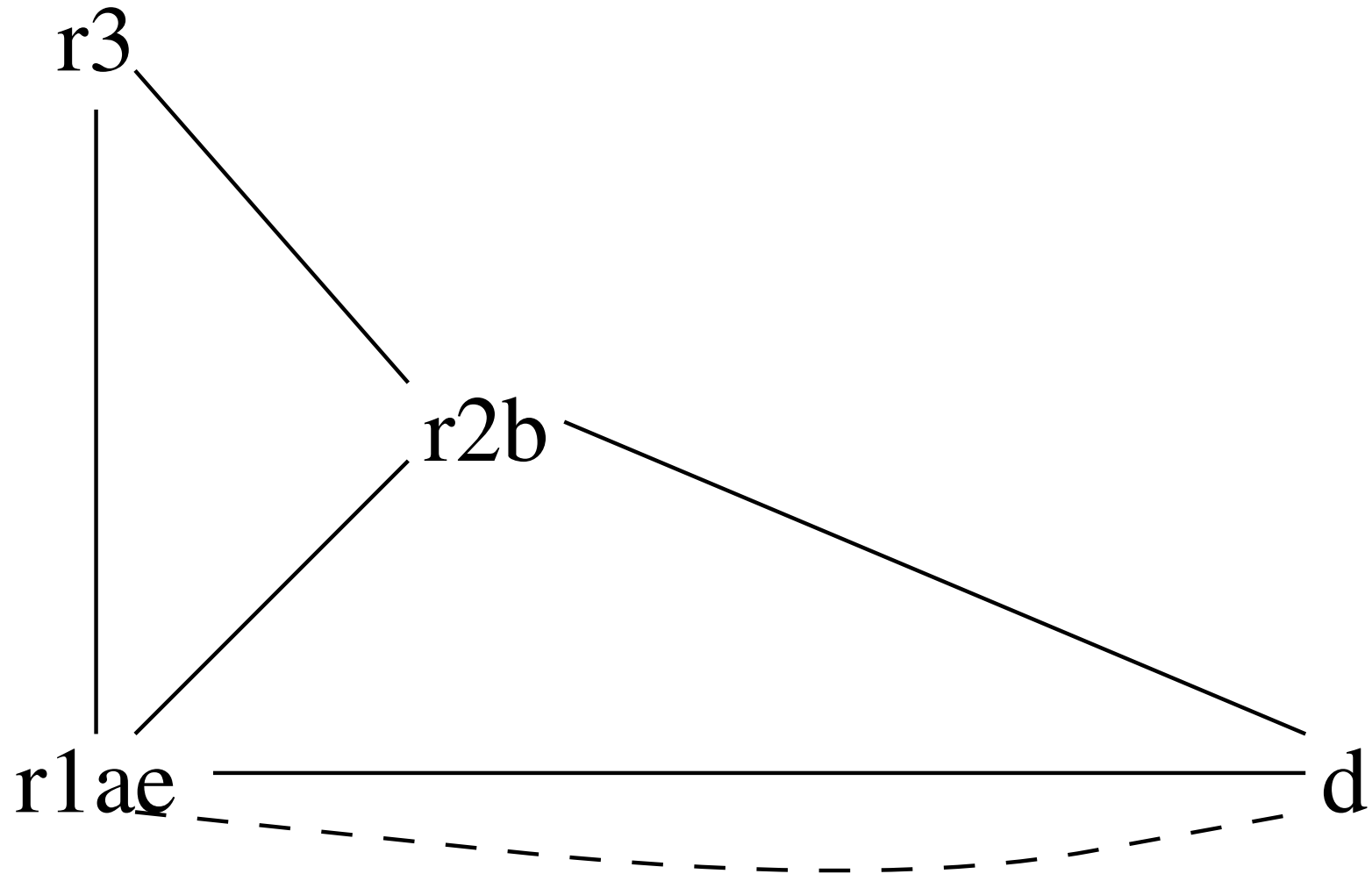
Can now *coalesce* b with r2 (or coalesce ae and r1):



