

Register Allocation

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EPITA — École Pour l'Informatique et les Techniques Avancées

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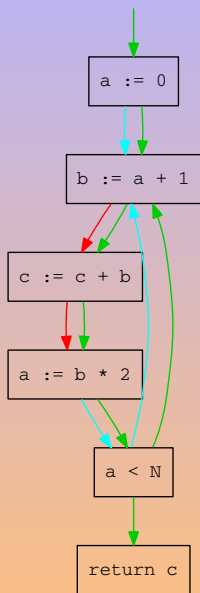
Register Allocation

- 1 Interference Graph
- 2 Coloring by Simplification
- 3 Alternatives to Graph Coloring

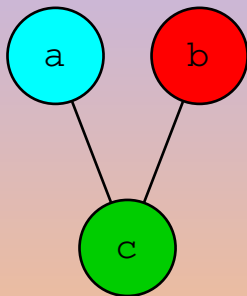
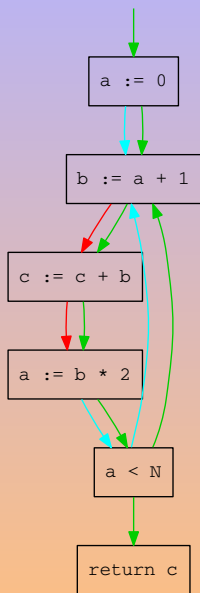
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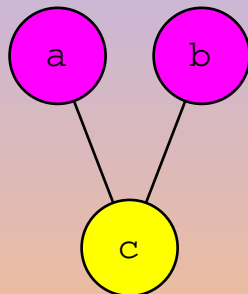
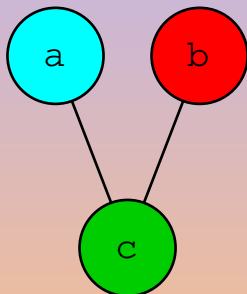
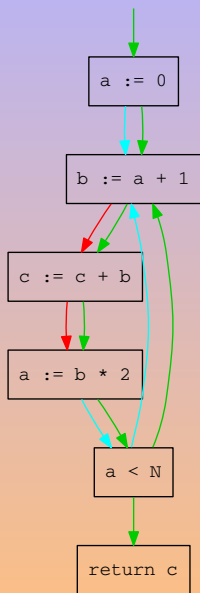
Interference Graph



Interference Graph



Interference Graph



Register Allocation

```
a := 0
L1: b := a + 1
   c := c + b
   a := b * 2
   if a < N goto L1
   return c
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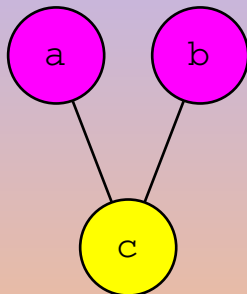
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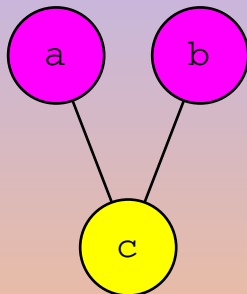
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```
r1 := 0
```

```
L1: r1 := r1 + 1
```

```
r2 := r2 + r1
```

```
r1 := r1 * 2
```

```
if r1 < N goto L1
```

```
return r2
```

Coloring by Simplification

- 1 Interference Graph
- 2 Coloring by Simplification
 - Spilling
 - Coalescing
 - Precolored Nodes
 - Implementation
- 3 Alternatives to Graph Coloring

Interference Graph [Appel, 1998]

Four registers: r1, r2, r3, r4.

