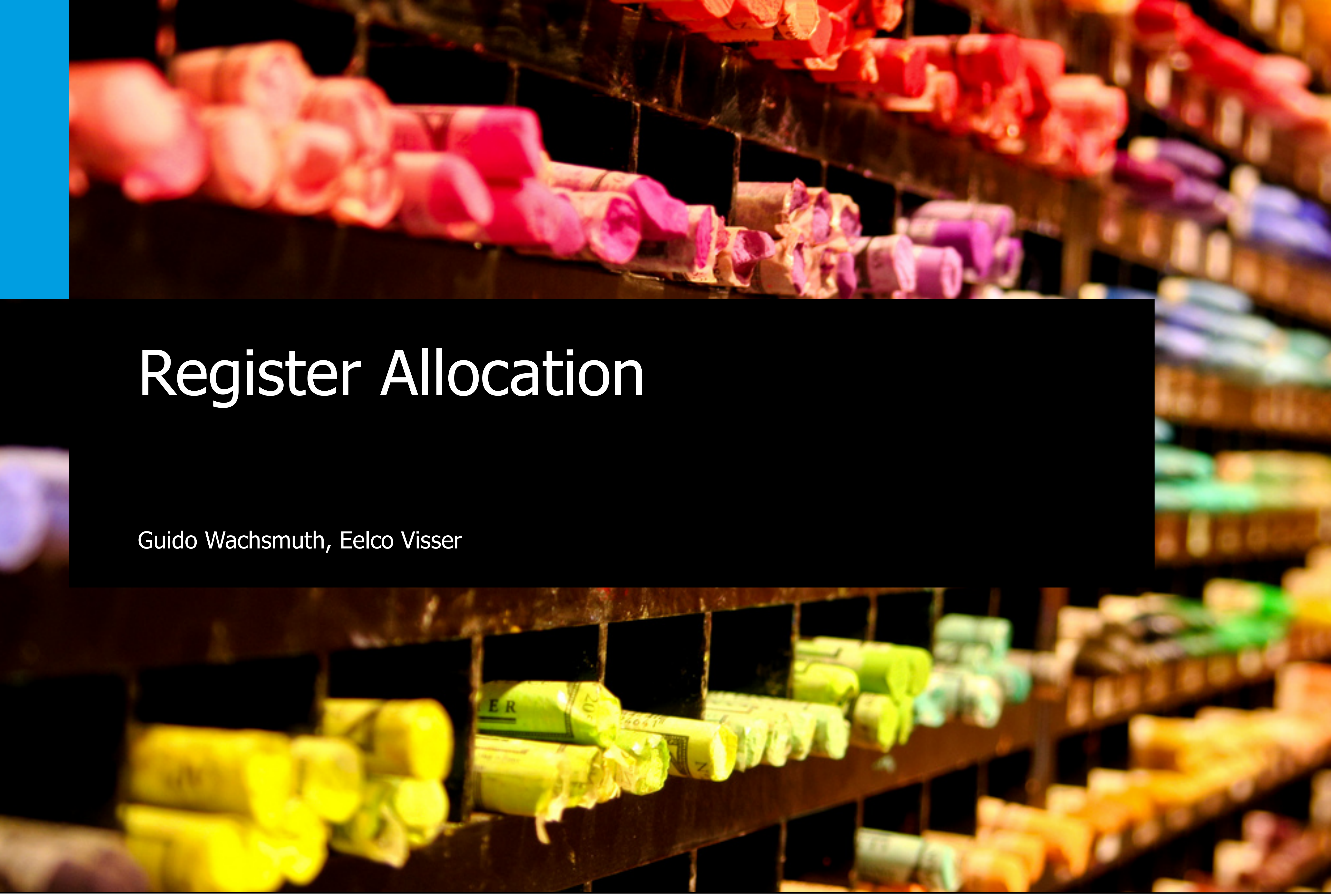


Register Allocation

Guido Wachsmuth, Eelco Visser

Delft University of Technology

Challenge the future

Course IN4303, 2016-2017
Compiler Construction

Allocate Minimal Number of Registers

exercise

```
live-in: k j
g := mem[j + 12]
h := k - 1
f := g * h
e := mem[j + 8]
m := mem[j + 16]
b := mem[f]
c := e + 8
d := c
k := m + 4
j := b
live out: d k j
```

Overview
today's lecture

Interference graphs

- construction during liveness analysis

Graph Coloring

- assign registers to local variables and compiler temporaries
- store local variables and temporaries in memory

Coalescing

- handle move instructions

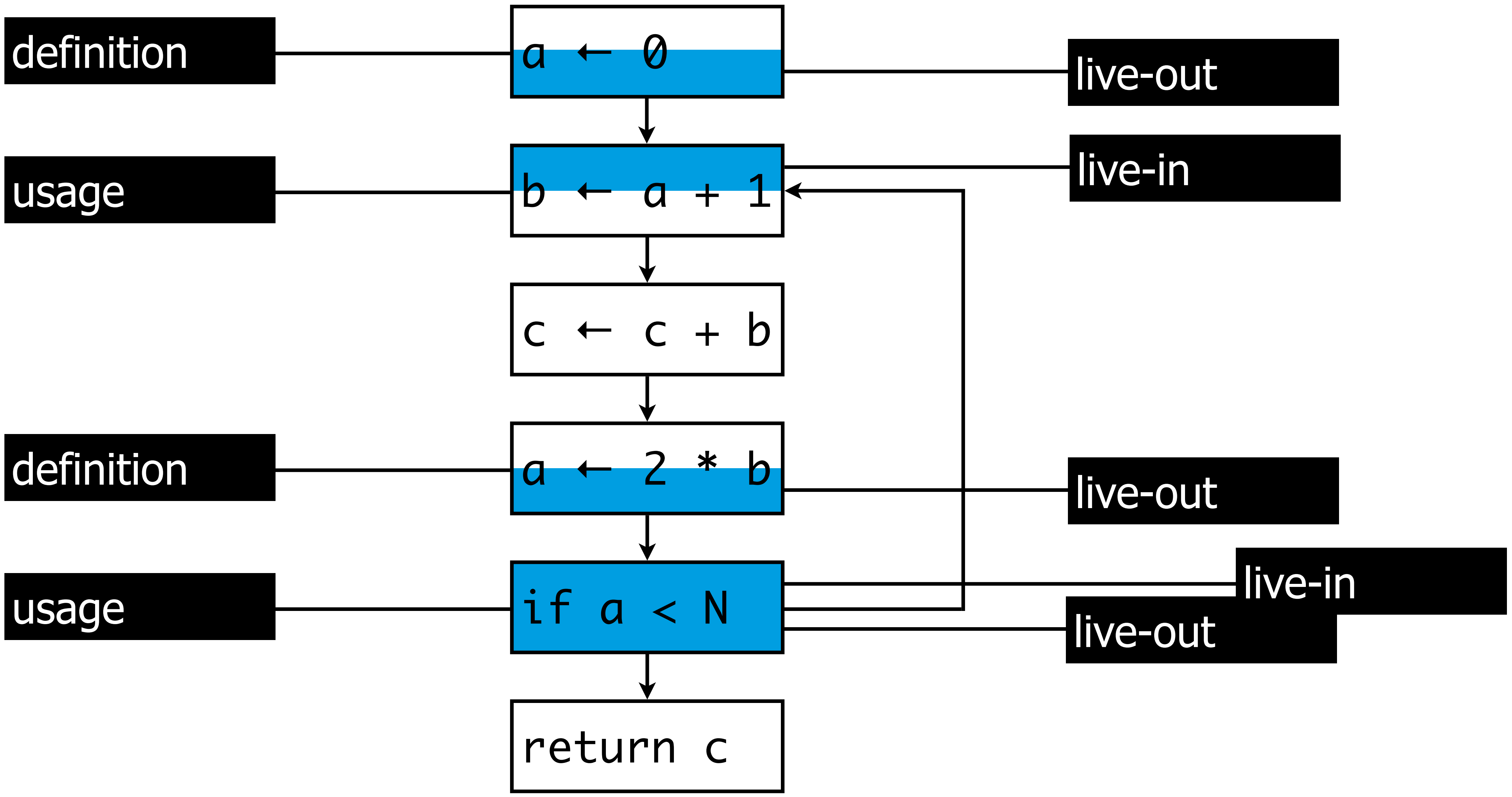
Pre-colored nodes

I

Interference Graphs

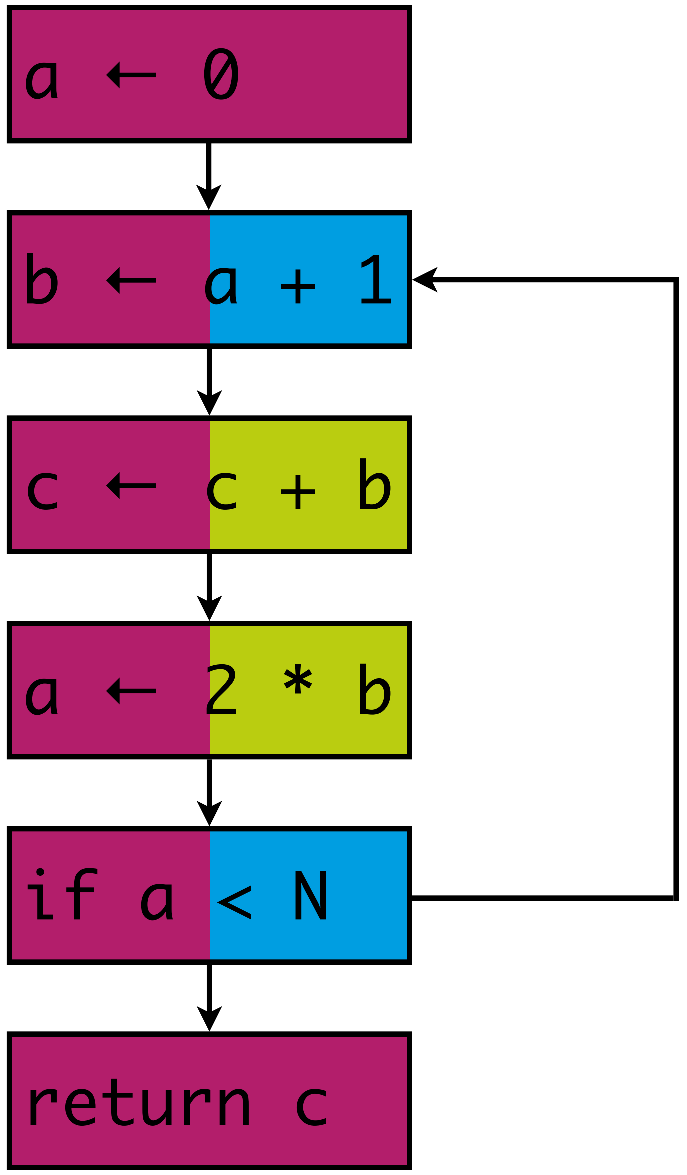
Recap: Liveness Analysis

terminology



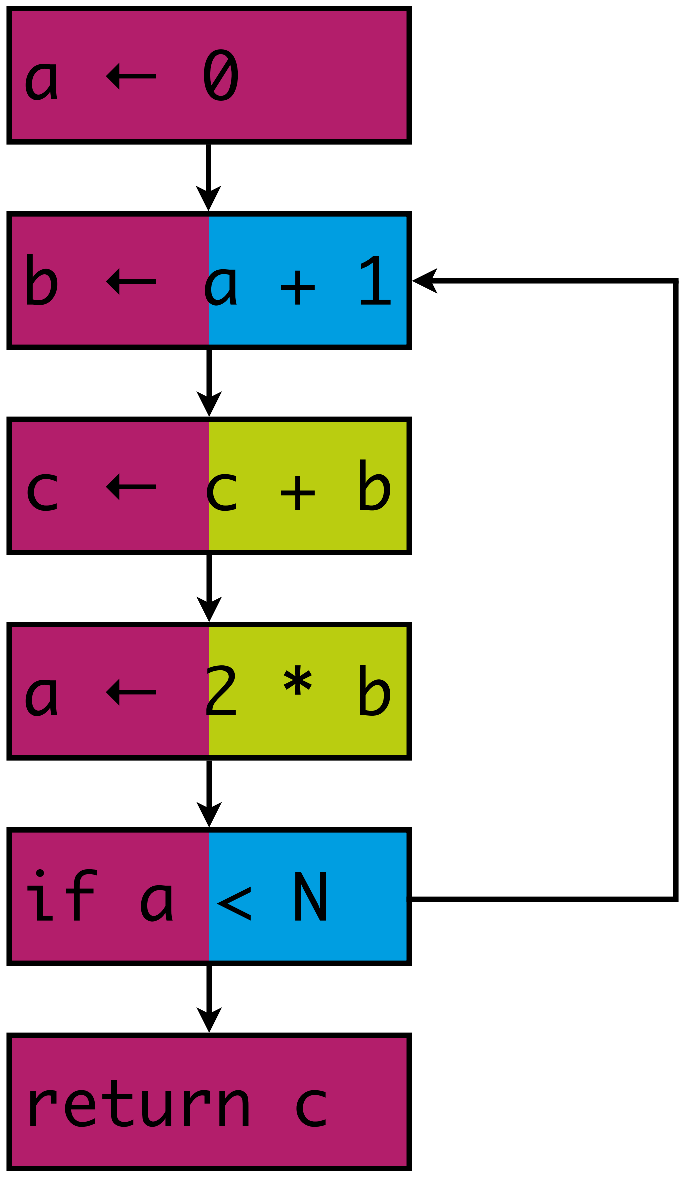
Recap: Liveness Analysis

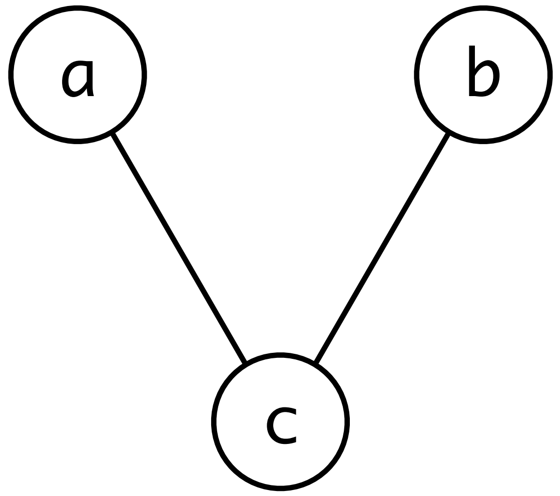
example



Interference Graphs

example



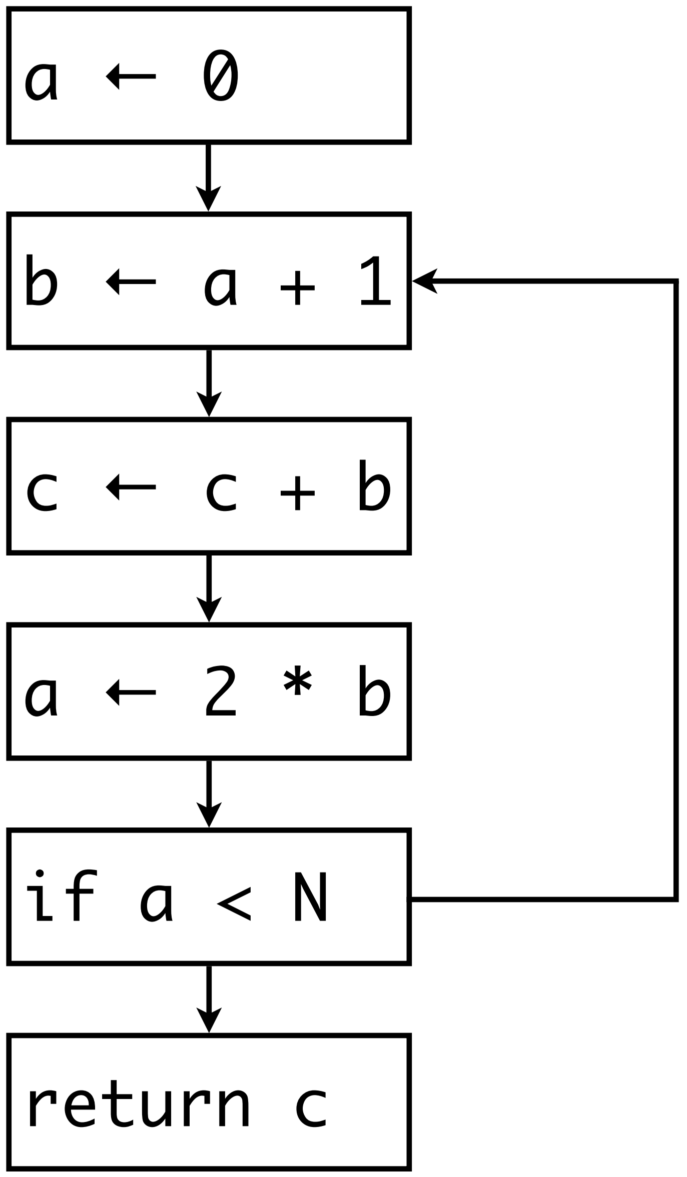


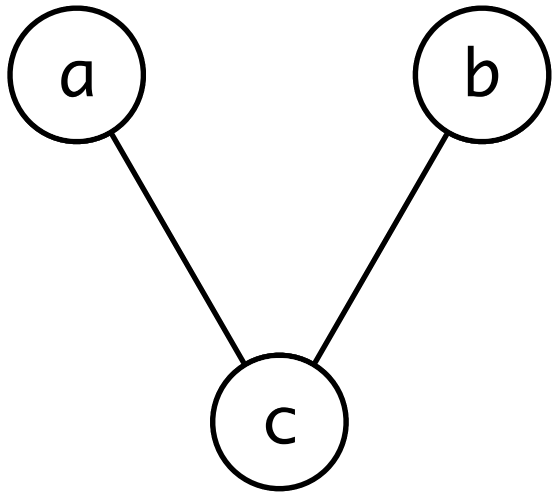
II

Graph Coloring

Graph Coloring

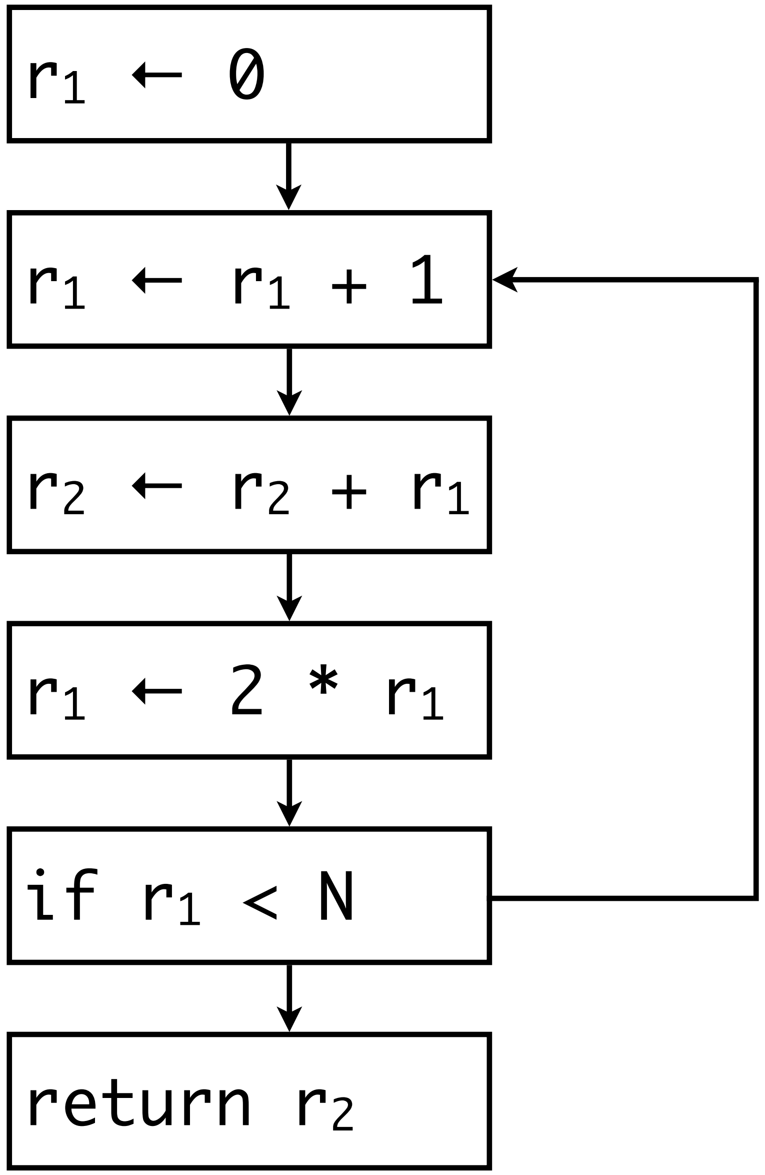
example

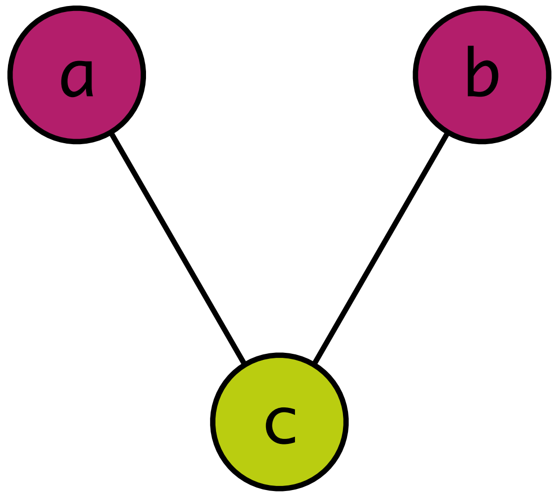




Graph Coloring

example





Graph Coloring
steps

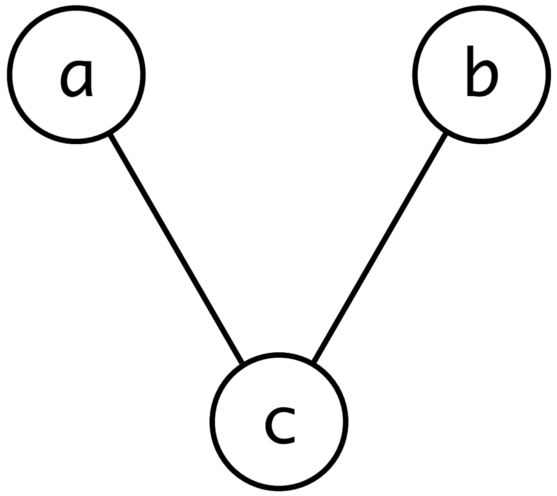
Simplify

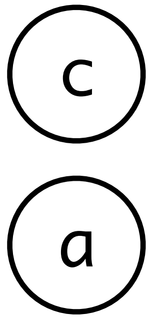
remove node of insignificant degree (fewer than k edges)

Select

add node, select color

Graph Coloring
example with 2 colors





Graph Coloring

example with 4 colors

```
live-in: k j
g := mem[j + 12]
h := k - 1
f := g * h
e := mem[j + 8]
m := mem[j + 16]
b := mem[f]
c := e + 8
d := c
k := m + 4
j := b
live out: d k j
```

Graph Coloring

example with 4 colors

r_1
r_2
r_3
r_4

```
live-in: k j
g := mem[j + 12]
h := k - 1
f := g * h
e := mem[j + 8]
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j := b
live out: d k j
```
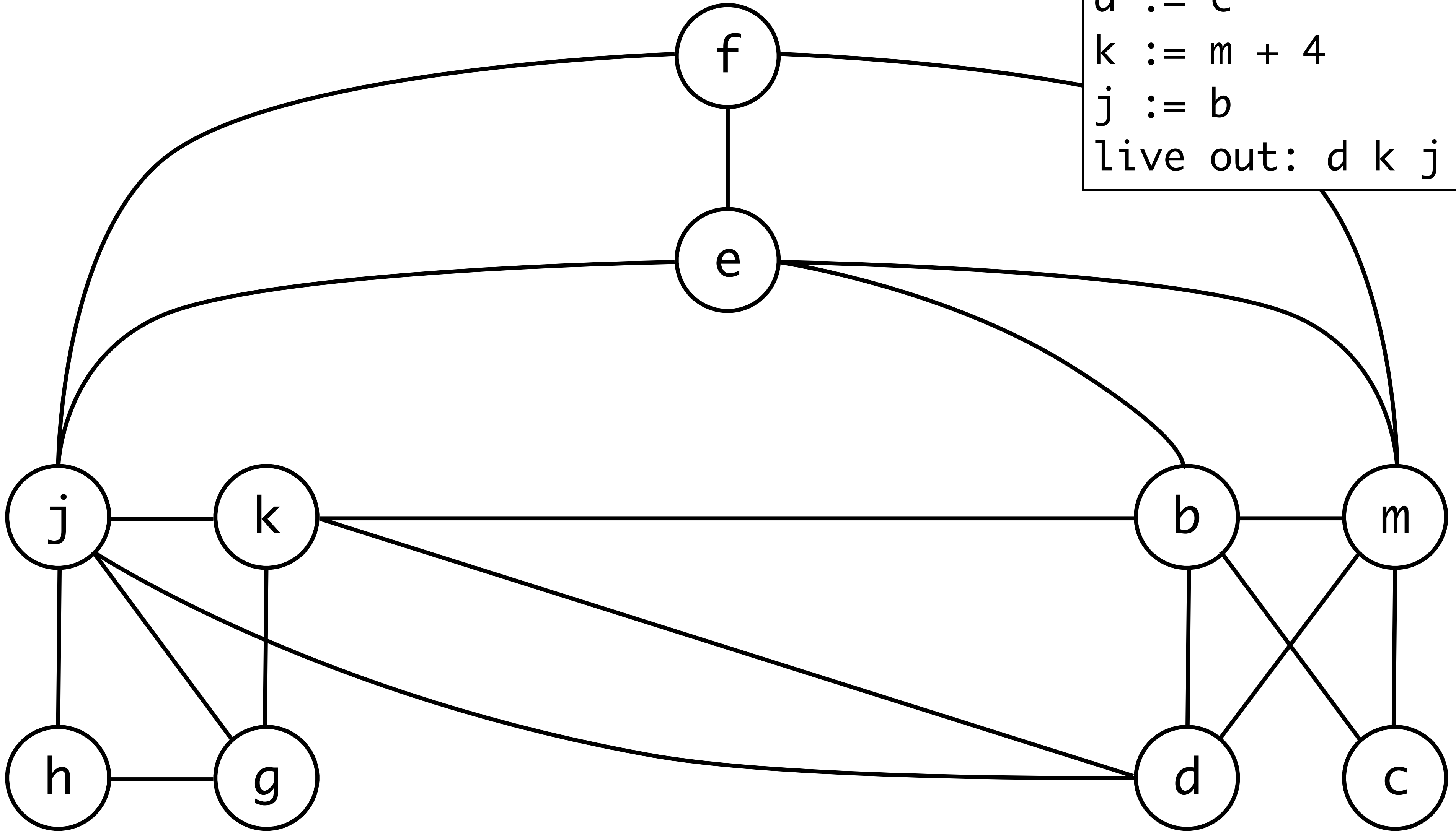
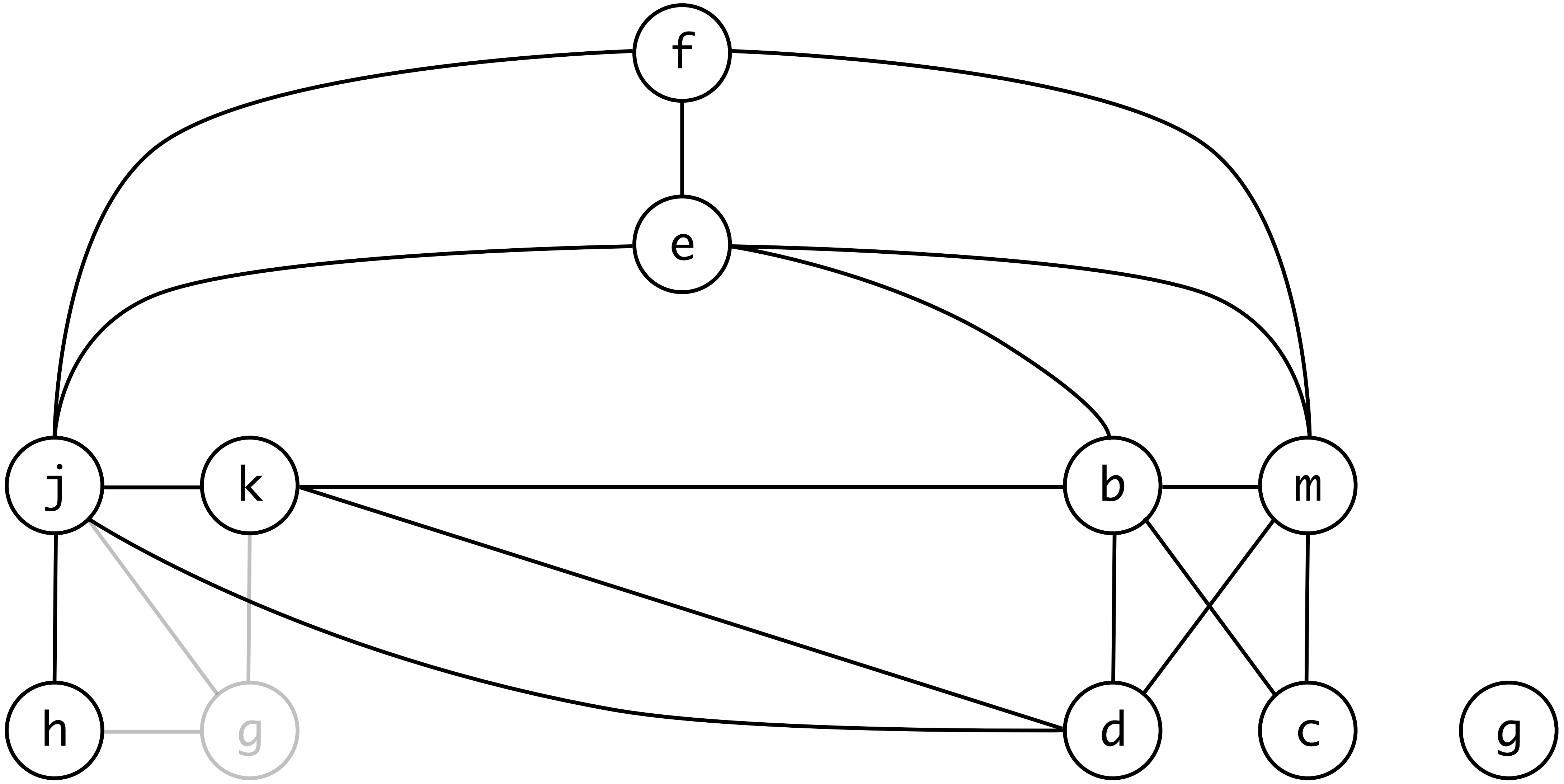



