Register Allocation

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EPITA — École Pour l'Informatique et les Techniques Avancées

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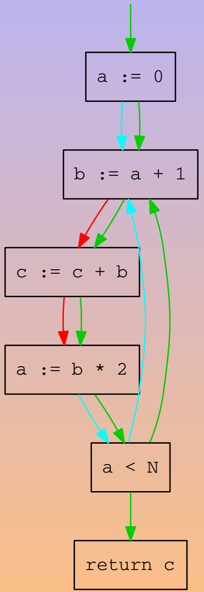
Register Allocation

Interference Graph



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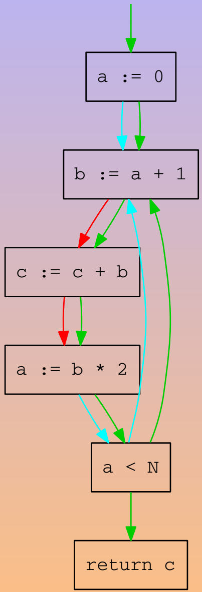

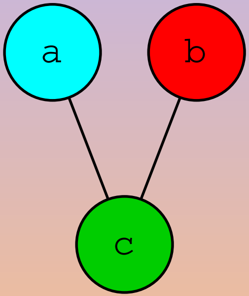

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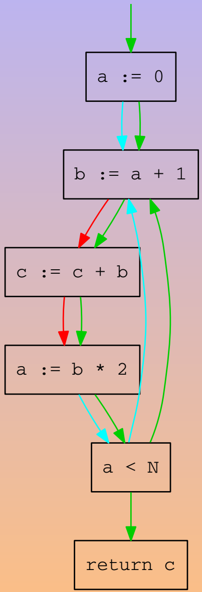

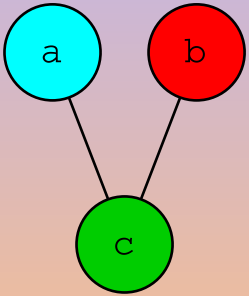

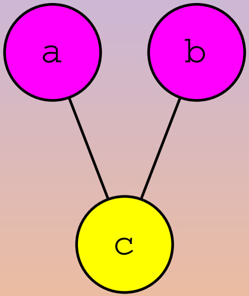

Register Allocation

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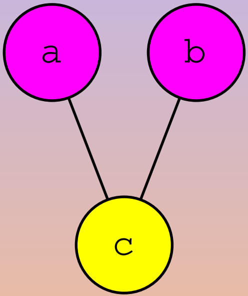

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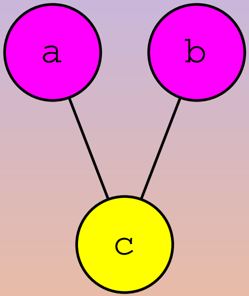
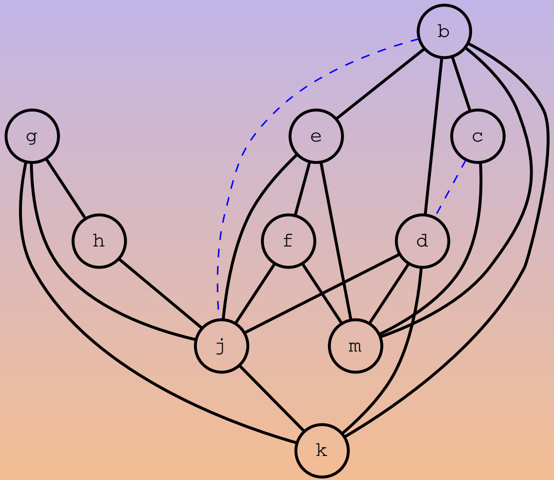



```
    r1 := 0
L1: r1 := r1 + 1
    r2 := r2 + r1
    r1 := r1 * 2
    if r1 < N goto L1
    return r2
```