live in: k j

`g := [j + 12]`

`h := k - 1`

`f := g * h`

`e := [j + 8]`

`m := [j + 16]`

`b := [f]`

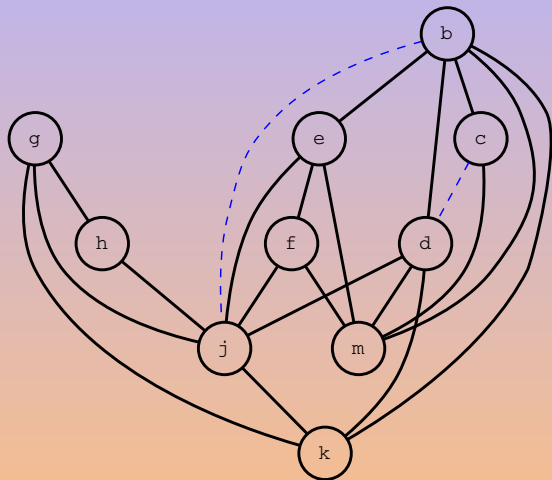
`c := e + 8`

`d := c`

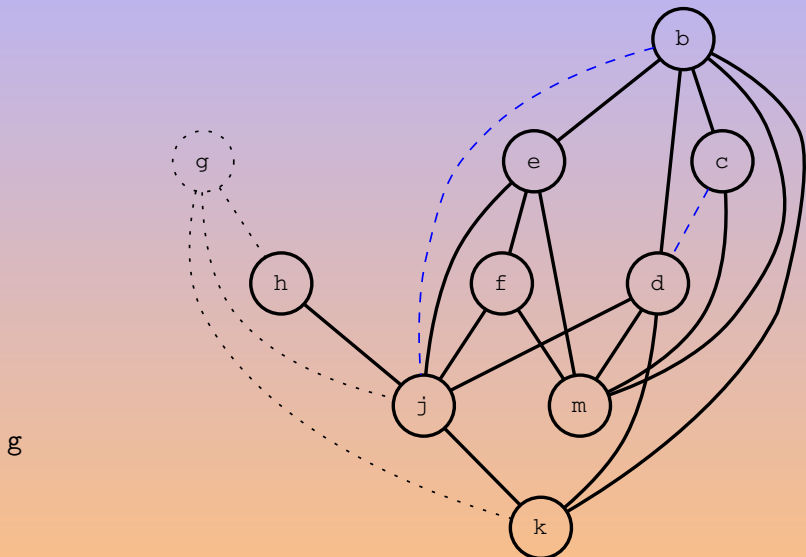
`k := m + 4`

`j := b`

live out: d k j

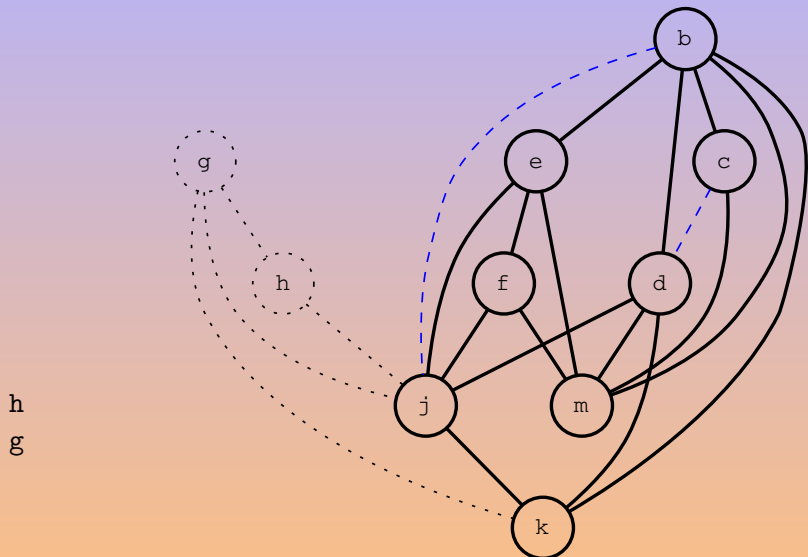


Interference Graph: Simplify 0



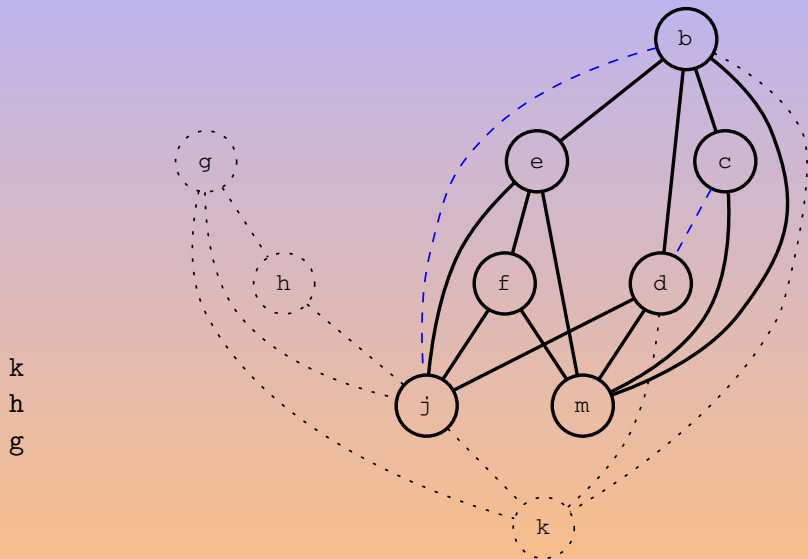
σ₀

Interference Graph: Simplify 1

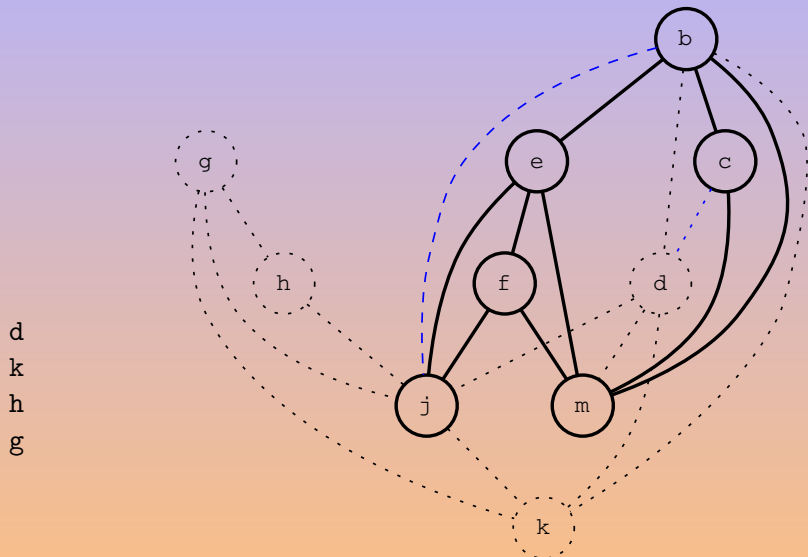


h
g

Interference Graph: Simplify 2

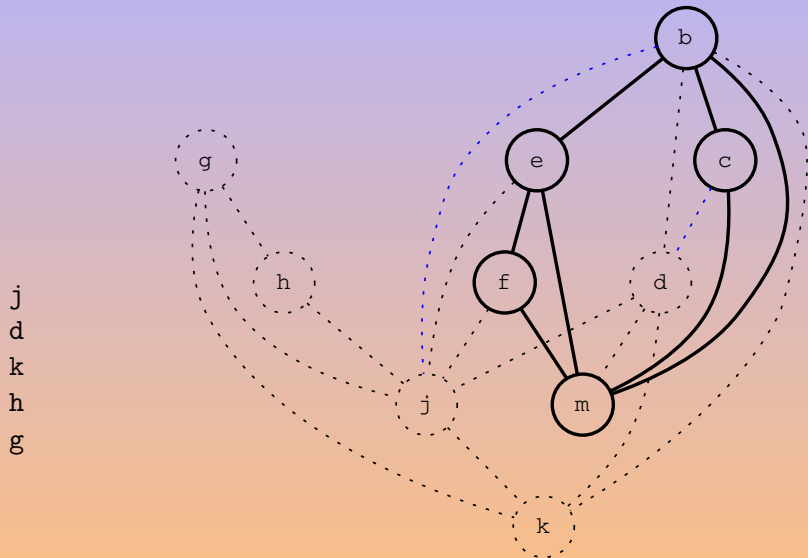


Interference Graph: Simplify 3

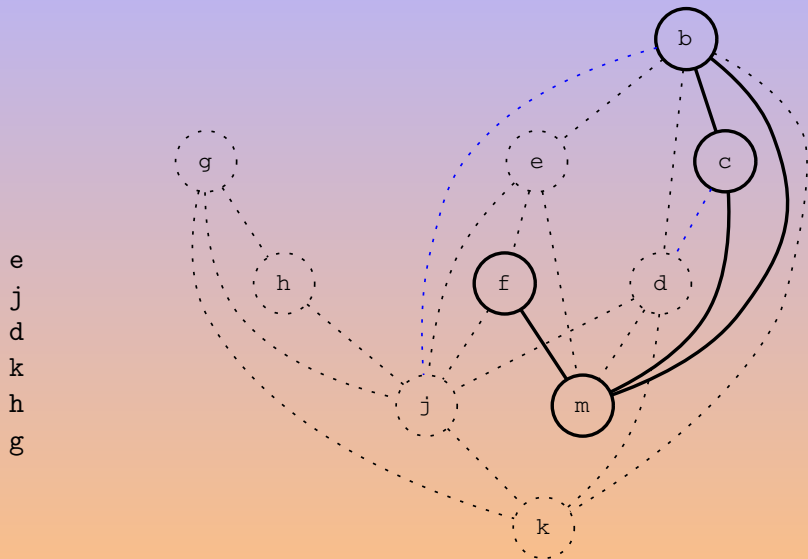


d
k
h
g

Interference Graph: Simplify 4

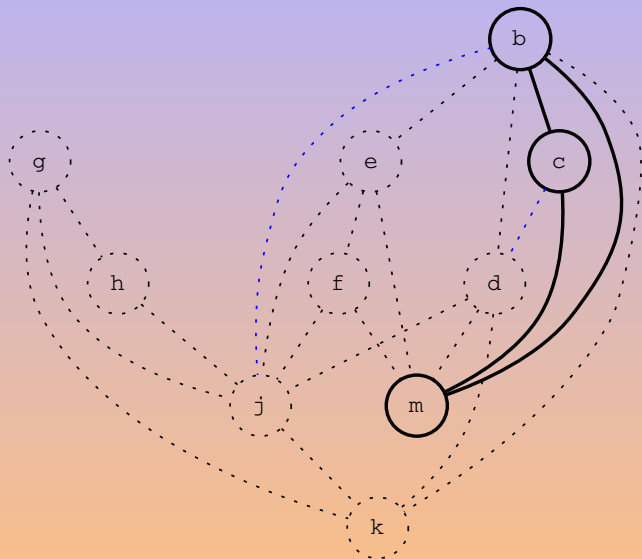


Interference Graph: Simplify 5



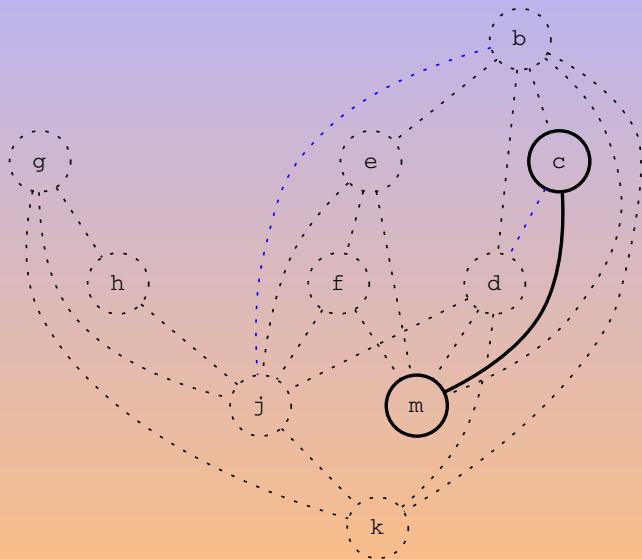
Interference Graph: Simplify 6

f
e
j
d
k
h