Graph Coloring

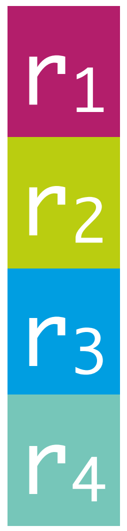
example with 4 colors

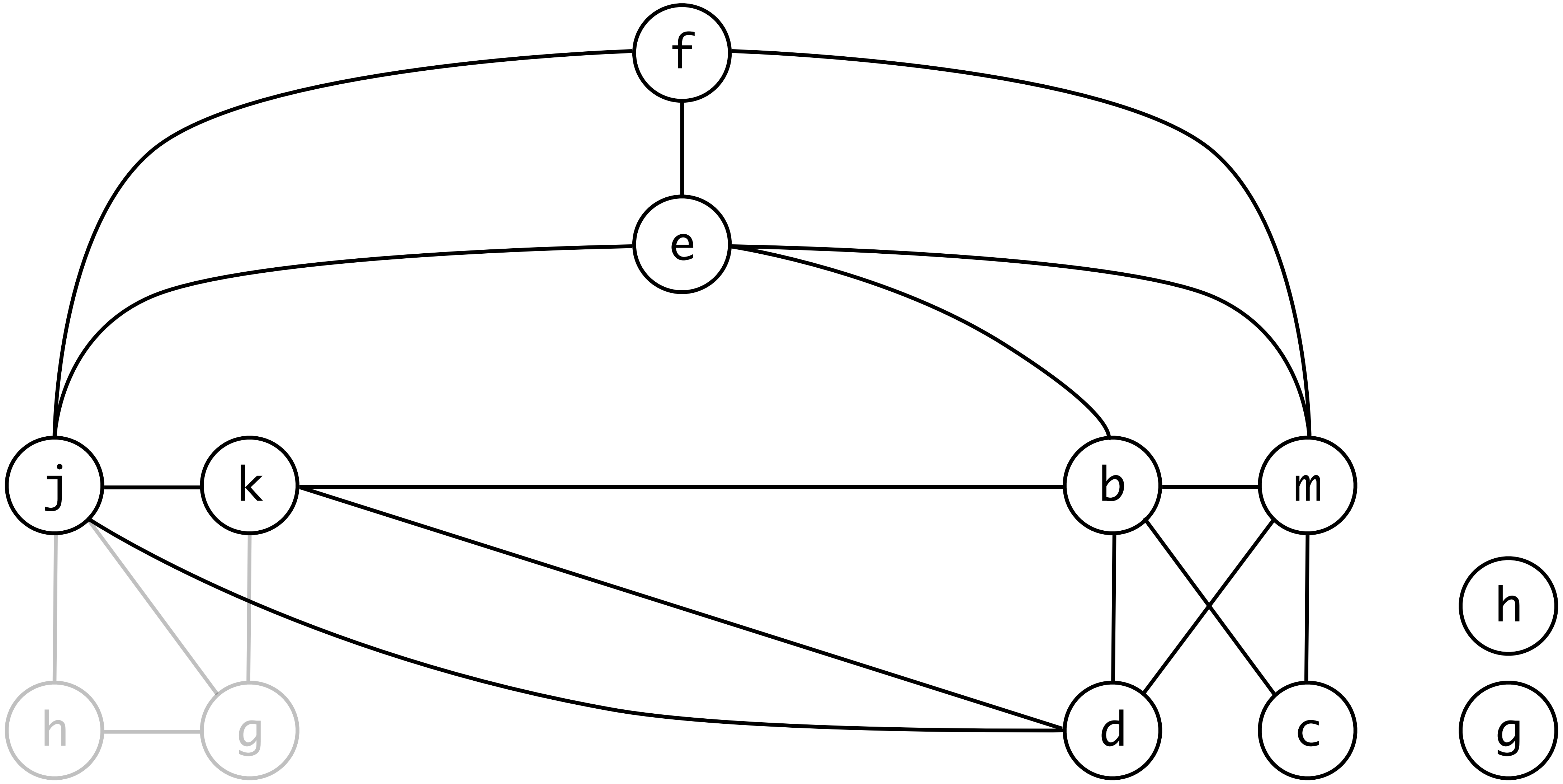
r_1
r_2
r_3
r_4



Graph Coloring

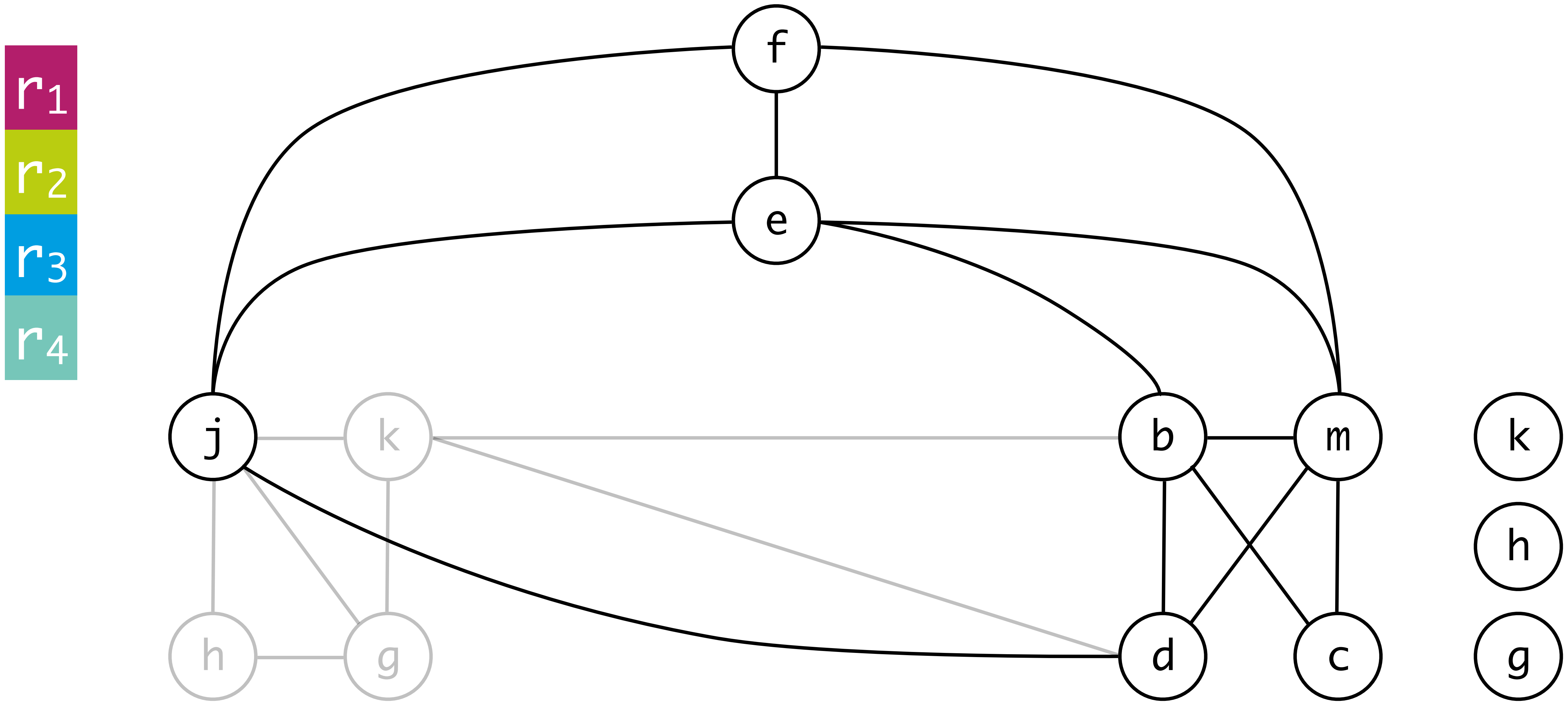
example with 4 colors





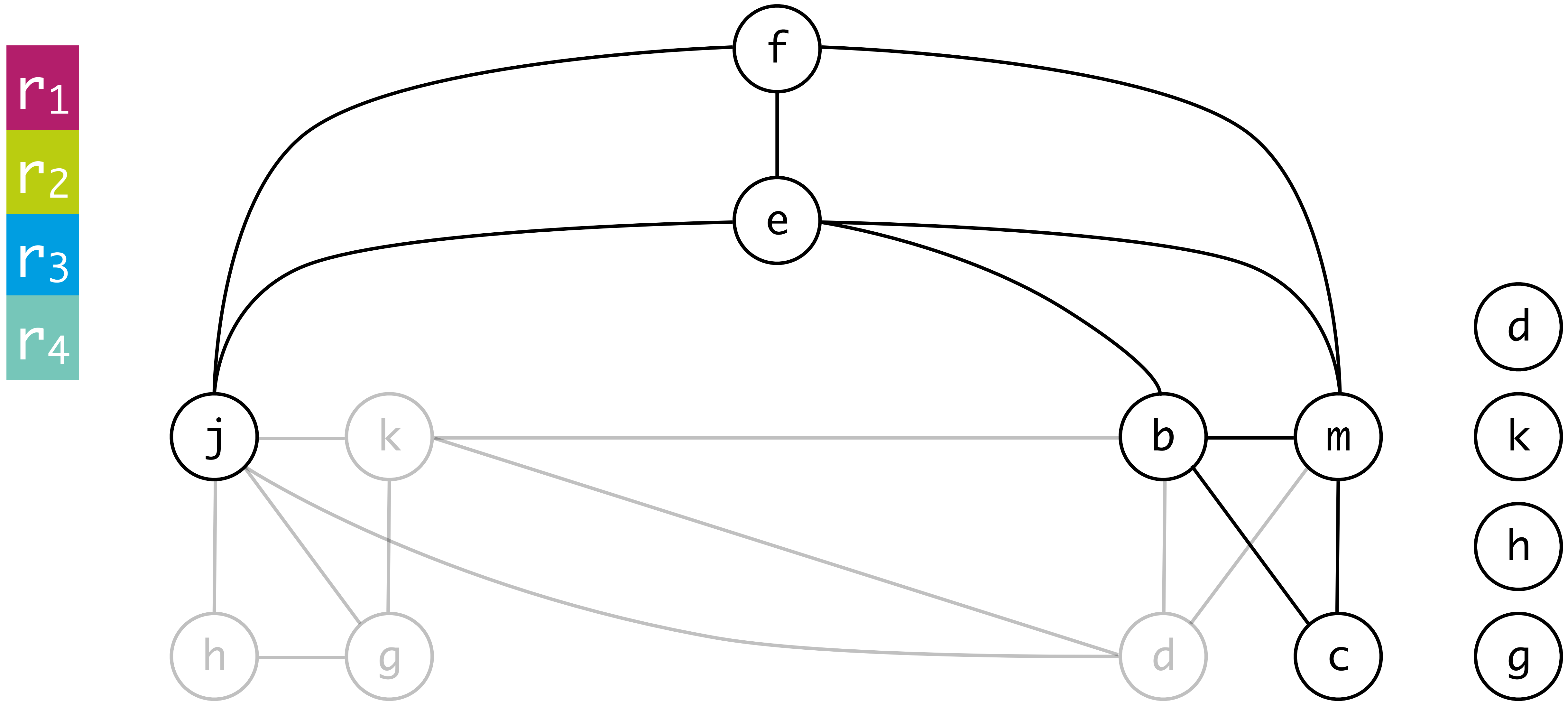
Graph Coloring

example with 4 colors



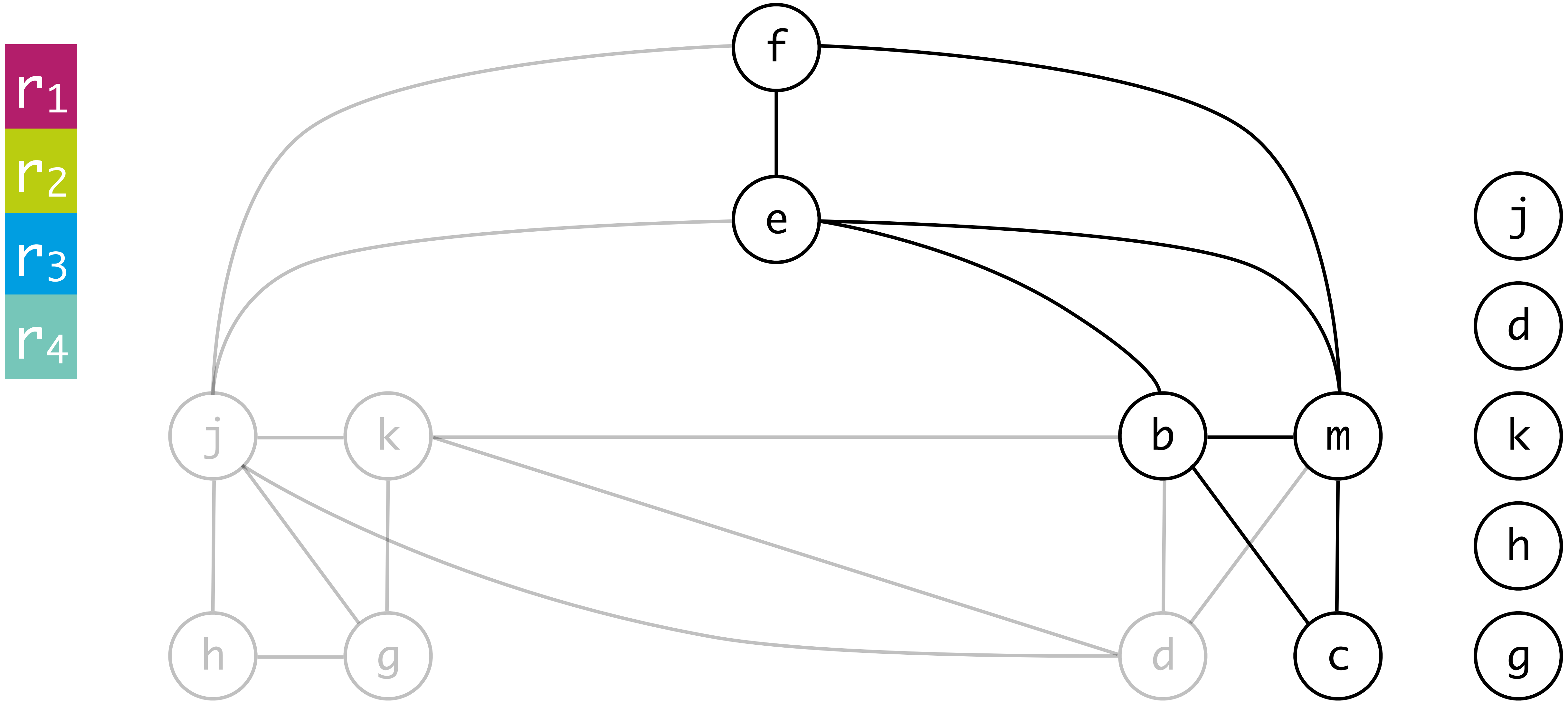
Graph Coloring

example with 4 colors



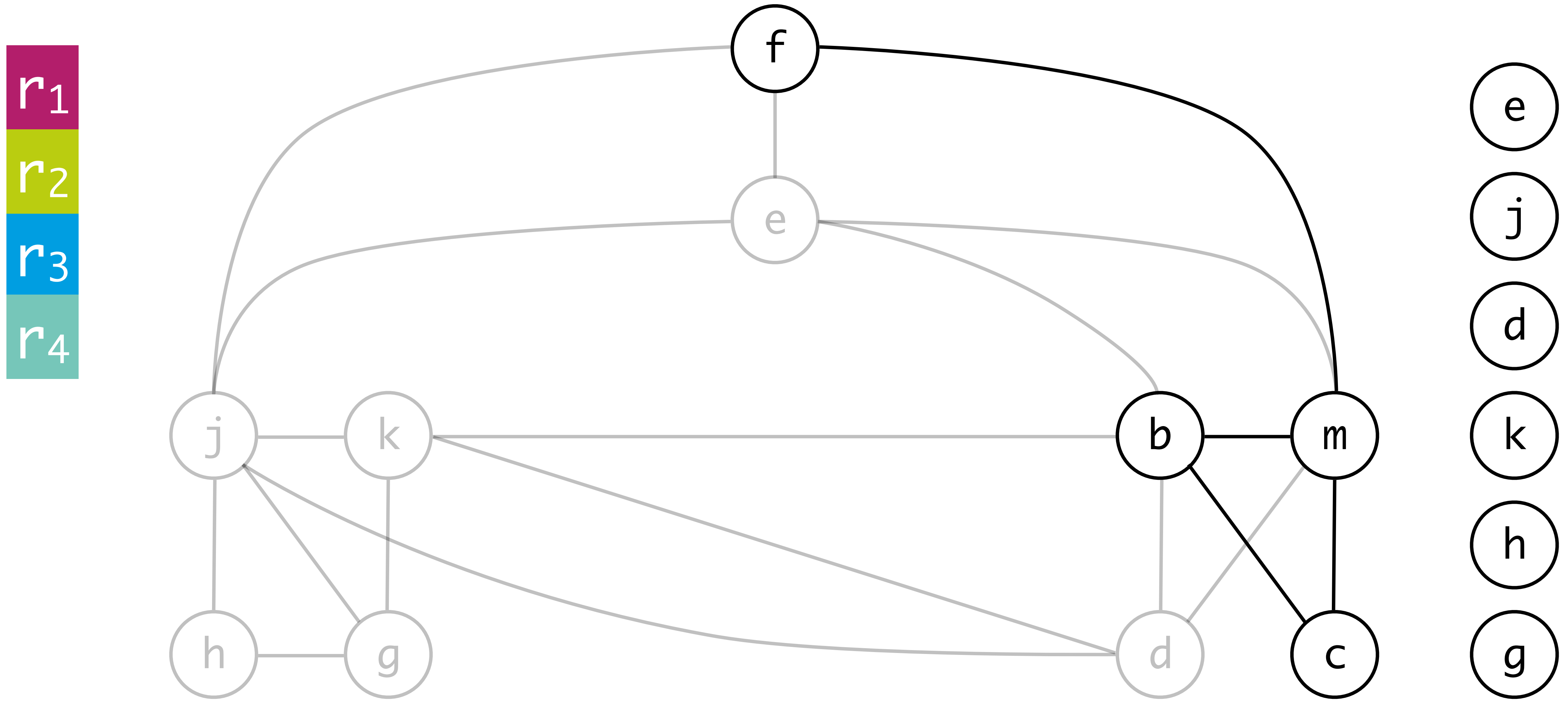
Graph Coloring

example with 4 colors



Graph Coloring

example with 4 colors



Graph Coloring

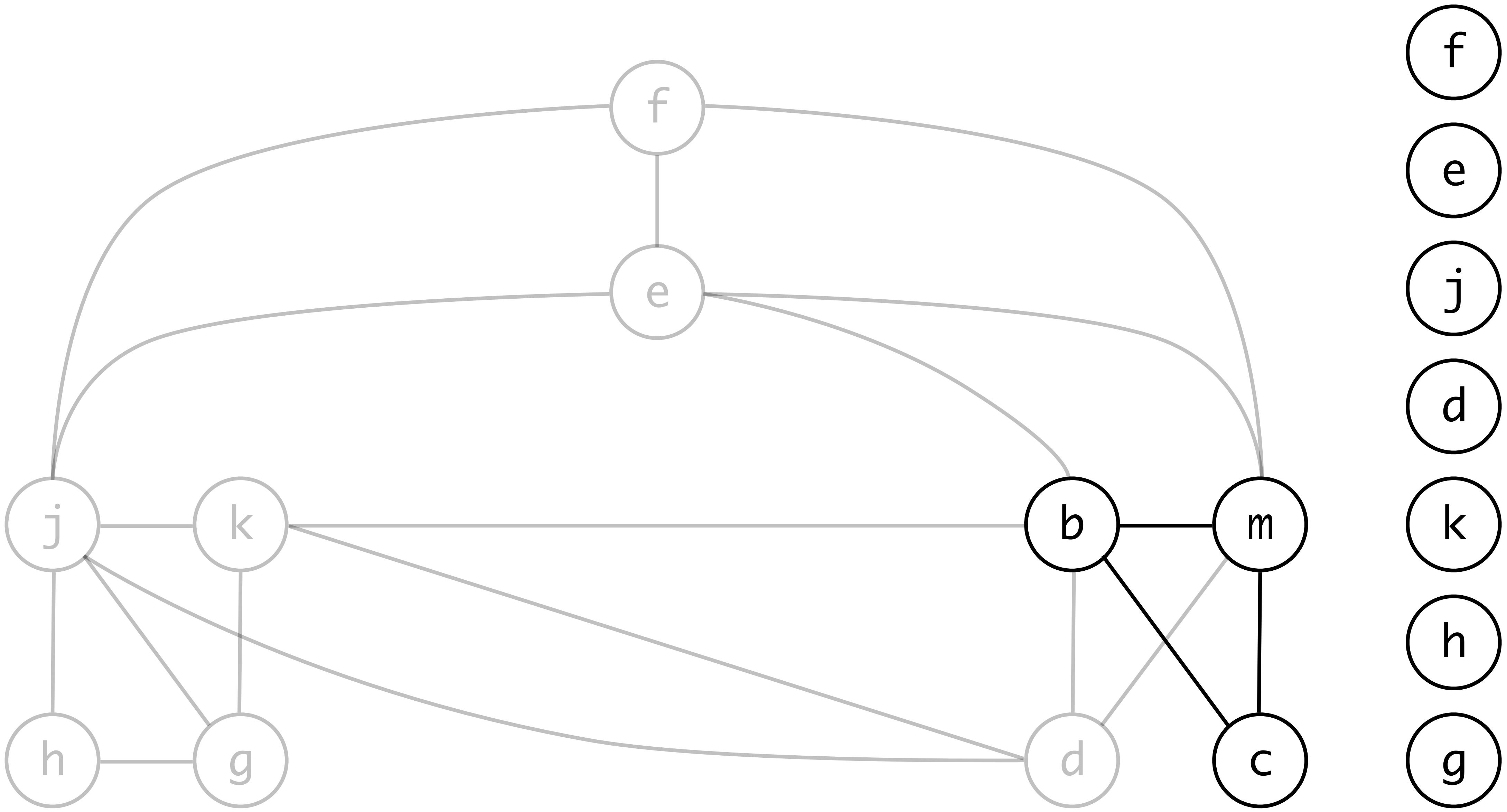
example with 4 colors

r_1

r_2

r_3

r_4



Graph Coloring

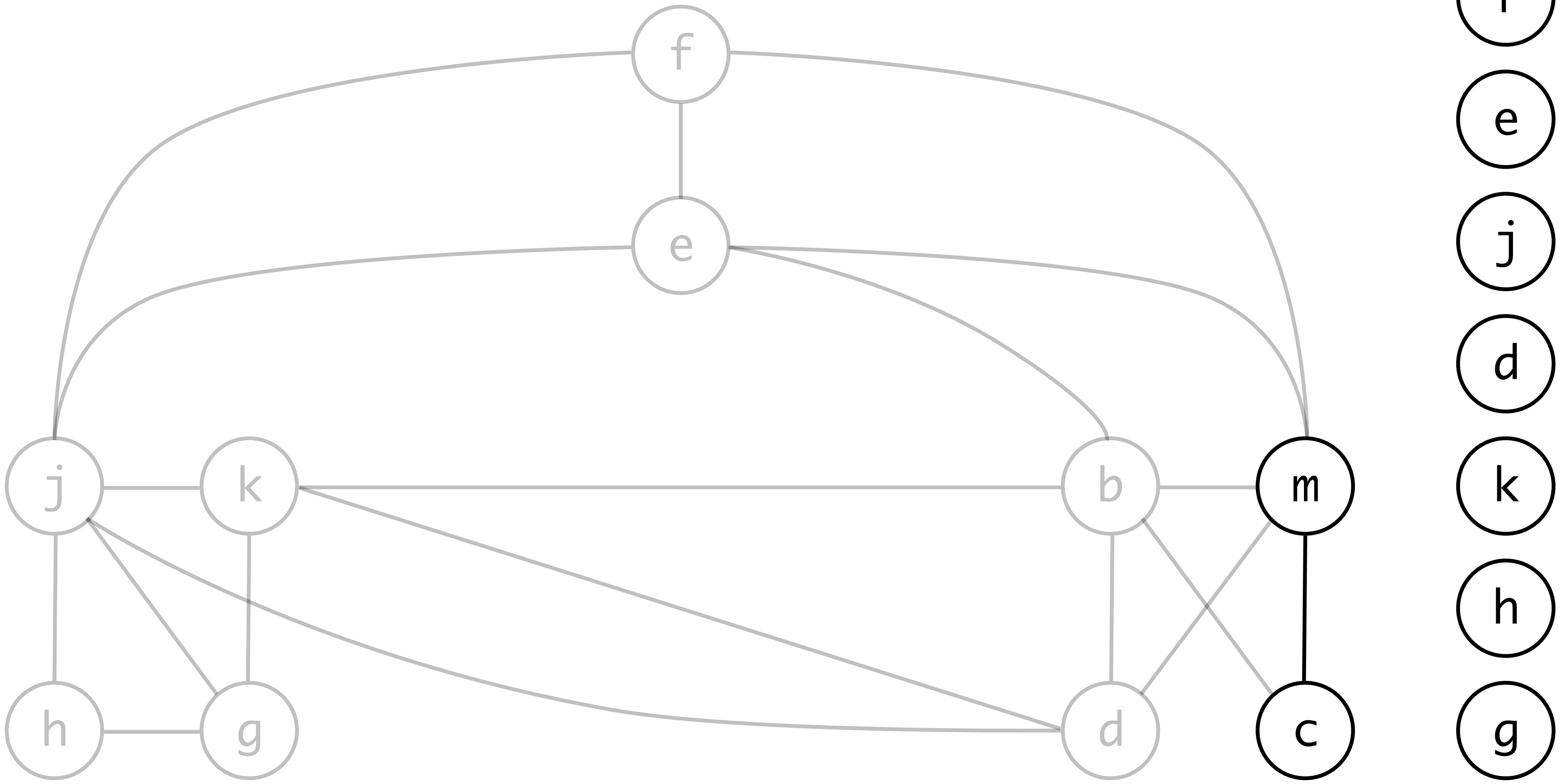
example with 4 colors

r_1

r_2

r_3

r_4

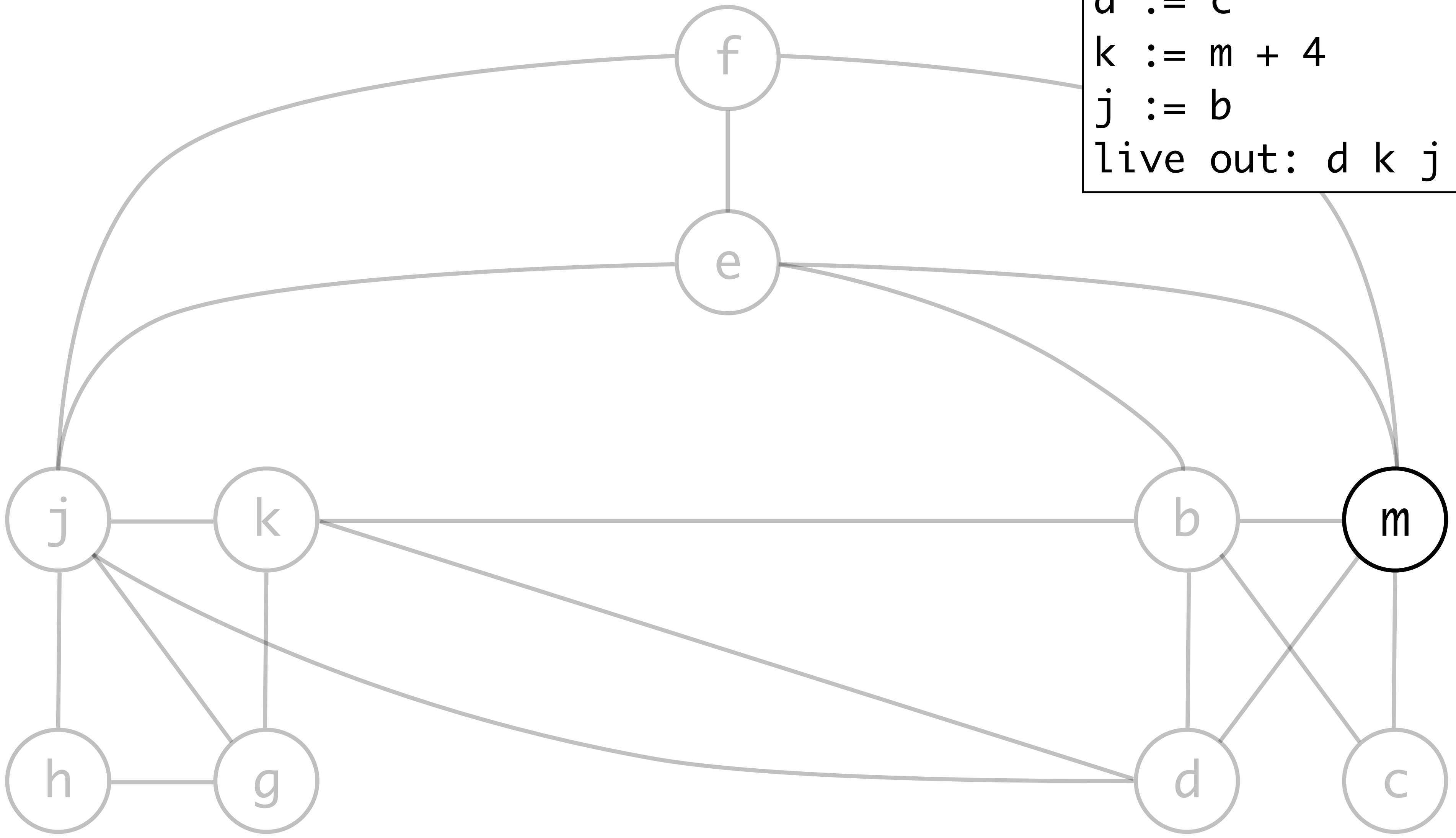


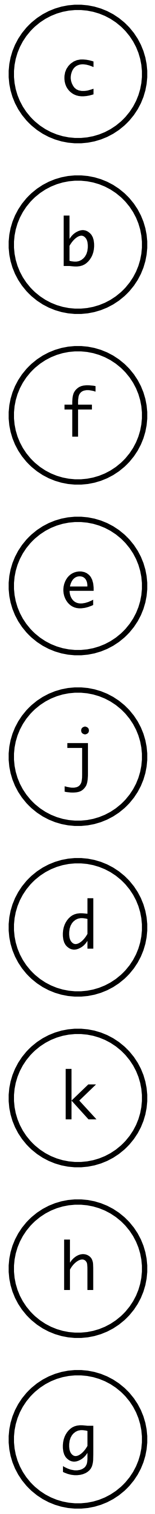
Graph Coloring

example with 4 colors

```
live-in: k j
g := mem[j + 12]
h := k - 1
f := g * h
e := mem[j + 8]
m := mem[j + 16]
b := mem[f]
c := e + 8
d := c
k := m + 4
j := b
live out: d k j
```

r_1
r_2
r_3
r_4



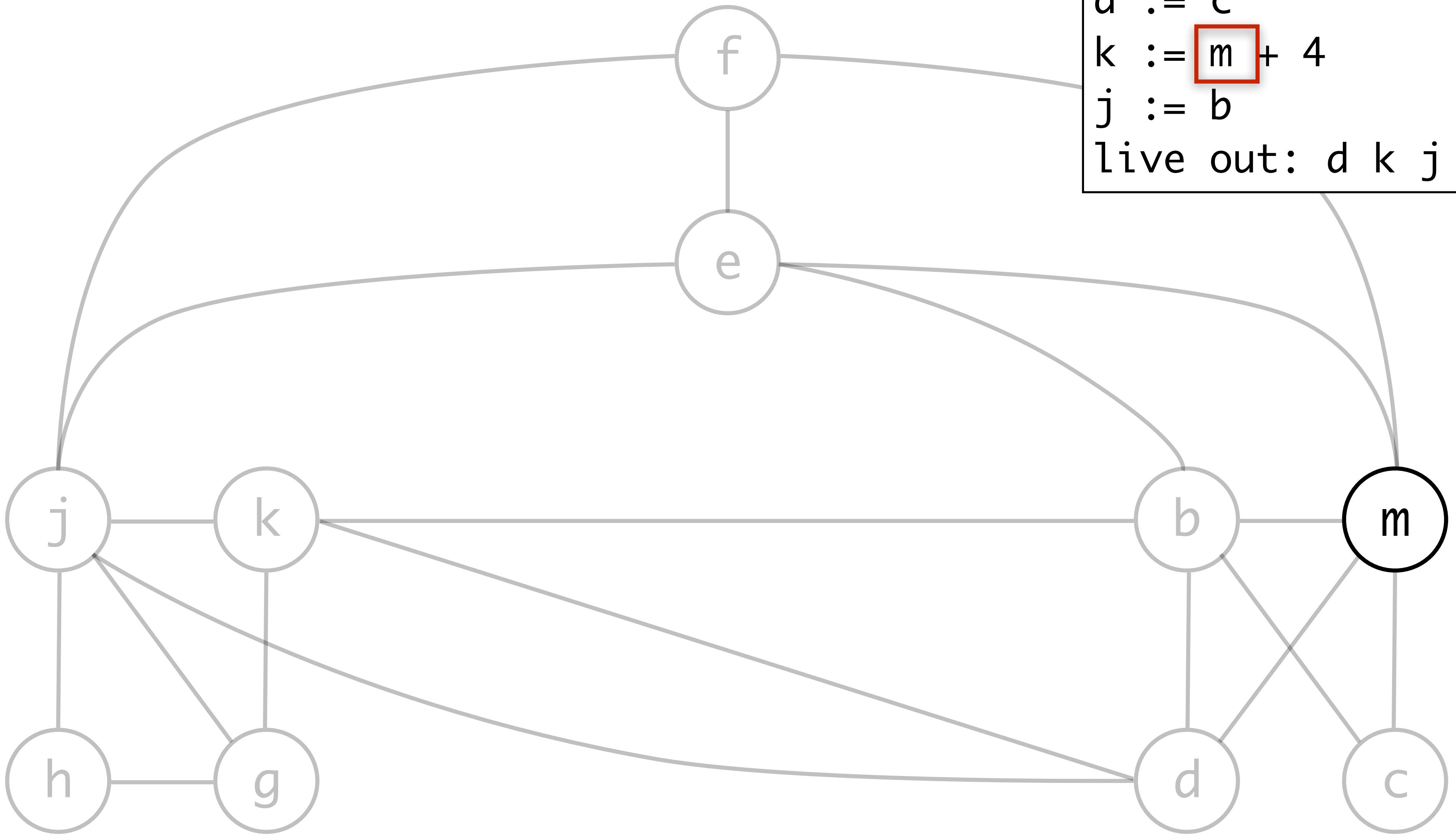


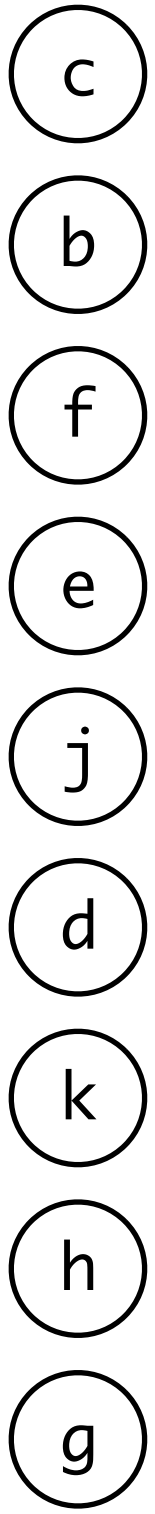
Graph Coloring

example with 4 colors

r_1
r_2
r_3
r_4

```
live-in: k j
g  := mem[j + 12]
h  := k - 1
f  := g * h
e  := mem[j + 8]
m  := mem[j + 16]
b  := mem[f]
c  := e + 8
d  := c
k  := m + 4
j  := b
live out: d k j
```

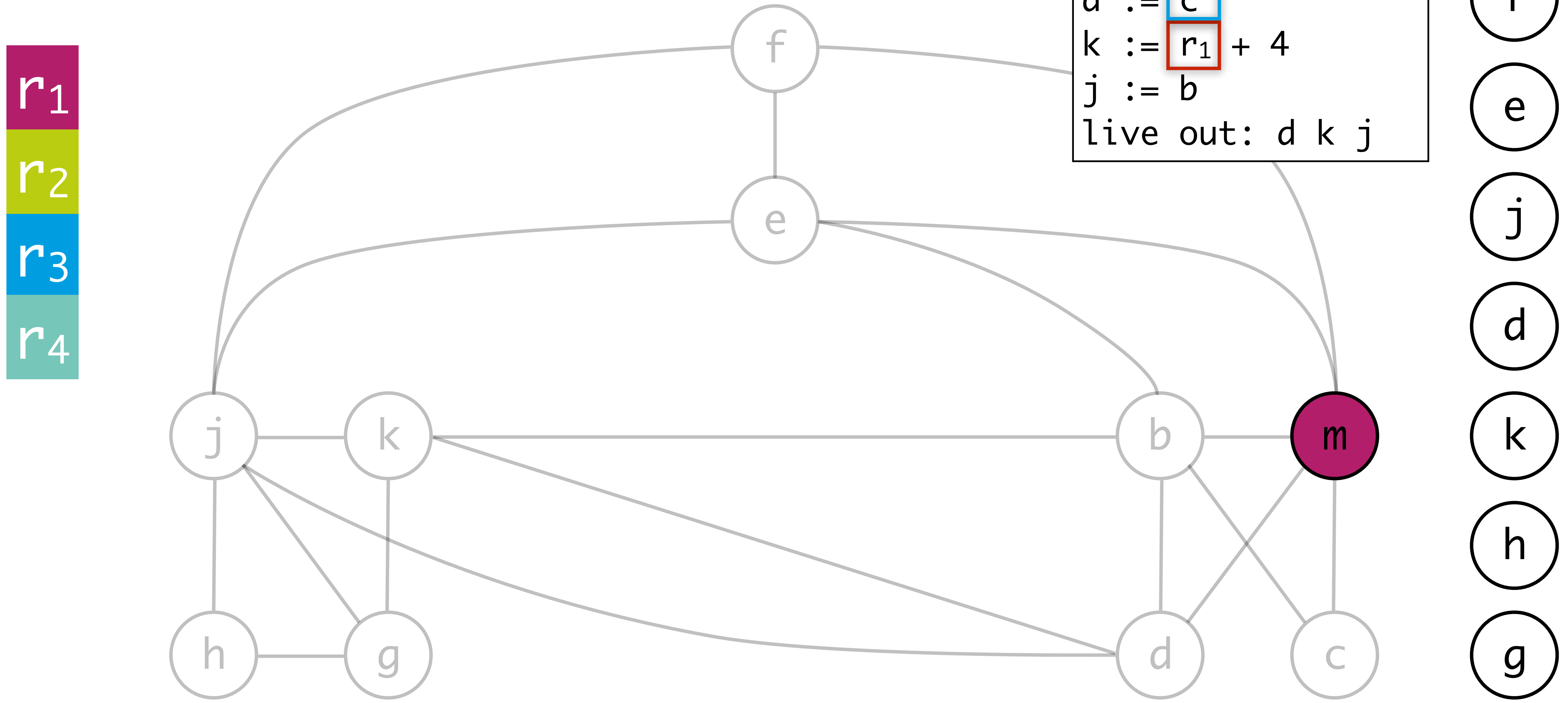




Graph Coloring

example with 4 colors

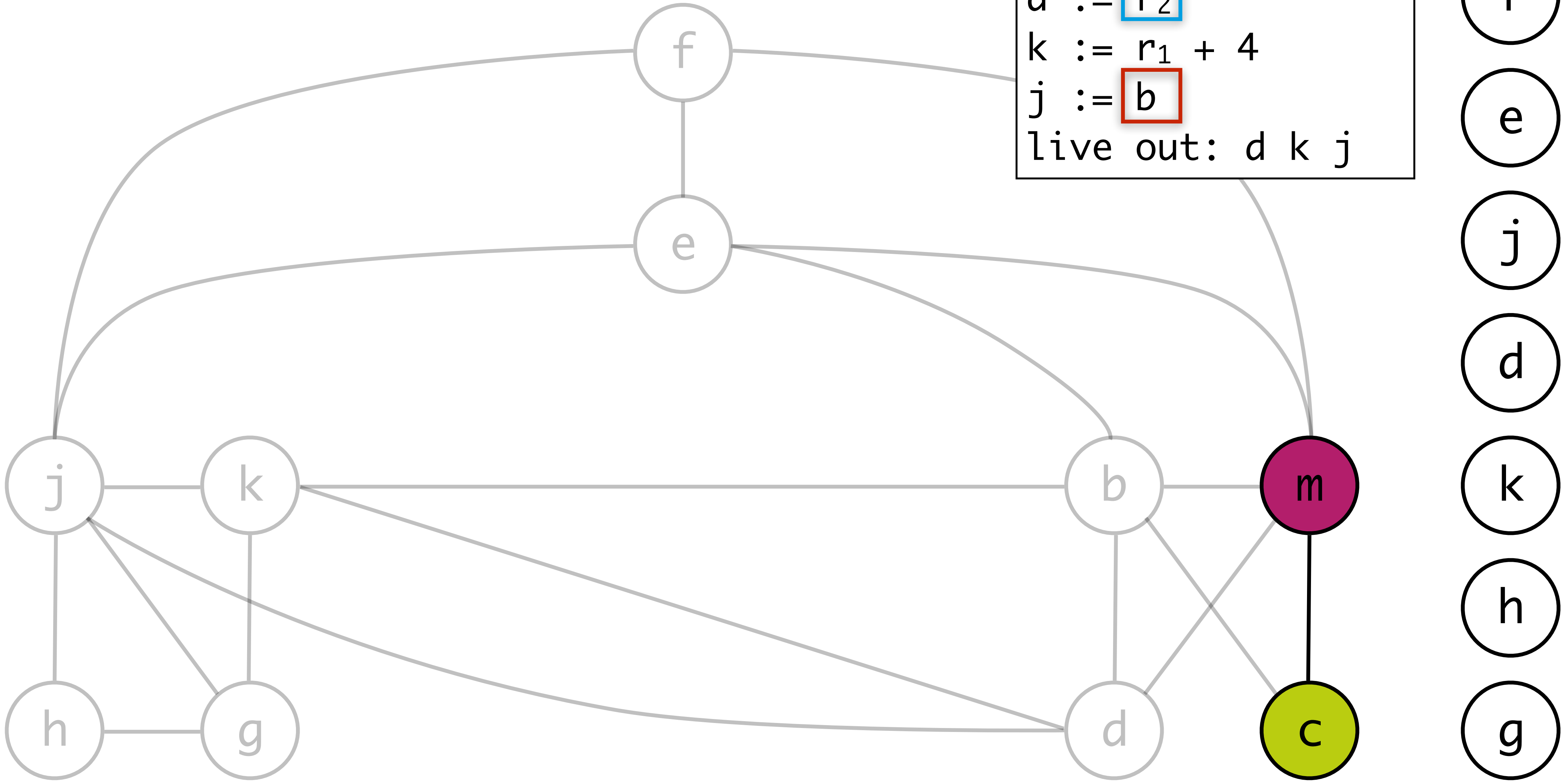
```
live-in: k j
g  := mem[j + 12]
h  := k - 1
f  := g * h
e  := mem[j + 8]
r1 := mem[j + 16]
b  := mem[f]
c  := e + 8
d  := c
k  := r1 + 4
j  := b
live out: d k j
```