## Example (cont.)

---

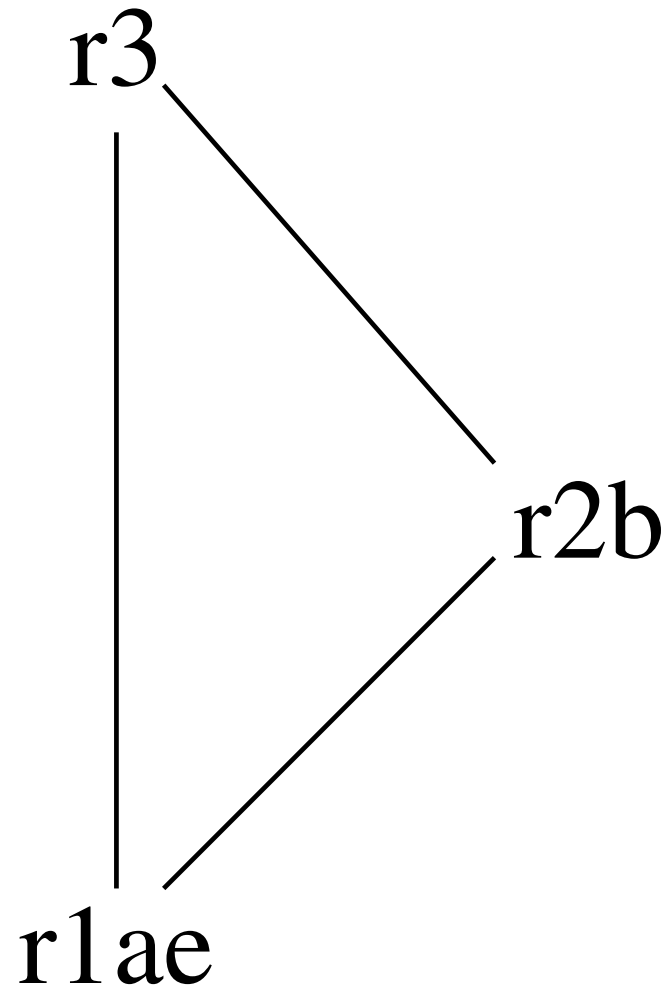
*Coalescing* ae and r1 (could also coalesce d with r1):



## Example (cont.)

---

Cannot *coalesce*  $r1ae$  with  $d$  because the move is *constrained*: the nodes interfere. Must *simplify*  $d$ :



## Example (cont.)

---

- Graph now has only precolored nodes, so pop nodes from stack coloring along the way
  - $d \equiv r3$
  - a, b, e have colors by coalescing
  - c must spill since no color can be found for it
- Introduce new temporaries  $c1$  and  $c2$  for each use/def, add loads before each use and stores after each def

## Example (cont.)

---

enter:

c1 := r3

M[c\_loc] := c1

a := r1

b := r2

d := 0

e := a

loop:

d := d + b

e := e - 1

if e > 0 goto loop

r1 := d

c2 := M[c\_loc]