g



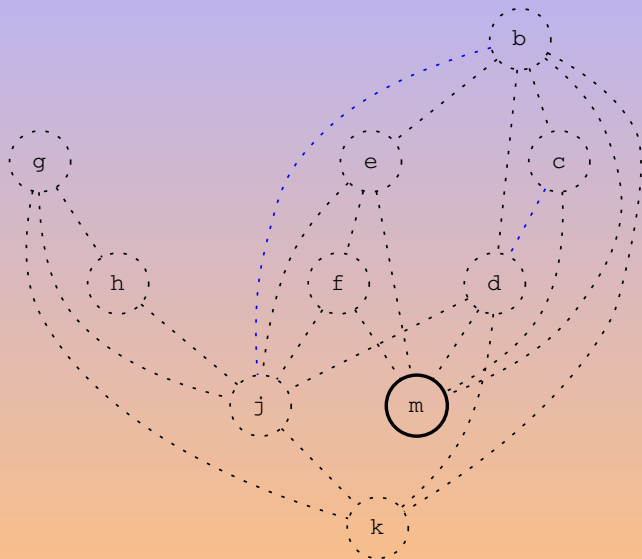
Interference Graph: Simplify 7

b
f
e
j
d
k
h
g



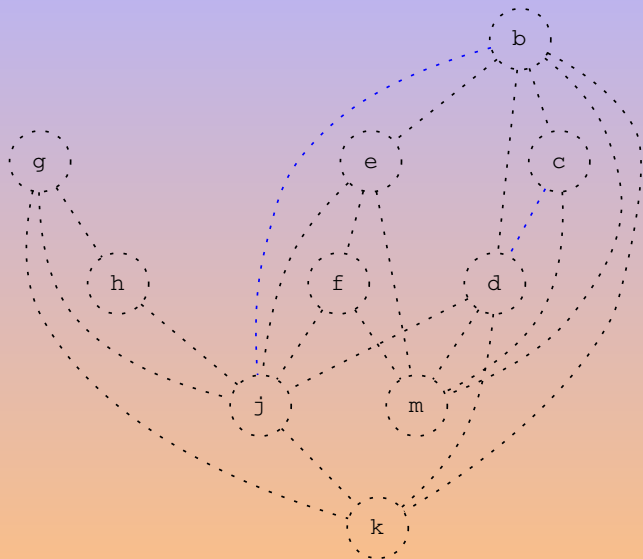
Interference Graph: Simplify 8

c
b
f
e
j
d
k
h
h
g



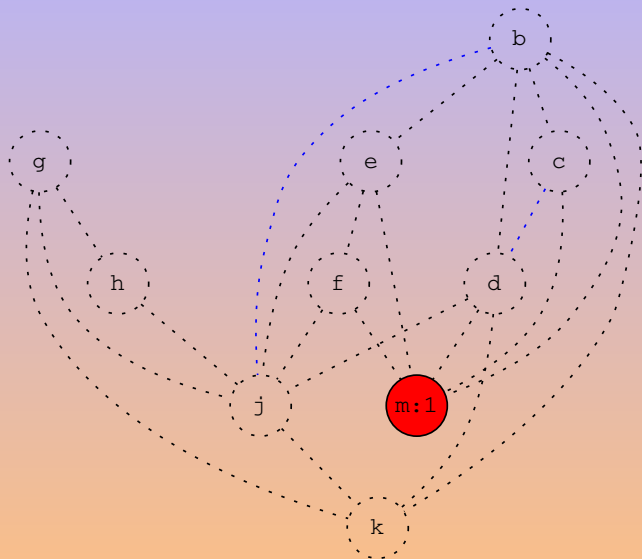
Interference Graph: Simplify 9

m
c
b
f
e
j
d
k
h
g



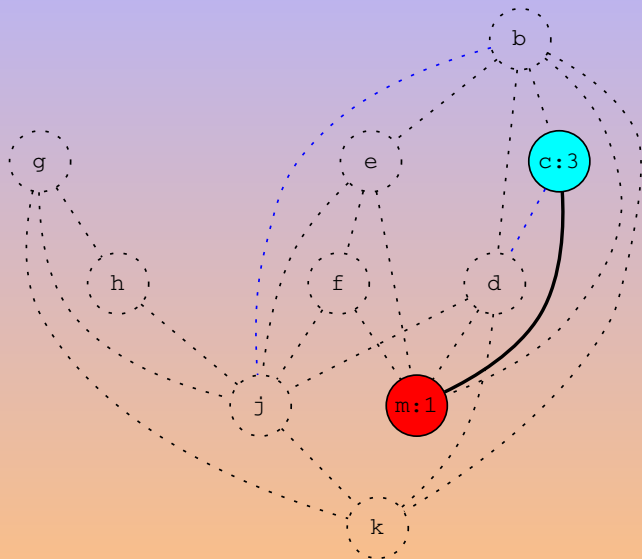
Interference Graph: Color 9

m
c
b
f
e
j
d
k
h
g



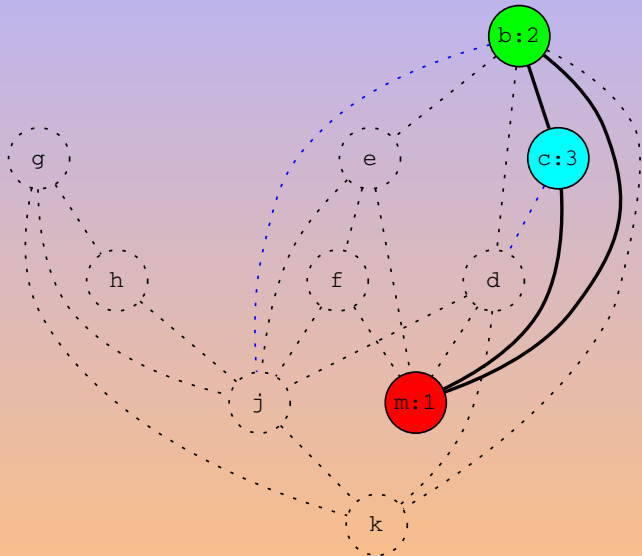
Interference Graph: Color 8

c
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f
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g

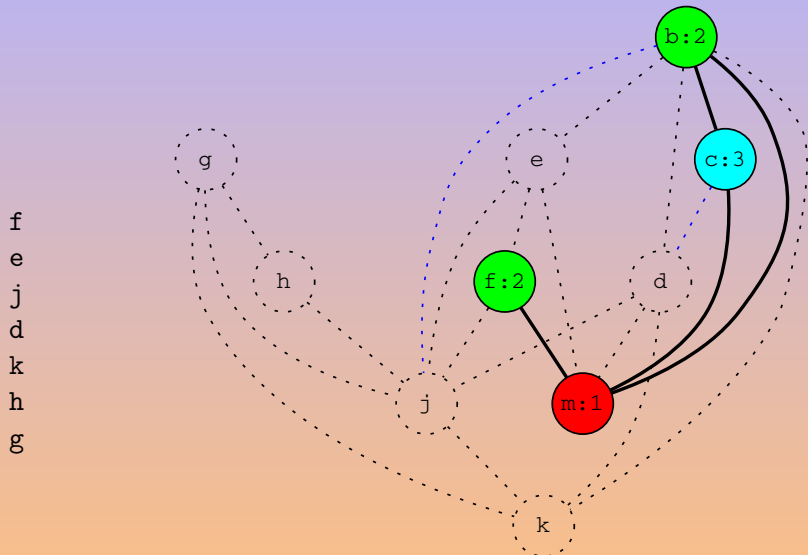


Interference Graph: Color 7

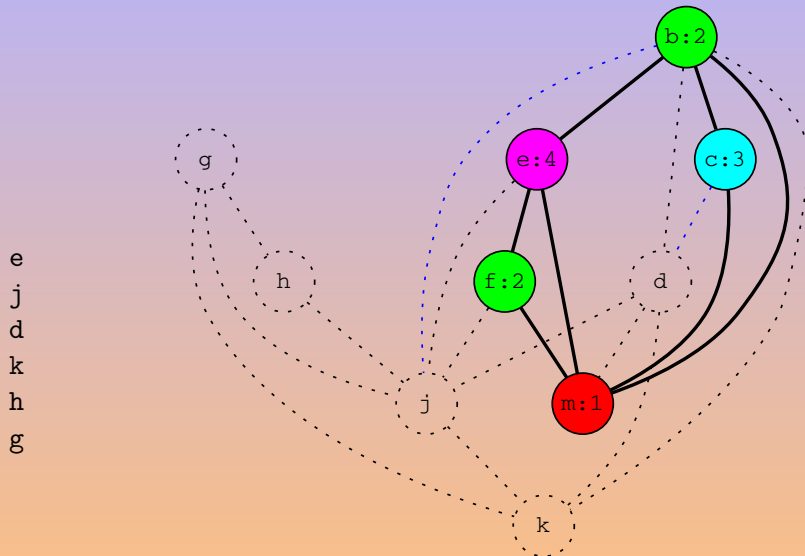
b
f
e
j
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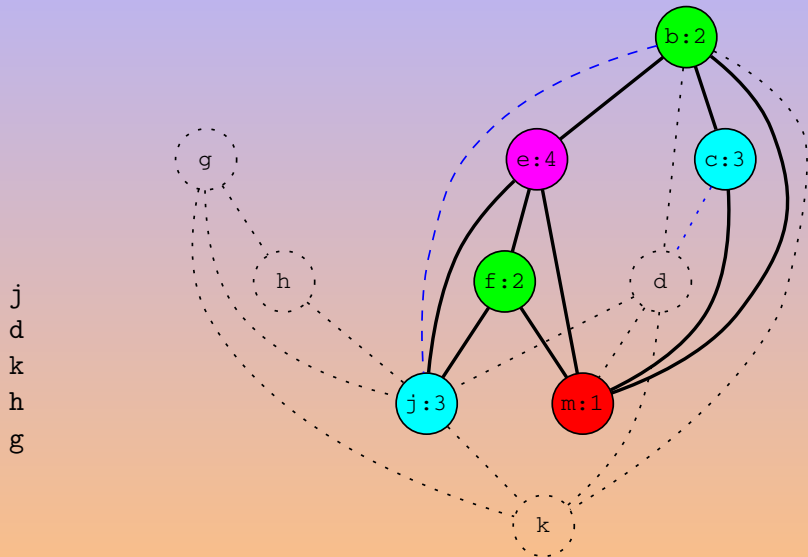
Interference Graph: Color 6