Graph Coloring

example with 4 colors

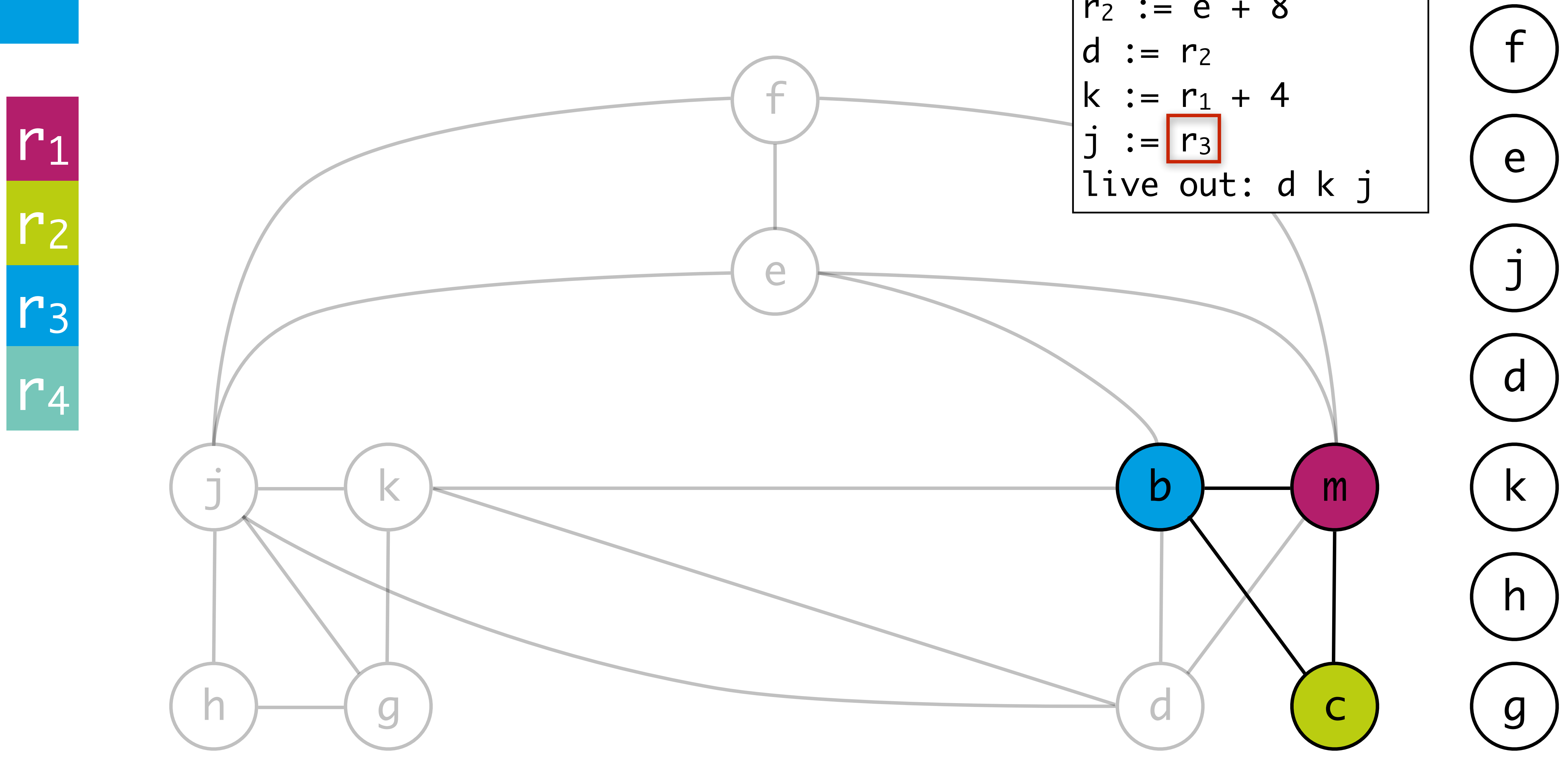
```
live-in: k j
g := mem[j + 12]
h := k - 1
f := g * h
e := mem[j + 8]
r1 := mem[j + 16]
b := mem[f]
r2 := e + 8
d := r2
k := r1 + 4
j := b
live out: d k j
```



Graph Coloring

example with 4 colors

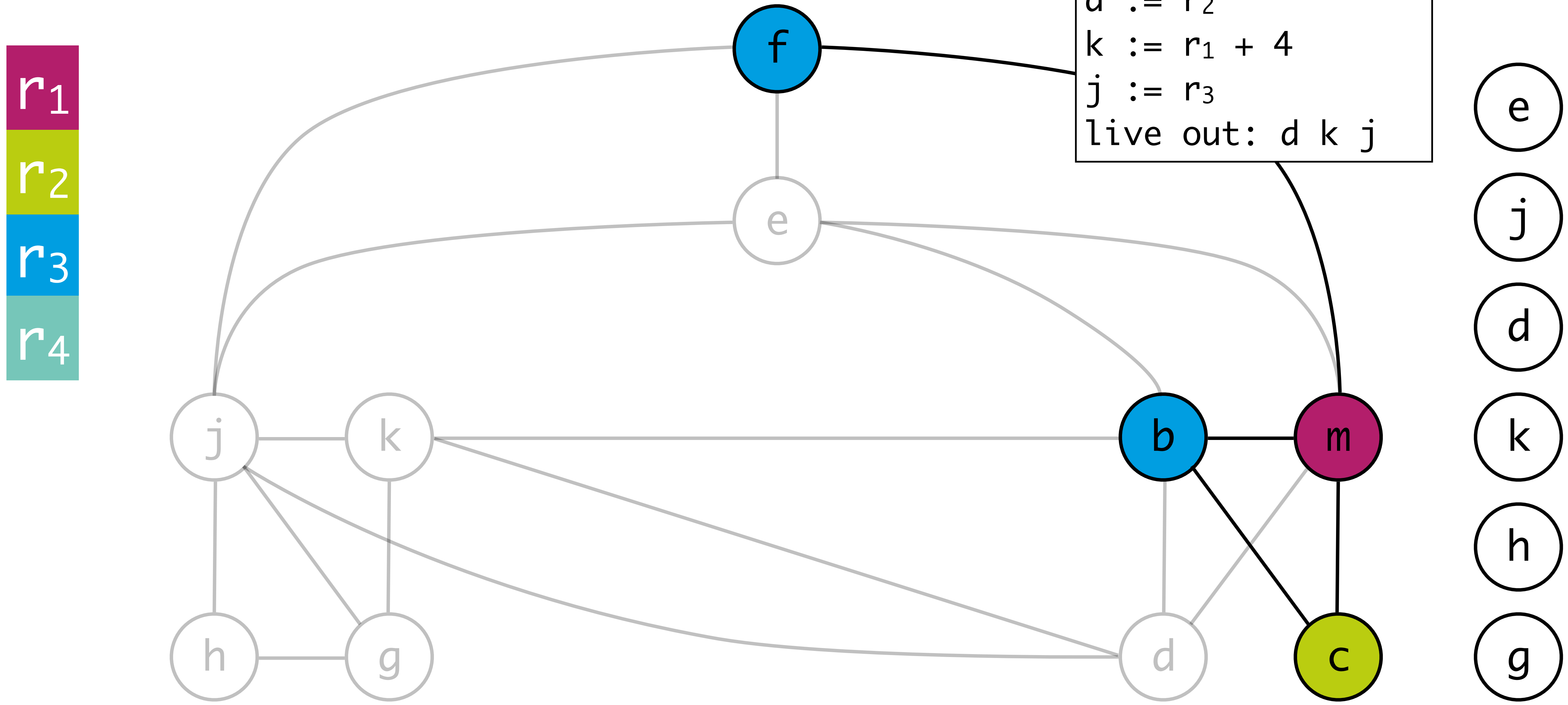
```
live-in: k j
g  := mem[j + 12]
h  := k - 1
f  := g * h
e  := mem[j + 8]
r1 := mem[j + 16]
r3 := mem[f]
r2 := e + 8
d  := r2
k  := r1 + 4
j  := r3
live out: d k j
```



Graph Coloring

example with 4 colors

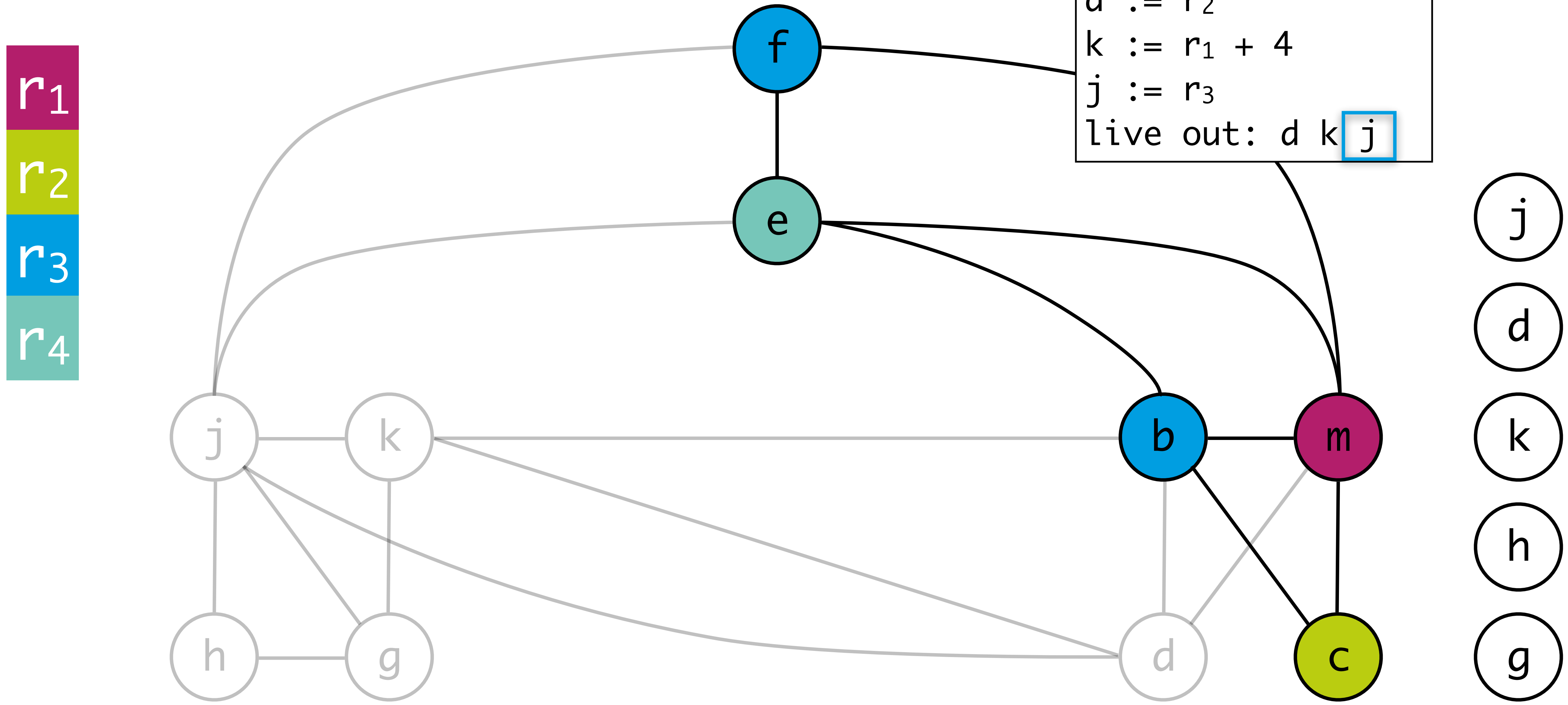
```
live-in: k j
g  := mem[j + 12]
h  := k - 1
r3  := g * h
e  := mem[j + 8]
r1 := mem[j + 16]
r3  := mem[r3]
r2  := e + 8
d  := r2
k  := r1 + 4
j  := r3
live out: d k j
```



Graph Coloring

example with 4 colors

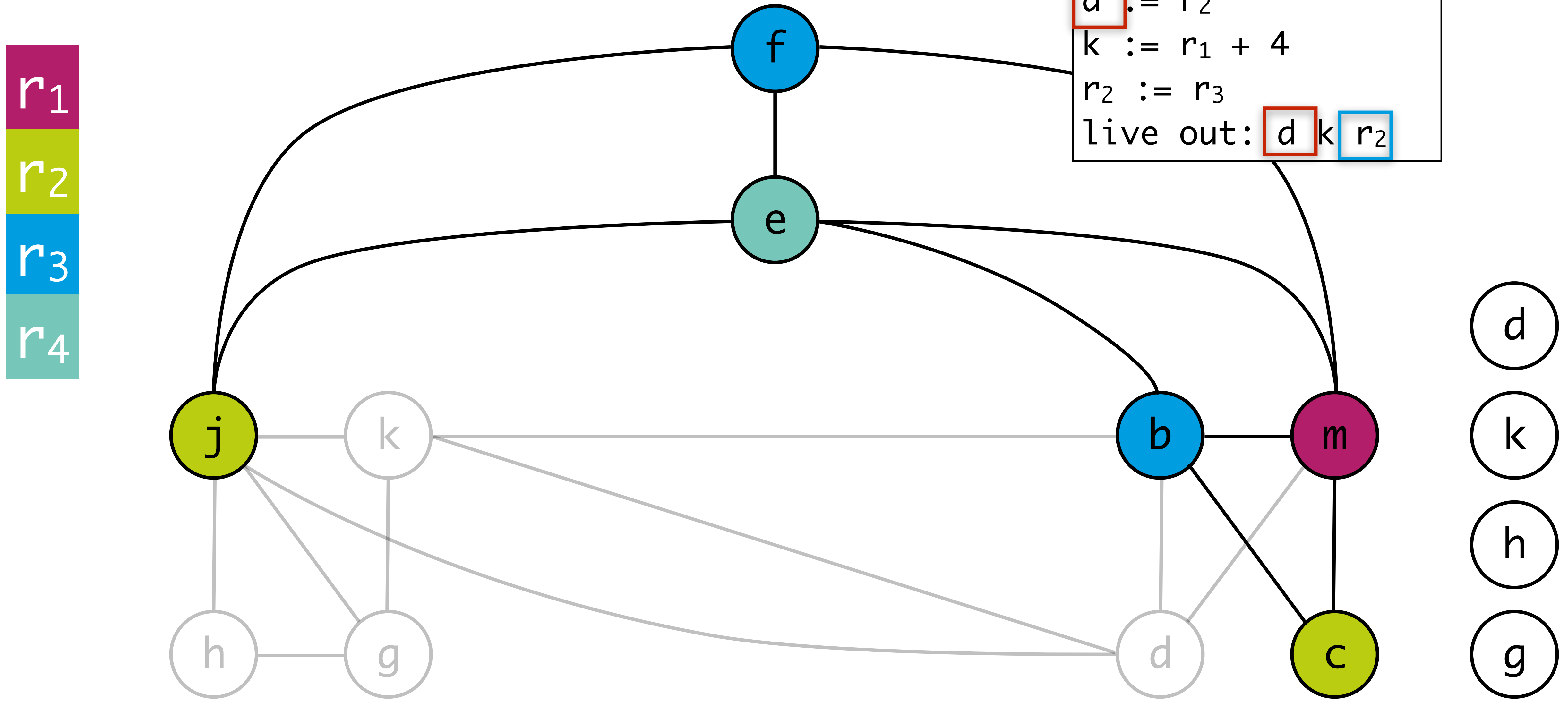
```
live-in: k j
g  := mem[j + 12]
h  := k - 1
r3  := g * h
r4  := mem[j + 8]
r1 := mem[j + 16]
r3  := mem[r3]
r2  := r4 + 8
d  := r2
k  := r1 + 4
j  := r3
live out: d k j
```



Graph Coloring

example with 4 colors

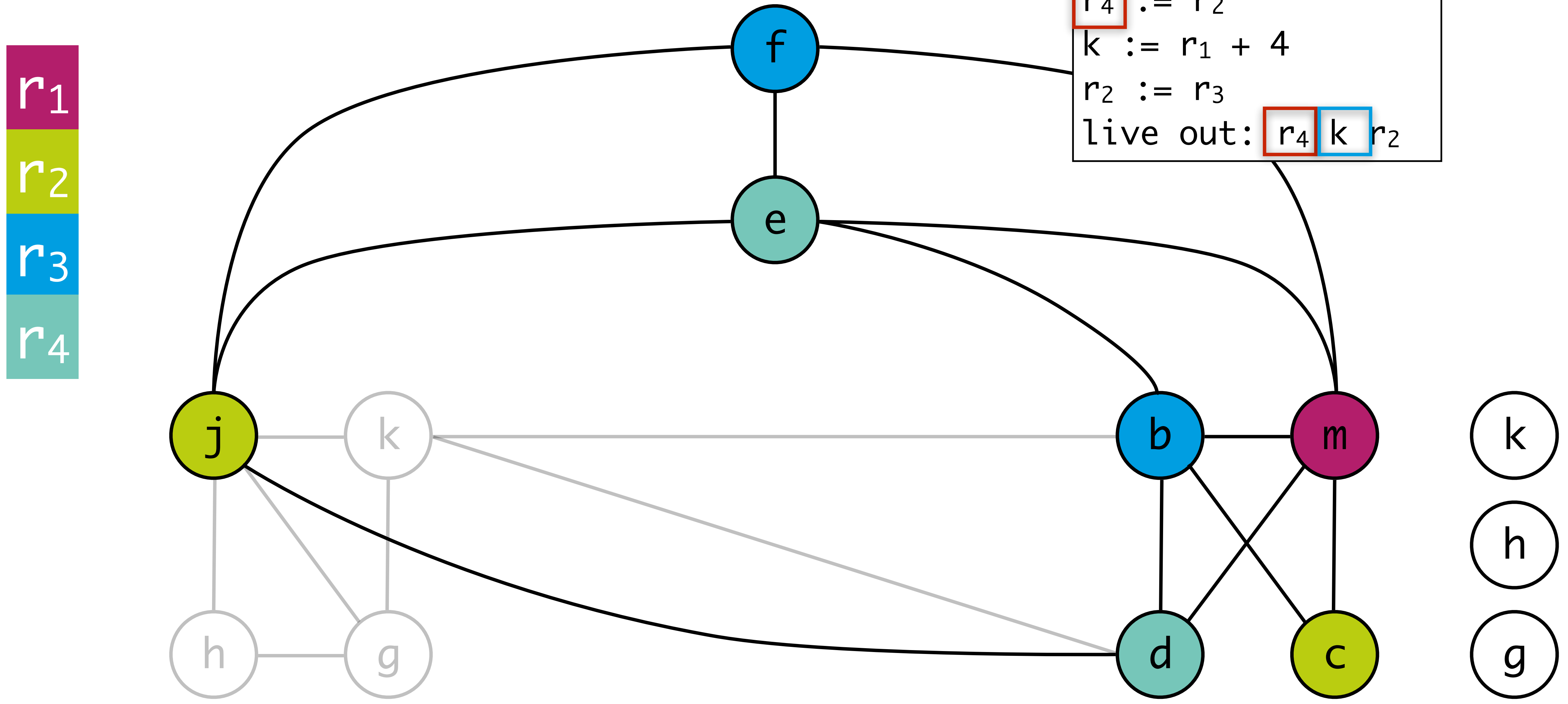
```
live-in: k r2
g  := mem[r2 + 12]
h  := k - 1
r3  := g * h
r4  := mem[r2 + 8]
r1 := mem[r2 + 16]
r3  := mem[r3]
r2  := r4 + 8
d  := r2
k  := r1 + 4
r2  := r3
live out: d k r2
```



Graph Coloring

example with 4 colors

```
live-in: k r2
g  := mem[r2 + 12]
h  := k + 1
r3  := g * h
r4  := mem[r2 + 8]
r1 := mem[r2 + 16]
r3  := mem[r3]
r2  := r4 + 8
r4  := r2
k  := r1 + 4
r2  := r3
live out: r4 k r2
```

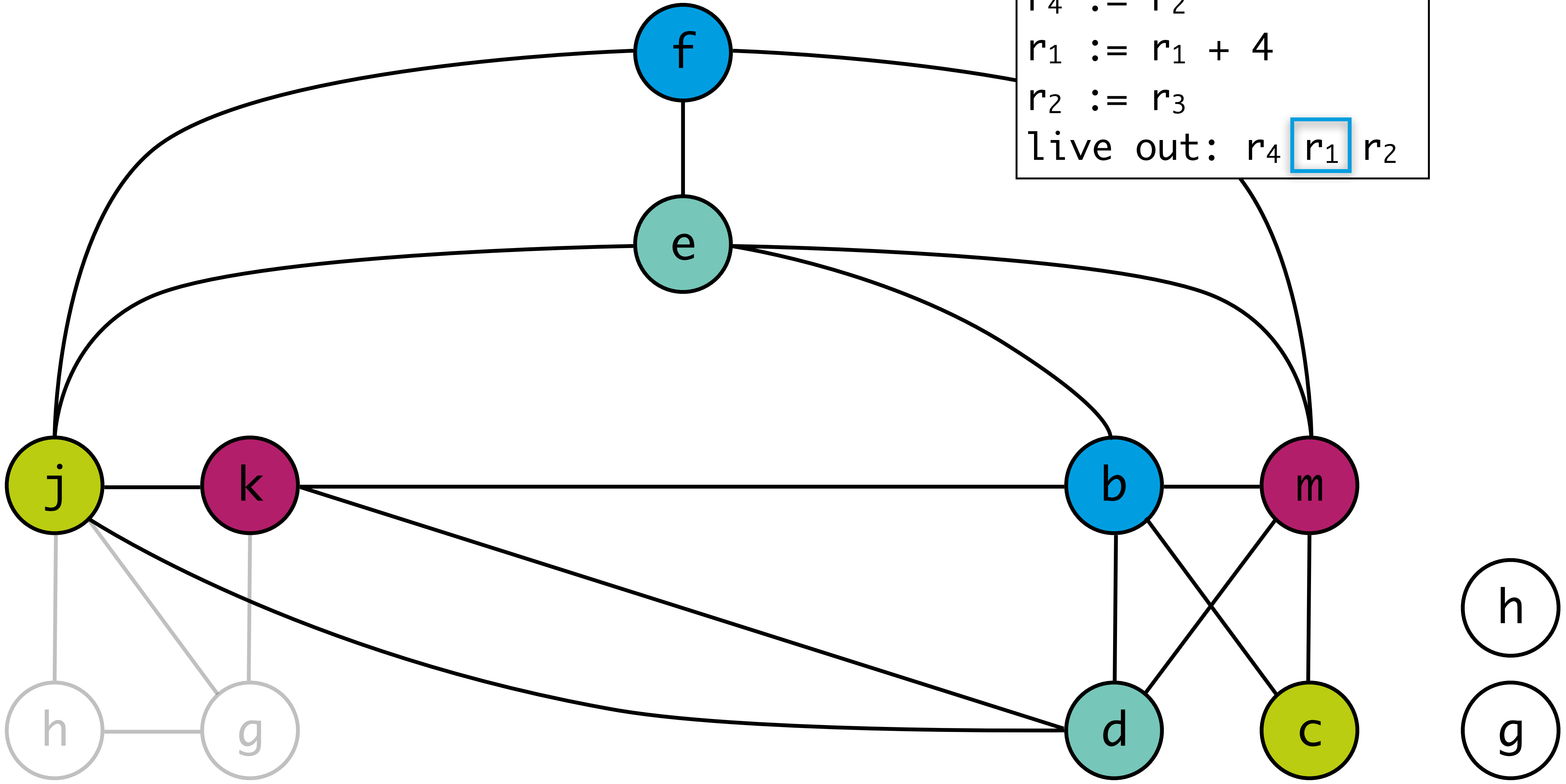


Graph Coloring

example with 4 colors

r_1
r_2
r_3
r_4

```
live-in: r1 r2
g  := mem[r2 + 12]
h  := r1 - 1
r3  := g * h
r4  := mem[r2 + 8]
r1 := mem[r2 + 16]
r3  := mem[r3]
r2  := r4 + 8
r4  := r2
r1  := r1 + 4
r2  := r3
live out: r4 r1 r2
```

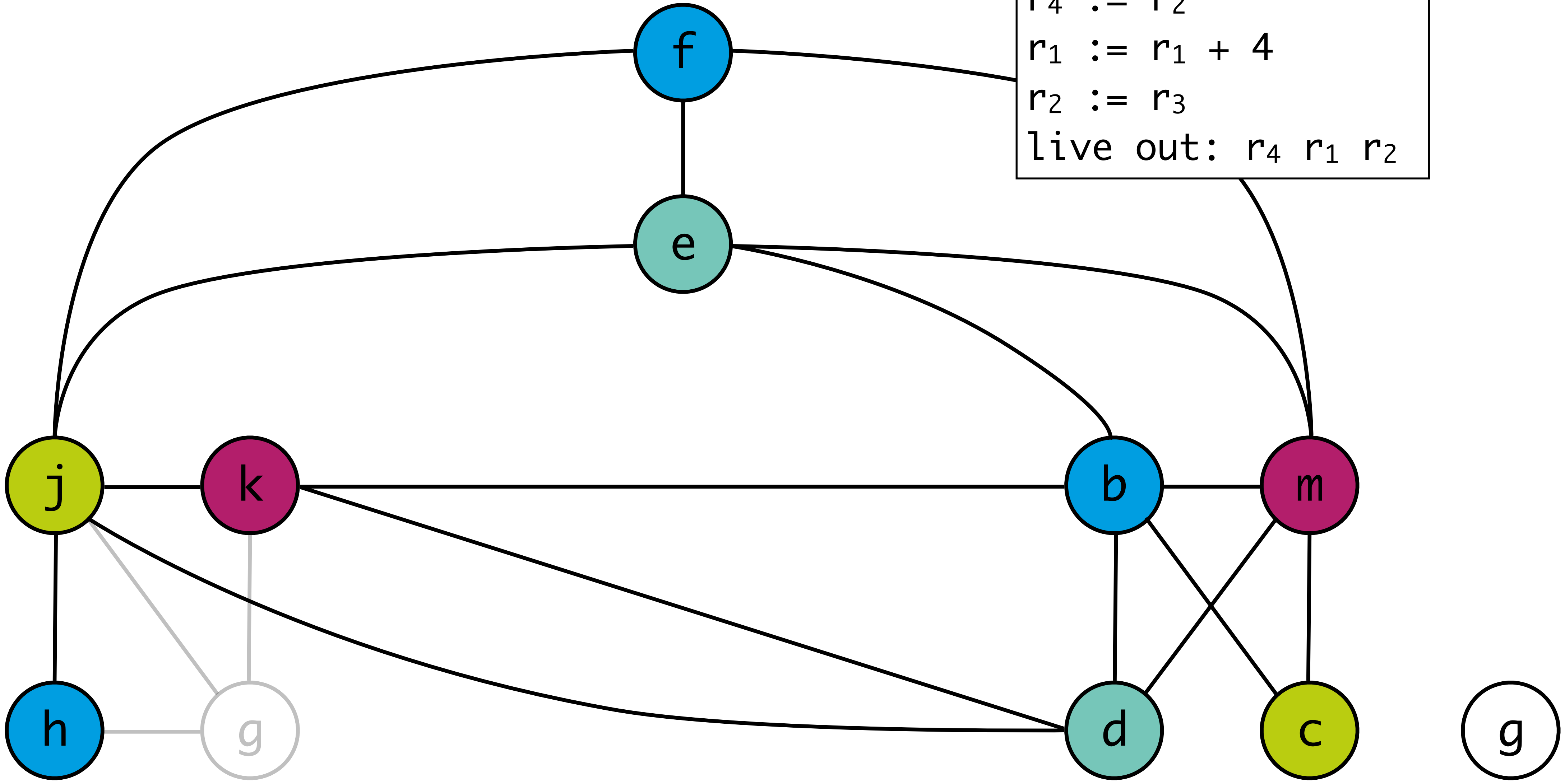


Graph Coloring

example with 4 colors

```
live-in: r1 r2
g := mem[r2 + 12]
r3 := r1 - 1
r3 := g * r3
r4 := mem[r2 + 8]
r1 := mem[r2 + 16]
r3 := mem[r3]
r2 := r4 + 8
r4 := r2
r1 := r1 + 4
r2 := r3
live out: r4 r1 r2
```

r_1
r_2
r_3
r_4



Graph Coloring

example with 4 colors

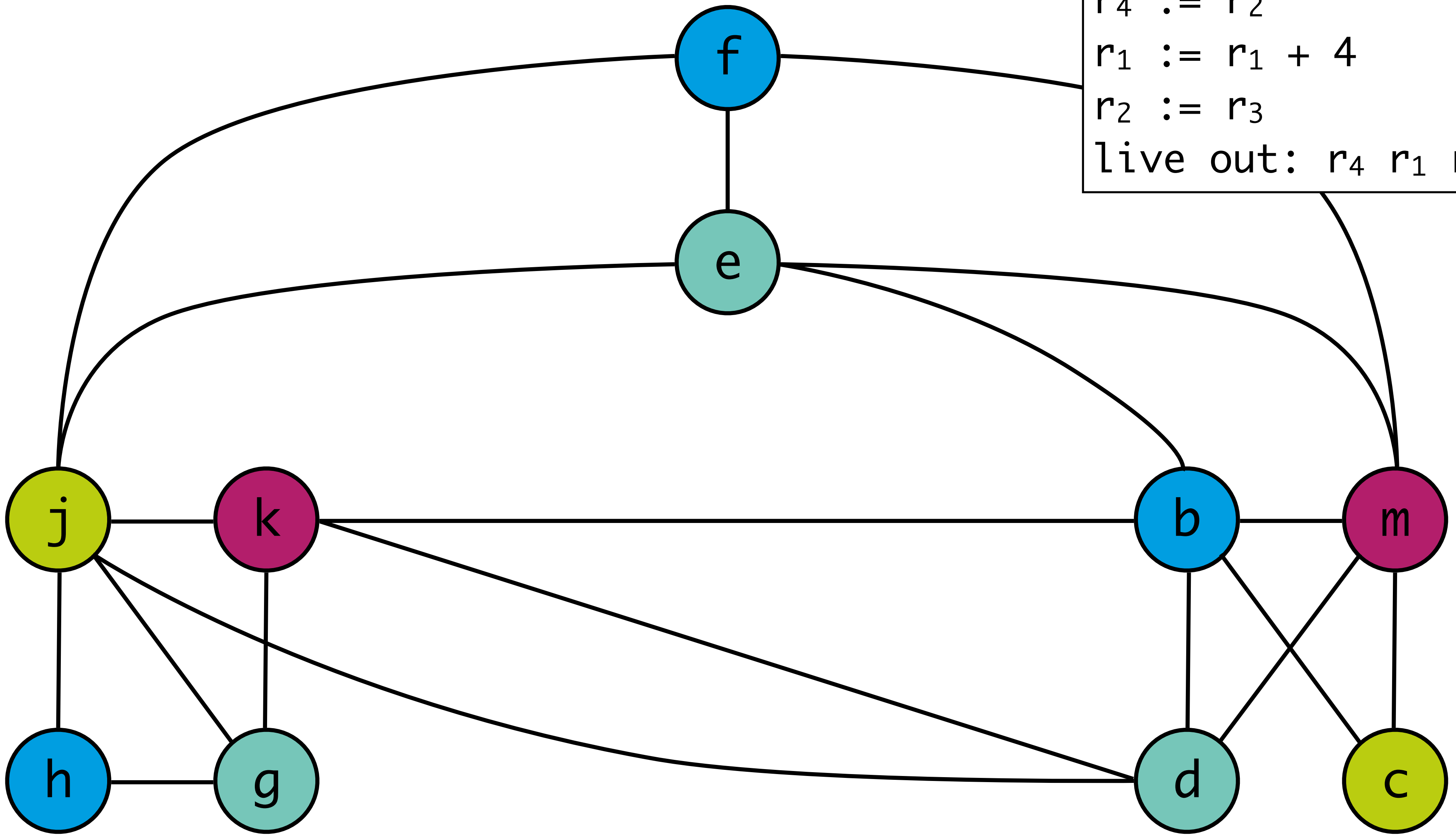
```
live-in: r1 r2
r4 := mem[r2 + 12]
r3 := r1 - 1
r3 := r4 * r3
r4 := mem[r2 + 8]
r1 := mem[r2 + 16]
r3 := mem[r3]
r2 := r4 + 8
r4 := r2
r1 := r1 + 4
r2 := r3
live out: r4 r1 r2
```

r_1

r_2

r_3

r_4



III

Spilling

Optimistic Coloring
steps

Simplify

remove node of insignificant degree (fewer than k edges)

