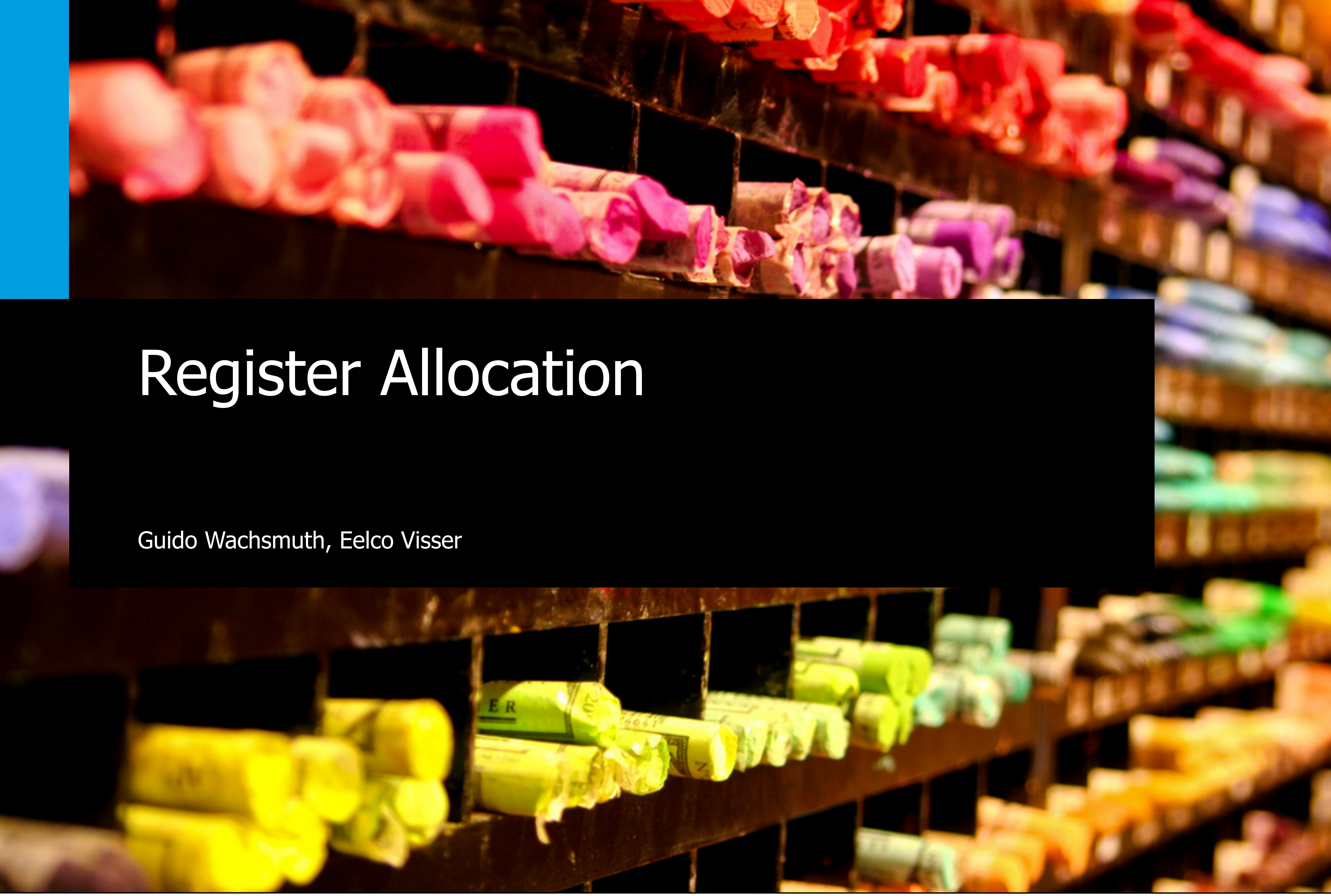

Register Allocation

Guido Wachsmuth, Eelco Visser

Delft University of Technology

Course IN4303, 2016-2017
Compiler Construction

Challenge the future

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

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

Overview
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Interference graphs

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- assign registers to local variables and compiler temporaries
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Coalescing