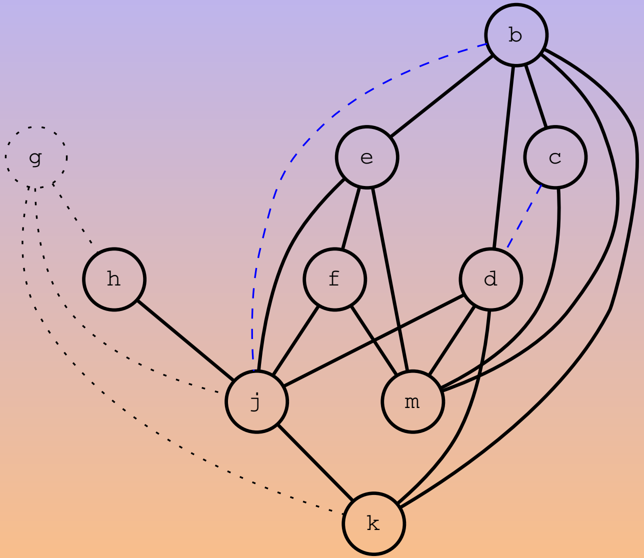
Interference Graph [Appel, 1998]

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
```

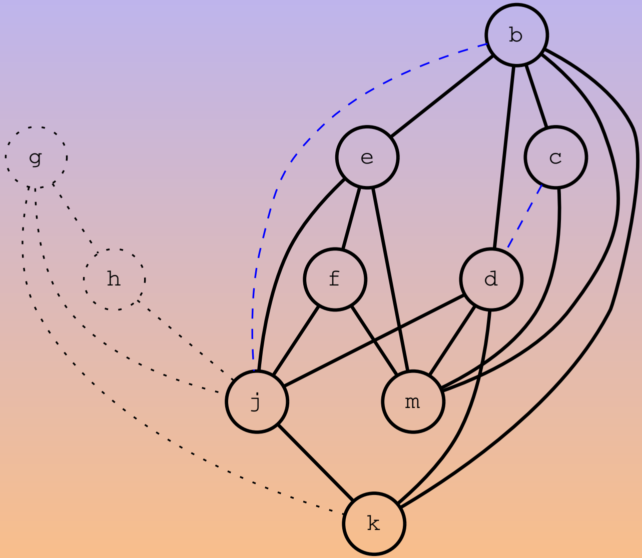


Interference Graph: Simplify 0



g

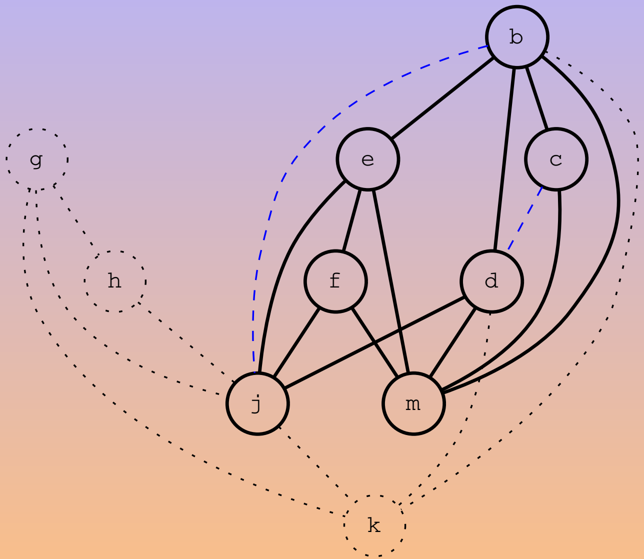
Interference Graph: Simplify 1



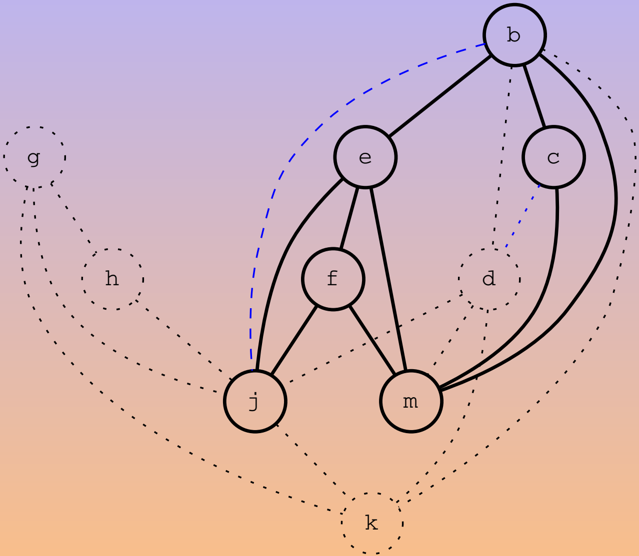