Spill

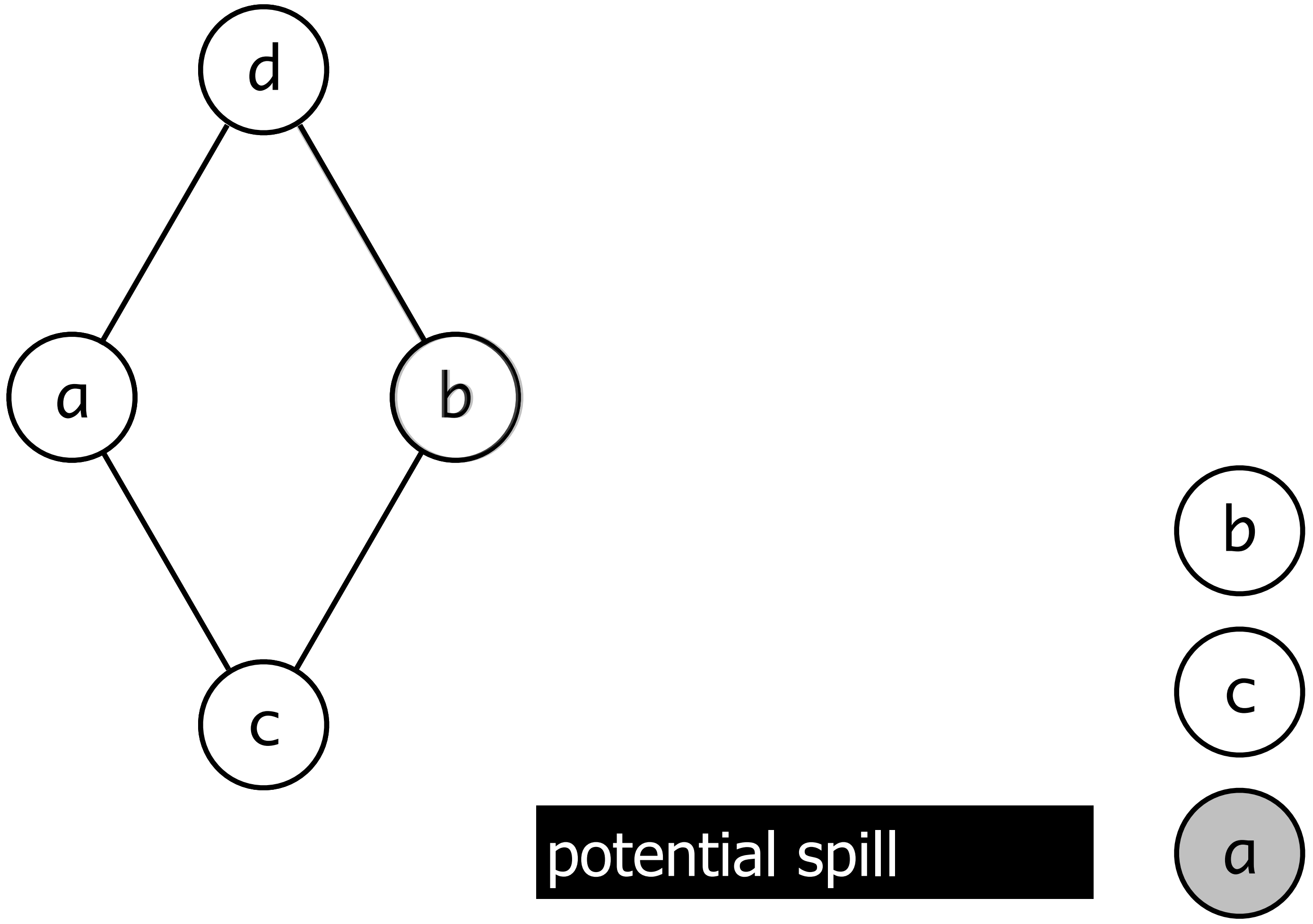
remove node of significant degree (k or more edges)

Select

add node, select color

Optimistic Coloring

example with 2 colors



Spilling

steps

Simplify

remove node of insignificant degree (less than k edges)

Spill

remove node of significant degree (k or more edges)

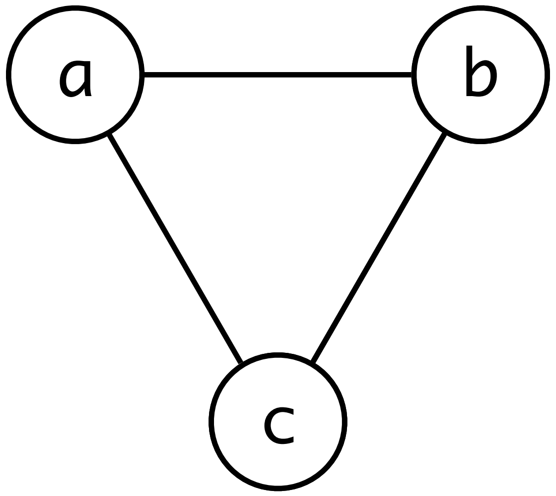
Select

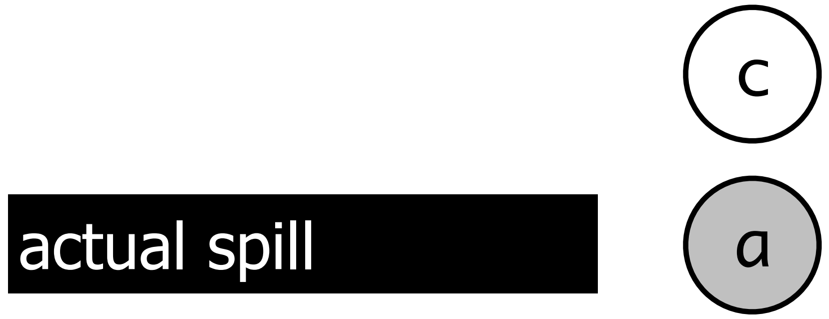
add node, select color

Actual spill

Start over

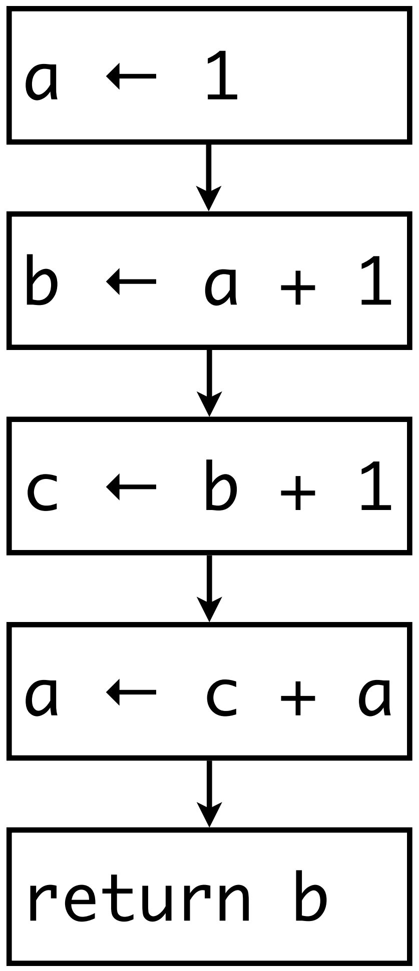
Spilling
example with 2 colors





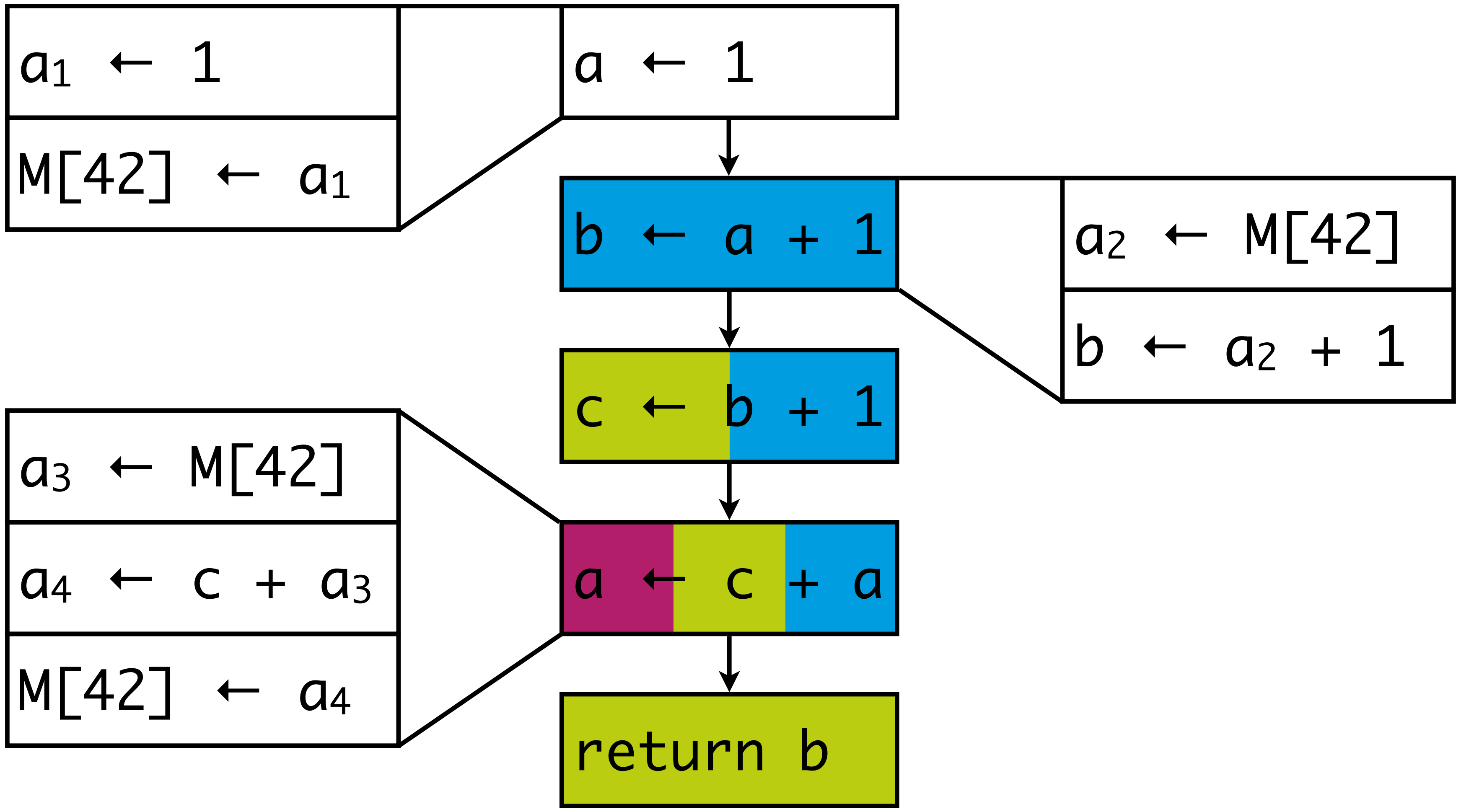
Spilling

example



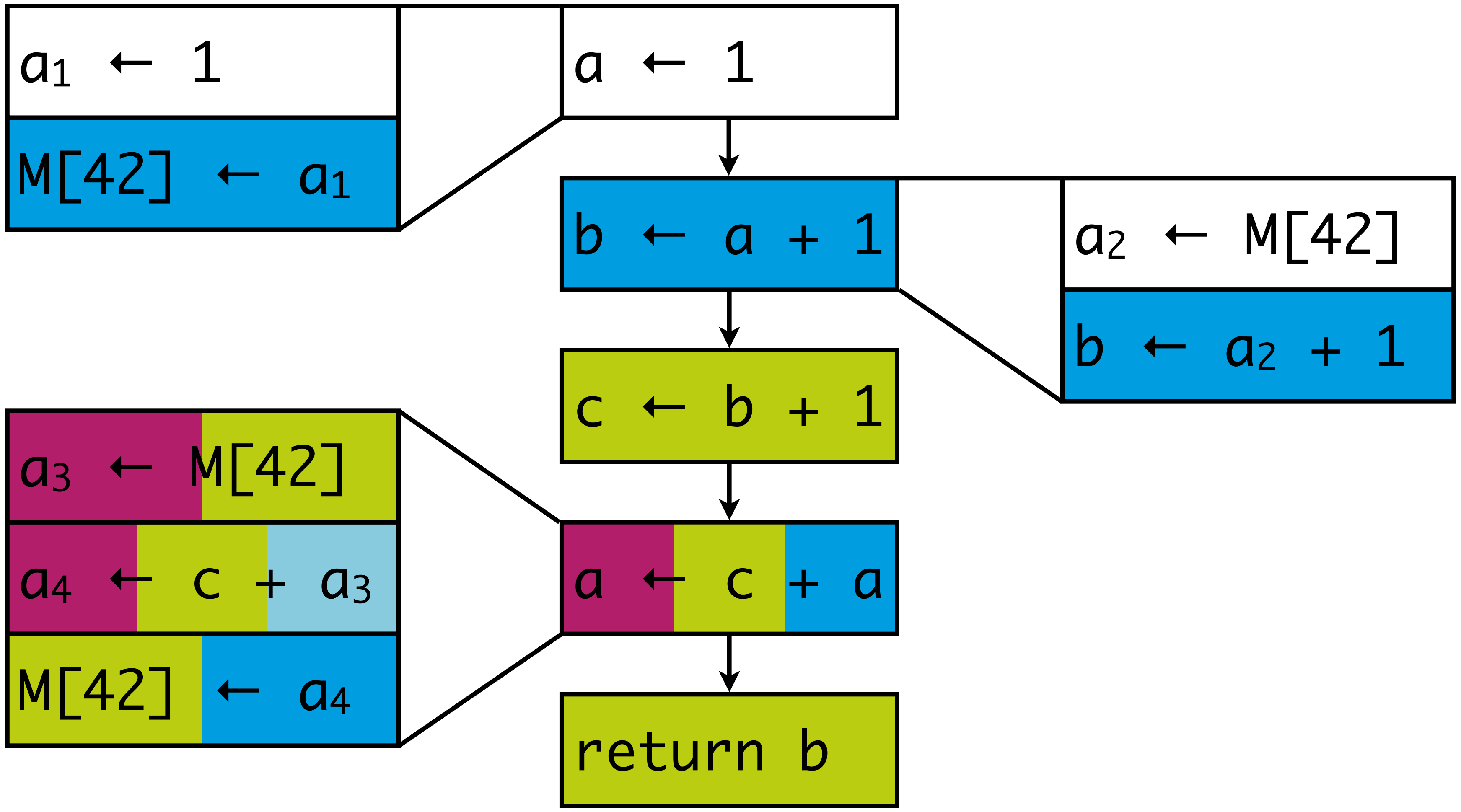
Spilling

example



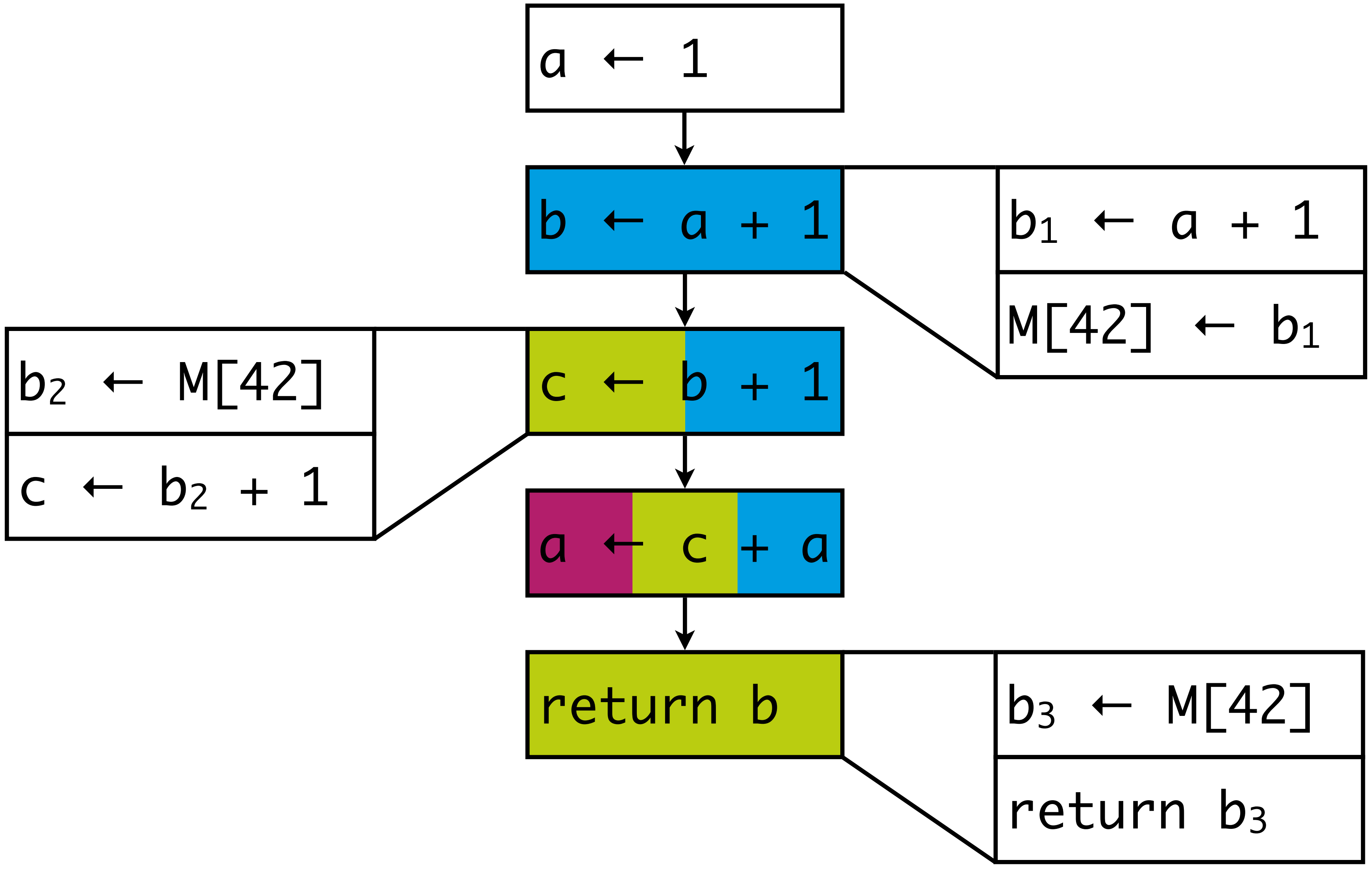
Spilling

example



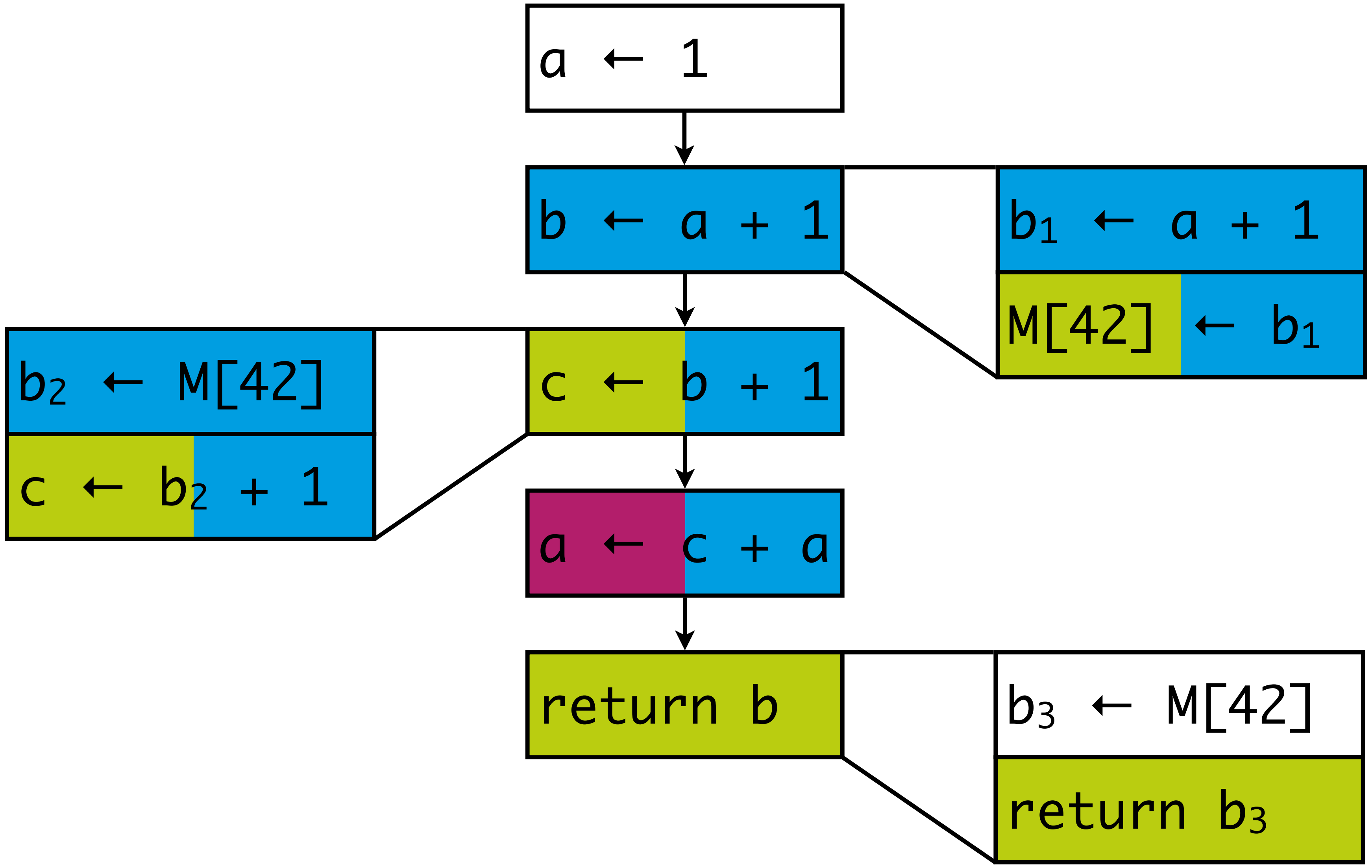
Spilling

example



Spilling

example



IV

Coalescing

Eliminating Move Instructions

coalescing

```
live-in: k j
g := mem[j + 12]
h := k - 1
f := g * h
e := mem[j + 8]
m := mem[j + 16]
b := mem[f]
c := e + 8
d := c
k := m + 4
j := b
live out: d k j
```

Eliminating Move Instructions

coalescing

```
live-in: k j
g := mem[j + 12]
h := k - 1
f := g * h
e := mem[j + 8]
m := mem[j + 16]
b := mem[f]
c := e + 8
d := c
k := m + 4
j := b
live out: d k j
```

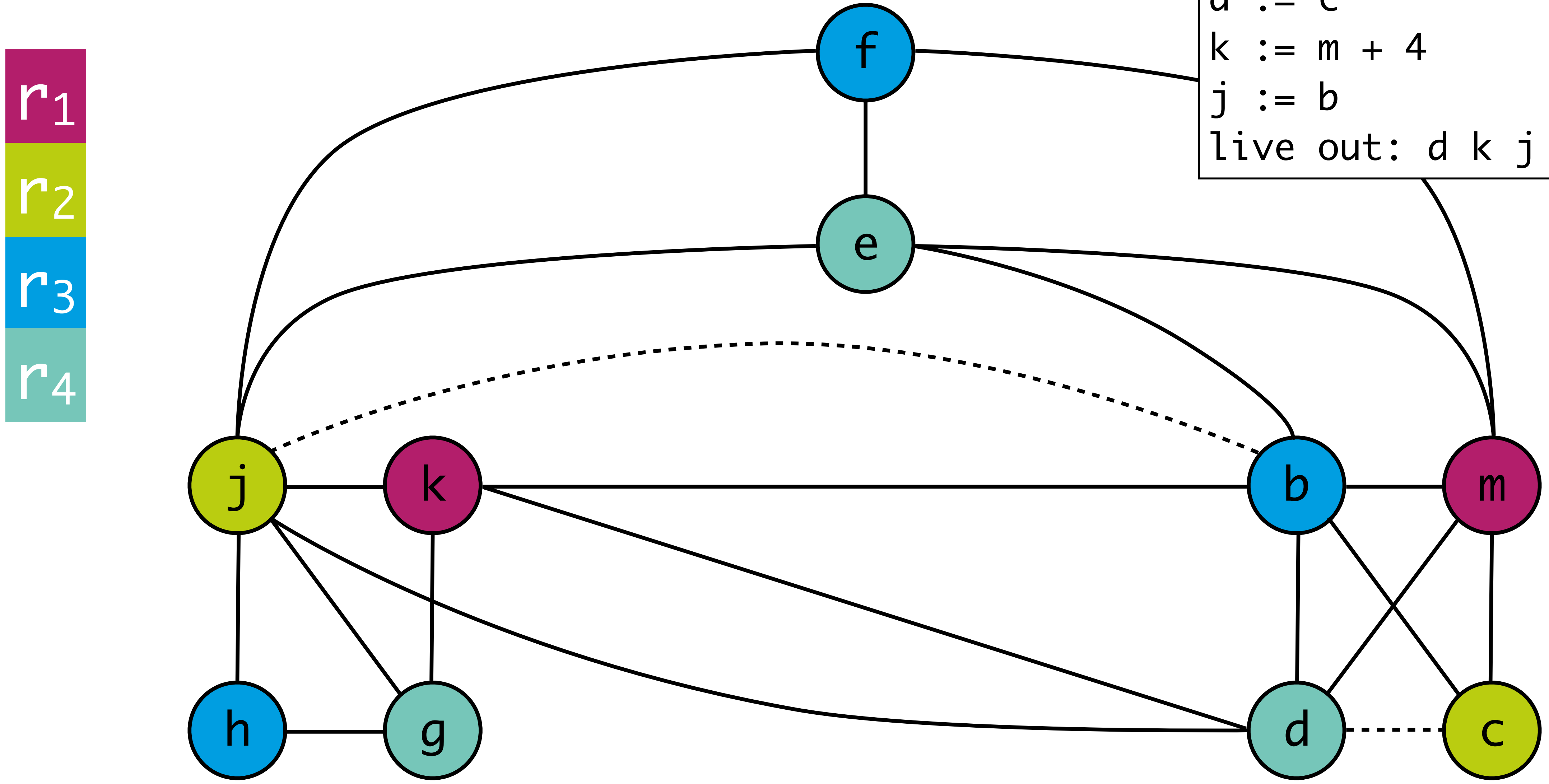
Coalescing

coalesce |ˌkəʊəˈlɛs|
verb *[no object]*
come together to form one mass or whole: *the puddles had **coalesced into** shallow streams*.
• *[with object]* combine (elements) in a mass or whole: *his idea served to **coalesce** all that happened **into** one connected whole*.

Recap: Graph Coloring

example

```
live-in: k j
g  := mem[j + 12]
h  := k - 1
f  := g * h
e  := mem[j + 8]
m := mem[j + 16]
b  := mem[f]
c  := e + 8
d  := c
k  := m + 4
j  := b
live out: d k j
```

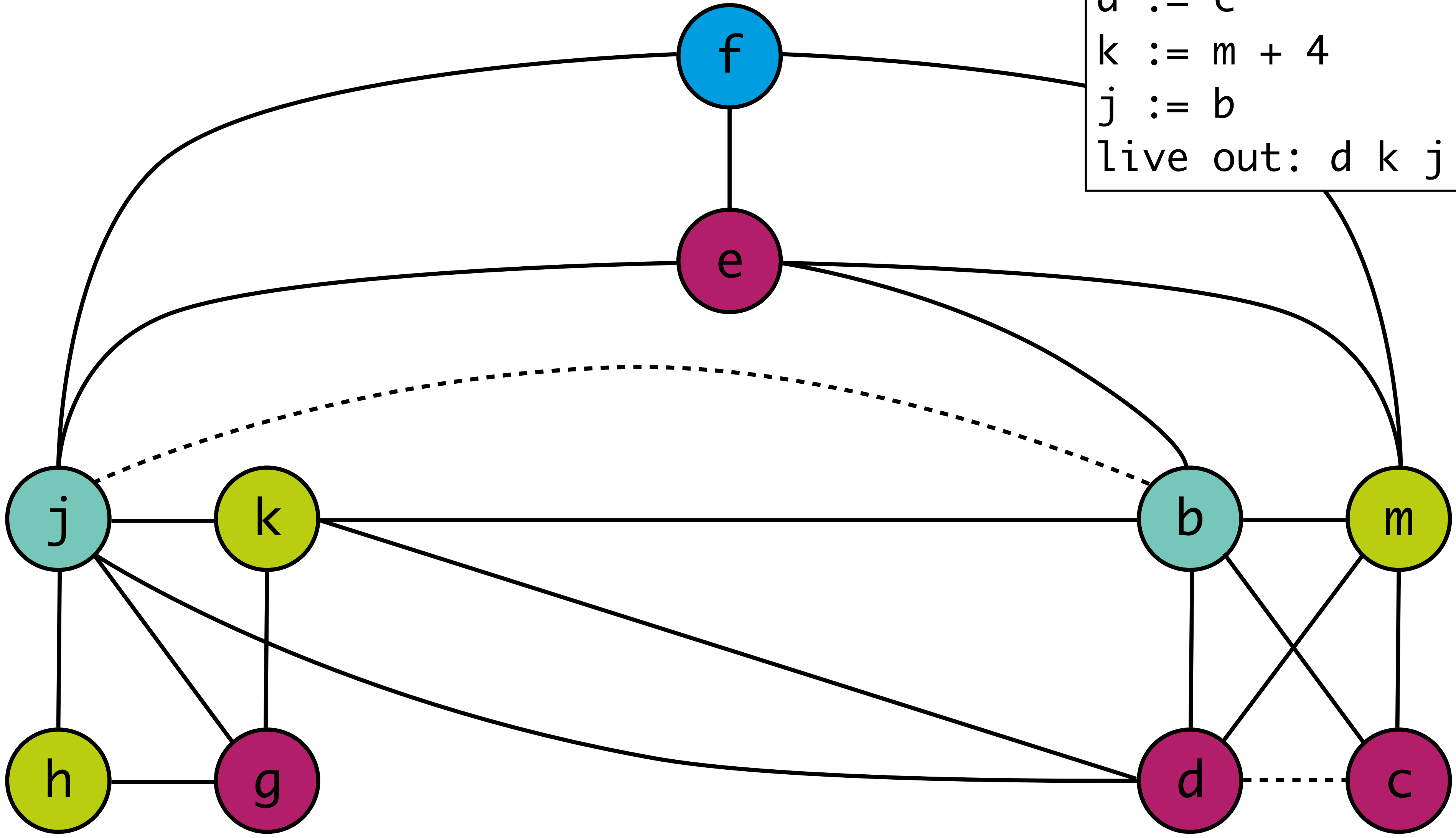


Coalescing

better solution

r_1
r_2
r_3
r_4

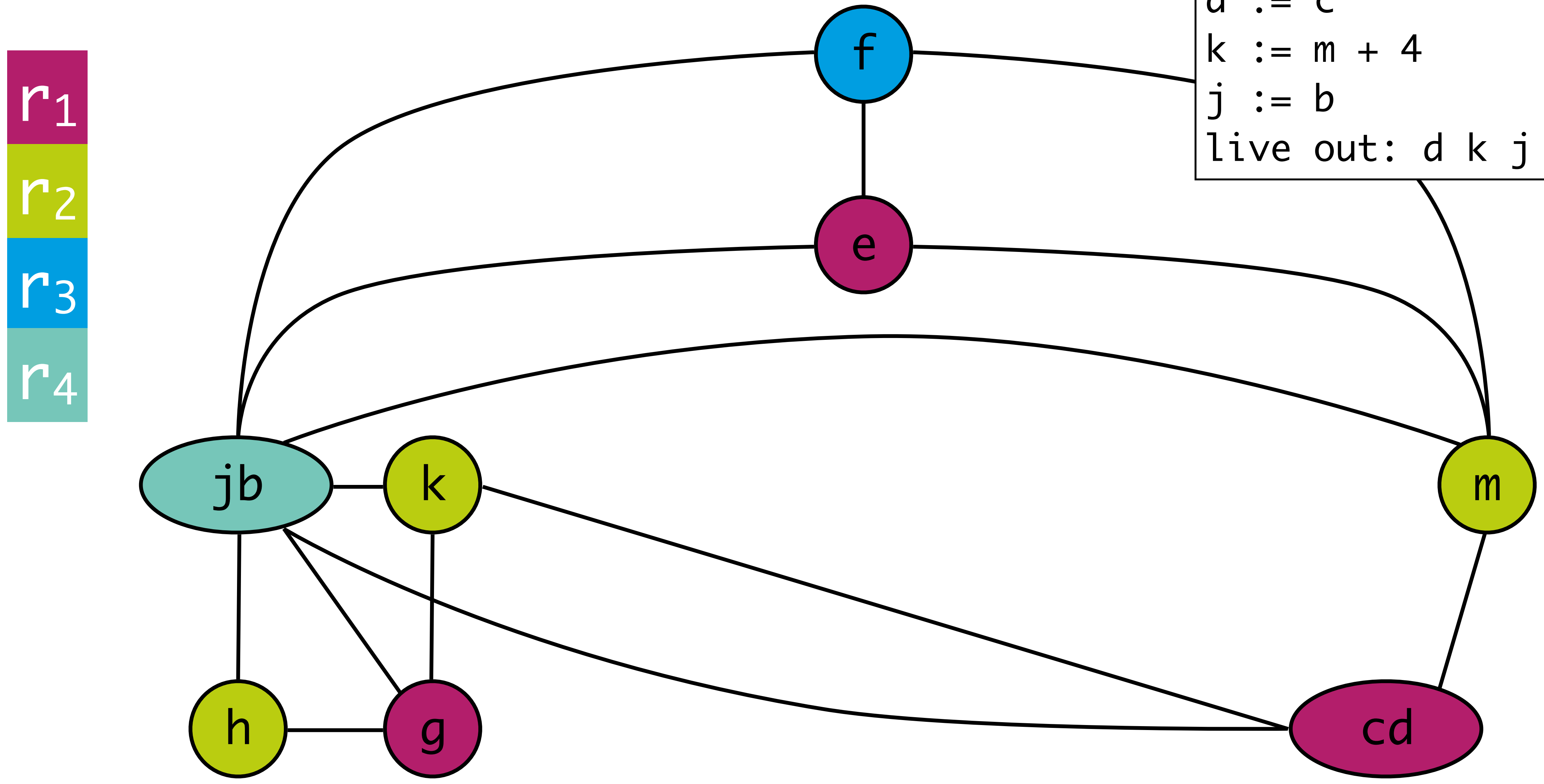
```
live-in: k j
g := mem[j + 12]
h := k - 1
f := g * h
e := mem[j + 8]
m := mem[j + 16]
b := mem[f]
c := e + 8
d := c
k := m + 4
j := b
live out: d k j
```



Coalescing

coalescing nodes

```
live-in: k j
g := mem[j + 12]
h := k - 1
f := g * h
e := mem[j + 8]
m := mem[j + 16]
b := mem[f]
c := e + 8
d := c
k := m + 4
j := b
live out: d k j
```



Coalescing

conservative strategies

Briggs

- a/b has fewer than k neighbours of significant degree
- nodes of insignificant degree and a/b can be simplified
- remaining graph is colorable

George

- all neighbours of a of significant degree interfere also with b
- neighbours of a of insignificant degree can be simplified
- subgraph of original graph is colorable