- handle move instructions

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

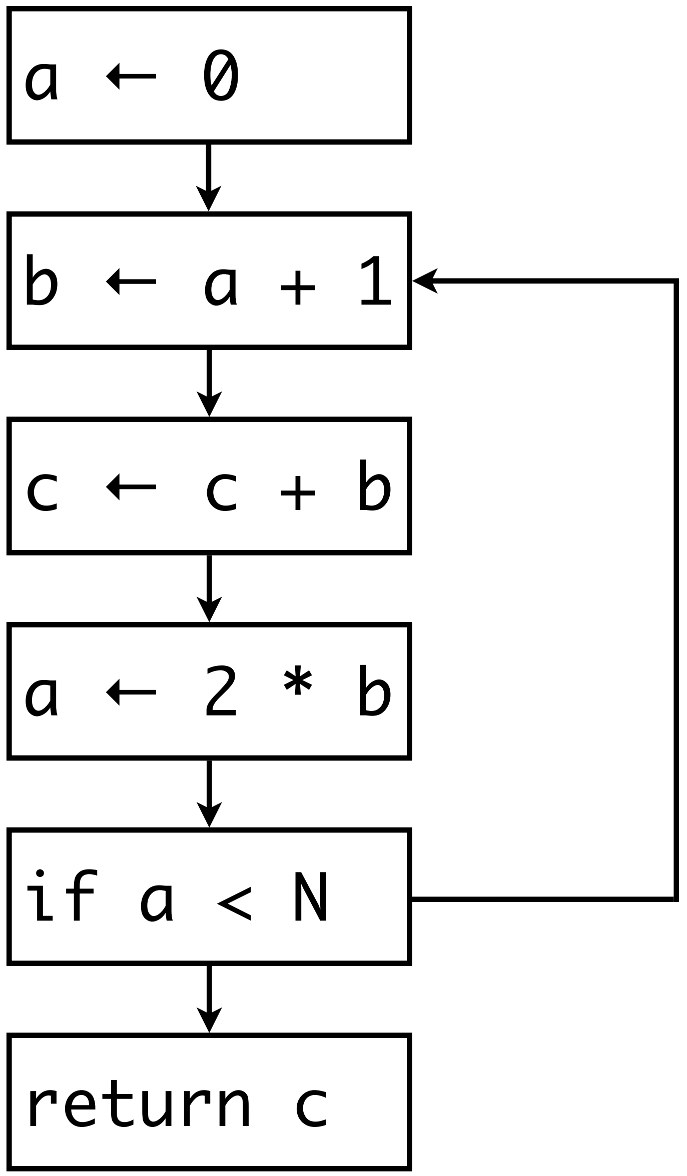
Pre-colored nodes

I

Interference Graphs

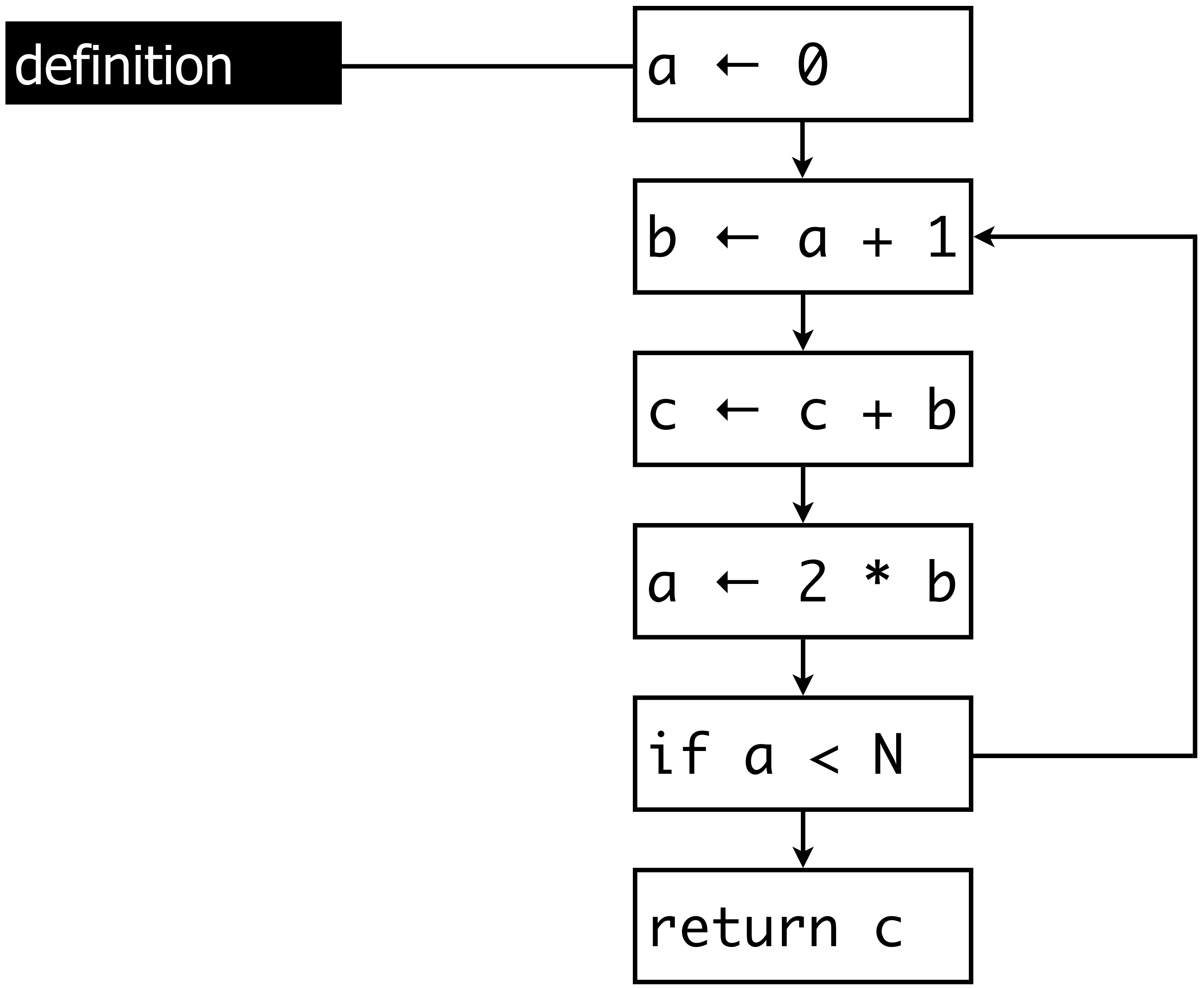
Recap: Liveness Analysis

terminology



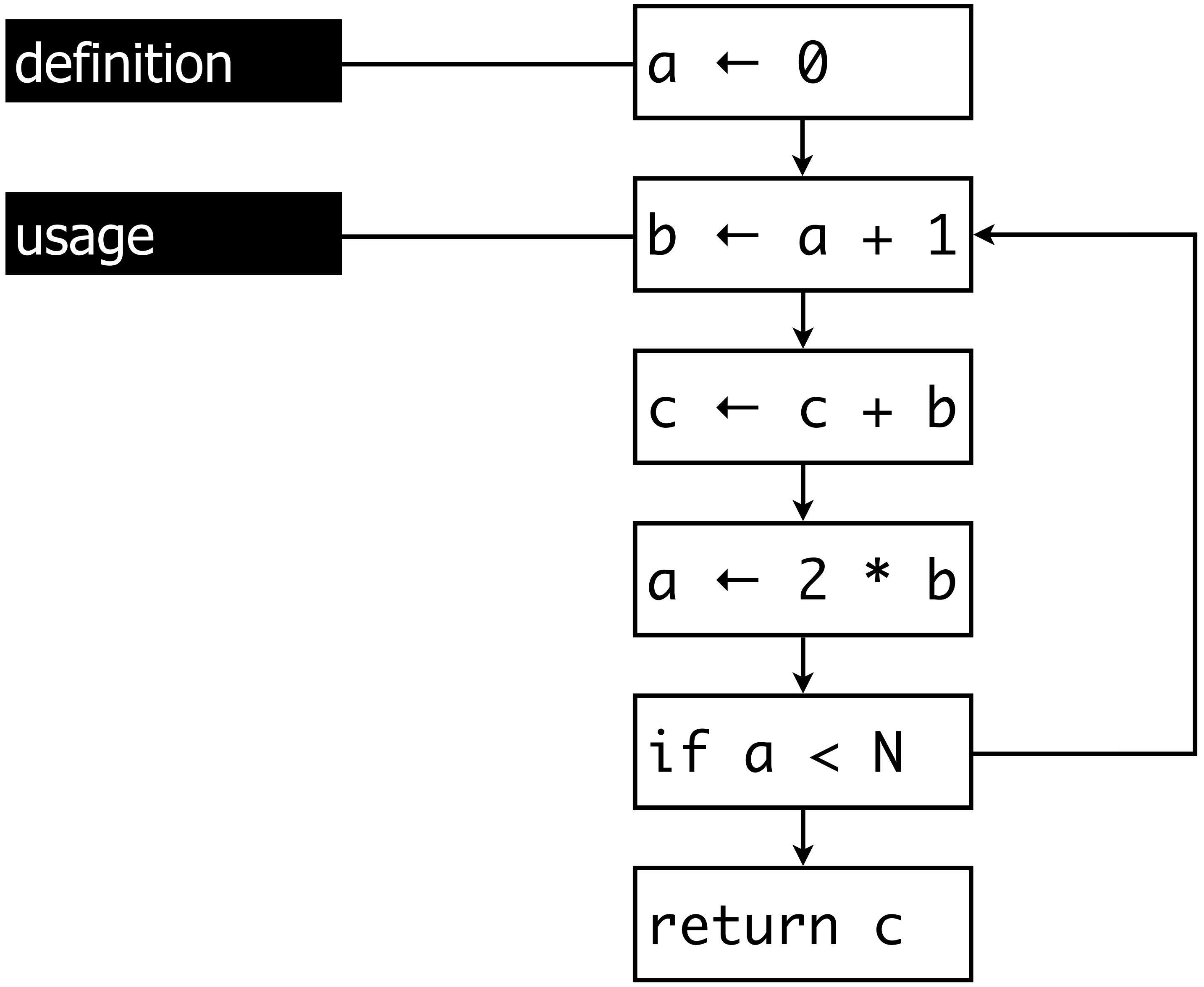
Recap: Liveness Analysis

terminology



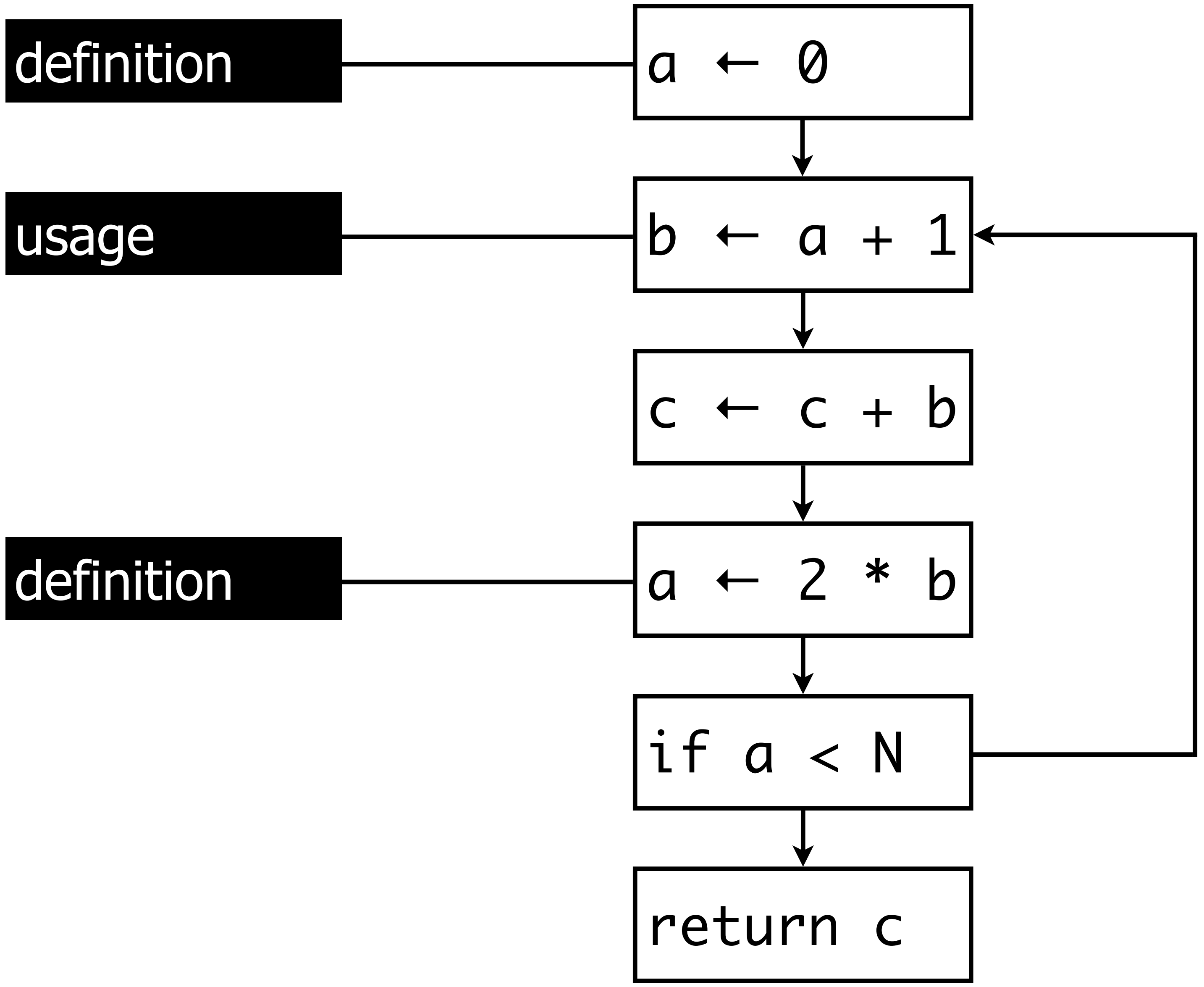
Recap: Liveness Analysis

terminology



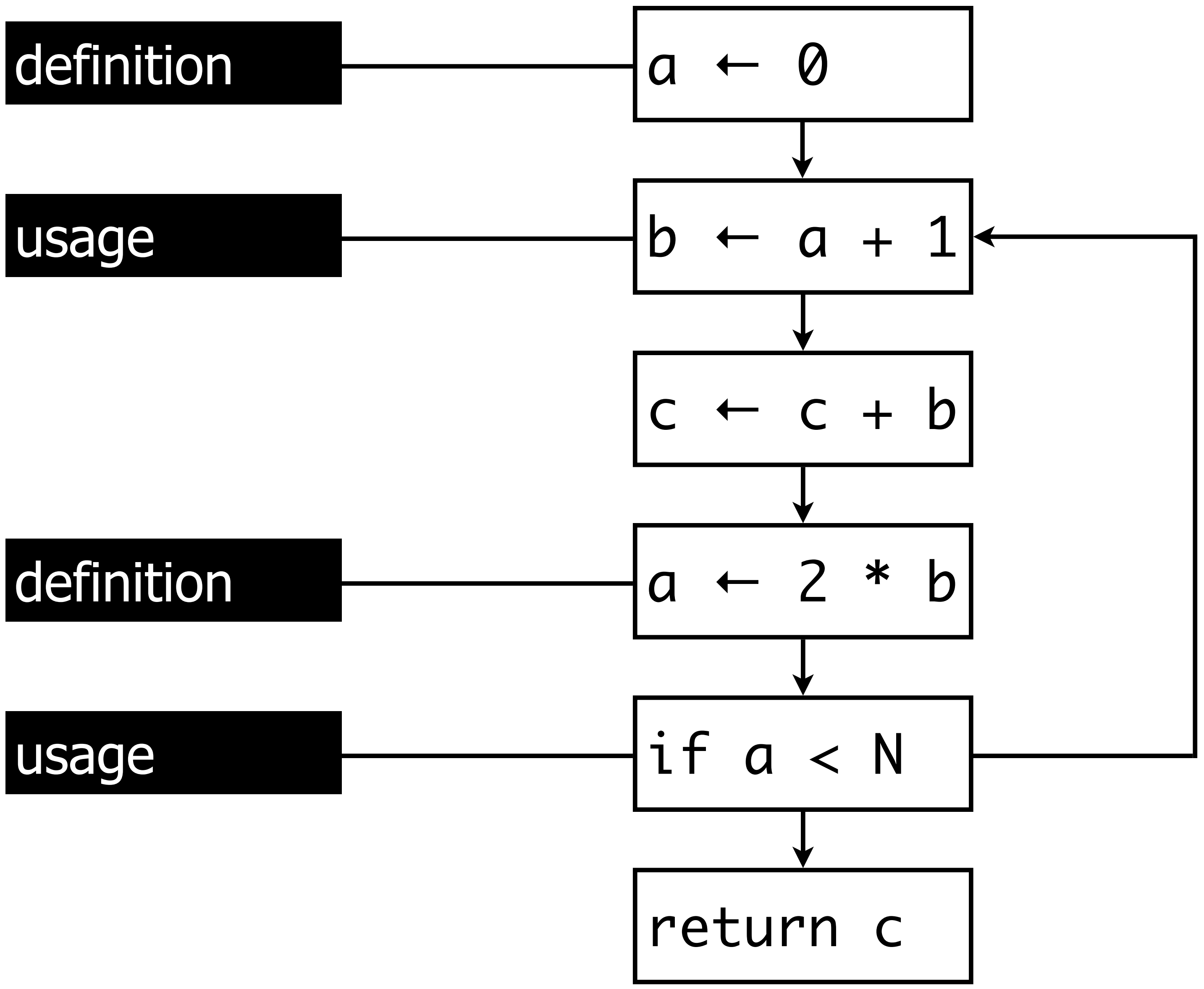
Recap: Liveness Analysis

terminology



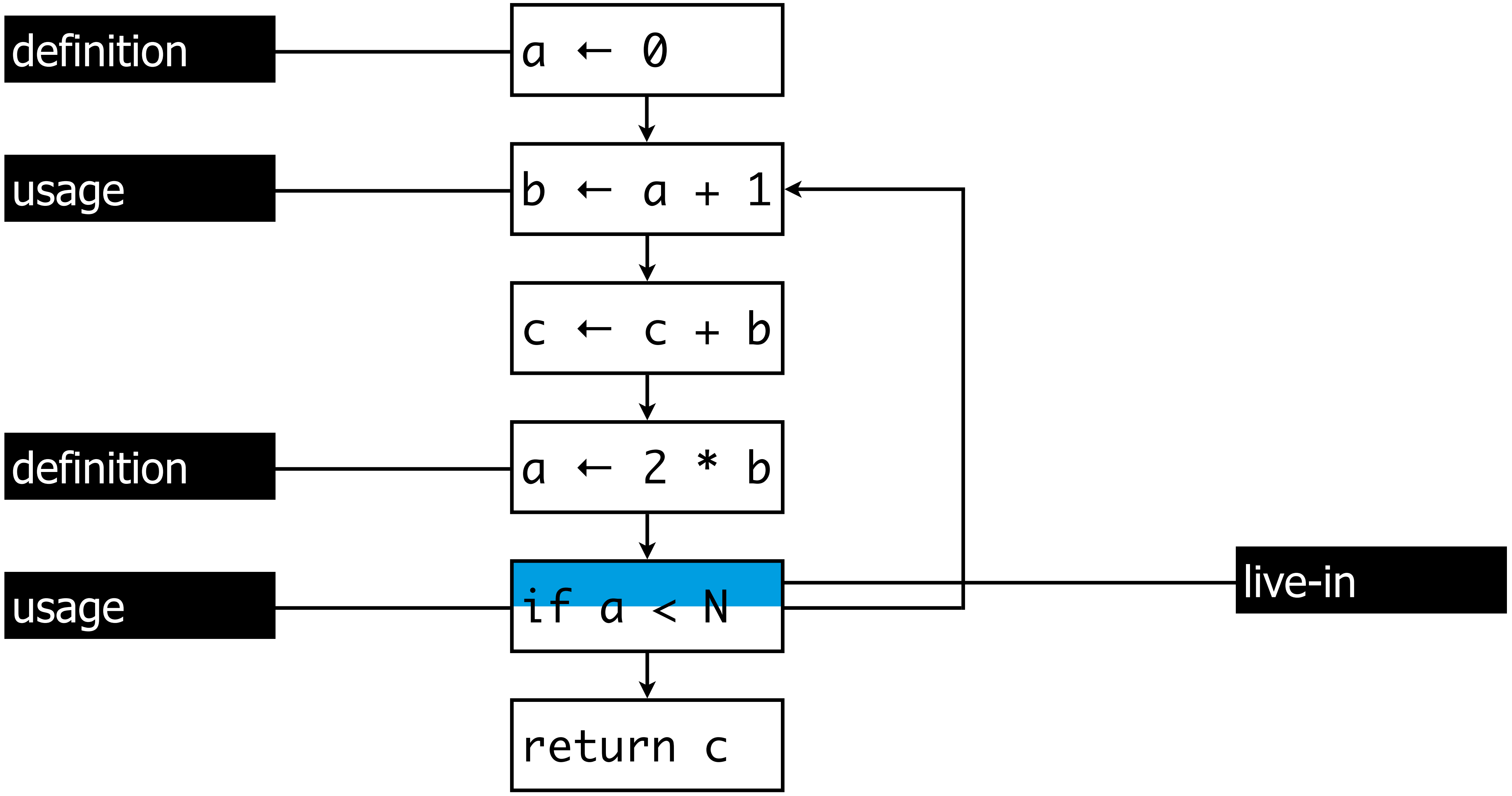
Recap: Liveness Analysis

terminology



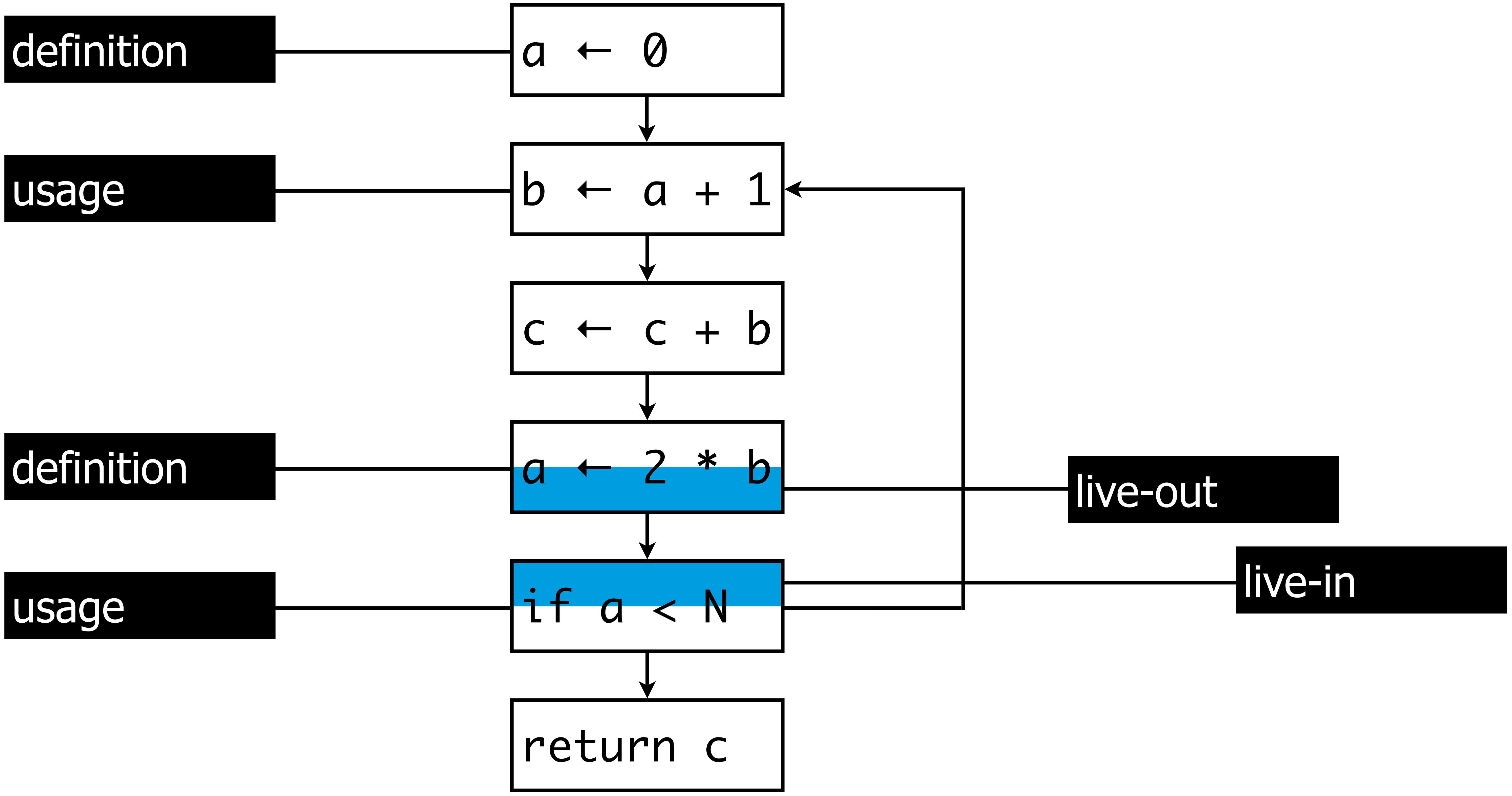
Recap: Liveness Analysis

terminology



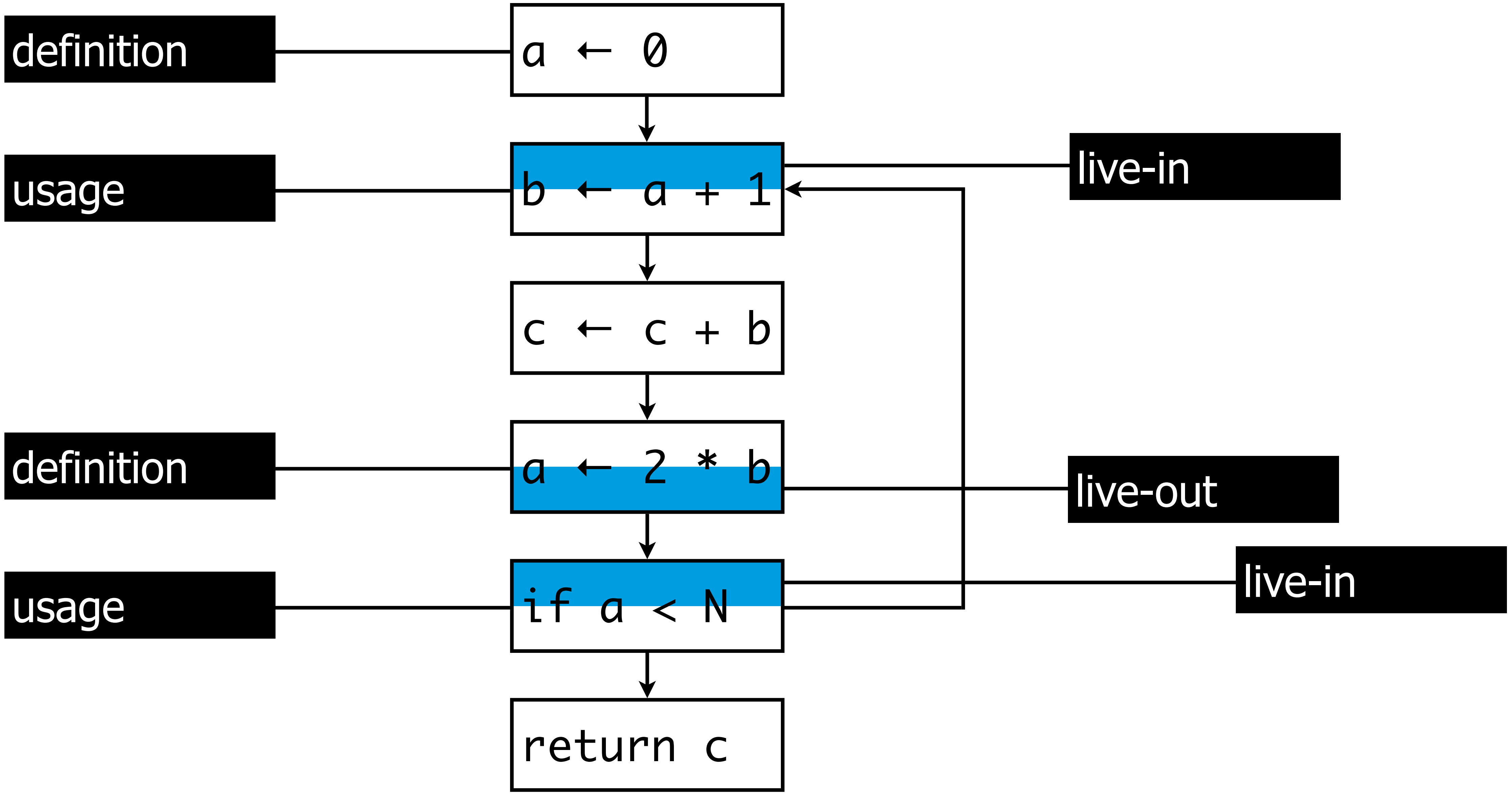
Recap: Liveness Analysis

terminology



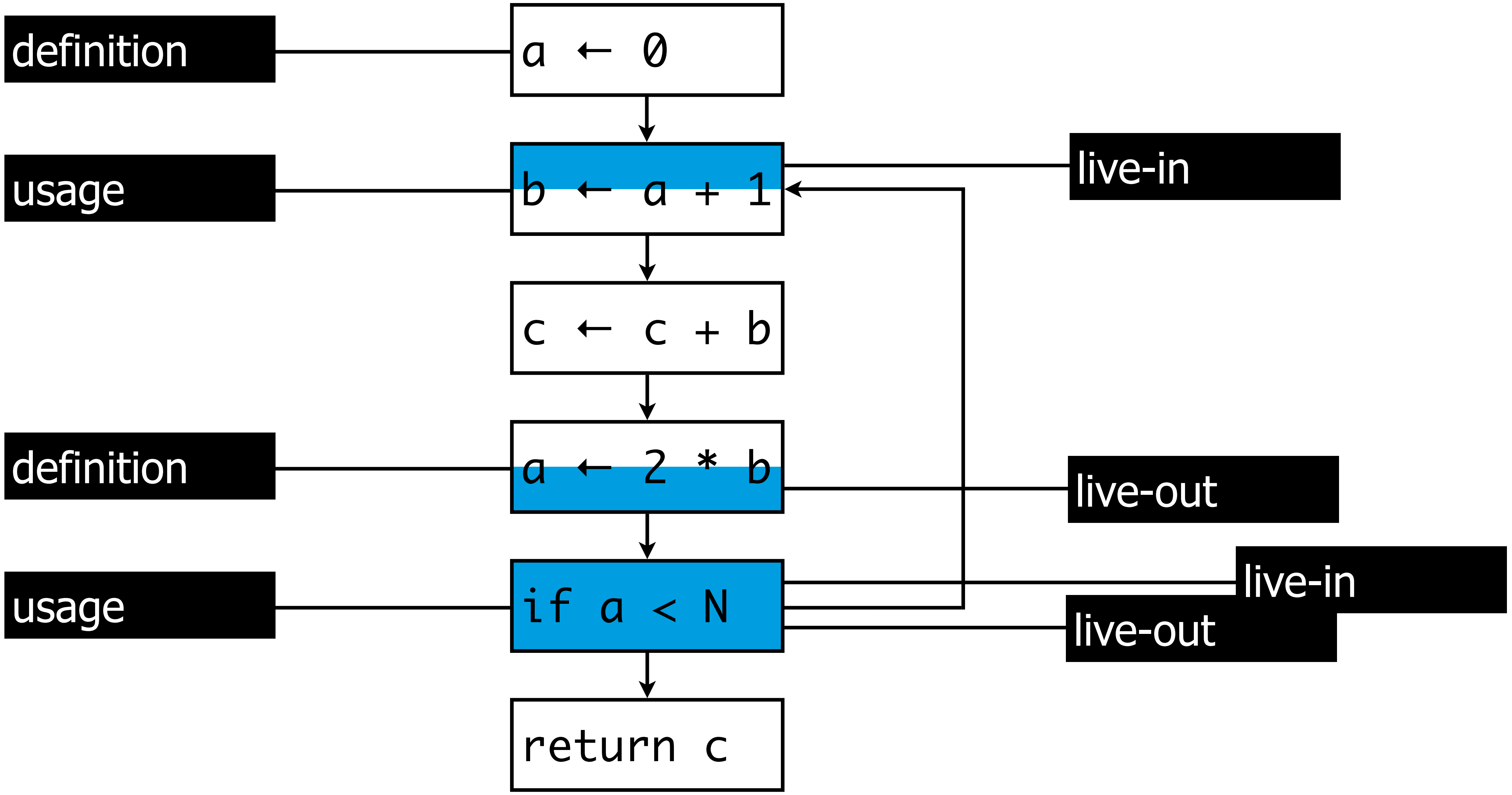
Recap: Liveness Analysis

terminology



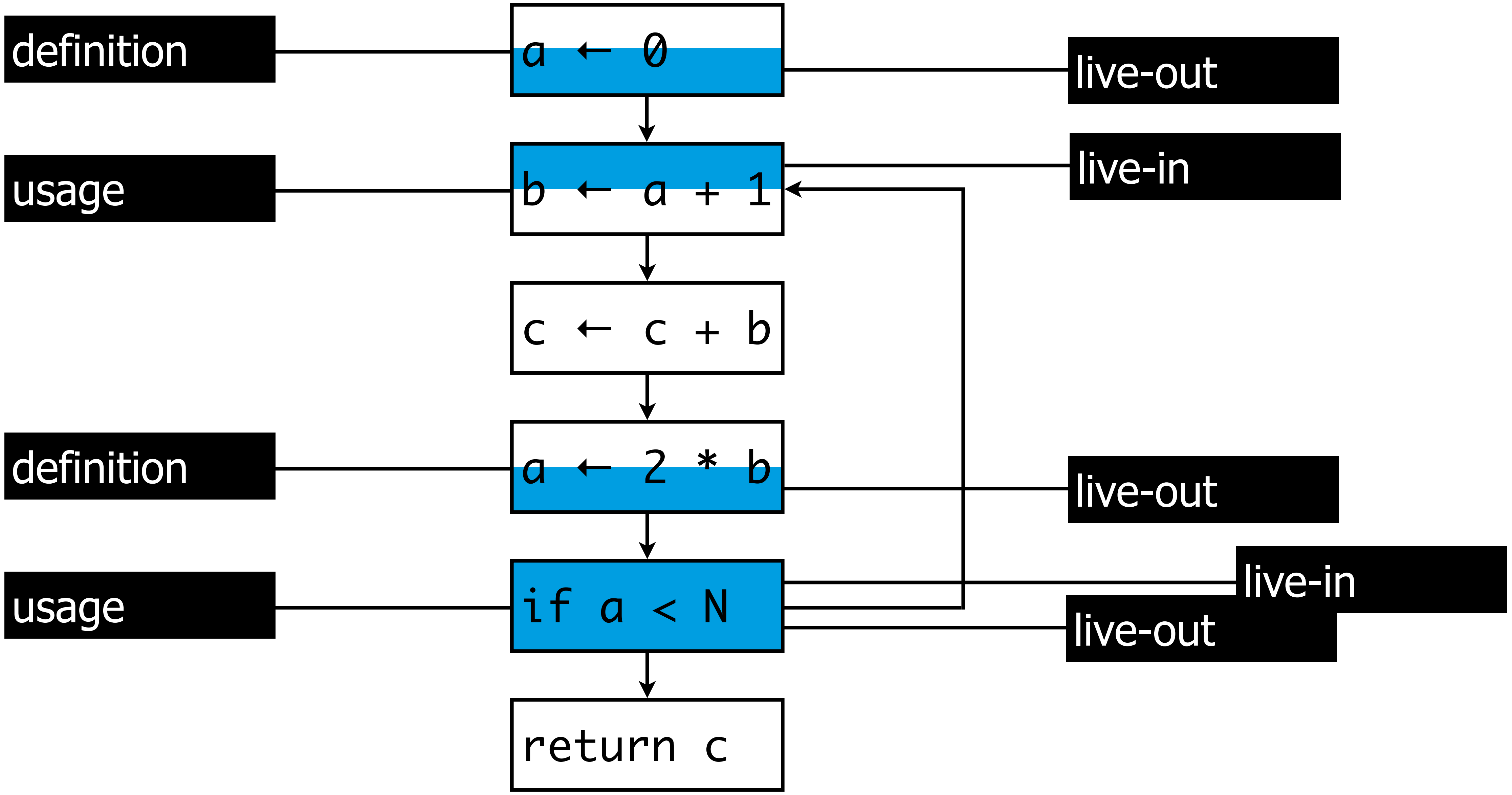
Recap: Liveness Analysis

terminology



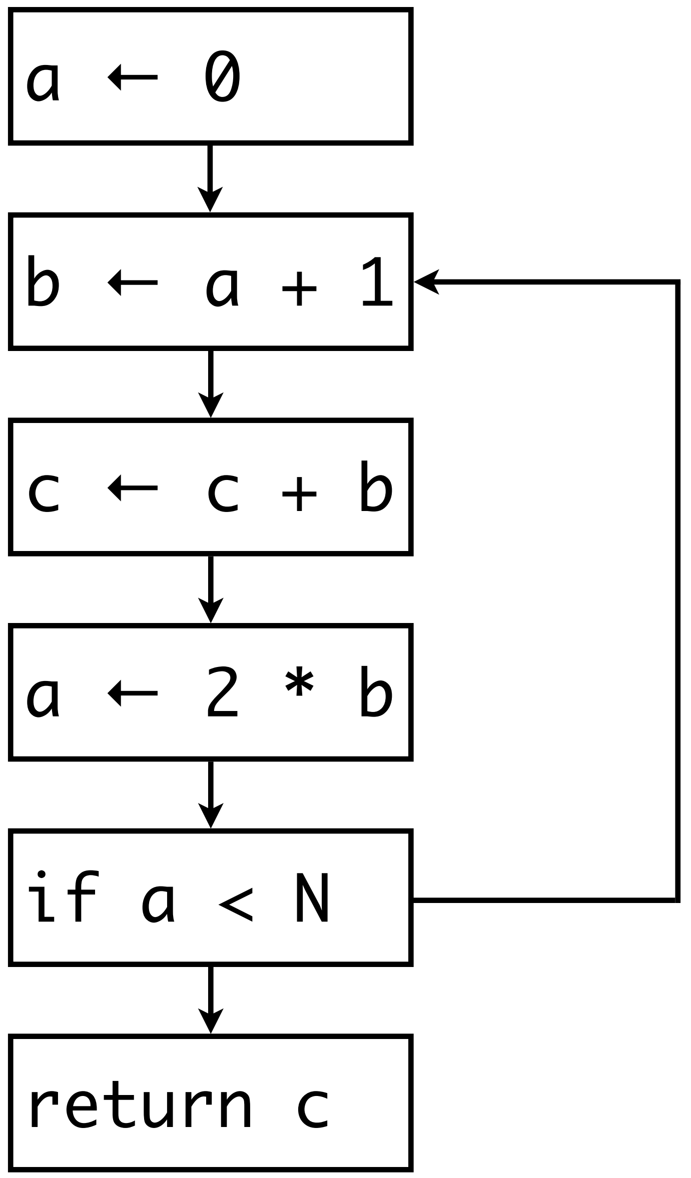
Recap: Liveness Analysis

terminology



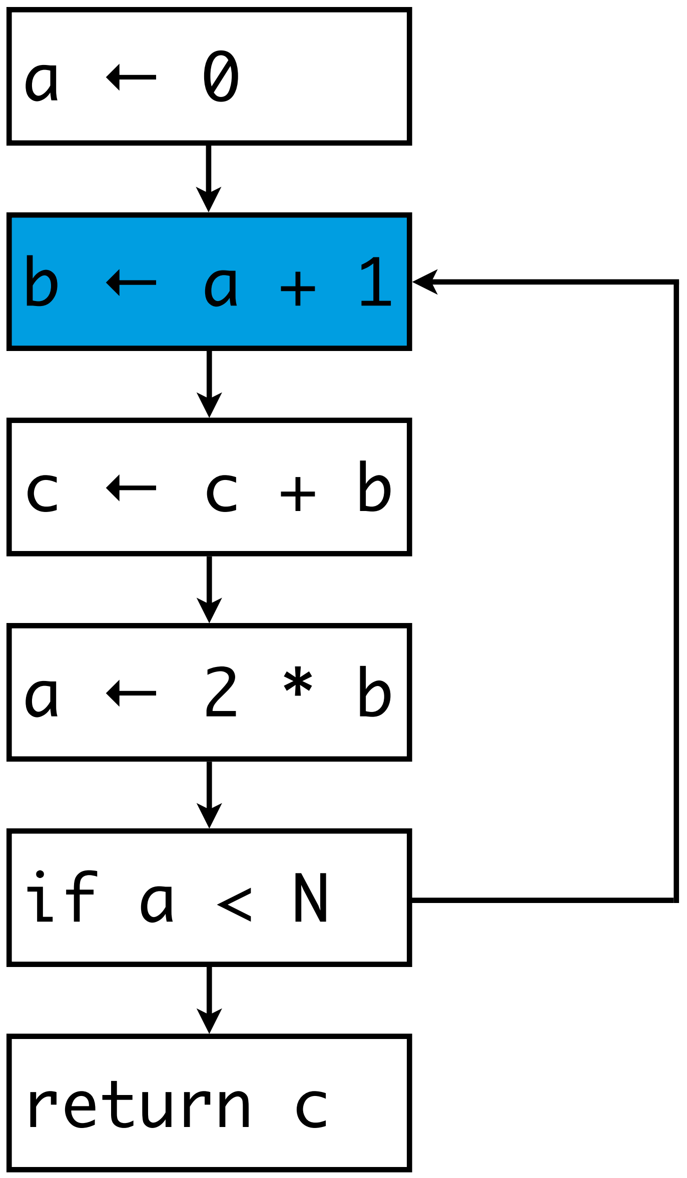
Recap: Liveness Analysis

example



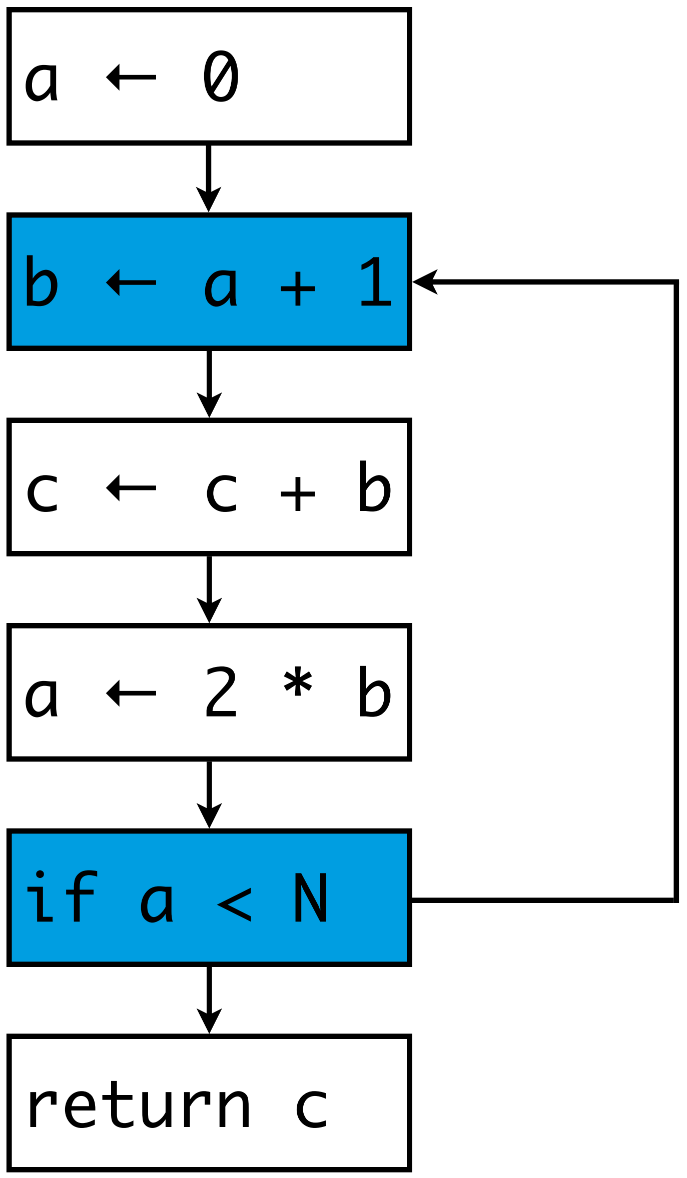
Recap: Liveness Analysis

example



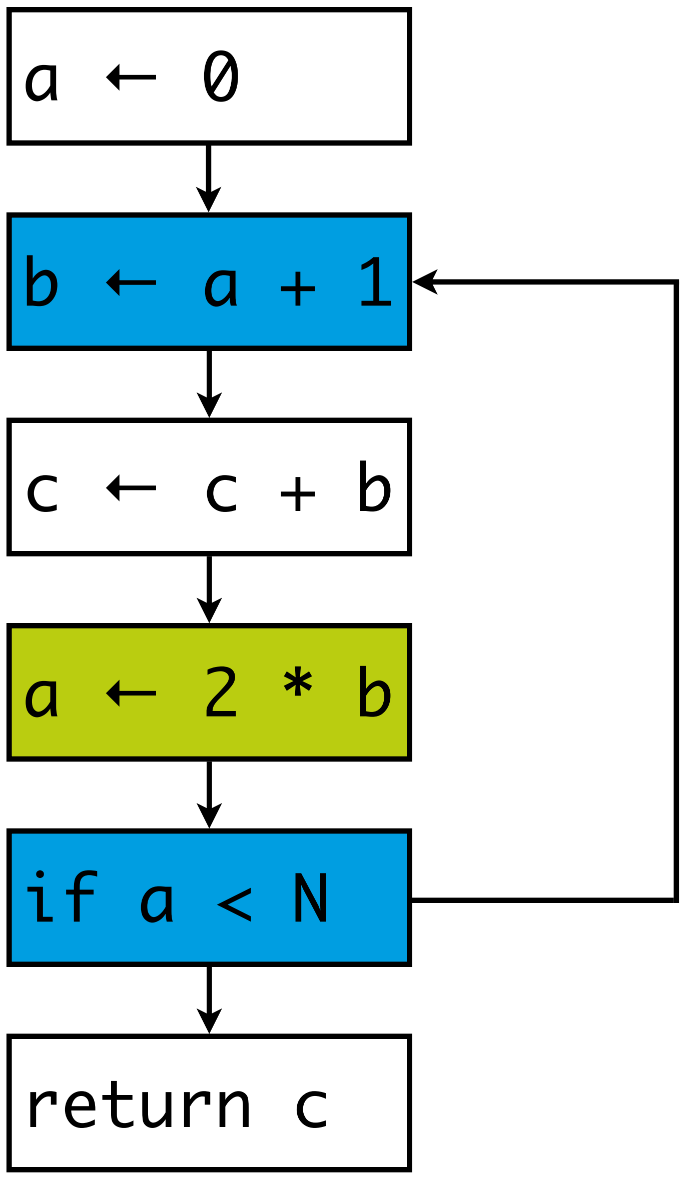
Recap: Liveness Analysis

example



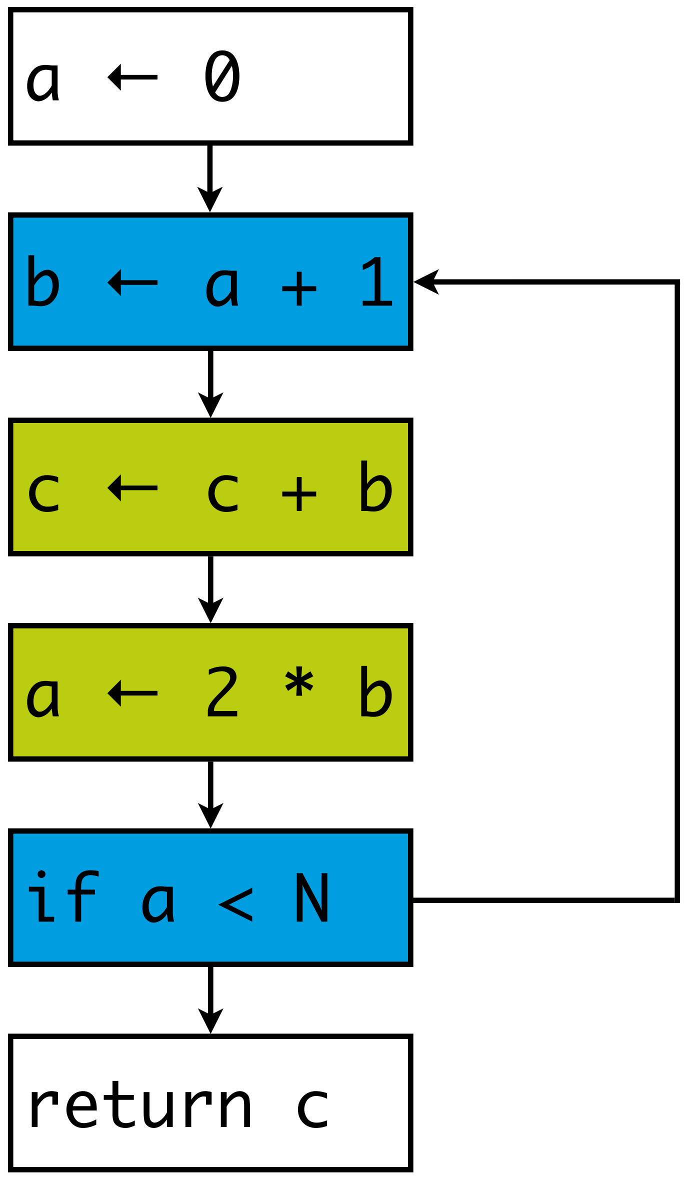
Recap: Liveness Analysis

example



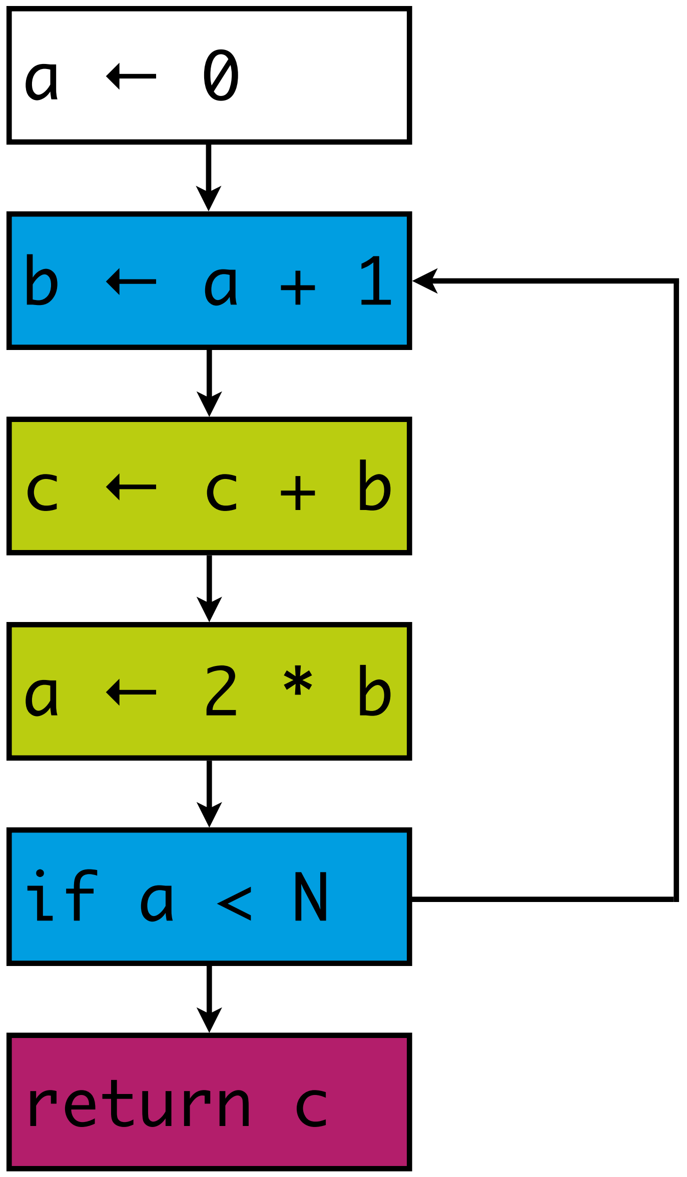
Recap: Liveness Analysis

example

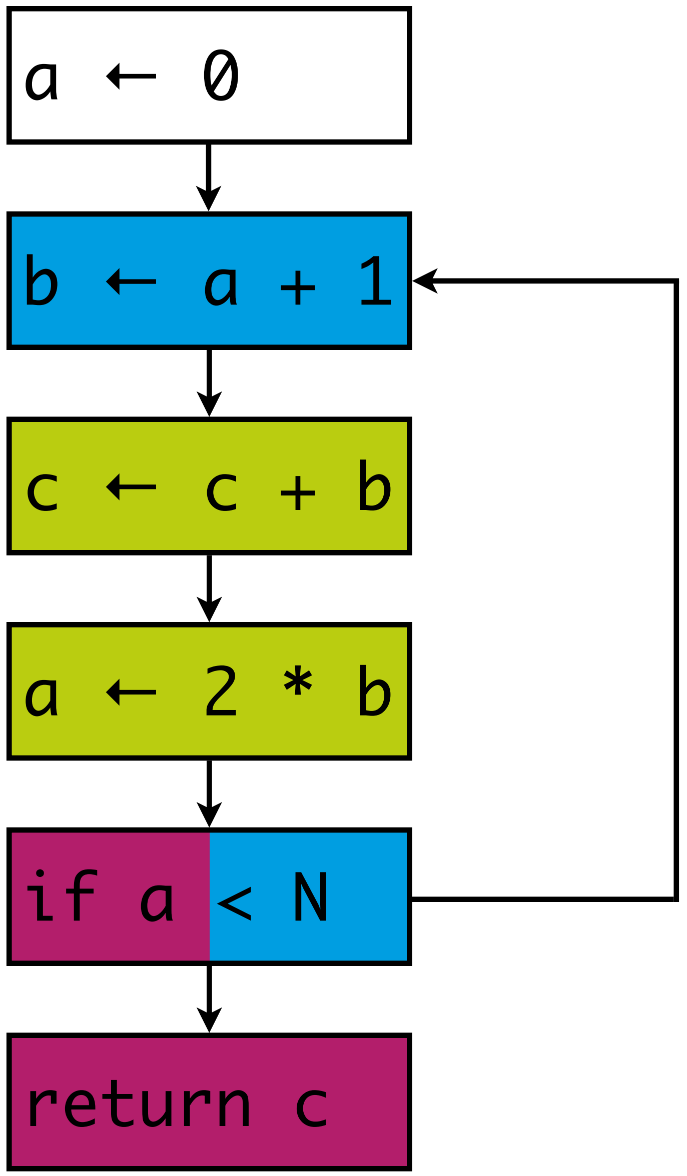


Recap: Liveness Analysis

example

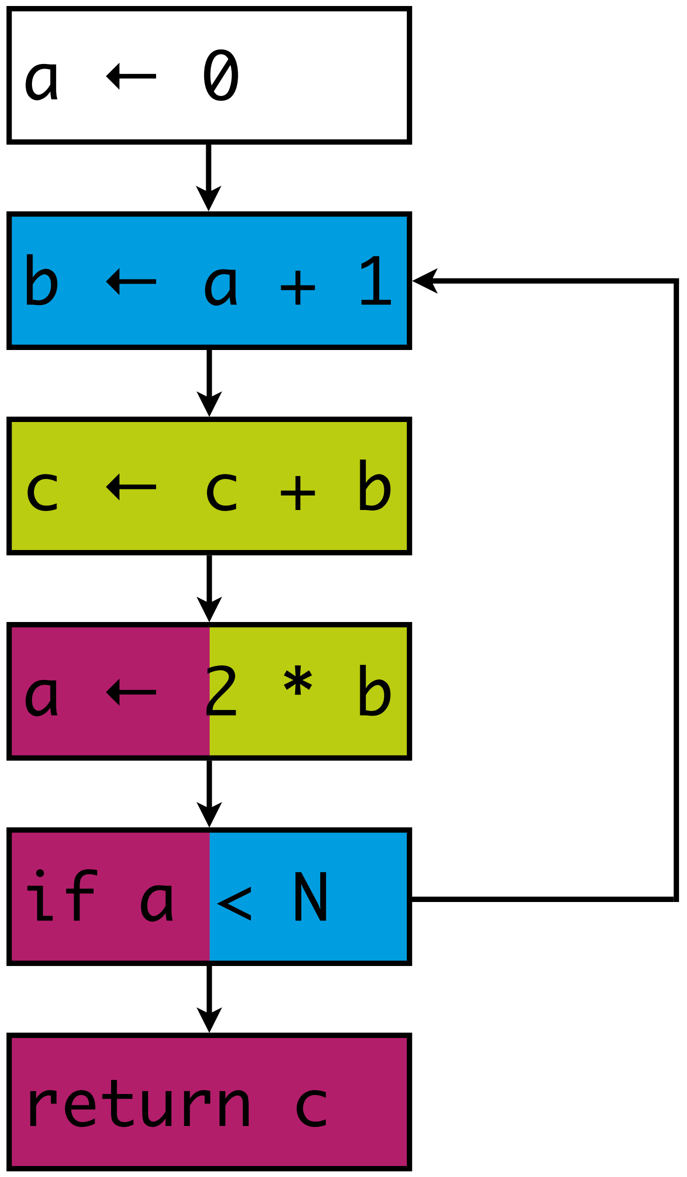


Recap: Liveness Analysis
example



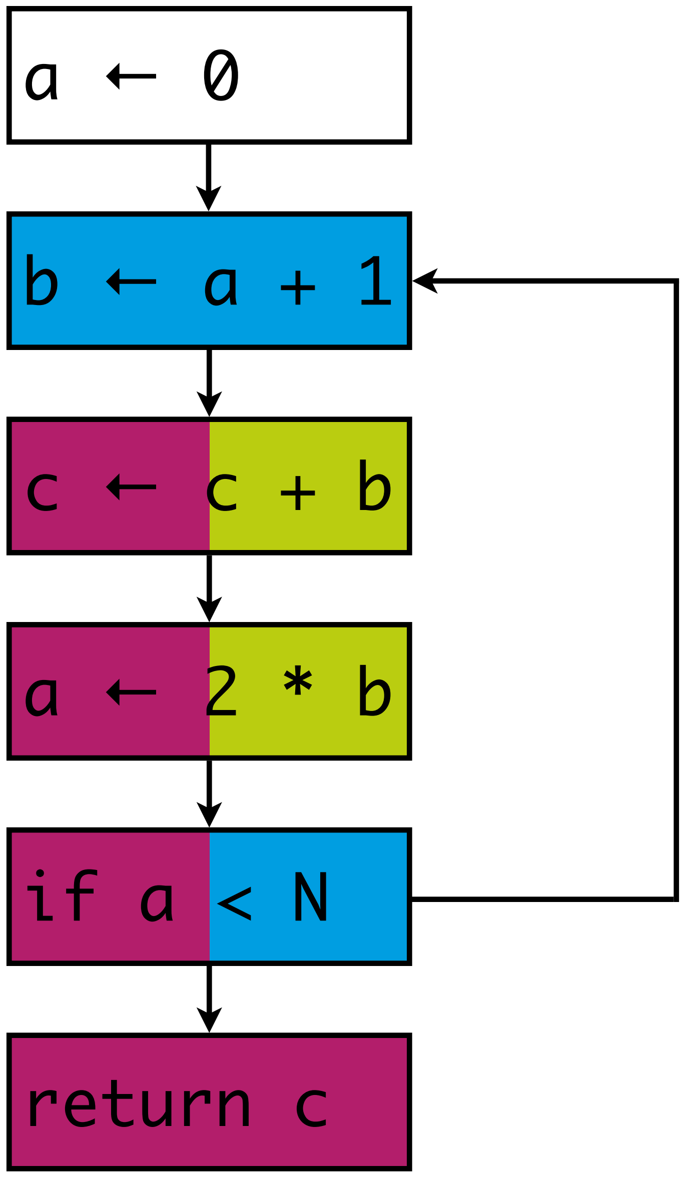
Recap: Liveness Analysis

example



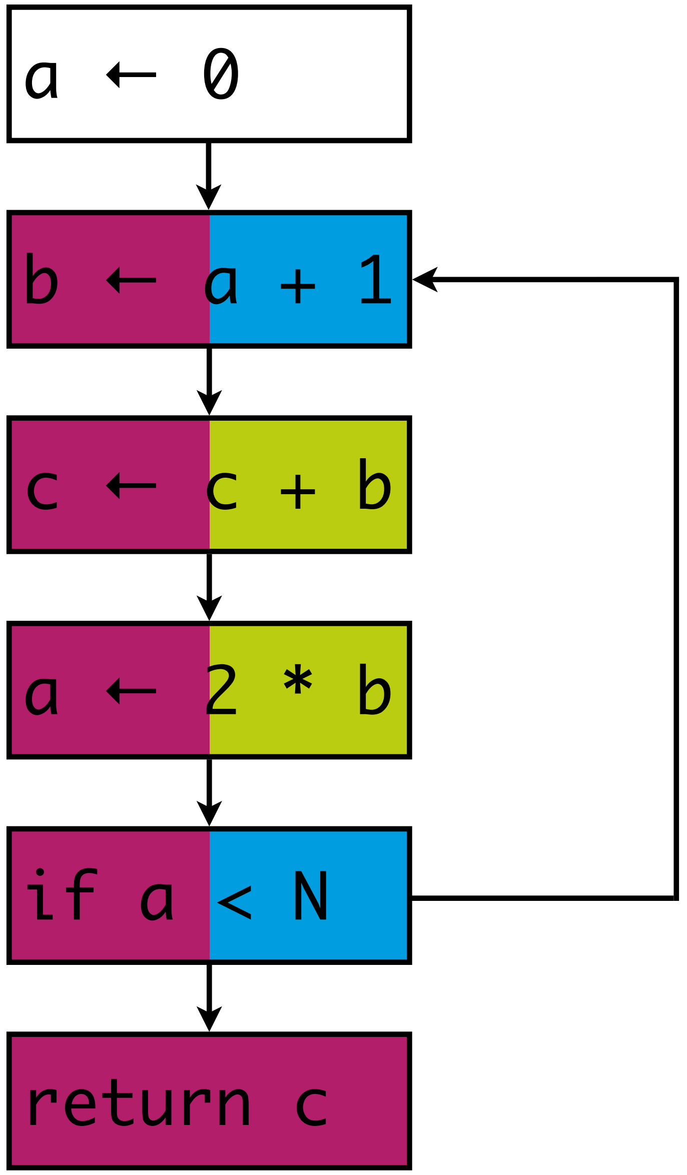
Recap: Liveness Analysis

example



Recap: Liveness Analysis

example



Recap: Liveness Analysis

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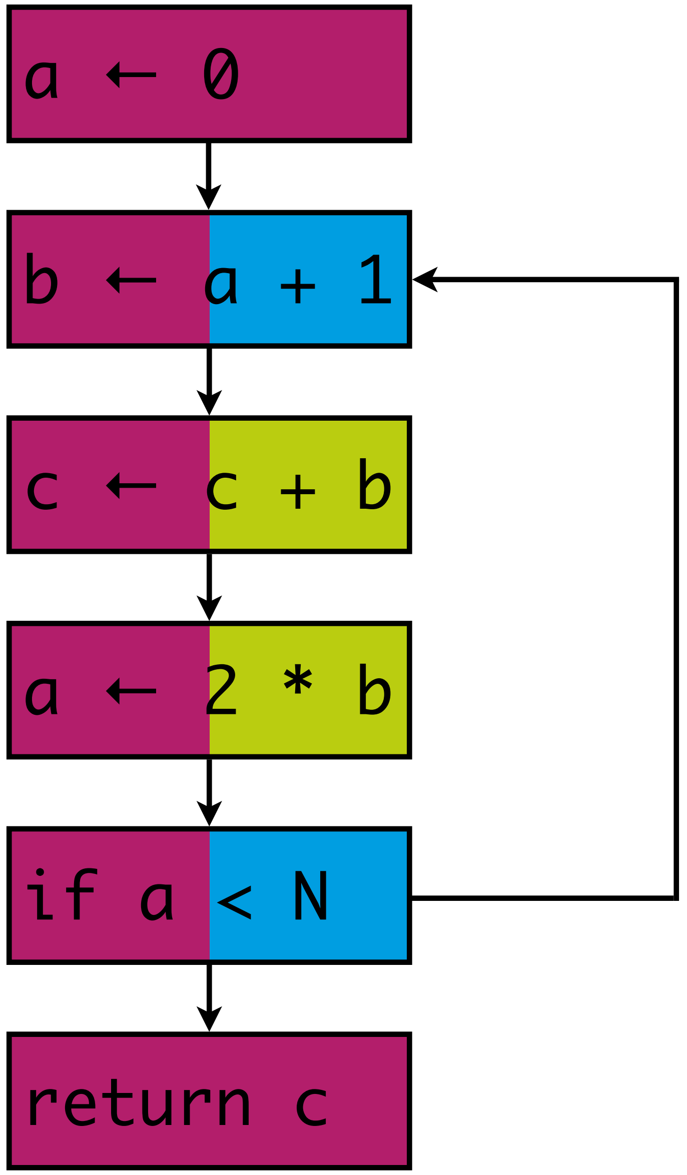
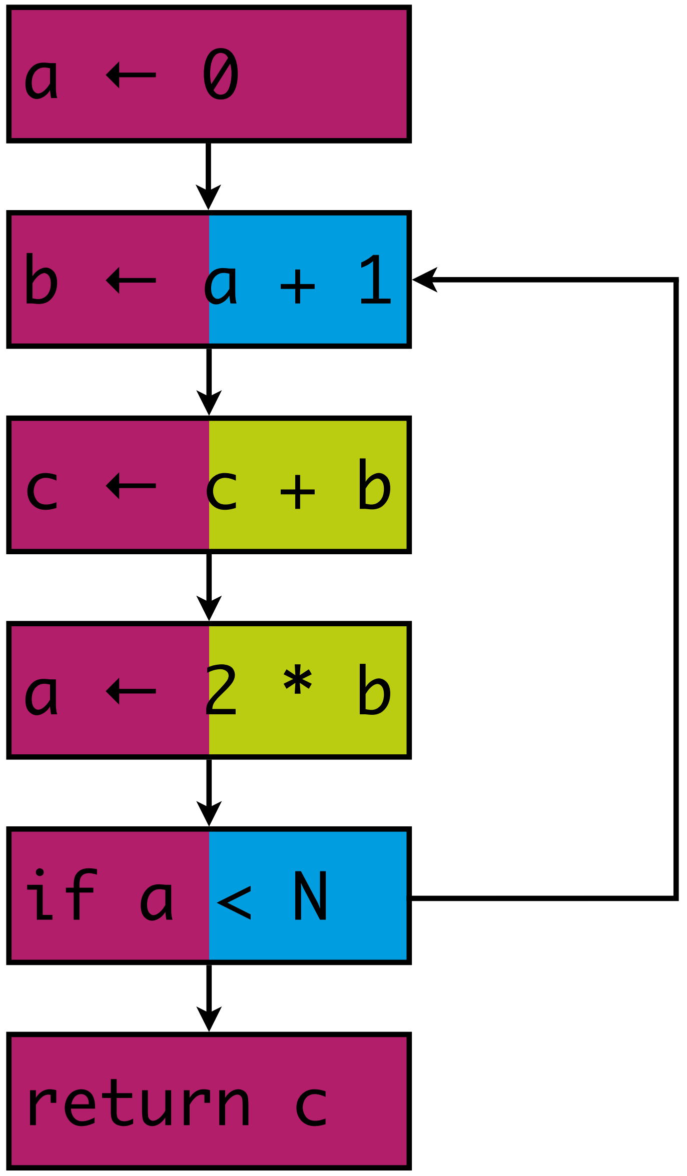


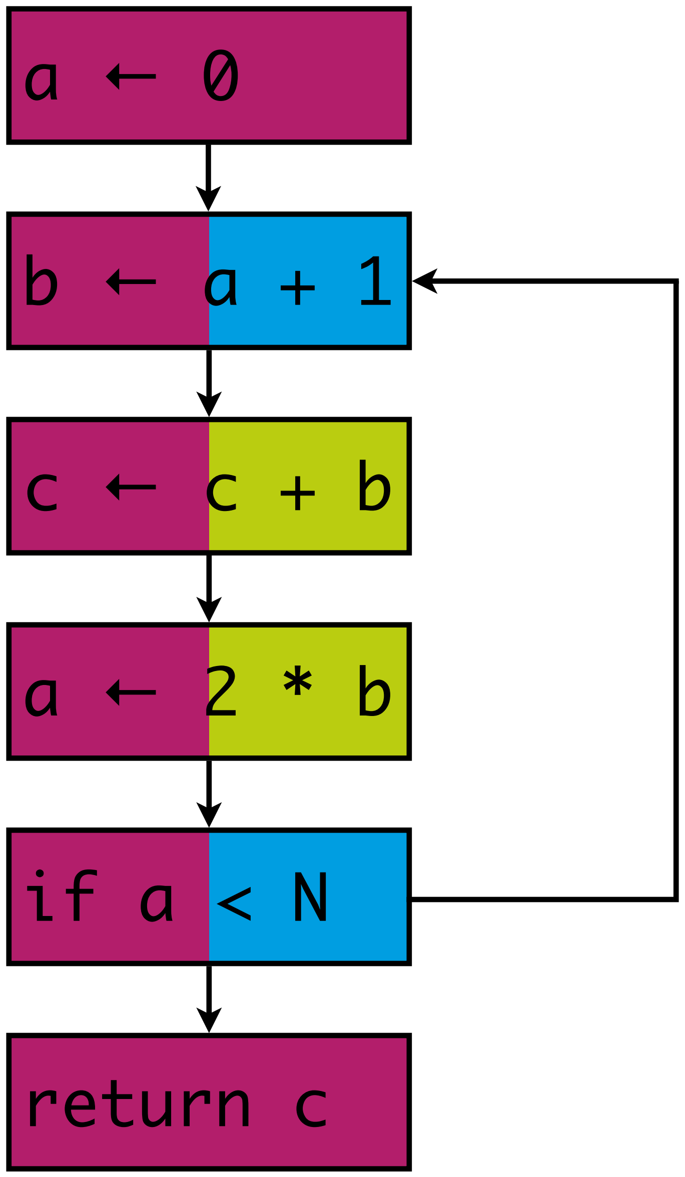
Interference Graphs

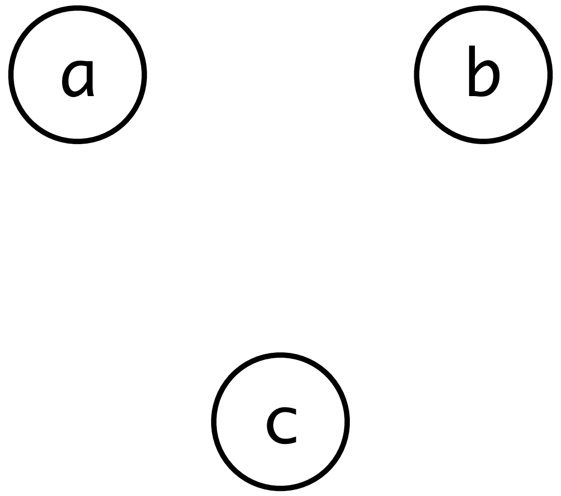
example



Interference Graphs

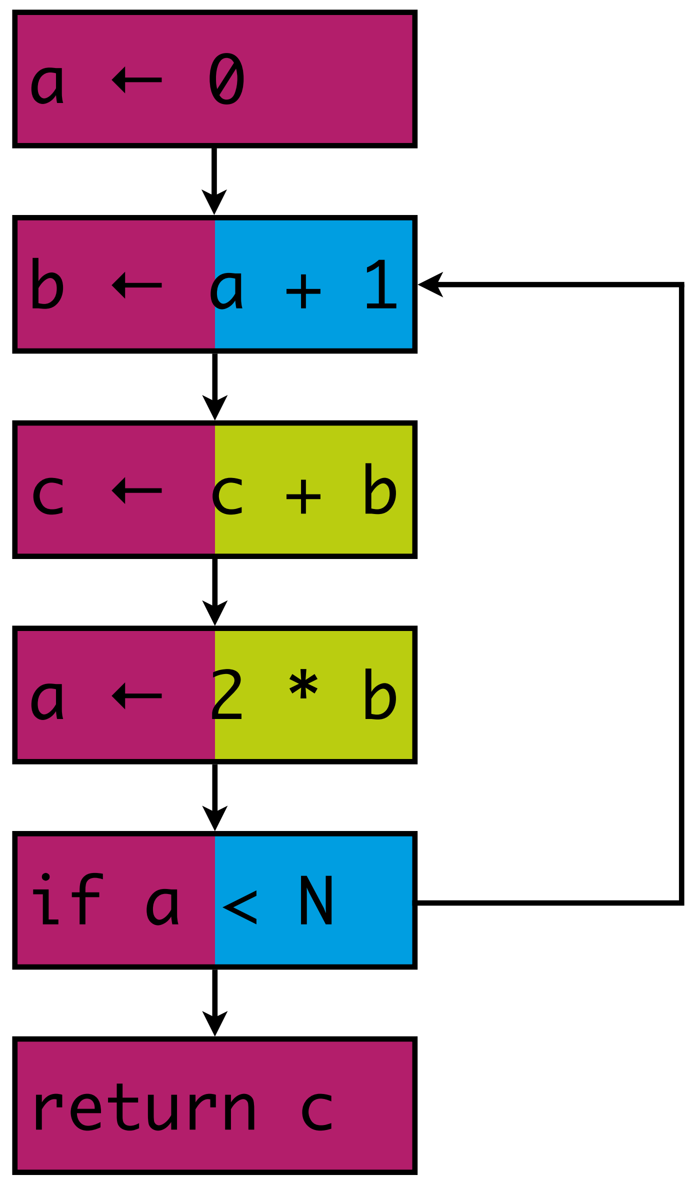
example

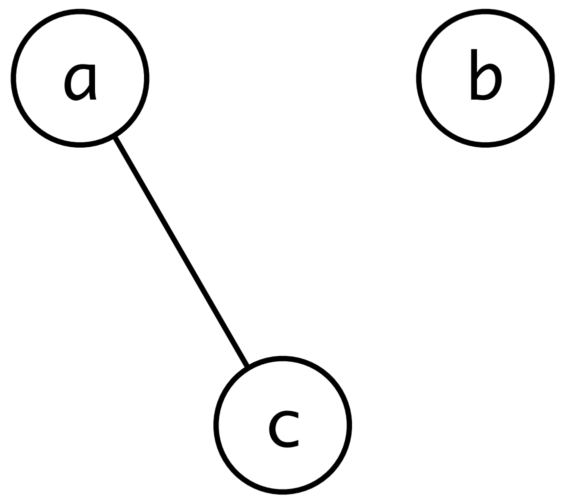




Interference Graphs

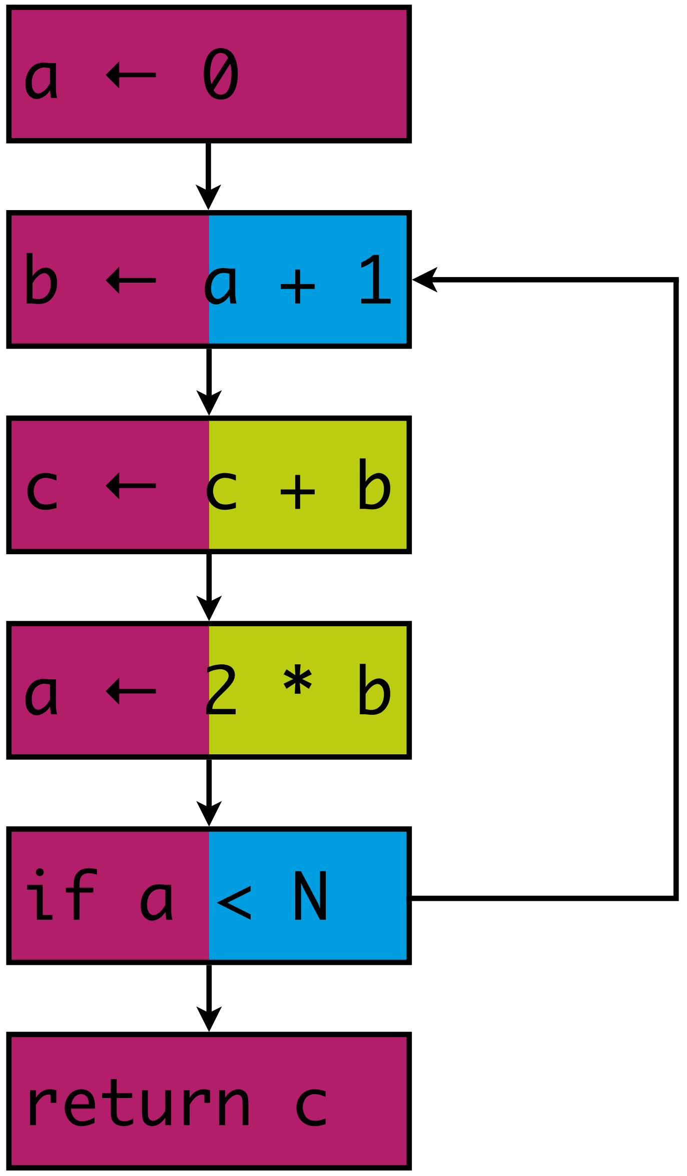
example

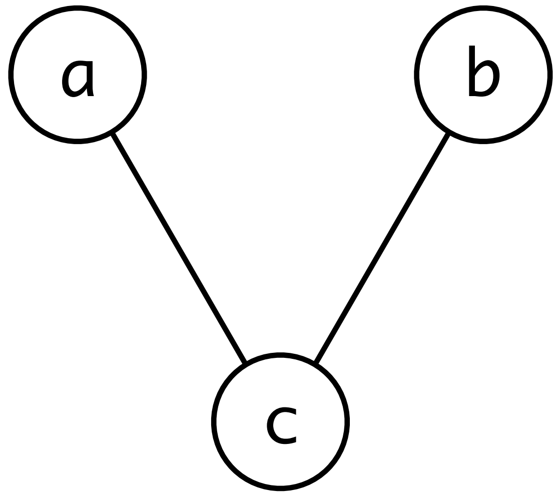




Interference Graphs

example



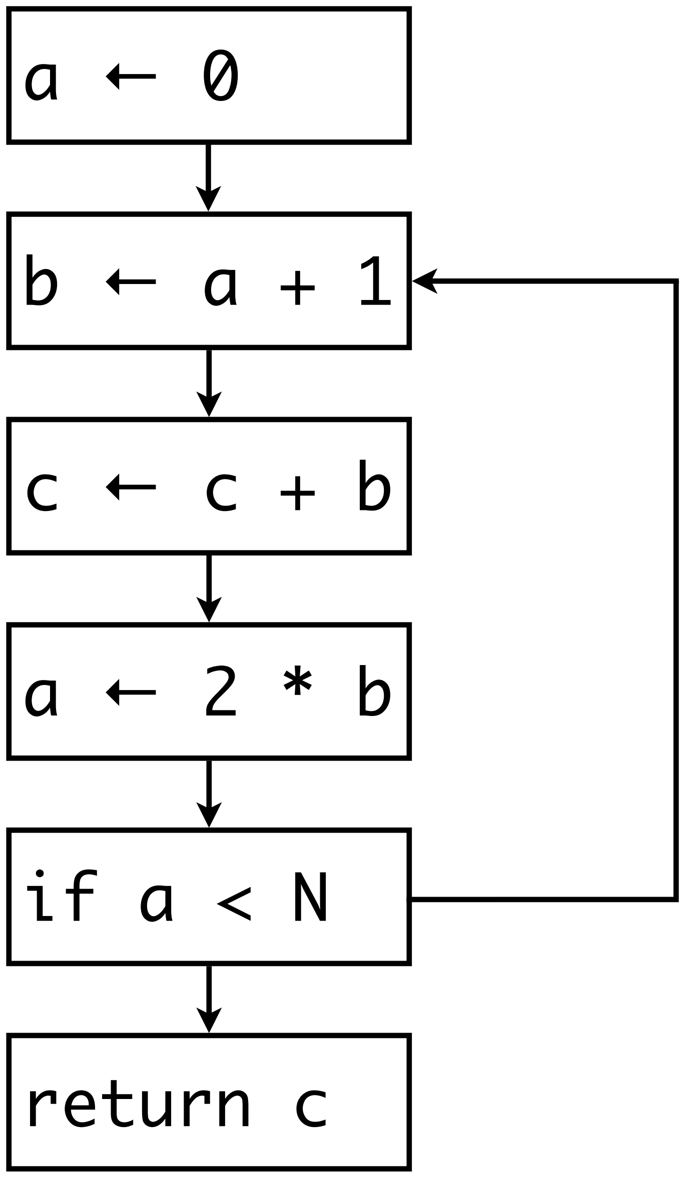


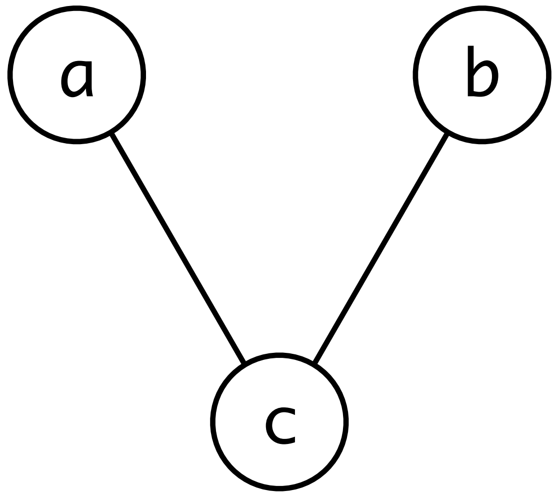
II

Graph Coloring

Graph Coloring

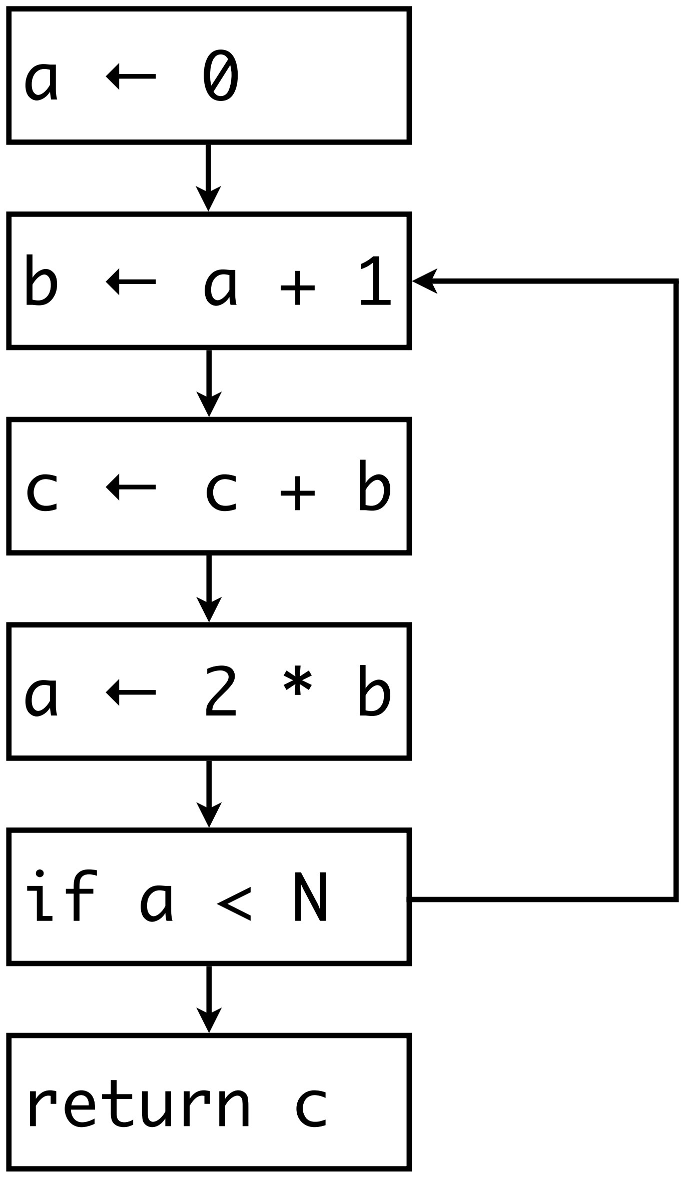
example

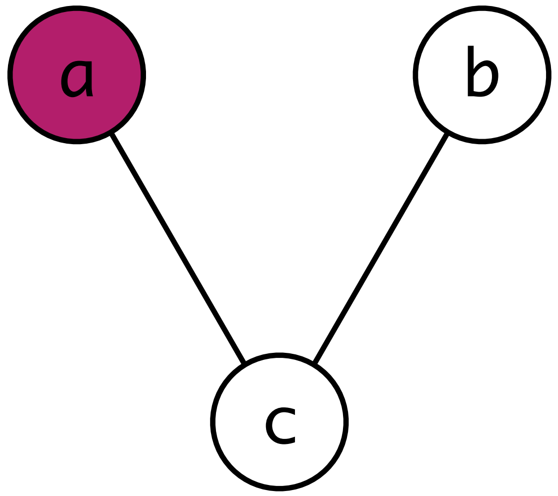




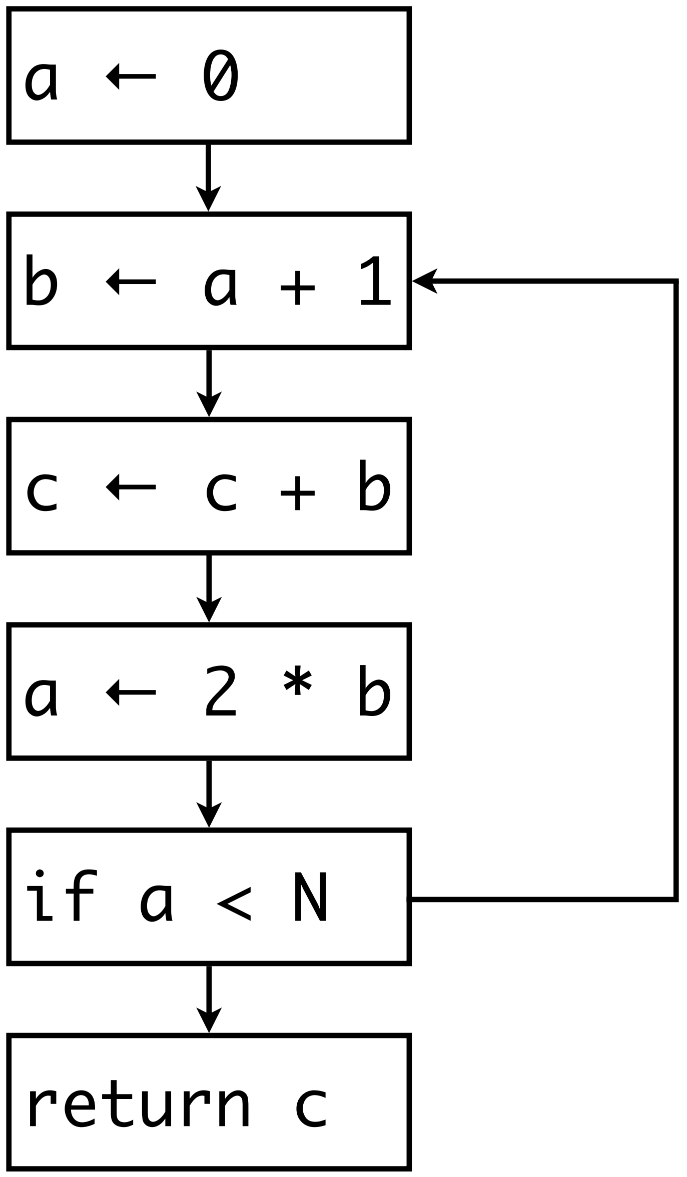
Graph Coloring

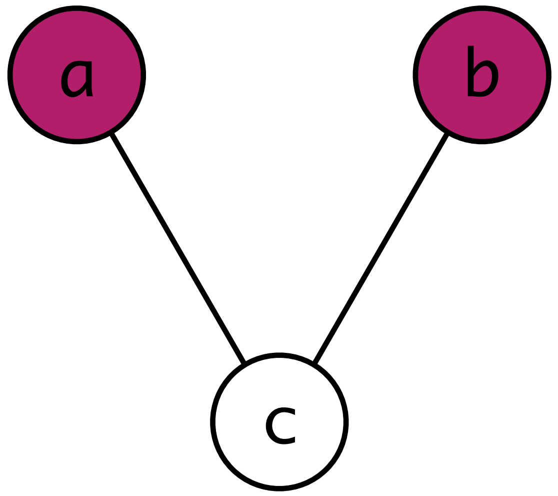
example





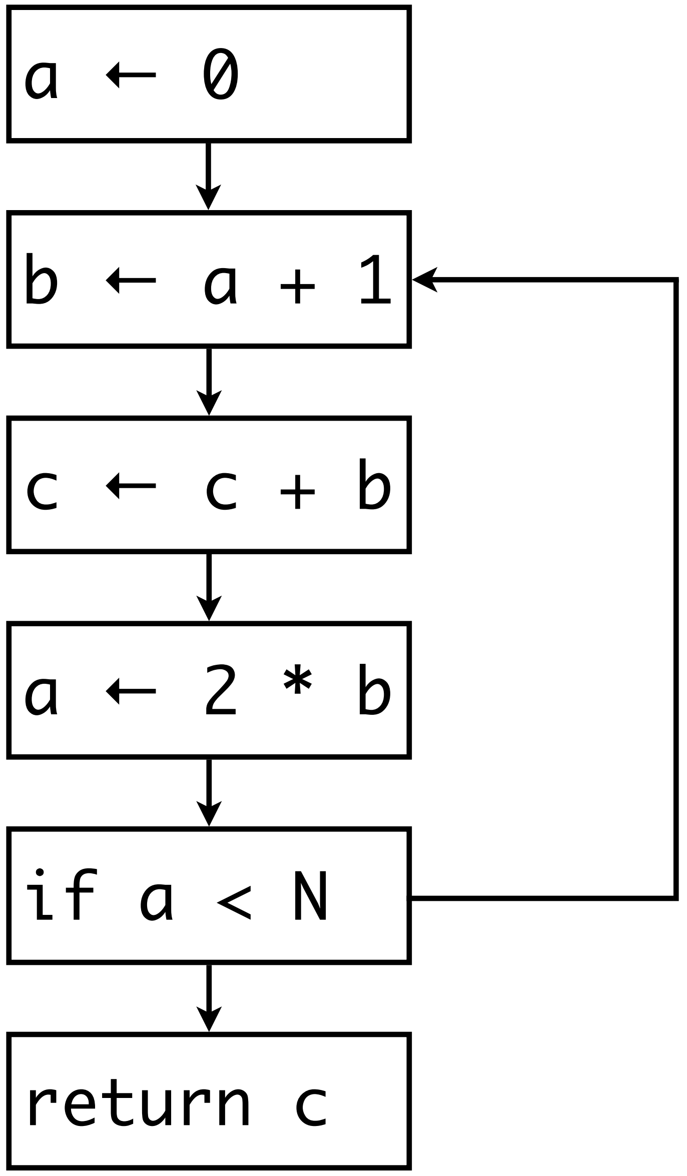
Graph Coloring
example

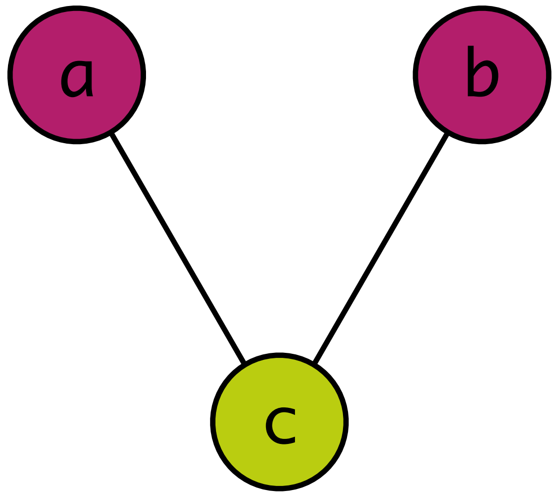




Graph Coloring

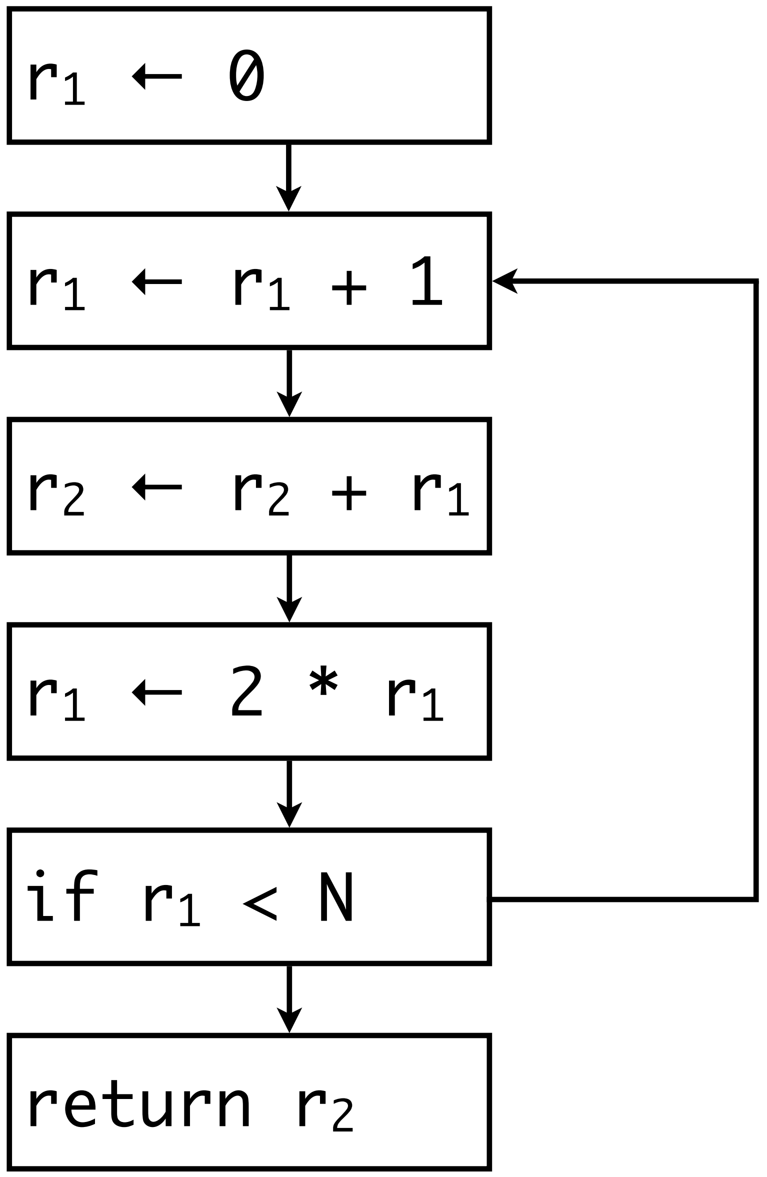
example

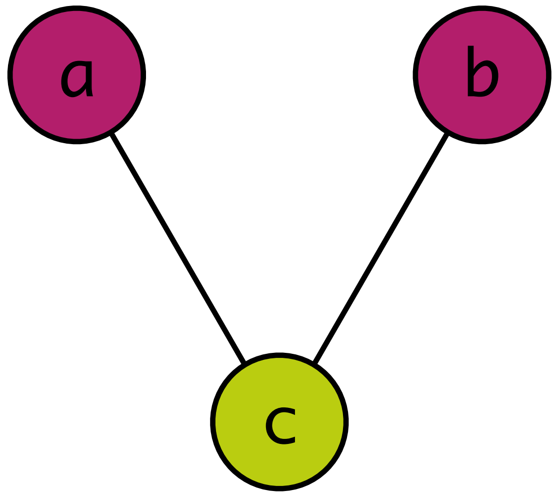




Graph Coloring

example





Graph Coloring
steps

Simplify

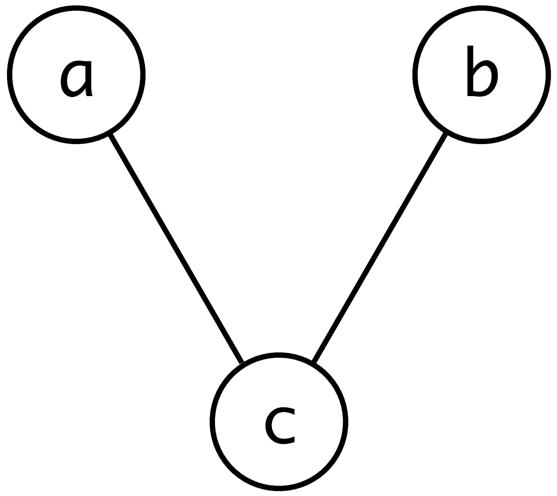
remove node of insignificant degree (fewer than k edges)