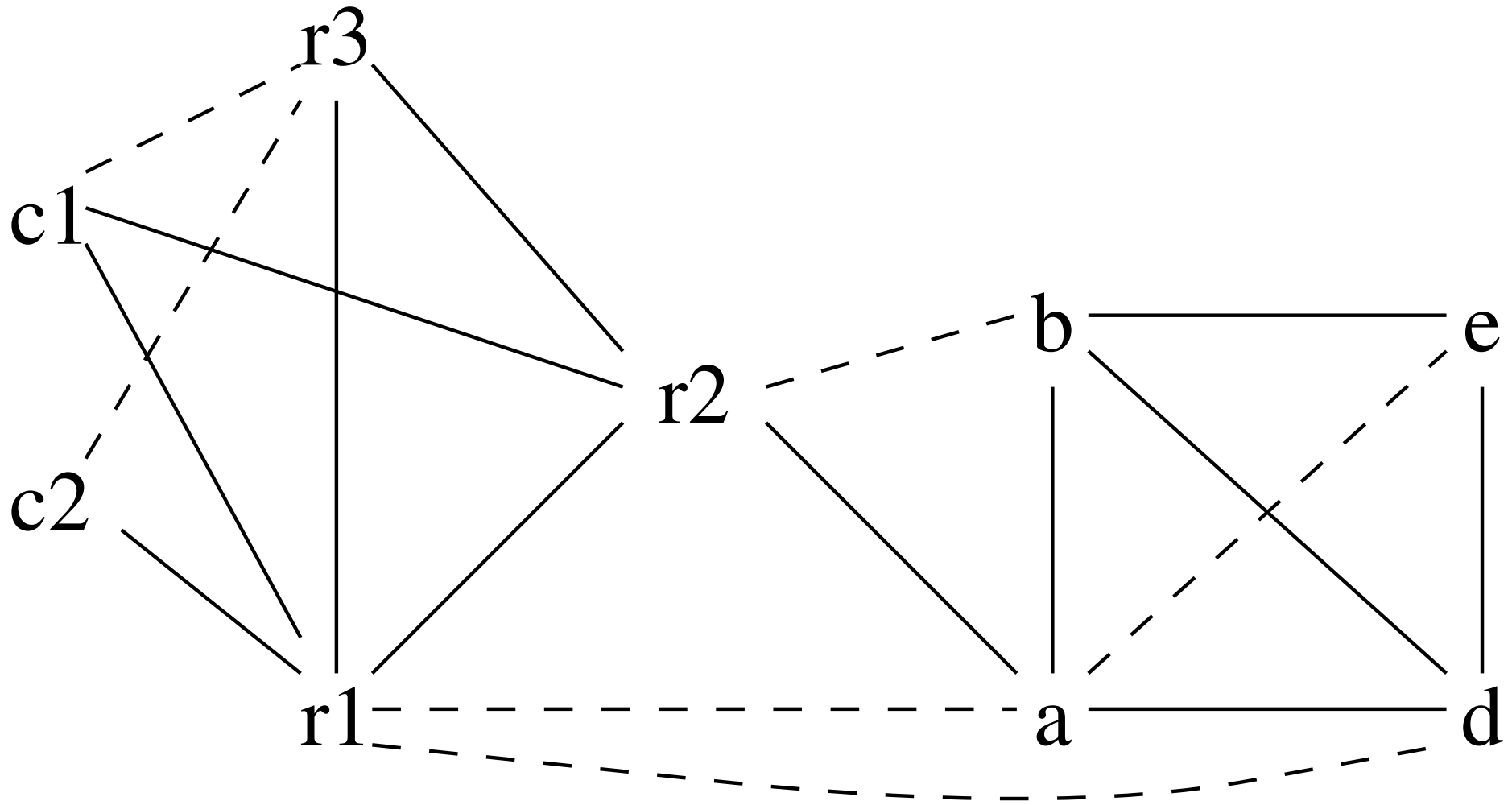
r3 := c2

return [ r1, r3 live out ]

## Example (cont.)

---

New interference graph:



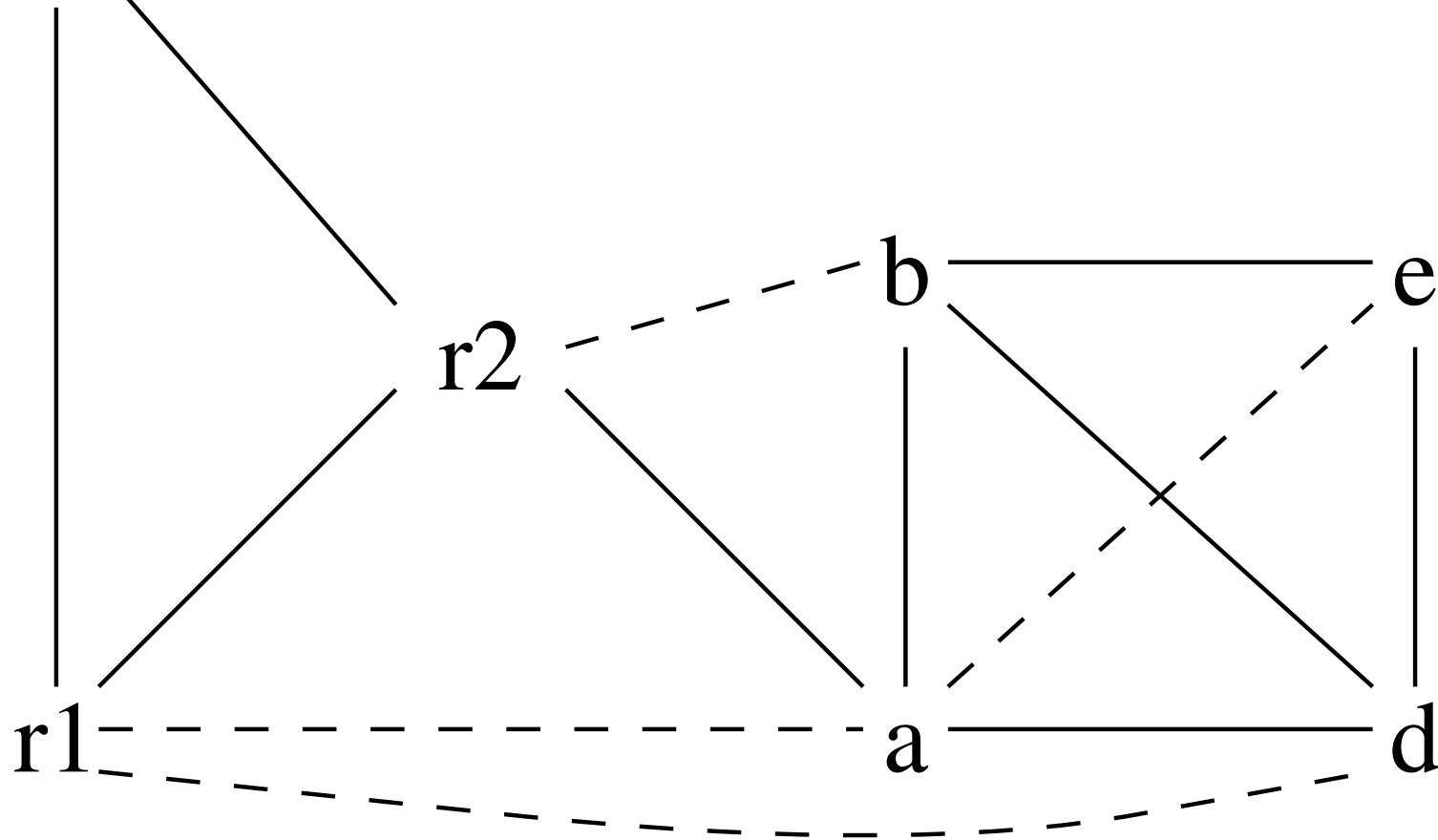


## Example (cont.)

---

Coalesce  $c_1$  with  $r_3$ , then  $c_2$  with  $r_3$ :