Graph Coloring

steps

Simplify

remove non-move-related node of insignificant degree

Coalesce

Freeze

turn move-related node of insignificant degree into non-move-related

Spill

Select

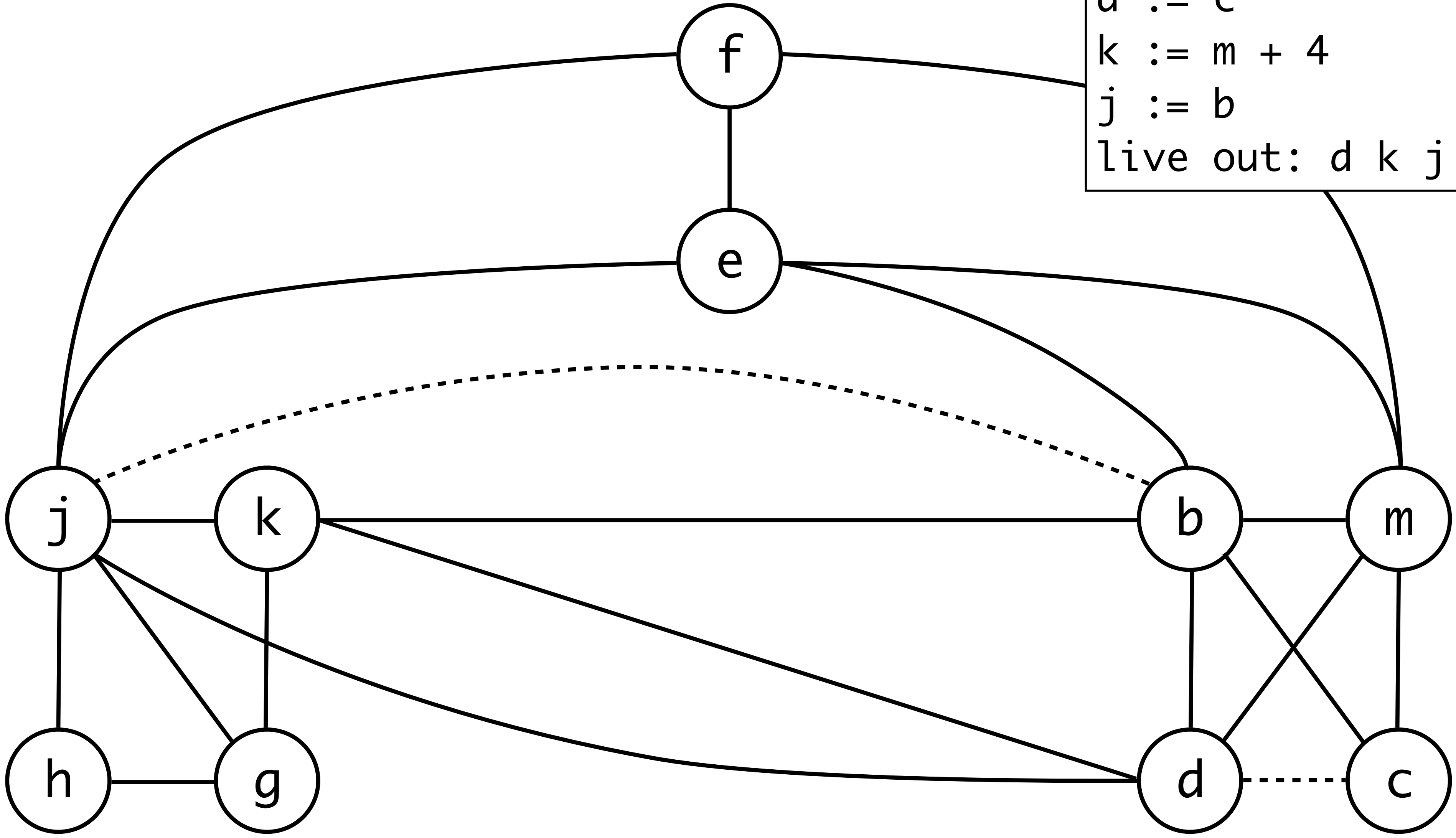
Start over

Coalescing

example

```
live-in: k j
g := mem[j + 12]
h := k - 1
f := g * h
e := mem[j + 8]
m := mem[j + 16]
b := mem[f]
c := e + 8
d := c
k := m + 4
j := b
live out: d k j
```

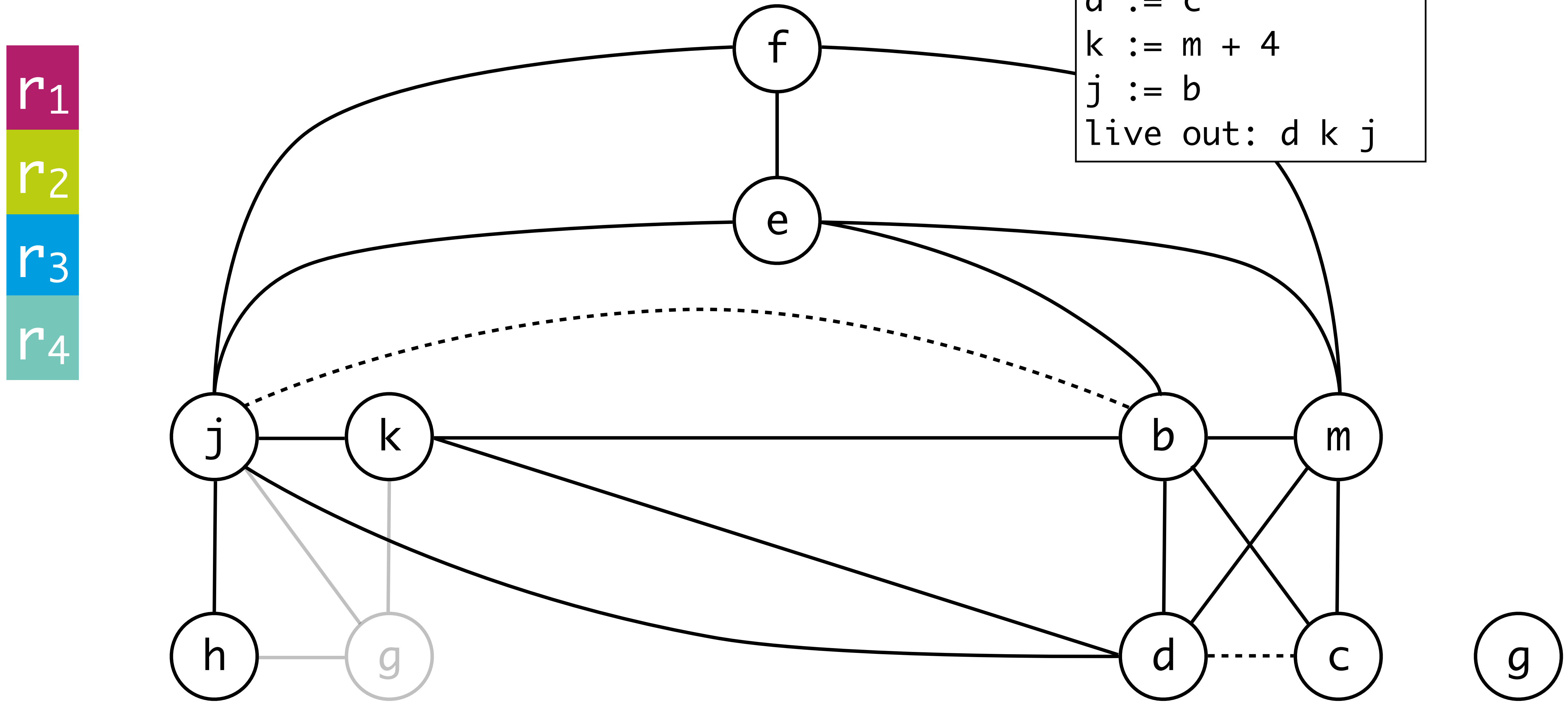
r_1
r_2
r_3
r_4



Coalescing

example

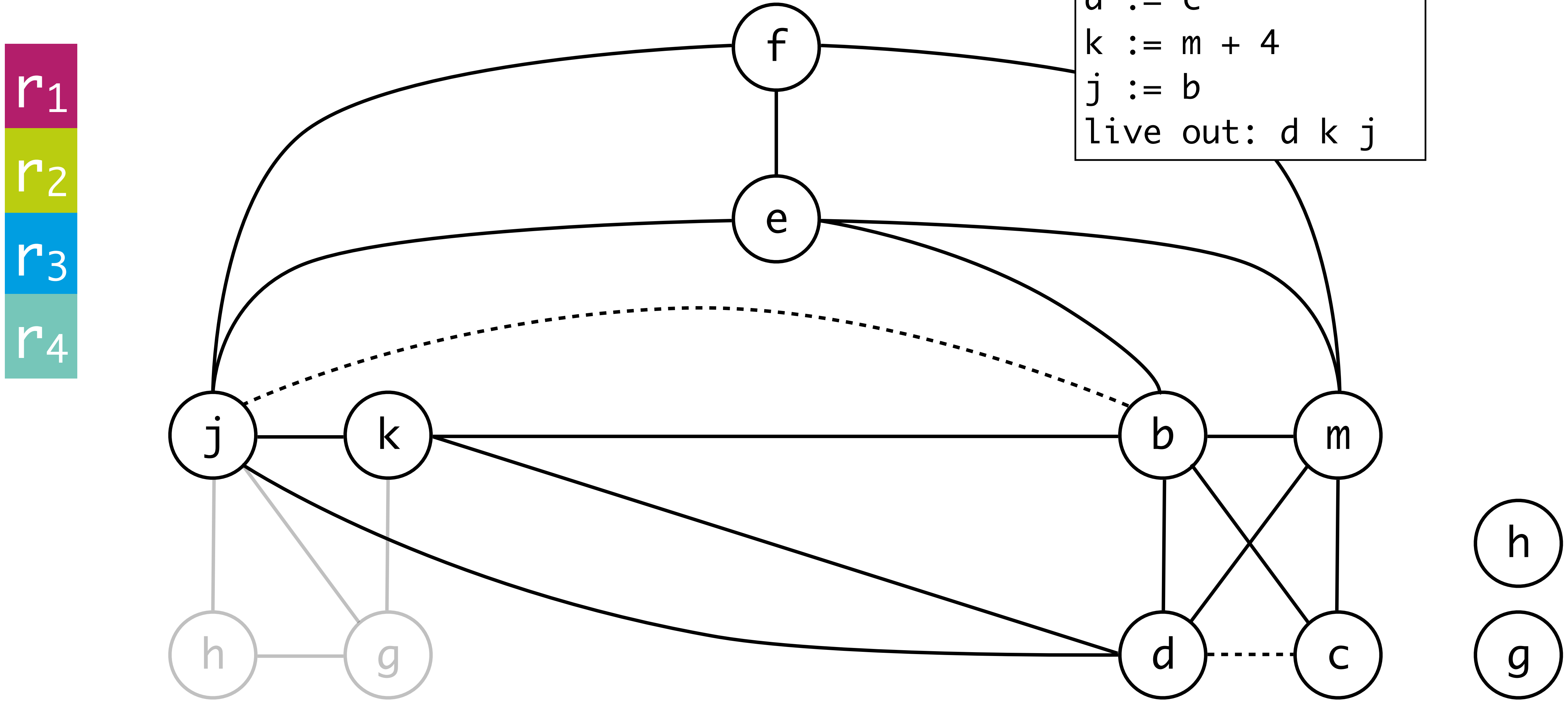
```
live-in: k j
g := mem[j + 12]
h := k - 1
f := g * h
e := mem[j + 8]
m := mem[j + 16]
b := mem[f]
c := e + 8
d := c
k := m + 4
j := b
live out: d k j
```



Coalescing

example

```
live-in: k j
g := mem[j + 12]
h := k - 1
f := g * h
e := mem[j + 8]
m := mem[j + 16]
b := mem[f]
c := e + 8
d := c
k := m + 4
j := b
live out: d k j
```

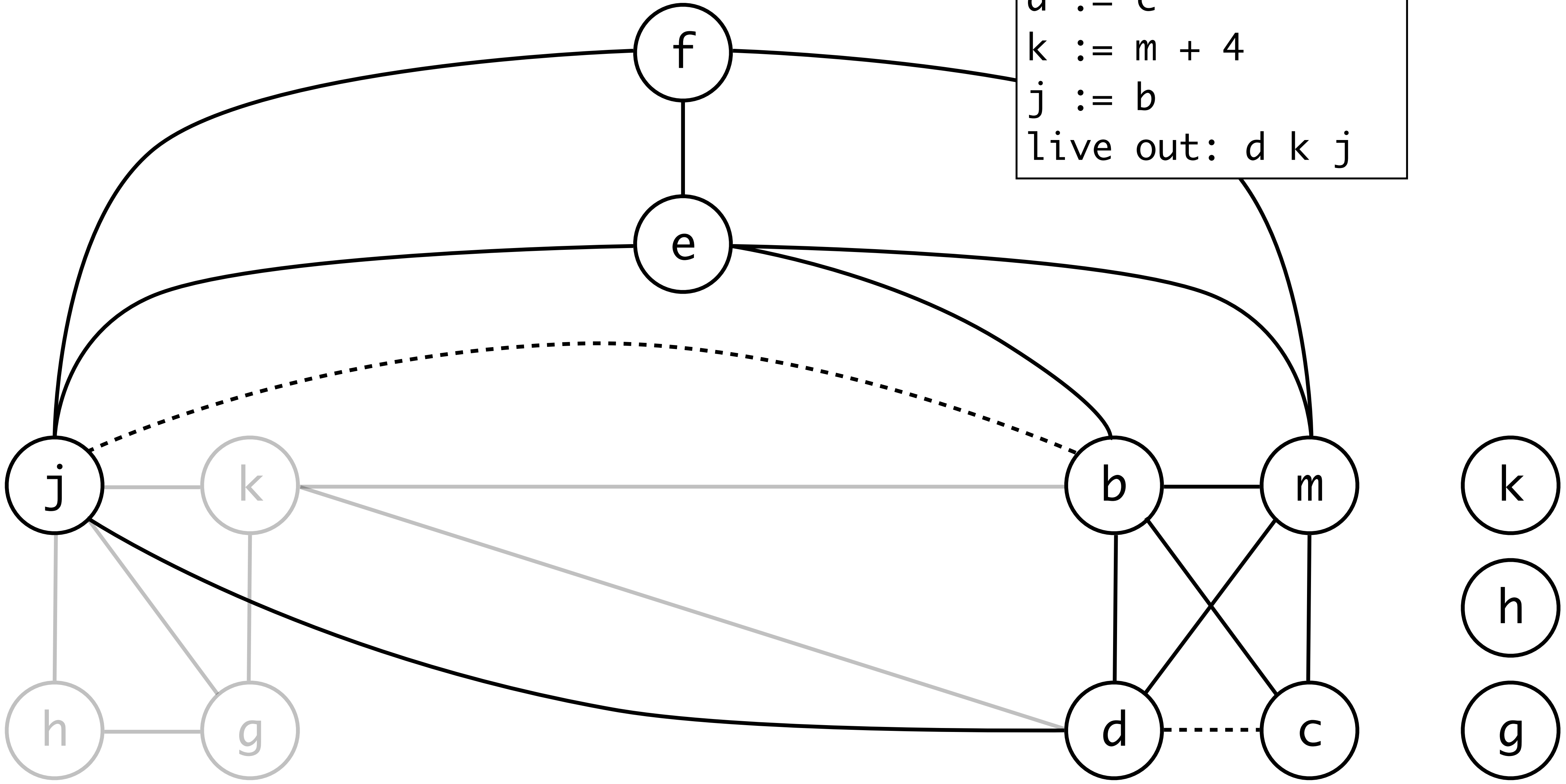


Coalescing

example

r1
r2
r3
r4

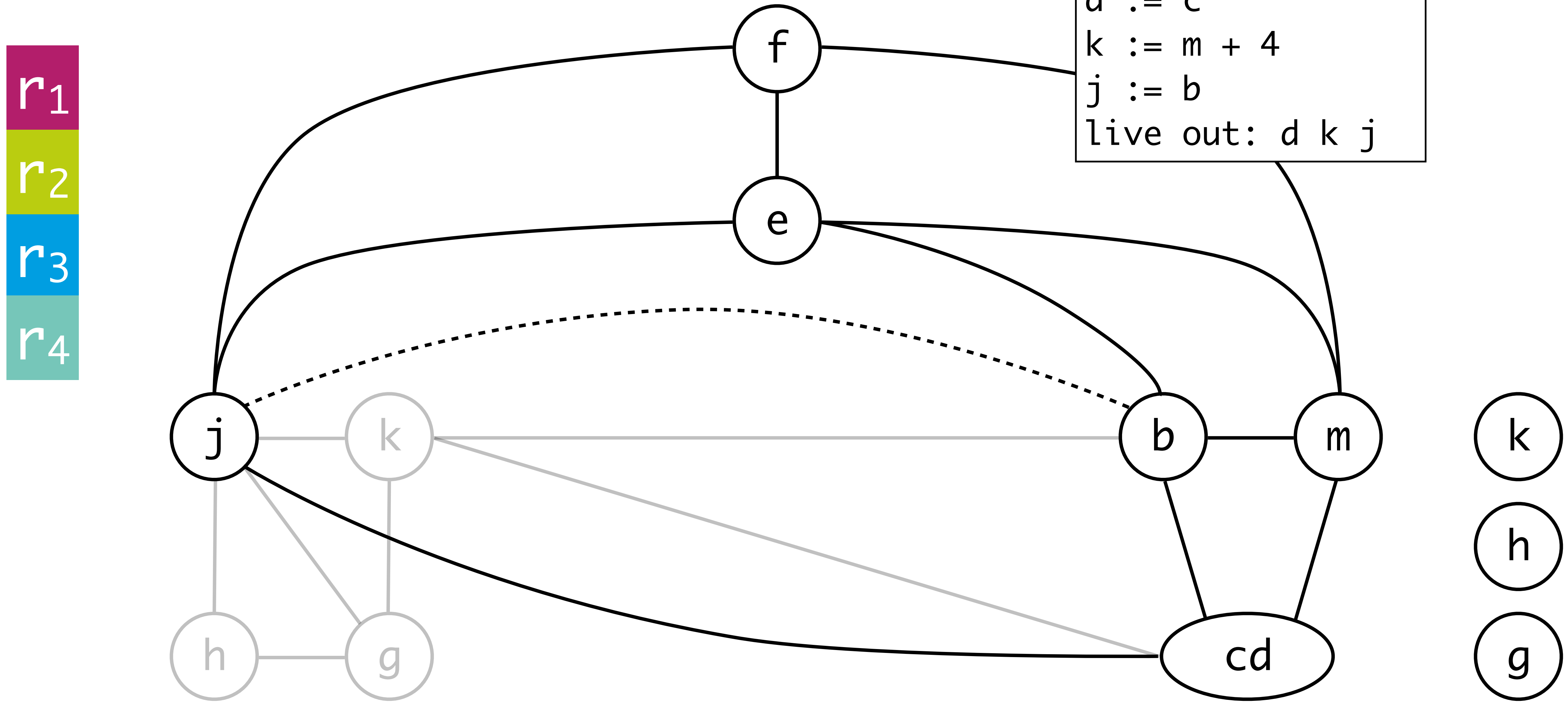
```
live-in: k j
g := mem[j + 12]
h := k - 1
f := g * h
e := mem[j + 8]
m := mem[j + 16]
b := mem[f]
c := e + 8
d := c
k := m + 4
j := b
live out: d k j
```



Coalescing

example

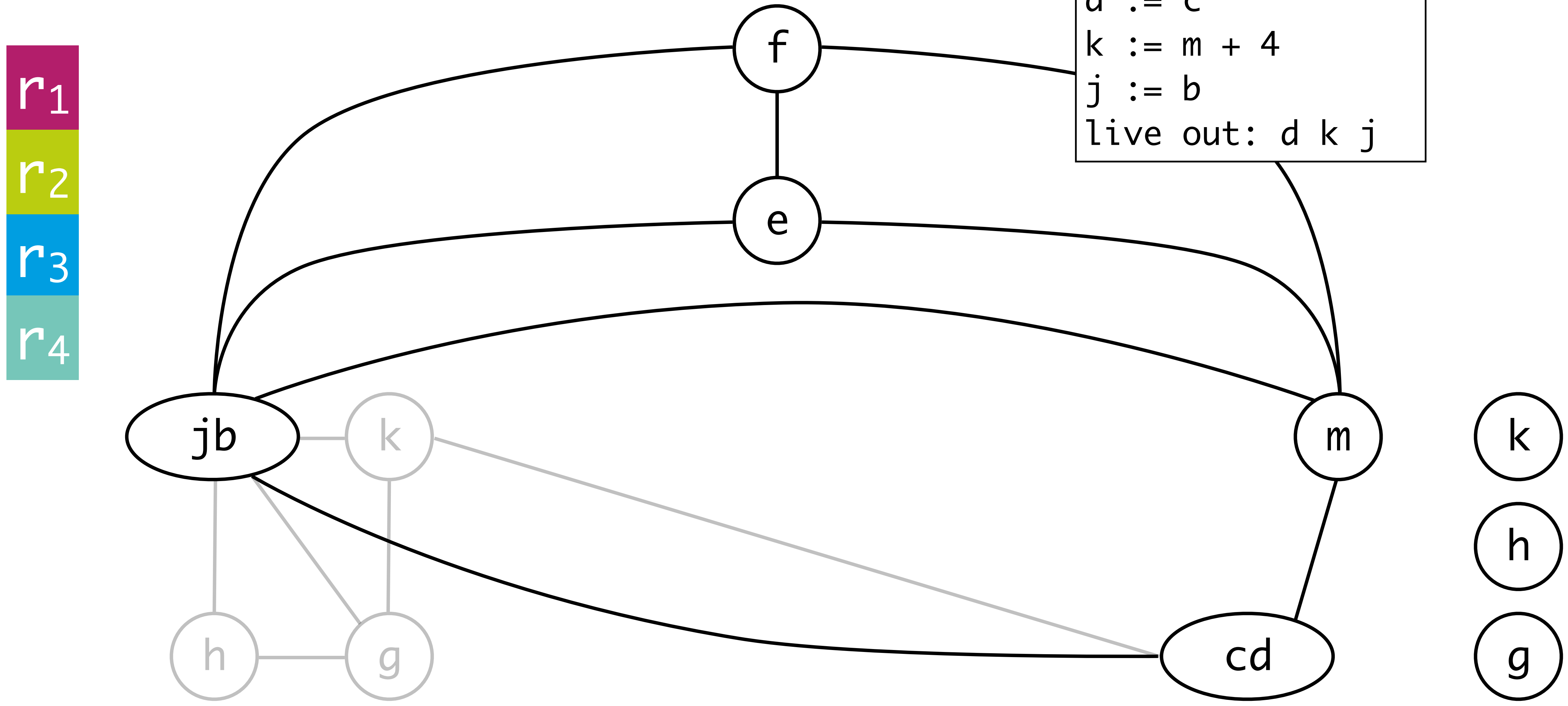
```
live-in: k j
g  := mem[j + 12]
h  := k - 1
f  := g * h
e  := mem[j + 8]
m := mem[j + 16]
b  := mem[f]
c  := e + 8
d  := c
k  := m + 4
j  := b
live out: d k j
```



Coalescing

example

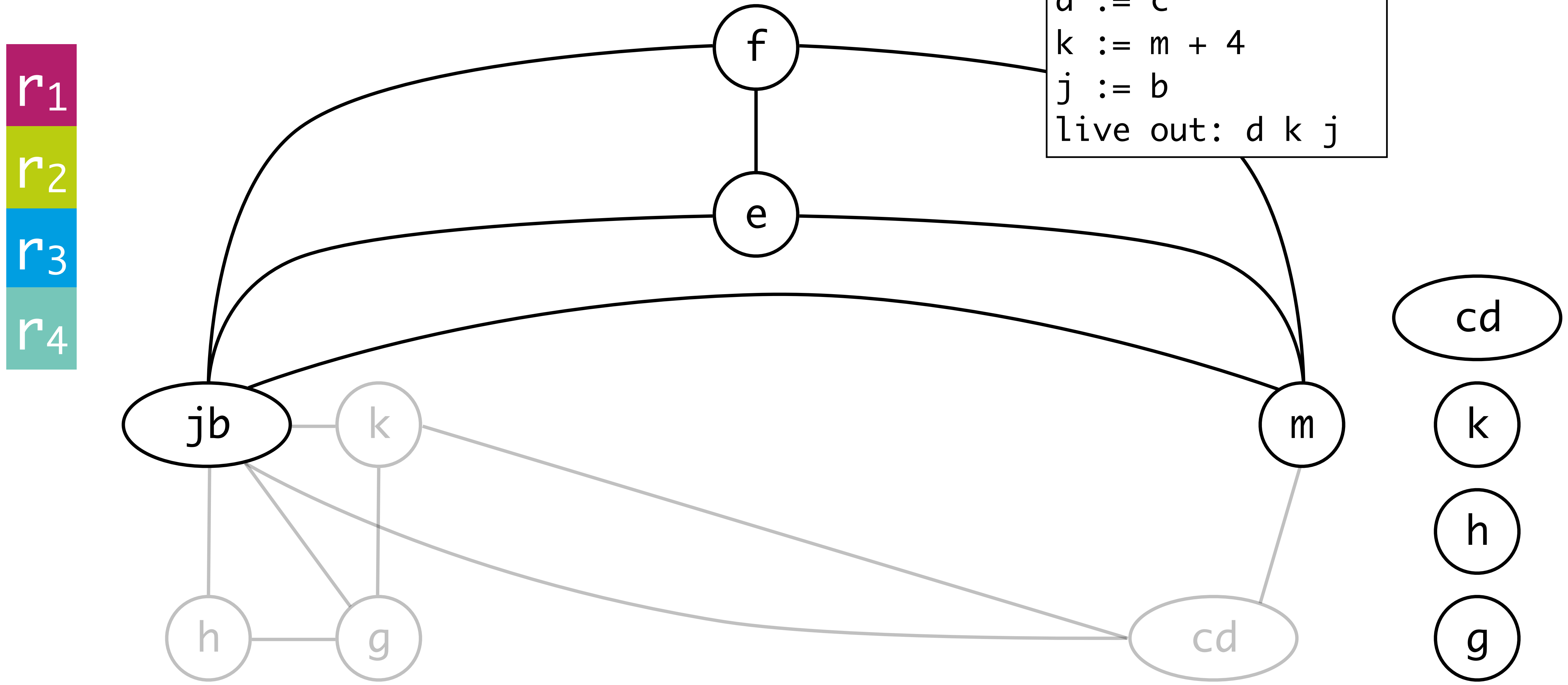
```
live-in: k j
g := mem[j + 12]
h := k - 1
f := g * h
e := mem[j + 8]
m := mem[j + 16]
b := mem[f]
c := e + 8
d := c
k := m + 4
j := b
live out: d k j
```



Coalescing

example

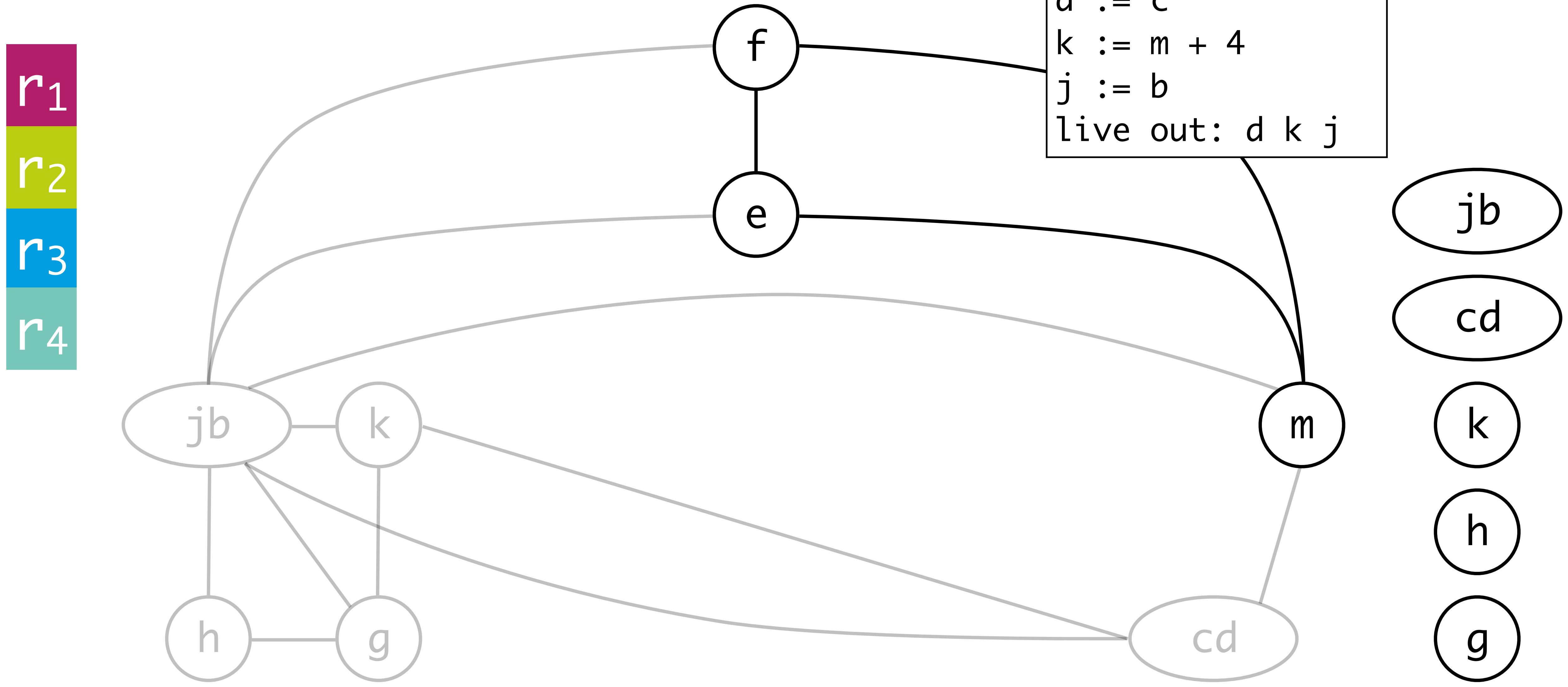
```
live-in: k j
g := mem[j + 12]
h := k - 1
f := g * h
e := mem[j + 8]
m := mem[j + 16]
b := mem[f]
c := e + 8
d := c
k := m + 4
j := b
live out: d k j
```



Coalescing

example

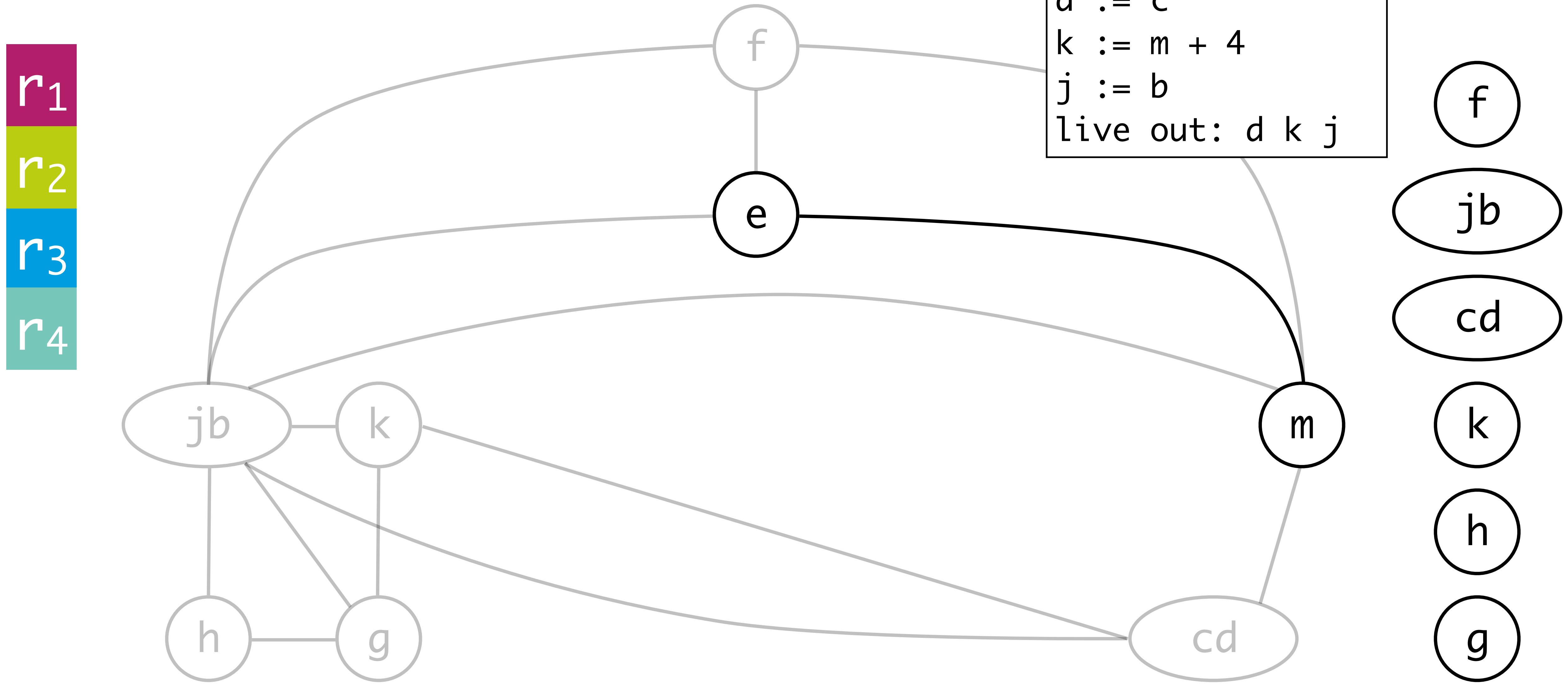
```
live-in: k j
g  := mem[j + 12]
h  := k - 1
f  := g * h
e  := mem[j + 8]
m := mem[j + 16]
b  := mem[f]
c  := e + 8
d  := c
k  := m + 4
j  := b
live out: d k j
```



Coalescing

example

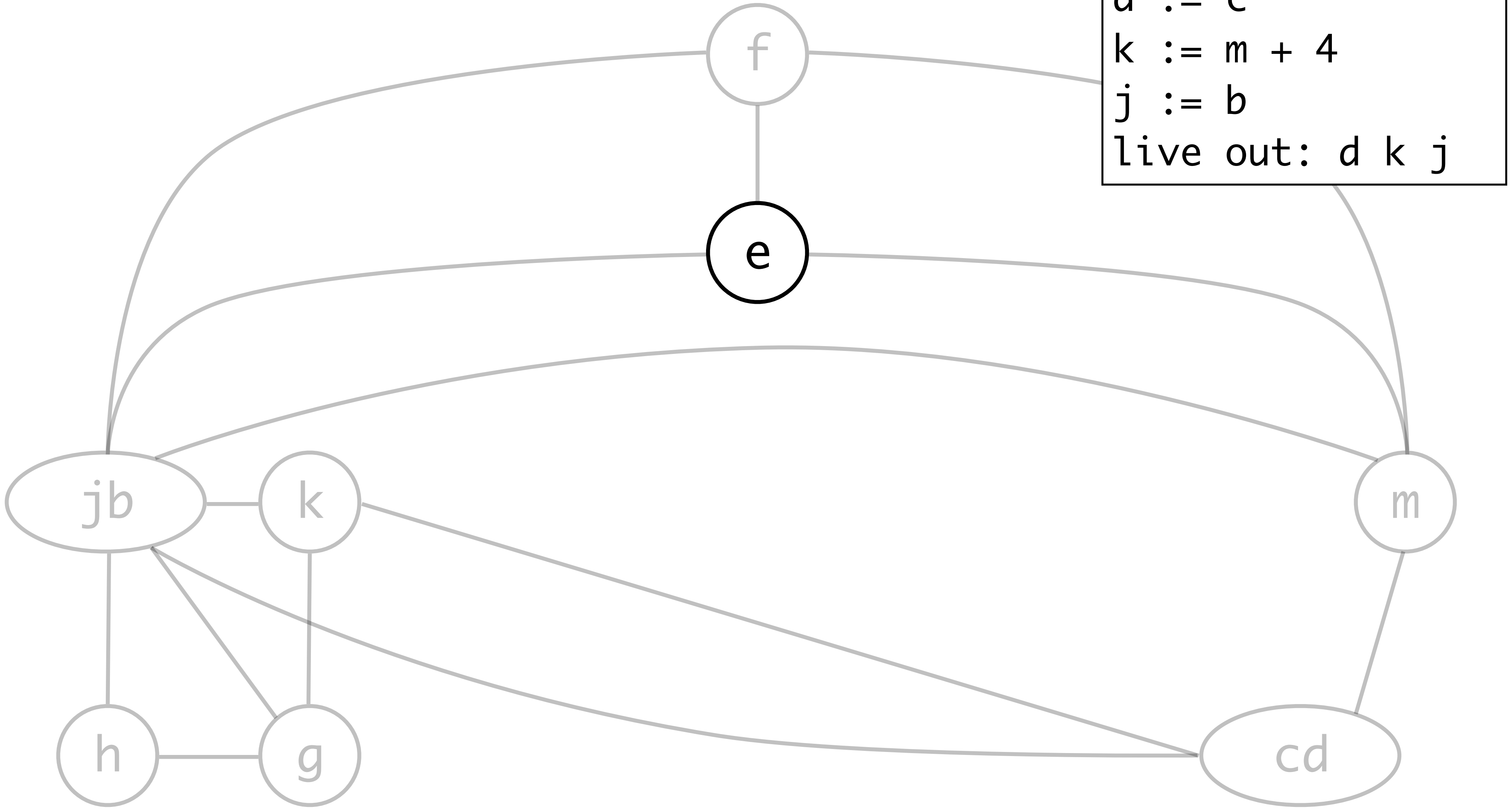
```
live-in: k j
g := mem[j + 12]
h := k - 1
f := g * h
e := mem[j + 8]
m := mem[j + 16]
b := mem[f]
c := e + 8
d := c
k := m + 4
j := b
live out: d k j
```