Select

add node, select color

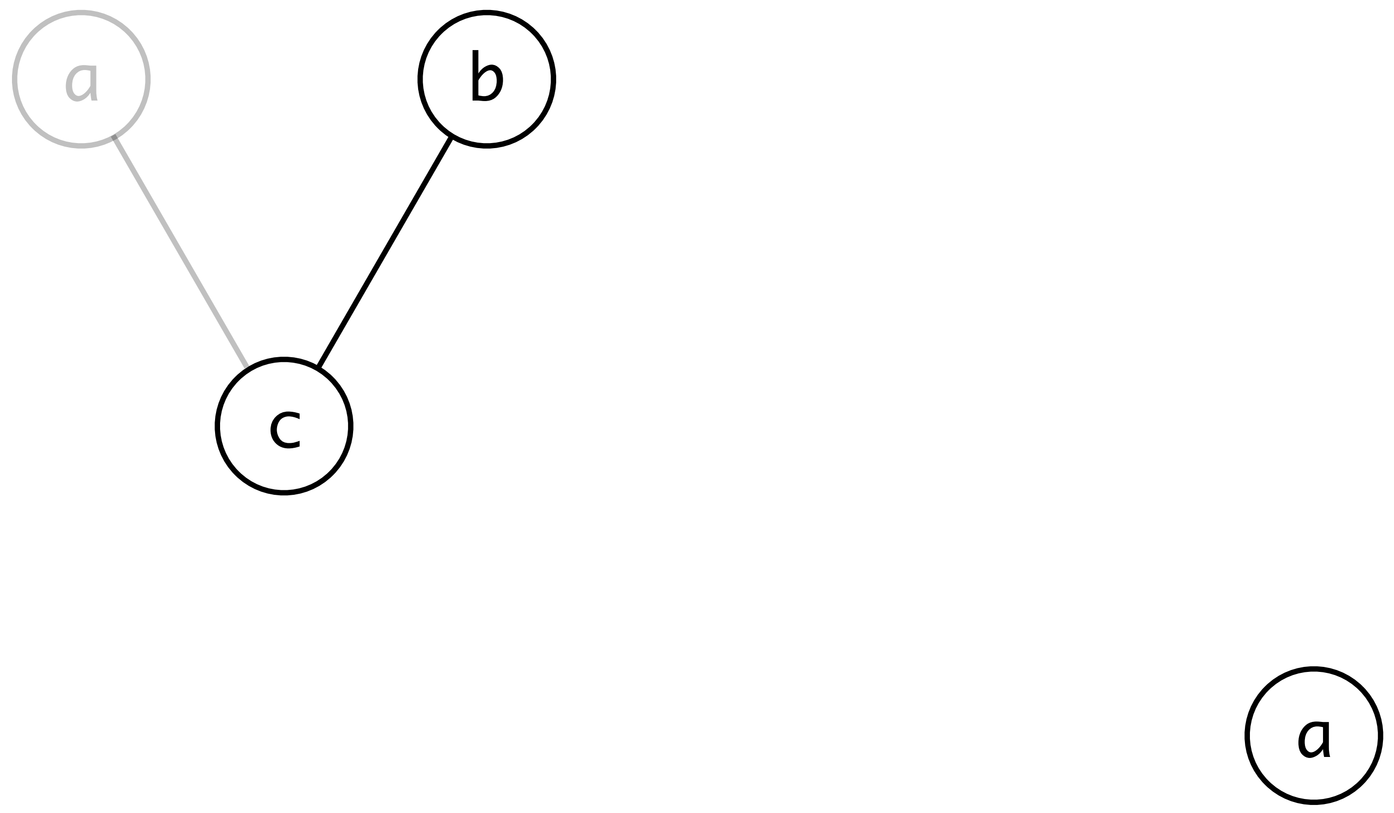
Graph Coloring

example with 2 colors



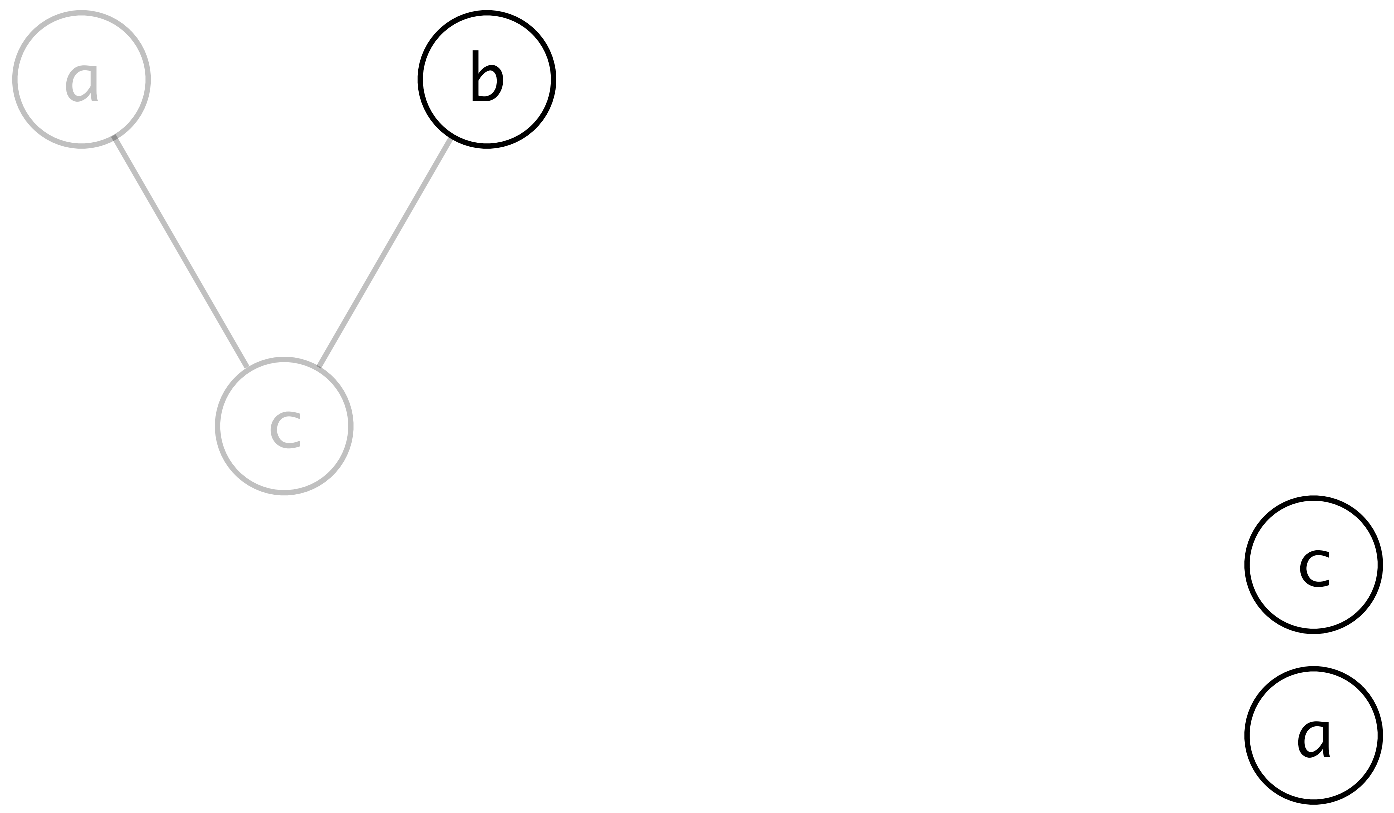
Graph Coloring

example with 2 colors



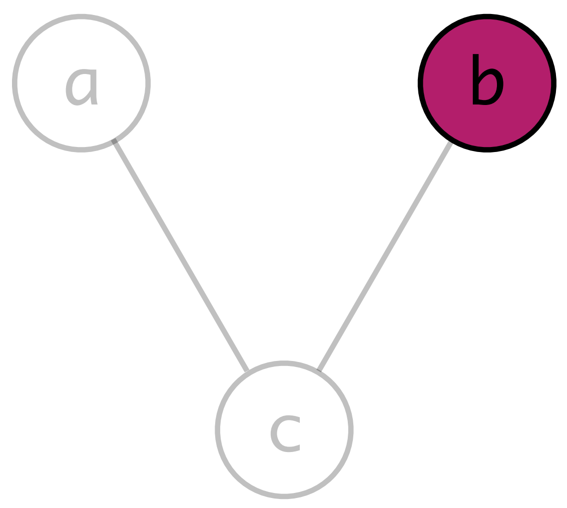
Graph Coloring

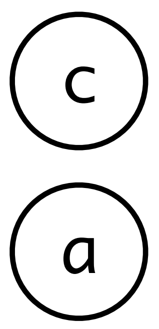
example with 2 colors



Graph Coloring

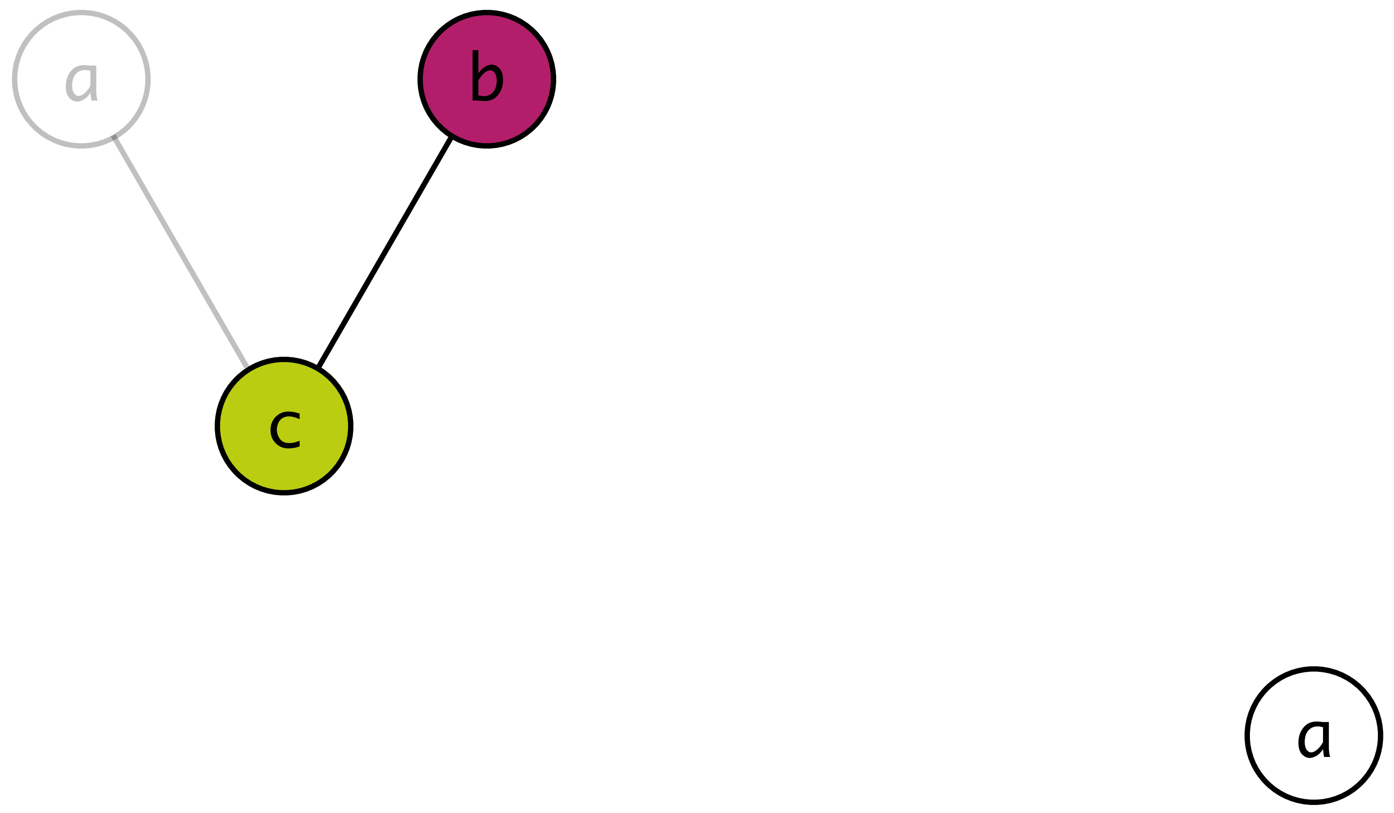
example with 2 colors





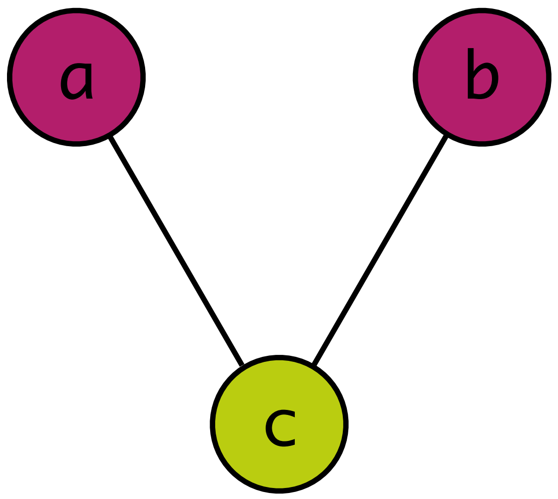
Graph Coloring

example with 2 colors



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

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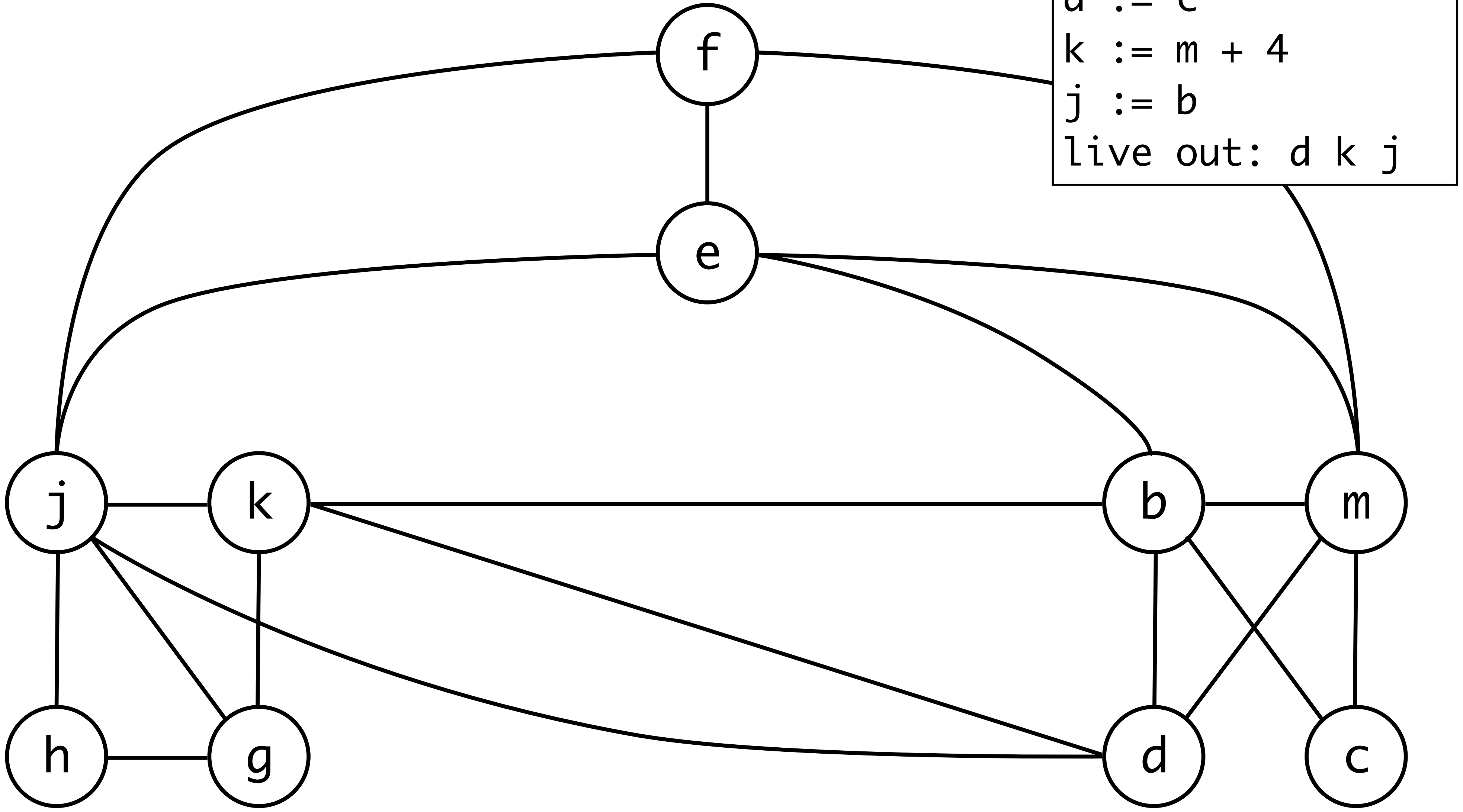
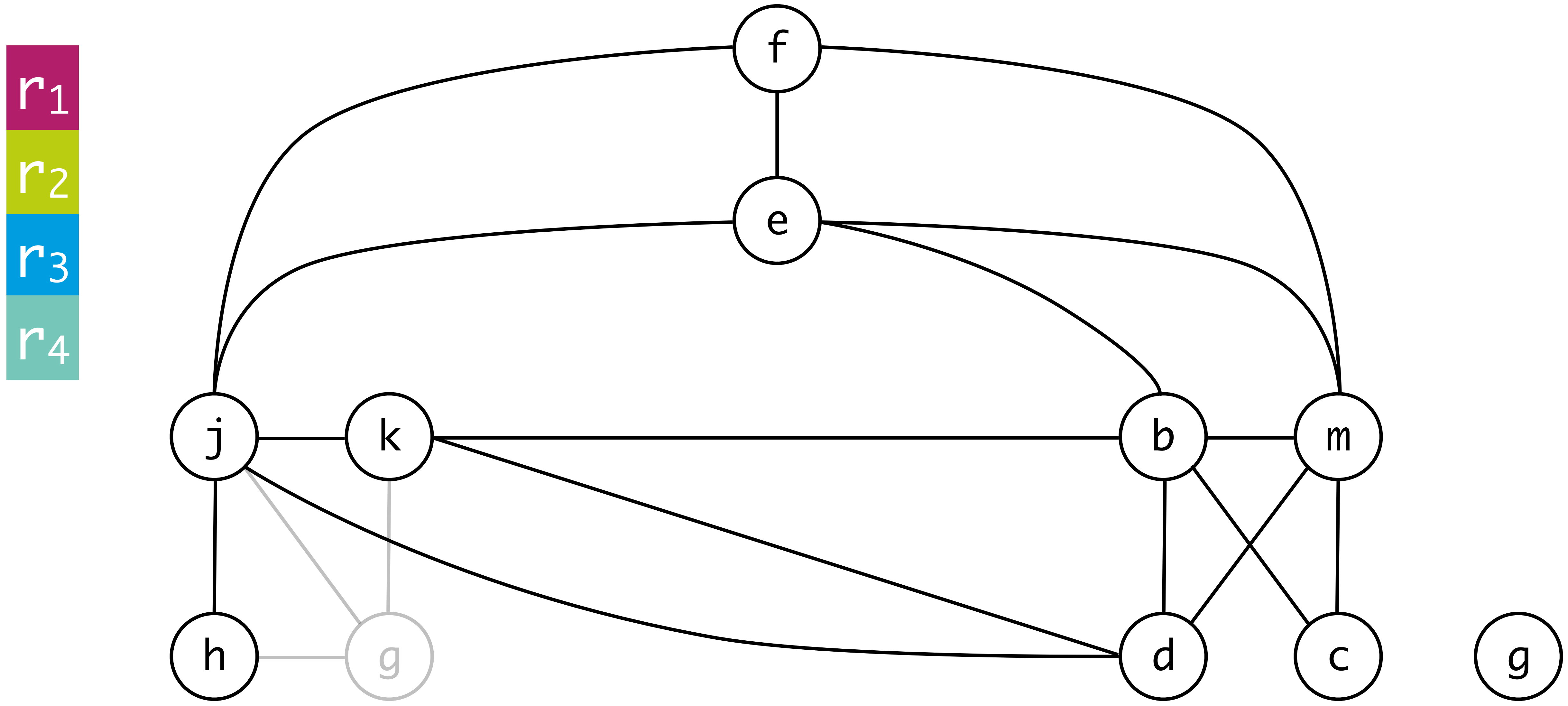
m := mem[j + 16]
b := mem[f]
c := e + 8
d := c
k := m + 4
j := b
live out: d k j
```



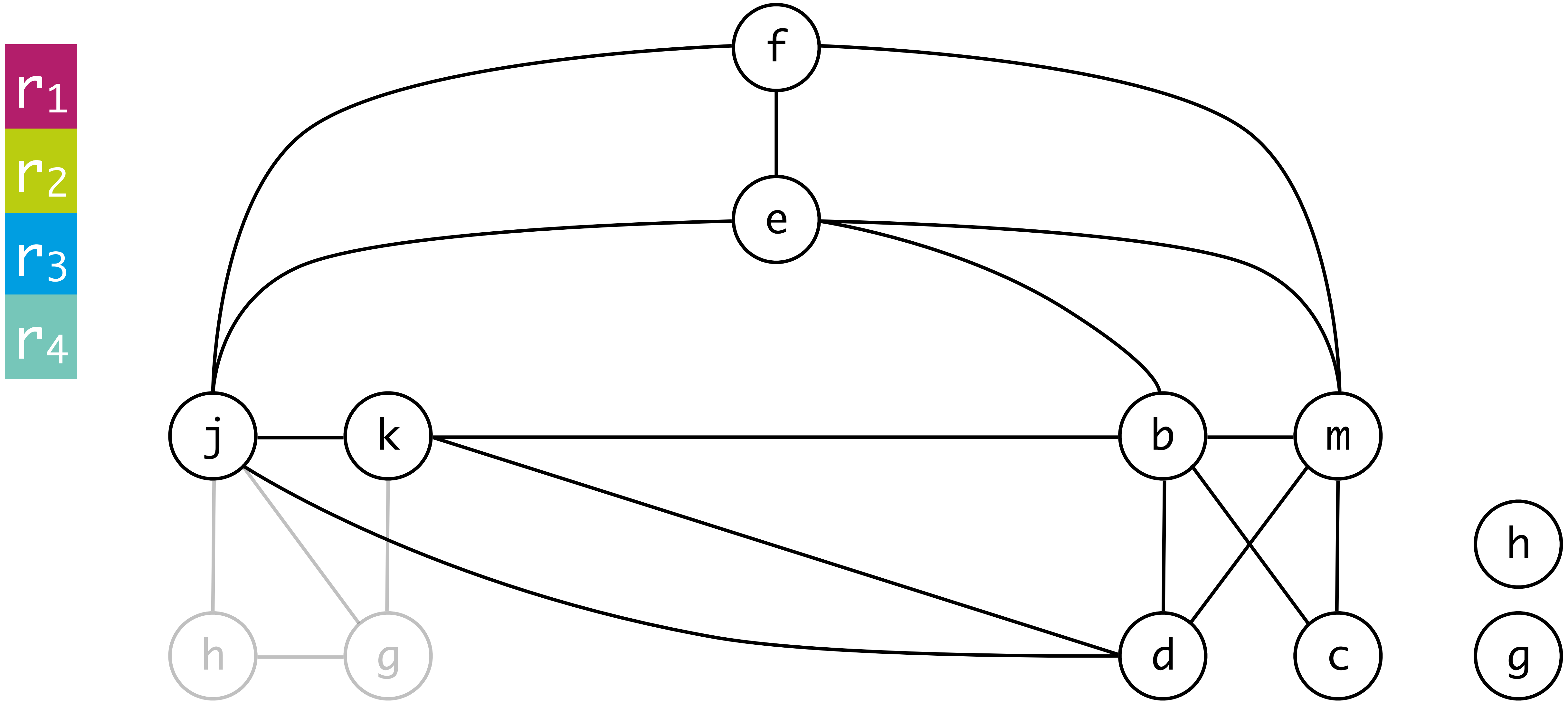
Graph Coloring

example with 4 colors



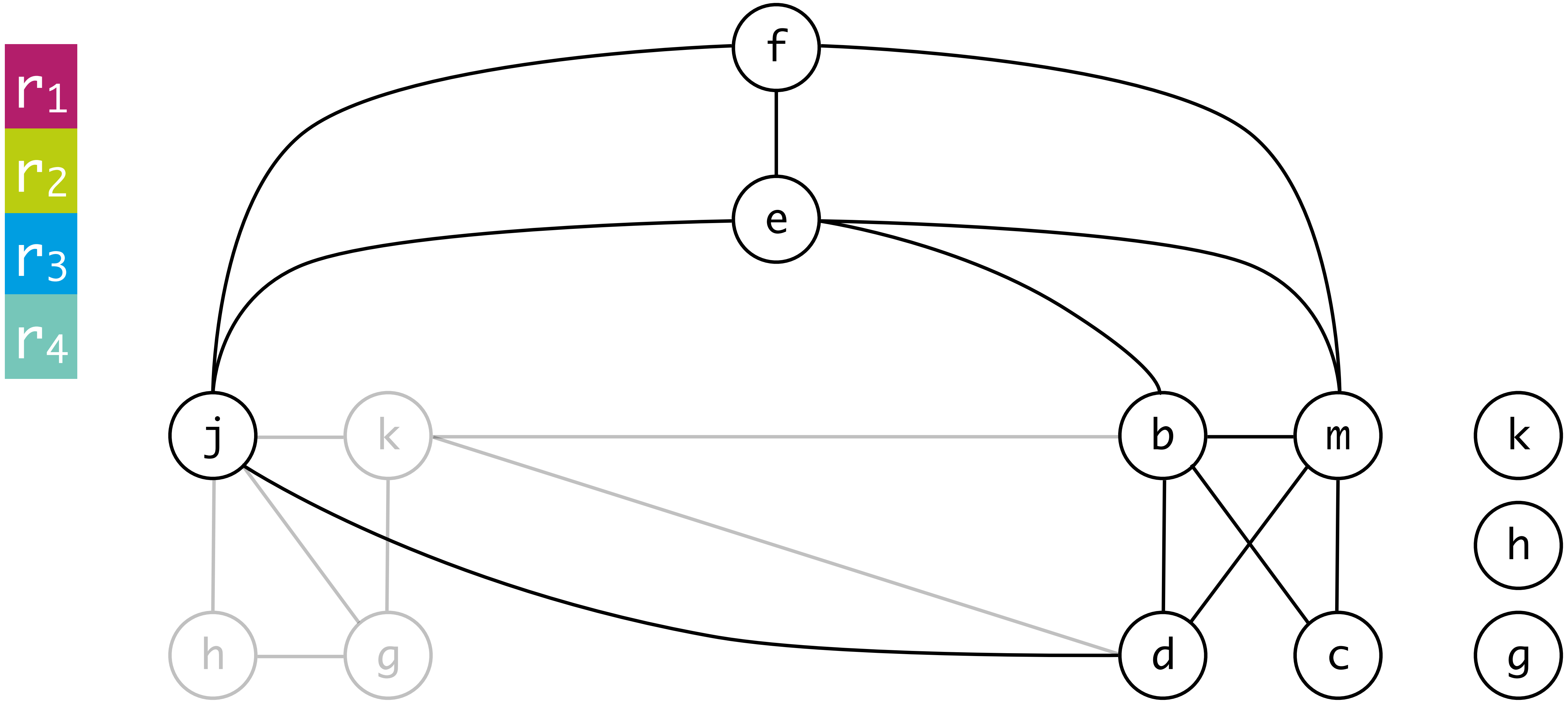
Graph Coloring

example with 4 colors



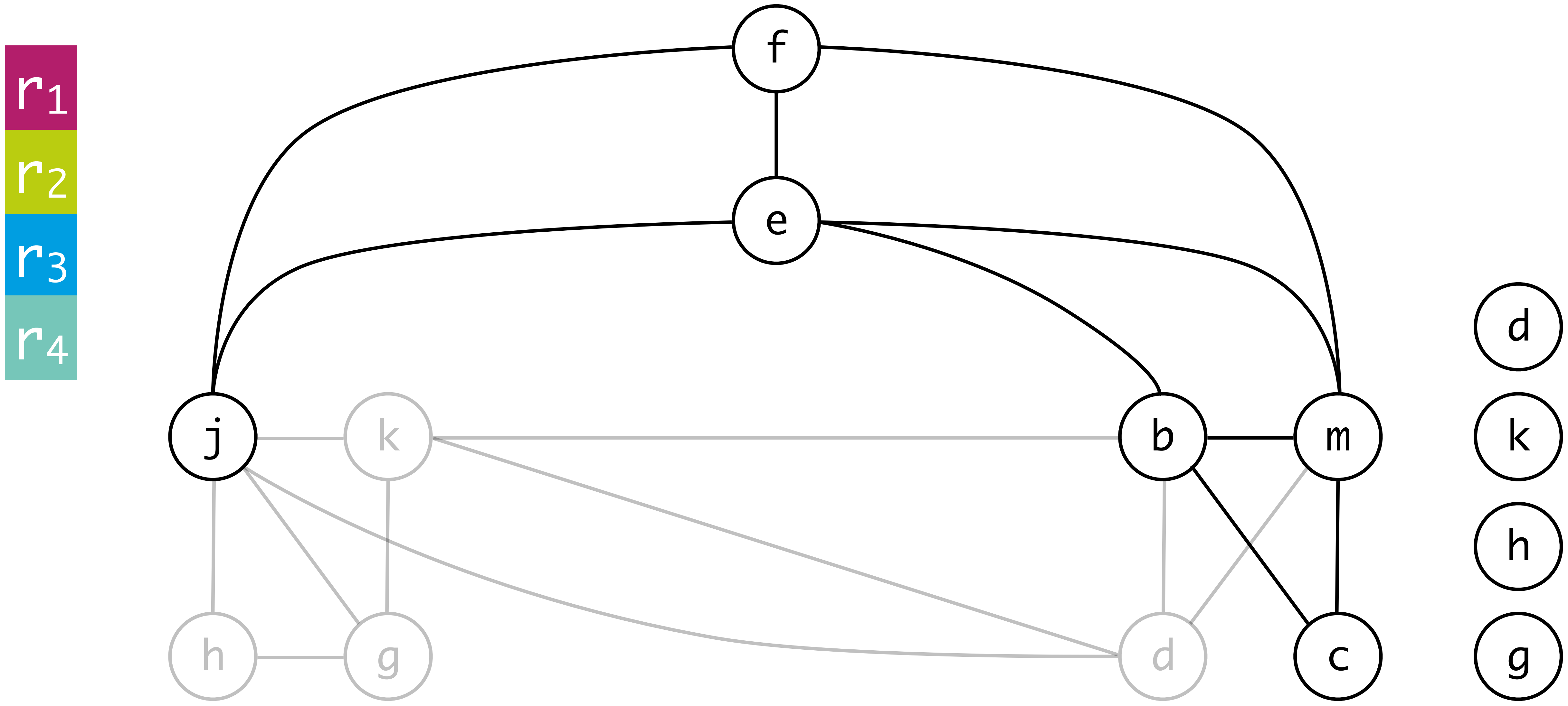
Graph Coloring

example with 4 colors



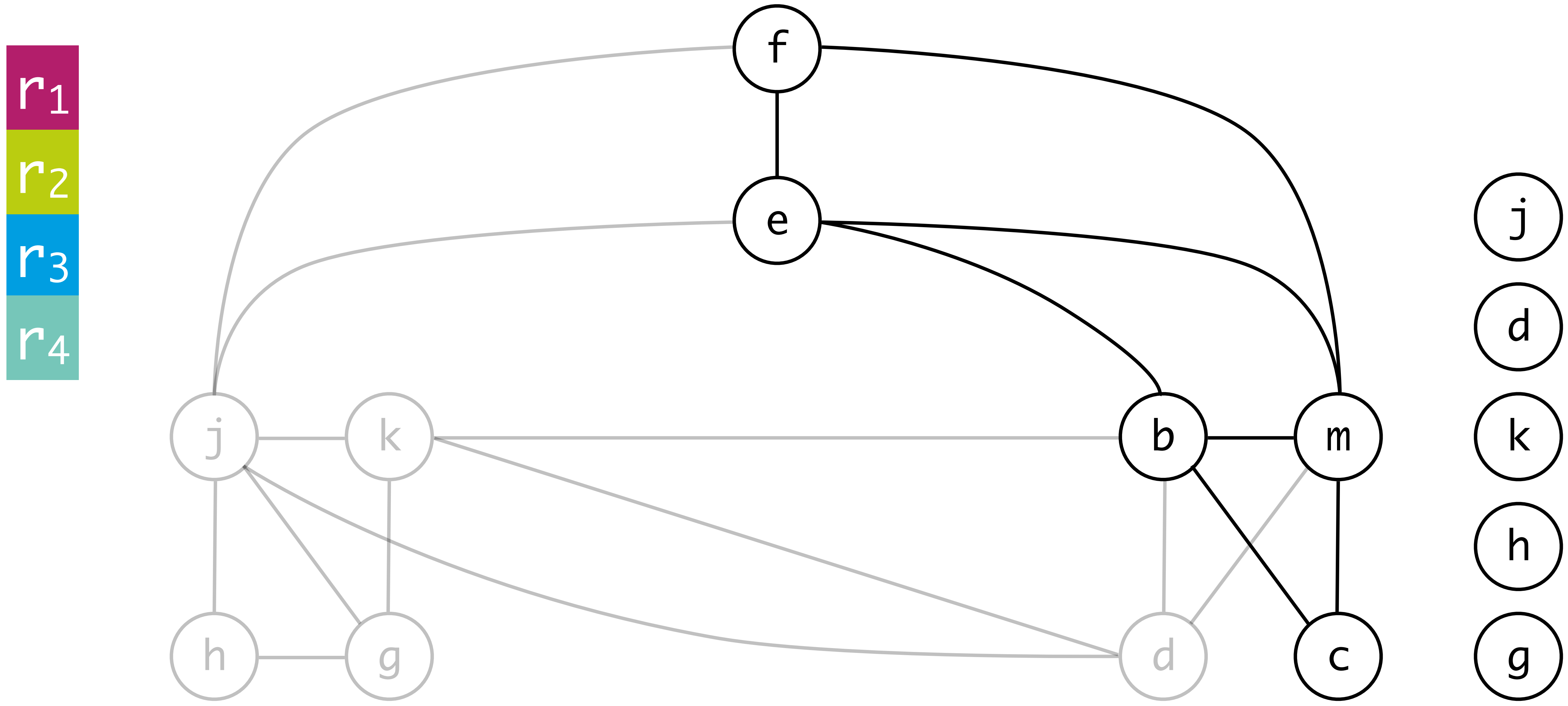
Graph Coloring

example with 4 colors



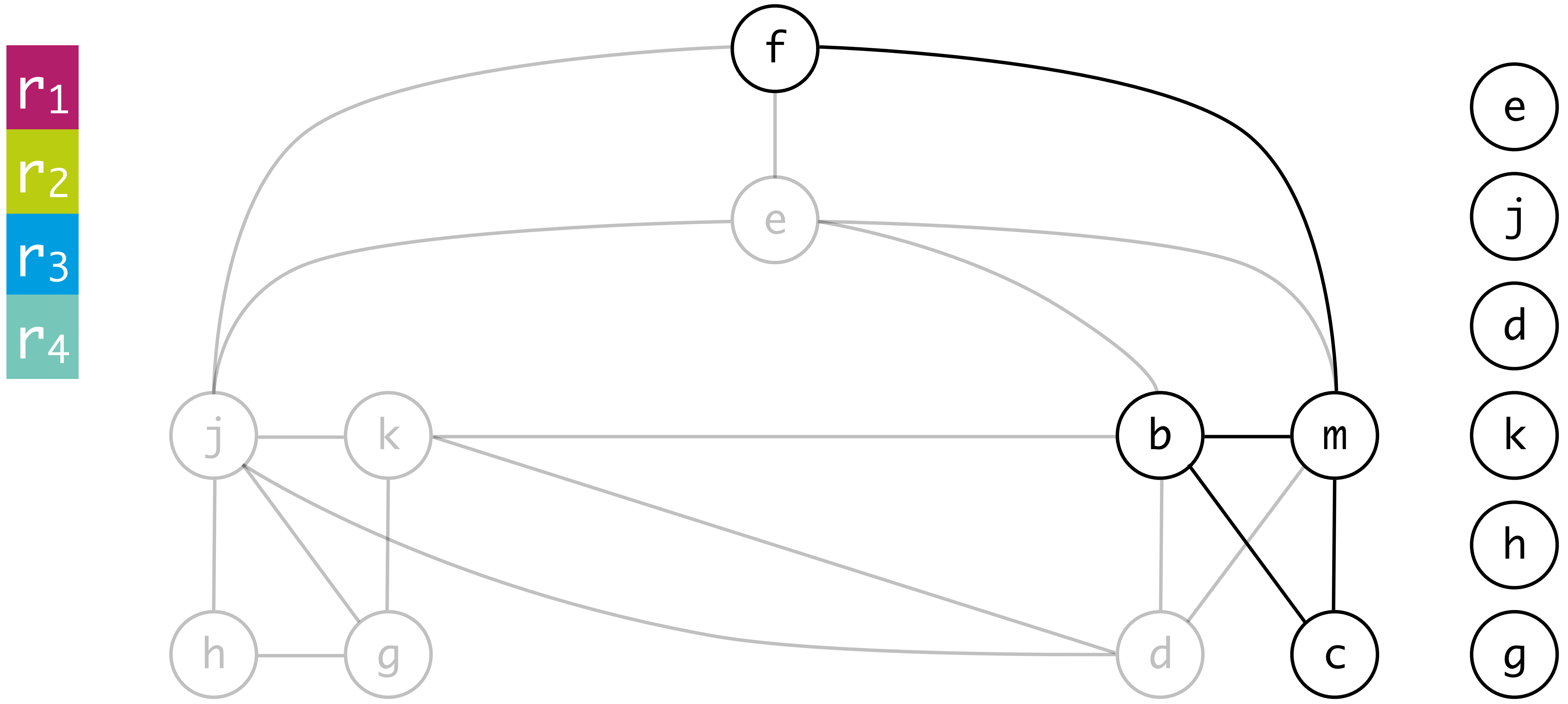
Graph Coloring

example with 4 colors



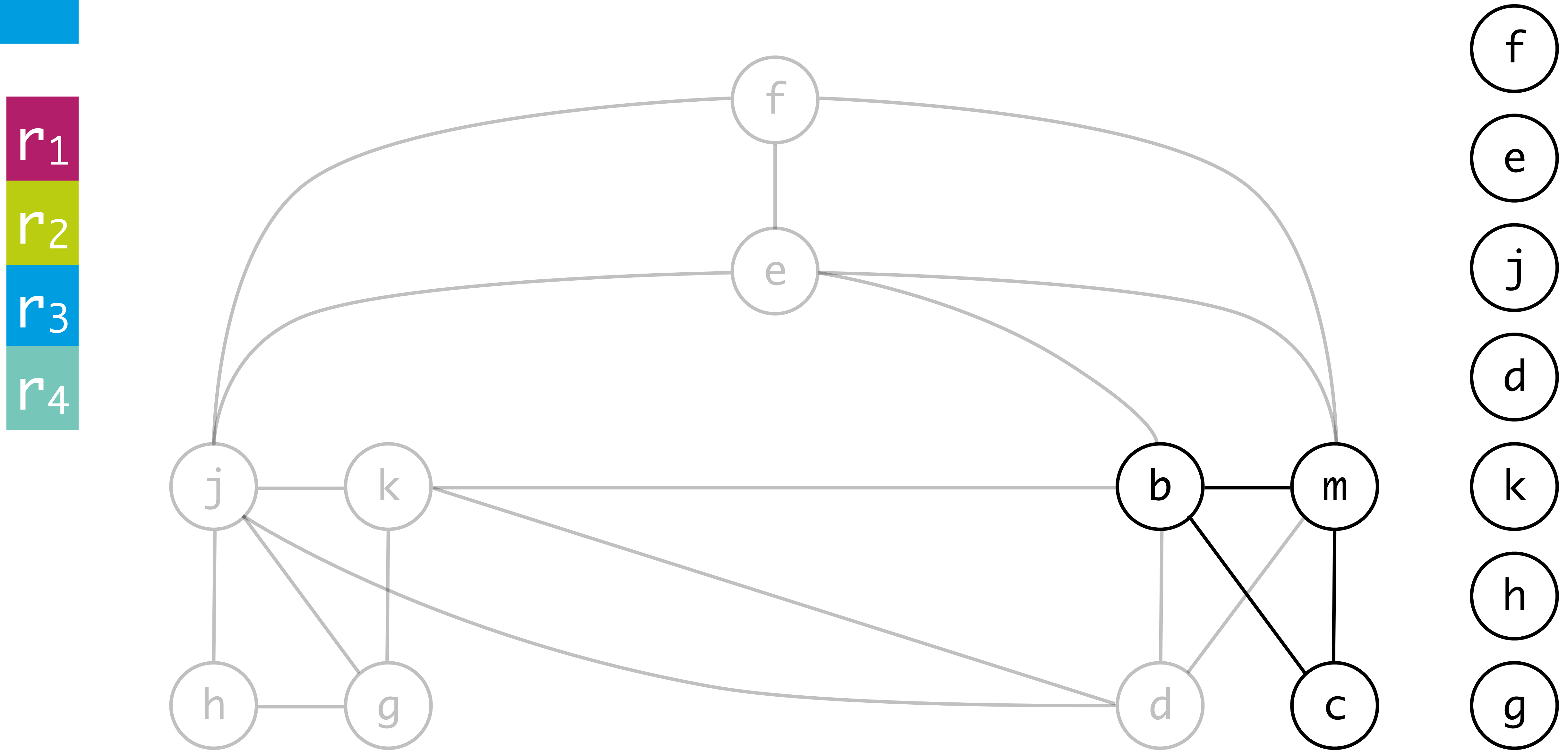
Graph Coloring

example with 4 colors



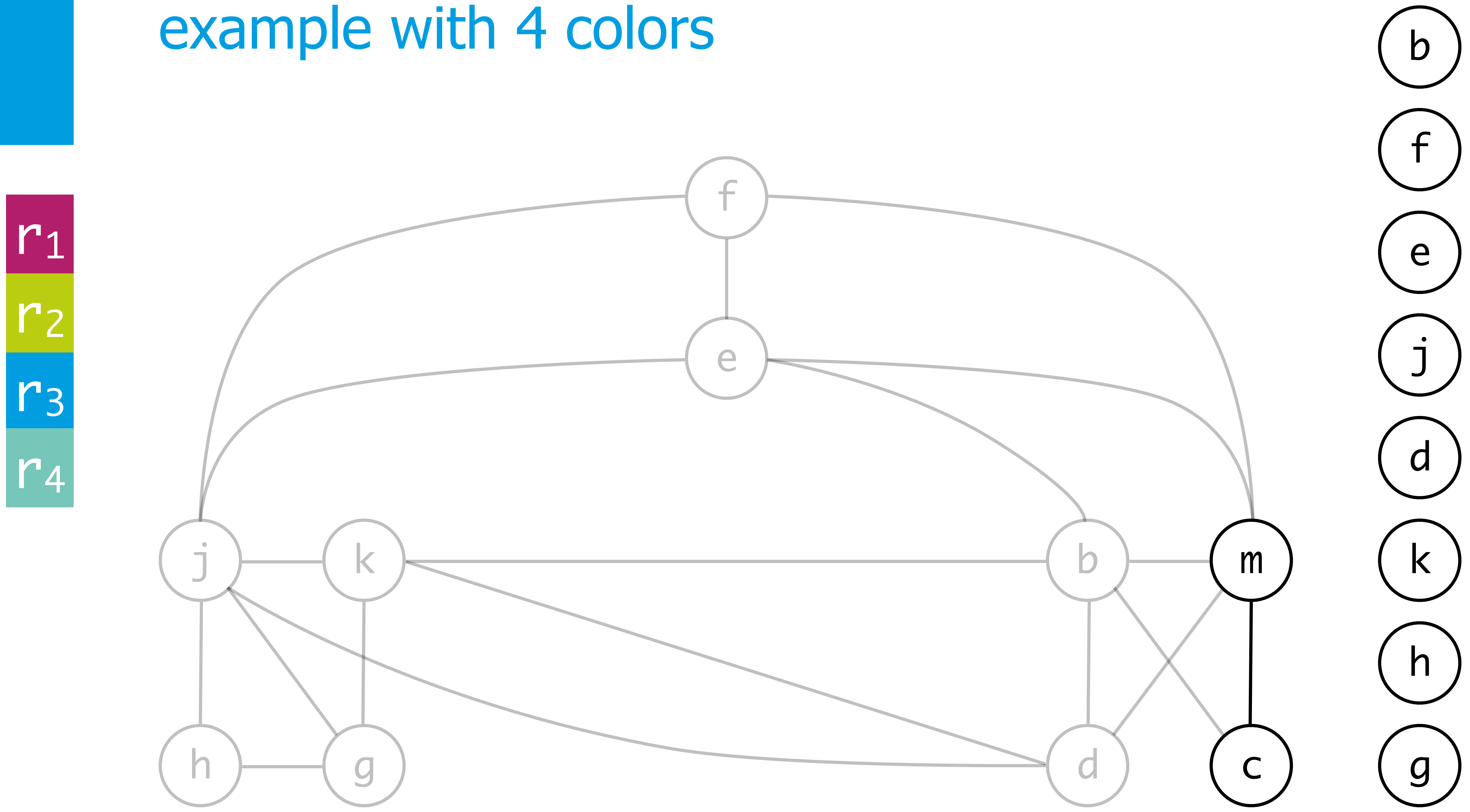
Graph Coloring

example with 4 colors



Graph Coloring

example with 4 colors



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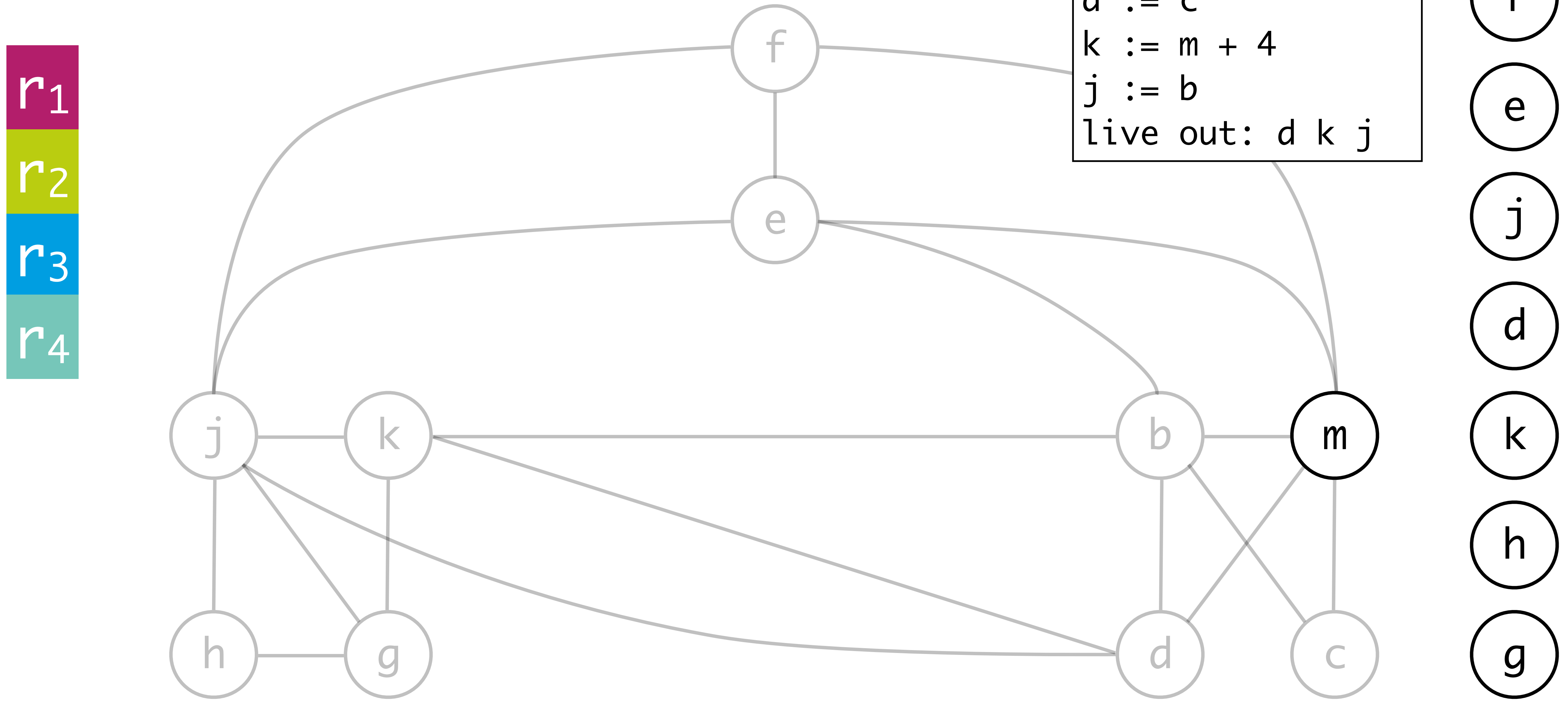
Graph Coloring

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

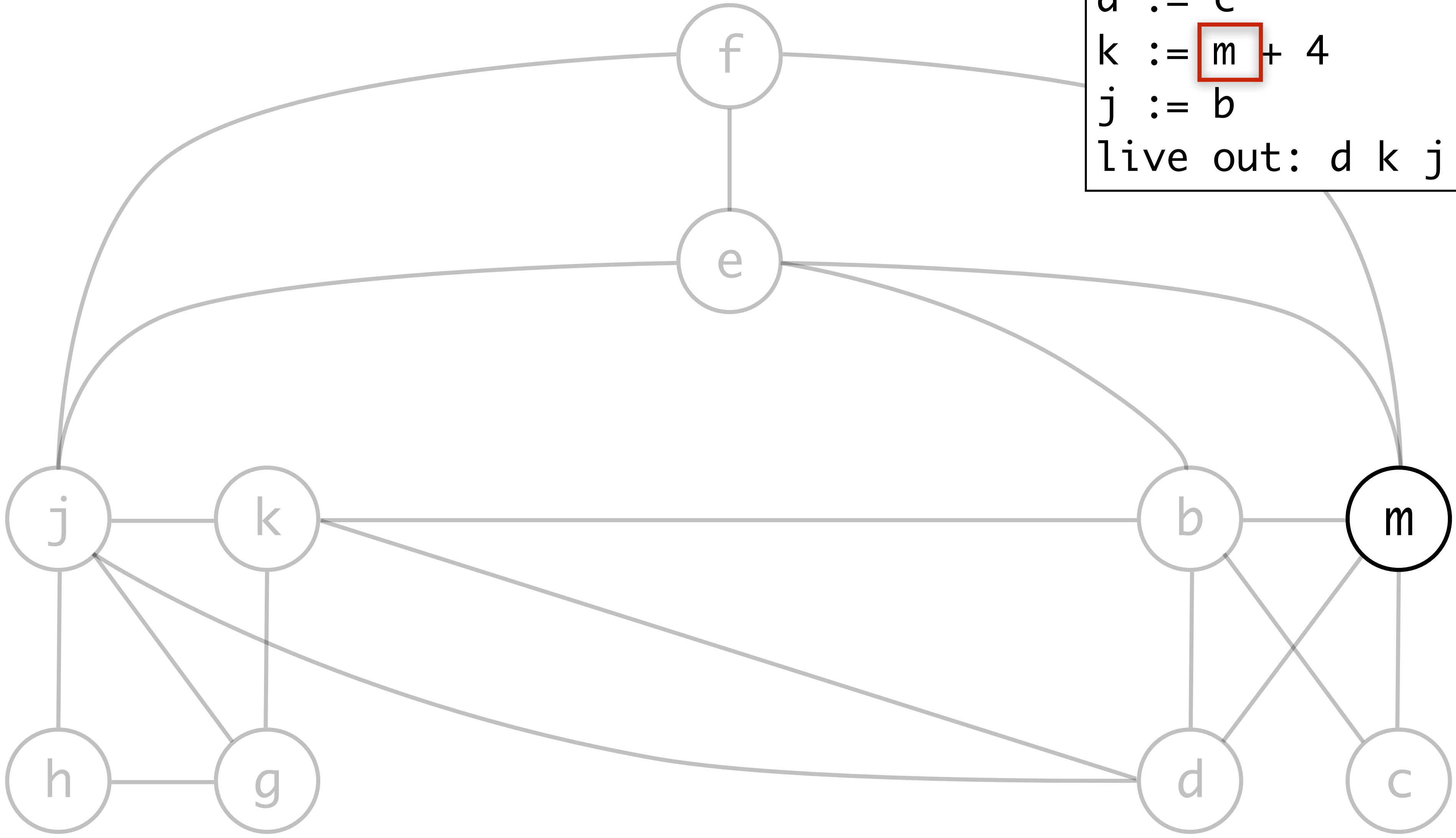
r_1

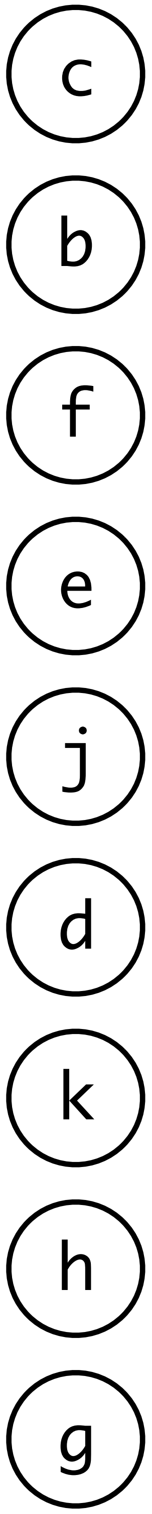
r_2

r_3

r_4

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



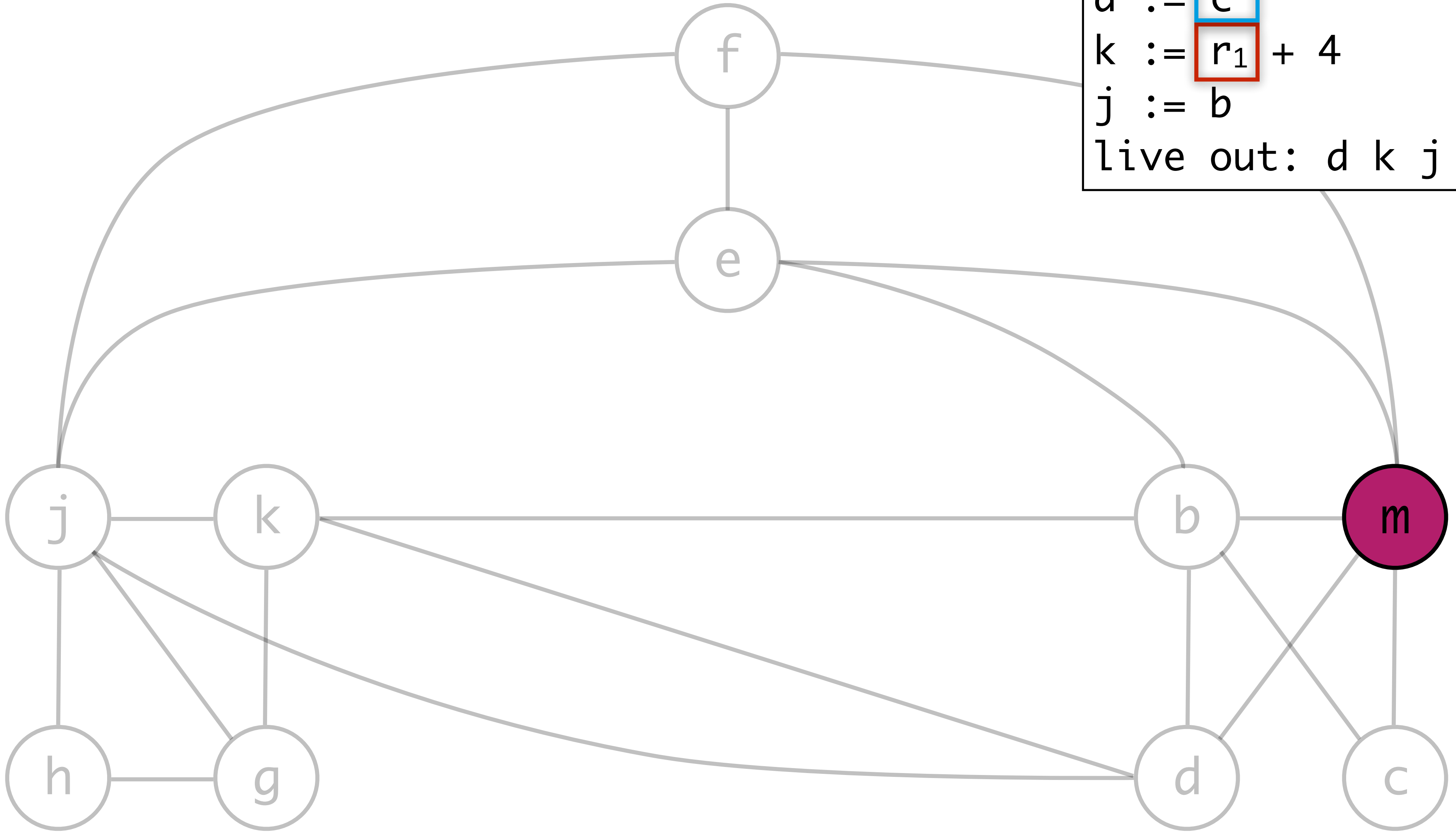


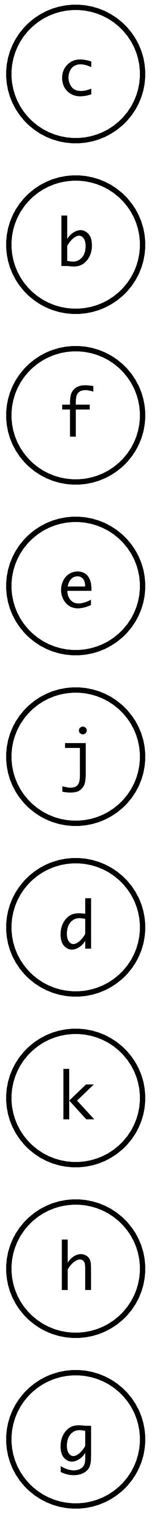
Graph Coloring

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]
r₁ := mem[j + 16]
b  := mem[f]
c  := e + 8
d  := c
k  := r₁ + 4
j  := b
live out: d k j
```

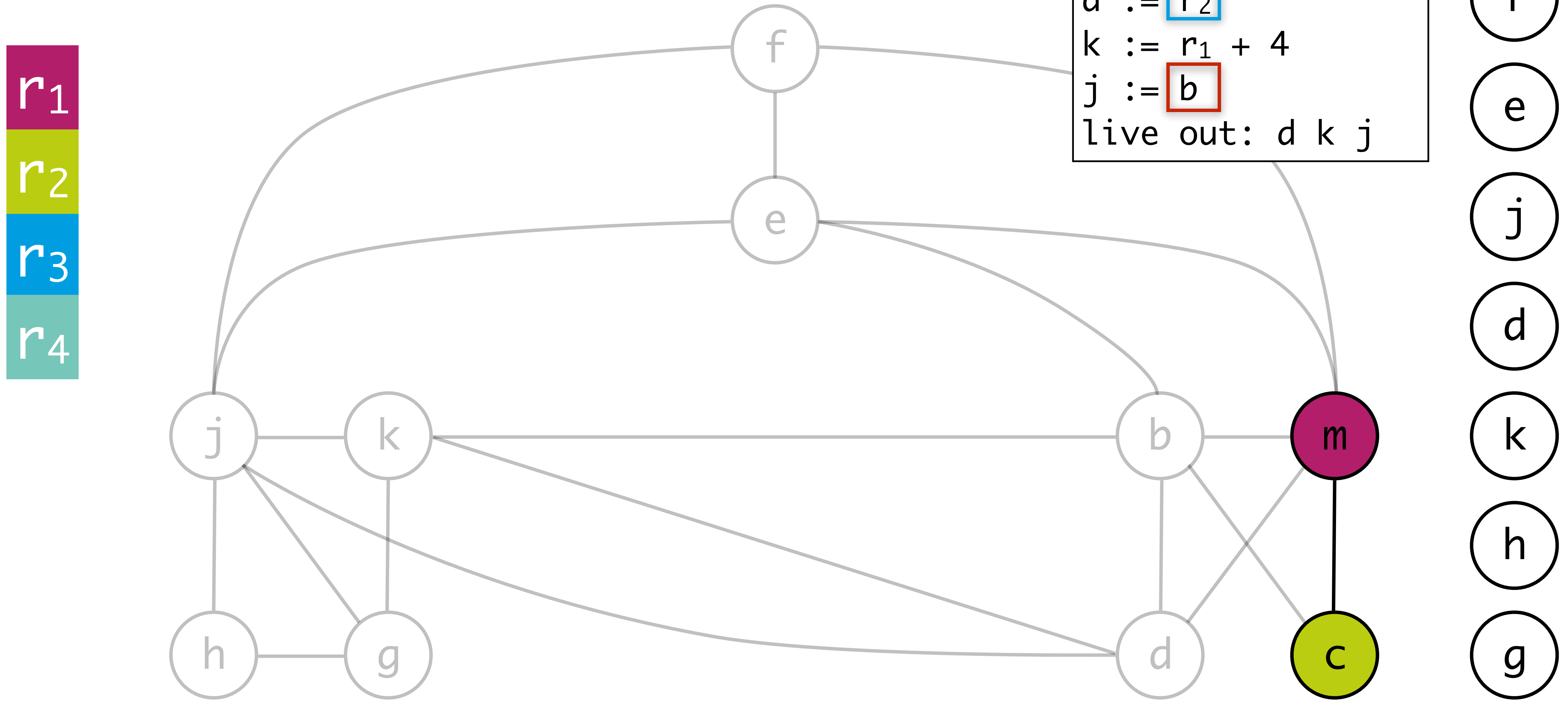




Graph Coloring

example with 4 colors

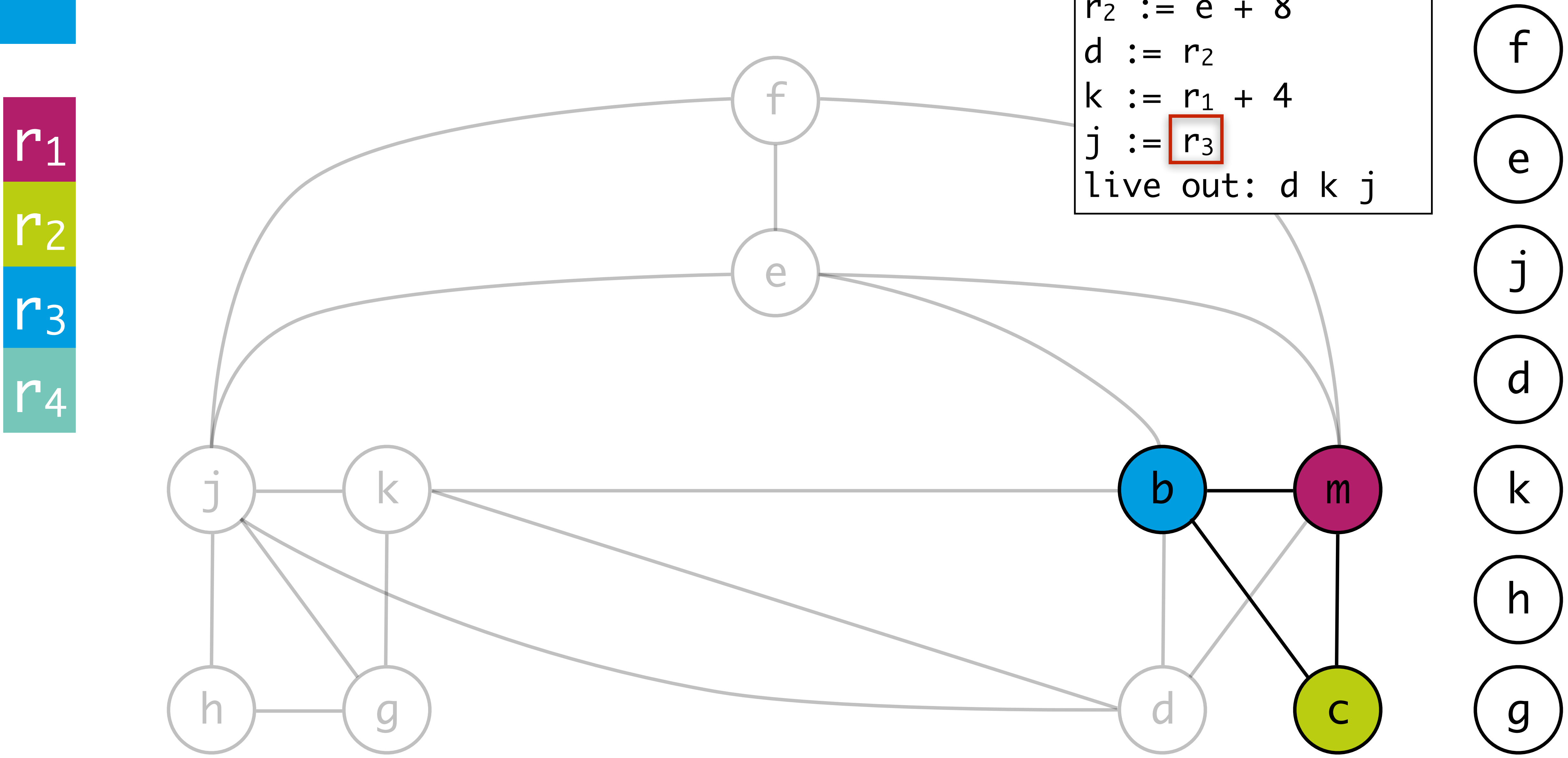
```
live-in: k j
g  := mem[j + 12]
h  := k - 1
f  := g * h
e  := mem[j + 8]
r1 := mem[j + 16]
b  := mem[f]
r2 := e + 8
d  := r2
k  := r1 + 4
j  := b
live out: d k j
```