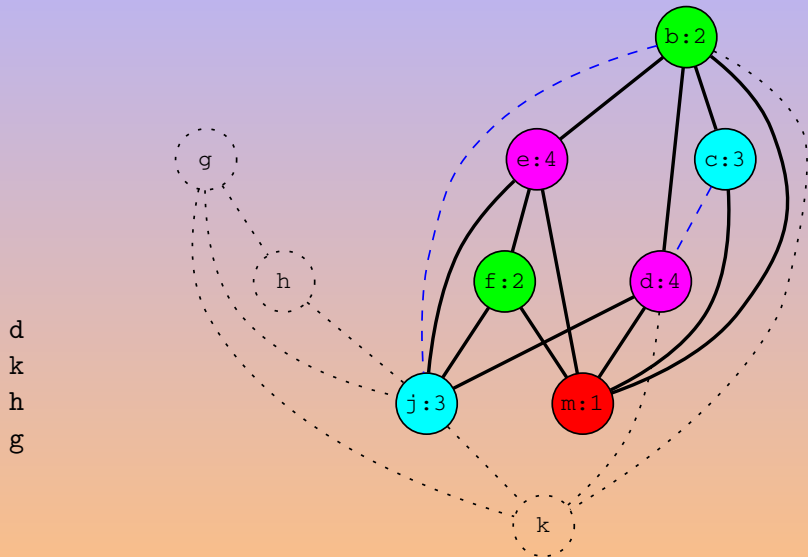
Interference Graph: Color 5



Interference Graph: Color 4

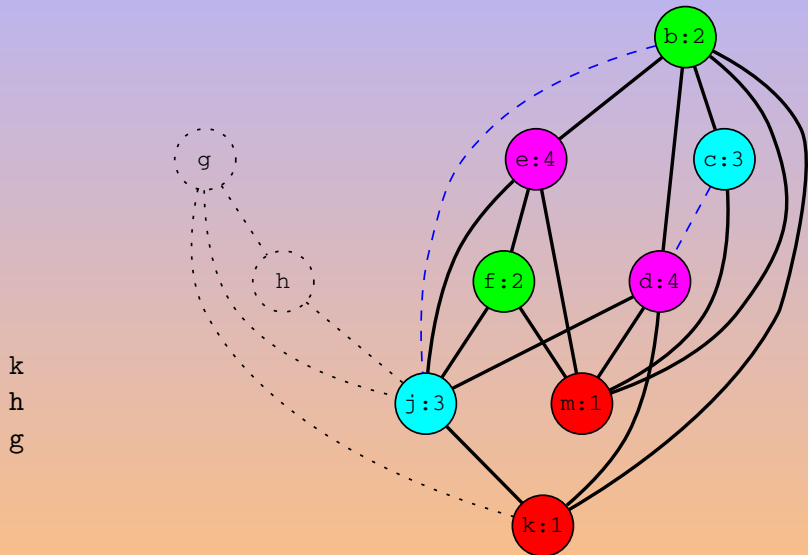


Interference Graph: Color 3

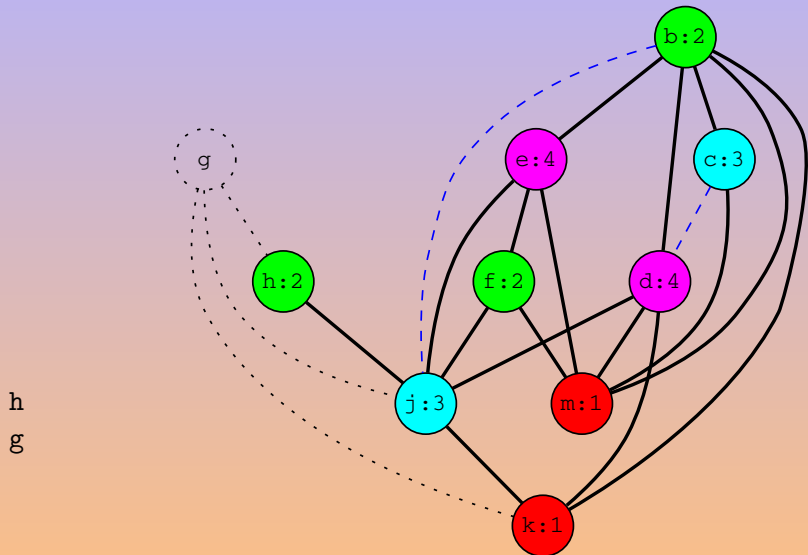


d
k
h
g

Interference Graph: Color 2

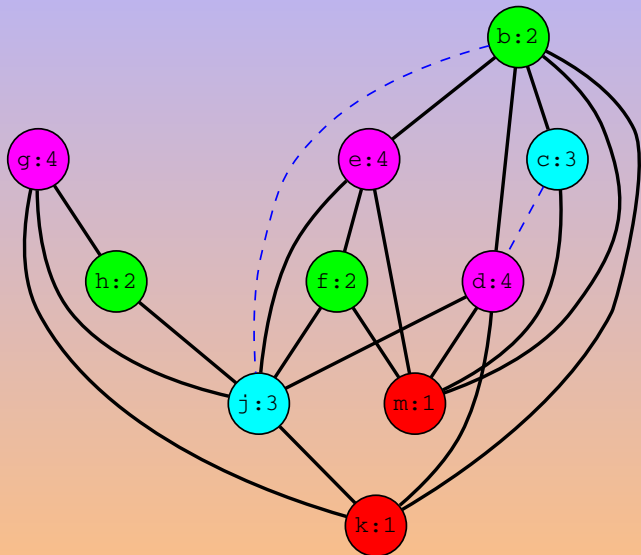


Interference Graph: Color 1



Interference Graph: Color 0

σ₀

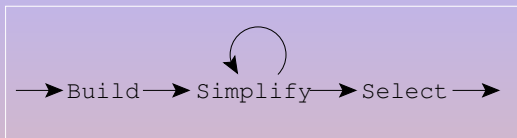


Result

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

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


Simple Register Allocation

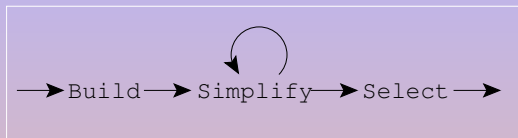


build the conflict graph from the program

simplify the nodes with insignificant degree

select (or color) while rebuilding the graph.

Simple Register Allocation

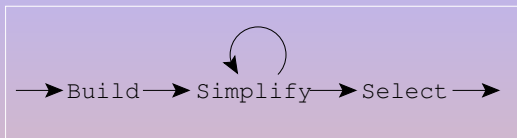


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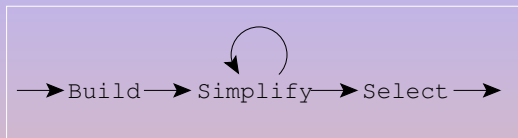


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Based on:

A.B. Kempe. On the Geographical problem of the four colors, Am. J. Math 2, 193–200, 1879.

[Appel, 1998, Matz, 2003]

Yes, but What Color? [Matz, 2003]

- Usually, first-fit (registers are ordered).
- Trying caller save first helps.
- **Biased Coloring.** [Briggs, 1992]
Use a color already unavailable to our neighbors.

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But for graph coloring, there is no reason for:

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- Not enough registers

$t1 := t1 + t2$

- So use the stack

$[sp + 4] := [sp + 4] + [sp + 8]$

- But use temporaries to do so!

$t12 := [sp + 4]$

$t13 := [sp + 8]$

$t12 := t12 + t13$

$[sp + 4] := t12$

- Why should it solve the problem?

- Not enough registers

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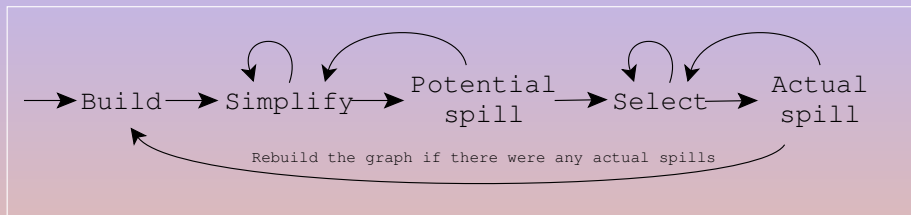
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Register Allocation with Spills



spill when one cannot simplify, the (uses of the) temporary must be rewritten using the stack.

rebuild but then, the conflict graph is to be rewritten

[Appel, 1998, Matz, 2003]

Yes, But Who Should be Spilled?

- The simplification order does not matter
- The spilling order matters
- Spilling decreases the degree of the neighbors
- ... hence it enables additional simplifications
- ... so “first spilled, last served”
- ... therefore: spill cheap temporaries
 - few *def/uses*
 - pay attention to loops

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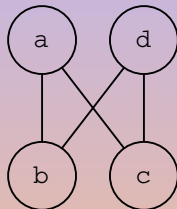
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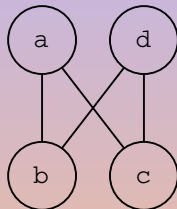
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- We miss many opportunities to avoid the stack



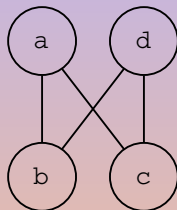
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- then try to color them
- There might not be *actual spills*

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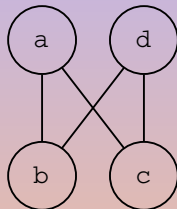
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 - Spilling
 - **Coalescing**
 - Precolored Nodes
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- 3 Alternatives to Graph Coloring

- Some low-level form of *copy propagation*
- While building traces we tried to remove jumps
- While allocating registers, we try to remove moves

live-in: t2

t1 := ...

t2 := t1 + t2

t3 := t2

t4 := t1 + t3

t2 := t3 + t4

t1 := t2 - t4

live-out: t1

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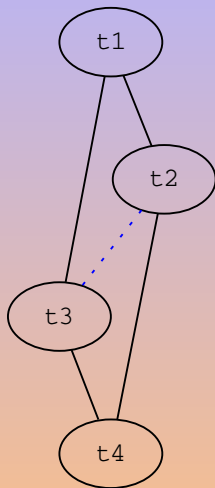
t4 := t1 + t3

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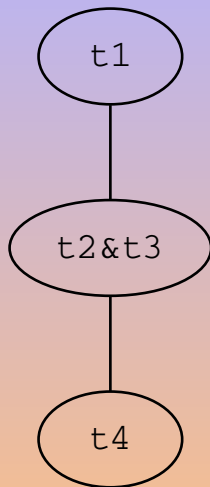
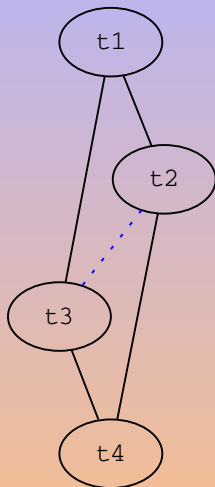
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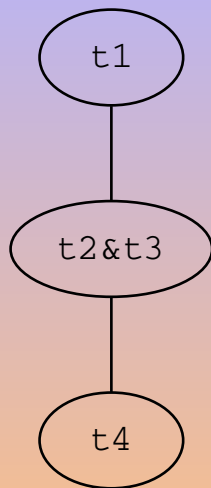
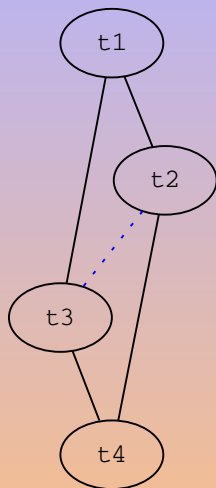
Coalescing Improves the Colorability



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t1 and t4 have **one neighbor less!**

Yes, But Coalesce Who?

- *Conservative Coalescing*: don't make it harder.
- Coalesce a and b if
 - ab has fewer than k neighbors of significant degree.
 - a and b are
 - of significant degree
 - already interfering with b
- George's criterion is well suited for real registers