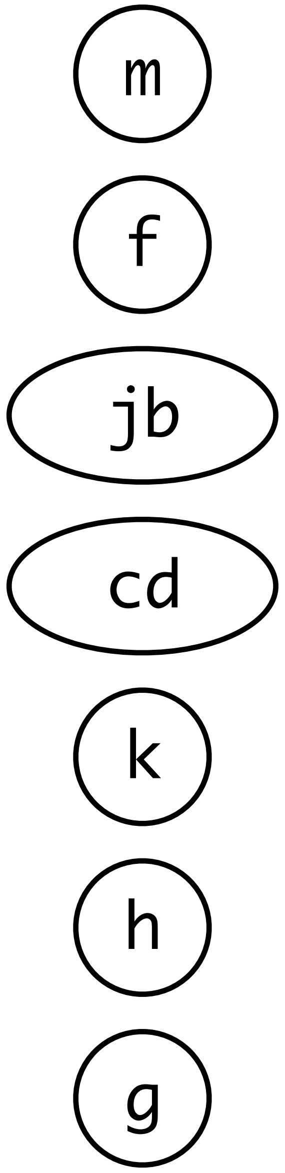


Coalescing

example

```
live-in: k j
g  := mem[j + 12]
h  := k - 1
f  := g * h
e  := mem[j + 8]
m := mem[j + 16]
b  := mem[f]
c  := e + 8
d  := c
k  := m + 4
j  := b
live out: d k j
```

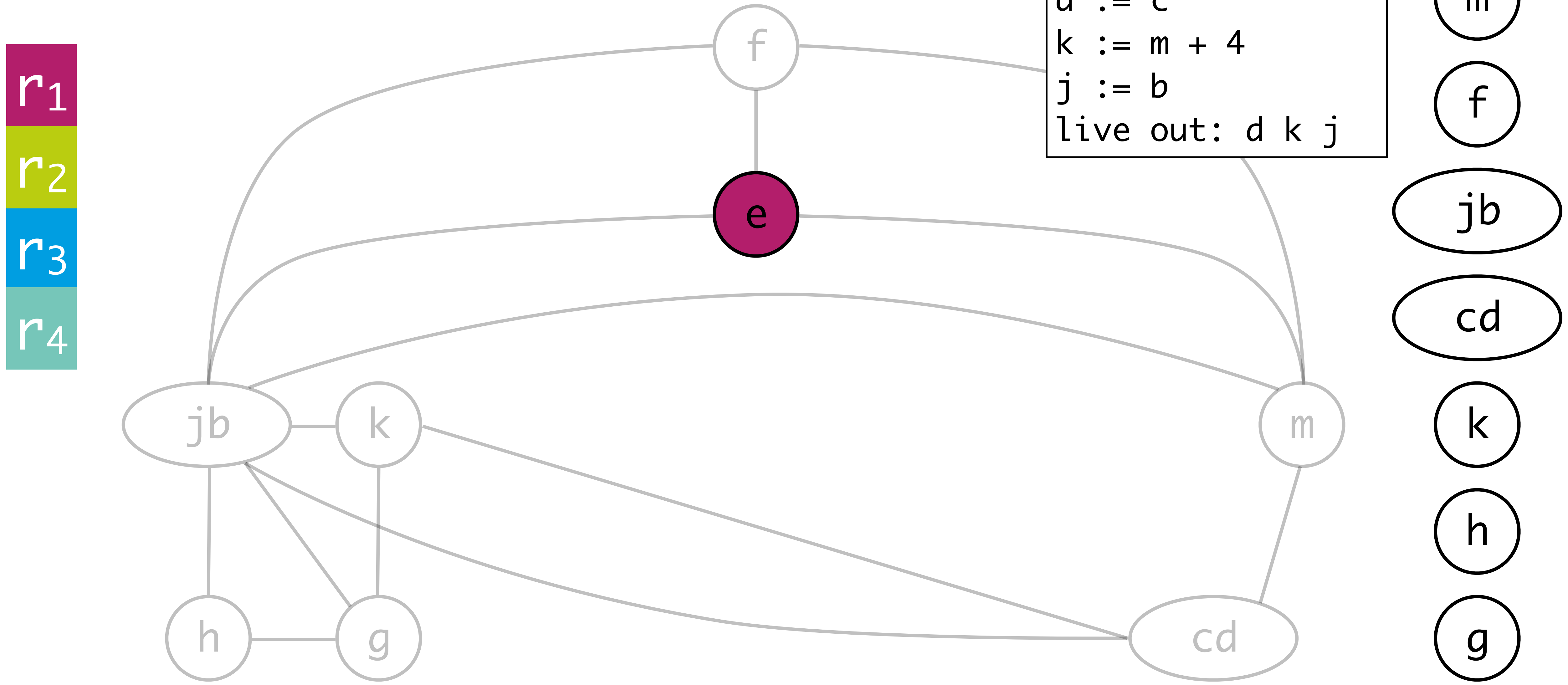




Coalescing

example

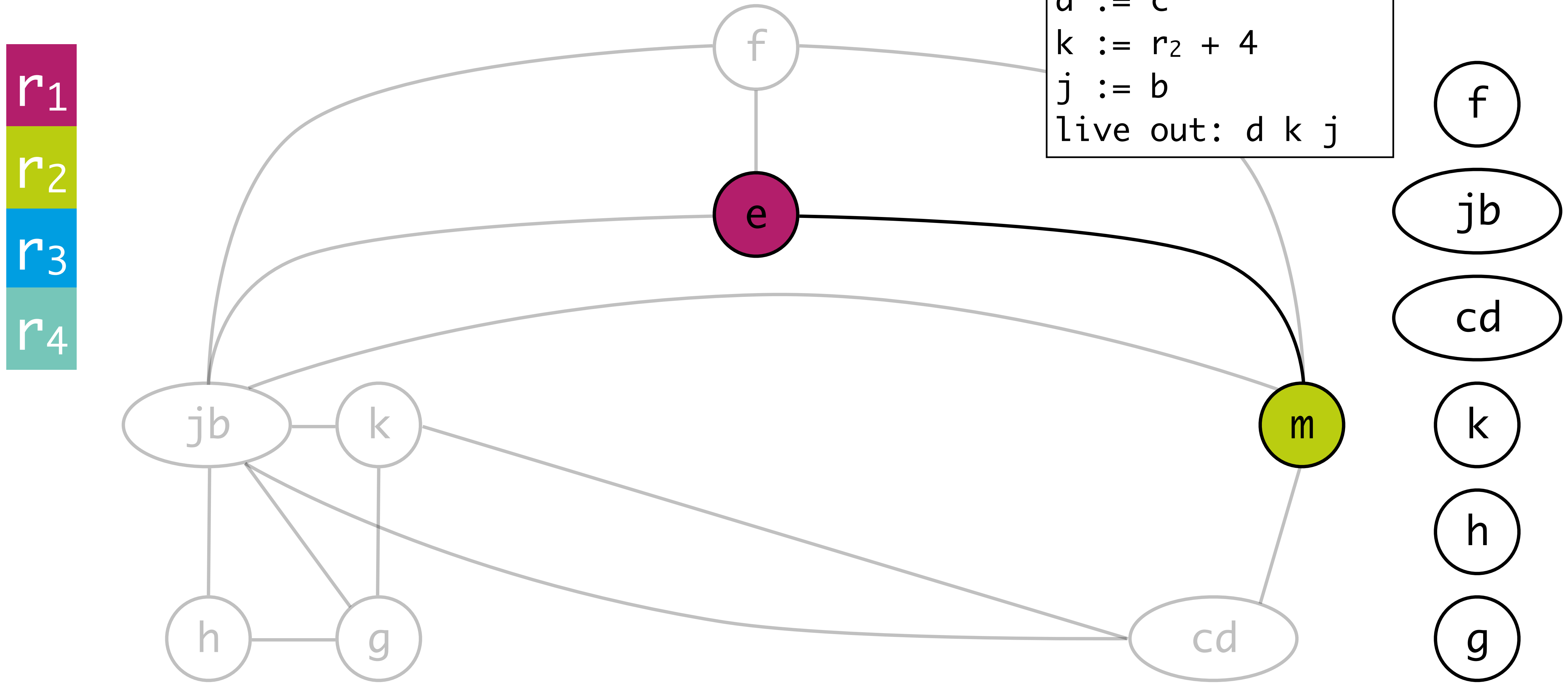
```
live-in: k j
g  := mem[j + 12]
h  := k - 1
f  := g * h
r₁  := mem[j + 8]
m := mem[j + 16]
b  := mem[f]
c  := r₁ + 8
d  := c
k  := m + 4
j  := b
live out: d k j
```



Coalescing

example

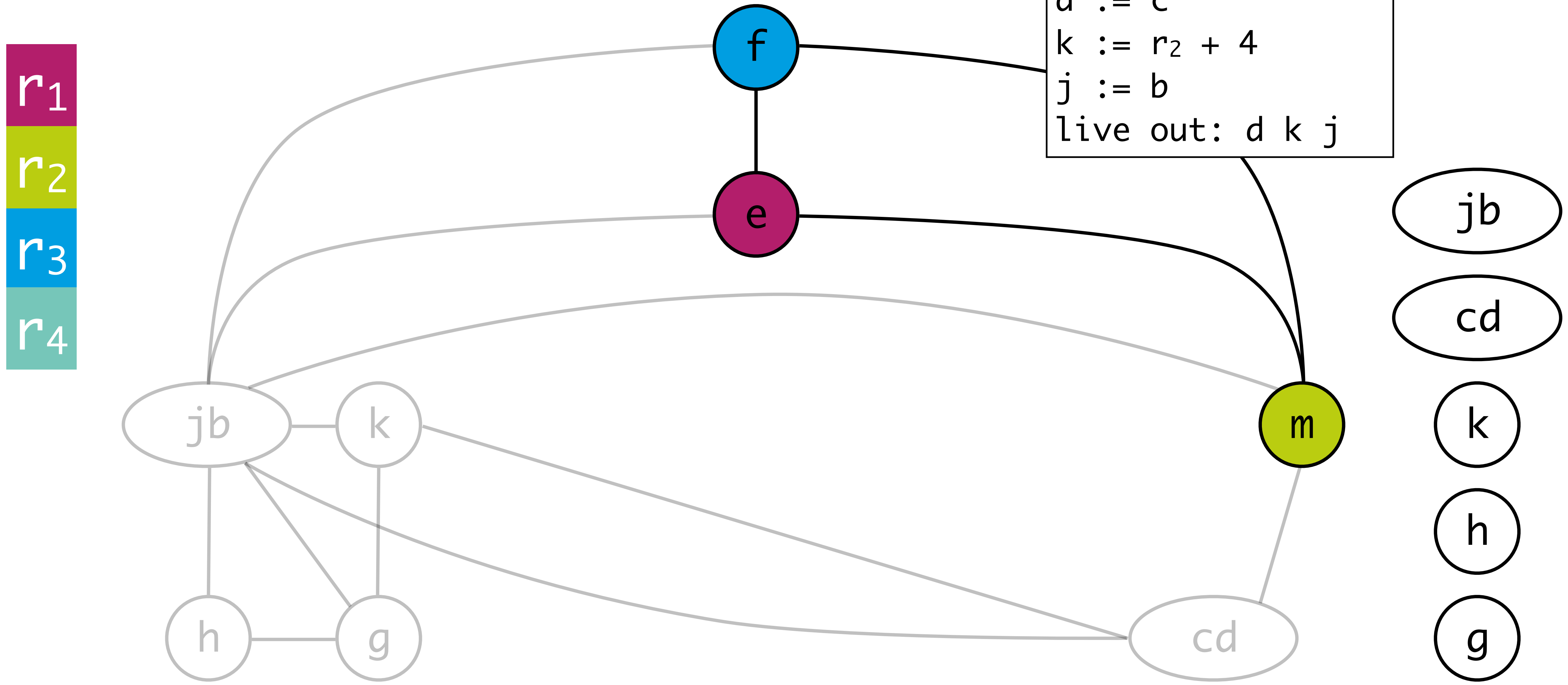
```
live-in: k j
g  := mem[j + 12]
h  := k - 1
f  := g * h
r1  := mem[j + 8]
r2 := mem[j + 16]
b  := mem[f]
c  := r1 + 8
d  := c
k  := r2 + 4
j  := b
live out: d k j
```



Coalescing

example

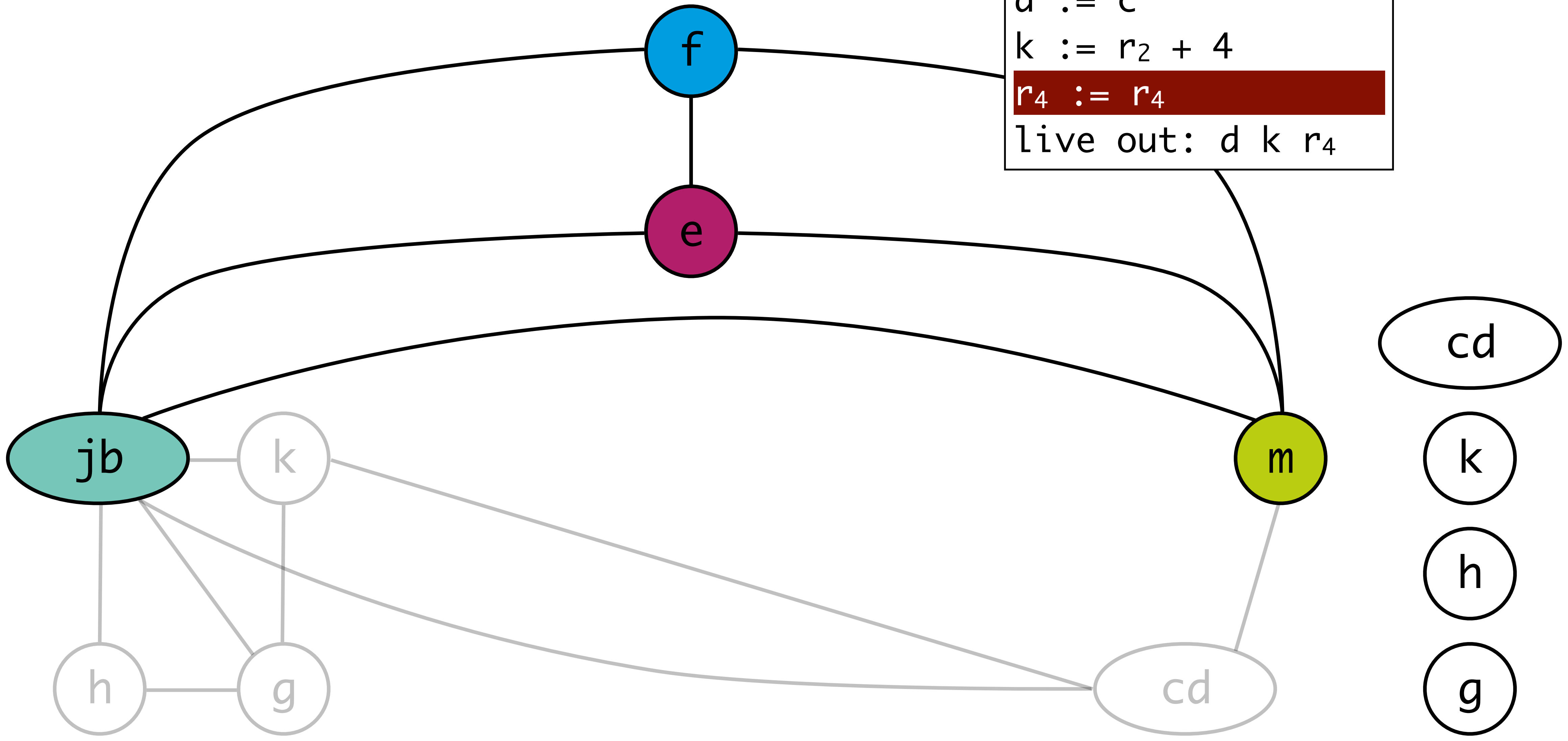
```
live-in: k j
g  := mem[j + 12]
h  := k - 1
r3  := g * h
r1  := mem[j + 8]
r2 := mem[j + 16]
b  := mem[r3]
c  := r1 + 8
d  := c
k  := r2 + 4
j  := b
live out: d k j
```



Coalescing

example

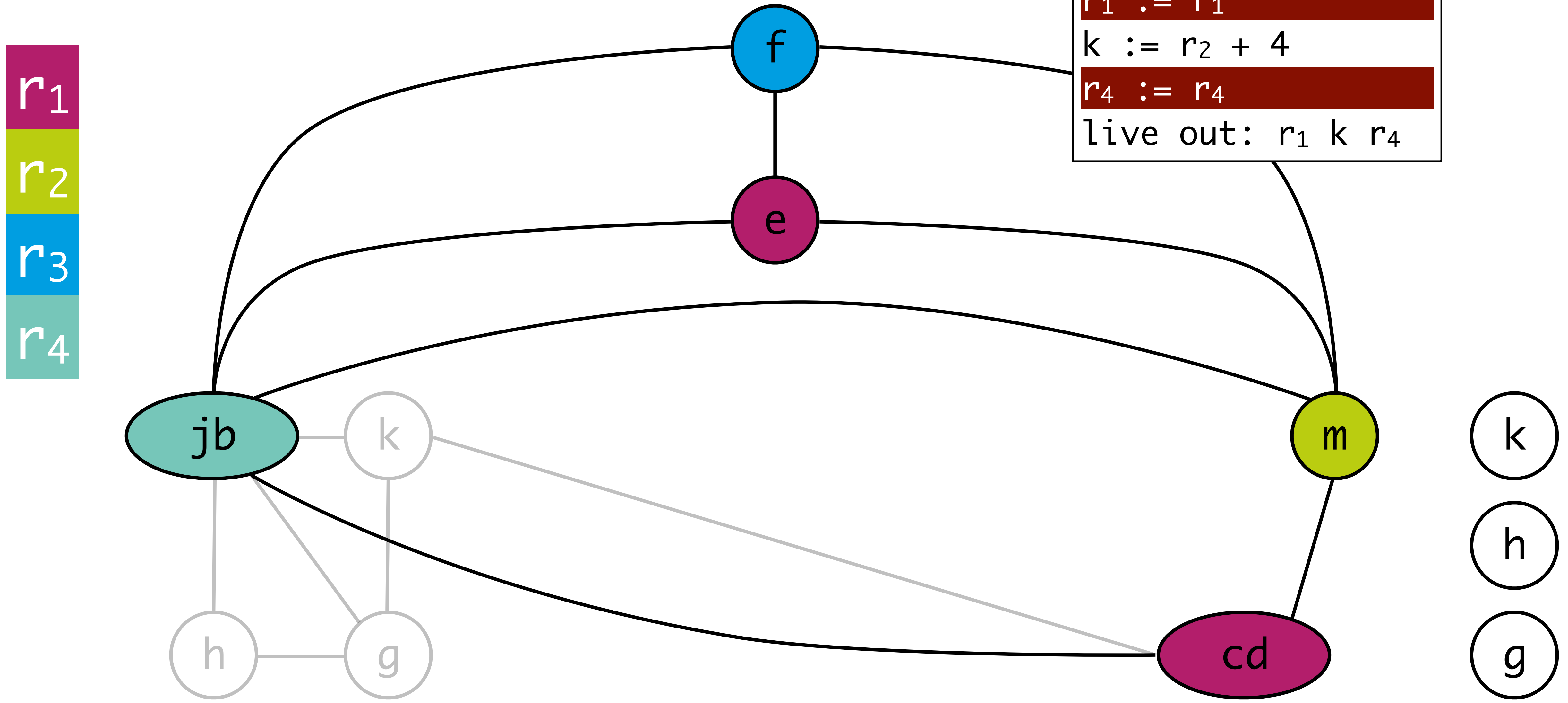
```
live-in: k r4
g  := mem[r4 + 12]
h  := k - 1
r3  := g * h
r1  := mem[r4 + 8]
r2 := mem[r4 + 16]
b  := mem[r3]
c  := r1 + 8
d  := c
k  := r2 + 4
r4  := r4
live out: d k r4
```



Coalescing

example

```
live-in: k r4
g  := mem[r4 + 12]
h  := k - 1
r3  := g * h
r1  := mem[r4 + 8]
r2 := mem[r4 + 16]
b  := mem[r3]
r1  := r1 + 8
r1  := r1
k  := r2 + 4
r4  := r4
live out: r1 k r4
```

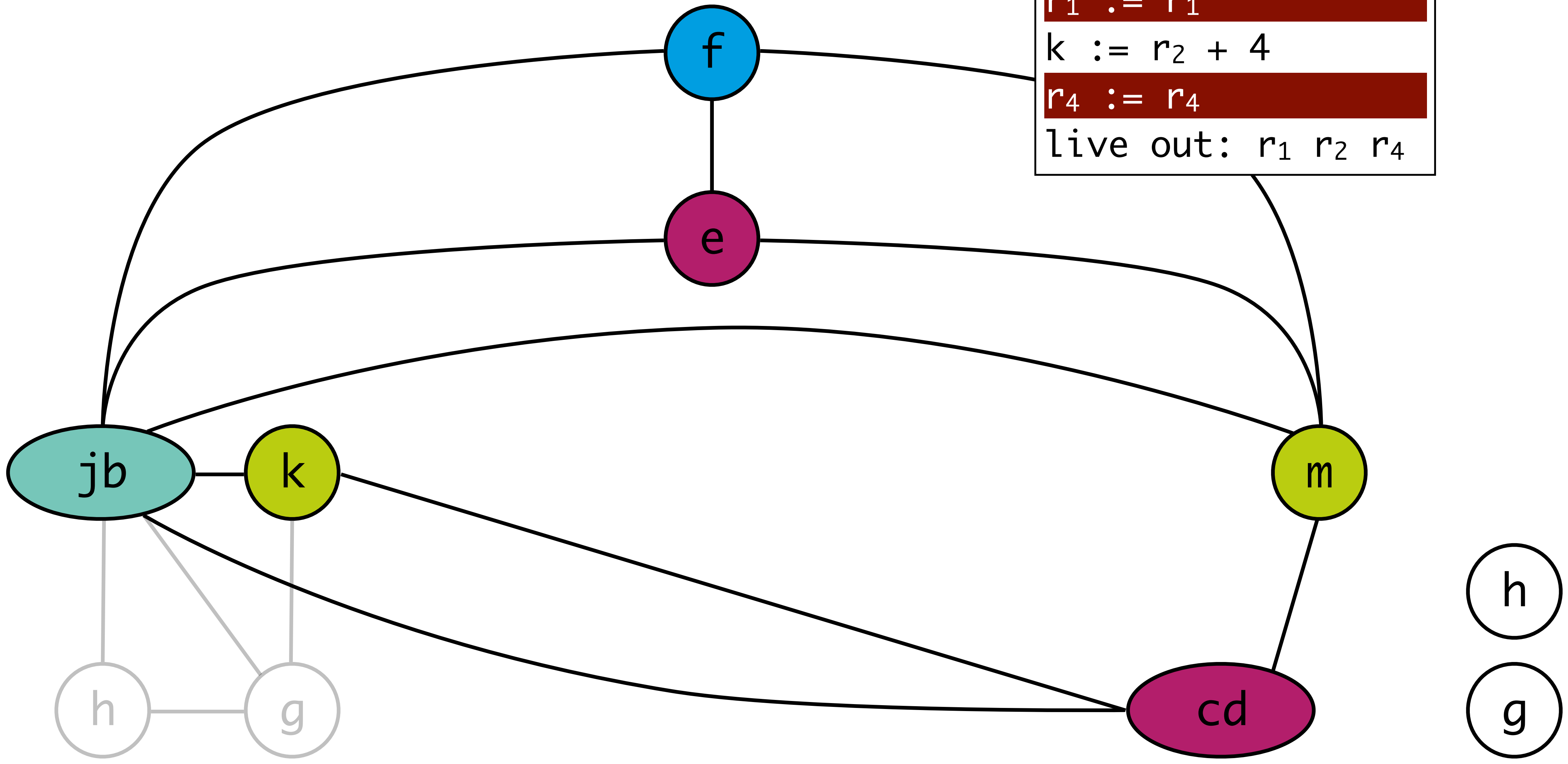


Coalescing

example

```
live-in: r2 r4
g  := mem[r4 + 12]
h  := r2 - 1
r3  := g * h
r1  := mem[r4 + 8]
r2 := mem[r4 + 16]
b  := mem[r3]
r1  := r1 + 8
r1  := r1
k  := r2 + 4
r4  := r4
live out: r1 r2 r4
```

r_1
r_2
r_3
r_4

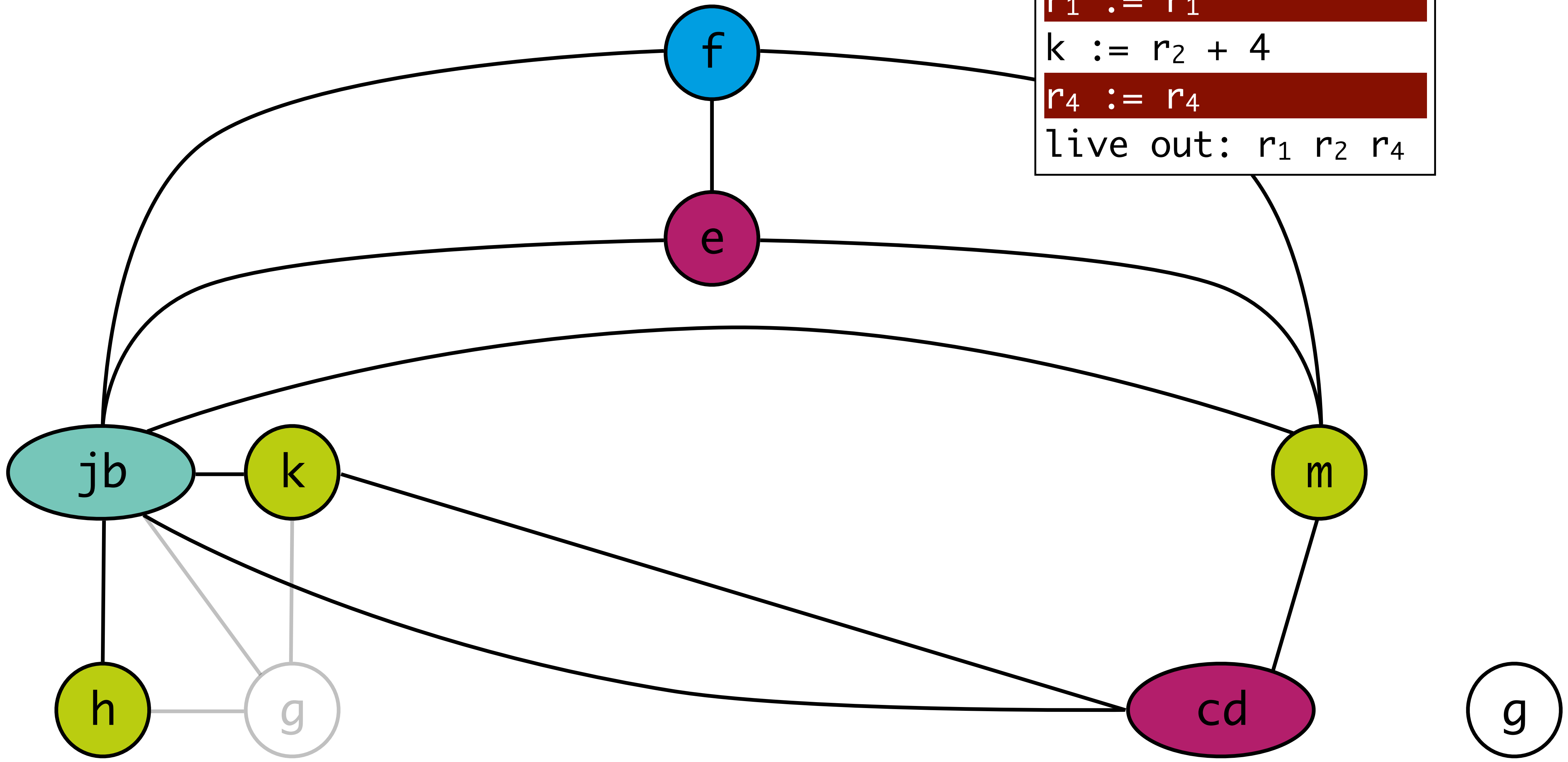


Coalescing

example

r1
r2
r3
r4

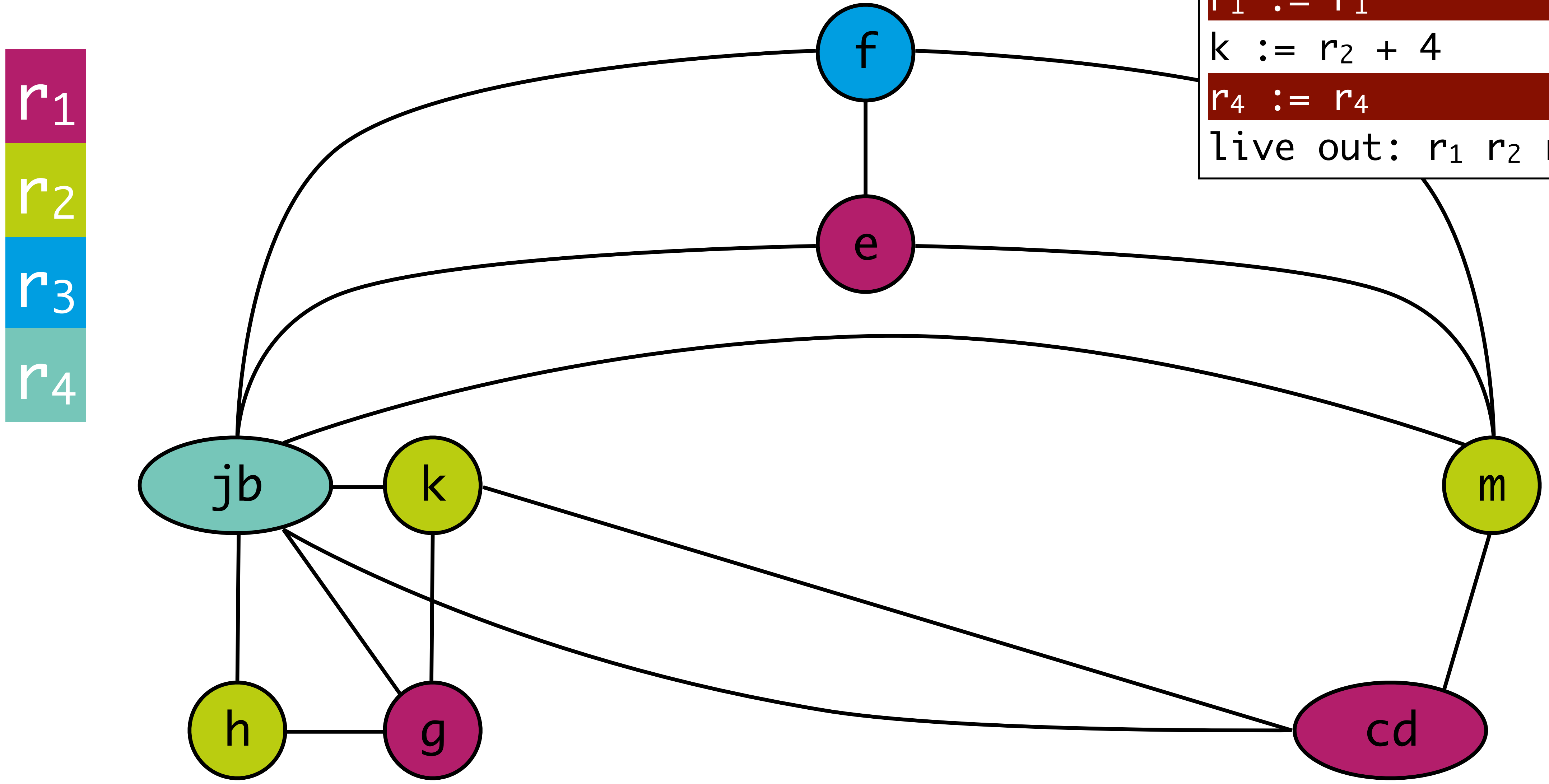
```
live-in: r2 r4
g  := mem[r4 + 12]
r2  := r2 - 1
r3  := g * r2
r1  := mem[r4 + 8]
r2 := mem[r4 + 16]
b  := mem[r3]
r1  := r1 + 8
r1  := r1
k  := r2 + 4
r4  := r4
live out: r1 r2 r4
```



Coalescing

coalescing nodes

```
live-in: r2 r4
r1  := mem[r4 + 12]
r2  := r2 - 1
r3  := r1 * r2
r1  := mem[r4 + 8]
r2 := mem[r4 + 16]
b  := mem[r3]
r1  := r1 + 8
r1  := r1
k  := r2 + 4
r4  := r4
live out: r1 r2 r4
```



V

Pre-Colored Nodes

Recap: Calling Conventions

CDECL

Caller

- push parameters right-to-left on the stack
- clean-up stack after call

```
push 21
push 42
call _f
add  ESP 8
```

Callee

- save old BP
- initialise new BP
- save registers
- return result in AX
- restore registers
- restore BP

```
push EBP
mov  EBP ESP
mov  EAX [EBP + 8]
mov  EDX [EBP + 12]
add  EAX EDX
pop  EBP
ret
```

Recap: Calling Conventions

STDCALL

Caller

- push parameters right-to-left on the stack

```
push 21
push 42
call _f@8
```

Callee

- save old BP
- initialise new BP
- save registers
- return result in AX
- restore registers
- restore BP

```
push EBP
mov  EBP ESP
mov  EAX [EBP + 8]
mov  EDX [EBP + 12]
add  EAX EDX
pop  EBP
ret  8
```

Recap: Calling Conventions

FASTCALL

Caller

```
mov  ECX 21
mov  EDX 42
call @f@8
```

- passes parameters in registers
- pushes additional parameters right-to-left on the stack
- cleans up the stack

Callee

```
push EBP
mov  EBP ESP
mov  EAX ECX
add  EAX EDX
pop  EBP
ret
```

- save old BP, initialise new BP
- save registers
- return result in AX
- restore registers
- restore BP