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

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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
```
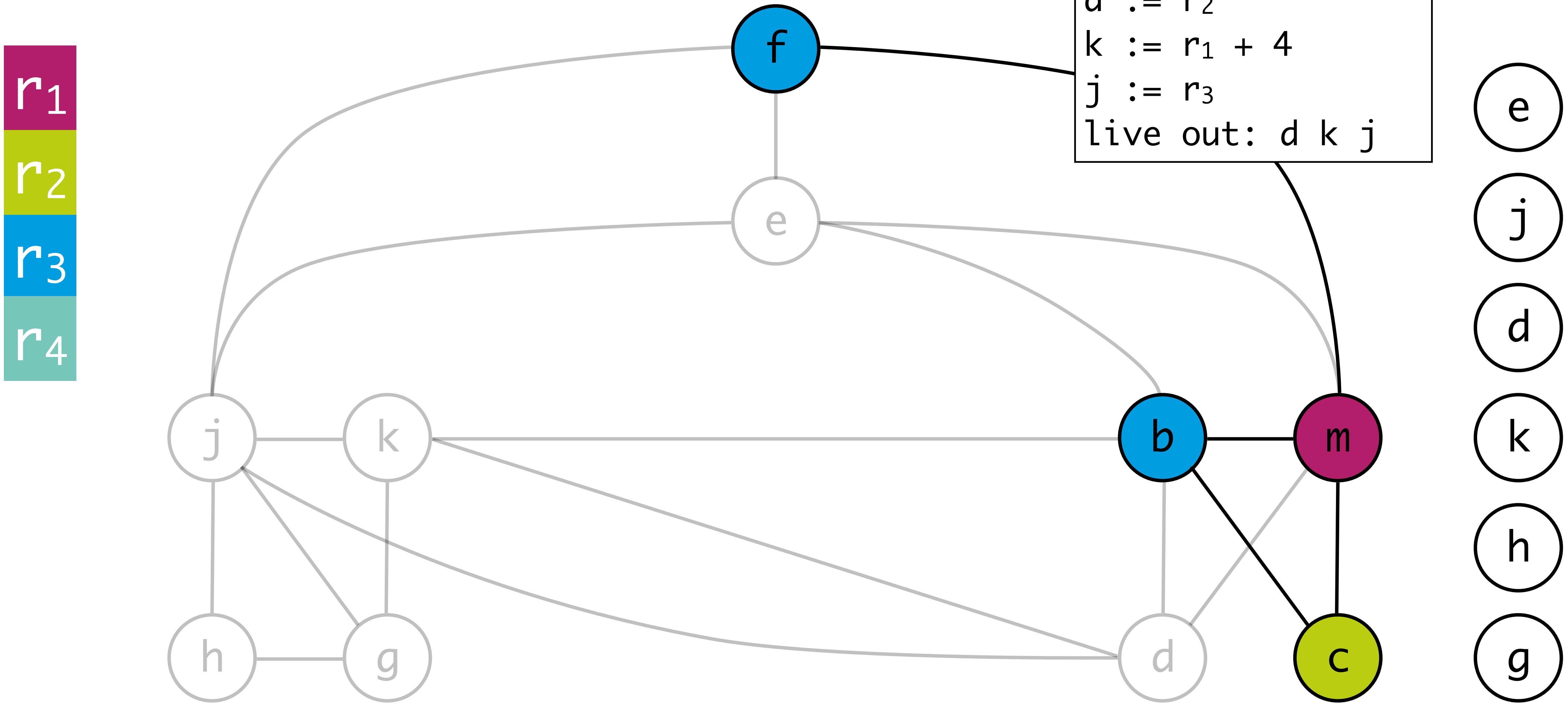
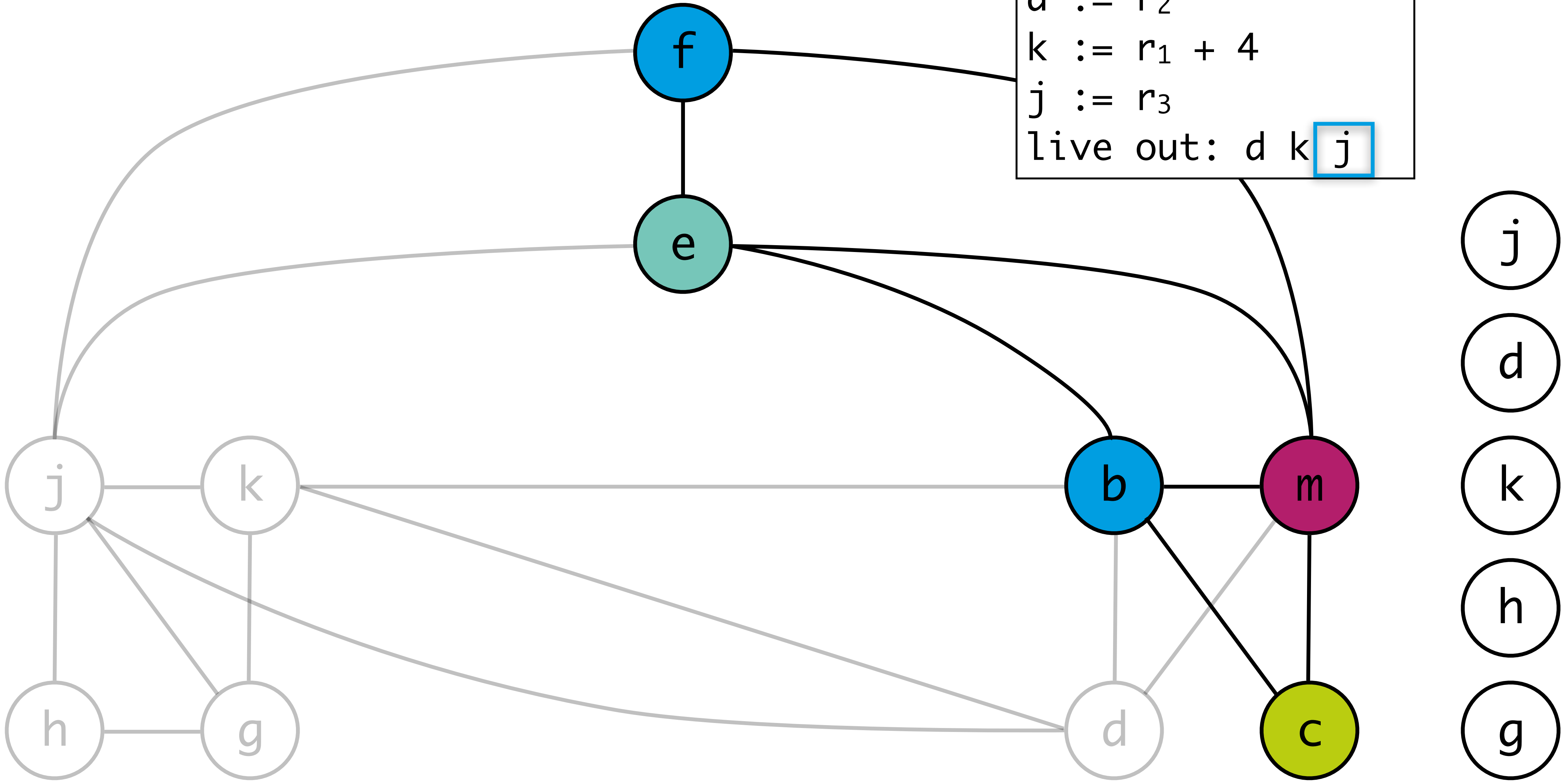



Graph Coloring

example with 4 colors

🟪 r_1
🟩 r_2
🟦 r_3
🟩 r_4

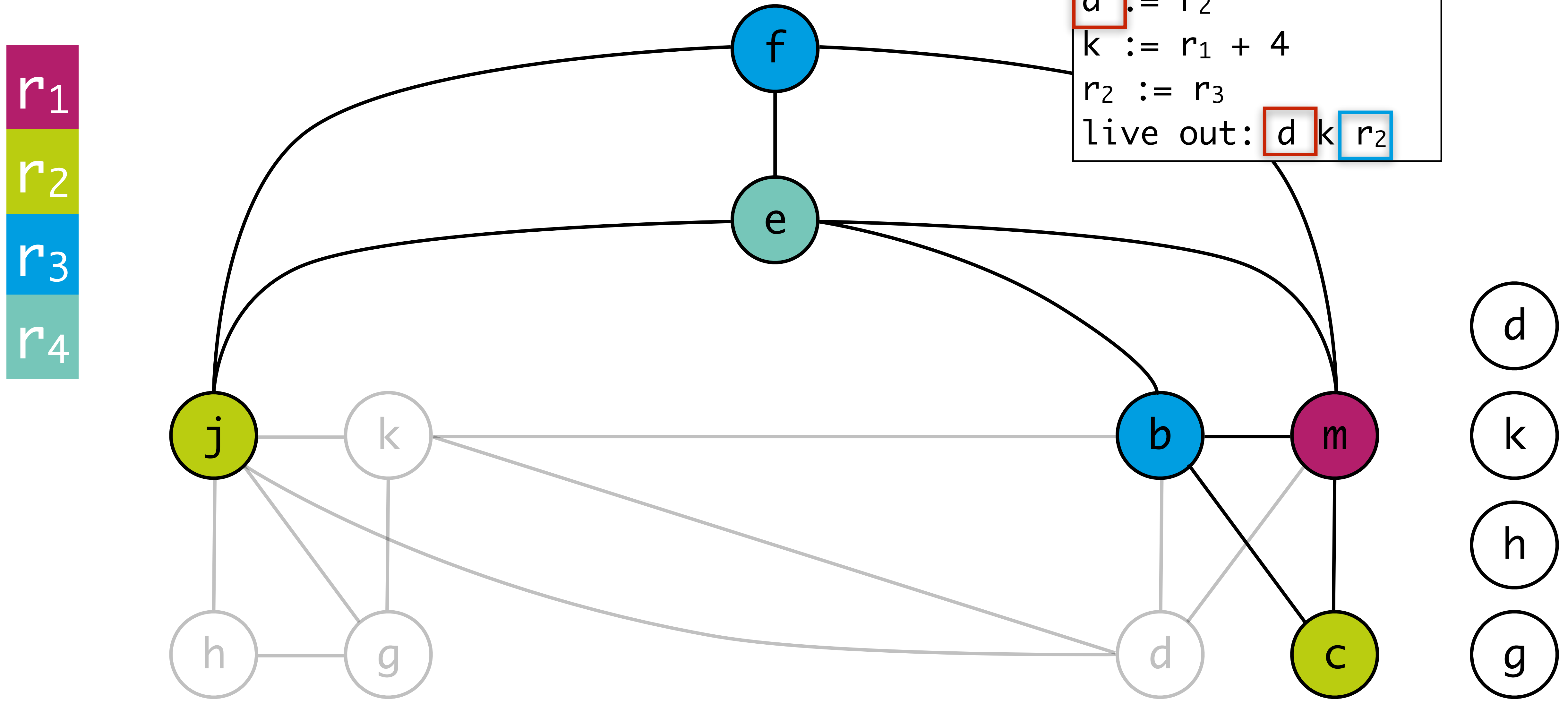
```
live-in: k j
g  := mem[j + 12]
h  := k - 1
r3  := g * h
r4  := mem[j + 8]
r1 := mem[j + 16]
r3  := mem[r3]
r2  := r4 + 8
d  := r2
k  := r1 + 4
j  := r3
live out: d k j
```



Graph Coloring

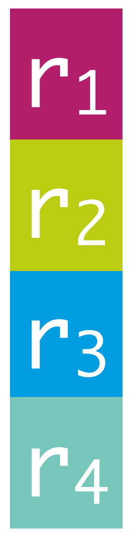
example with 4 colors

```
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
```

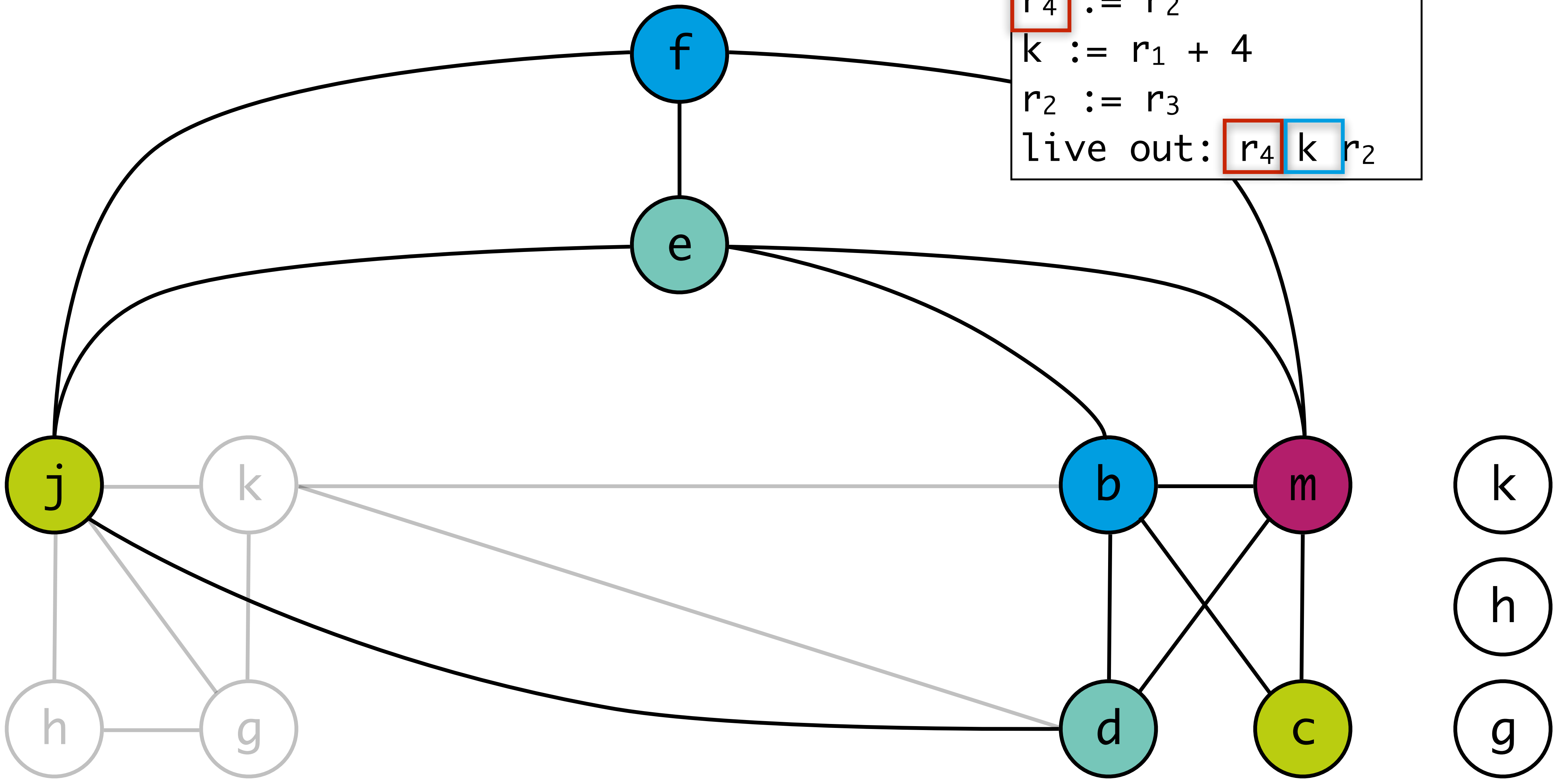


Graph Coloring

example with 4 colors



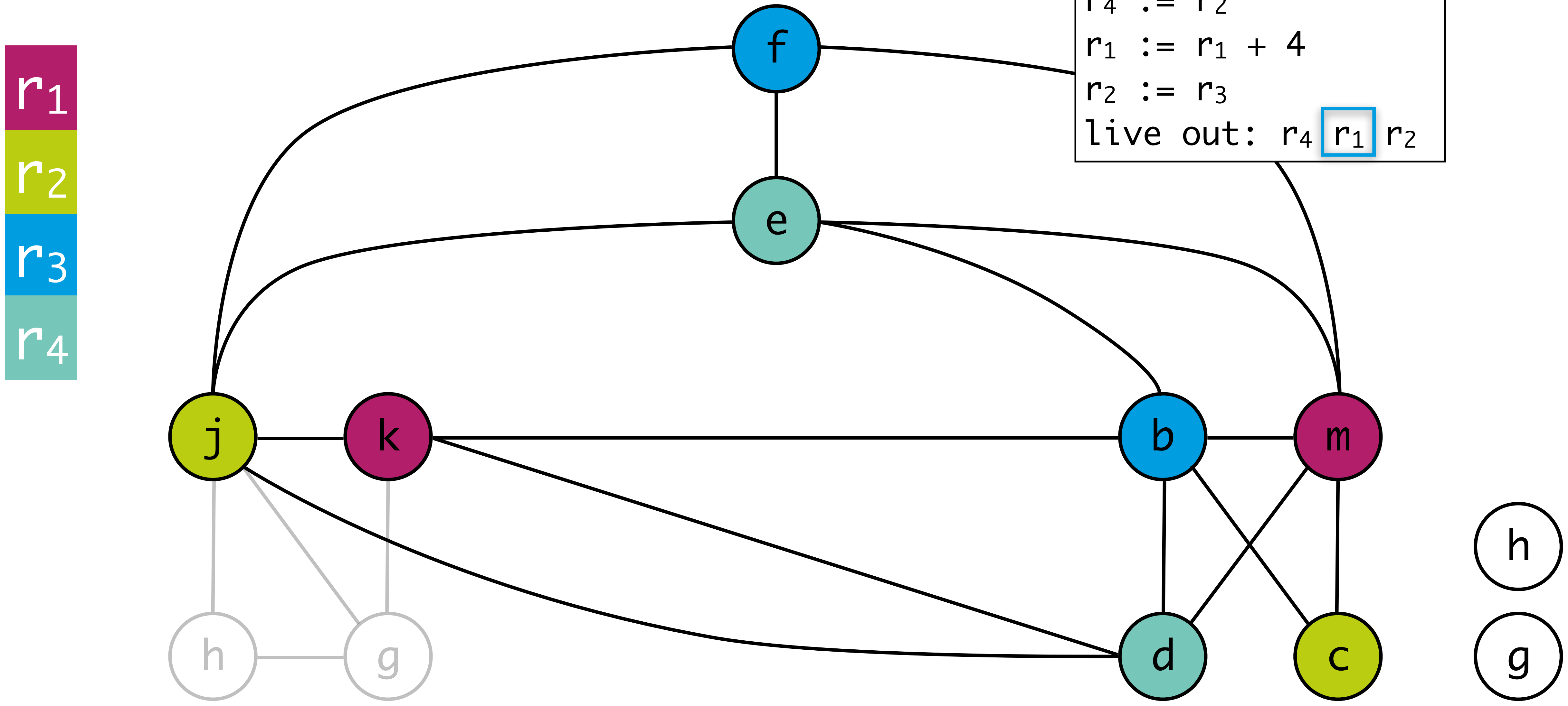
```
live-in: k r2
g  := mem[r2 + 12]
h  := k - 1
r3 := g * h
r4 := mem[r2 + 8]
r1 := mem[r2 + 16]
r3 := mem[r3]
r2 := r4 + 8
r4 := r2
k  := r1 + 4
r2 := r3
live out: r4 k r2
```



Graph Coloring

example with 4 colors

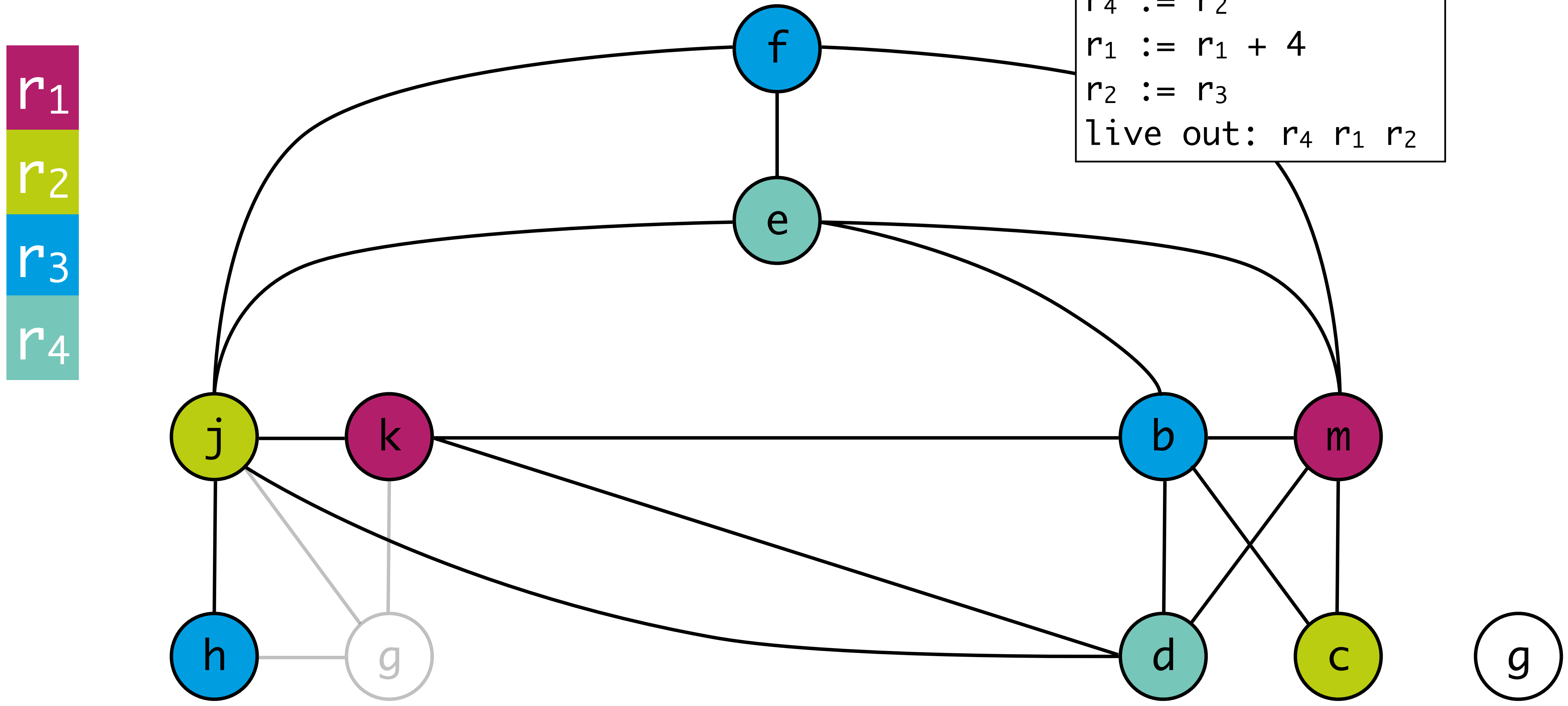
```
live-in: r1 r2
g  := mem[r2 + 12]
h  := r1 - 1
r3 := g * h
r4 := mem[r2 + 8]
r1 := mem[r2 + 16]
r3 := mem[r3]
r2 := r4 + 8
r4 := r2
r1 := r1 + 4
r2 := r3
live out: r4 r1 r2
```



Graph Coloring

example with 4 colors

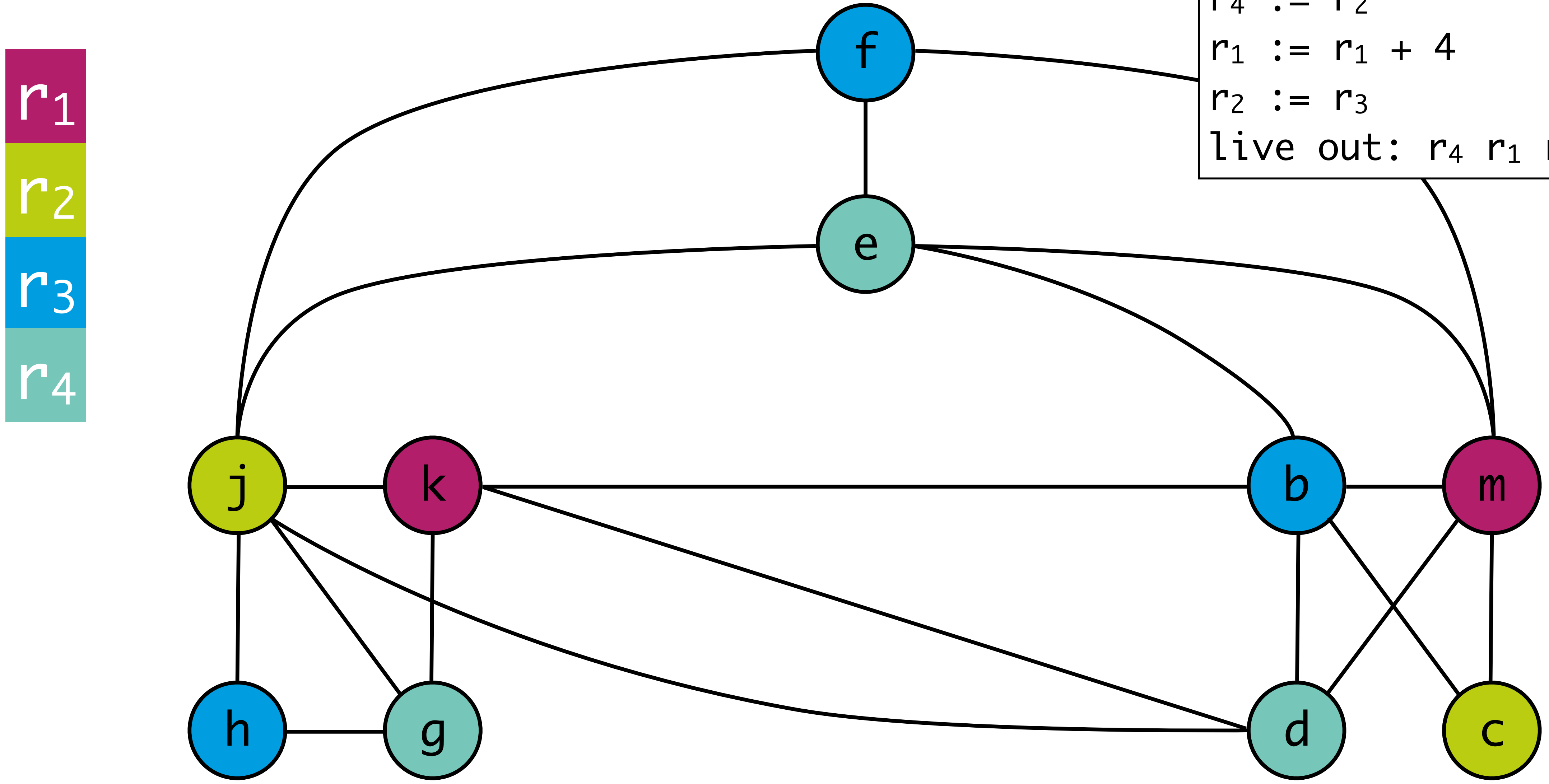
```
live-in: r1 r2
g := mem[r2 + 12]
r3 := r1 - 1
r3 := g * r3
r4 := mem[r2 + 8]
r1 := mem[r2 + 16]
r3 := mem[r3]
r2 := r4 + 8
r4 := r2
r1 := r1 + 4
r2 := r3
live out: r4 r1 r2
```



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
```



III

Spilling

Optimistic Coloring

steps

Simplify

remove node of insignificant degree (fewer than k edges)

Spill

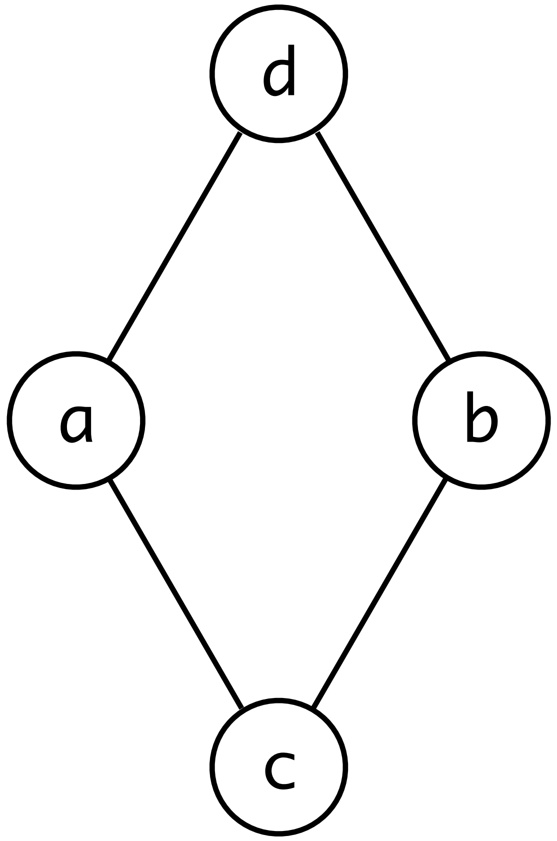
remove node of significant degree (k or more edges)

Select

add node, select color

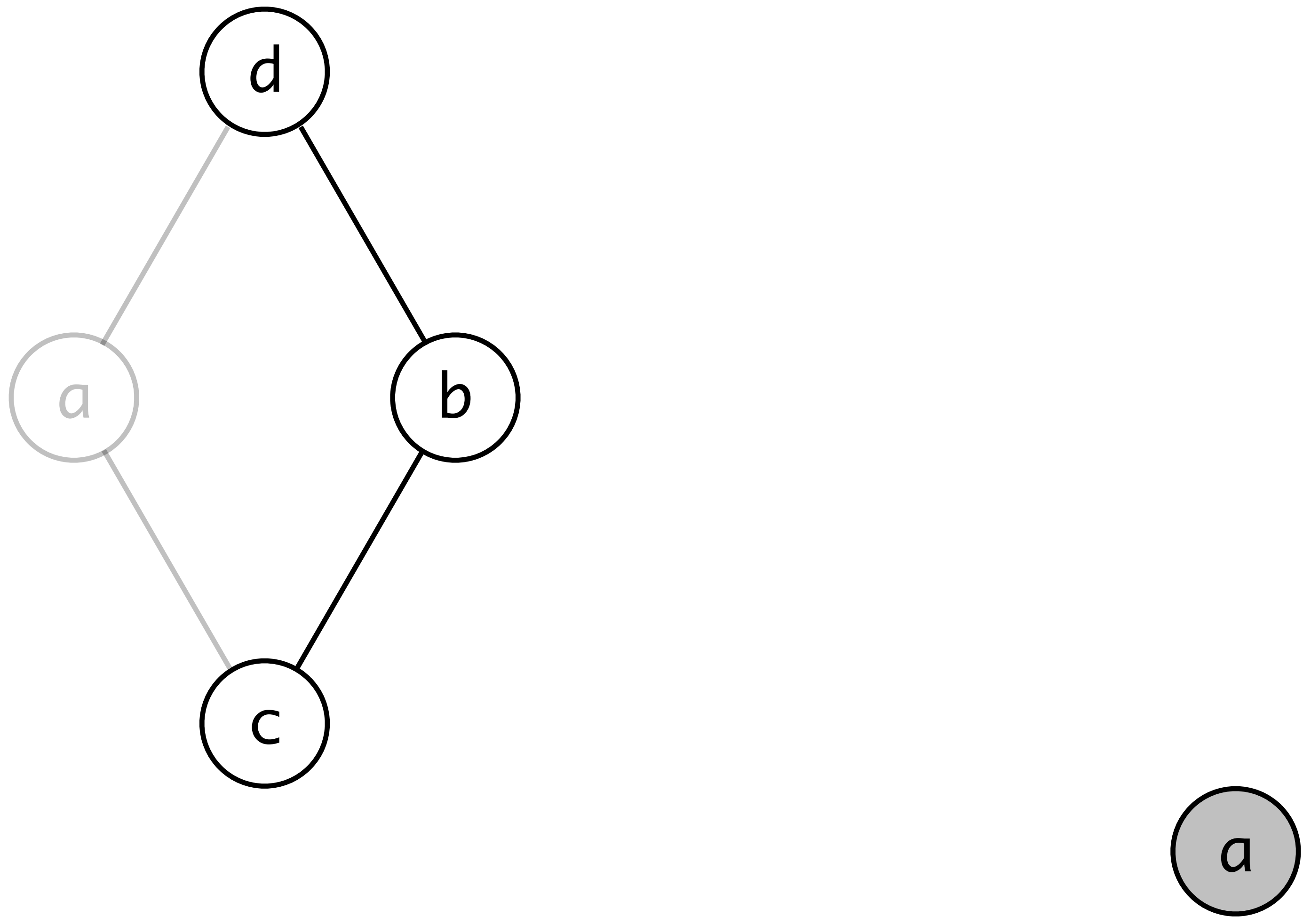
Optimistic Coloring

example with 2 colors



Optimistic Coloring

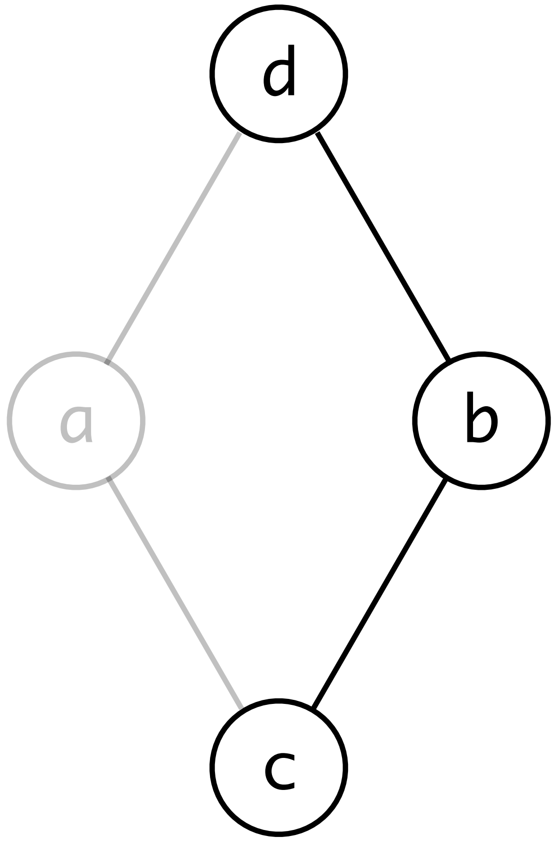
example with 2 colors



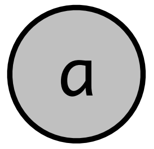
TU Delft

Optimistic Coloring

example with 2 colors

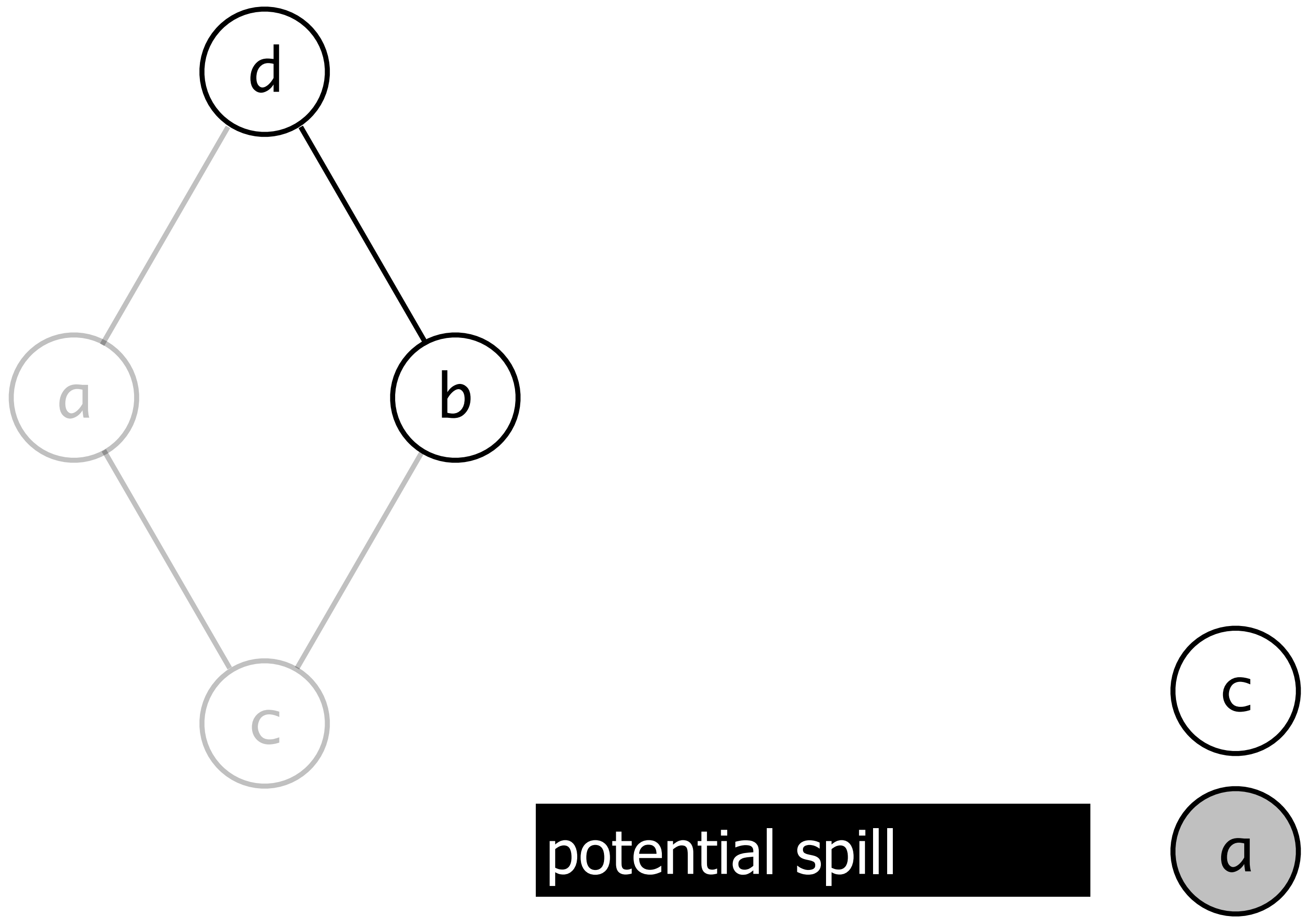


potential spill



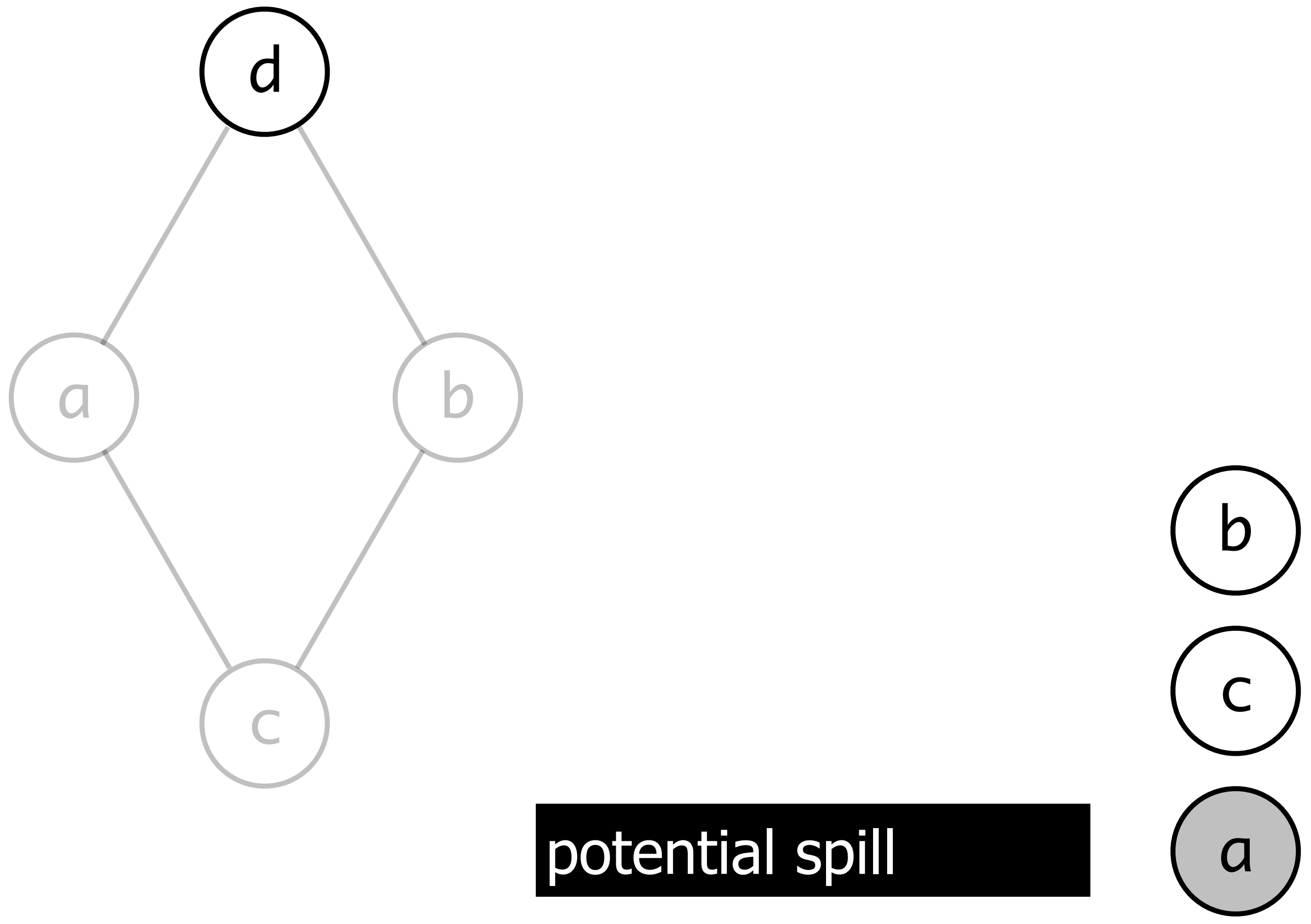
Optimistic Coloring

example with 2 colors



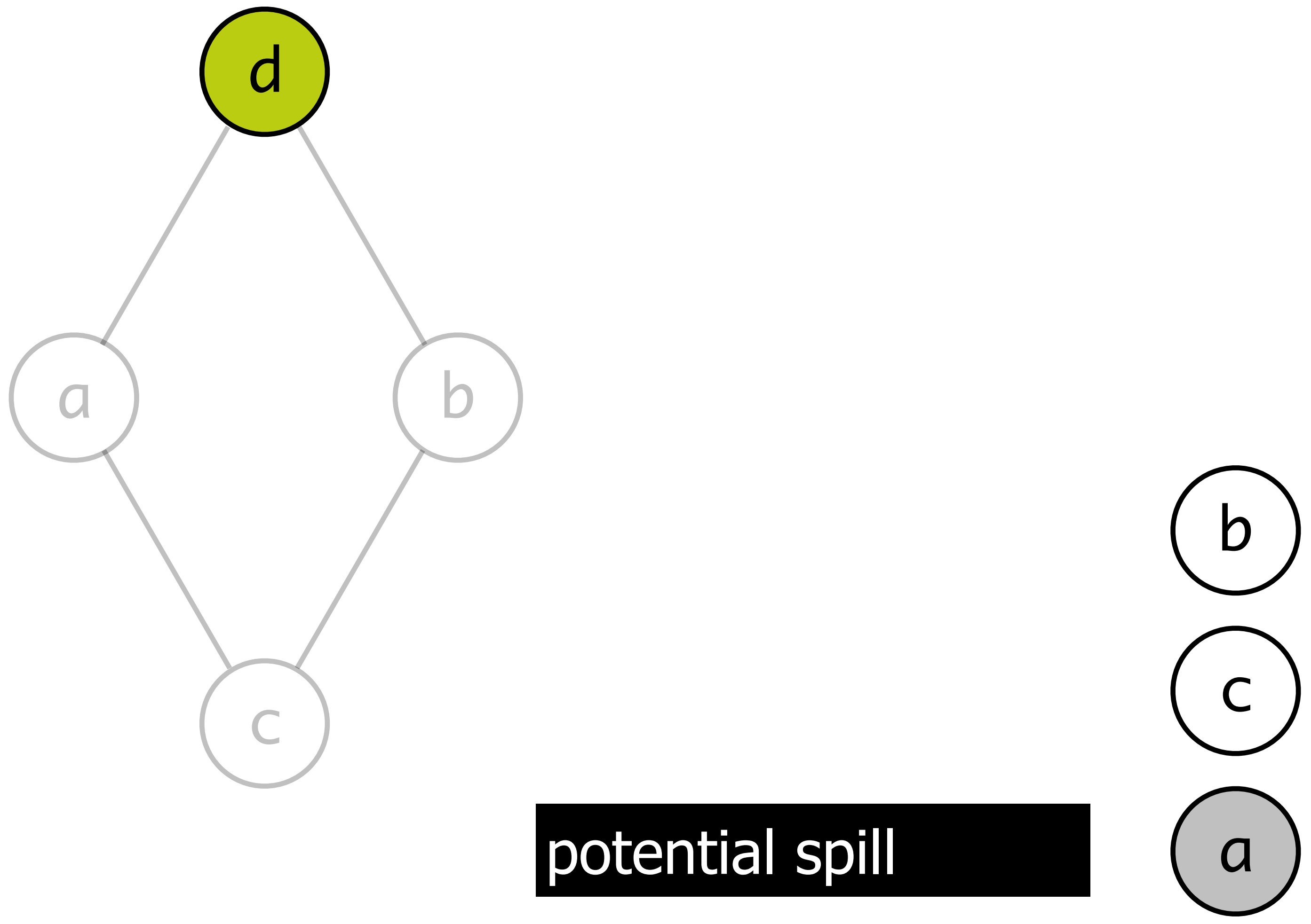
Optimistic Coloring

example with 2 colors



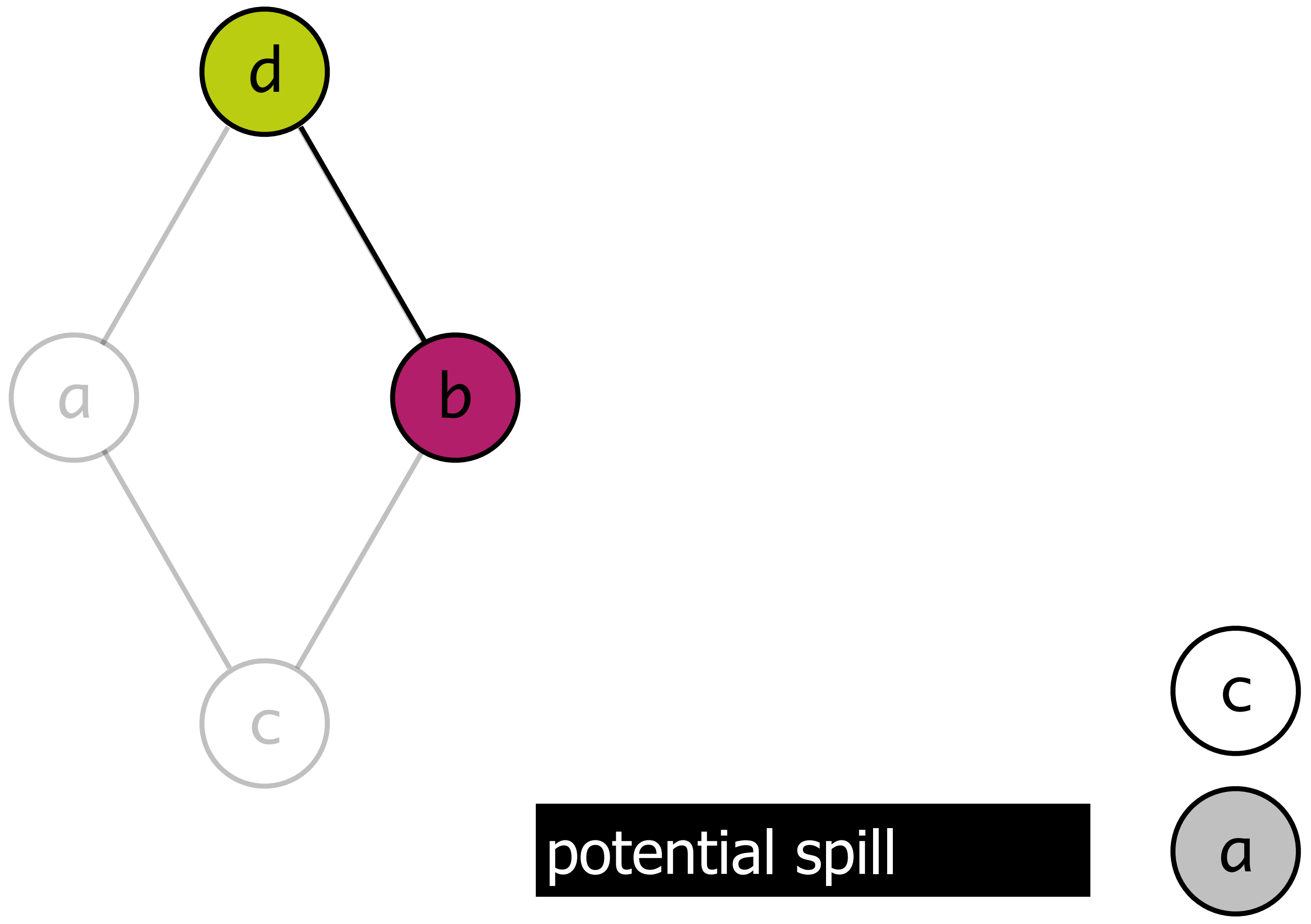
Optimistic Coloring

example with 2 colors



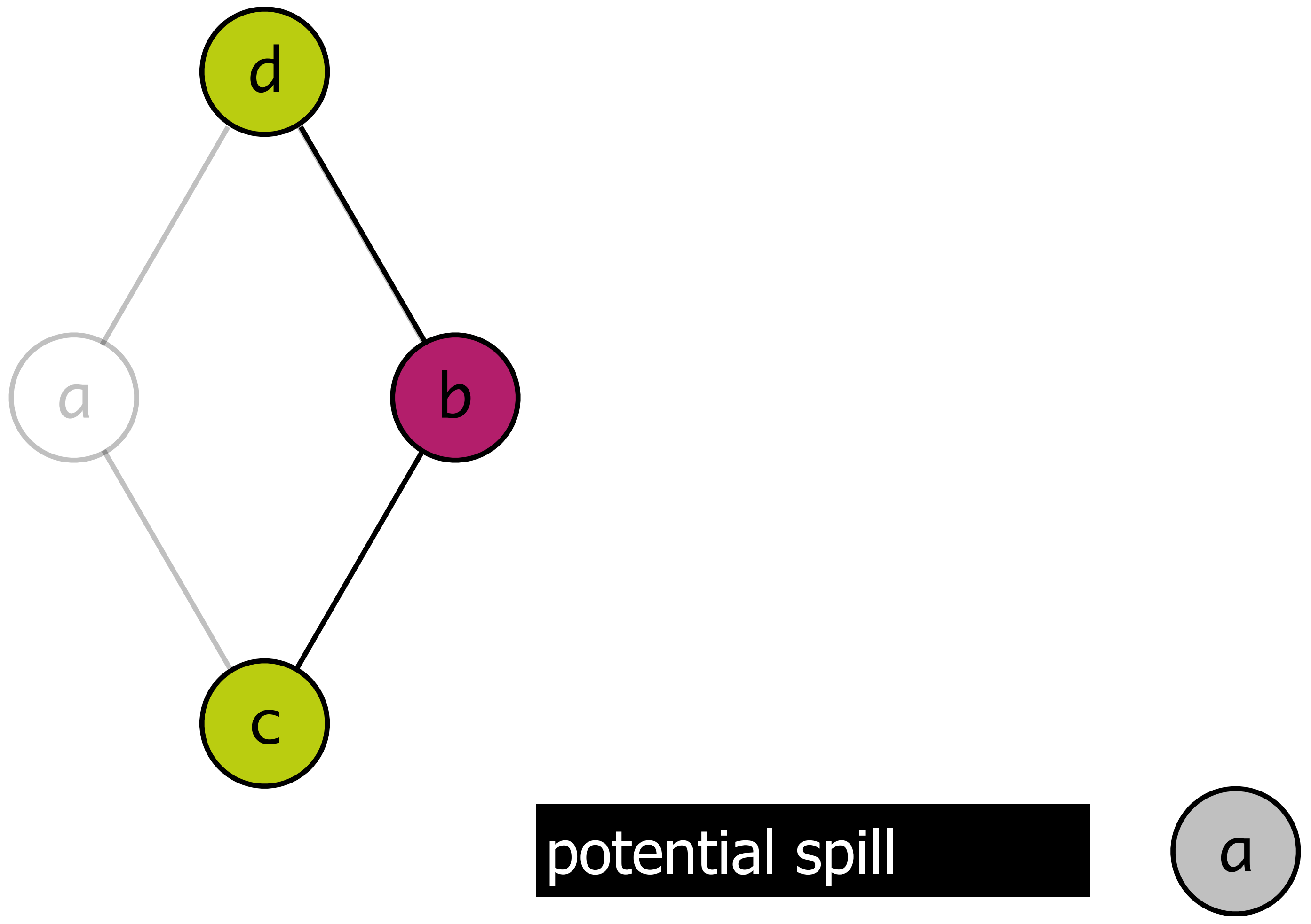
Optimistic Coloring

example with 2 colors



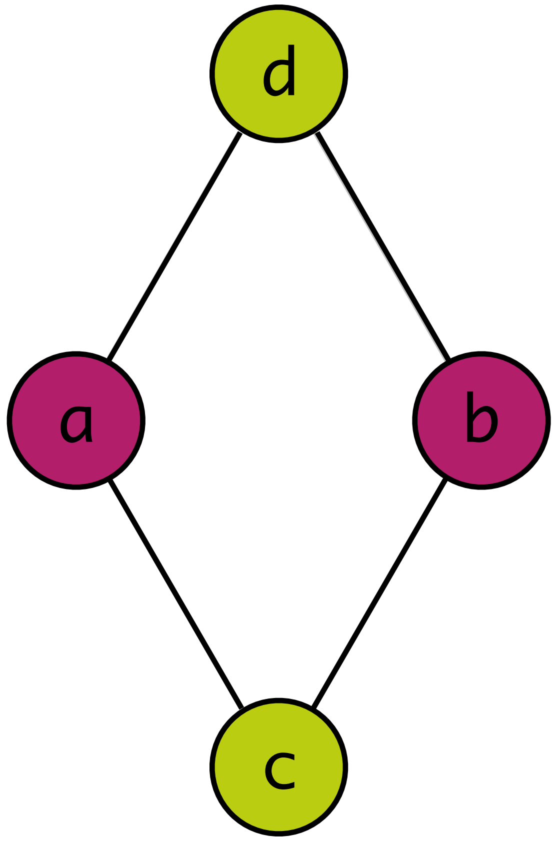
Optimistic Coloring

example with 2 colors



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

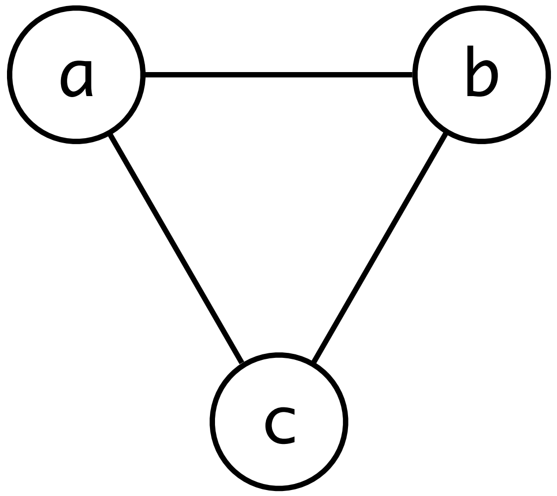
add node, select color

Actual spill

Start over

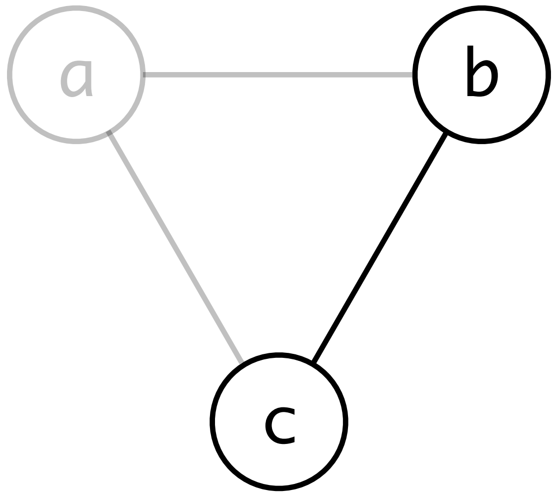
Spilling

example with 2 colors

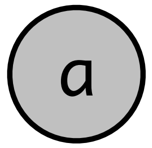


Spilling

example with 2 colors

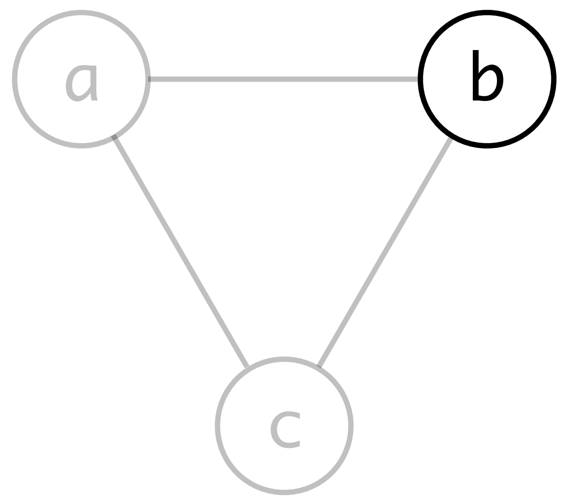


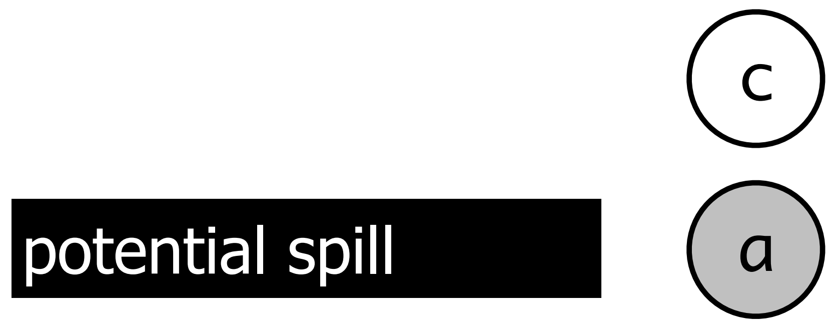
potential spill



Spilling

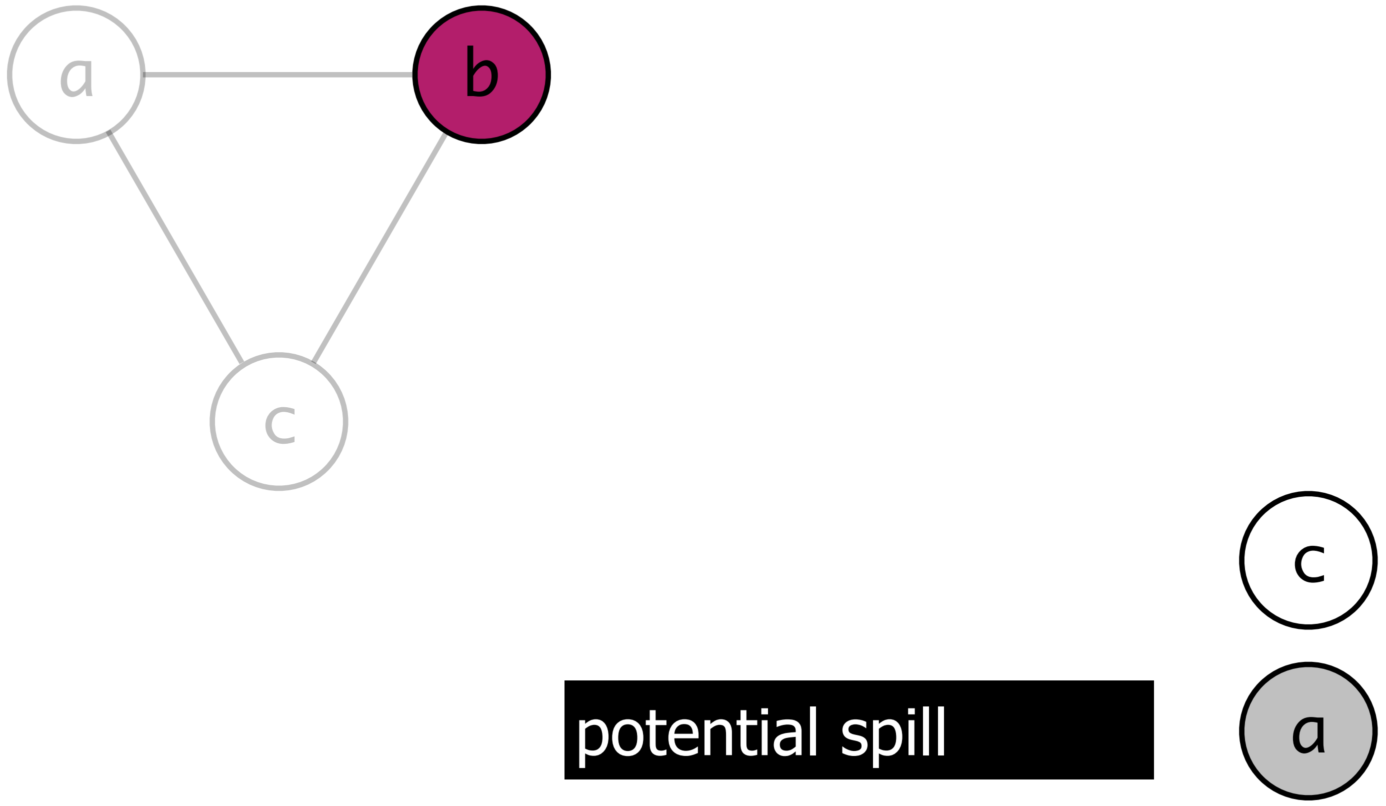
example with 2 colors





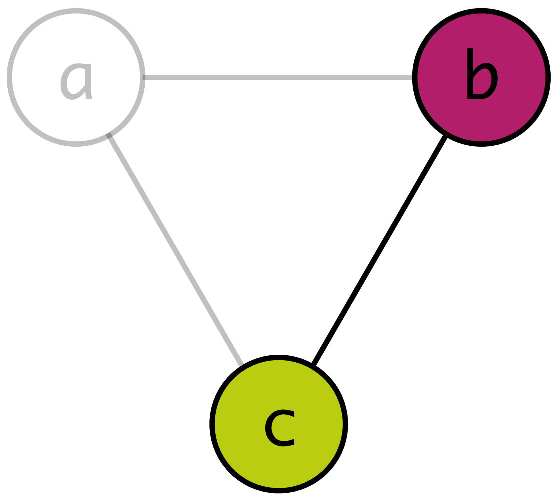
Spilling

example with 2 colors

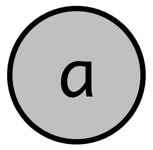


Spilling

example with 2 colors

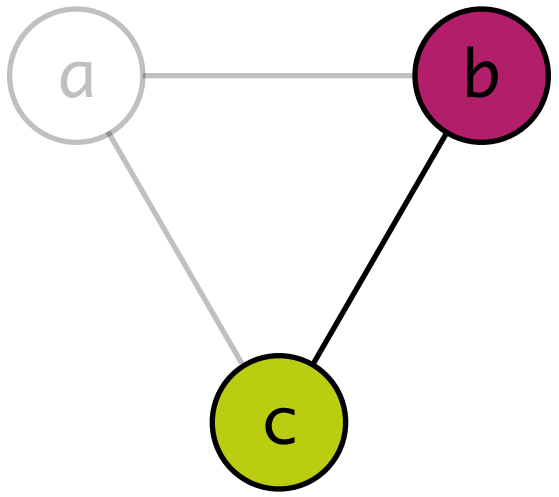


potential spill

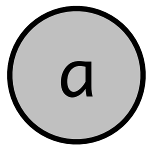


Spilling

example with 2 colors

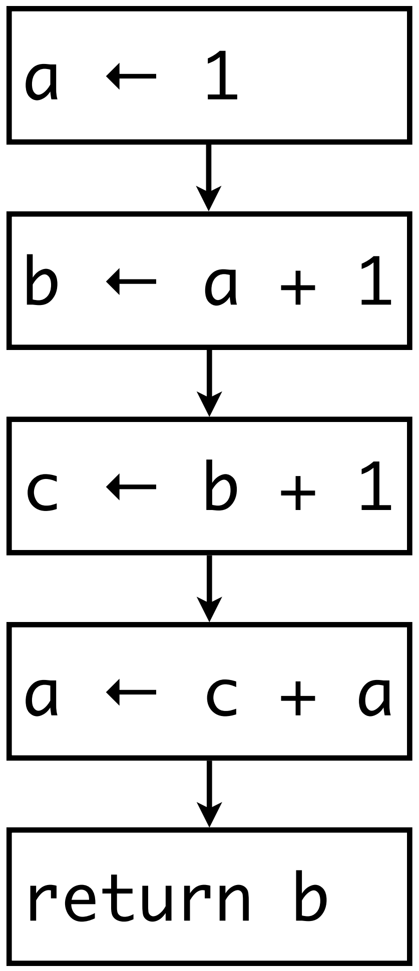


actual spill



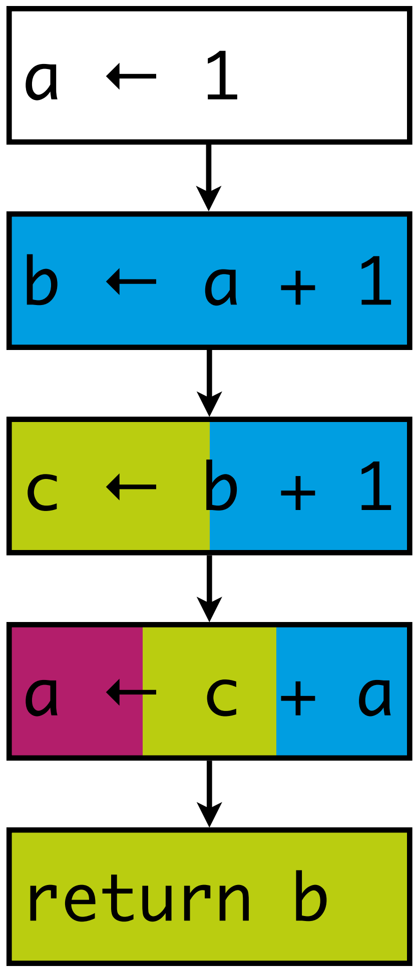
Spilling

example



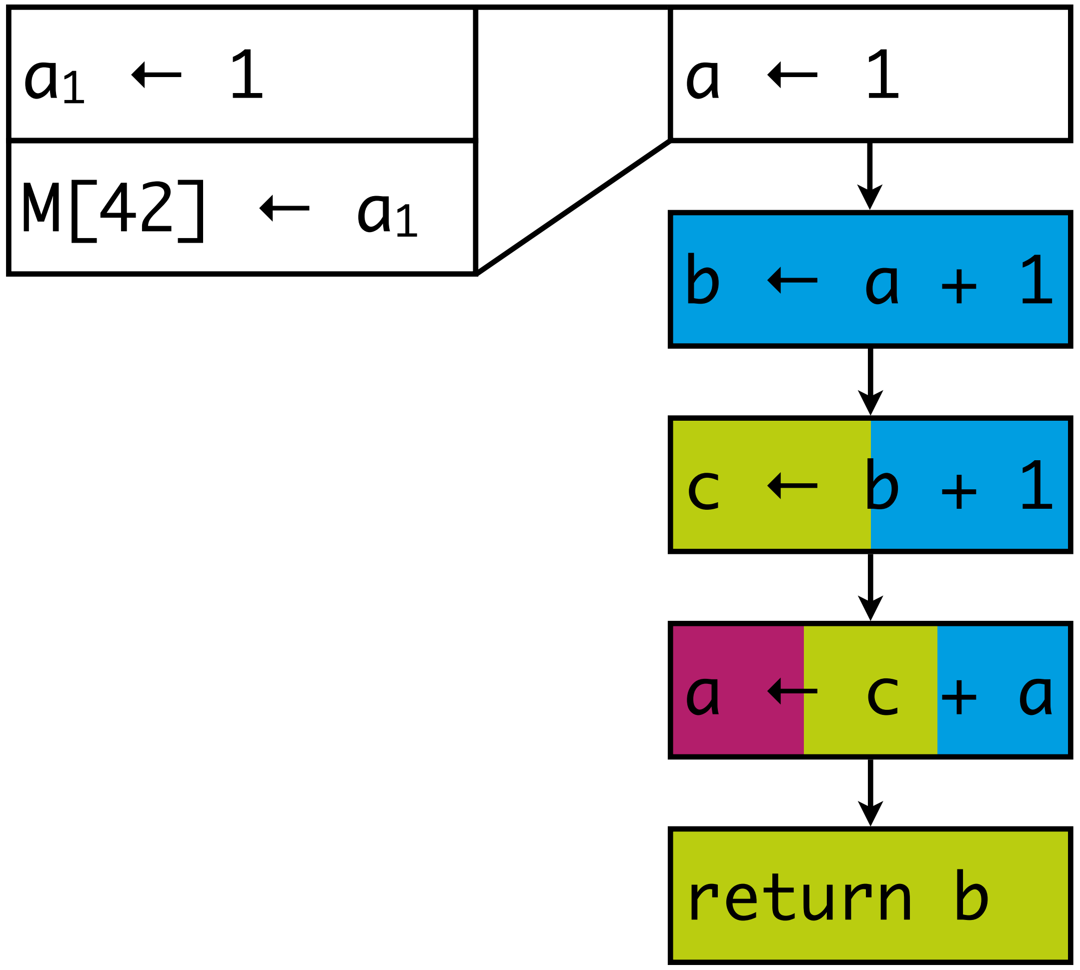
```
a ← 1
b ← a + 1
c ← b + 1
a ← c + a
return b
```