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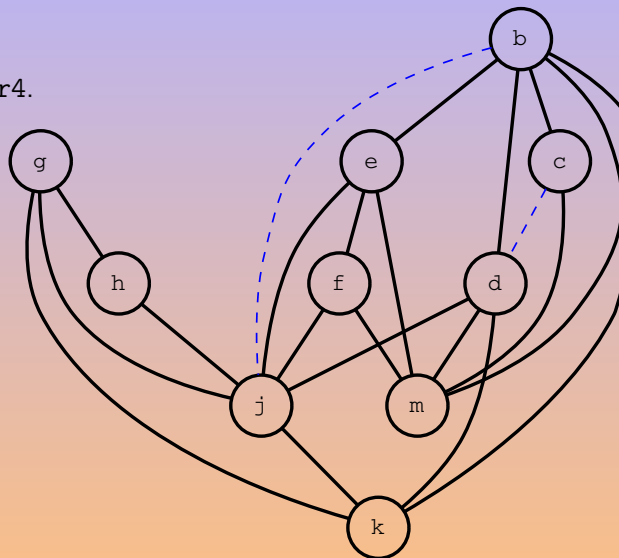
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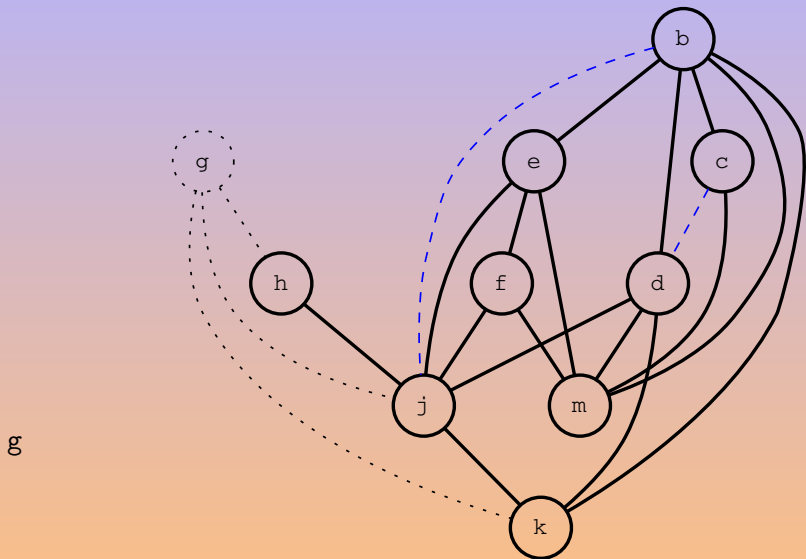
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live out: d k j
```

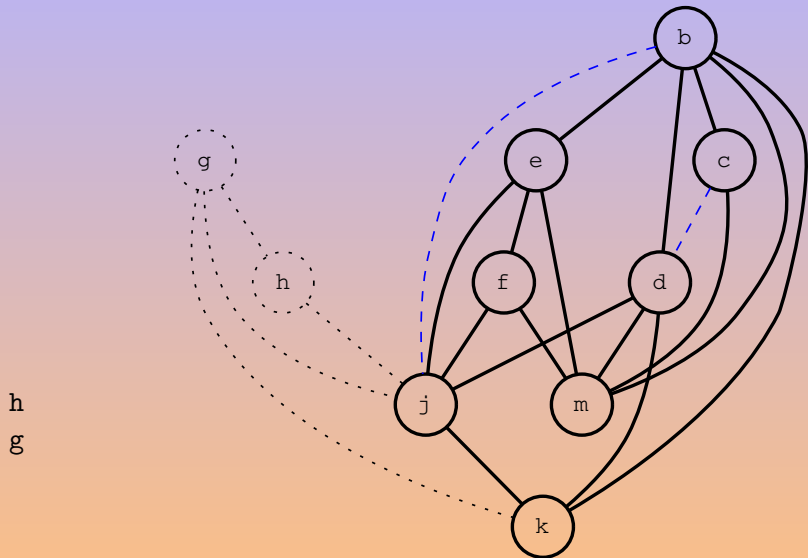


Interference Graph: Simplify 0

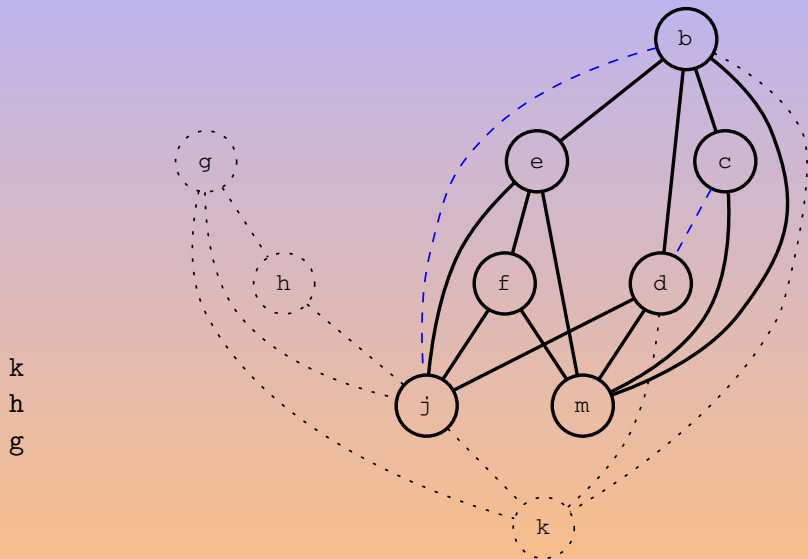


σ₀

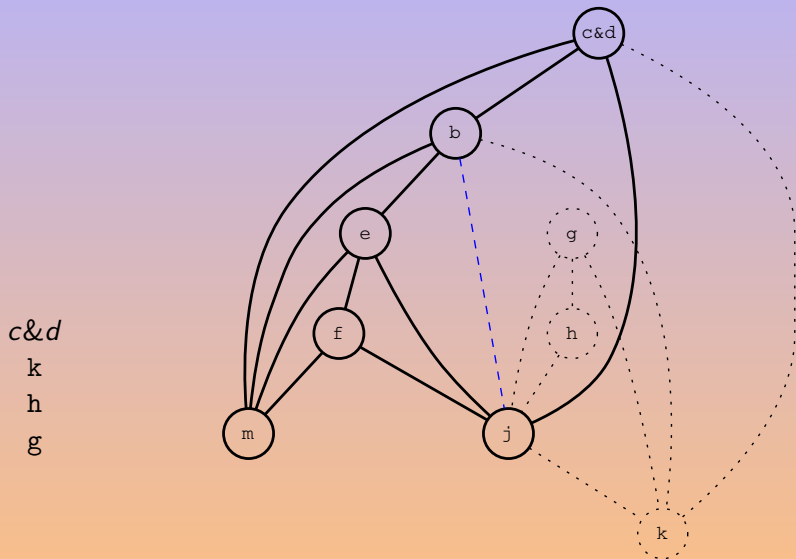
Interference Graph: Simplify 1



Interference Graph: Simplify 2

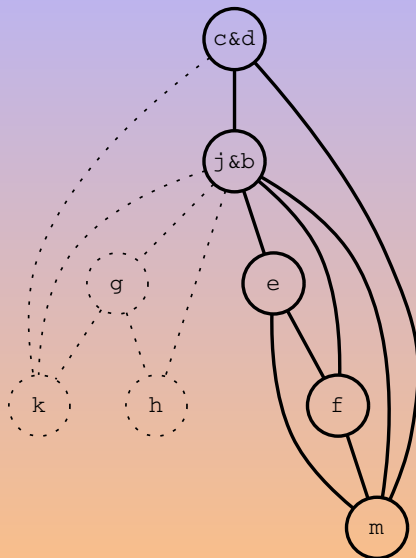


Interference Graph: Simplify 3



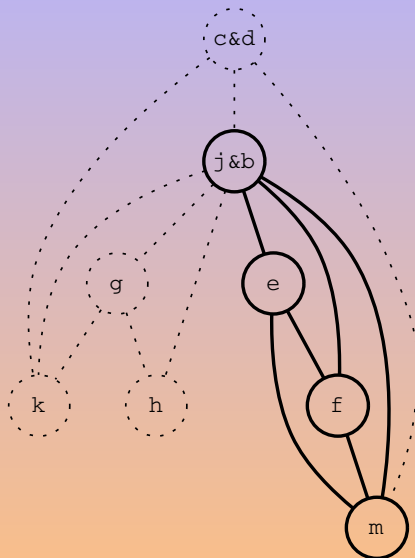
Interference Graph: Simplify 4

j&b
c&d
k
h
g



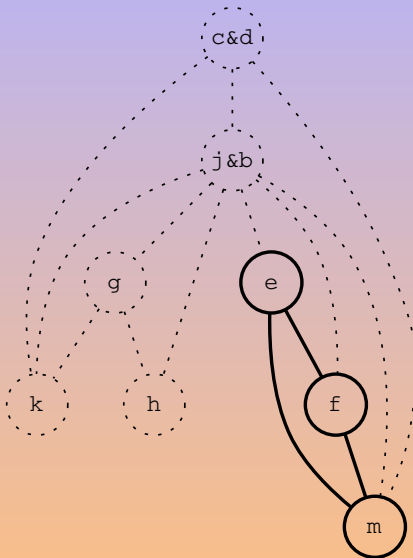
Interference Graph: Simplify 5

c&d
j&b
c&d
k
h
g



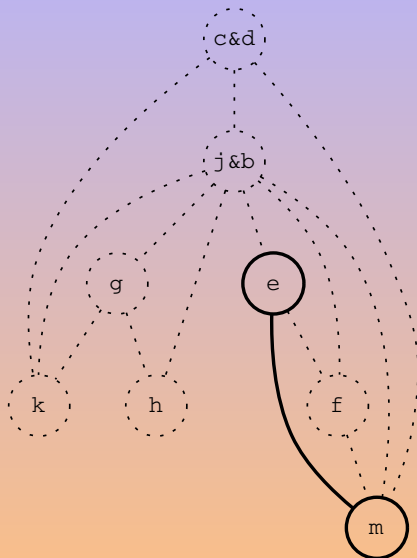
Interference Graph: Simplify 6

j&b
c&d
j&b
c&d
k
h
g



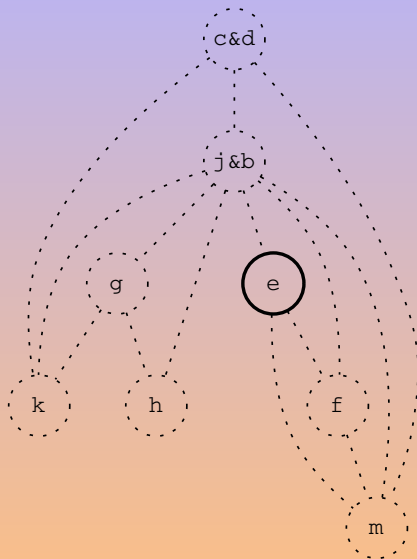
Interference Graph: Simplify 7

f
j&b
c&d
j&b
c&d
k
h
g



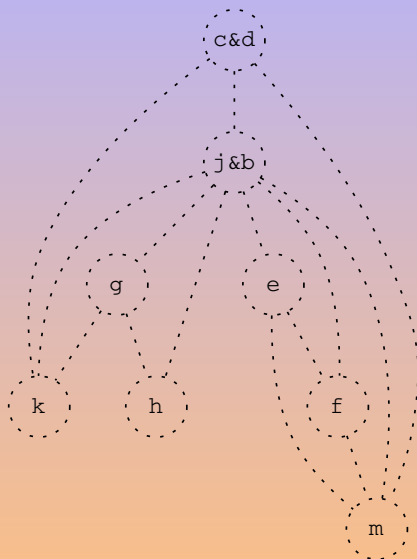
Interference Graph: Simplify 8

m
f
j&b
c&d
j&b
c&d
k
h
g



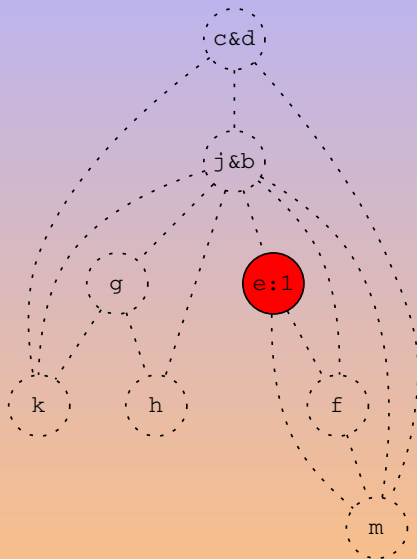
Interference Graph: Simplify 9

e
m
f
j&b
c&d
j&b
c&d
k
h
g



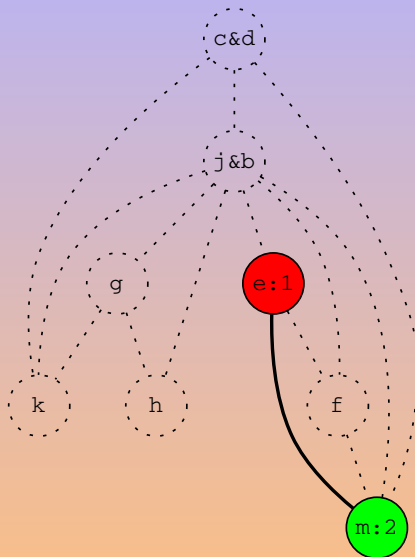
Interference Graph: Simplify 9

e
m
f
j&b
c&d
j&b
c&d
k
h
g



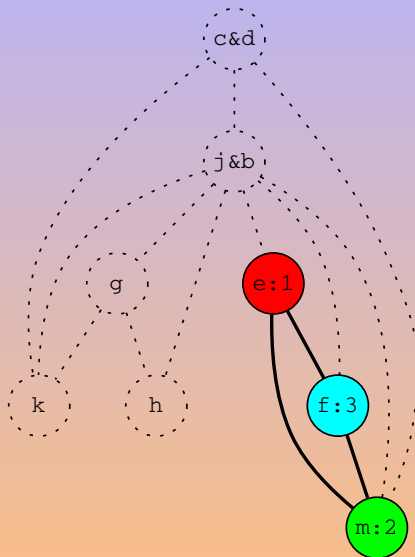
Interference Graph: Simplify 8

m
f
j&b
c&d
j&b
c&d
k
h
g



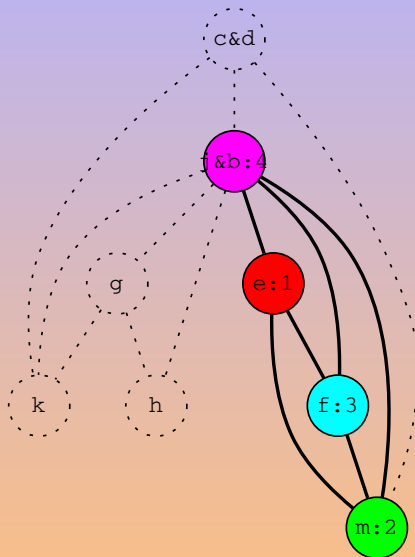
Interference Graph: Simplify 7

f
j&b
c&d
j&b
c&d
k
h
g



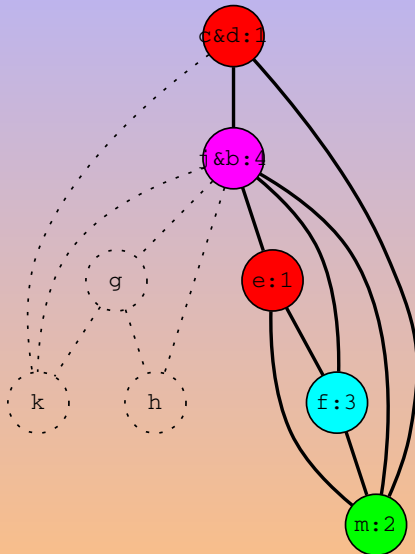