h
g

Interference Graph: Simplify 2

k
h
g



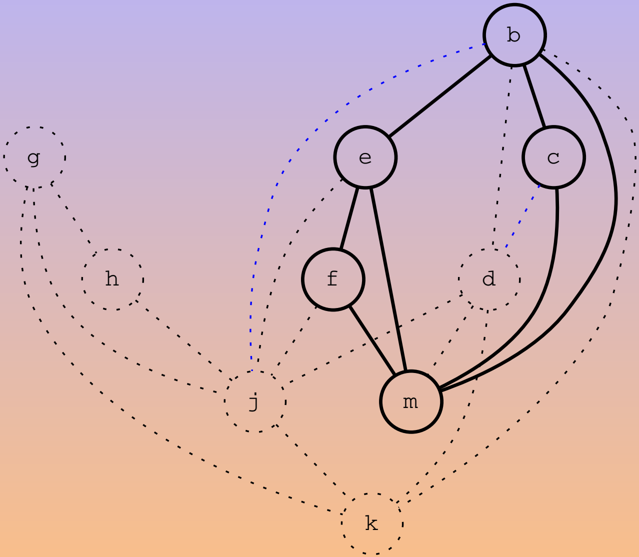
Interference Graph: Simplify 3



d
k
h
g

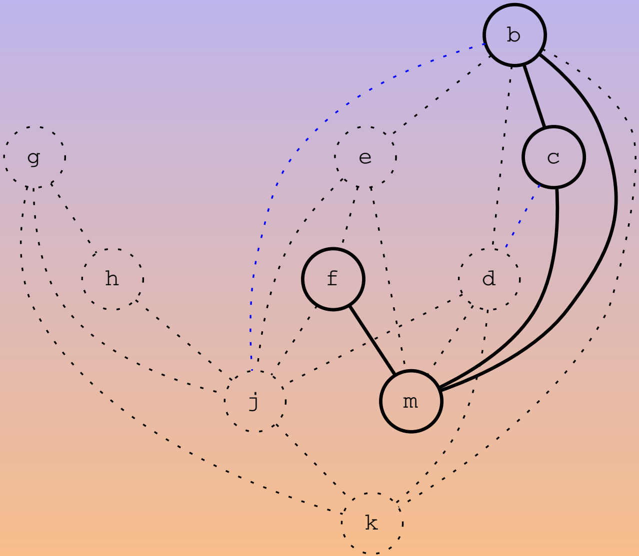
Interference Graph: Simplify 4

j
d
k
h
g



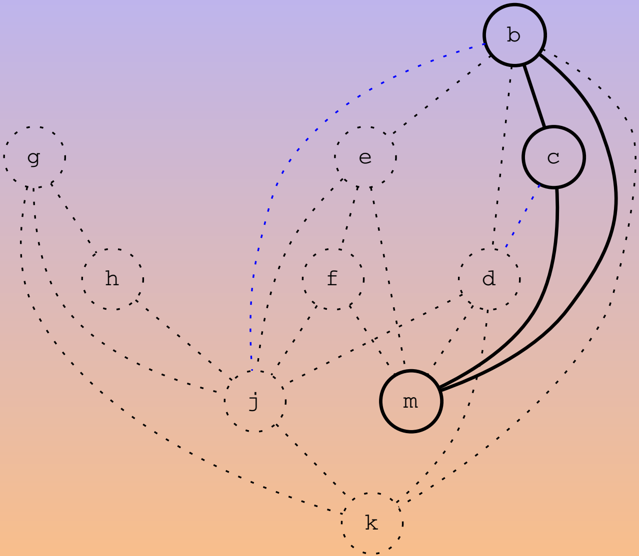
Interference Graph: Simplify 5

e
j
d
k
h
g