Spilling
example



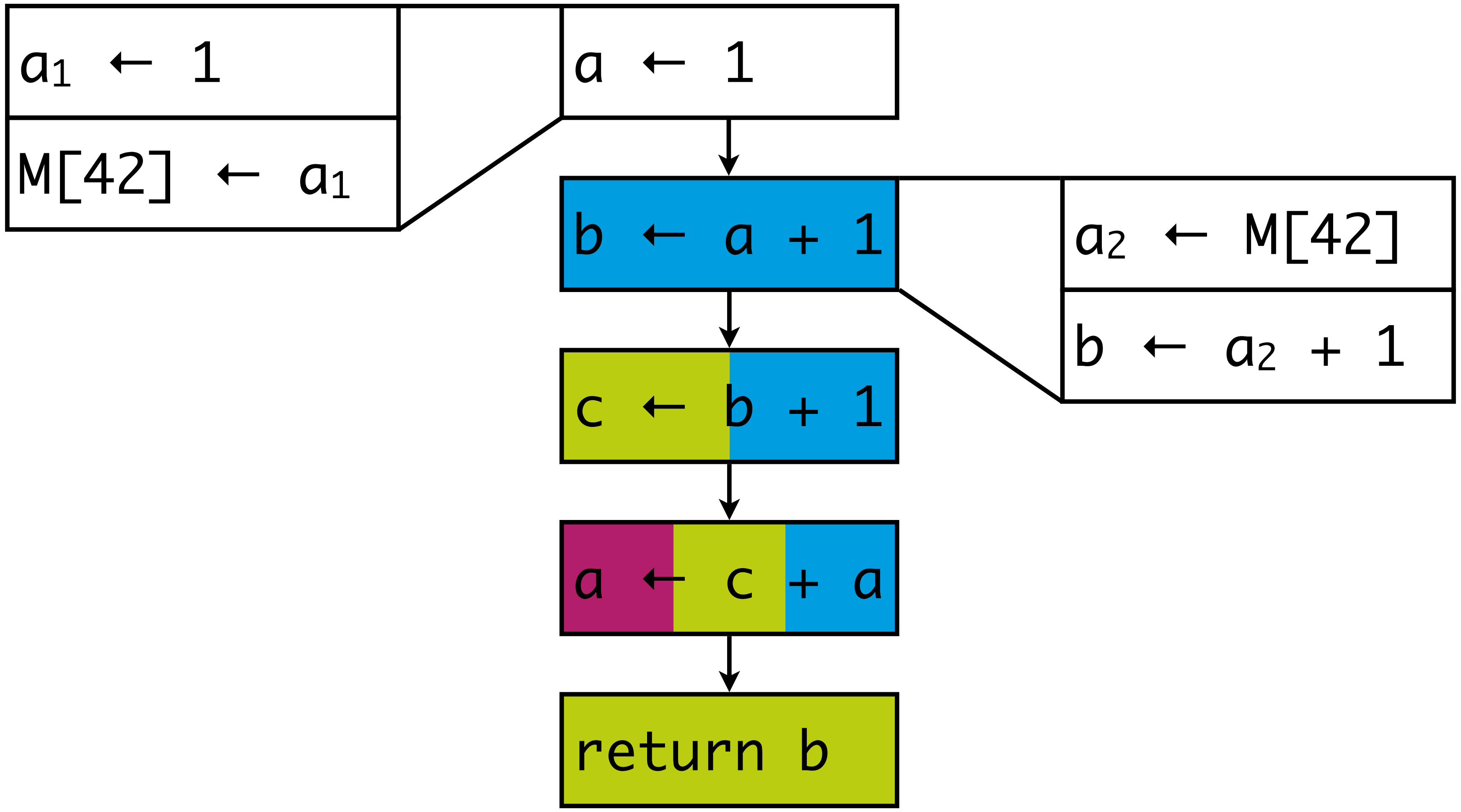
Spilling

example

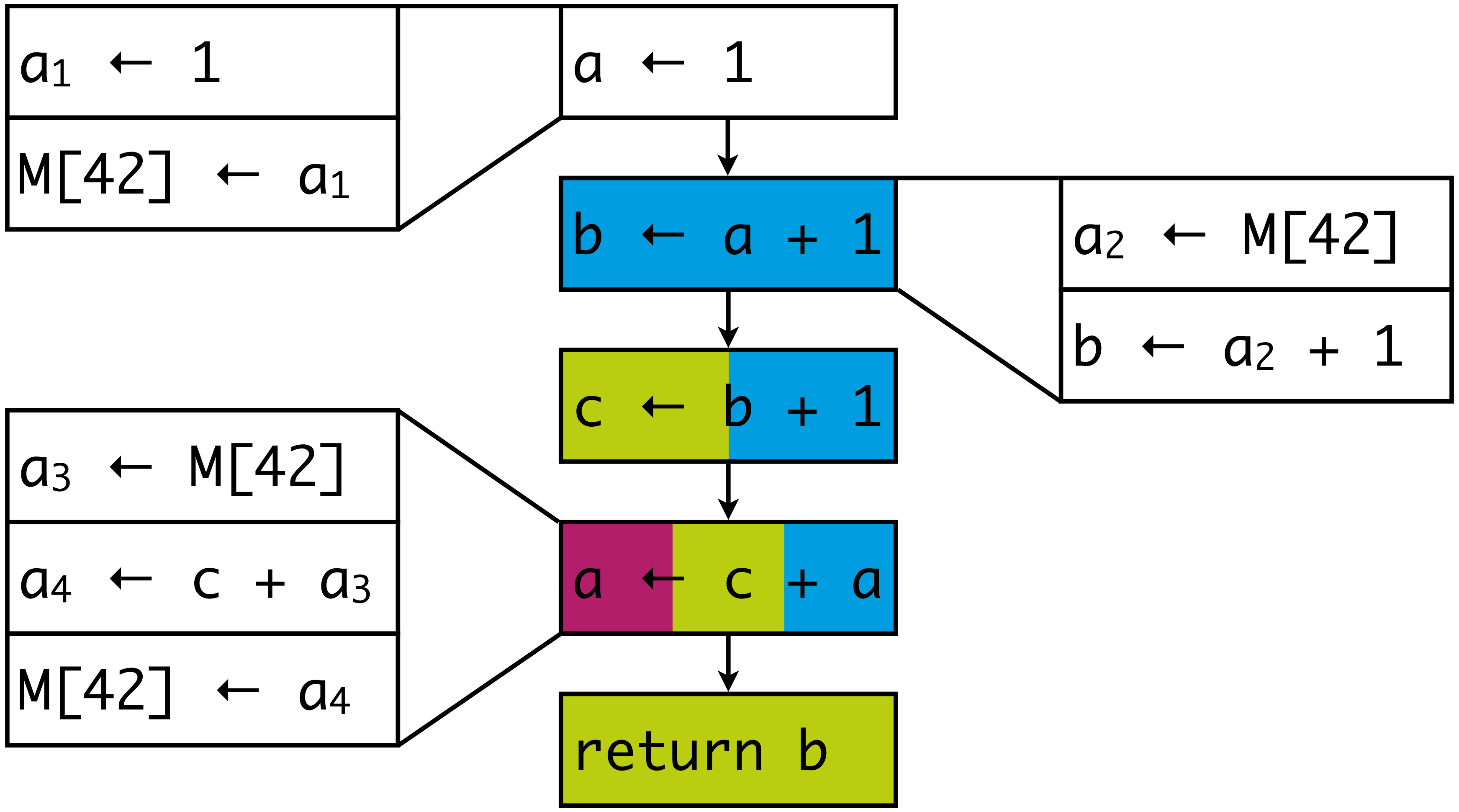


Spilling

example

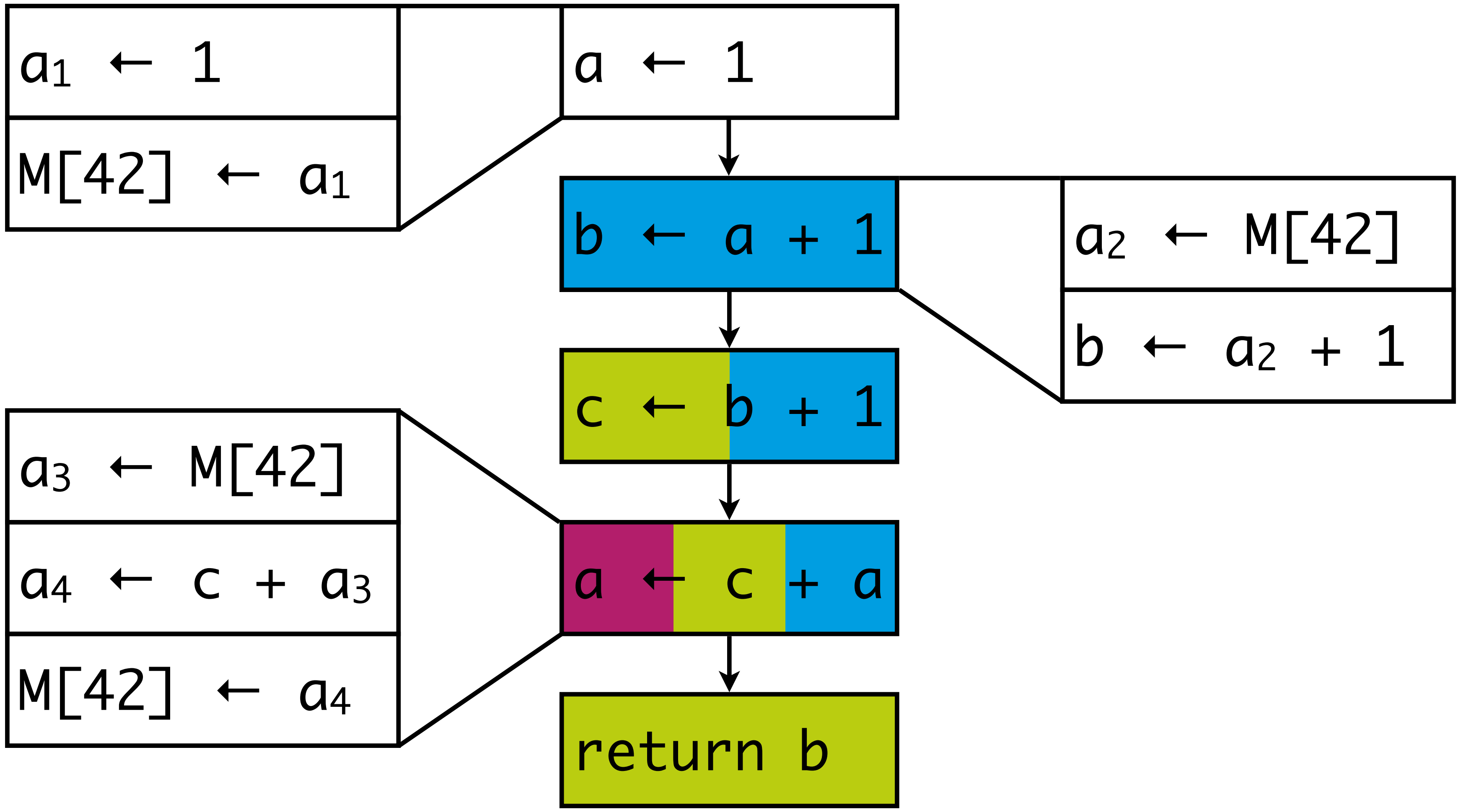


Spilling
example



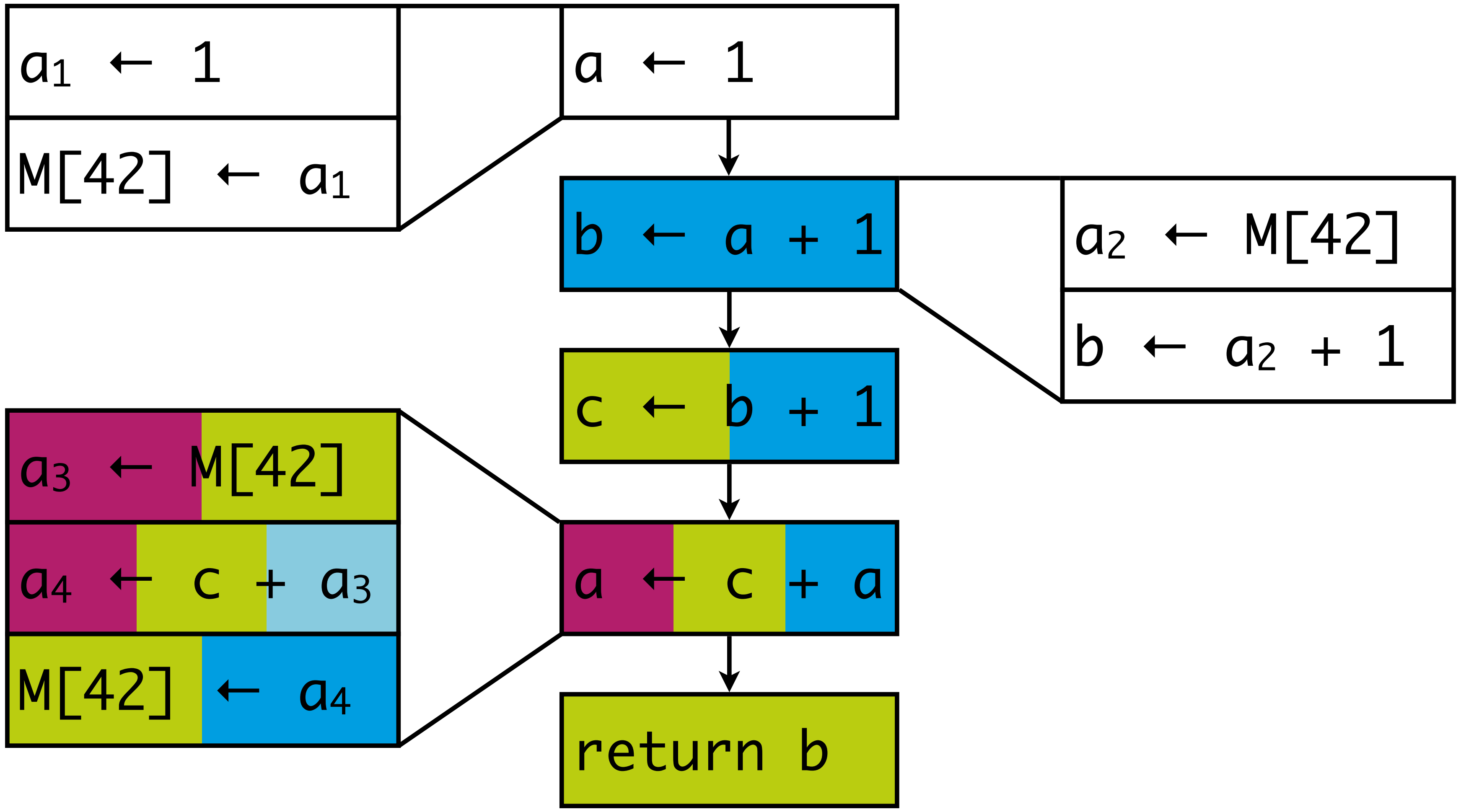
Spilling

example



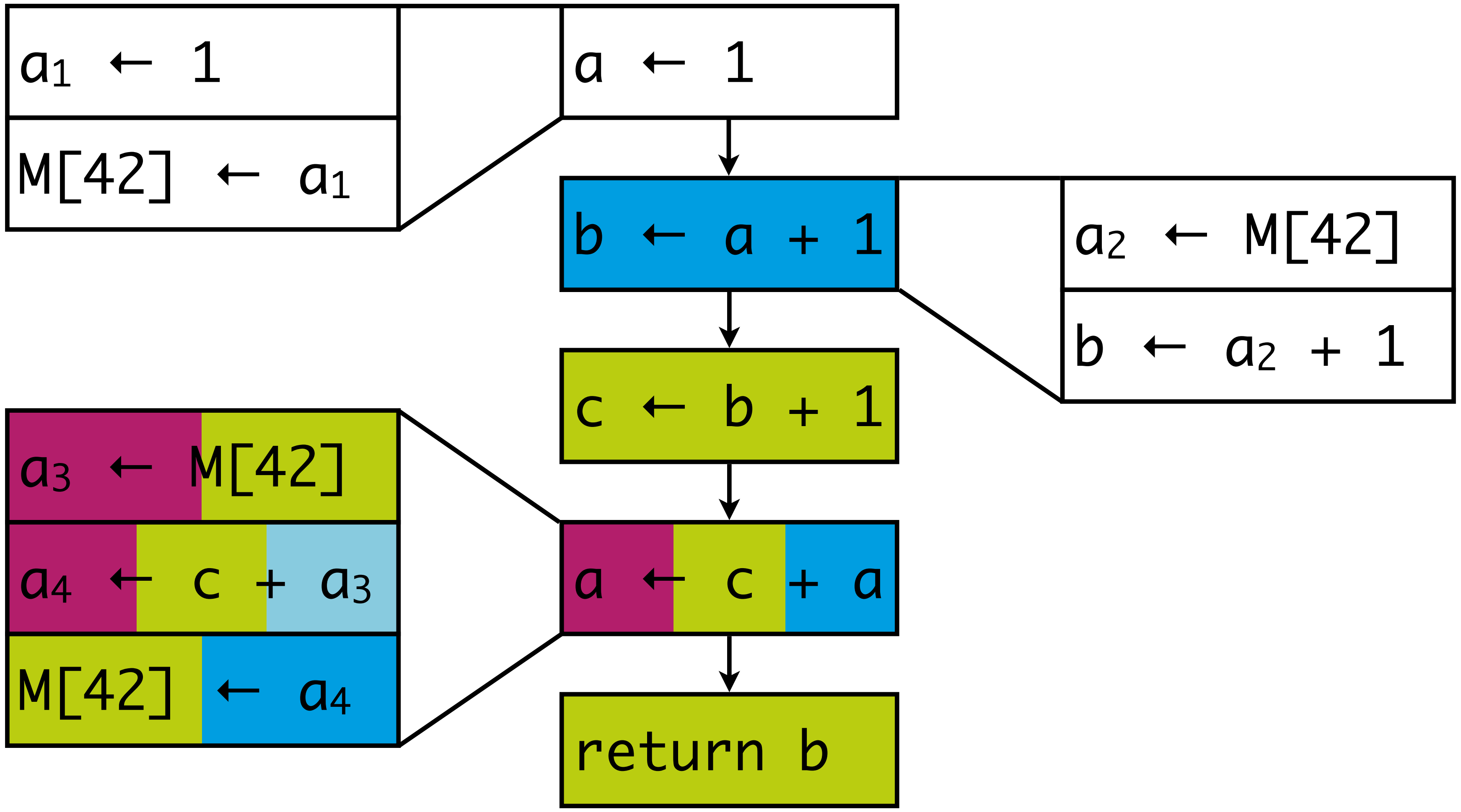
Spilling

example



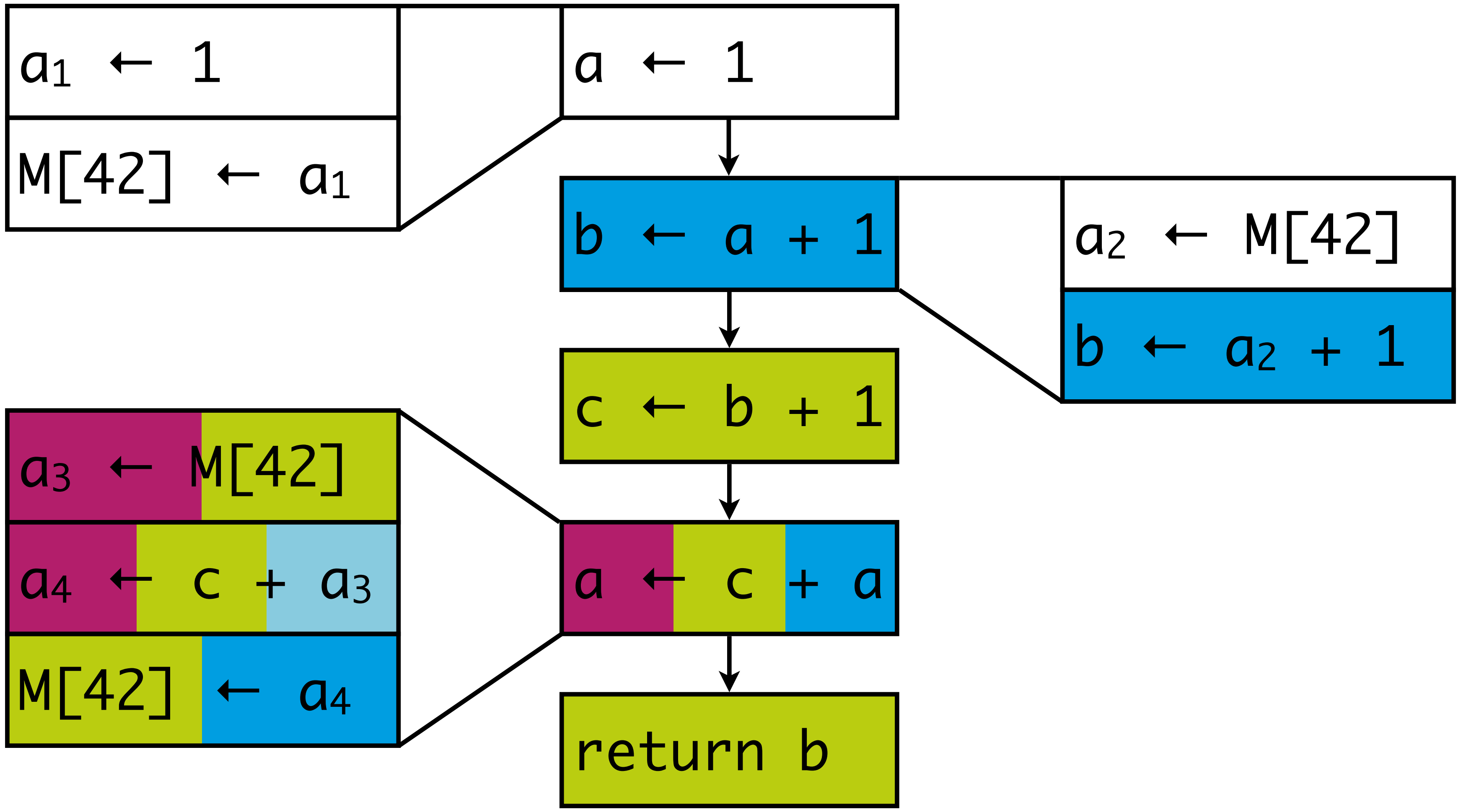
Spilling

example



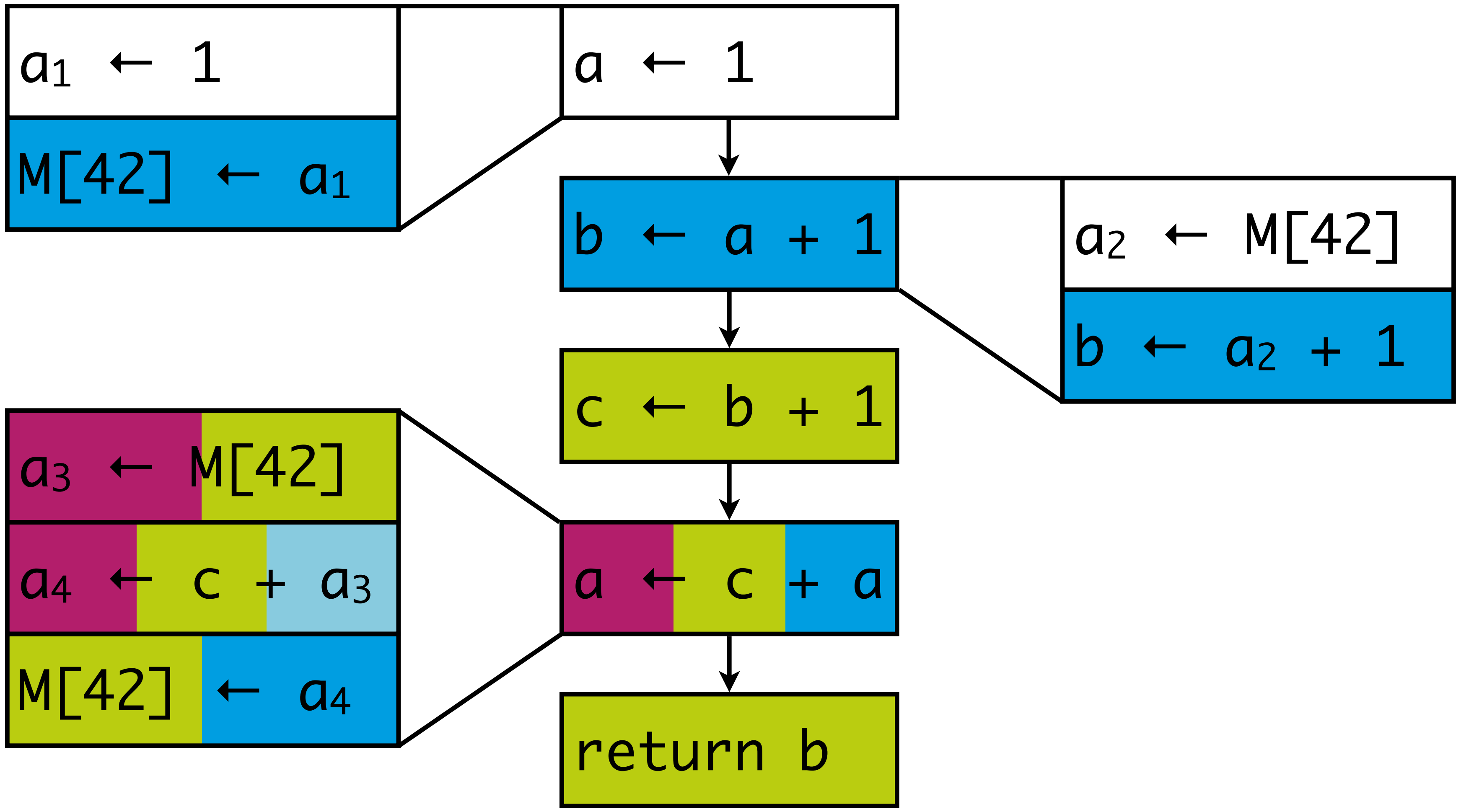
Spilling

example



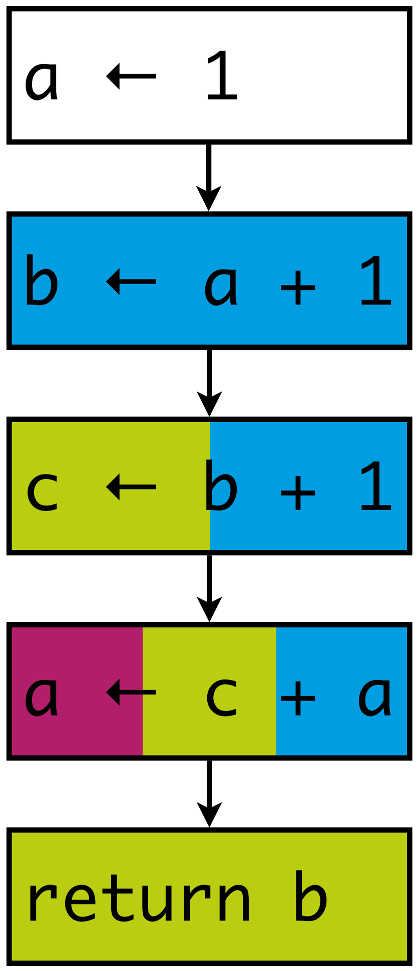
Spilling

example



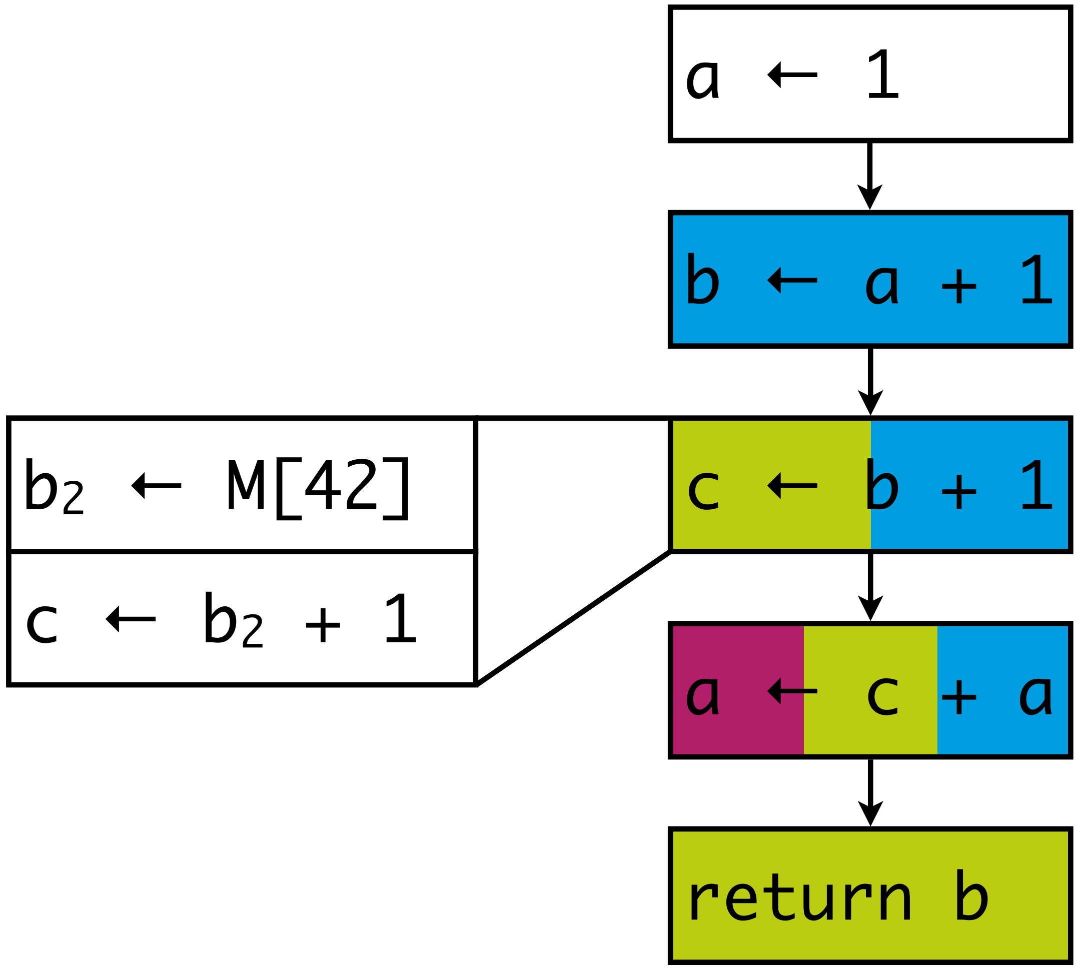
Spilling

example



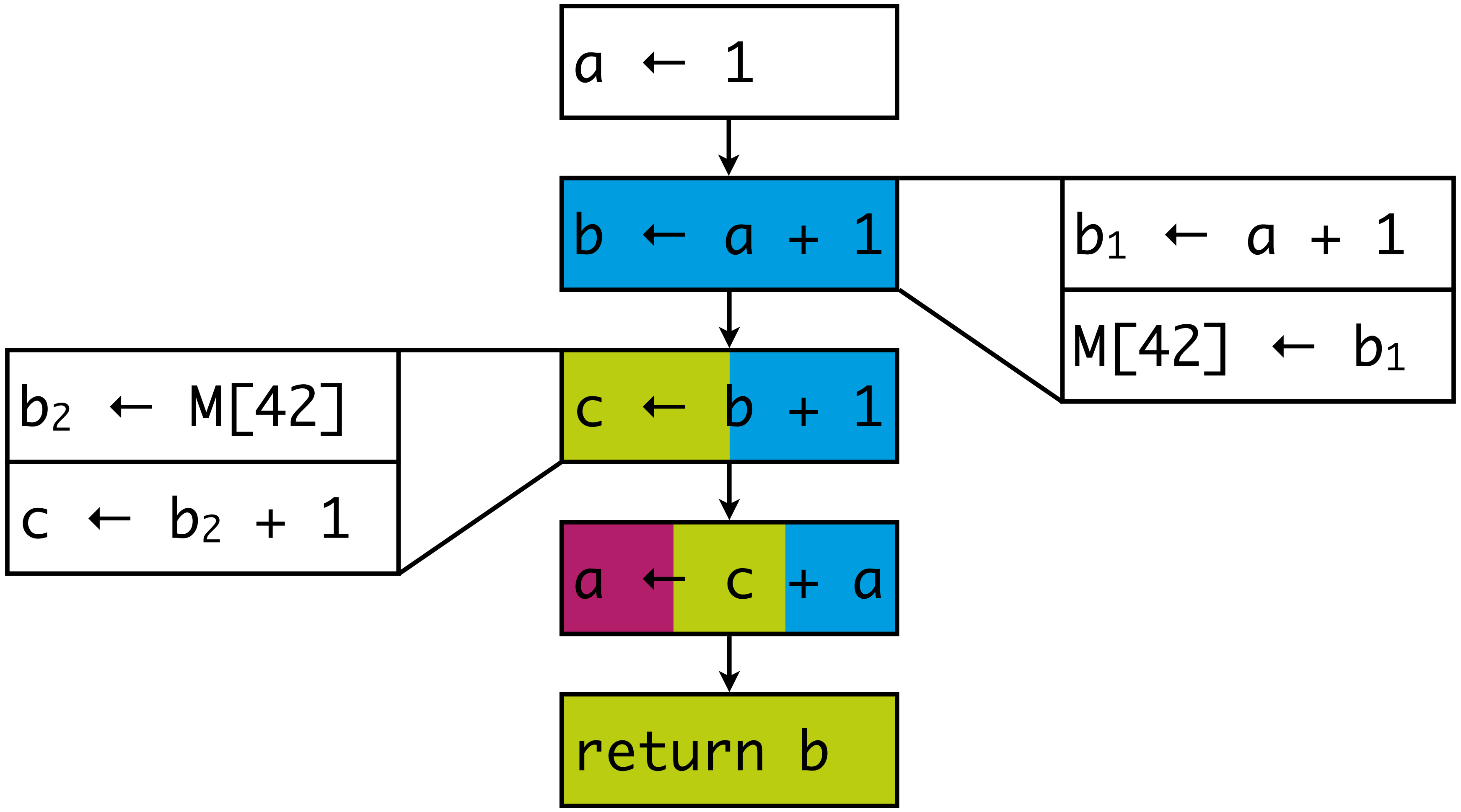
Spilling

example



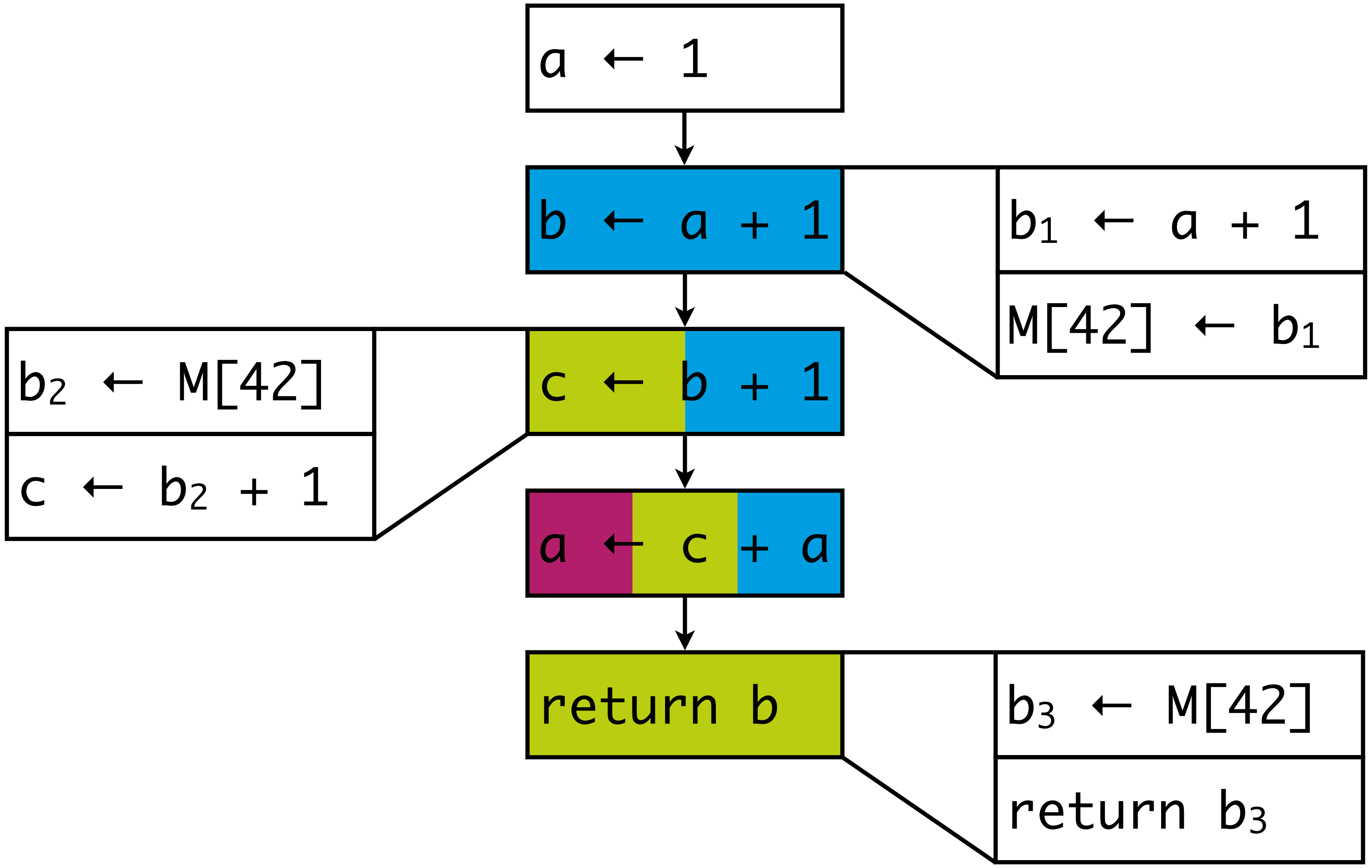
Spilling

example

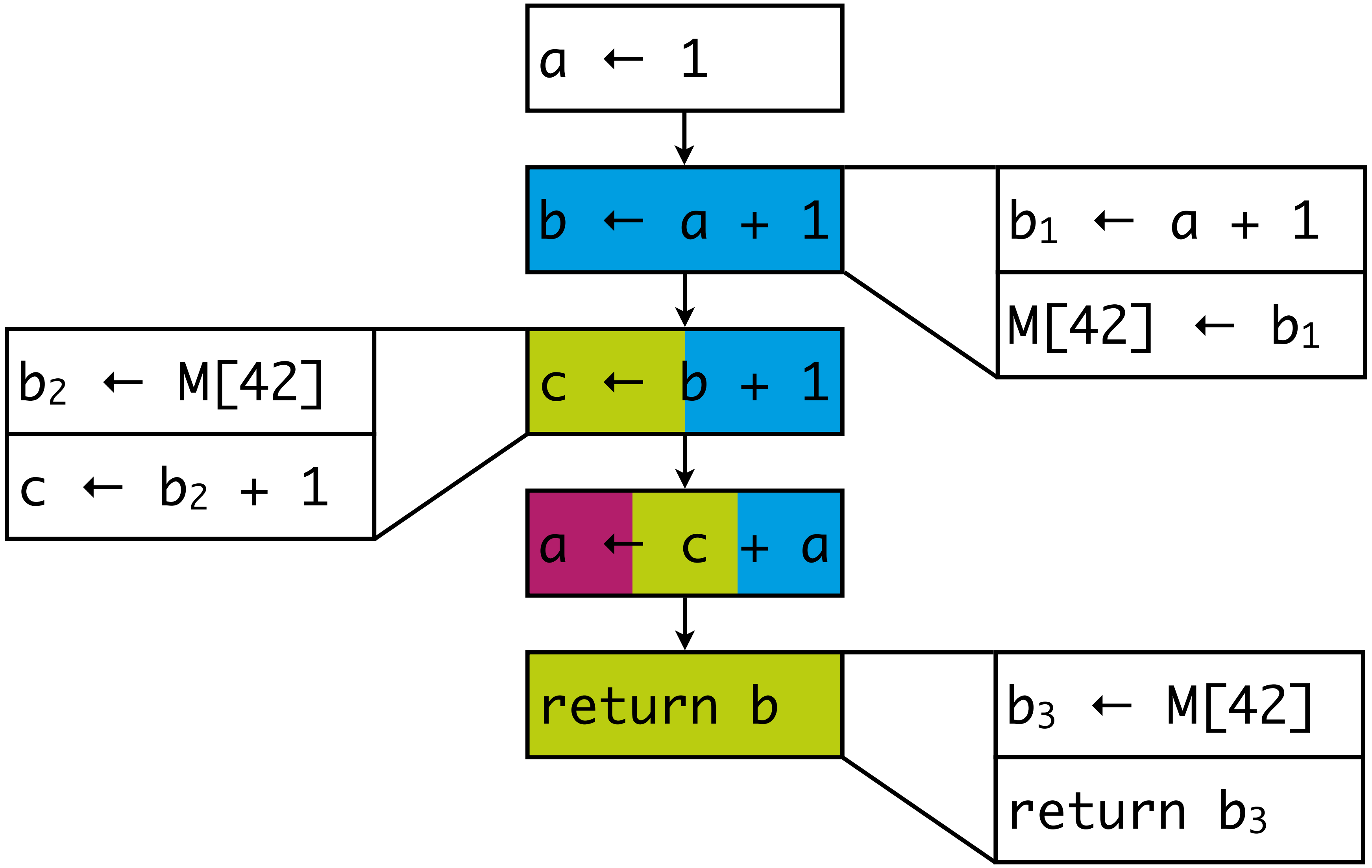


Spilling

example

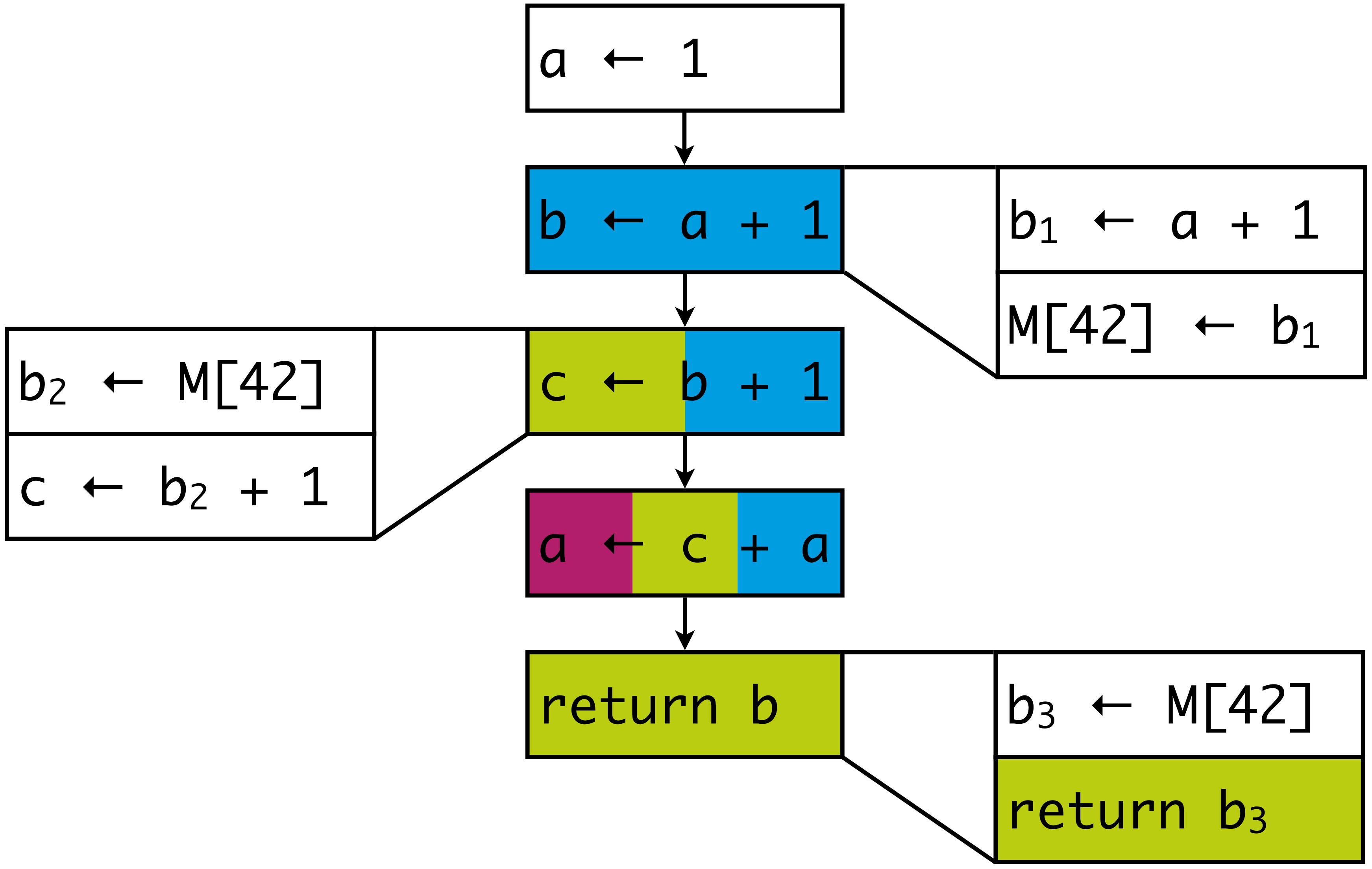


Spilling
example



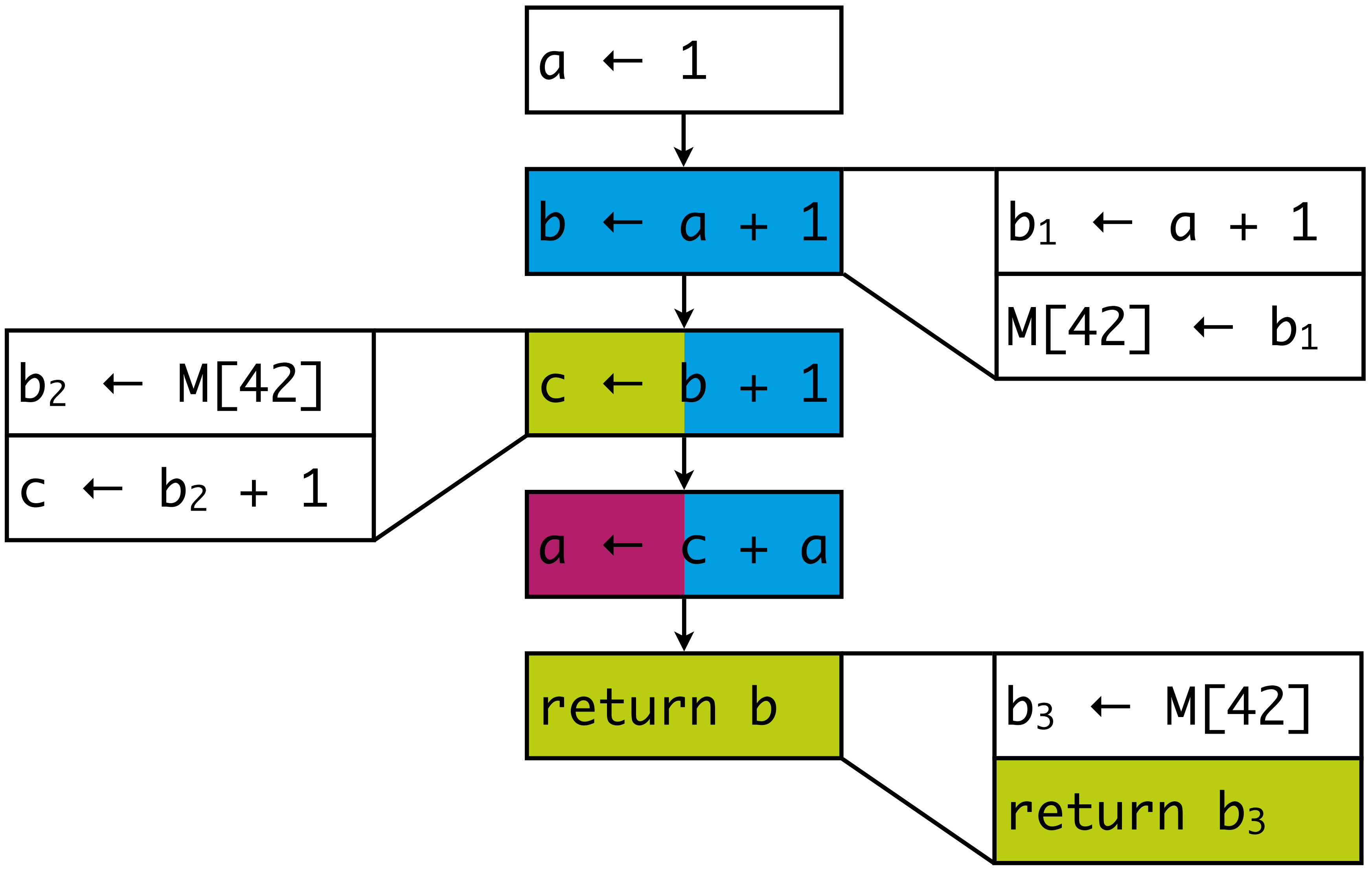
Spilling

example

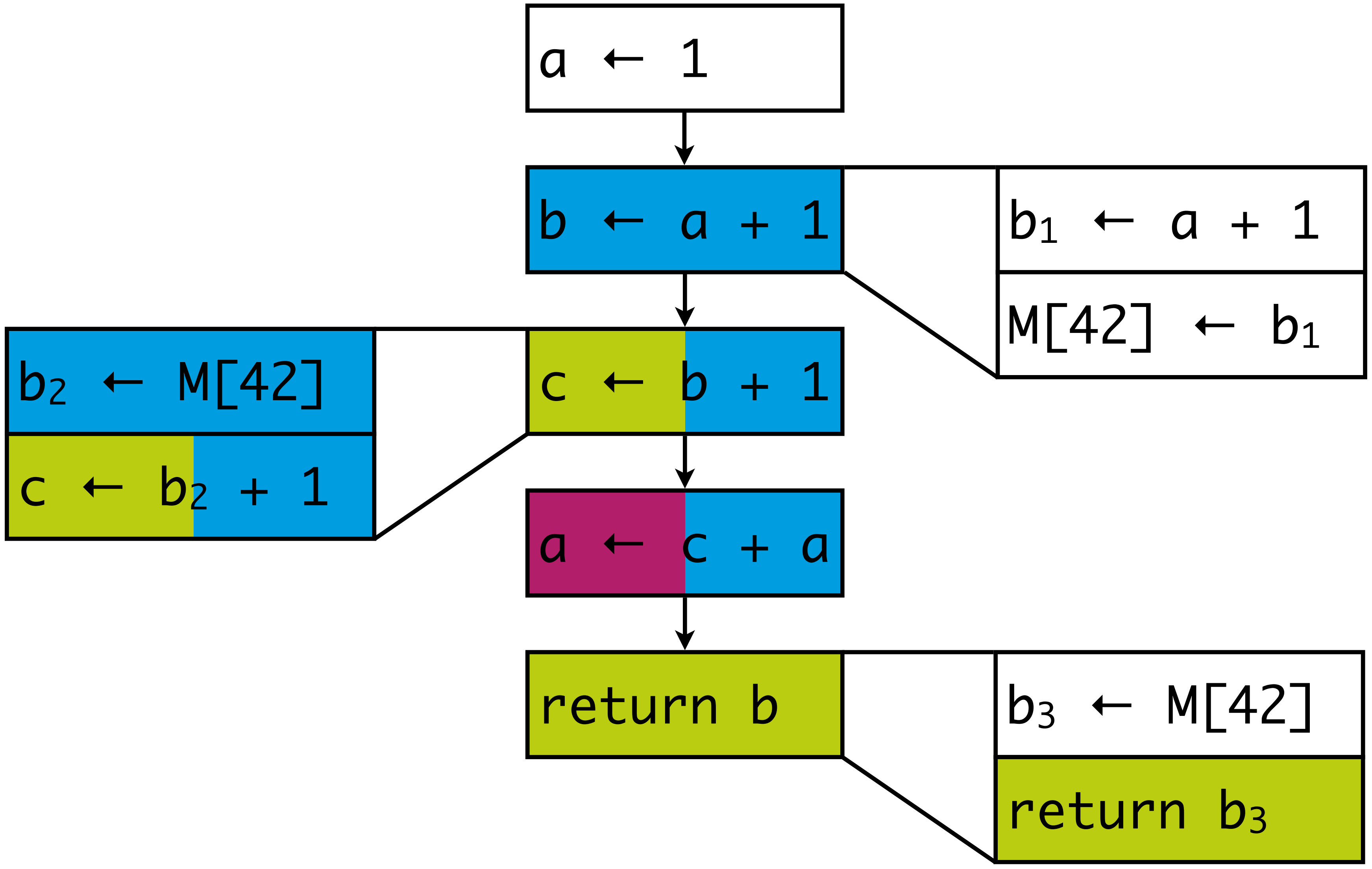


Spilling

example

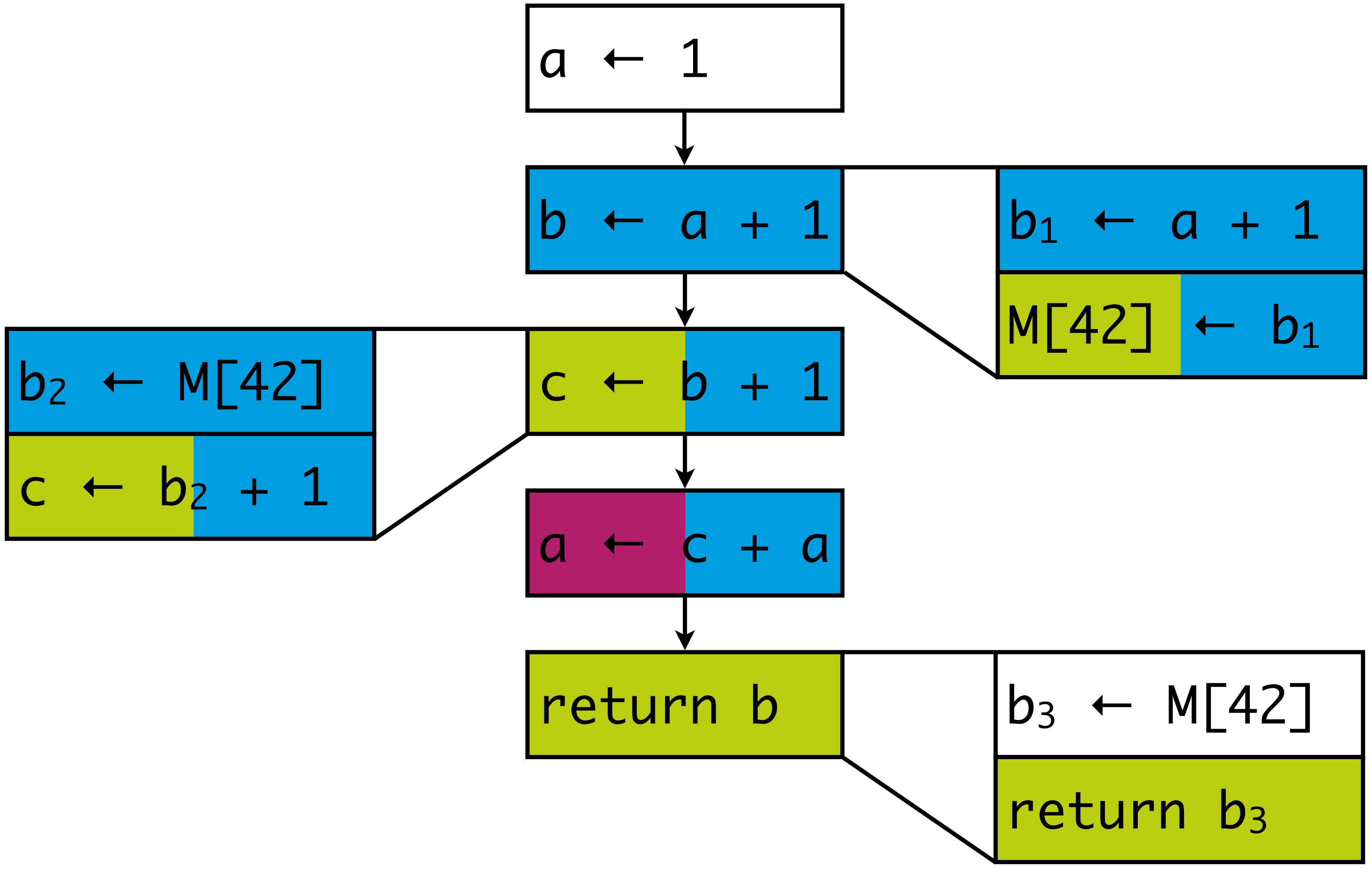


Spilling
example



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
```

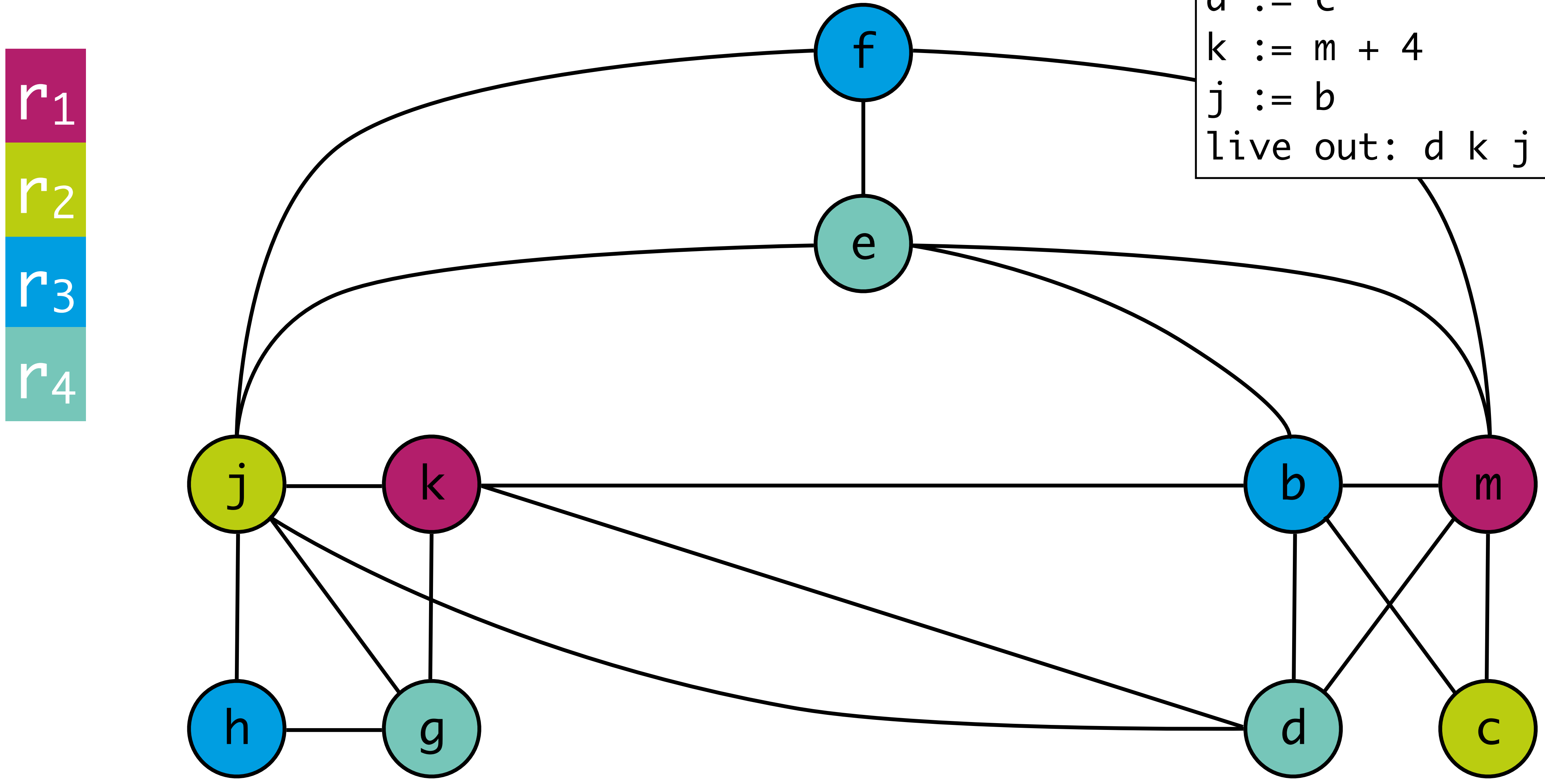
Coalescing

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

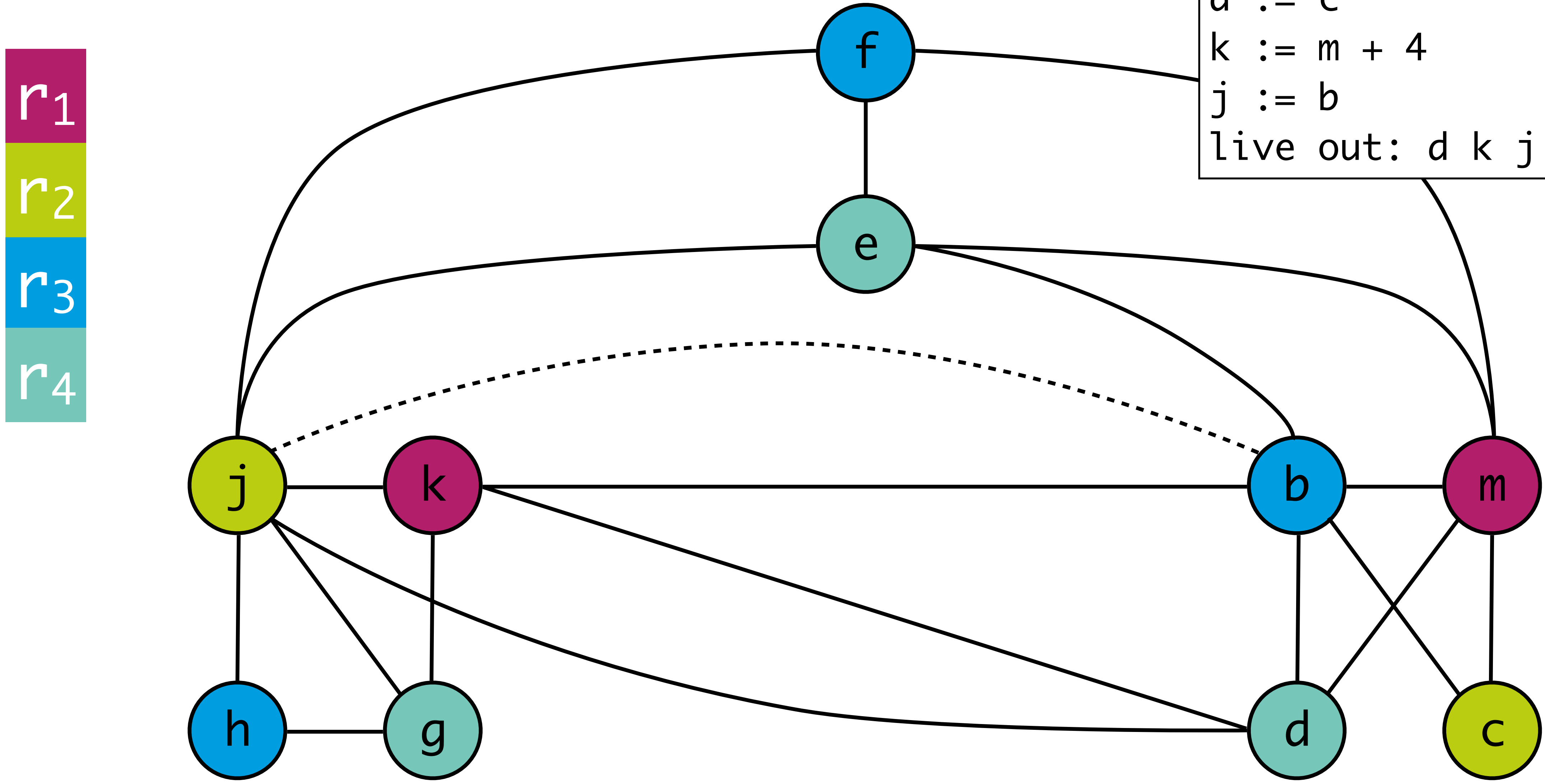
```
live-in: k j
g := mem[j + 12]
h := k - 1
f := g * h
e := mem[j + 8]
m := mem[j + 16]
b := mem[f]
c := e + 8
d := c
k := m + 4
j := b
live out: d k j
```



Recap: Graph Coloring

example

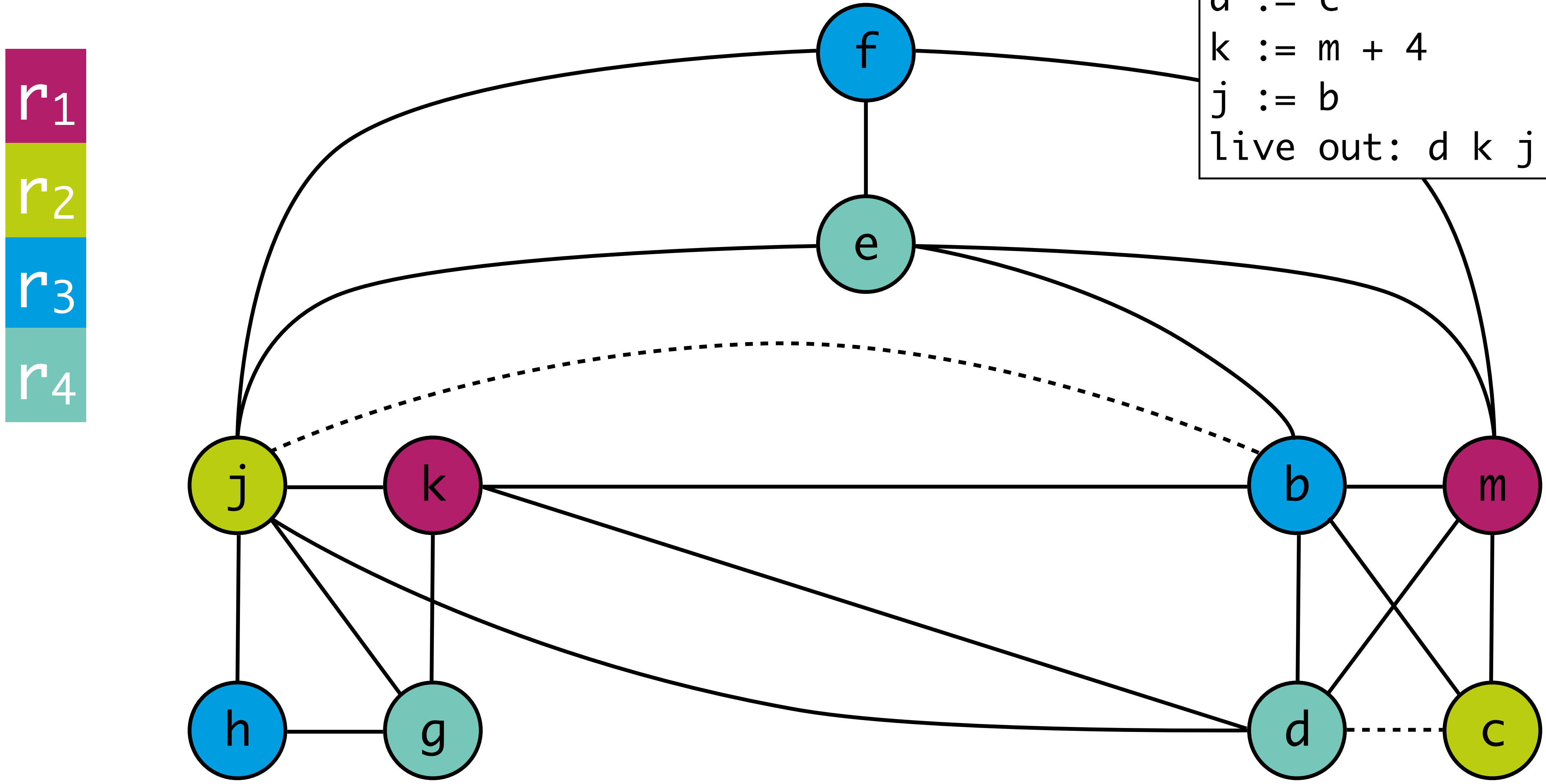
```
live-in: k j
g := mem[j + 12]
h := k - 1
f := g * h
e := mem[j + 8]
m := mem[j + 16]
b := mem[f]
c := e + 8
d := c
k := m + 4
j := b
live out: d k j
```



Recap: Graph Coloring

example

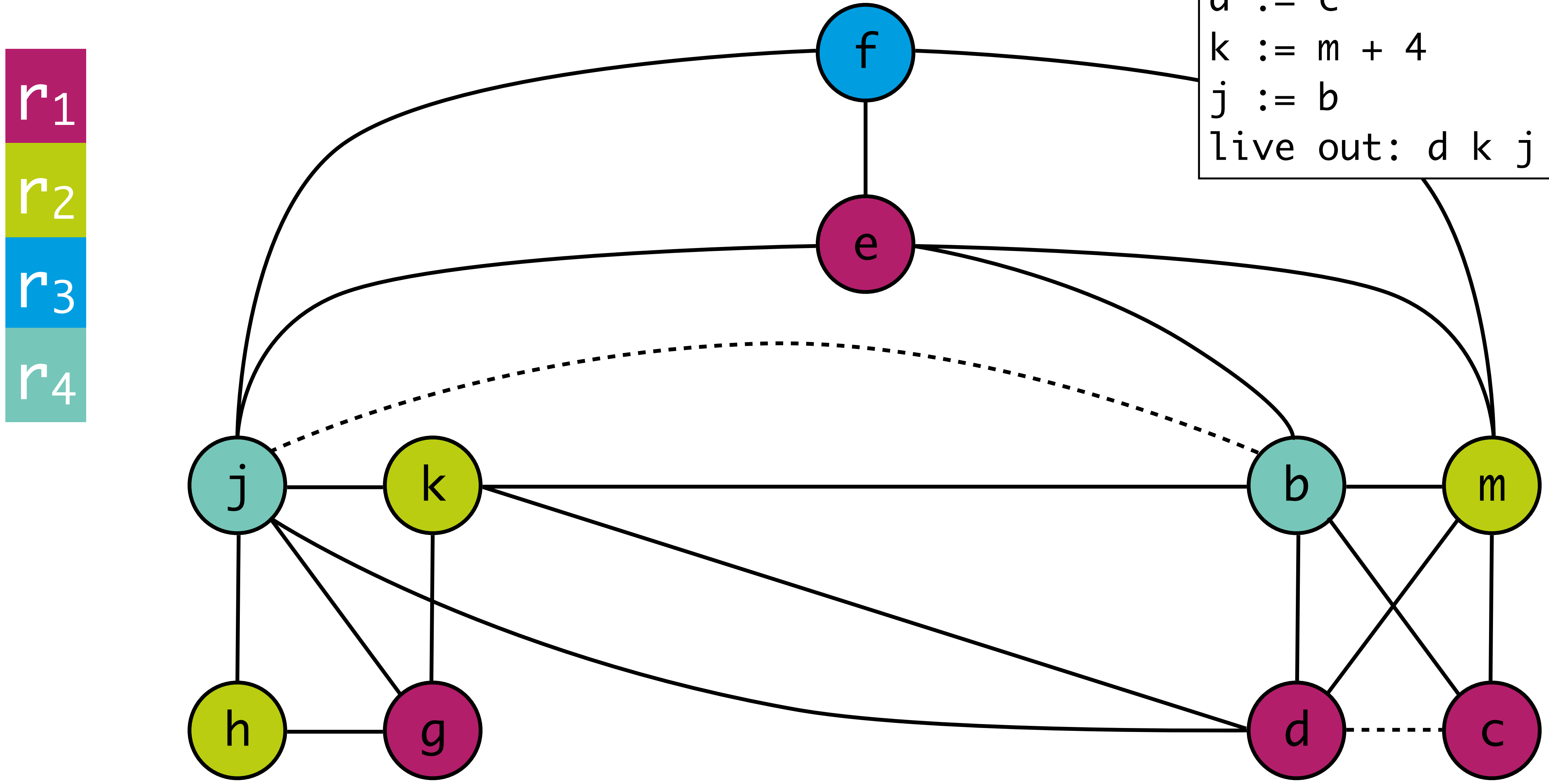
```
live-in: k j
g := mem[j + 12]
h := k - 1
f := g * h
e := mem[j + 8]
m := mem[j + 16]
b := mem[f]
c := e + 8
d := c
k := m + 4
j := b
live out: d k j
```



Coalescing