Interference Graph: Simplify 6

j&b
c&d
j&b
c&d
k
h
g



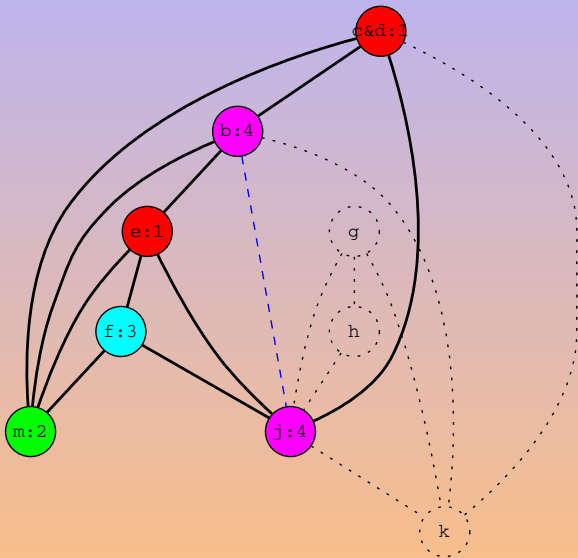
Interference Graph: Simplify 5

c&d
j&b
c&d
k
h
g

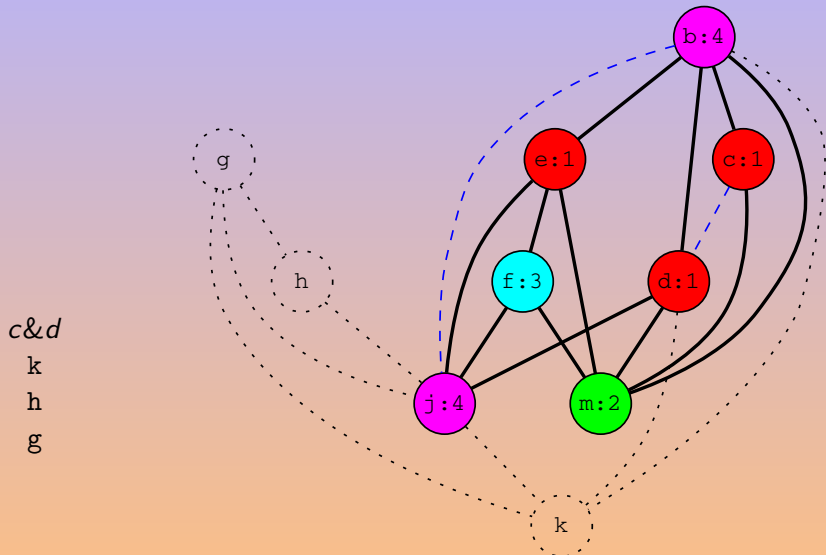


Interference Graph: Simplify 4

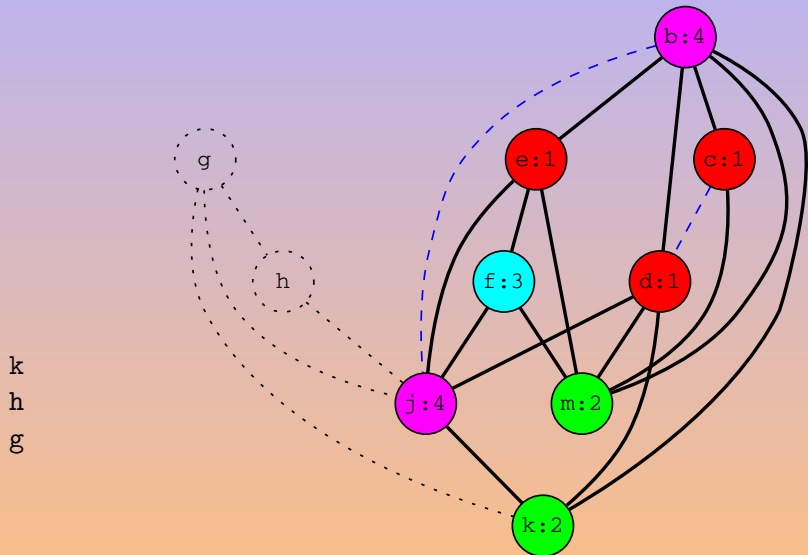
j&b
c&d
k
h
g



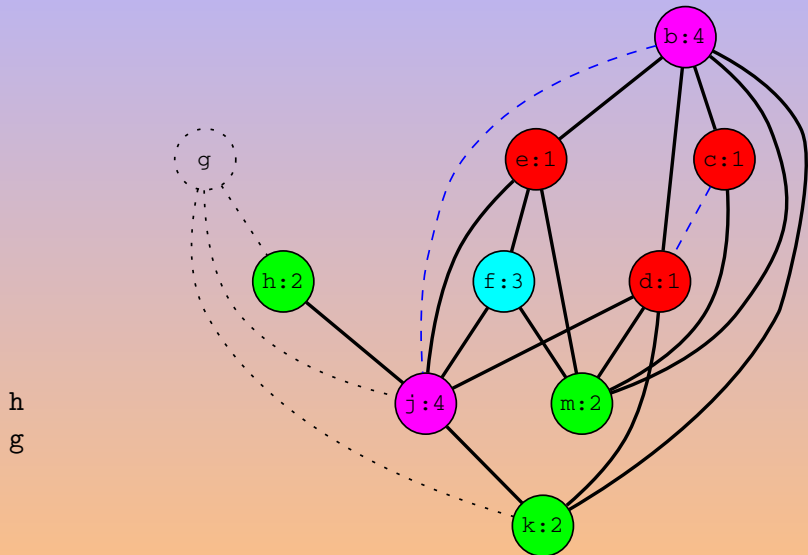
Interference Graph: Simplify 3



Interference Graph: Simplify 2

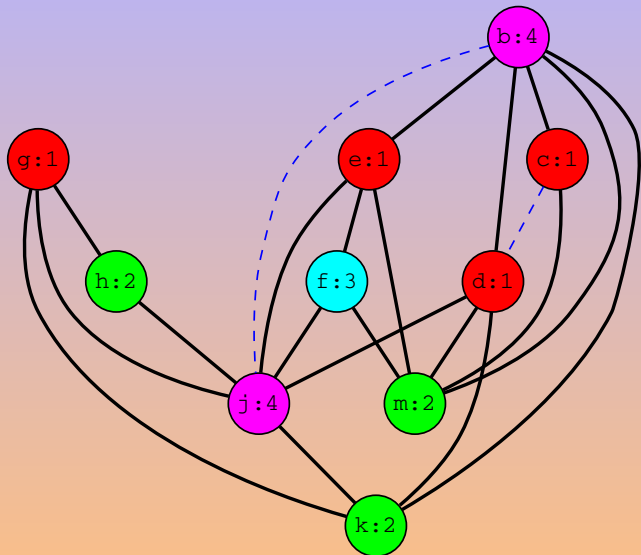


Interference Graph: Simplify 1



Interference Graph: Simplify 0

09



Interference Graph: Result

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

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


Precolored Nodes

- 1 Interference Graph
- 2 Coloring by Simplification
 - Spilling
 - Coalescing
 - **Precolored Nodes**
 - Implementation
- 3 Alternatives to Graph Coloring

- Some nodes are precolored: the real registers
 - the stack pointer (\$sp)
 - the frame pointer (\$fp)
 - the argument registers (\$a0, \$a1, etc.)
 - the return value (\$v0, \$v1)
 - the return address (\$ra)
 - etc.
- They all interfere with each other
- They cannot be simplified (infinite degree)

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Callee & Caller Save Registers

- It just rocks!

 - Caller Save Def'd by calls.

 - Callee Save Def'd at entry, used at exit of functions.

- Register pressure will push temporaries live across calls into callee save.

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Minimize the conflicts (“pressure”) with hard regs. Source and sink.

Routine: fact