Recap: Calling Conventions

saving registers

Not enough registers for all local variables across life time

- save register to memory to free for other use

Caller-save registers

- Caller is responsible for saving and restoring register

Callee-save registers

- Callee is responsible for saving and restoring register

Use callee-save registers to pass parameters

Pre-Colored Nodes

representing registers

Nodes

- register = pre-colored node
- no simplify, no spill
- coalesce possible

Edges

- all registers interfere with each other
- explicit usage of registers
- call and return instructions influence liveness

Callee-Save Register in Temporary

pre-colored nodes

```
enter: def(r7)



        …



exit: use(r7)
```

```
enter: def(r7)
       t ← r7


       …


       r7 ← t
exit:  use(r7)
```

Pre-Colored Nodes

example

```
int f(int a, int b) {
  int d = 0;
  int e = a;
  do {
    d = d + b;
    e = e - 1;
  } while (e > 0);
  return d;
}
```

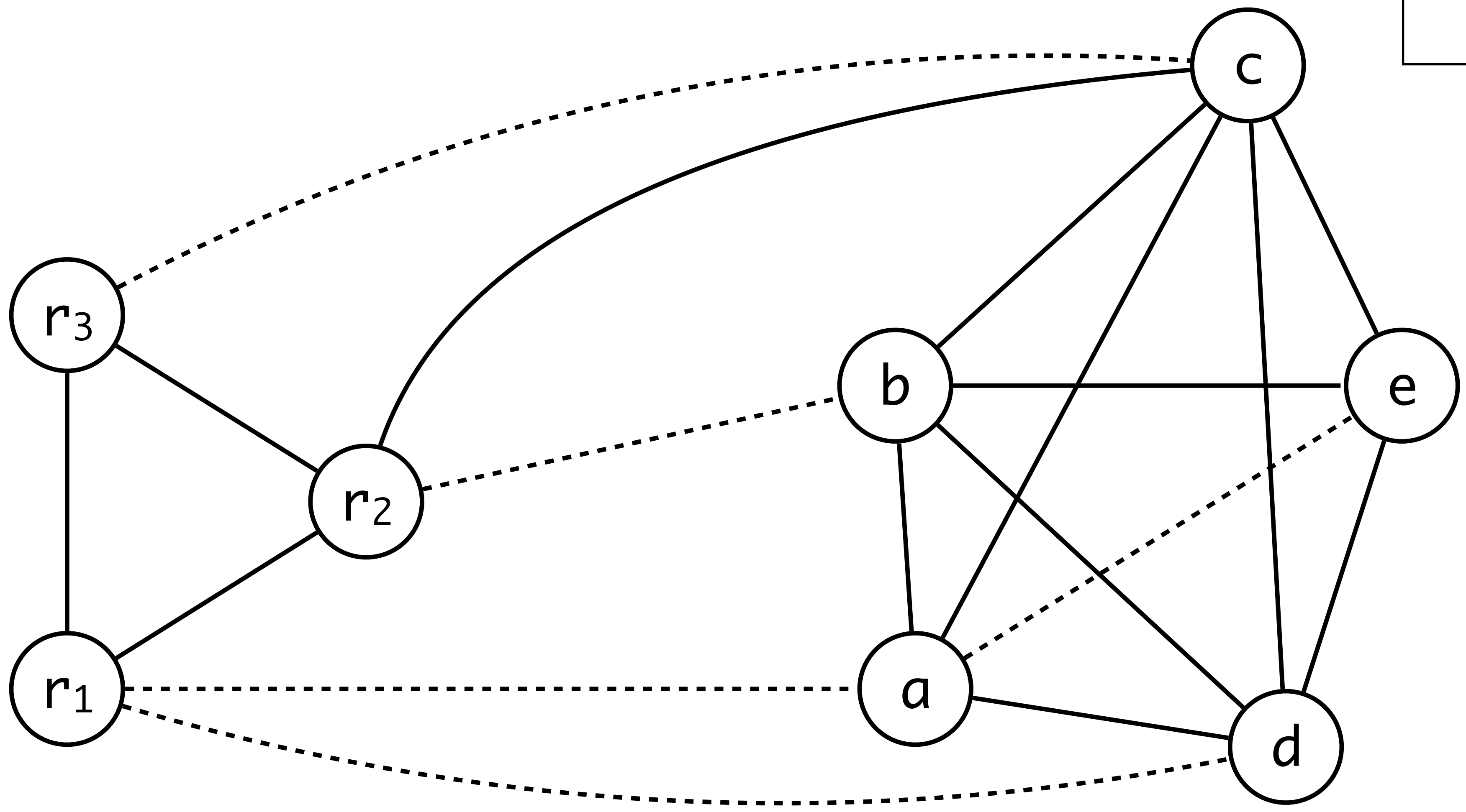
```
enter : c ← r3    // callee-save
        a ← r1    // caller-save
        b ← r2    // caller-save
        d ← 0
        e ← a
loop :  d ← d + b
        e ← e - 1
        if e > 0 goto loop
        r1 ← d
        r3 ← c
        return (r1, r3 live out)
```

machine has 3 registers

Pre-Colored Nodes

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)
```

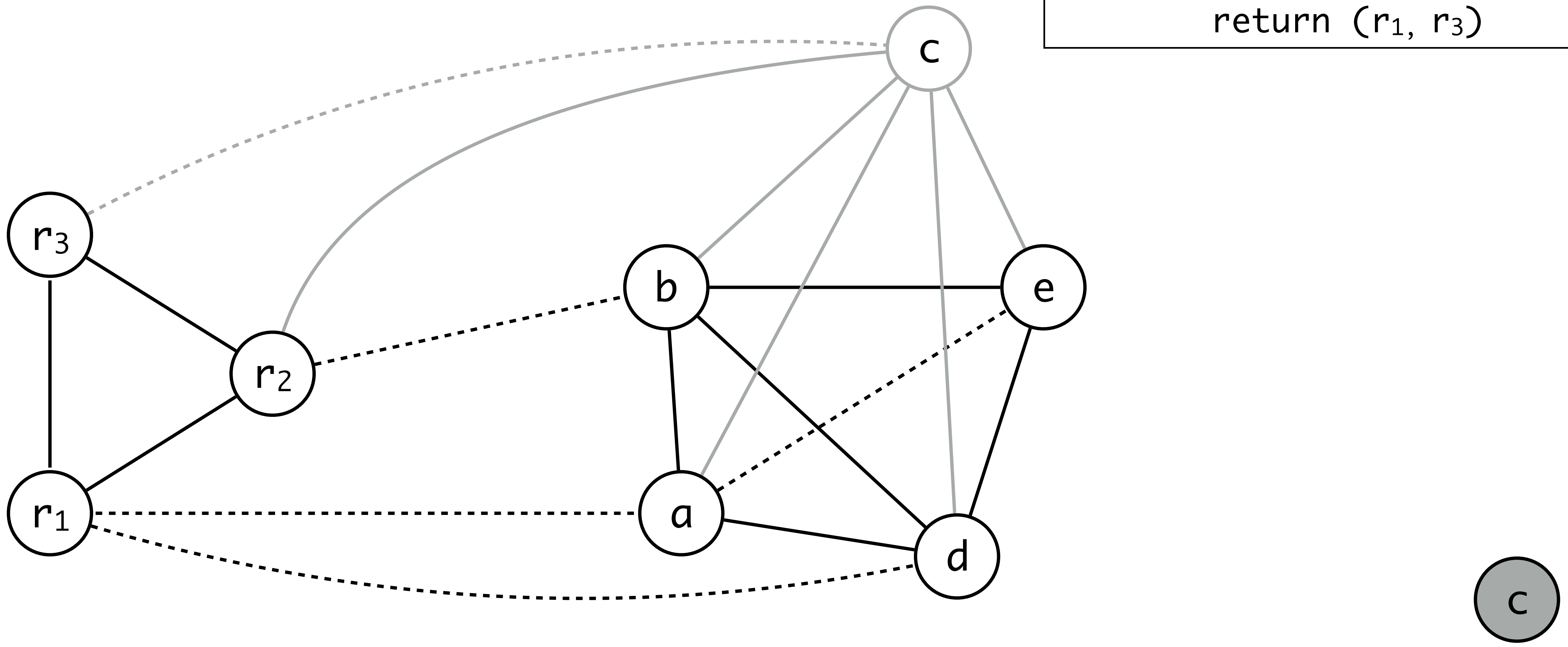


Pre-Colored Nodes

example

spill c

```
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)
```

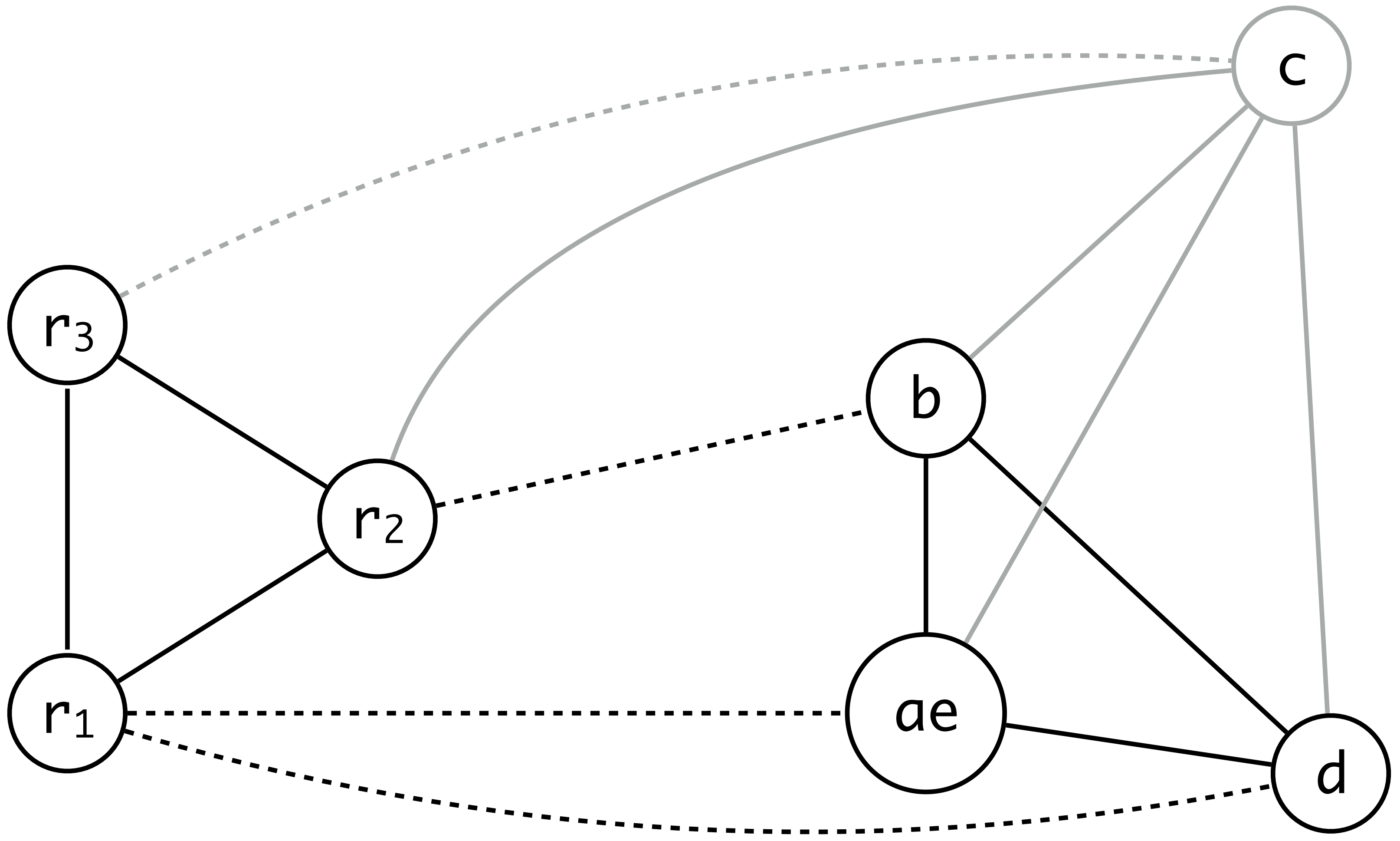


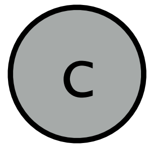
Pre-Colored Nodes

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)
```

coalesce a and e



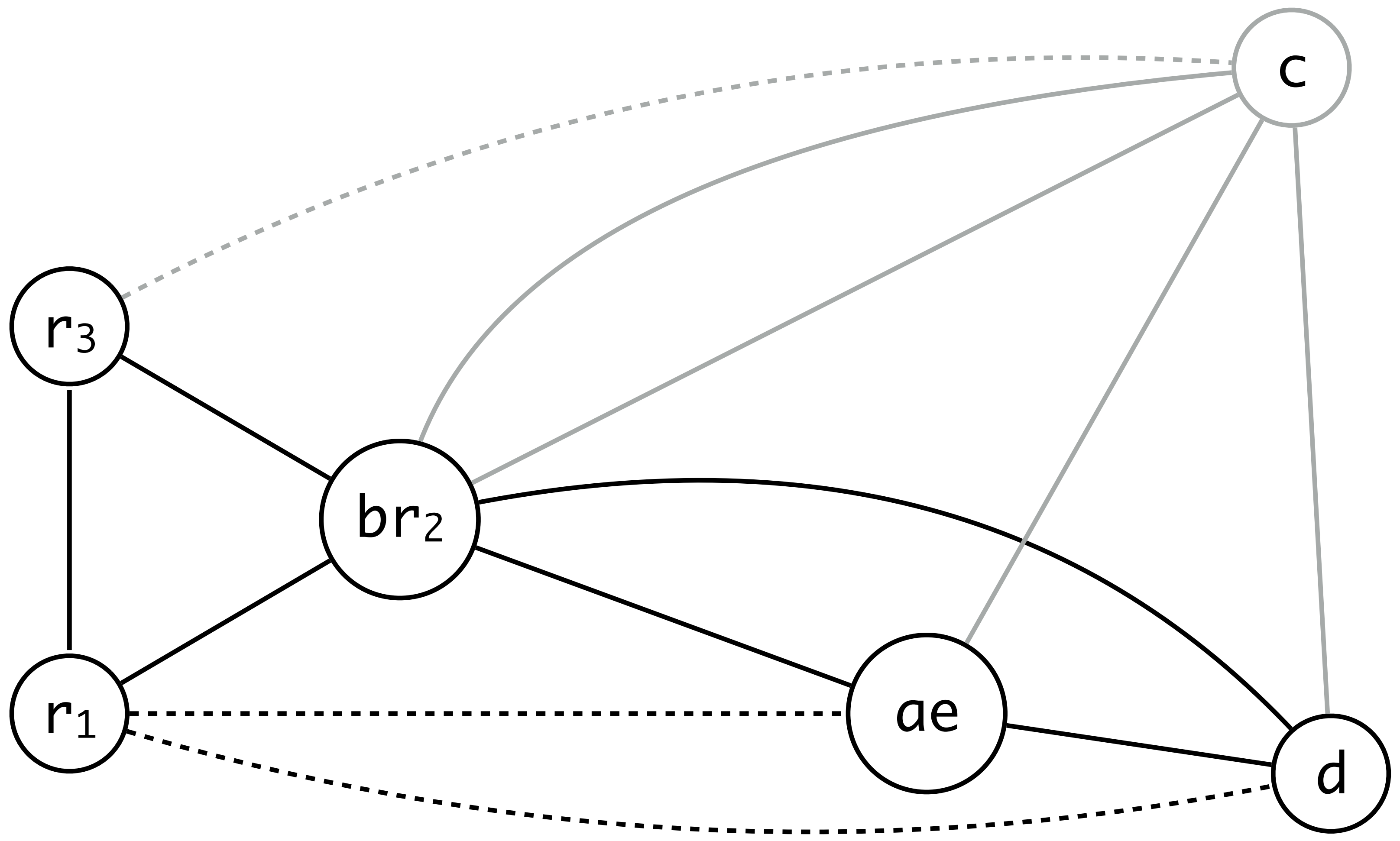


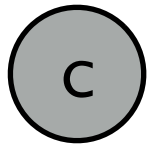
Pre-Colored Nodes

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)
```

coalesce r_2 and b

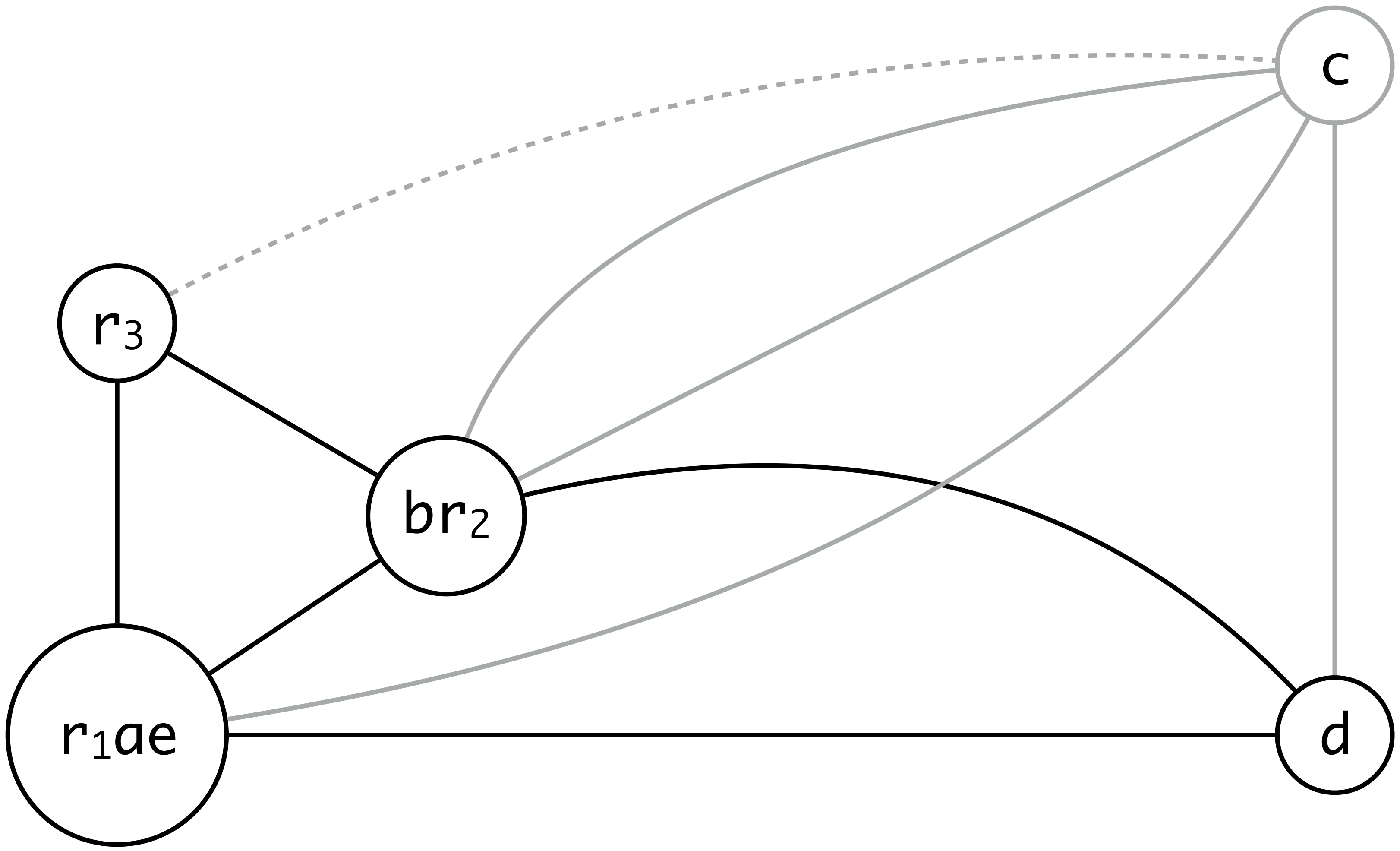




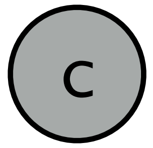
Pre-Colored Nodes

example

coalesce r_1 and ae



```
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)
```

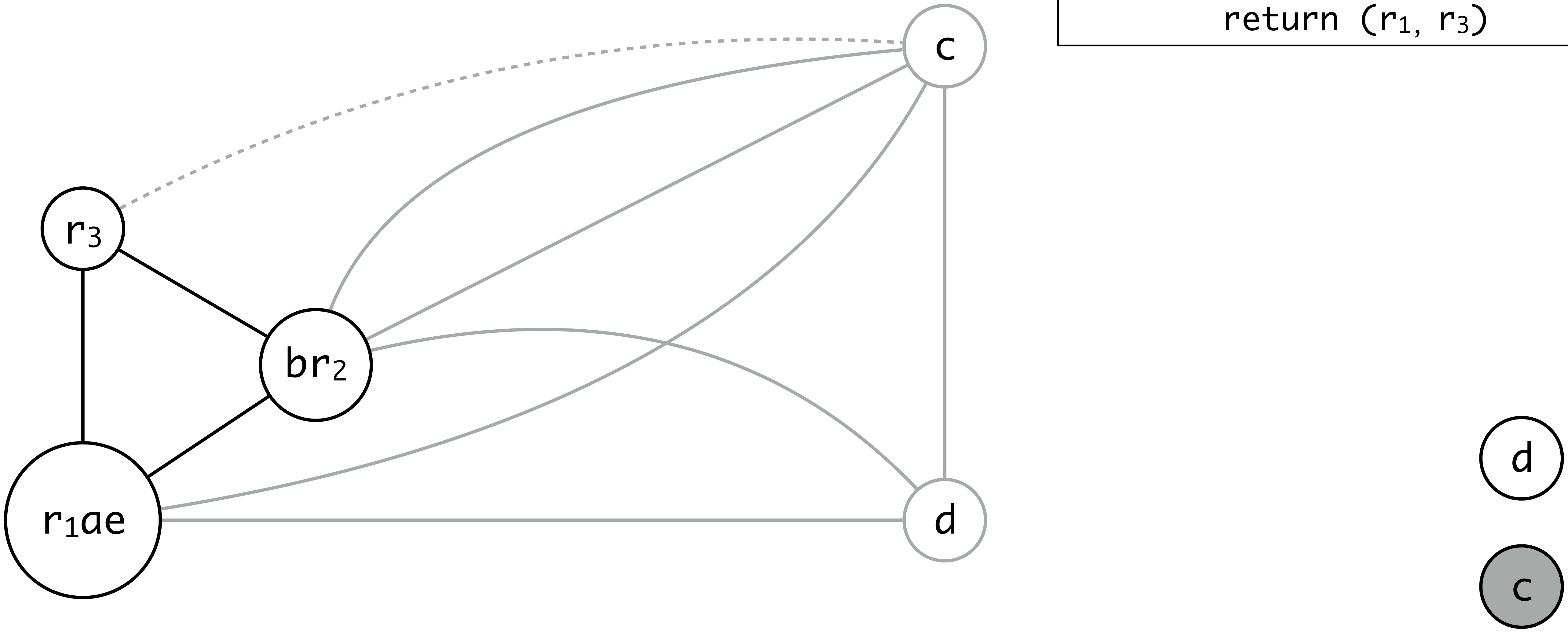


Pre-Colored Nodes

example

simplify d

```
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)
```

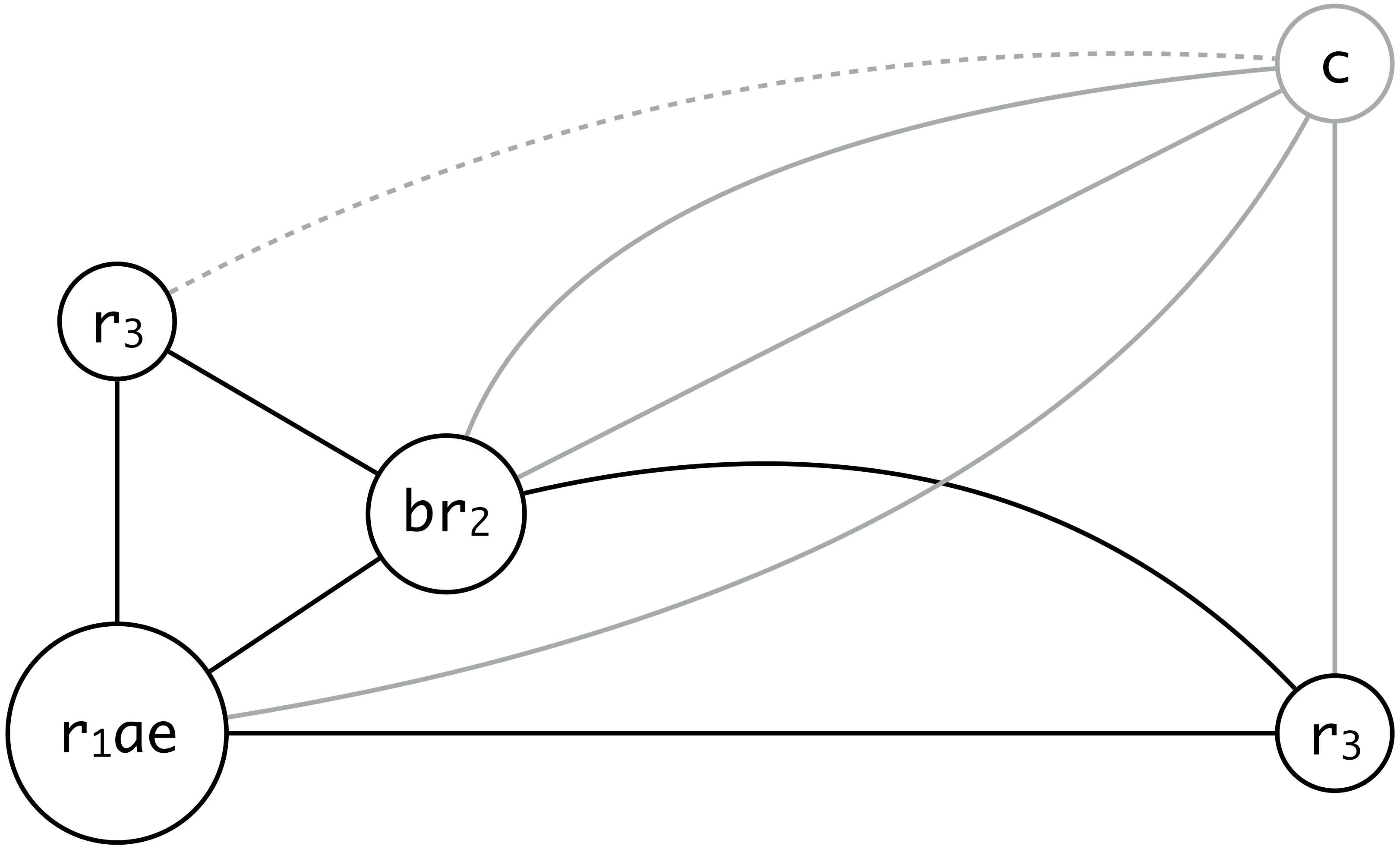


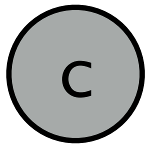
Pre-Colored Nodes

example

color d as r_3

```
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)
```



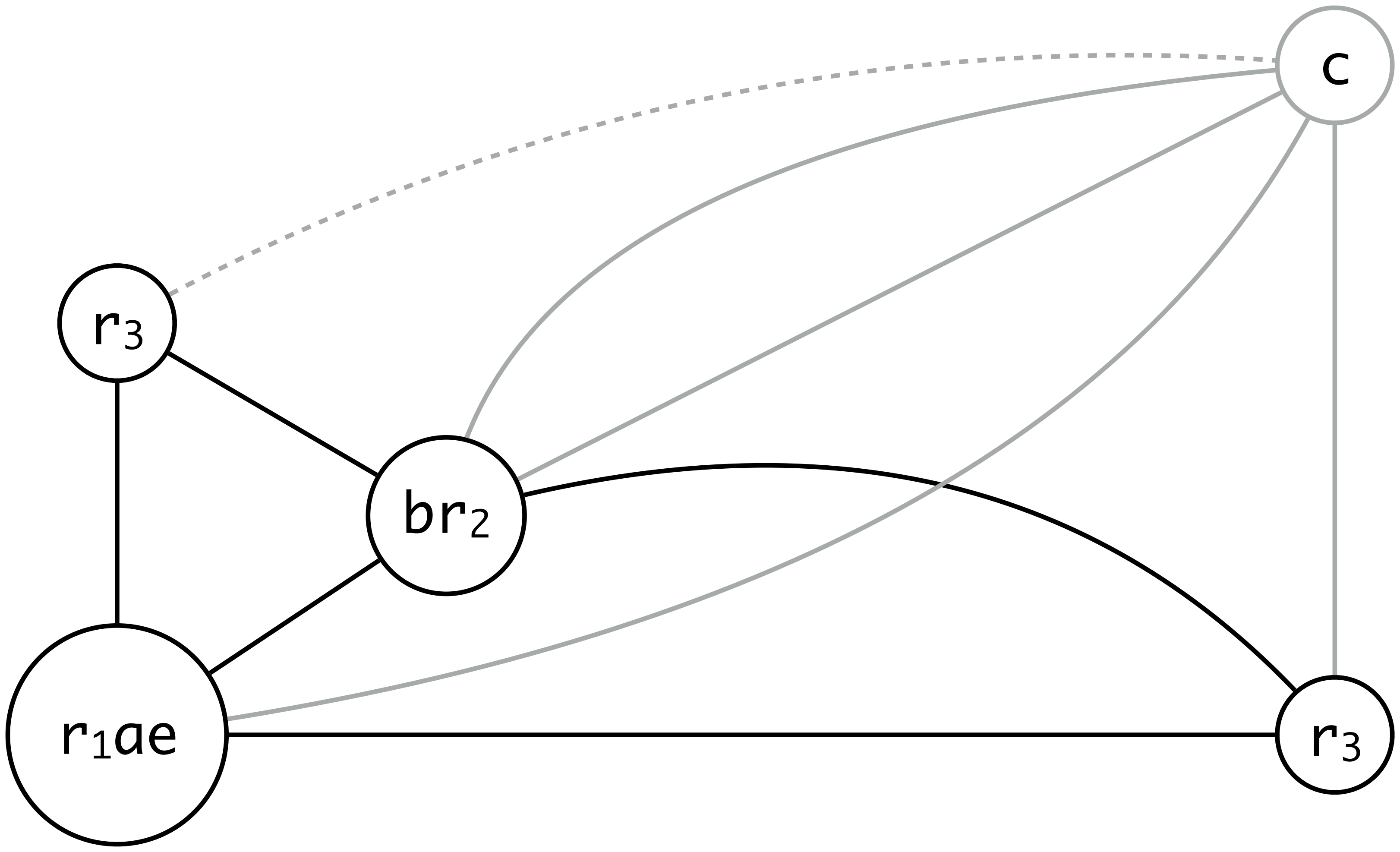


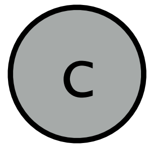
Pre-Colored Nodes

example

spill c

```
enter :  c₁ ← r₃
         M[cloc] ← c₁
         a ← r₁
         b ← r₂
         d ← 0
         e ← a
loop :   d ← d + b
         e ← e - 1
         if e > 0 goto loop
         r₁ ← d
         r₃ ← c₂
         c₂ ← M[cloc]
         return (r₁, r₃)
```



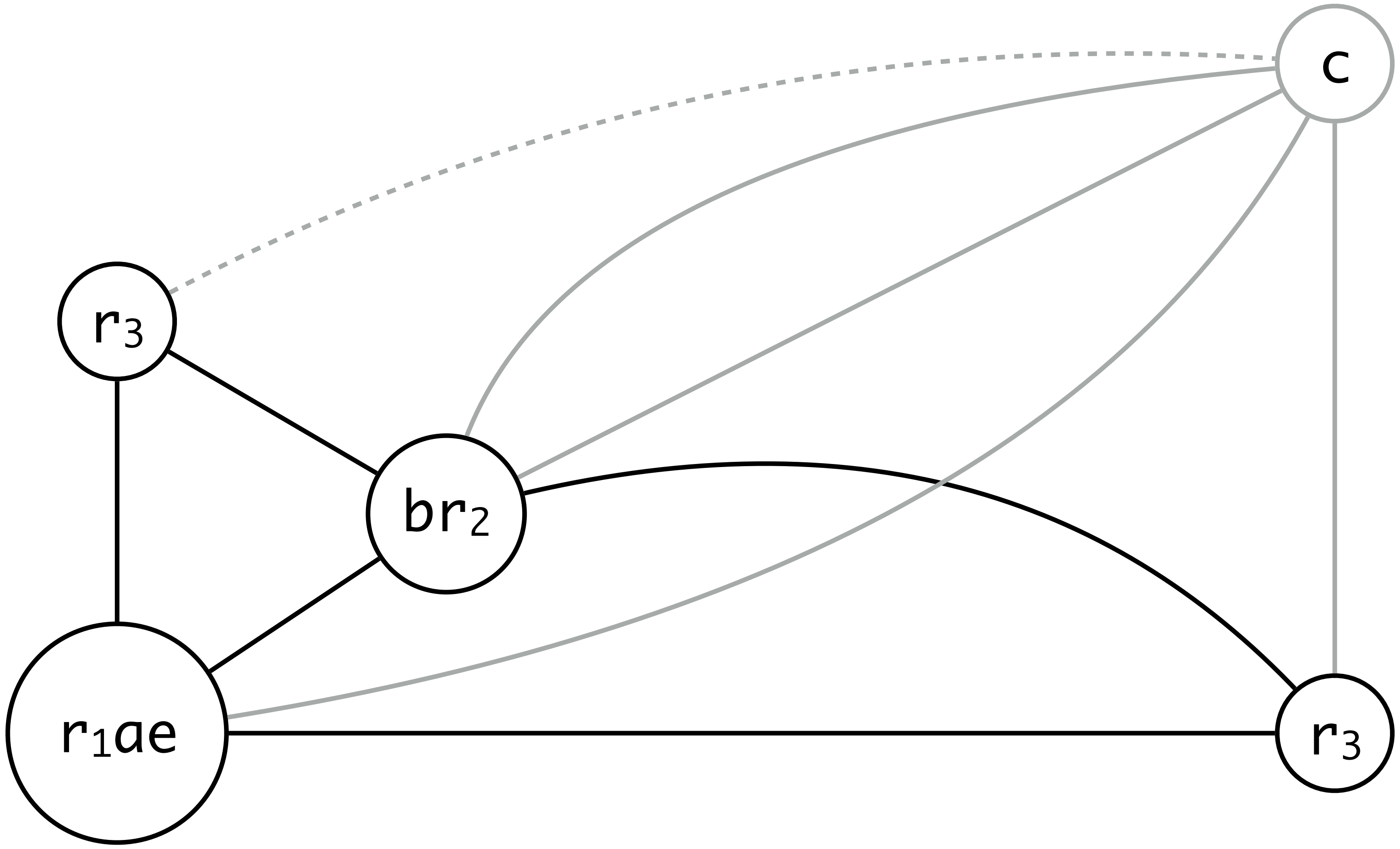


Pre-Colored Nodes

example

spill c