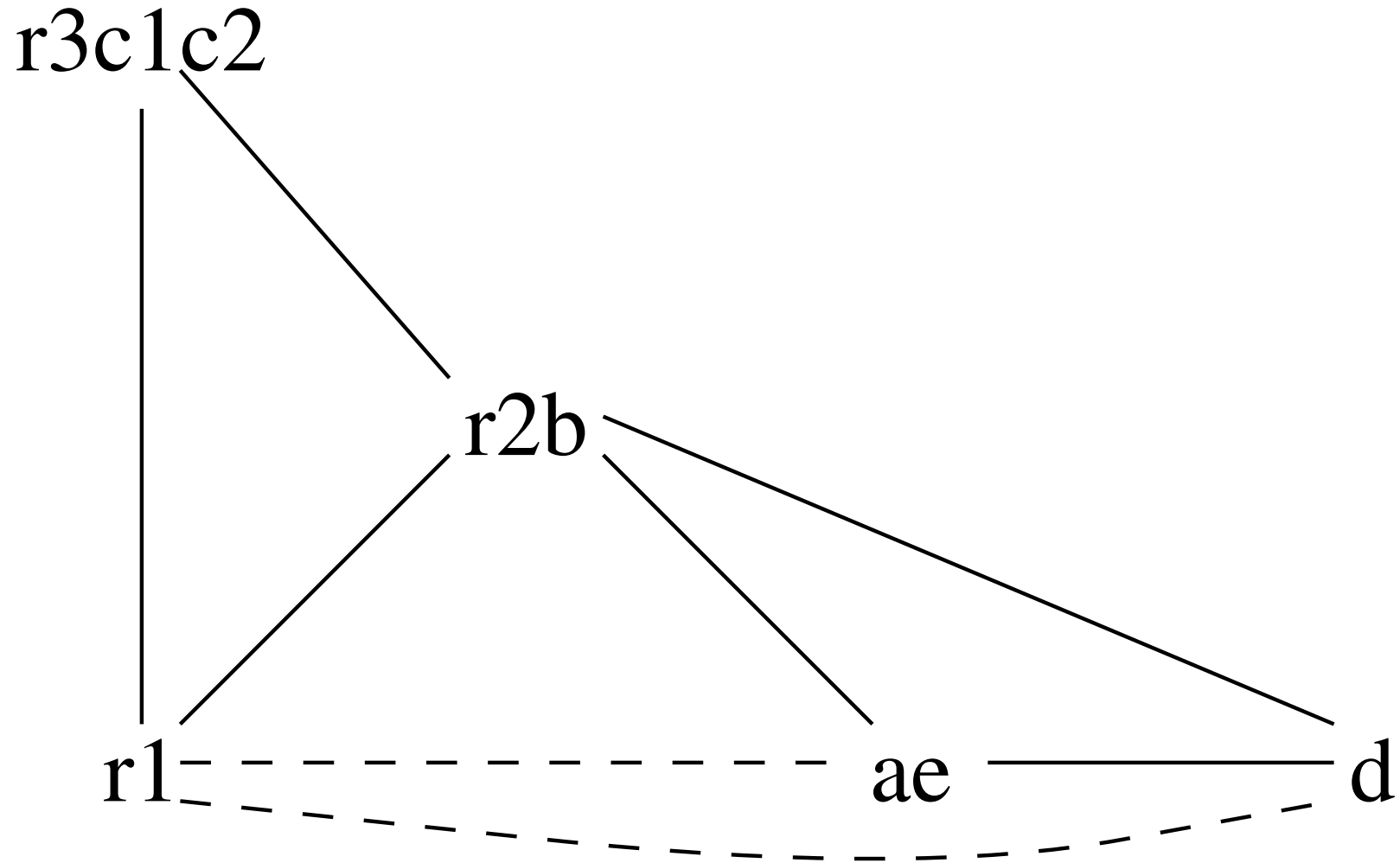
$r_3c_1c_2$



## Example (cont.)

---

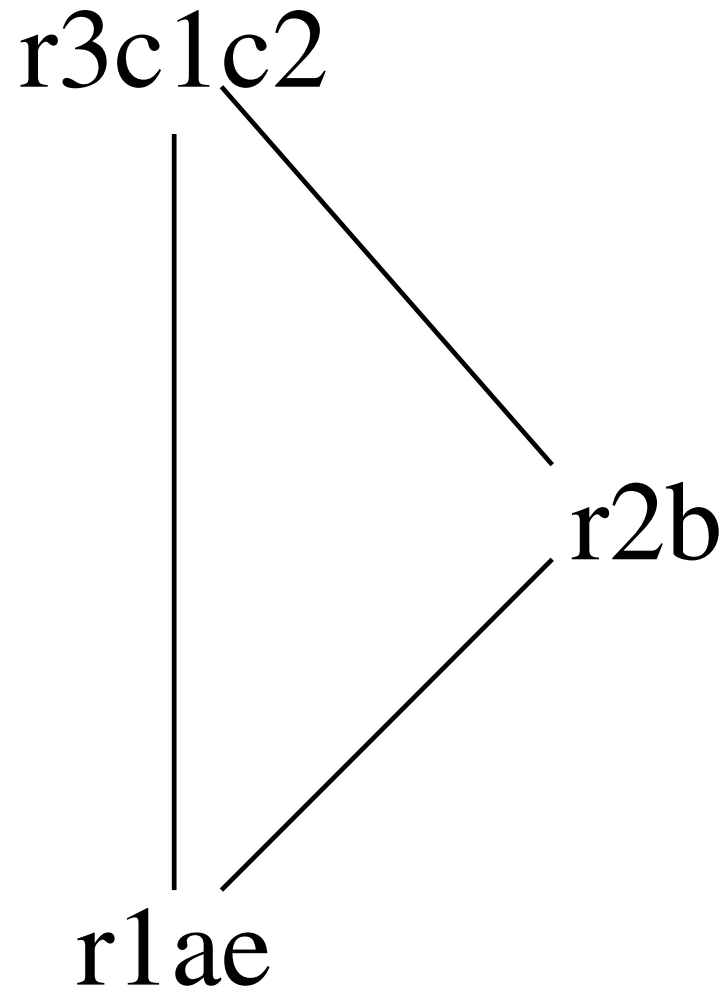
As before, *coalesce* a with e, then b with r2:



## Example (cont.)

---

As before, *coalesce* ae with r1 and *simplify* d:



## Example (cont.)

---

Pop  $d$  from stack: select  $r3$ . All other nodes were coalesced or precolored. So, the coloring is:

- $a \equiv r1$
- $b \equiv r2$
- $c \equiv r3$
- $d \equiv r3$
- $e \equiv r1$

## Example (cont.)

---

Rewrite the program with this assignment:

enter:

r3 := r3

M[c\_loc] := r3

r1 := r1

r2 := r2

r3 := 0

r1 := r1

loop:

r3 := r3 + r2

r1 := r1 - 1

if r1 > 0 goto loop

r1 := r3

r3 := M[c\_loc]

r3 := r3

return [ r1, r3 live out ]

## Example (cont.)

---

- Delete moves with source and destination the same (coalesced):

```
enter:
```

```
    M[c_loc] := r3
```

```
    r3 := 0
```

```
loop:
```

```
    r2 := r3 + r2
```

```
    r1 := r1 - 1
```

```
    if r1 > 0 goto loop
```

```
    r1 := r3
```

```
    r3 := M[c_loc]
```

```
    return [ r1, r3 live out ]
```

- One uncoalesced move remains