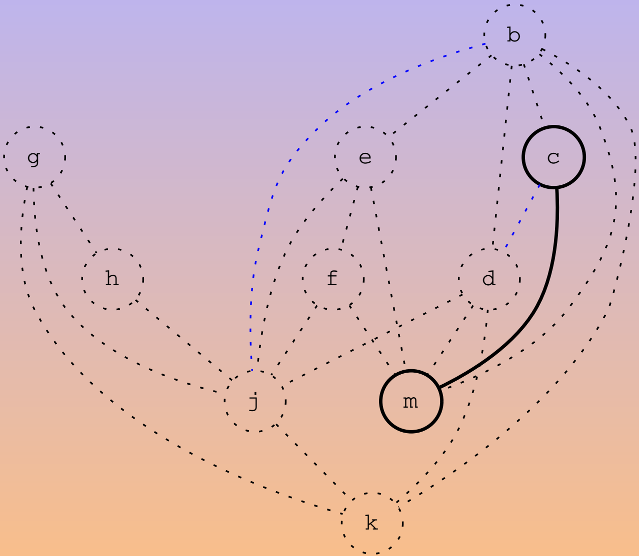
Interference Graph: Simplify 6

f
e
j
d
k
h
g



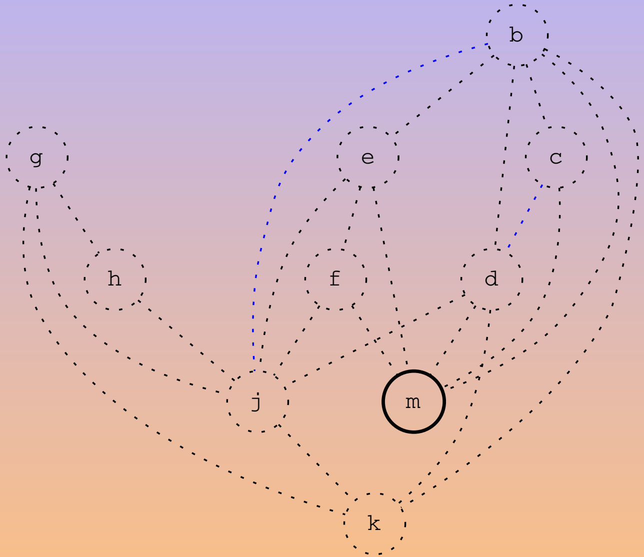
Interference Graph: Simplify 7

b
f
e
j
d
k
h
g



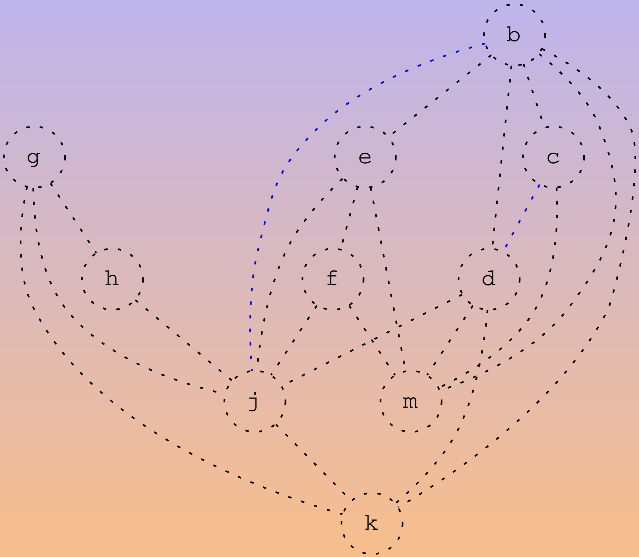
Interference Graph: Simplify 8

c
b
f
e
j
d
k
h
g



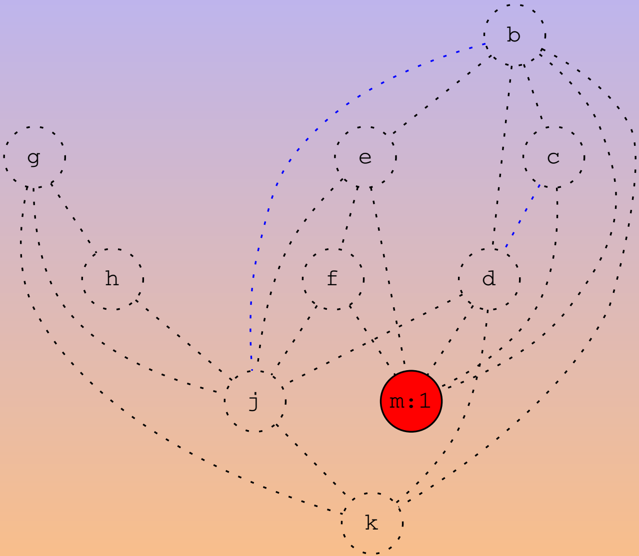
Interference Graph: Simplify 9