```
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
        r₃ ← c₂
        c₂ ← M[c_loc]
        return (r₁, r₃)
```

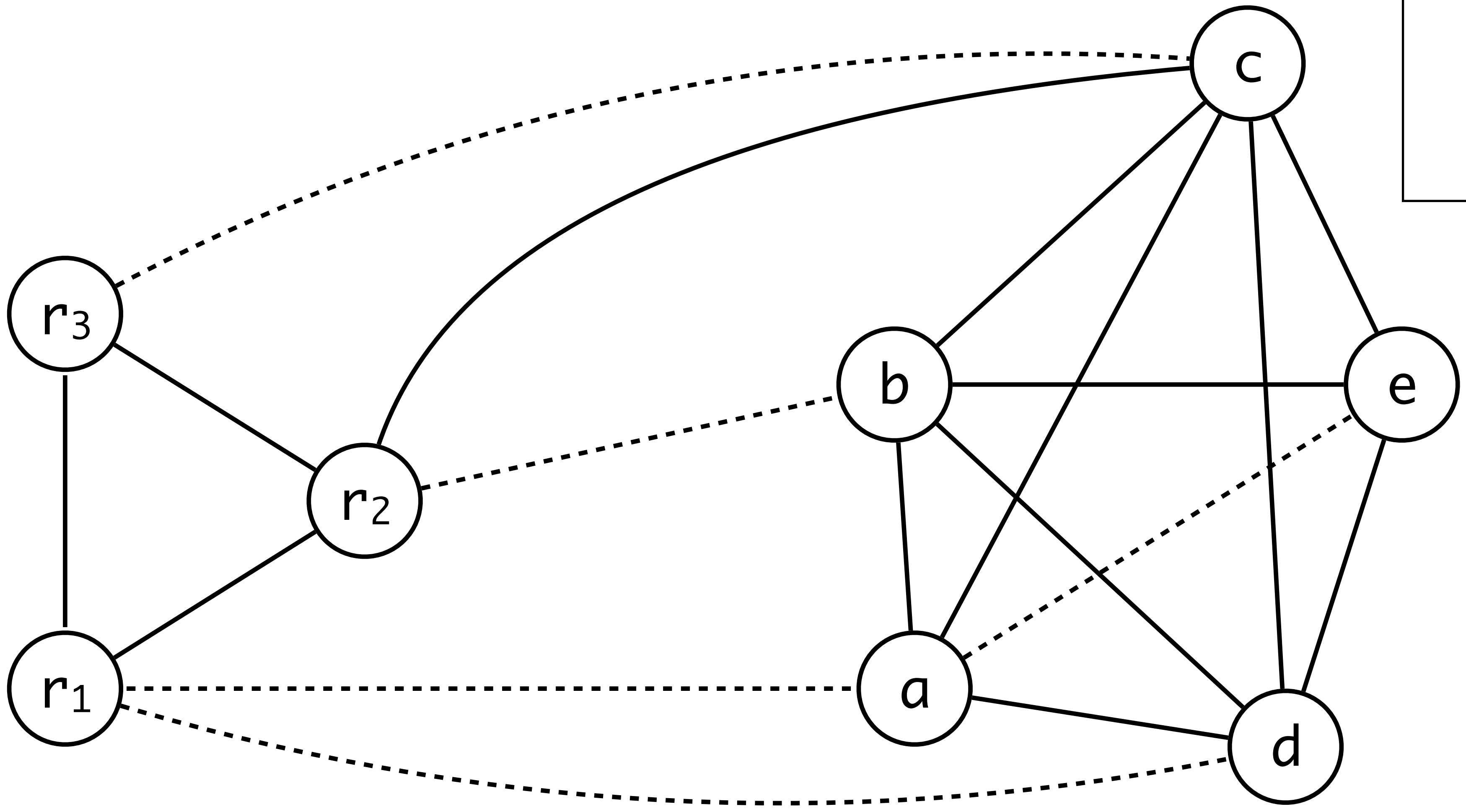


Pre-Colored Nodes

examples

start over

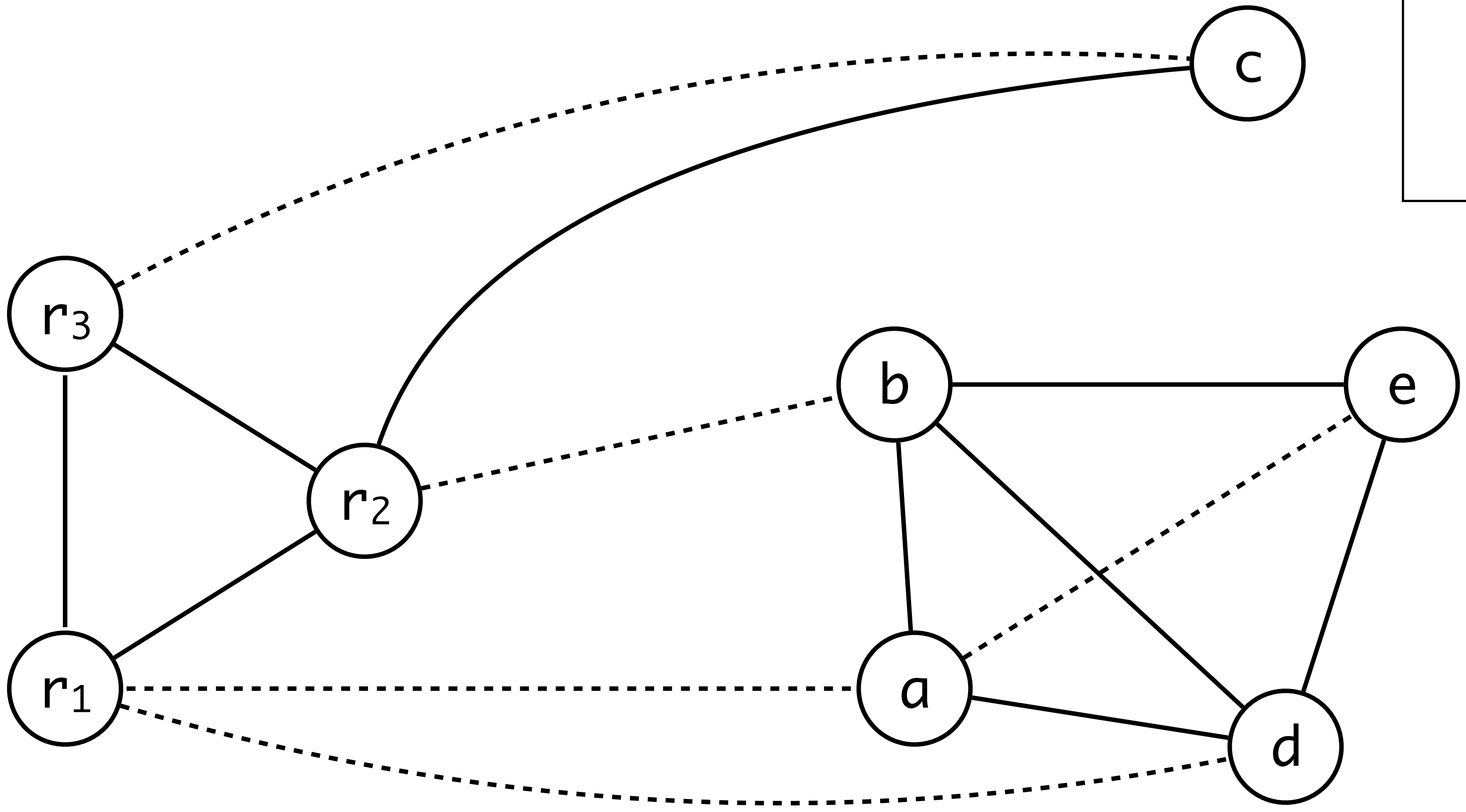
```
enter :  c₁ ← r₃
         M[c_loc] ← c₁
         a ← r₁
         b ← r₂
         d ← 0
         e ← a
loop :   d ← d + b
         e ← e - 1
         if e > 0 goto loop
         r₁ ← d
         r₃ ← c₂
         c₂ ← M[c_loc]
         return (r₁, r₃)
```



Pre-Colored Nodes

examples

```
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
        r₃ ← c₂
        c₂ ← M[c_loc]
        return (r₁, r₃)
```

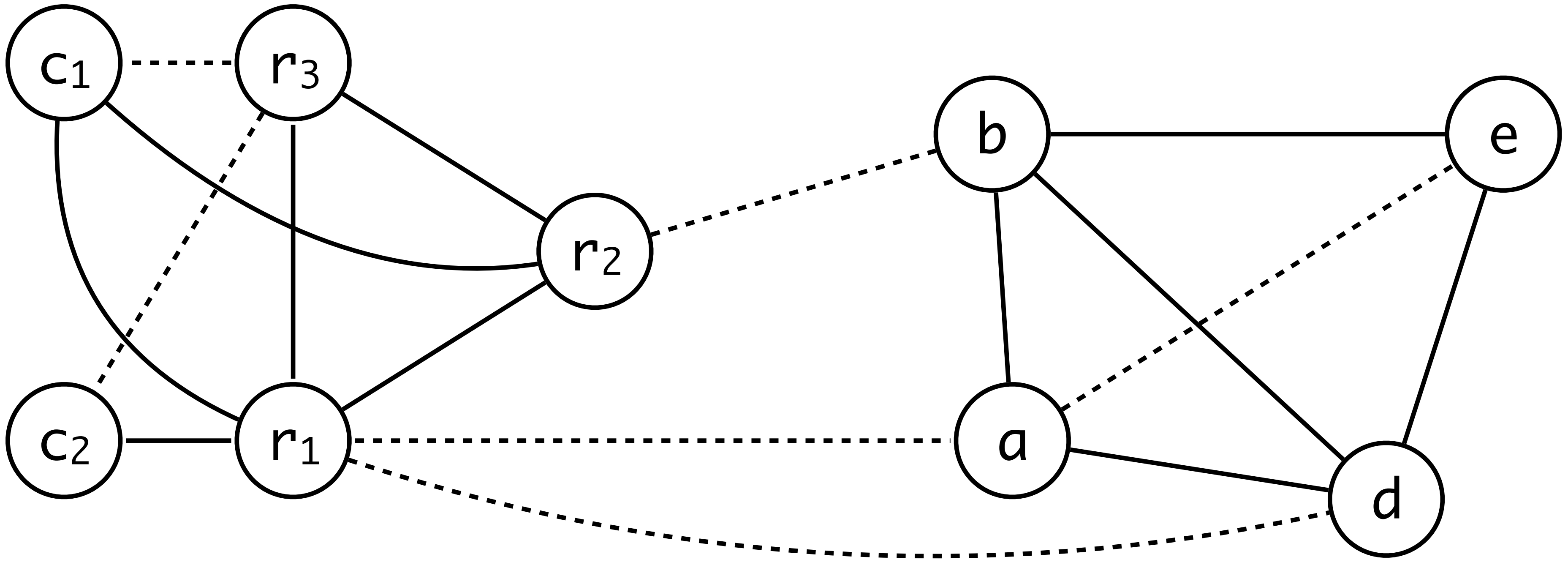


Pre-Colored Nodes

examples

new graph

```
enter :  c₁ ← r₃
         M[cloc] ← c₁
         a ← r₁
         b ← r₂
         d ← 0
         e ← a
loop :   d ← d + b
         e ← e - 1
         if e > 0 goto loop
         r₁ ← d
         r₃ ← c₂
         c₂ ← M[cloc]
         return (r₁, r₃)
```

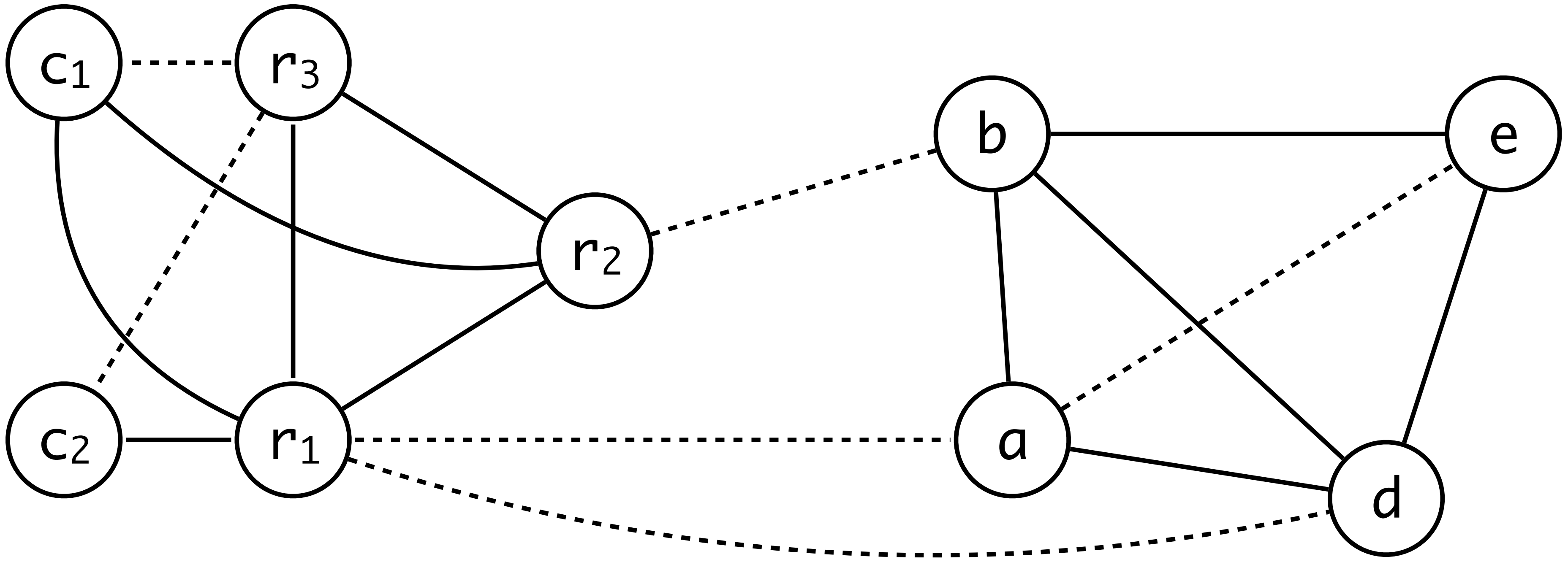


Pre-Colored Nodes

examples

coalesce c_1, c_2, r_3

```
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
        r₃ ← c₂
        c₂ ← M[c_loc]
        return (r₁, r₃)
```

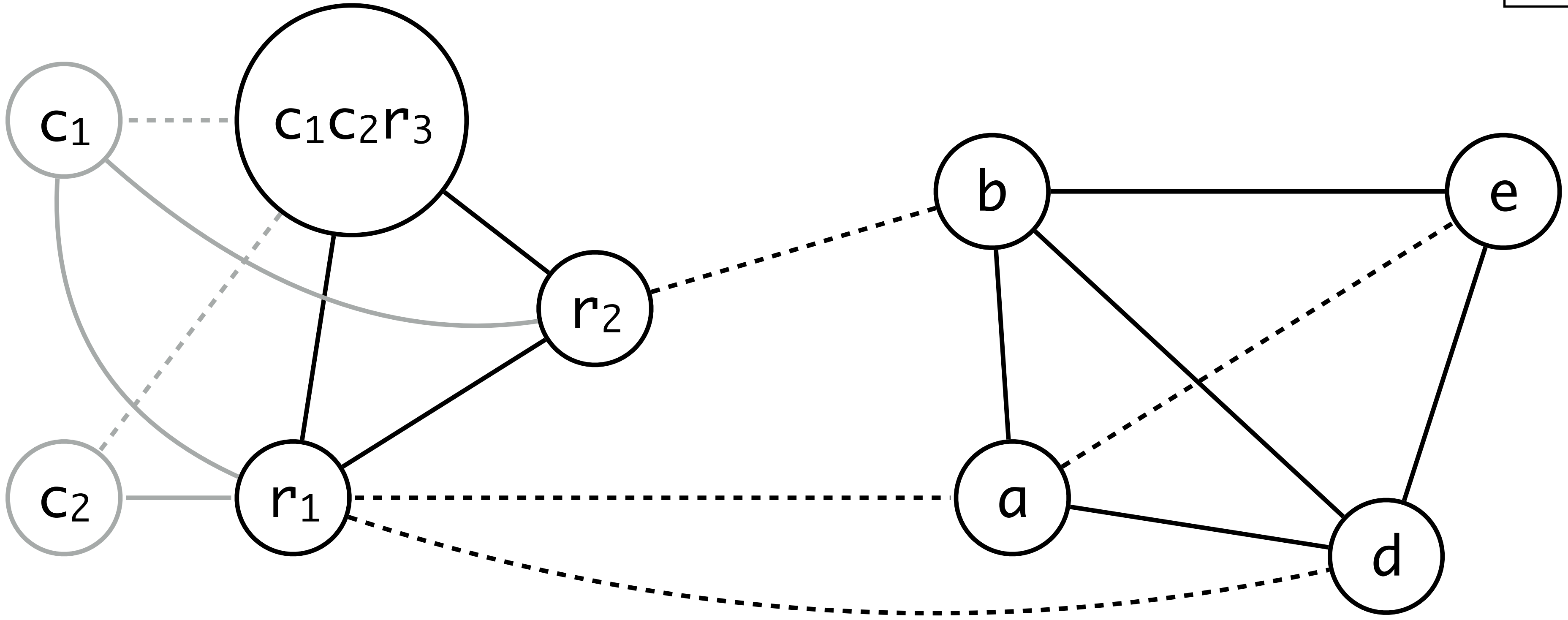


Pre-Colored Nodes

examples

coalesce c_1, c_2, r_3

```
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
        r₃ ← c₂
        c₂ ← M[c_loc]
        return (r₁, r₃)
```

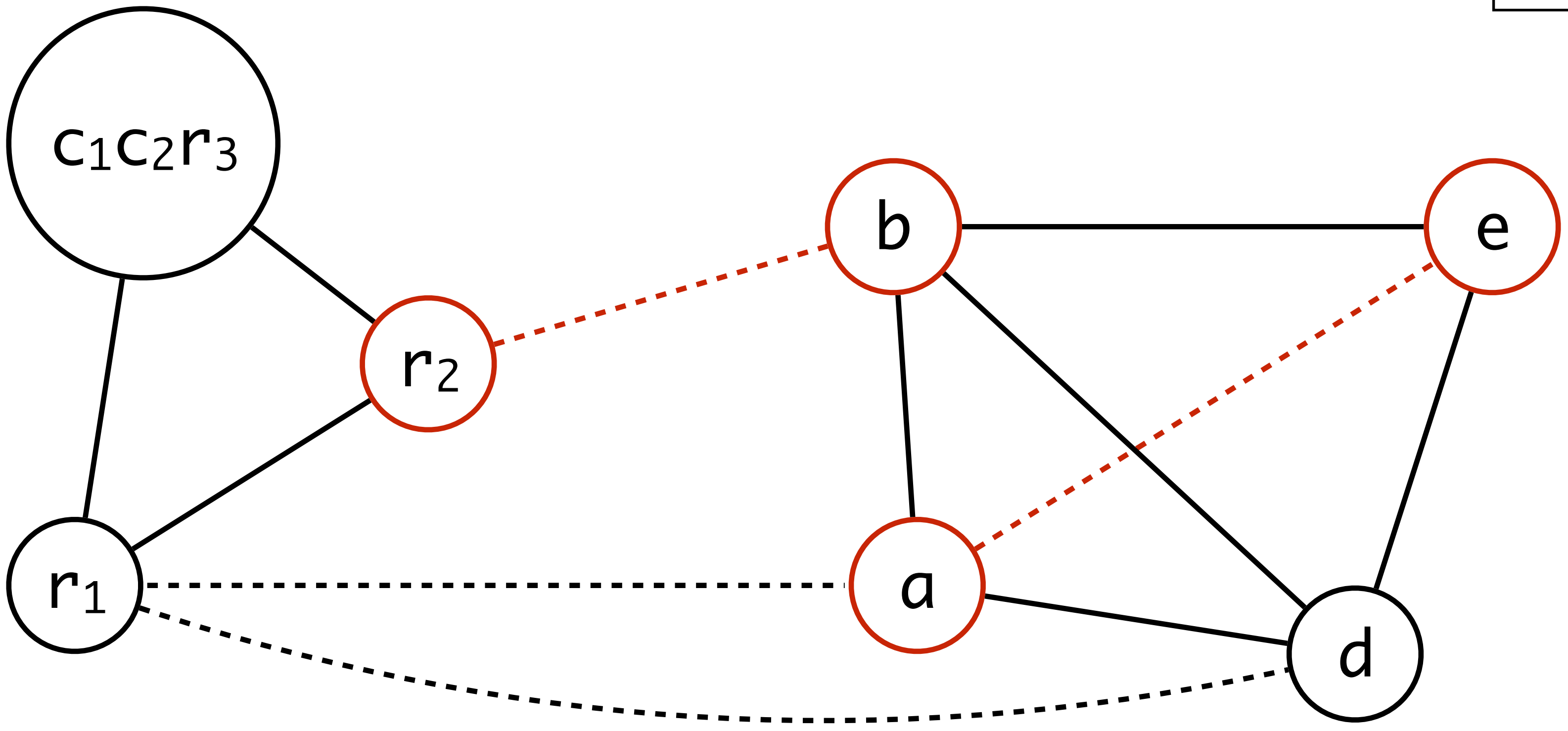


Pre-Colored Nodes

examples

coalesce (b, r_2) and (a, e)

```
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
         r₃ ← c₂
         c₂ ← M[c_loc]
         return (r₁, r₃)
```

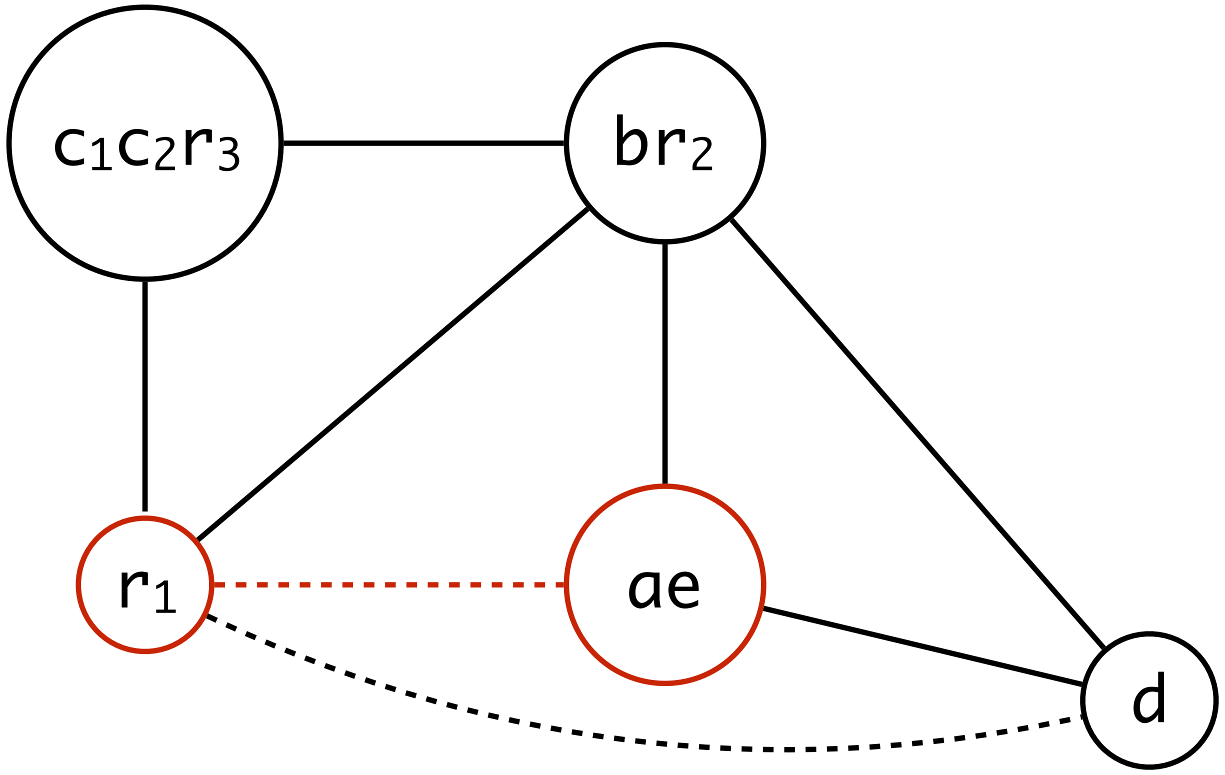


Pre-Colored Nodes

examples

coalesce (ae, r_1)

```
enter : c₁ ← r₃
        M[cloc] ← c₁
        a ← r₁
        b ← r₂
        d ← 0
        e ← a
loop :  d ← d + b
        e ← e - 1
        if e > 0 goto loop
        r₁ ← d
        r₃ ← c₂
        c₂ ← M[cloc]
        return (r₁, r₃)
```

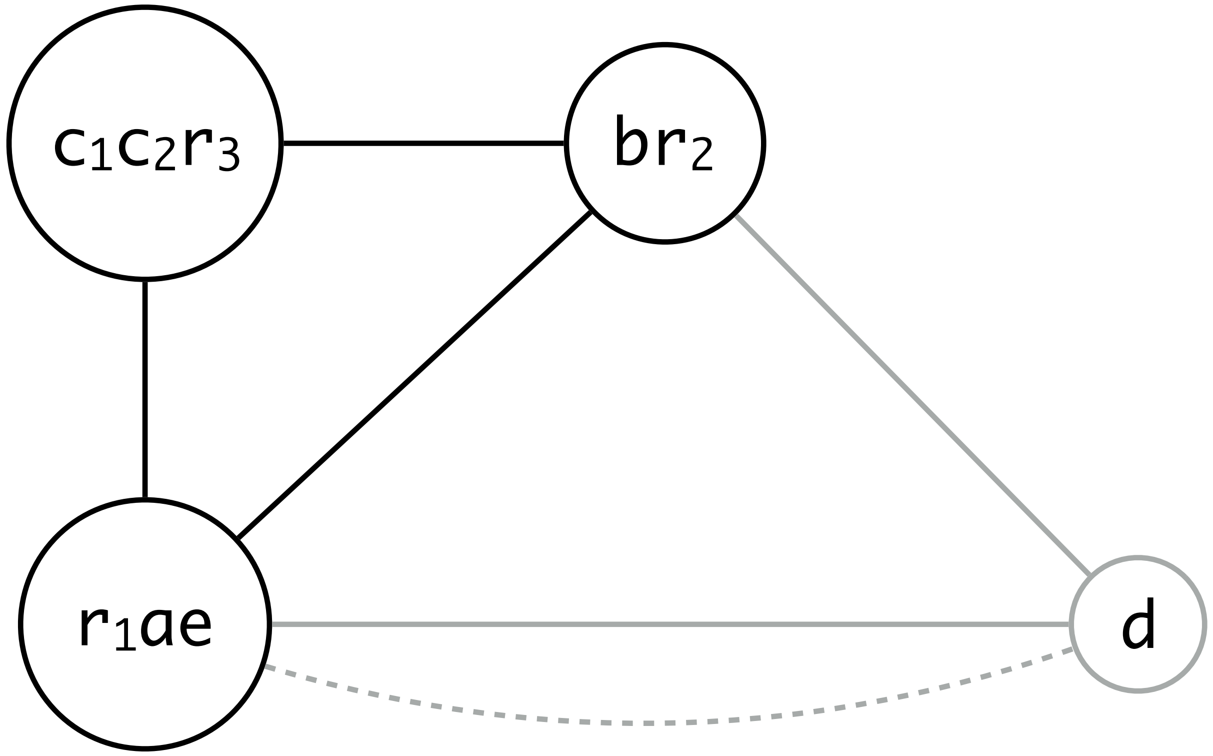


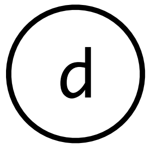
Pre-Colored Nodes

examples

simplify d

```
enter : c₁ ← r₃
        M[cloc] ← c₁
        a ← r₁
        b ← r₂
        d ← 0
        e ← a
loop :  d ← d + b
        e ← e - 1
        if e > 0 goto loop
        r₁ ← d
        r₃ ← c₂
        c₂ ← M[cloc]
        return (r₁, r₃)
```



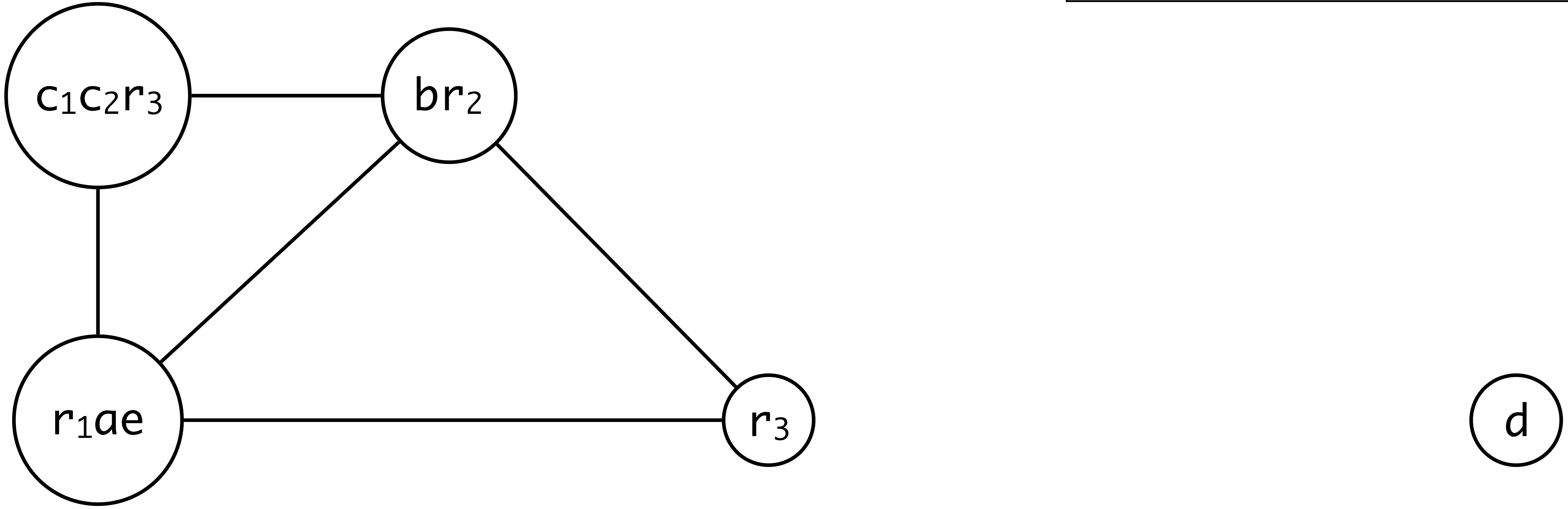


Pre-Colored Nodes

examples

color d as r_3

```
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
        r₃ ← c₂
        c₂ ← M[c_loc]
        return (r₁, r₃)
```

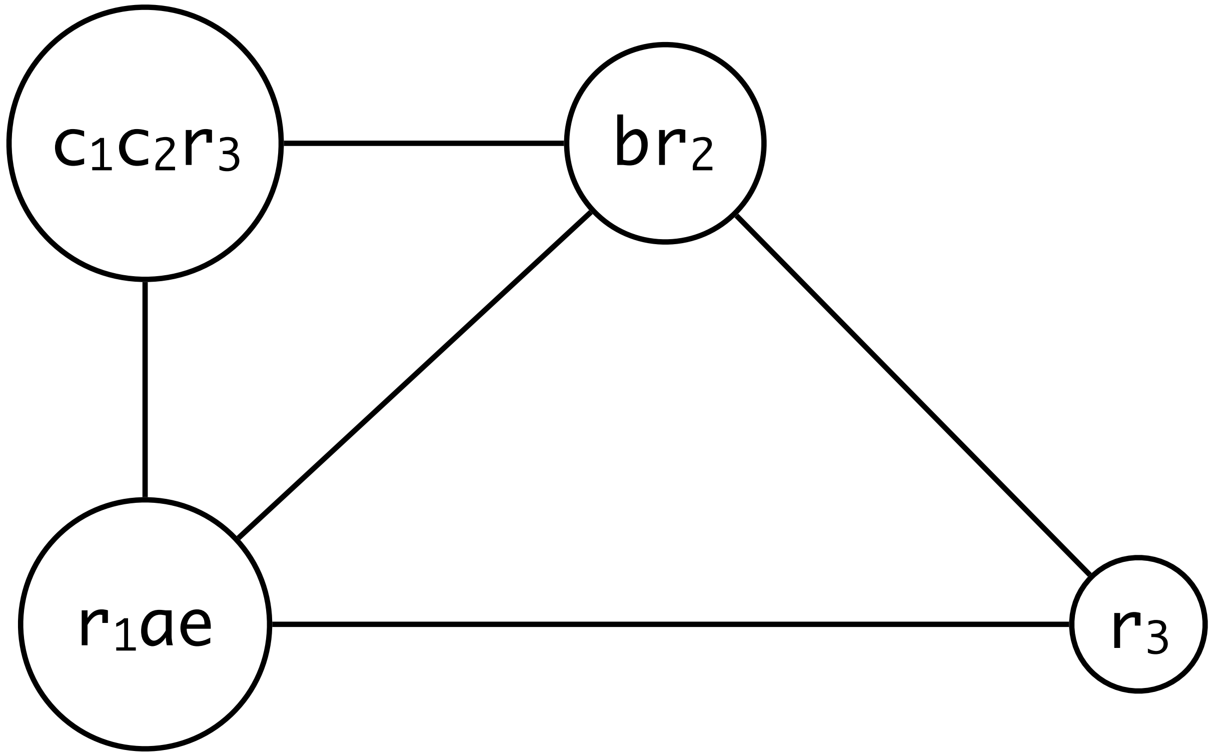


Pre-Colored Nodes

examples

apply register assigment

```
enter : r3 ← r3
        M[cloc] ← r3
        r1 ← r1
        r2 ← r2
        r3 ← 0
        r1 ← r1
loop :  r3 ← r3 + r2
        r1 ← r1 - 1
        if r1 > 0 goto loop
        r1 ← r3
        r3 ← r3
        r3 ← M[cloc]
        return (r1, r3)
```



Pre-Colored Nodes

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)
```

```
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 ← r₃
        r₃ ← M[c_loc]
        return (r₁, r₃)
```

Pre-Colored Nodes

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)
```

```
enter : r3 ← r3
        M[cloc] ← r3
        r1 ← r1
        r2 ← r2
        r3 ← 0
        r1 ← r1
loop :  r3 ← r3 + r2
        r1 ← r1 - 1
        if r1 > 0 goto loop
        r1 ← r3
        r3 ← r3
        r3 ← M[cloc]
        return (r1, r3)
```

Pre-Colored Nodes

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)
```

```
enter : M[cloc] ← r3
        r3 ← 0
loop :  r3 ← r3 + r2
        r1 ← r1 - 1
        if r1 > 0 goto loop
        r1 ← r3
        r3 ← M[cloc]
        return (r1, r3)
```

Pre-Colored Nodes

example

```
int f(int a, int b) {
  int d = 0;
  int e = a;
  do {
    d = d + b;
    e = e - 1;
  } while (e > 0);
  return d;
}
```

```
enter : M[c_loc] ← r3
        r3 ← 0
loop :  r3 ← r3 + r2
        r1 ← r1 - 1
        if r1 > 0 goto loop
        r3 ← M[c_loc]
        return (r1, r3)
```

VI

Summary

Summary
lessons learned

How can we assign registers to local variables and temporaries?

- perform liveness analysis
- build interference graph
- color interference graph

What to do if the graph is not colorable?

- keep local variables in memory

How to handle move instructions efficiently?

- coalesce nodes safely

Literature
learn more

Andrew W. Appel, Jens Palsberg: Modern Compiler Implementation in Java, 2nd edition. 2002

Lal George, Andrew W. Appel: Iterative Register Coalescing. POPL 1996

Lal George, Andrew W. Appel: Iterative Register Coalescing. TOPLAS 18(3), 1996

Outlook

coming next

Compiler components & their generators

- Lecture 12: Data-Flow Analysis **Dec 6**
- Lecture 13: Register Allocation **Dec 13**
- Lecture 14: LL Parsing **Dec 20**
- Lecture 15: LR Parsing **Jan 10**

Exam preparation

- Question & Answer & Outlook **Jan 24**
- Exam **Jan 31**

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