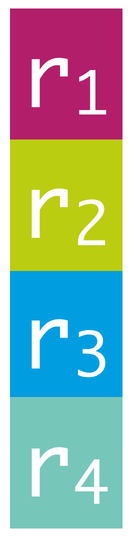
better solution

```
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
```

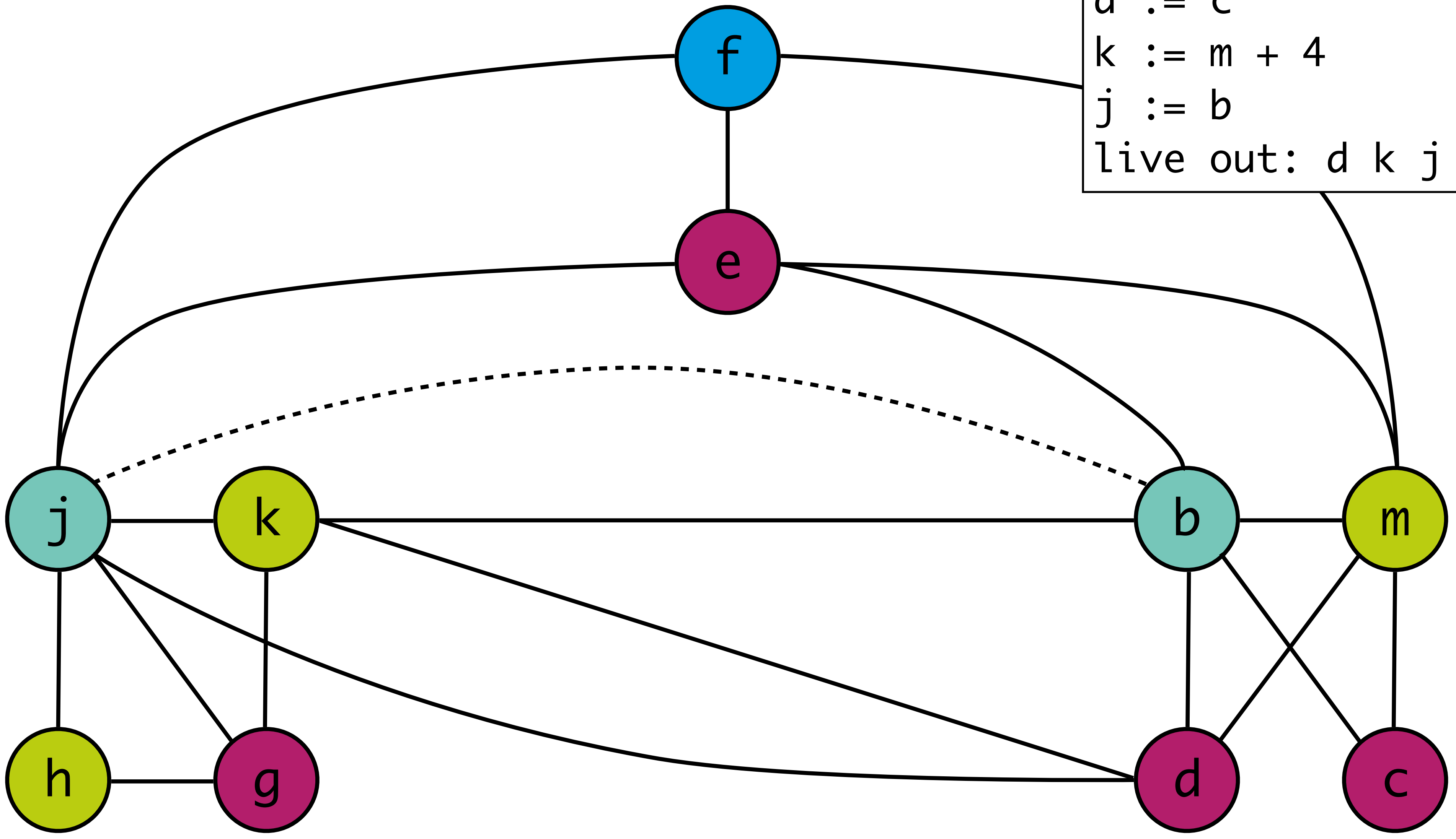


Coalescing

better solution

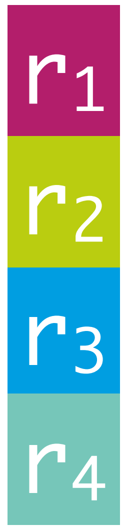


```
live-in: k j
g := mem[j + 12]
h := k - 1
f := g * h
e := mem[j + 8]
m := mem[j + 16]
b := mem[f]
c := e + 8
d := c
k := m + 4
j := b
live out: d k j
```

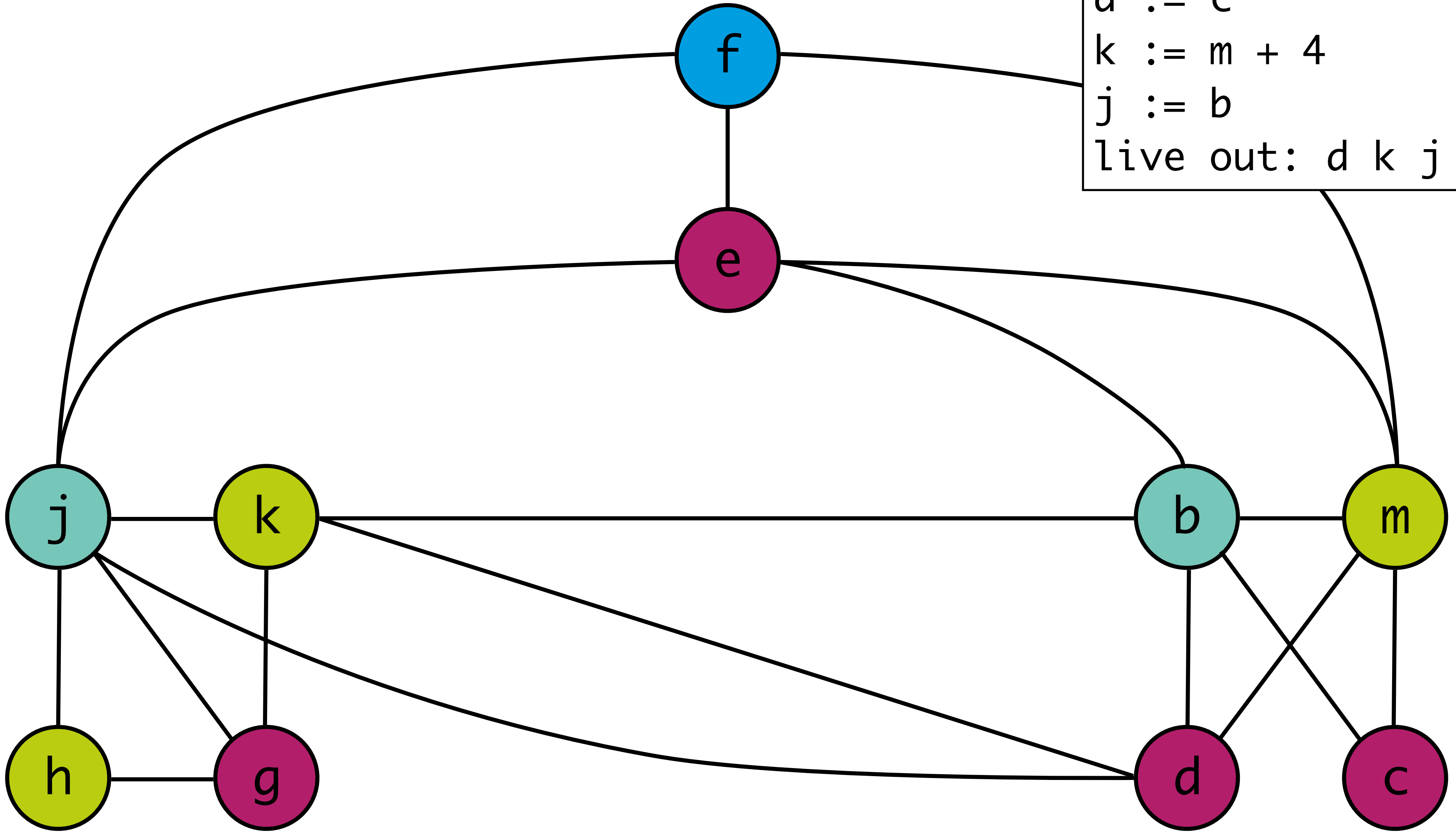


Coalescing

better solution



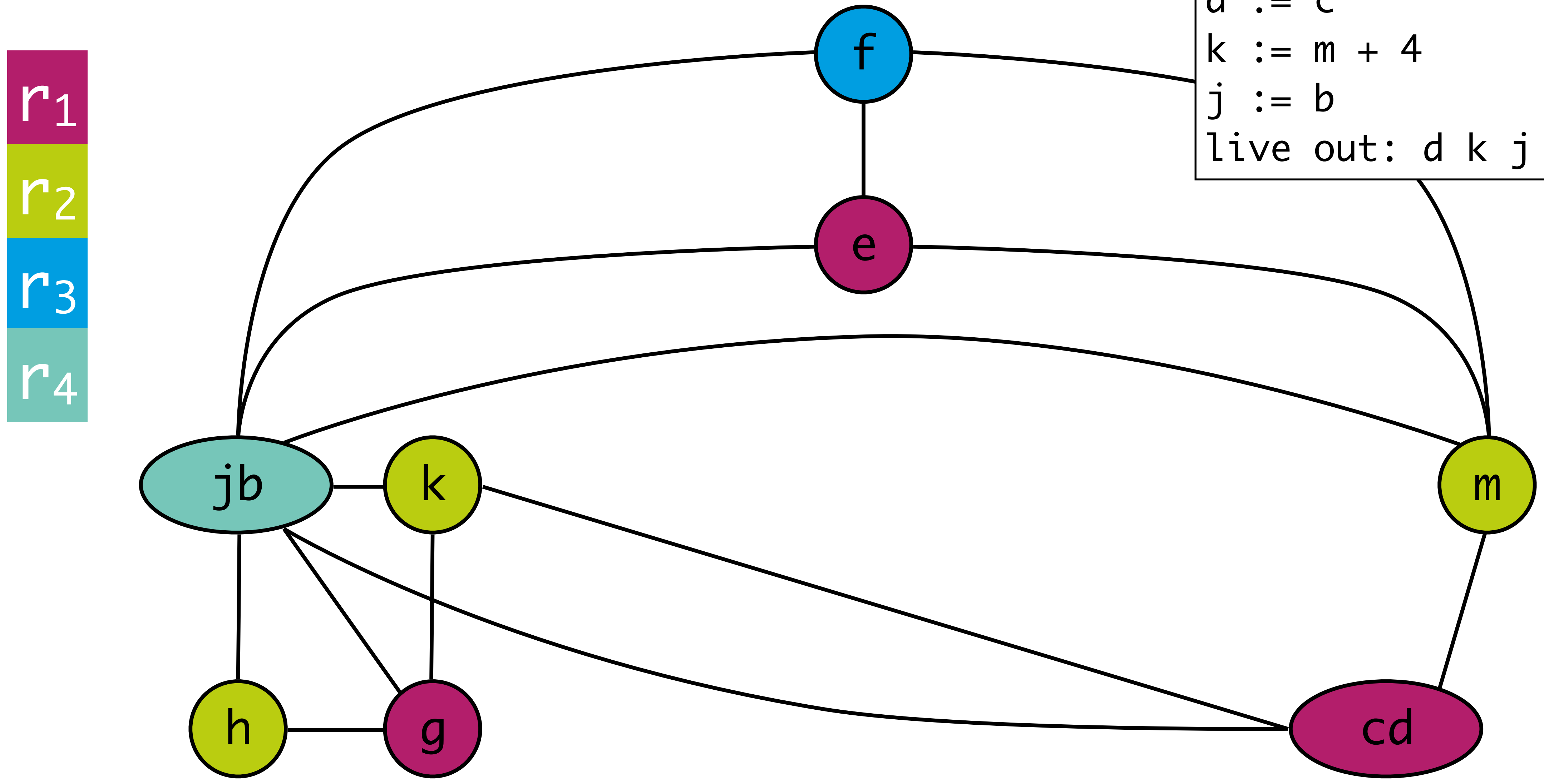
```
live-in: k j
g := mem[j + 12]
h := k - 1
f := g * h
e := mem[j + 8]
m := mem[j + 16]
b := mem[f]
c := e + 8
d := c
k := m + 4
j := b
live out: d k j
```



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

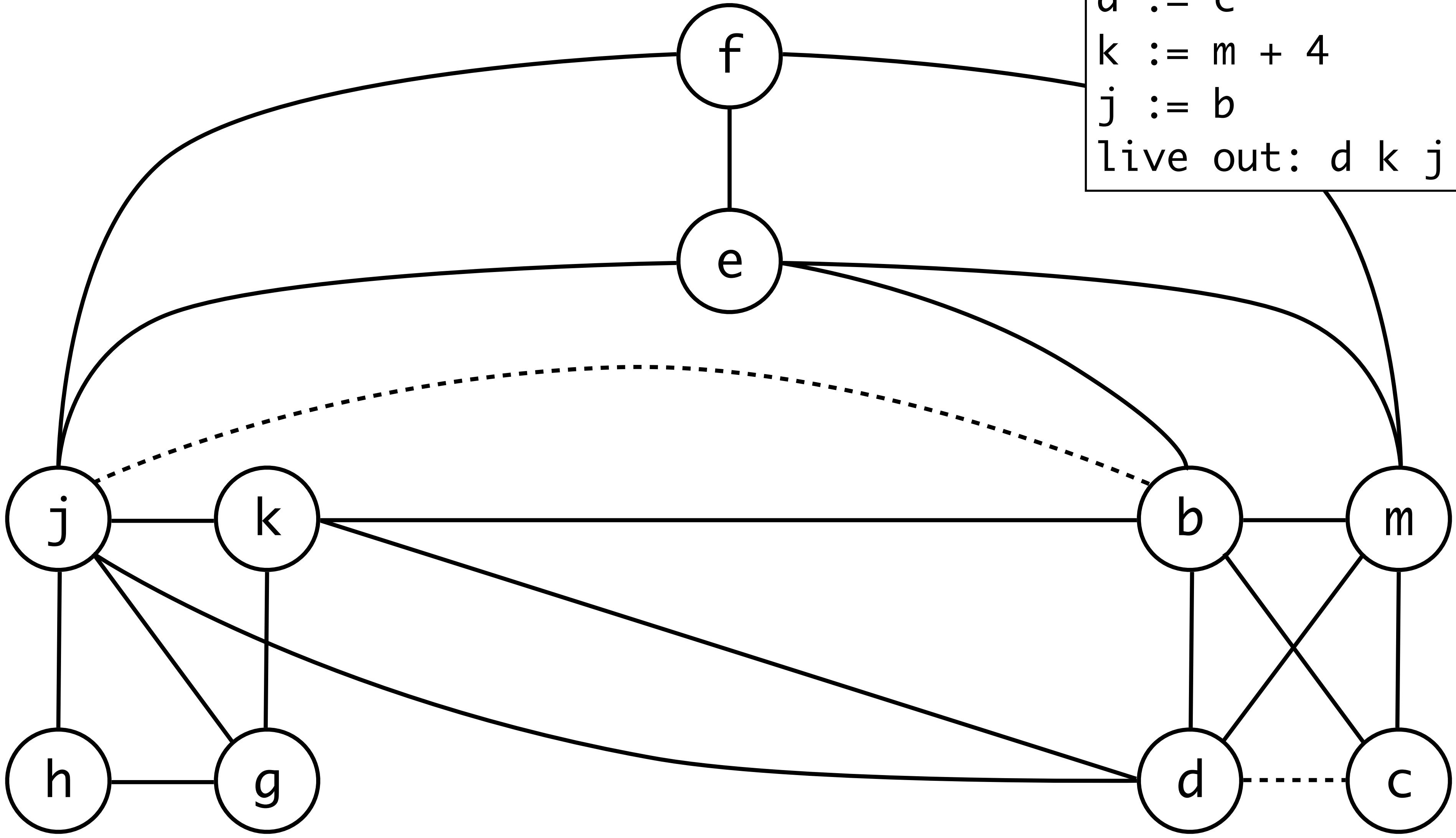
r1

r2

r3

r4

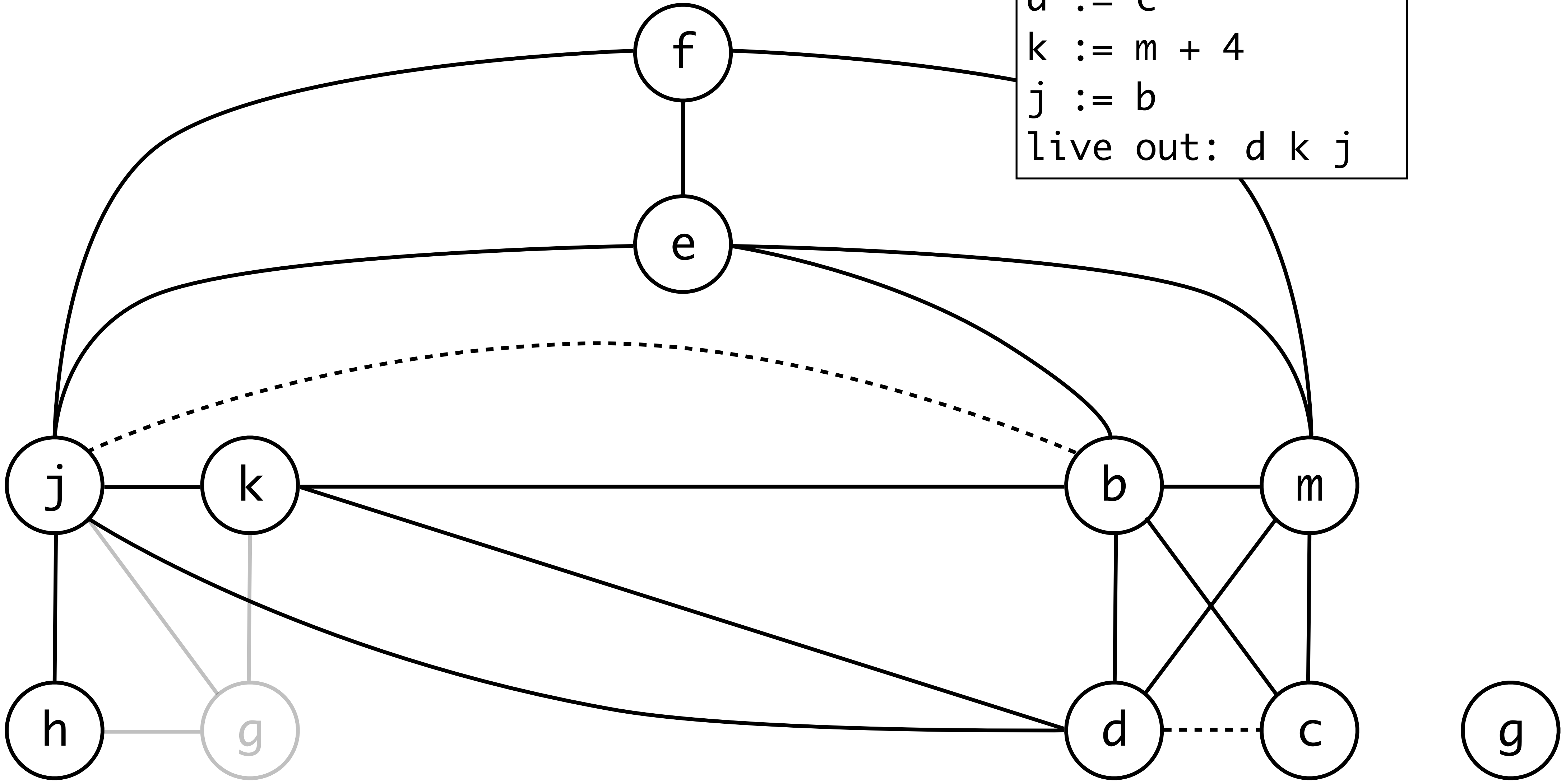
```
live-in: k j
g := mem[j + 12]
h := k - 1
f := g * h
e := mem[j + 8]
m := mem[j + 16]
b := mem[f]
c := e + 8
d := c
k := m + 4
j := b
live out: d k j
```



Coalescing

example

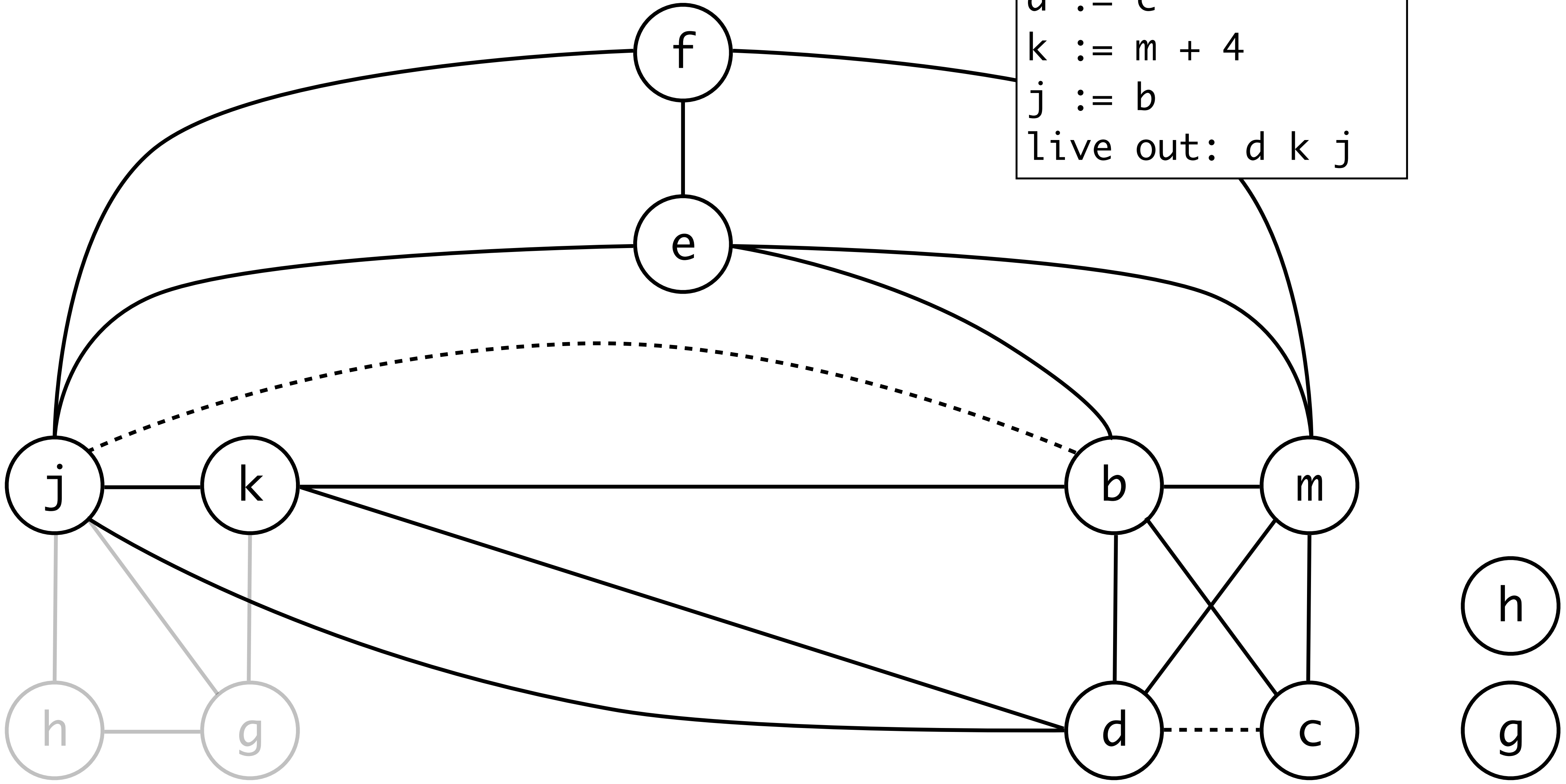
```
live-in: k j
g  := mem[j + 12]
h  := k - 1
f  := g * h
e  := mem[j + 8]
m := mem[j + 16]
b  := mem[f]
c  := e + 8
d  := c
k  := m + 4
j  := b
live out: d k j
```



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
```

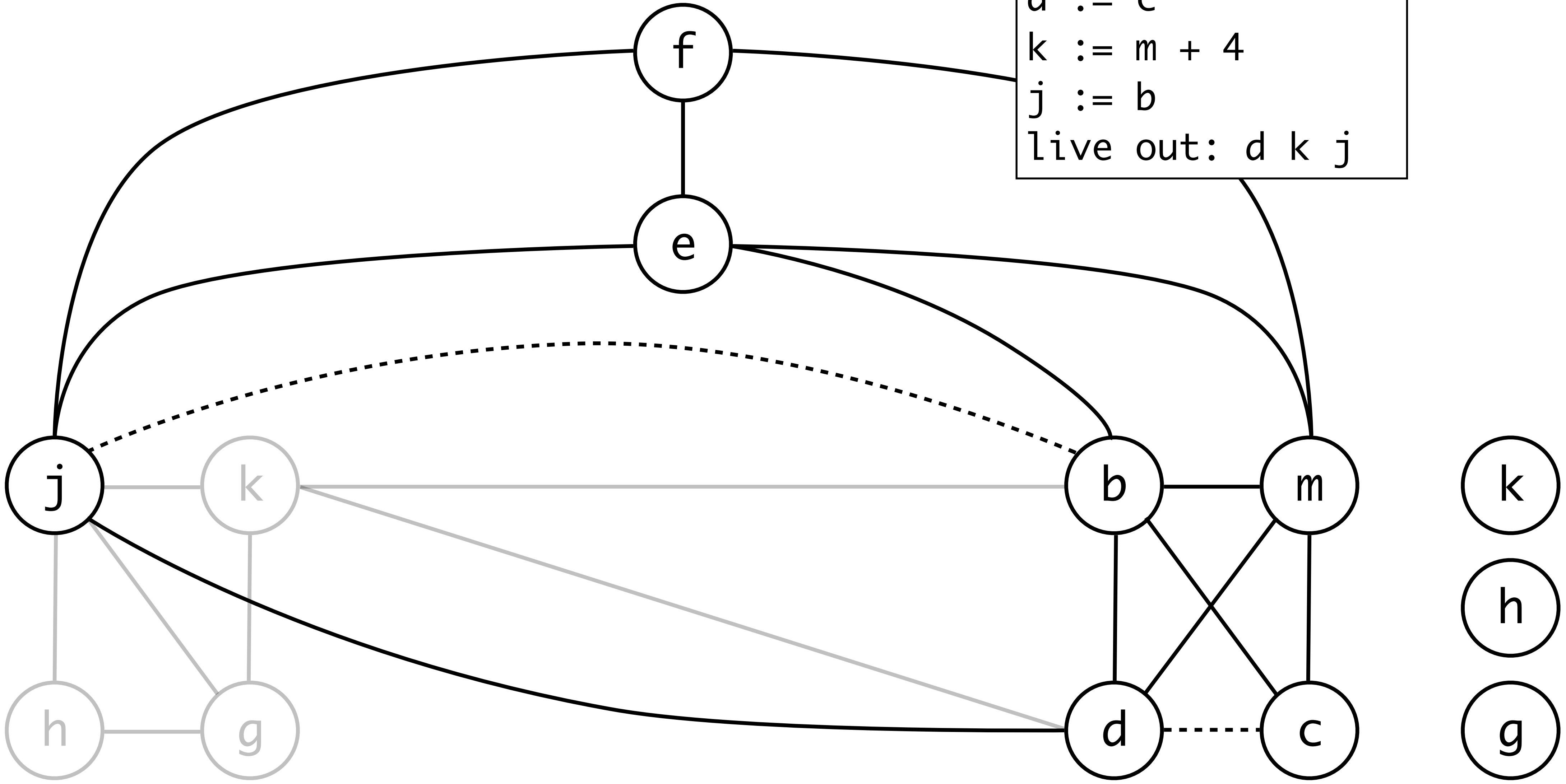


Coalescing

example

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

example

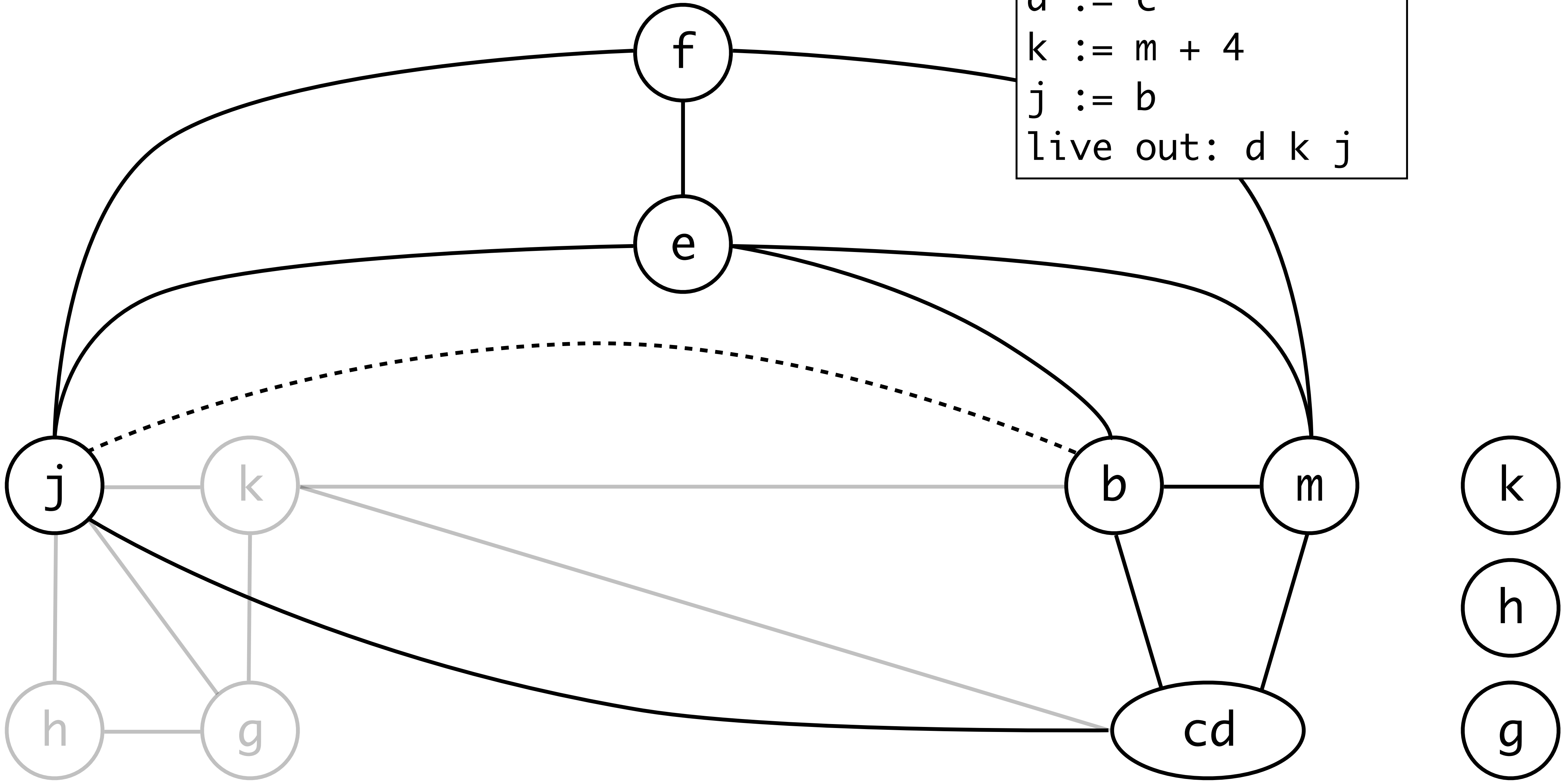
```
live-in: k j
g := mem[j + 12]
h := k - 1
f := g * h
e := mem[j + 8]
m := mem[j + 16]
b := mem[f]
c := e + 8
d := c
k := m + 4
j := b
live out: d k j
```

r_1

r_2

r_3

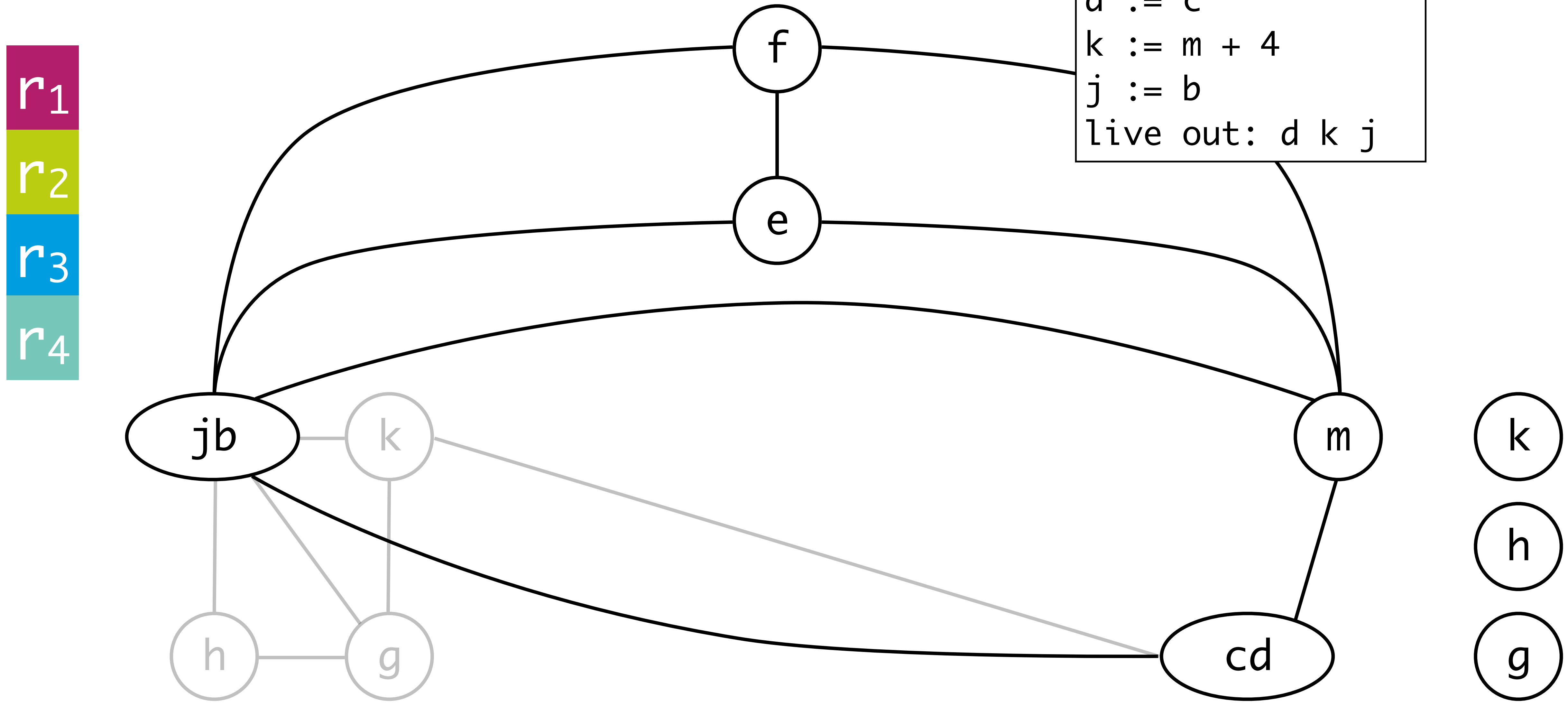
r_4



Coalescing

example

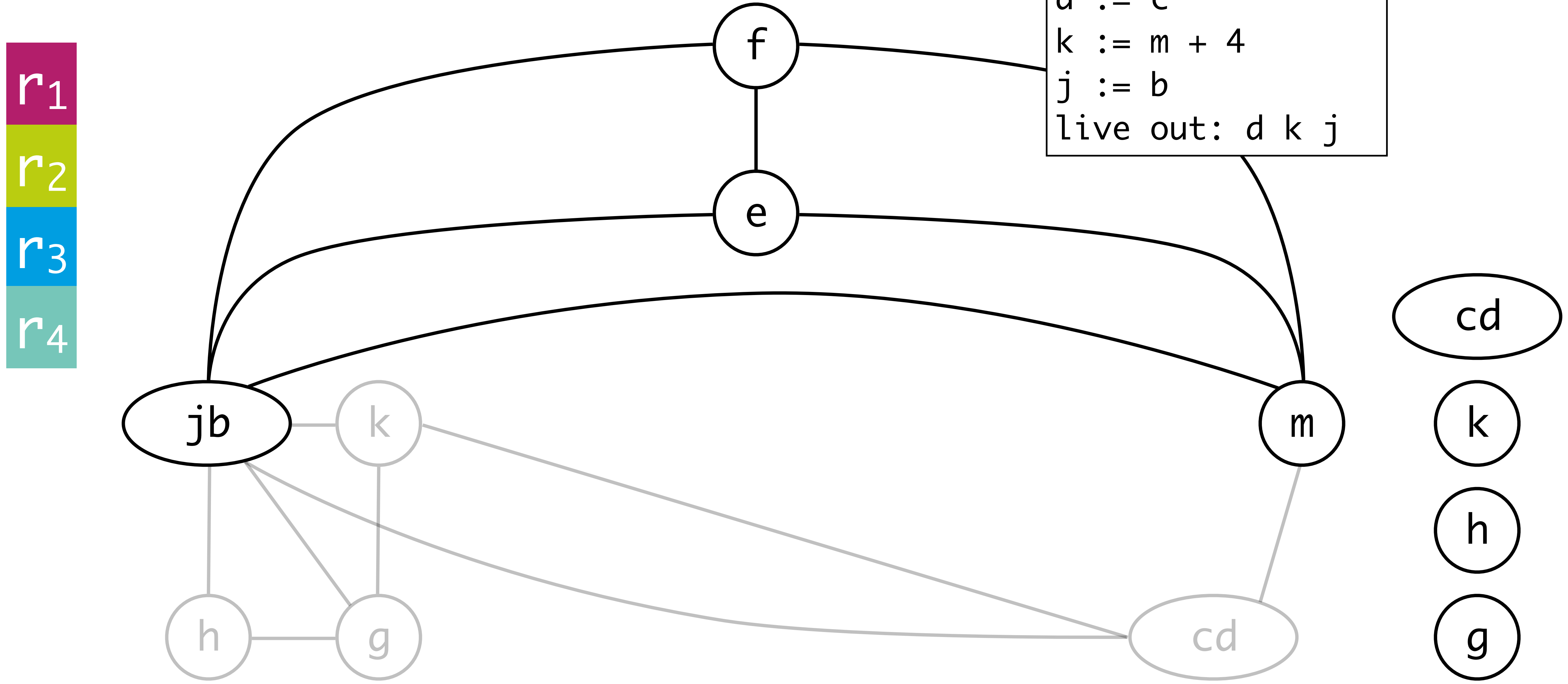
```
live-in: k j
g  := mem[j + 12]
h  := k - 1
f  := g * h
e  := mem[j + 8]
m := mem[j + 16]
b  := mem[f]
c  := e + 8
d  := c
k  := m + 4
j  := b
live out: d k j
```