m
c
b
f
e
j
d
k
h
g



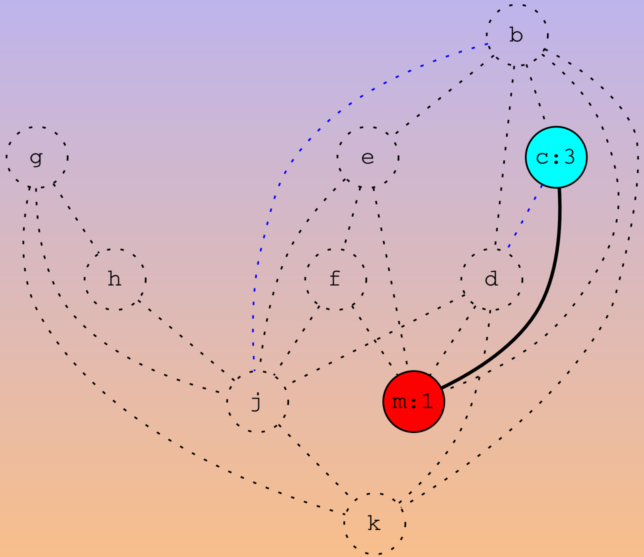
Interference Graph: Color 9

m
c
b
f
e
j
d
k
h
g



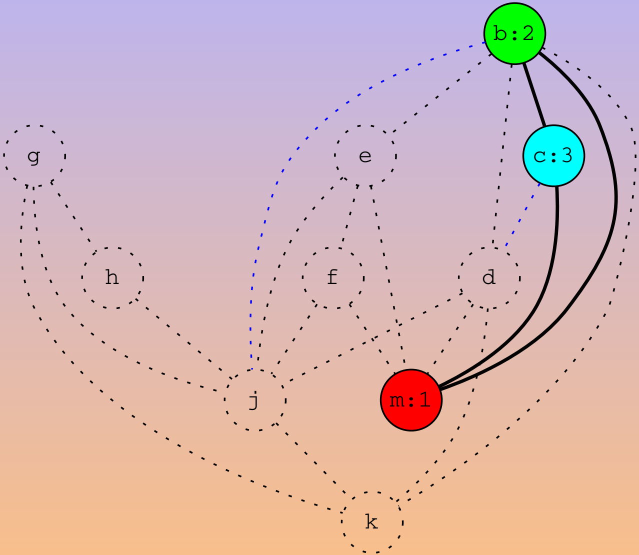
Interference Graph: Color 8

c
b
f
e
j
d
k
h
g



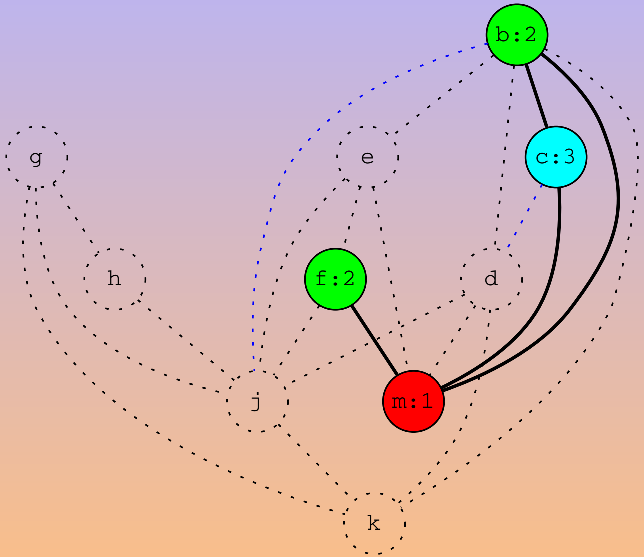
Interference Graph: Color 7

b
f
e
j
d
k
h
g