```
10:                                # def $s0, $s1...
    move $x11, $s0                 # def: $x11 use: $s0
    move $x12, $s1                 # def: $x12 use: $s1
    ...
16:
    move $s0, $x11                 # def: $s0 use: $x11
    move $s1, $x12                 # def: $s1 use: $x12
    ...
                                    # use: $fp, $ra, $sp,
                                    # ... $v0, $zero
```

Example [Appel, 1998]

```
int
f (int a, int b)
{
  int d = 0;
  int e = a;
  do
  {
    d += b;
    --e;
  } while (e > 0);
  return 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
# liveout: r1, r3
```

Example

```
enter:
```

```
  c := r3
```

```
  a := r1
```

```
  b := r2
```

```
  d := 0
```

```
  e := a
```

```
loop:
```

```
  d := d + b
```

```
  e := e - 1
```

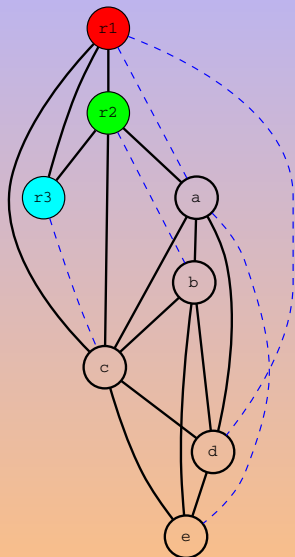
```
  if e > 0 goto loop
```

```
  r1 := d
```

```
  r3 := c
```

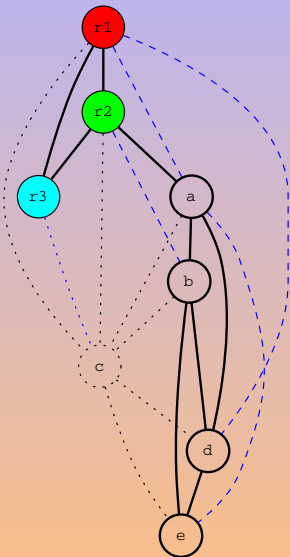
```
  return
```

```
# liveout: r1, r3
```



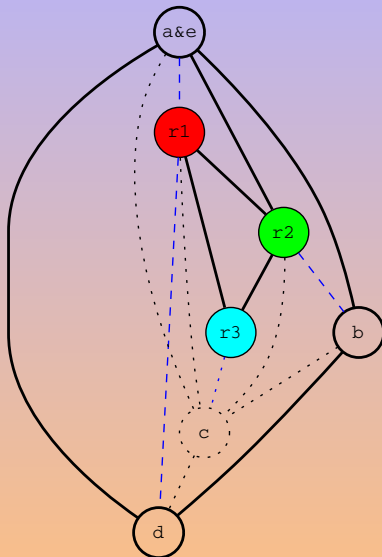
Interference Graph: Simplify 0

c



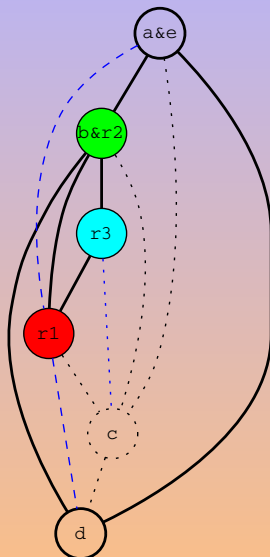
Interference Graph: Simplify 1

a&e
c



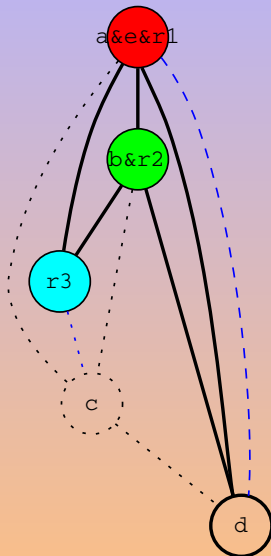
Interference Graph: Simplify 2

b&r2
a&e
c



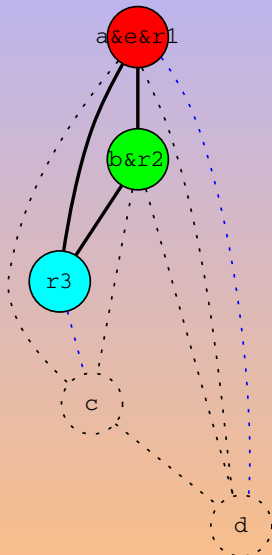
Interference Graph: Simplify 3

`a&e&r1`
`b&r2`
`a&e`
`c`



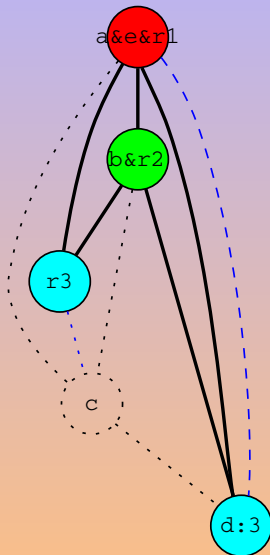
Interference Graph: Simplify 4

d
a&e&r1
b&r2
a&e
c



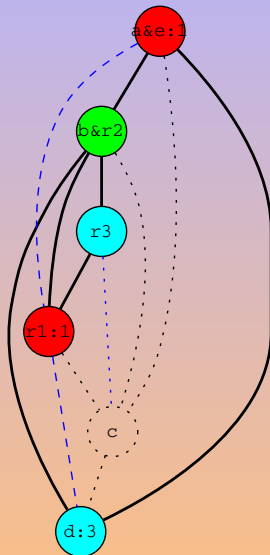
Interference Graph: Simplify 4

d
a&e&r1
b&r2
a&e
c



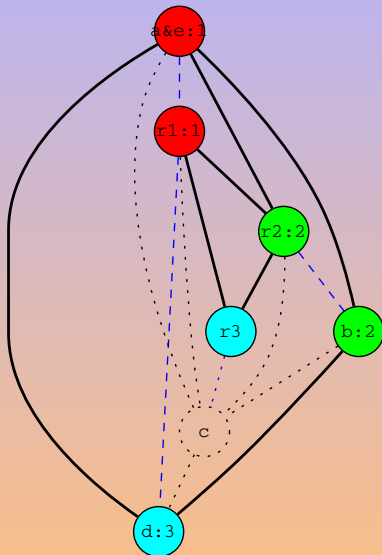
Interference Graph: Simplify 3

`a&e&r1`
`b&r2`
`a&e`
`c`



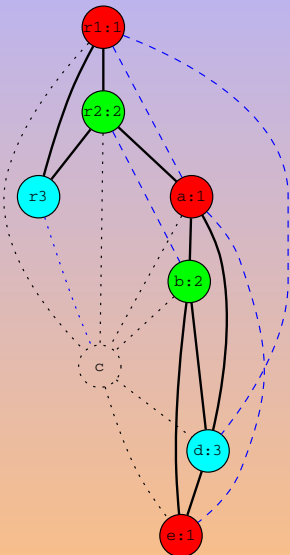
Interference Graph: Simplify 2

b&*r2*
a&*e*
c



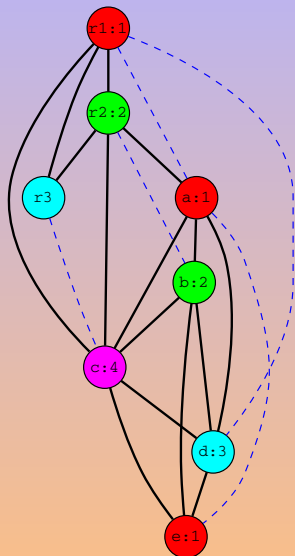
Interference Graph: Simplify 1

a&e
c



Interference Graph: Simplify 0

C



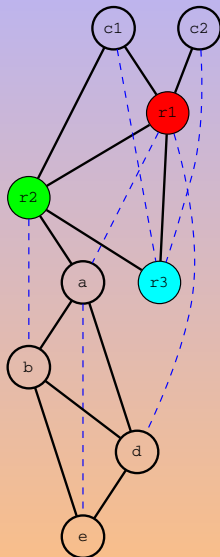
Spilling