Coalescing

example

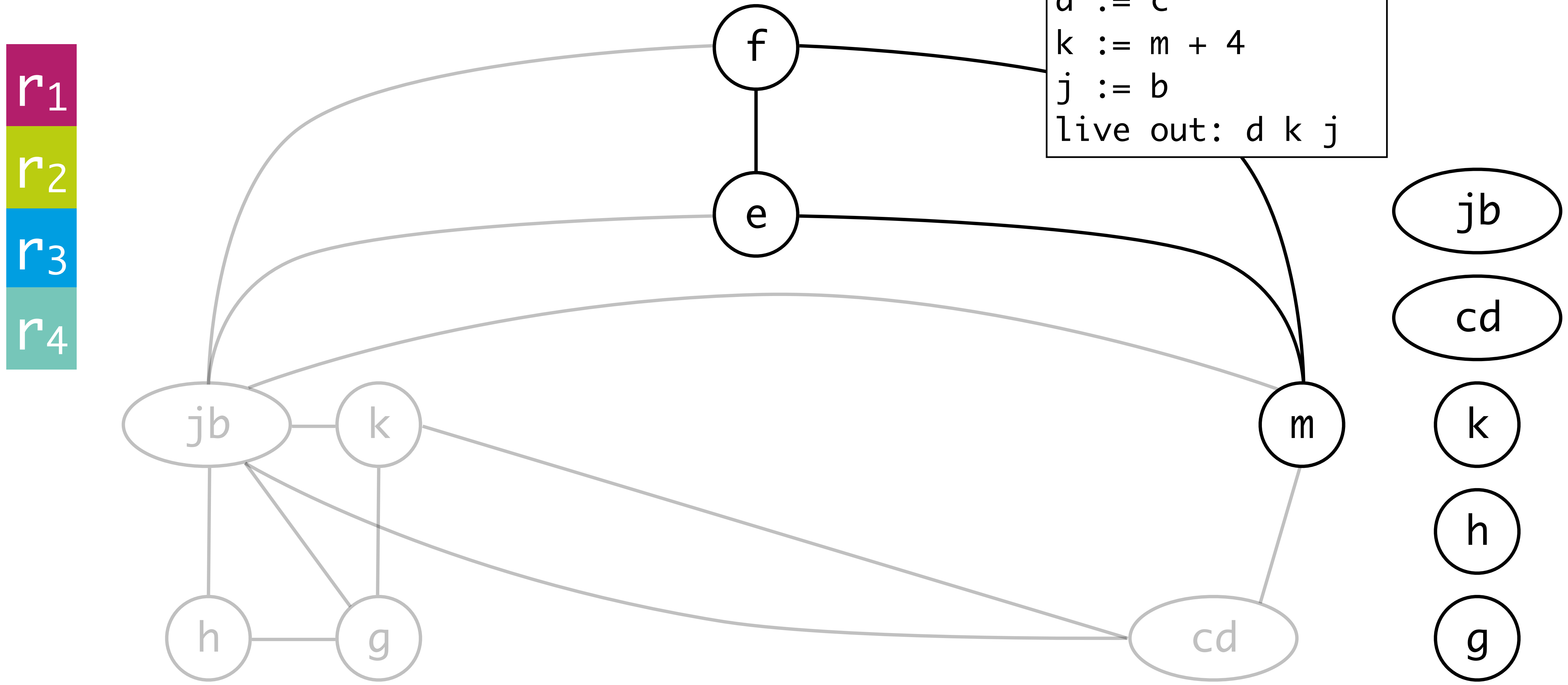
```
live-in: k j
g  := mem[j + 12]
h  := k - 1
f  := g * h
e  := mem[j + 8]
m := mem[j + 16]
b  := mem[f]
c  := e + 8
d  := c
k  := m + 4
j  := b
live out: d k j
```



Coalescing

example

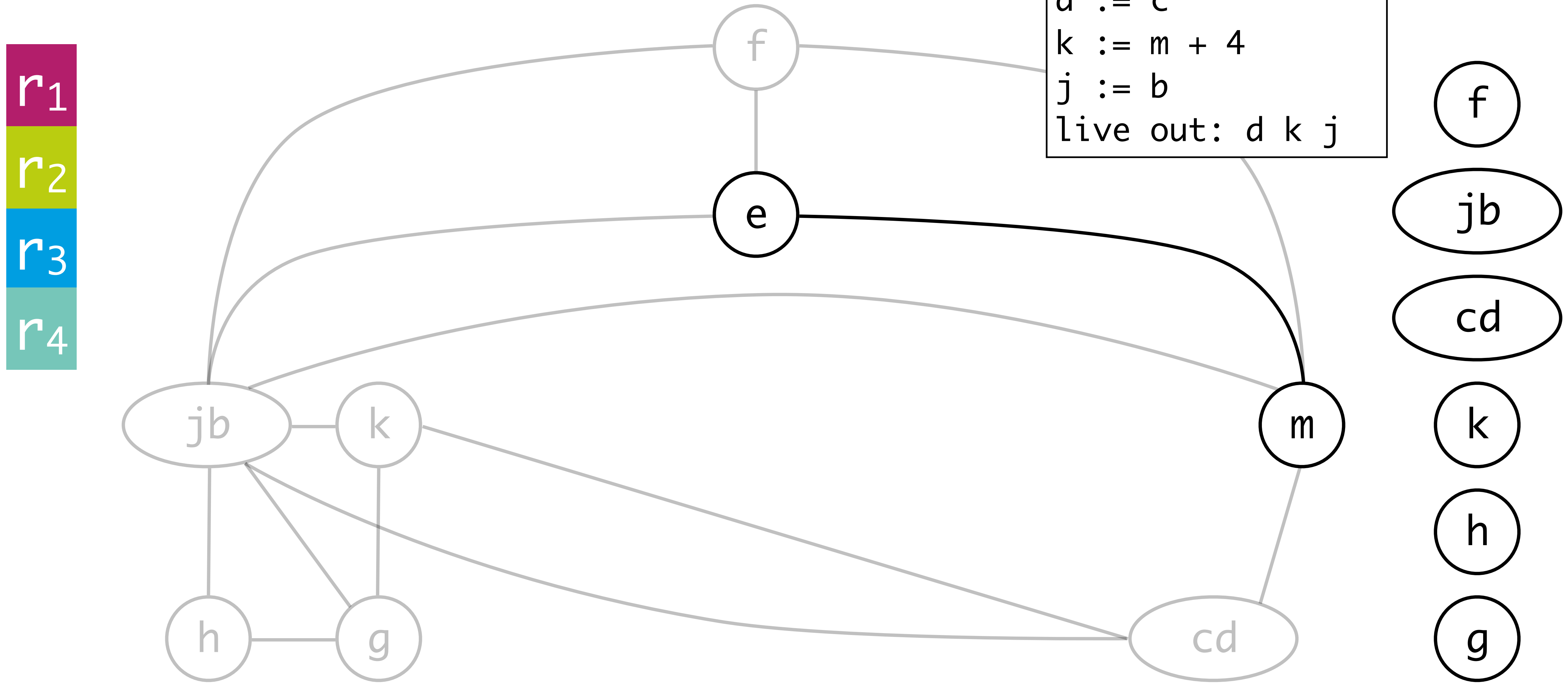
```
live-in: k j
g := mem[j + 12]
h := k - 1
f := g * h
e := mem[j + 8]
m := mem[j + 16]
b := mem[f]
c := e + 8
d := c
k := m + 4
j := b
live out: d k j
```



Coalescing

example

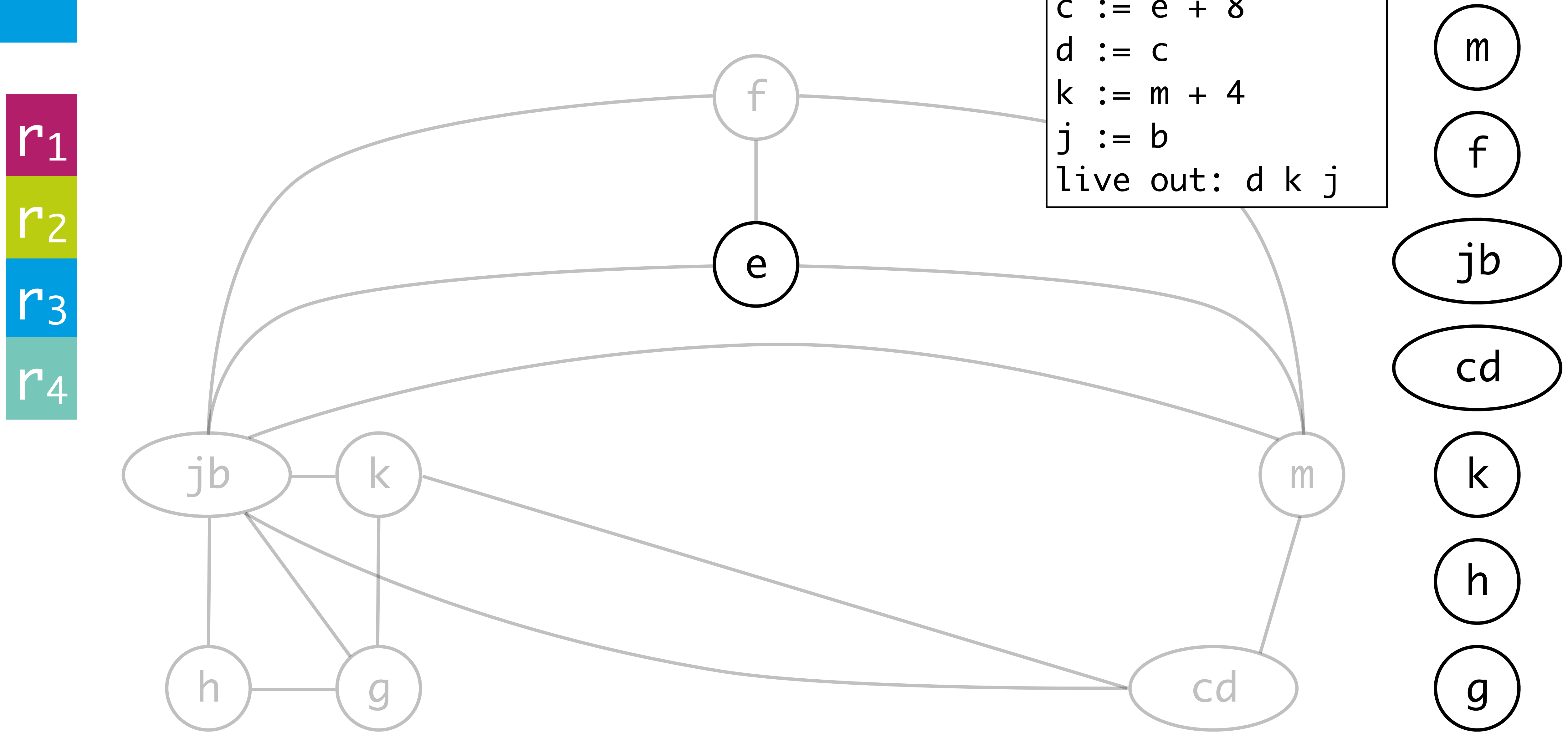
```
live-in: k j
g := mem[j + 12]
h := k - 1
f := g * h
e := mem[j + 8]
m := mem[j + 16]
b := mem[f]
c := e + 8
d := c
k := m + 4
j := b
live out: d k j
```



Coalescing

example

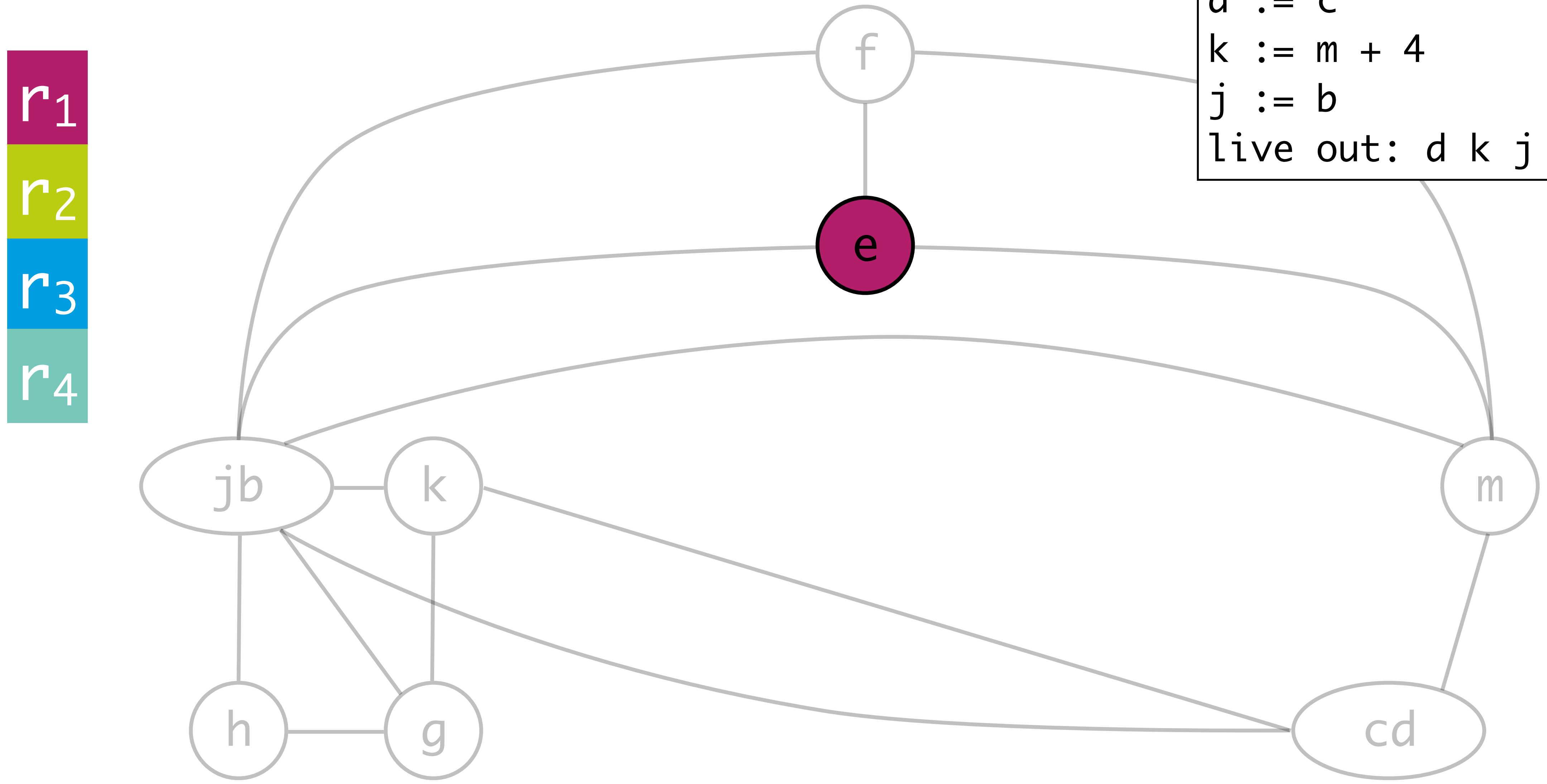
```
live-in: k j
g := mem[j + 12]
h := k - 1
f := g * h
e := mem[j + 8]
m := mem[j + 16]
b := mem[f]
c := e + 8
d := c
k := m + 4
j := b
live out: d k j
```

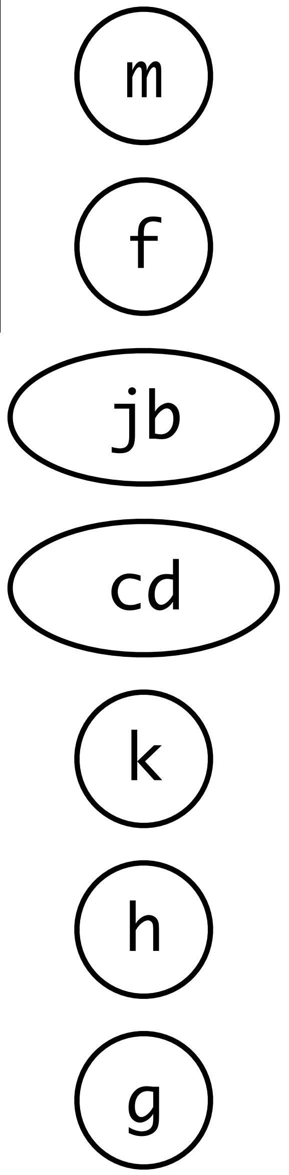


Coalescing

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
```

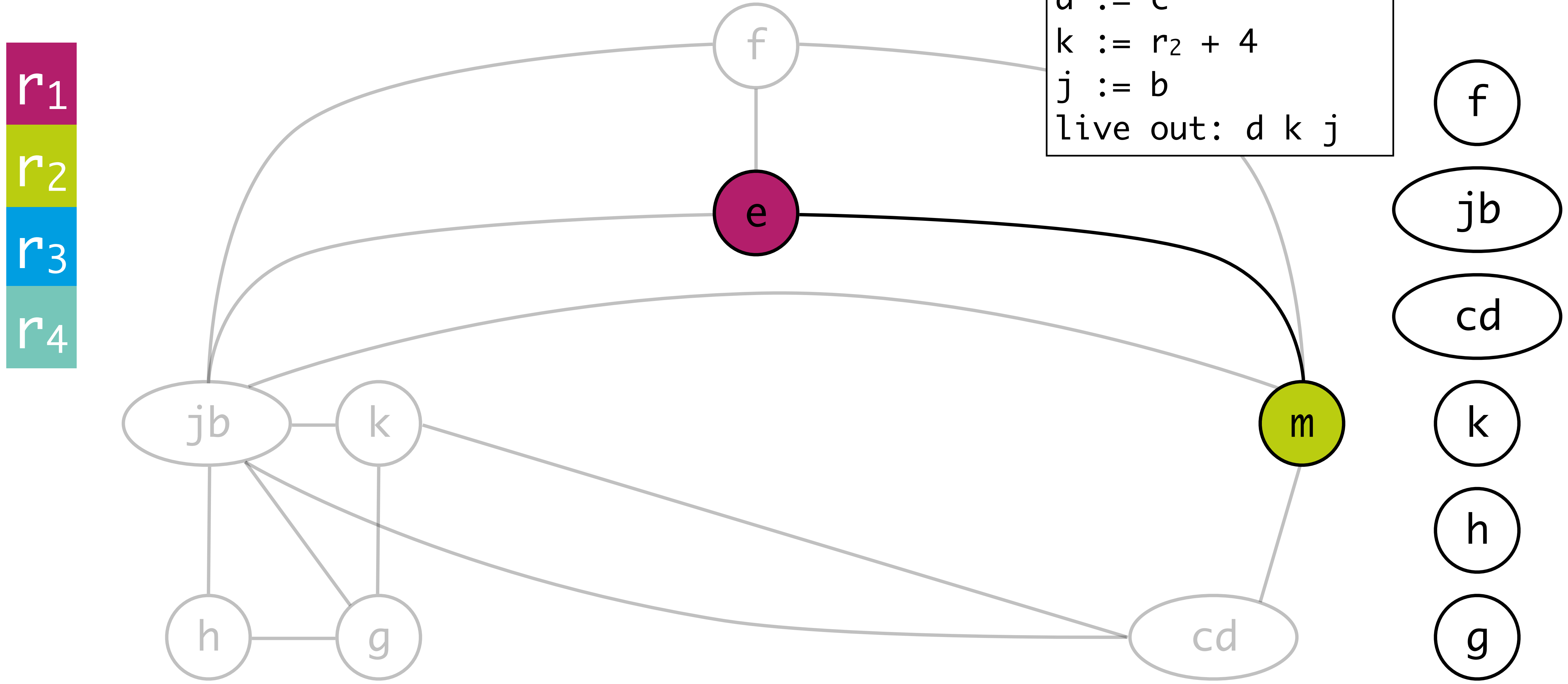




Coalescing

example

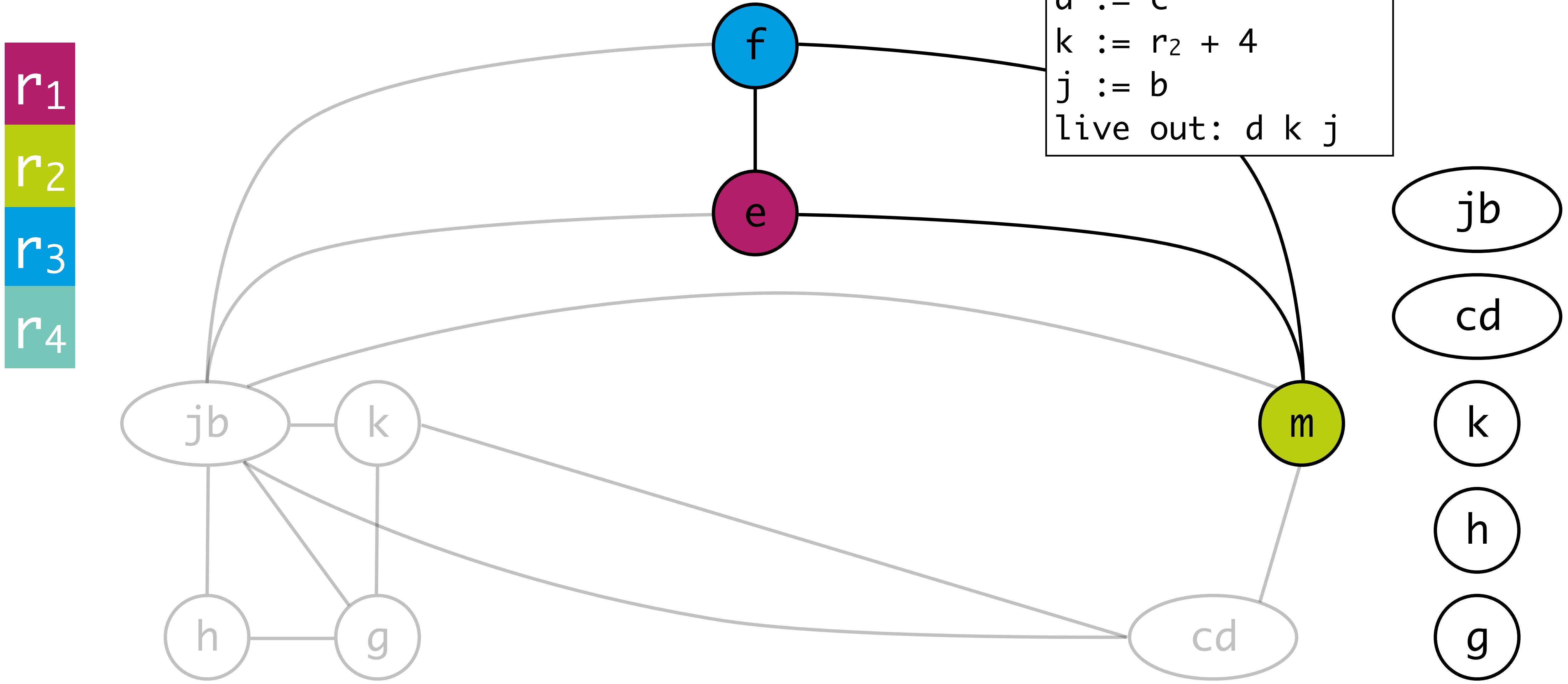
```
live-in: k j
g  := mem[j + 12]
h  := k - 1
f  := g * h
r1  := mem[j + 8]
r2 := mem[j + 16]
b  := mem[f]
c  := r1 + 8
d  := c
k  := r2 + 4
j  := b
live out: d k j
```



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
```

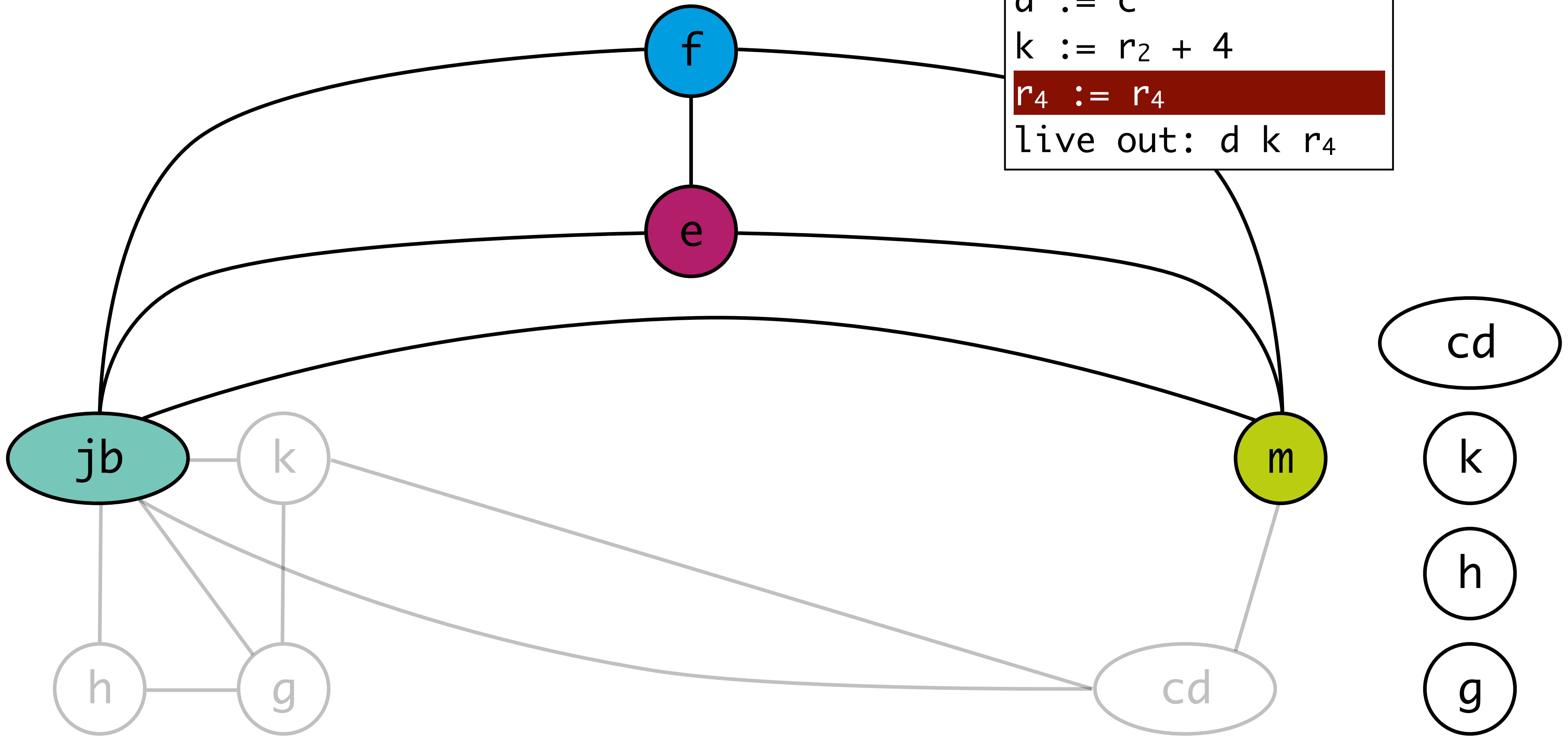


Coalescing

example

r_1
r_2
r_3
r_4

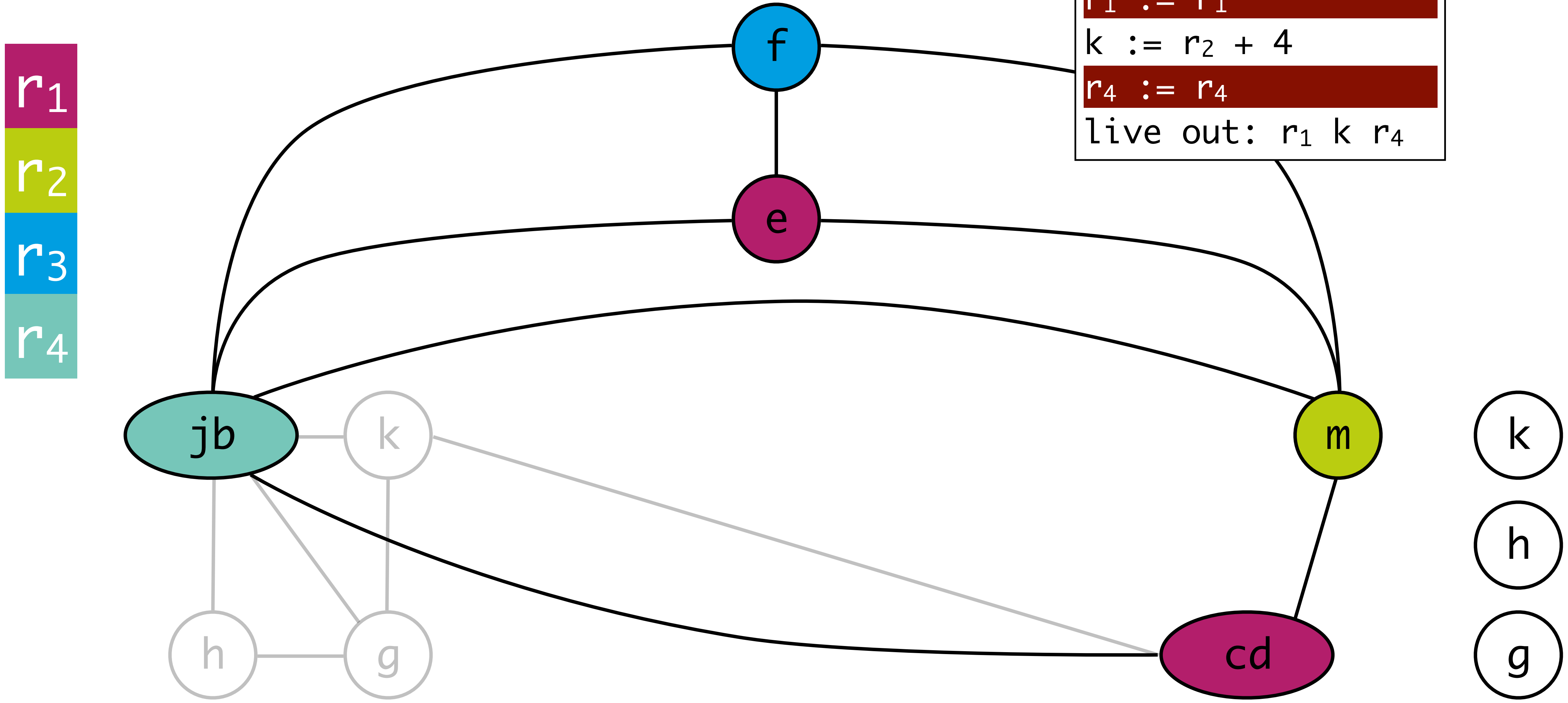
```
live-in: k r4
g  := mem[r4 + 12]
h  := k - 1
r3  := g * h
r1  := mem[r4 + 8]
r2 := mem[r4 + 16]
b  := mem[r3]
c  := r1 + 8
d  := c
k  := r2 + 4
r4  := r4
live out: d k r4
```



Coalescing

example

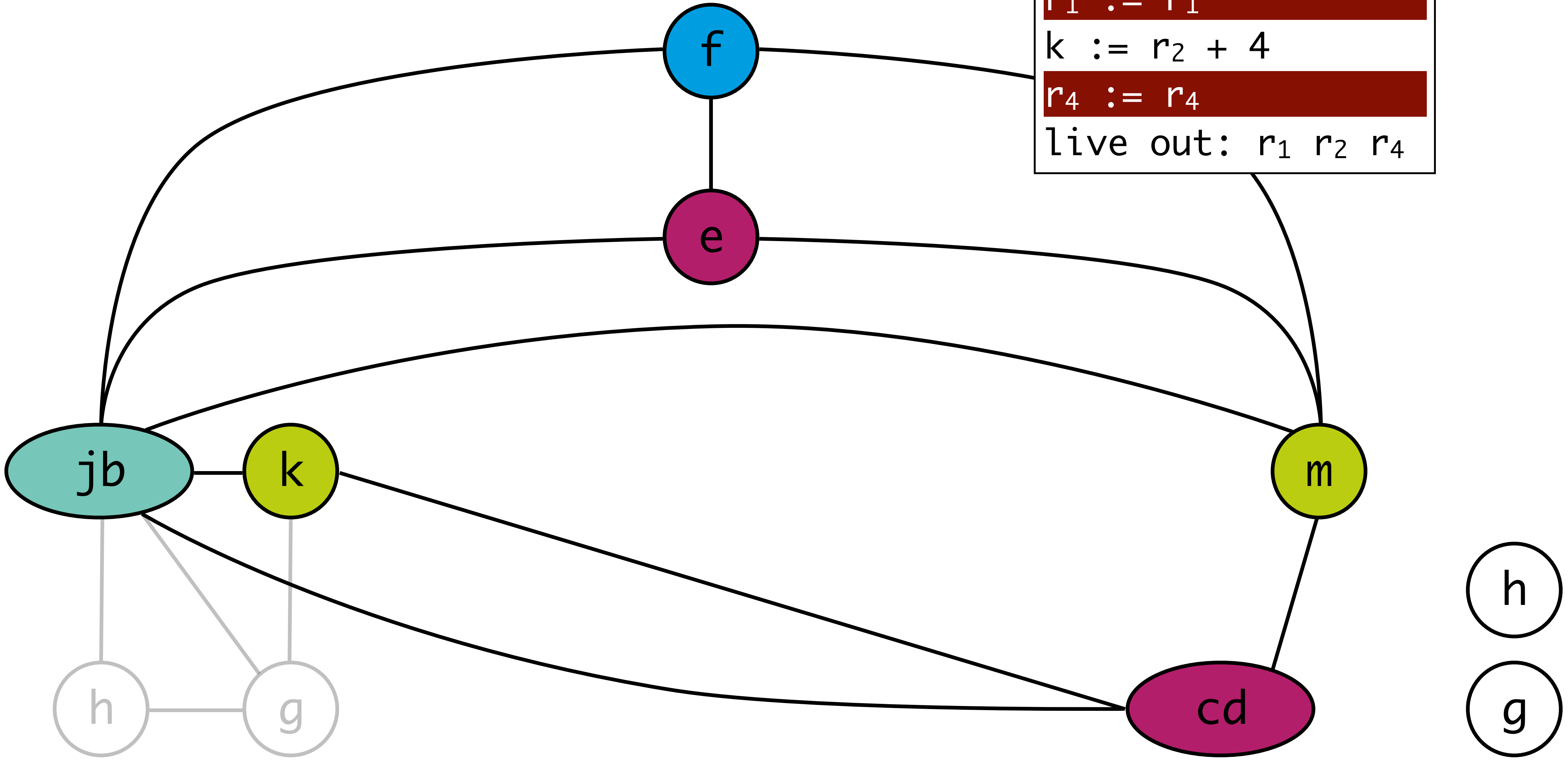
```
live-in: k r4
g  := mem[r4 + 12]
h  := k - 1
r3  := g * h
r1  := mem[r4 + 8]
r2 := mem[r4 + 16]
b  := mem[r3]
r1  := r1 + 8
r1  := r1
k  := r2 + 4
r4  := r4
live out: r1 k r4
```



Coalescing

example

r1
r2
r3
r4

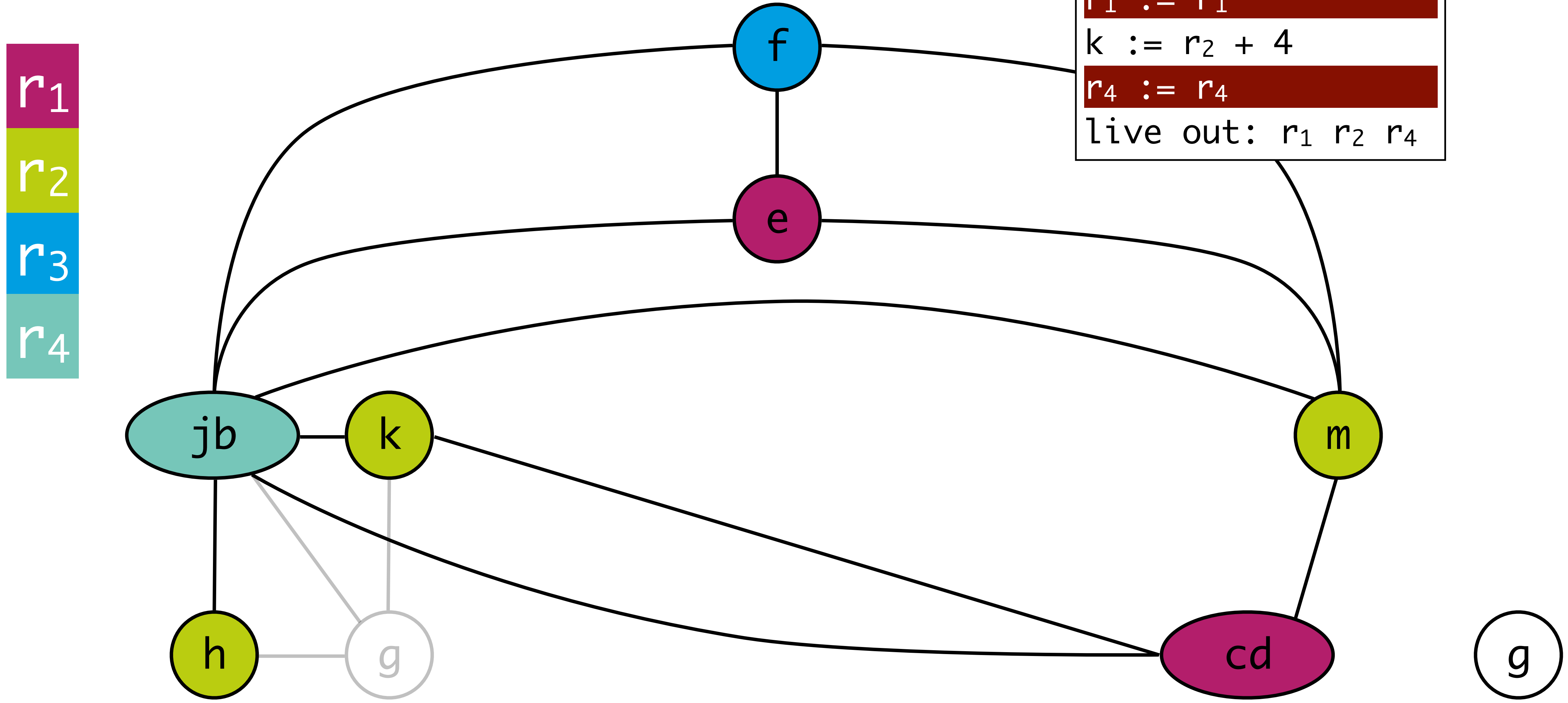


```
live-in: r2 r4
g  := mem[r4 + 12]
h  := r2 - 1
r3  := g * h
r1  := mem[r4 + 8]
r2 := mem[r4 + 16]
b  := mem[r3]
r1  := r1 + 8
r1  := r1
k  := r2 + 4
r4  := r4
live out: r1 r2 r4
```

Coalescing

example

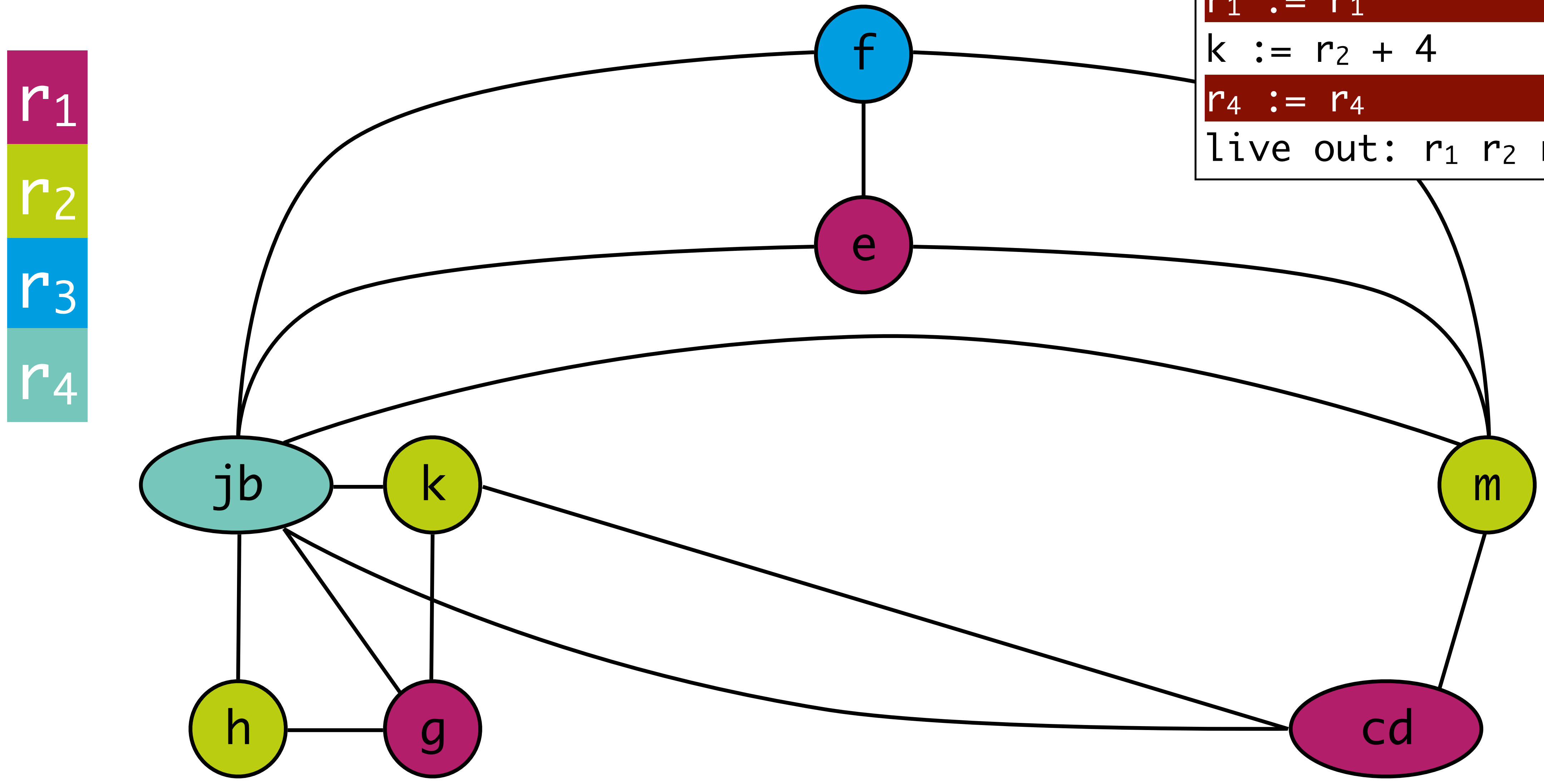
```
live-in: r2 r4
g  := mem[r4 + 12]
r2  := r2 - 1
r3  := g * r2
r1  := mem[r4 + 8]
r2 := mem[r4 + 16]
b  := mem[r3]
r1  := r1 + 8
r1  := r1
k  := r2 + 4
r4  := r4
live out: r1 r2 r4
```



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

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

```
mov  ECX 21
mov  EDX 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 ECX
add  EAX EDX
pop  EBP
ret
```

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;
}
```

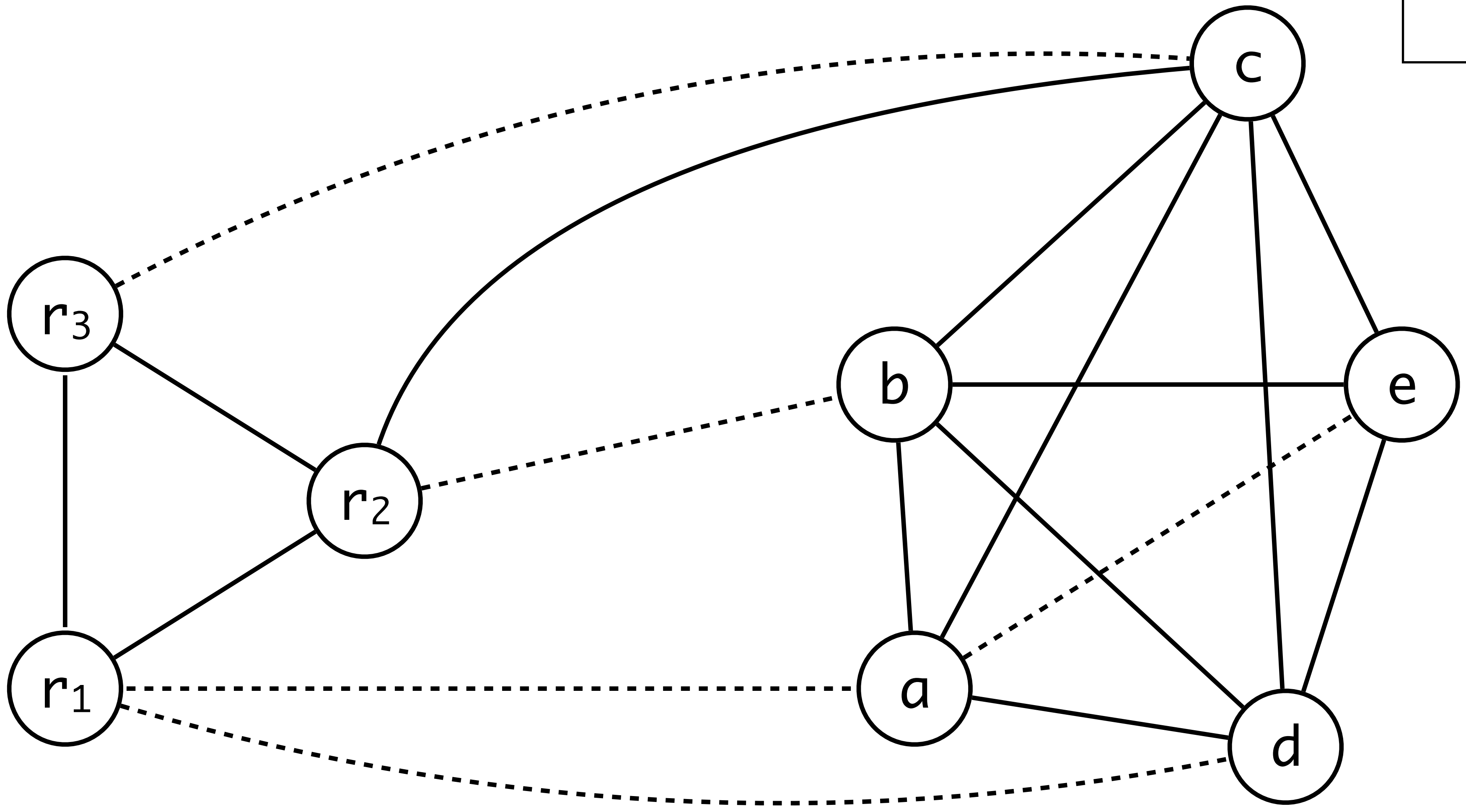
```
enter : c ← r3    // callee-save
        a ← r1    // caller-save
        b ← r2    // caller-save
        d ← 0
        e ← a
loop :  d ← d + b
        e ← e - 1
        if e > 0 goto loop
        r1 ← d
        r3 ← c
        return (r1, r3 live out)
```

machine has 3 registers

Pre-Colored Nodes

example

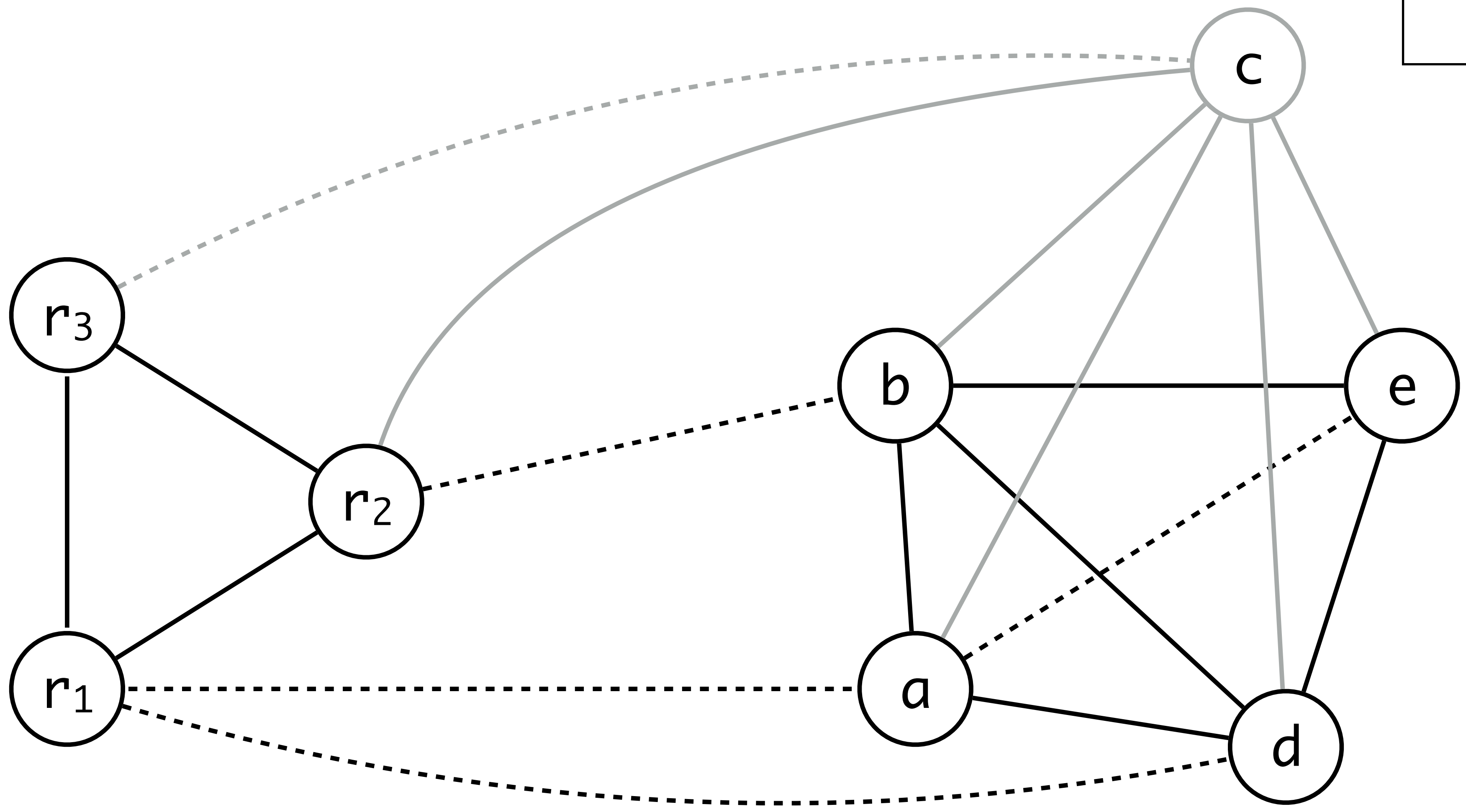
```
enter : c ← r3
        a ← r1
        b ← r2
        d ← 0
        e ← a
loop :  d ← d + b
        e ← e - 1
        if e > 0 goto loop
        r1 ← d
        r3 ← c
        return (r1, r3)
```

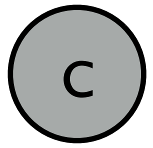


Pre-Colored Nodes
example

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)
```