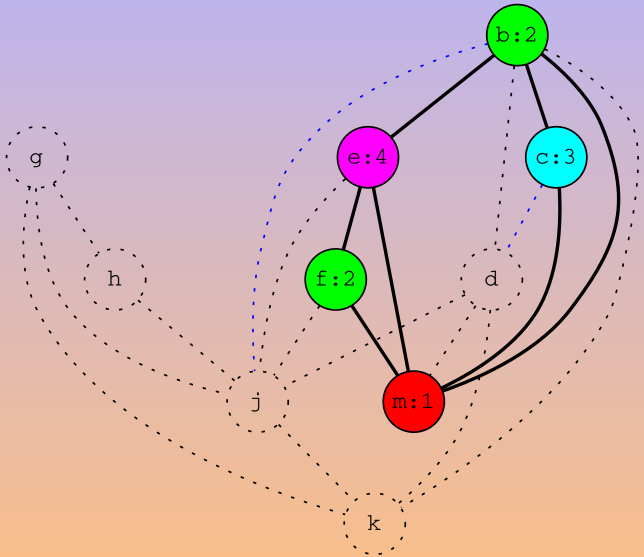
Interference Graph: Color 6

f
e
j
d
k
h
g



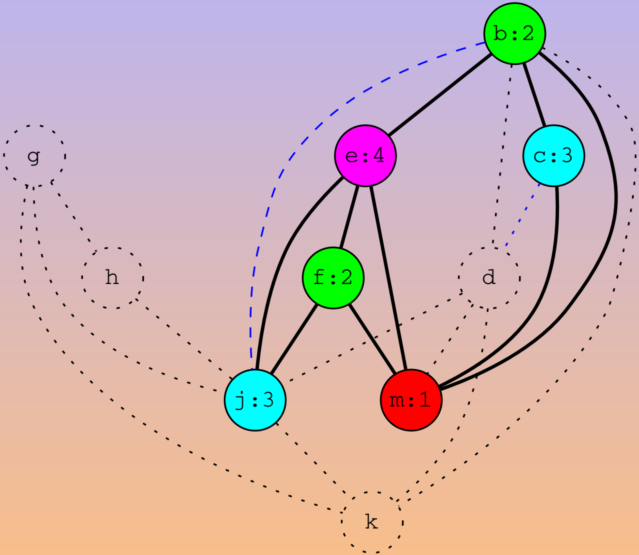
Interference Graph: Color 5

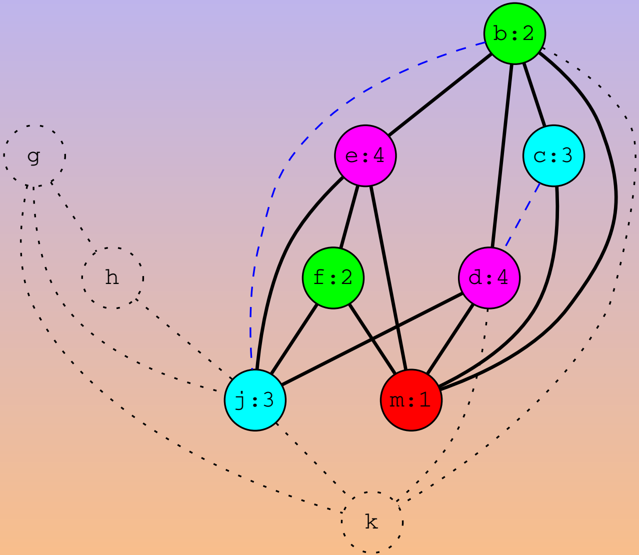
e
j
d
k
h
g



Interference Graph: Color 4

j
d
k
h
g

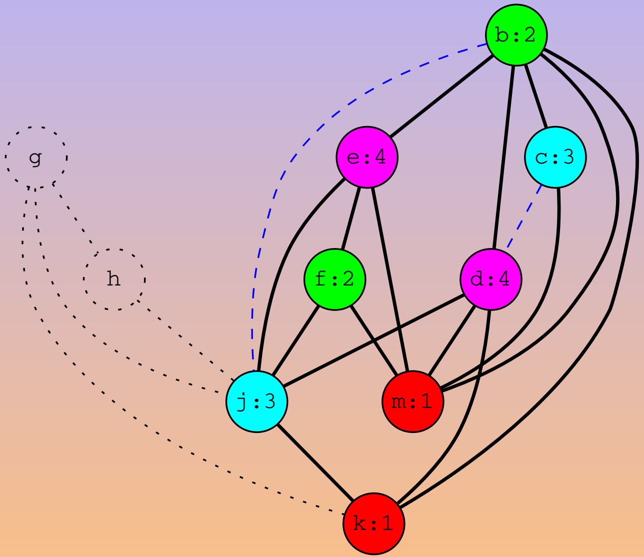




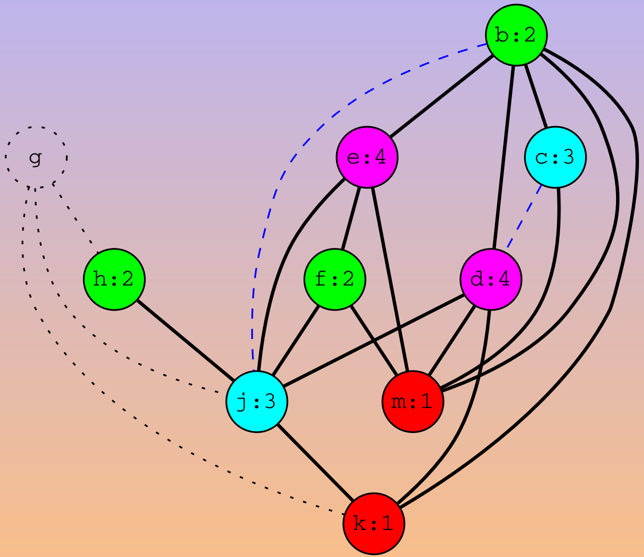
d
k
h