```
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
# liveout: r1, r3
```

```
enter:
  c1 := r3
  [sp+8] := c1
  a := r1
  b := r2
  d := 0
  e := a
loop:
  d := d + b
  e := e - 1
  if e > 0
    goto loop
  r1 := d
  c2 := [sp+8]
  r3 := c2
  return
# liveout: r1, r3
```

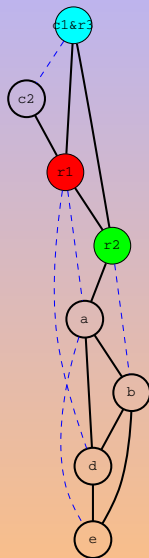

Example

```
enter:
  c1 := r3
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  a := r1
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    goto loop
  r1 := d
  c2 := [sp+8]
  r3 := c2
  return
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```



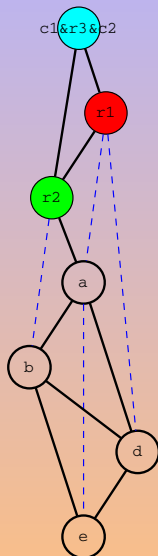
Interference Graph: Simplify 0

$c1&r3$



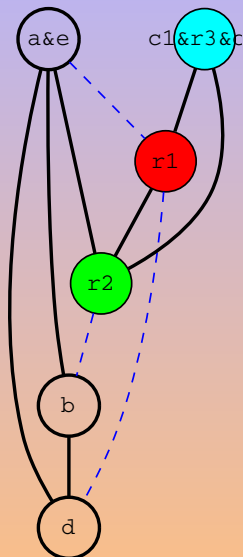
Interference Graph: Simplify 1

$c1 \& r3 \& c2$
 $c1 \& r3$



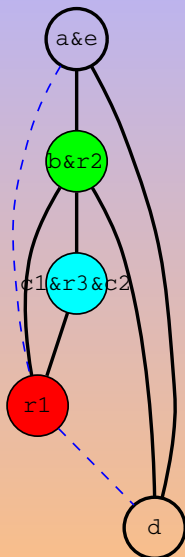
Interference Graph: Simplify 2

a&e
c1&r3&c2
c1&r3



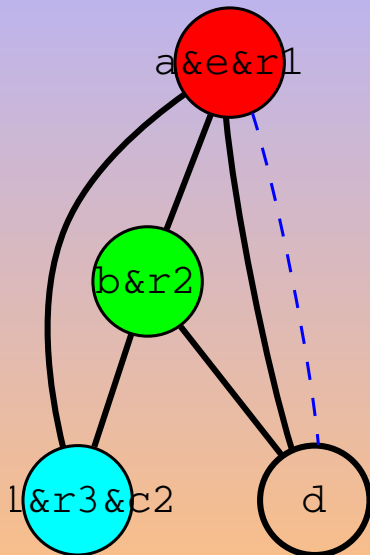
Interference Graph: Simplify 3

$b \& r2$
 $a \& e$
 $c1 \& r3 \& c2$
 $c1 \& r3$

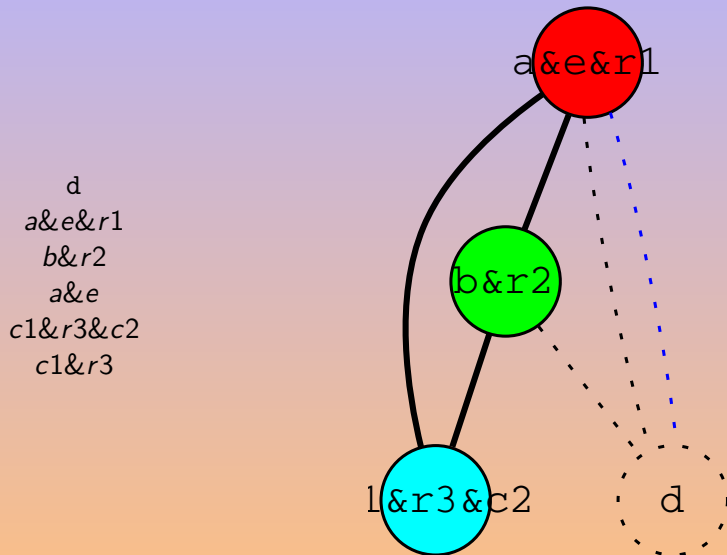


Interference Graph: Simplify 4

`a&e&r1`
`b&r2`
`a&e`
`c1&r3&c2`
`c1&r3`

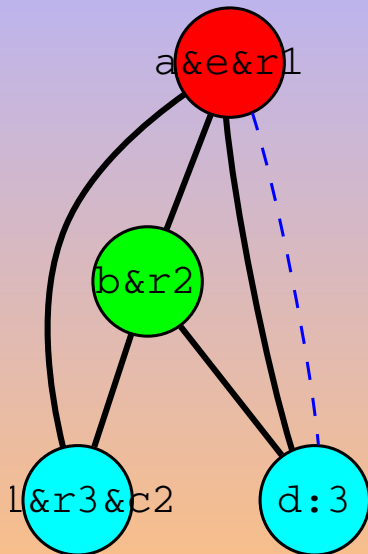


Interference Graph: Simplify 5



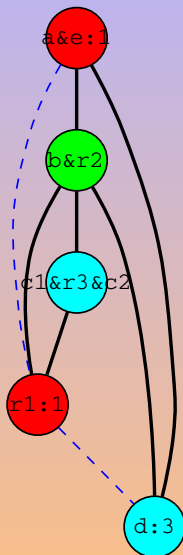
Interference Graph: Simplify 5

d
a&e&r1
b&r2
a&e
c1&r3&c2
c1&r3



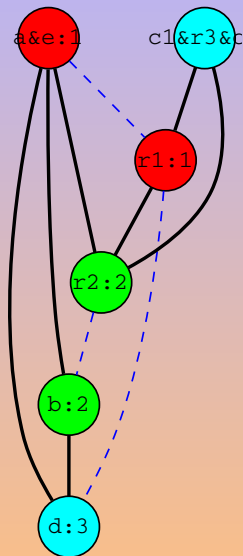
Interference Graph: Simplify 4

`a&e&r1`
`b&r2`
`a&e`
`c1&r3&c2`
`c1&r3`



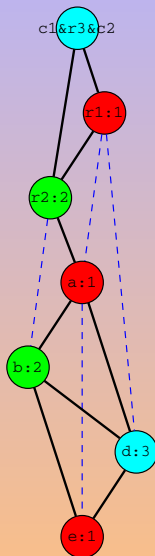
Interference Graph: Simplify 3

b&r2
a&e
c1&r3&c2
c1&r3



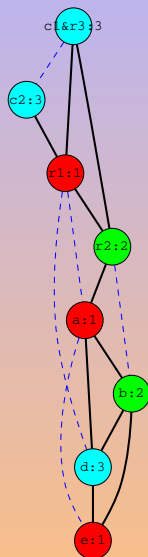
Interference Graph: Simplify 2

$a \& e$
 $c1 \& r3 \& c2$
 $c1 \& r3$



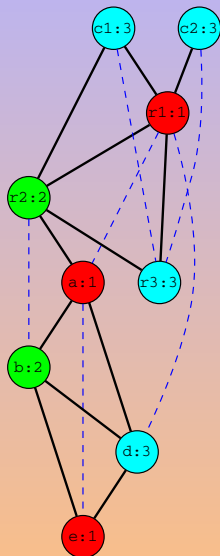
Interference Graph: Simplify 1

$c1 \& r3 \& c2$
 $c1 \& r3$



Interference Graph: Simplify 0

$c1 \& r3$



Result

```
enter:
  c1 := r3
  [sp+8] := c1
  a := r1
  b := r2
  d := 0
  e := a
loop:
  d := d + b
  e := e - 1
  if e > 0
    goto loop
  r1 := d
  c2 := [sp+8]
  r3 := c2
  return
# liveout: r1, r3
```

```
enter:
  r3 := r3
  [sp+8] := r3
  r1 := r1
  r2 := r2
  r3 := 0
  r1 := r1
loop:
  r3 := r3 + r2
  r1 := r1 - 1
  if r1 > 0
    goto loop
  r1 := r3
  r3 := [sp+8]
  r3 := r3
  return
# liveout: r1, r3
```

```
enter:
  [sp+8] := r3
  r3 := 0
loop:
  r3 := r3 + r2
  r1 := r1 - 1
  if r1 > 0
    goto loop
  r1 := r3
  r3 := [sp+8]
  return
# liveout: r1, r3
```

Implementation

- 1 Interference Graph
- 2 Coloring by Simplification
 - Spilling
 - Coalescing
 - Precolored Nodes
 - Implementation
- 3 Alternatives to Graph Coloring

- Naive implementation is quadratic
- Lower with heavy use of *worklists*
- Queries on the conflict graph
 - Existence of an edge between two nodes, hence bit matrix.
- For more information, see [Appel, 1998].

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Use both!

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Alternatives to Graph Coloring

- 1 Interference Graph
- 2 Coloring by Simplification
- 3 Alternatives to Graph Coloring

Register Allocation for Trees

Can be done during instruction selection with maximal munch

```
function SimpleAlloc (t)
```

```
  for each nontrivial tile u child of t
```

```
    SimpleAlloc (u)
```

```
  for each nontrivial tile u child of t
```

```
    n := n - 1
```

```
  n := n + 1
```

```
  assign rn to (the root of) t
```

```
[Appel, 1998]
```




Appel, A. W. (1998).

Modern Compiler Implementation in C, Java, ML.
Cambridge University Press.



Briggs, P. (1992).

Register Allocation via Graph Coloring.
PhD thesis, Rice University, Houston, Texas.



Matz, M. (2003).

Design and Implementation of a Graph Coloring Register Allocator for gcc.
pages 151–169.