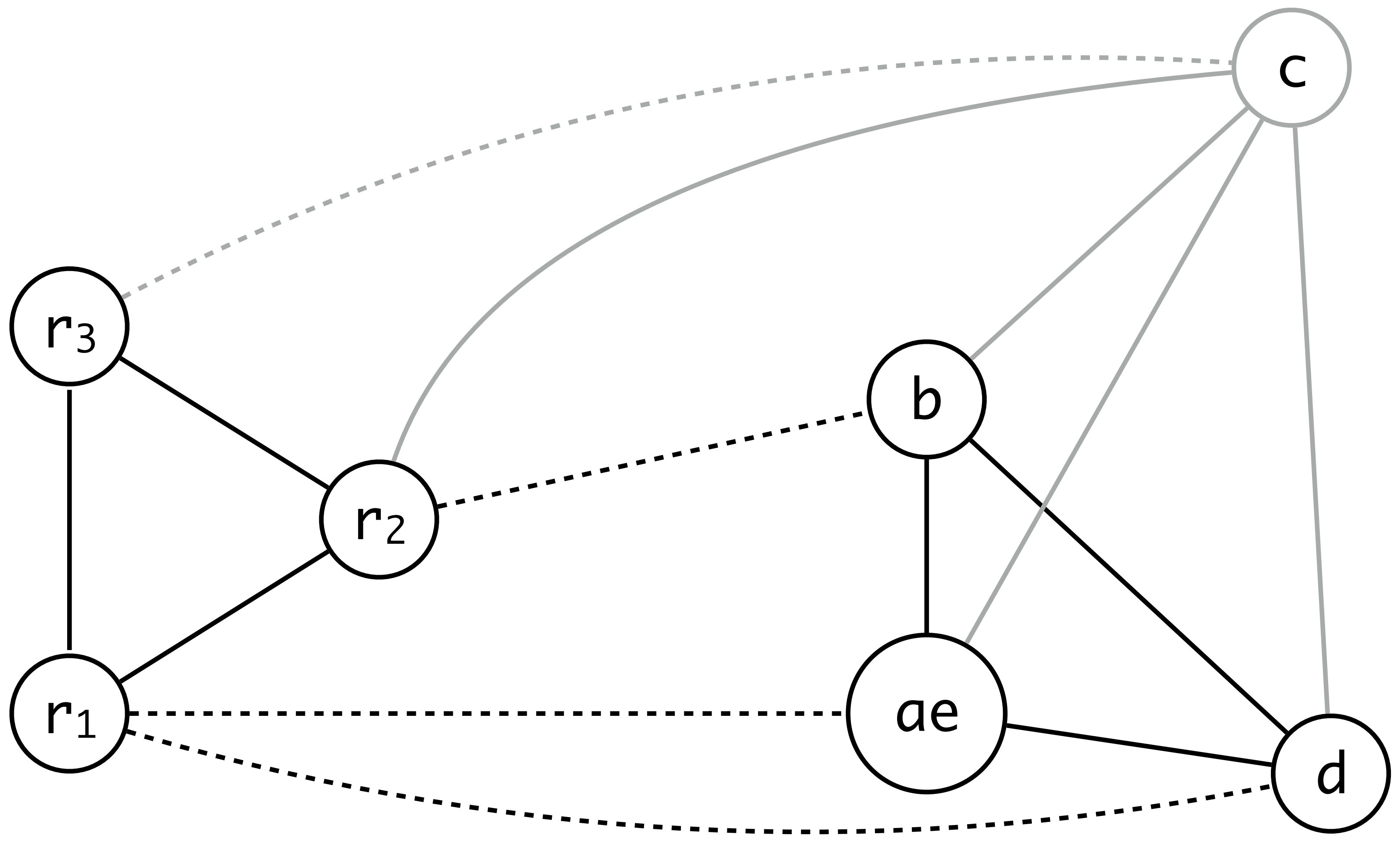


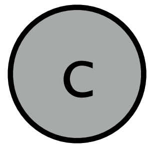
Pre-Colored Nodes

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



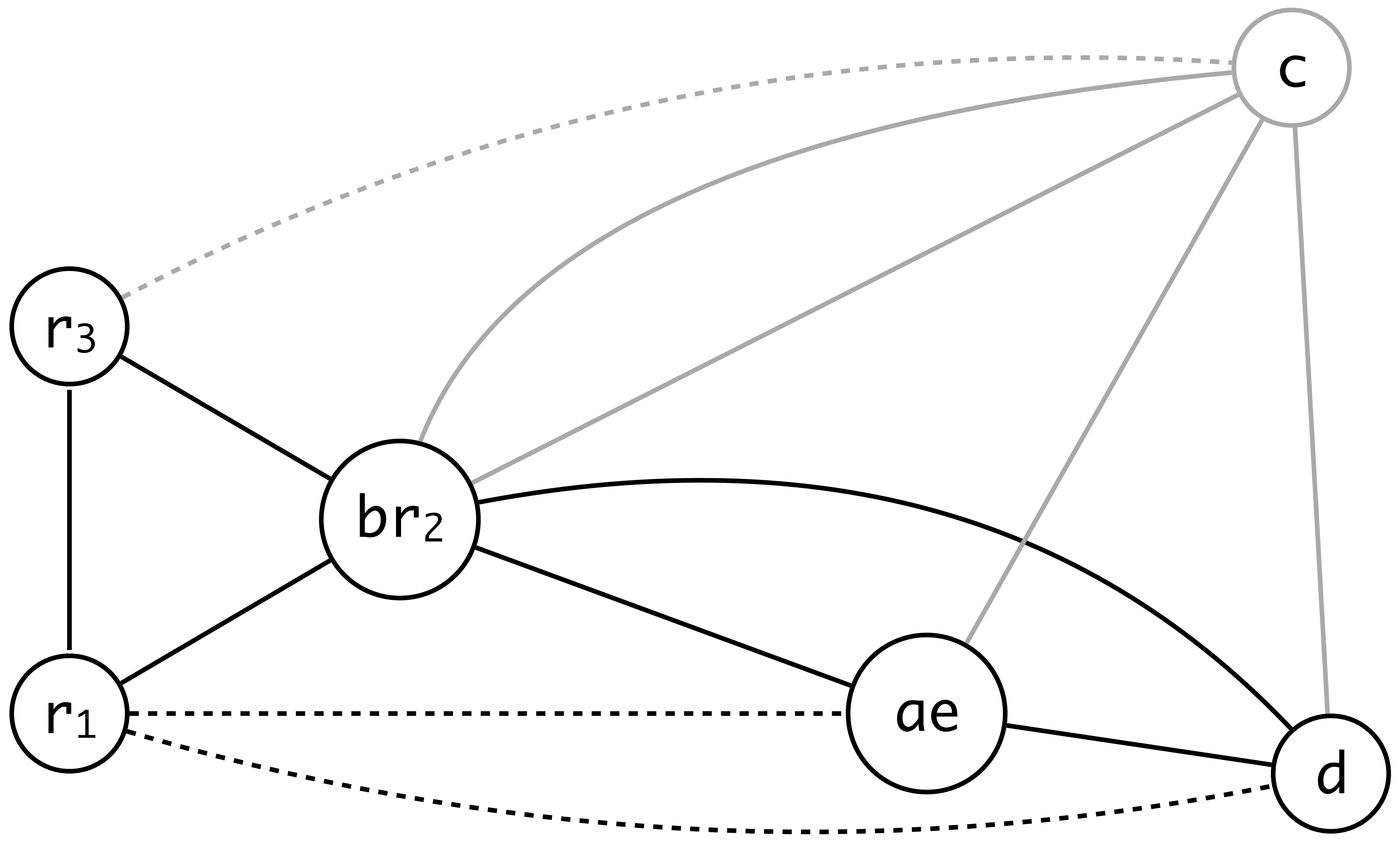


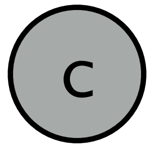
Pre-Colored Nodes

example

coalesce r_2 and b

```
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)
```



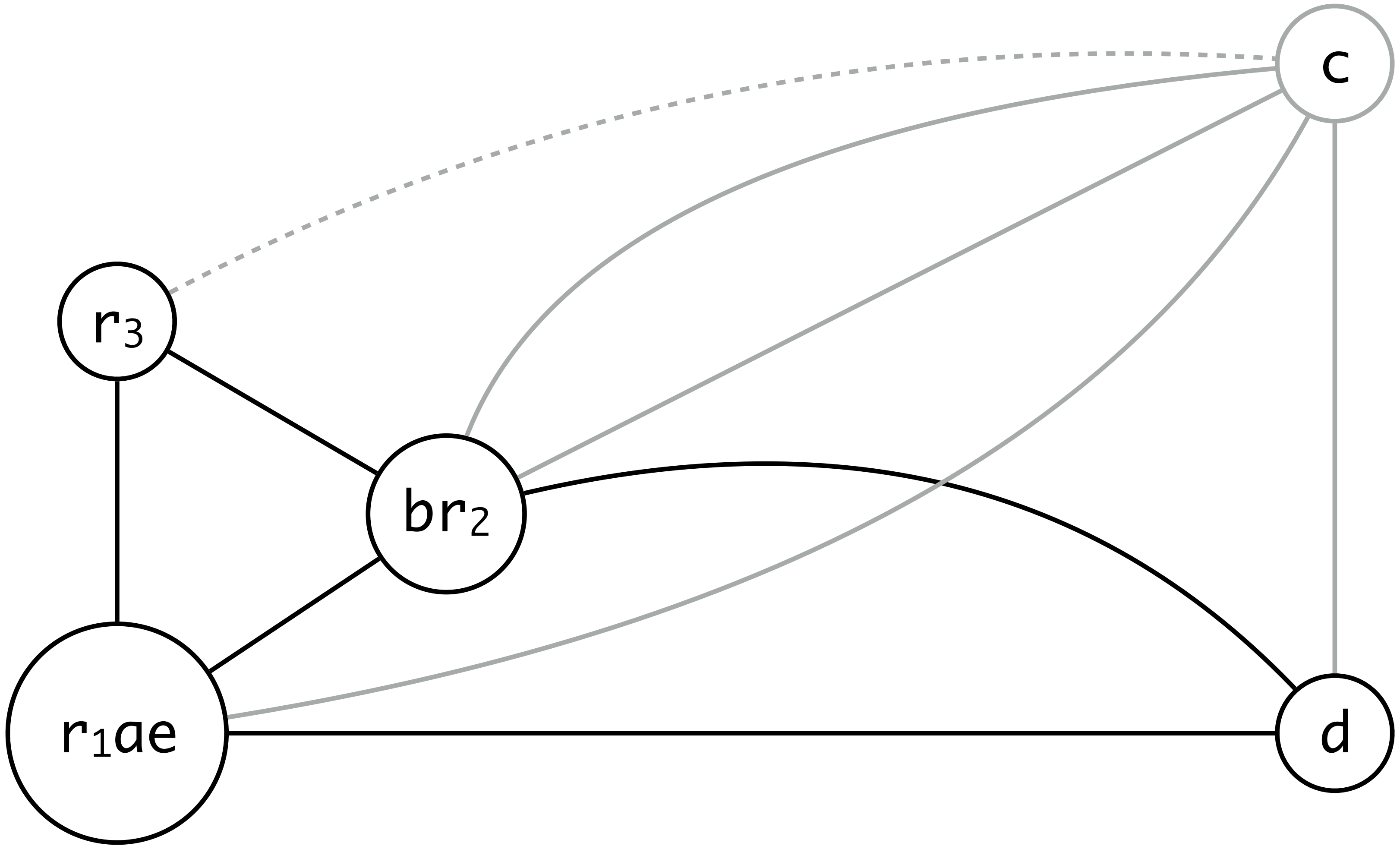


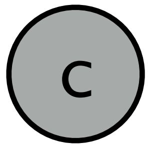
Pre-Colored Nodes

example

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)
```



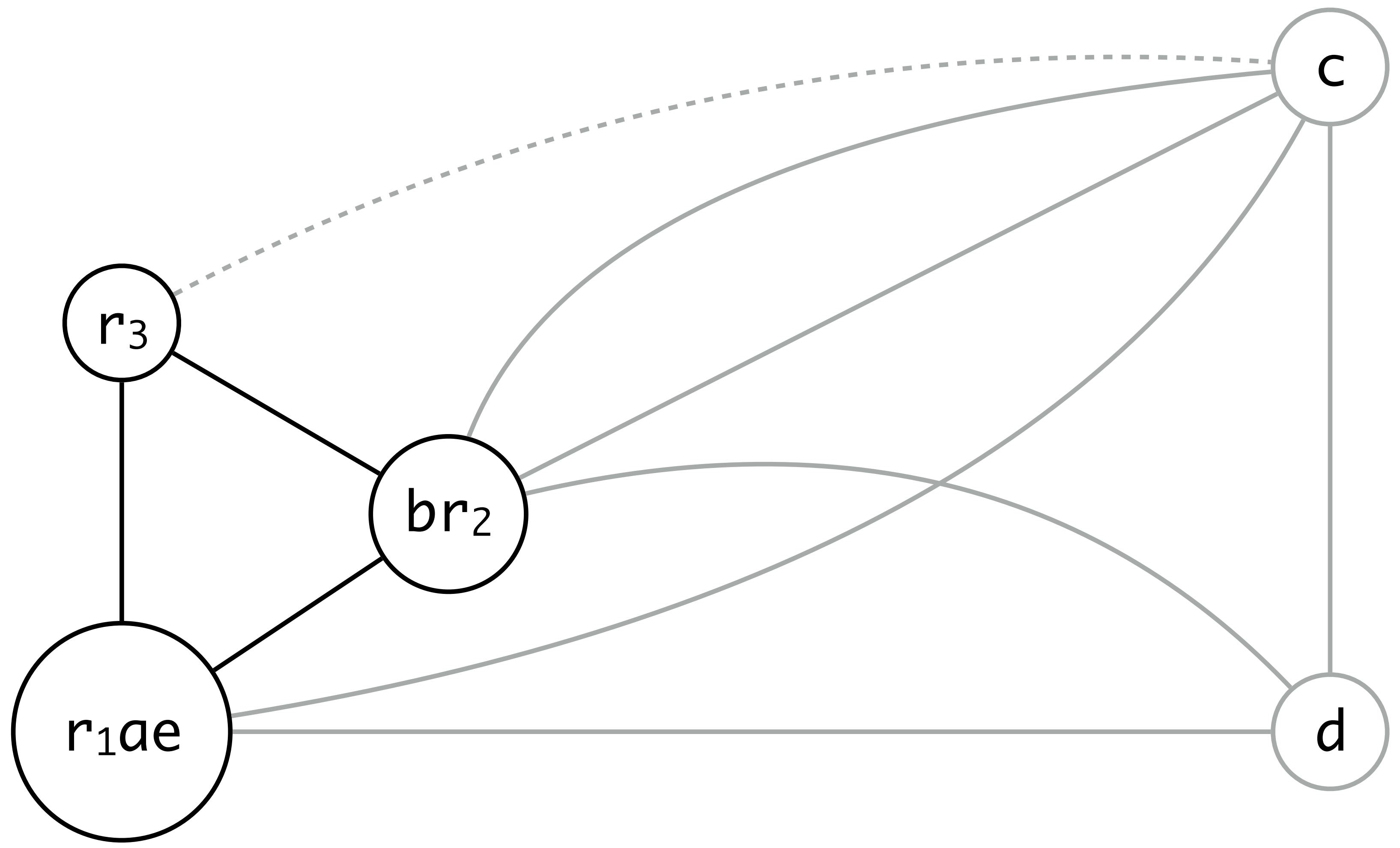


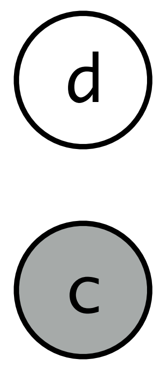
Pre-Colored Nodes

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)
```



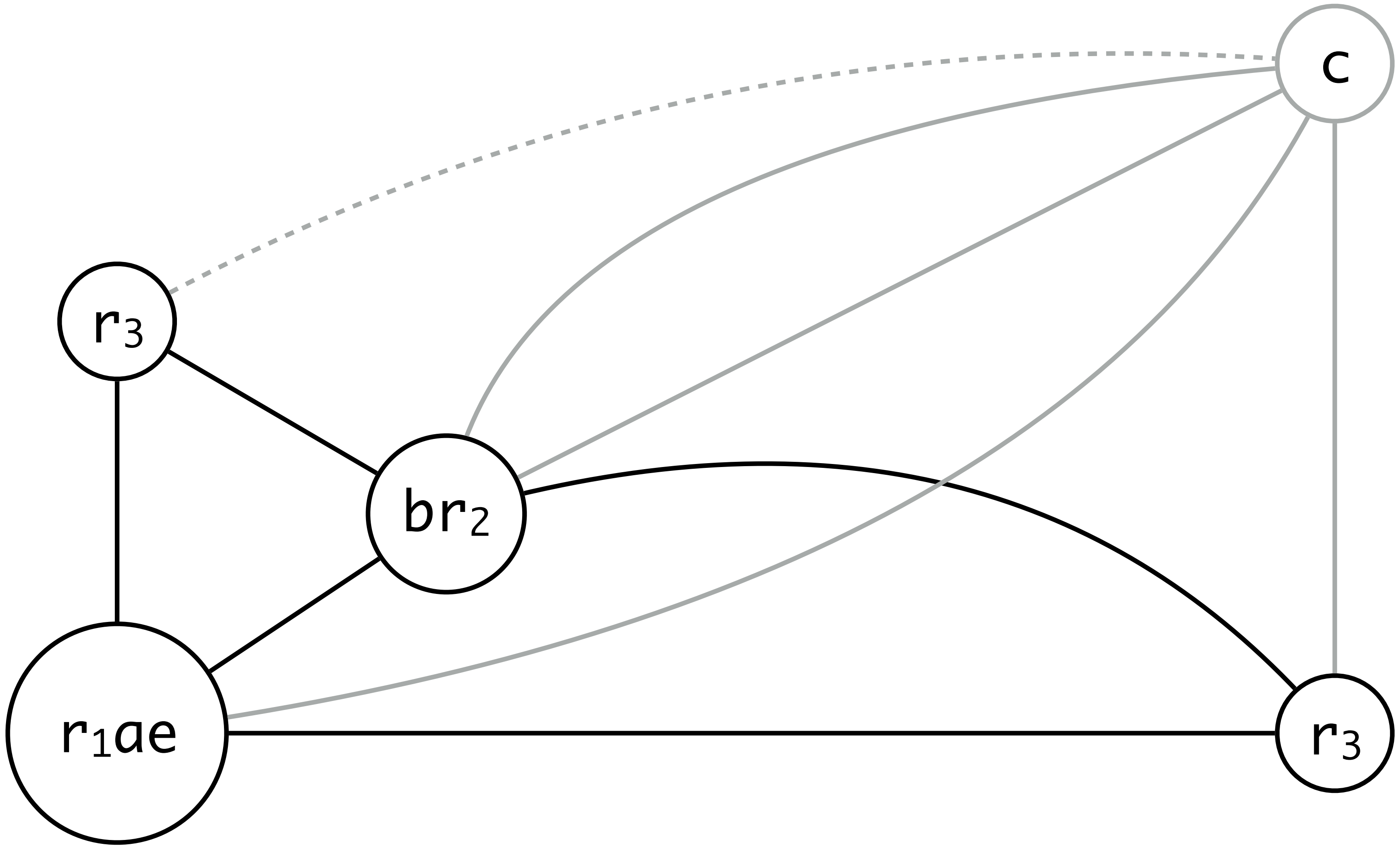


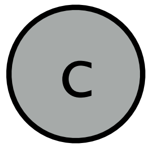
Pre-Colored Nodes

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)
```



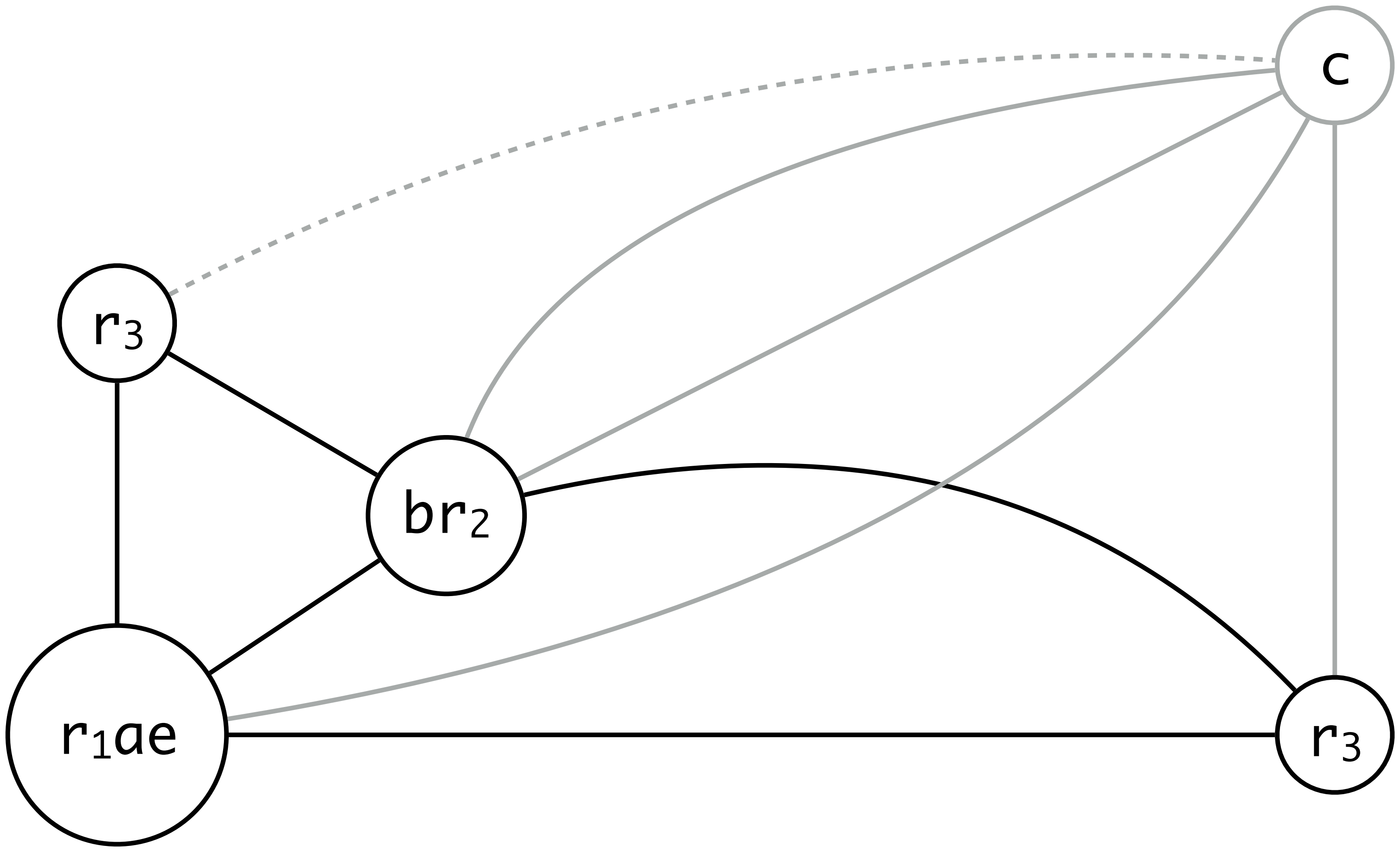


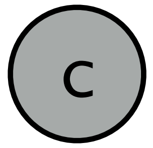
Pre-Colored Nodes

example

spill c

```
enter : c₁ ← r₃
        M[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)
```

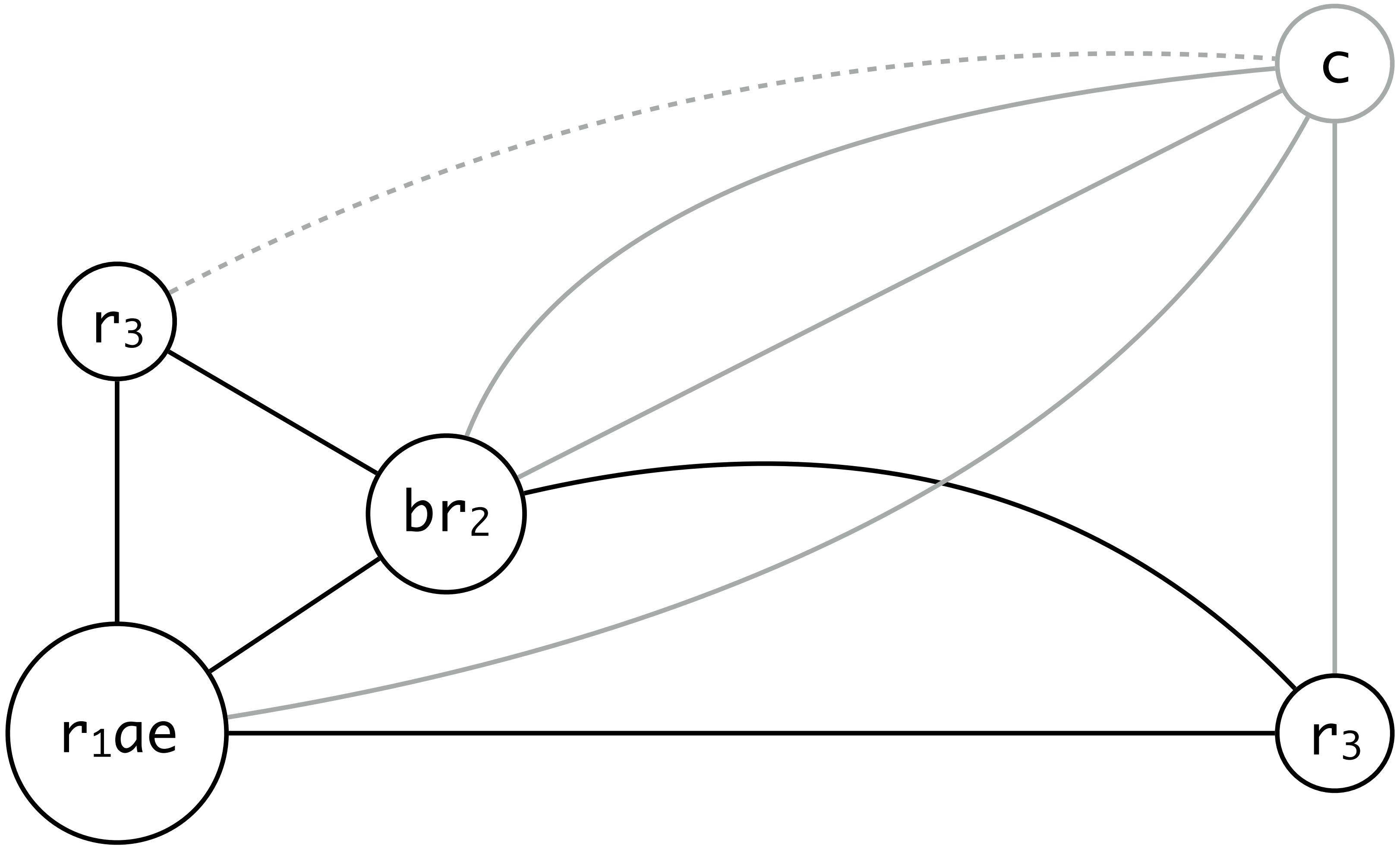




Pre-Colored Nodes

example

spill c

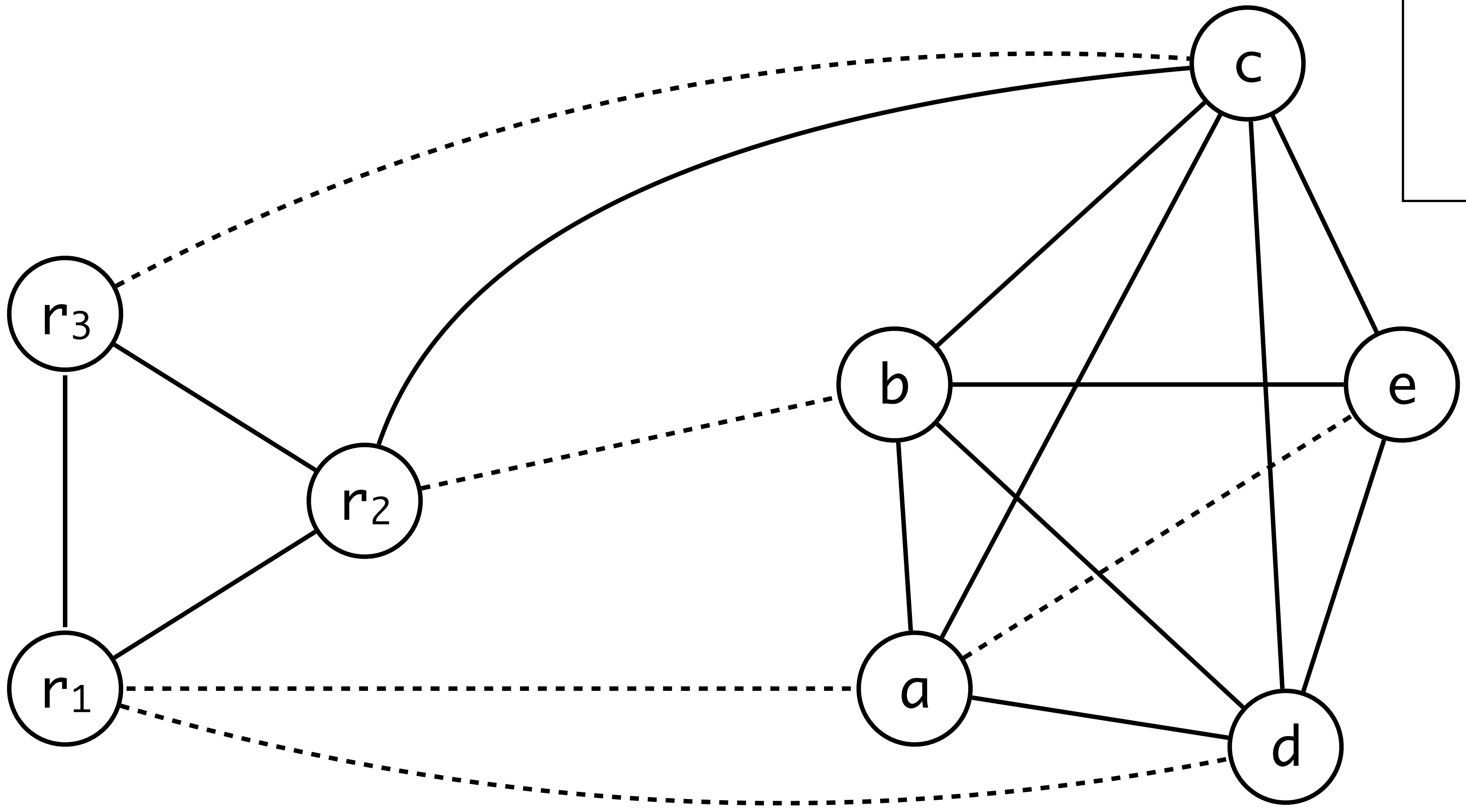


```
enter : c1 ← r3
        M[cloc] ← c1
        a ← r1
        b ← r2
        d ← 0
        e ← a
loop :  d ← d + b
        e ← e - 1
        if e > 0 goto loop
        r1 ← d
        r3 ← c2
        c2 ← M[cloc]
        return (r1, r3)
```

Pre-Colored Nodes

examples

start over

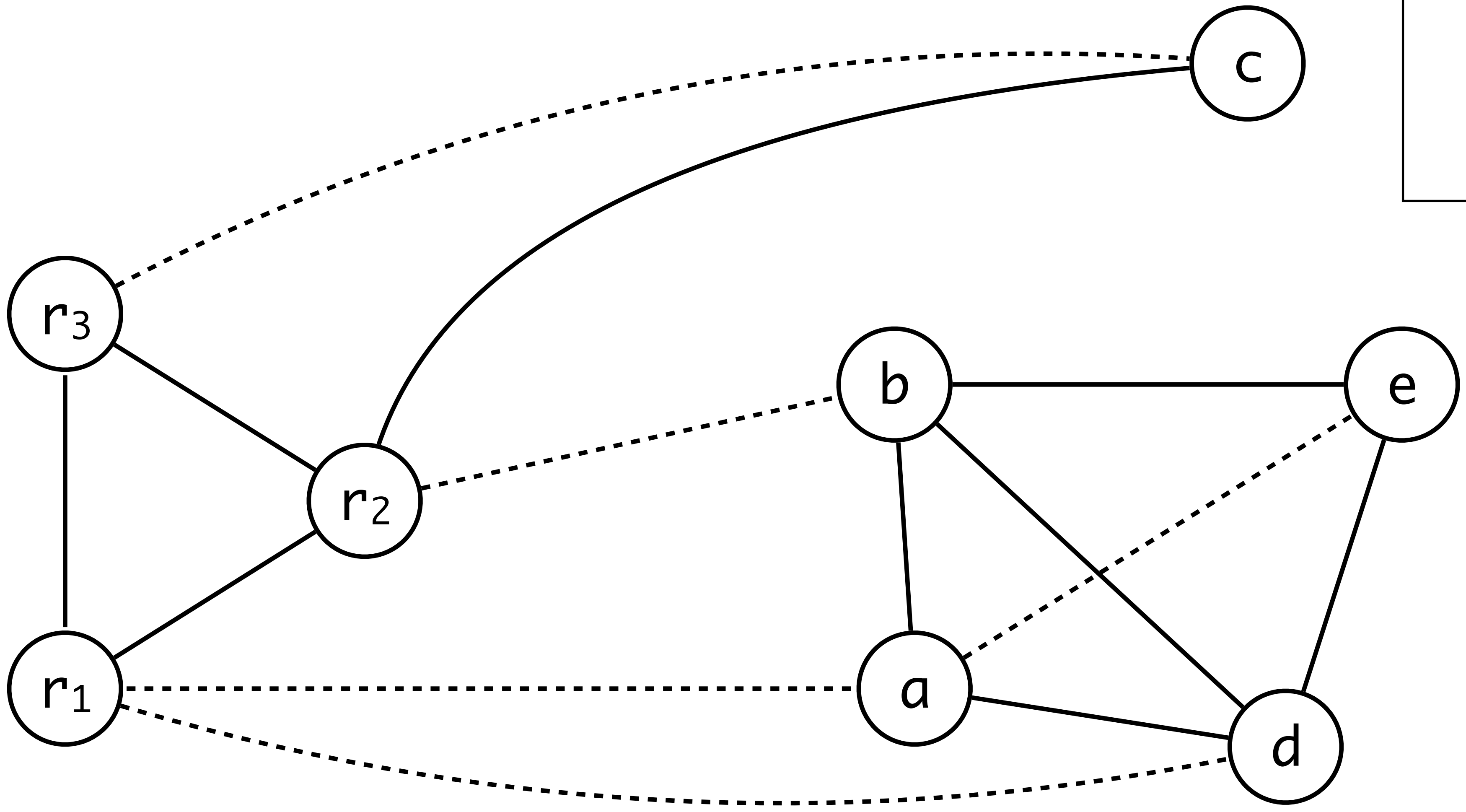


```
enter : c₁ ← r₃
        M[c_loc] ← c₁
        a ← r₁
        b ← r₂
        d ← 0
        e ← a
loop :  d ← d + b
        e ← e - 1
        if e > 0 goto loop
        r₁ ← d
        r₃ ← c₂
        c₂ ← M[c_loc]
        return (r₁, r₃)
```

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)
```

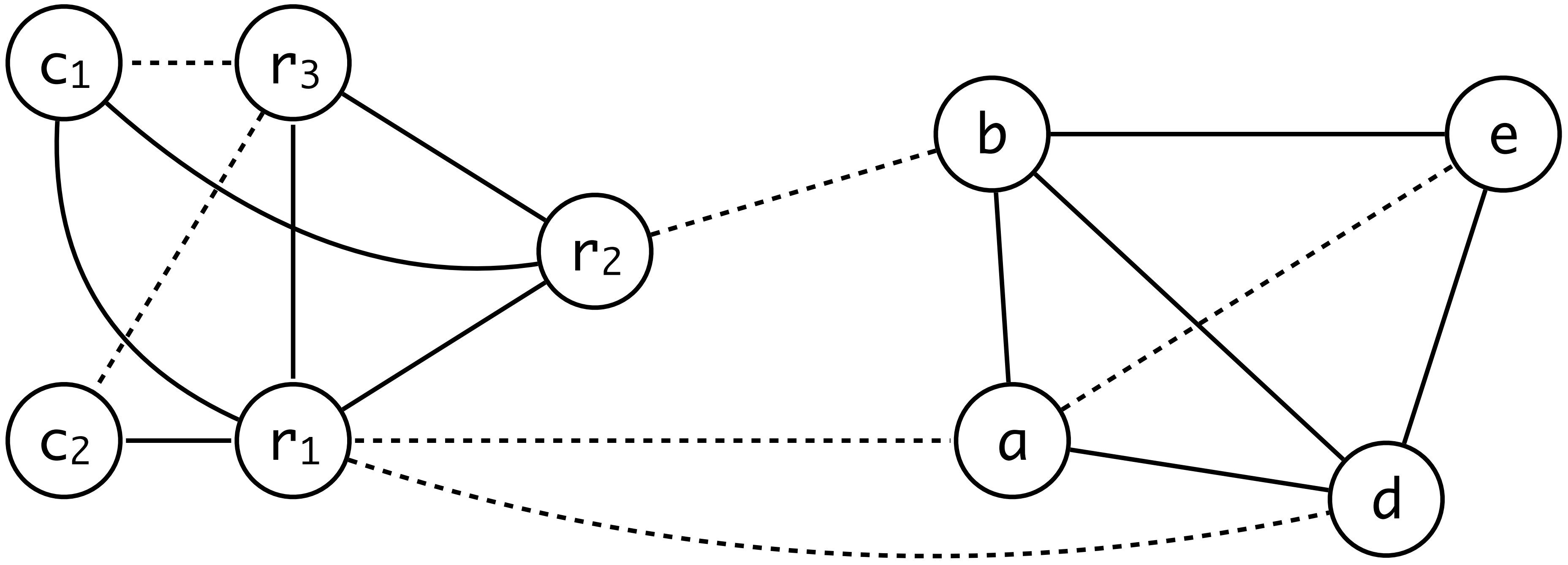


Pre-Colored Nodes

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)
```

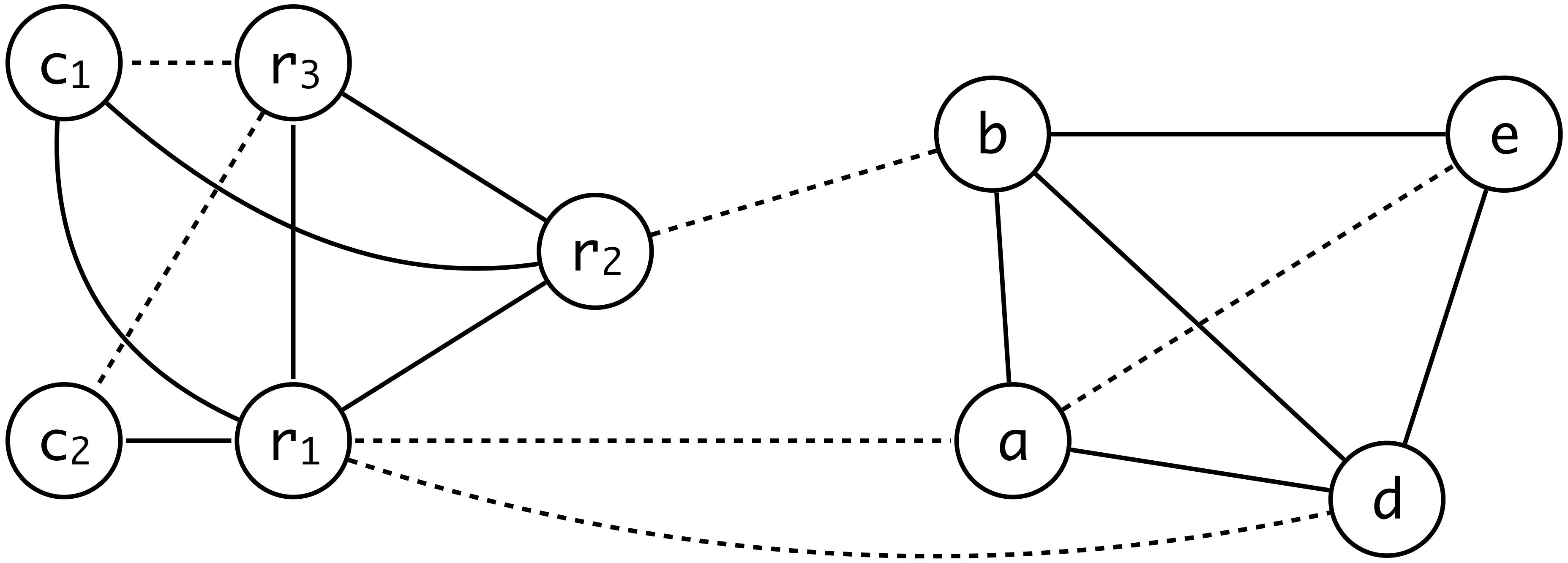


Pre-Colored Nodes

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)
```

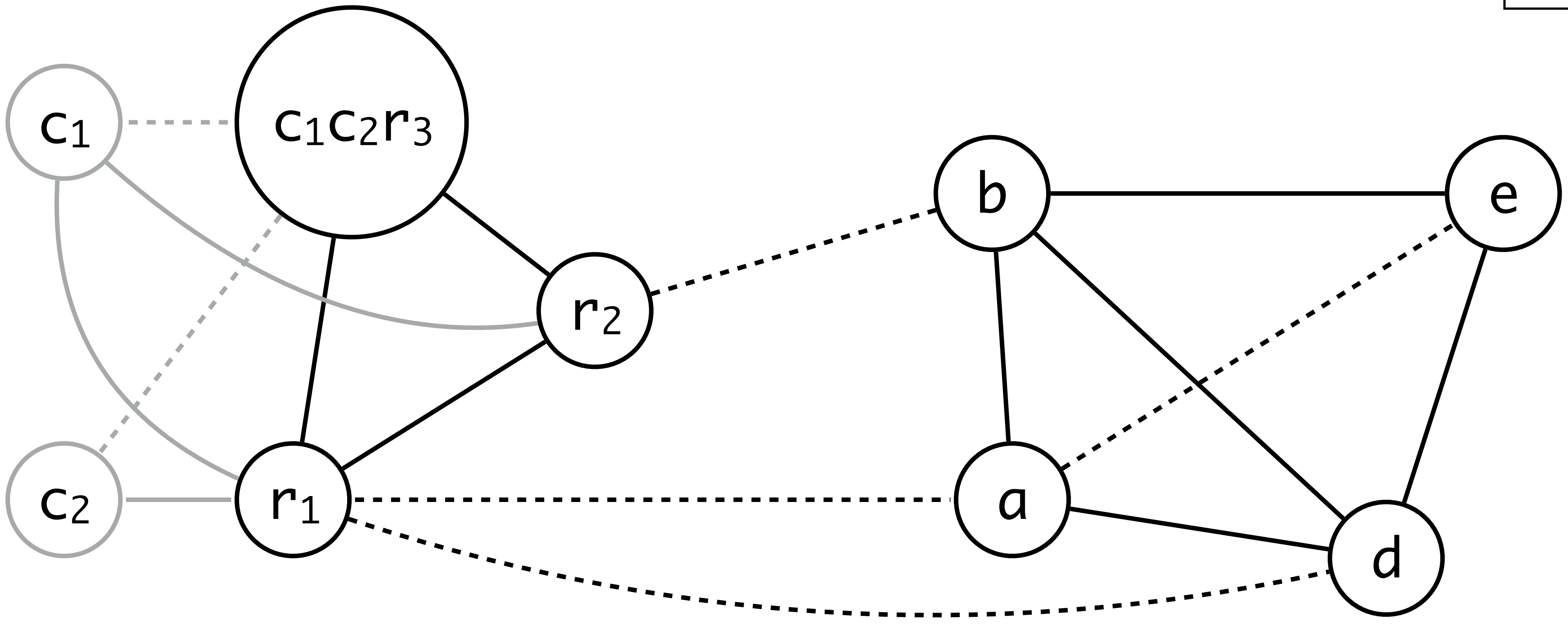


Pre-Colored Nodes

examples

coalesce c_1, c_2, r_3

```
enter : c₁ ← r₃
        M[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)
```

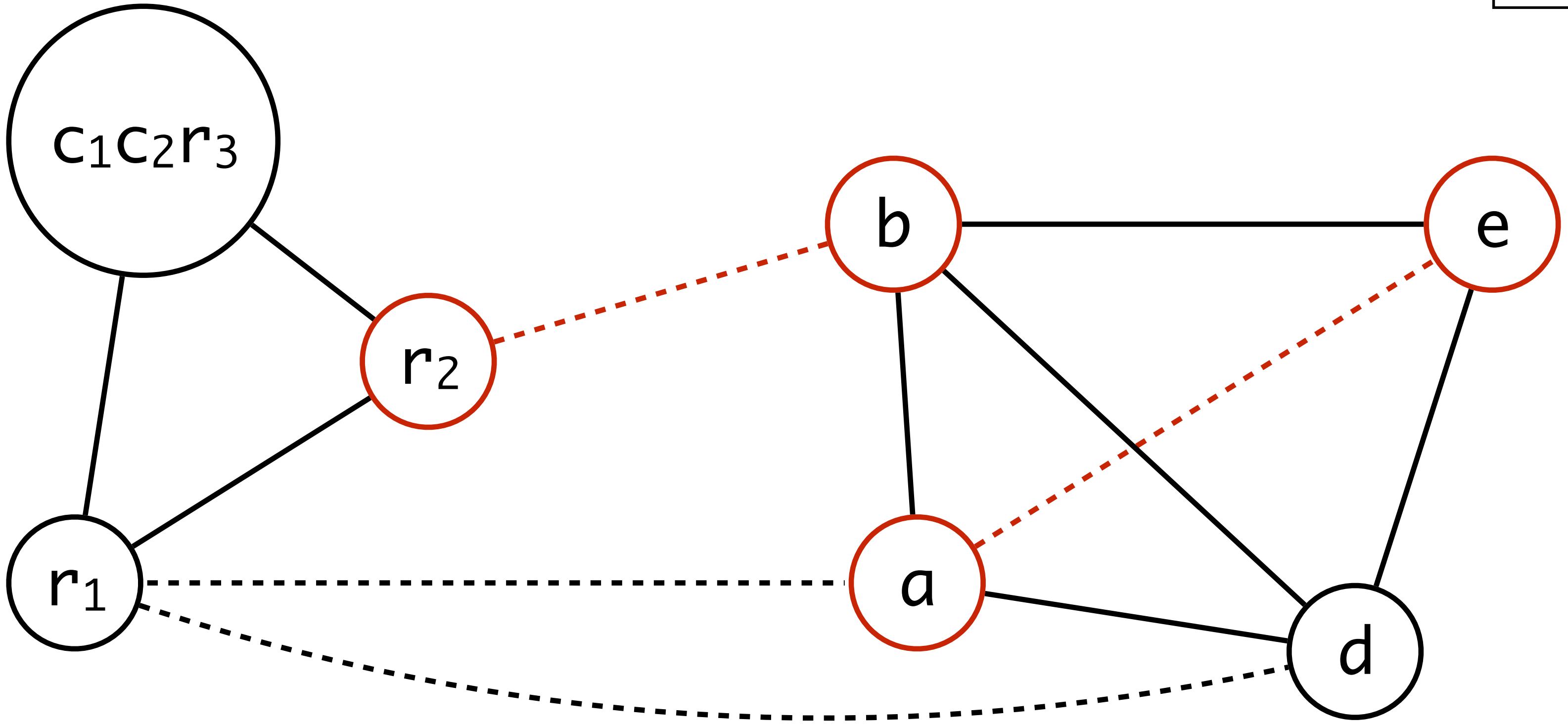


Pre-Colored Nodes

examples

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

```
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)
```

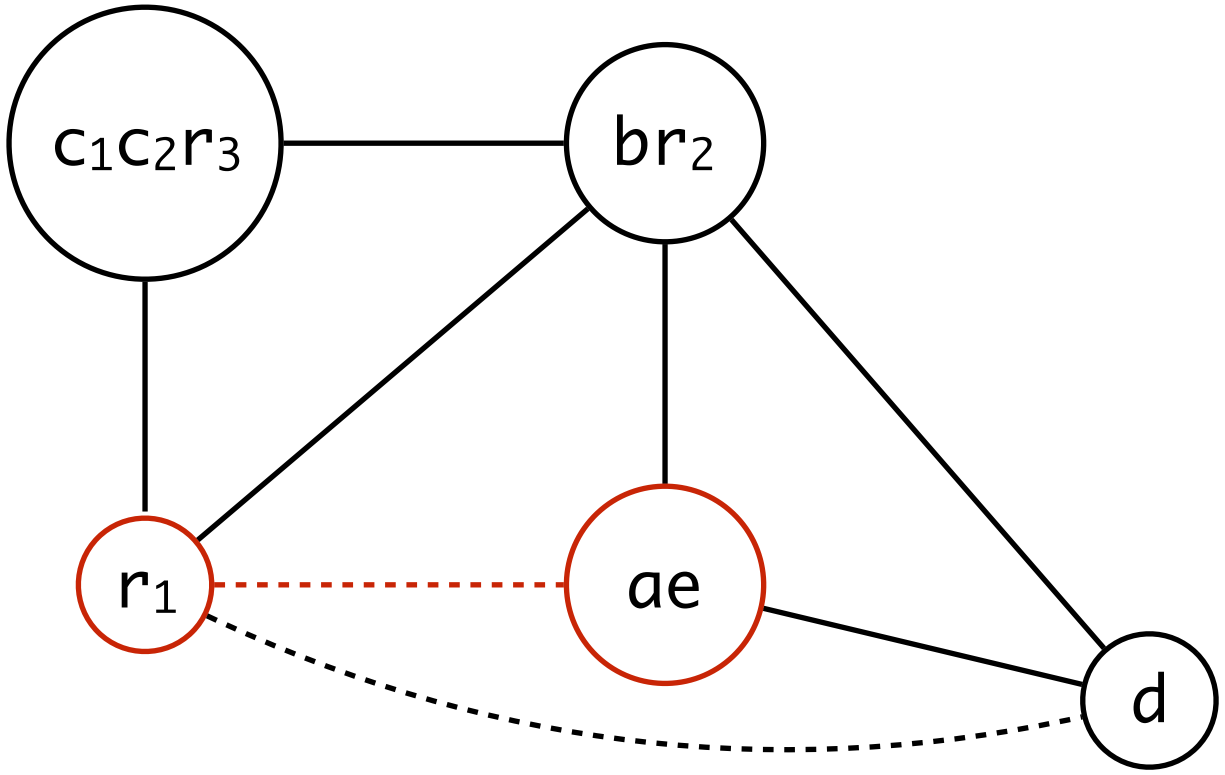


Pre-Colored Nodes

examples

coalesce (ae, r_1)

```
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)
```

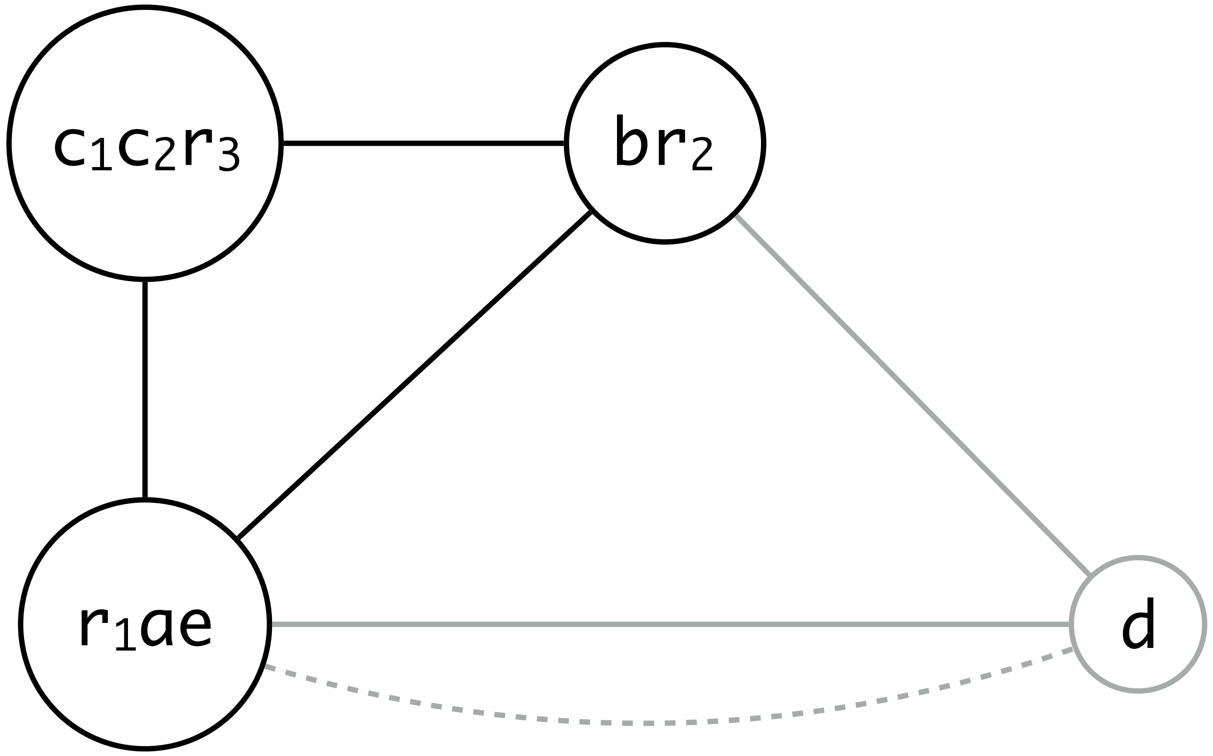


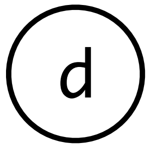
Pre-Colored Nodes

examples

simplify d

```
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)
```



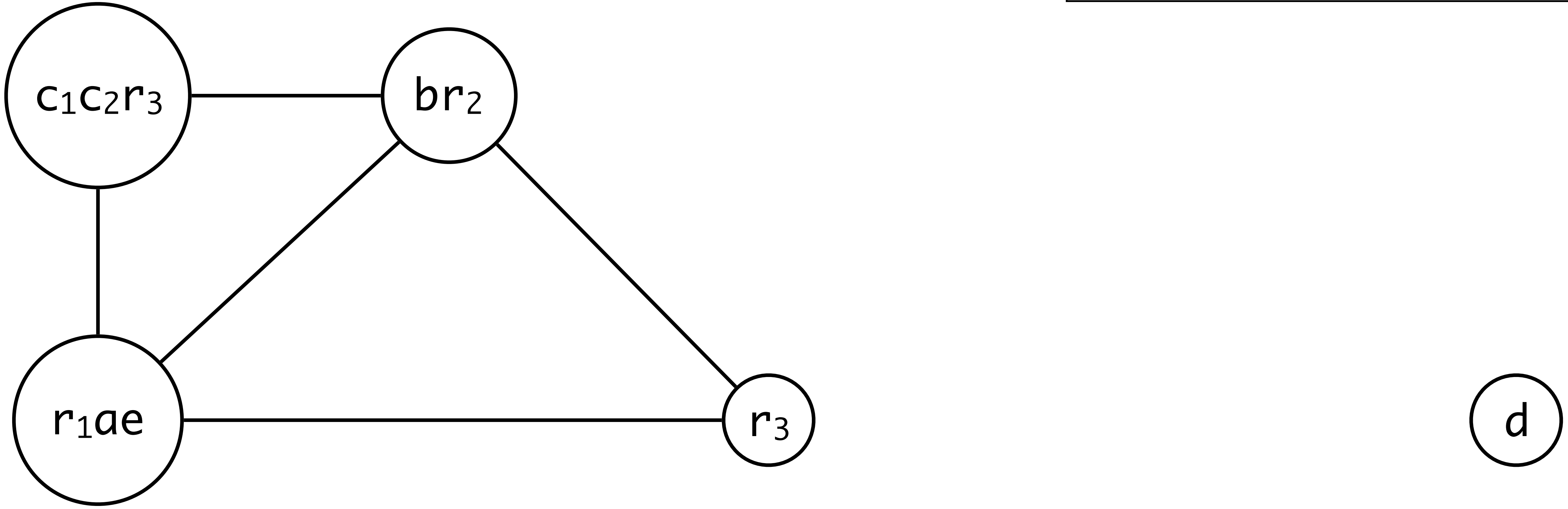


Pre-Colored Nodes

examples

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)
```

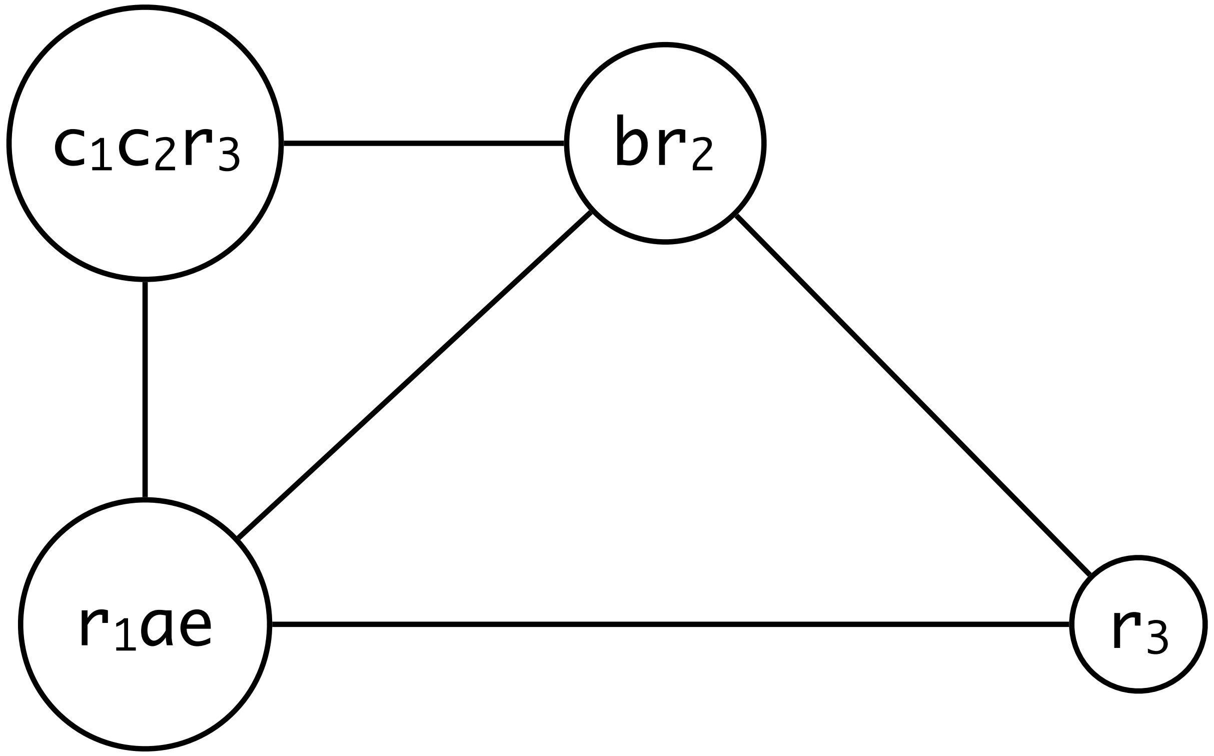


Pre-Colored Nodes

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[cloc] ← r3
        r3 ← 0
loop :  r3 ← r3 + r2
        r1 ← r1 - 1
        if r1 > 0 goto loop
        r3 ← M[cloc]
        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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