g

Interference Graph: Color 2

k
h
g



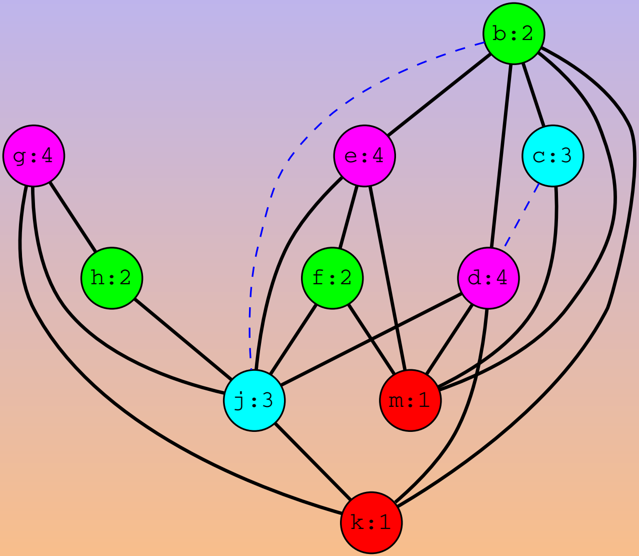
Interference Graph: Color 1



h
g

Interference Graph: Color 0

g



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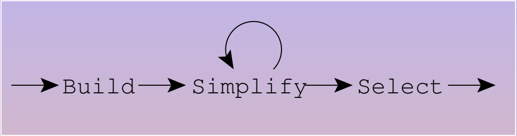
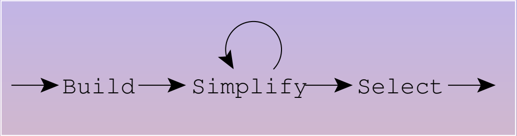
  r3 := r2
live out: r4 r1 r3
```



build the conflict graph from the program

simplify the nodes with insignificant degree

select (or color) while rebuilding the graph.



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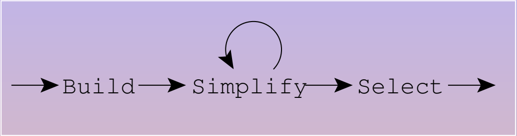
Simple Register Allocation



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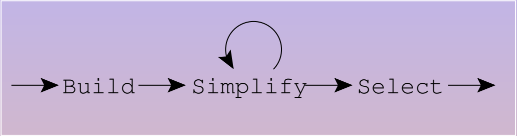

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Based on:

> *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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Spilling

- 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?

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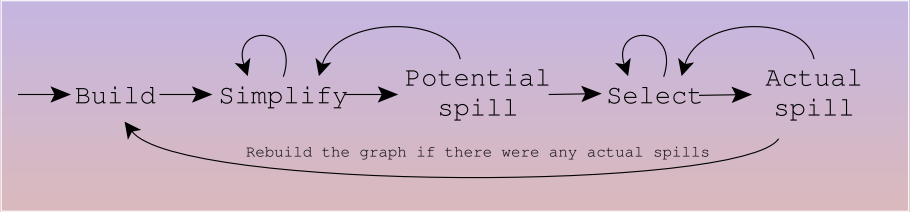
Register Allocation with Spills



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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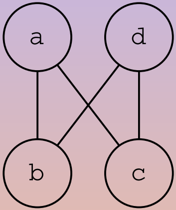
Optimistic Coloring

- 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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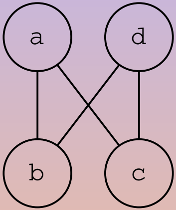

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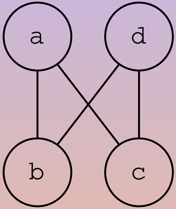

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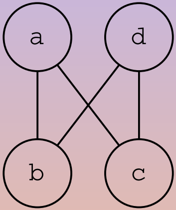

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Coalescing

Coalescing

- 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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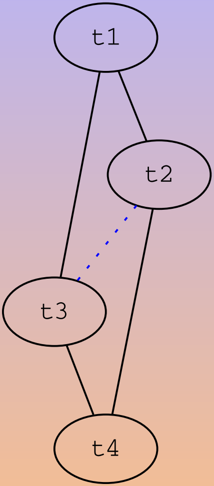
Coalescing Improves the Coloralibility



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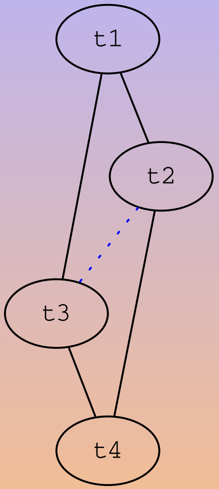

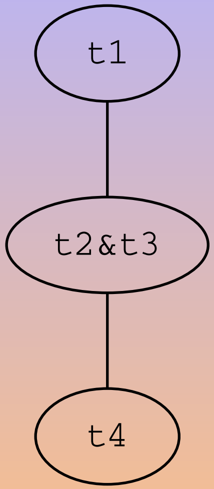

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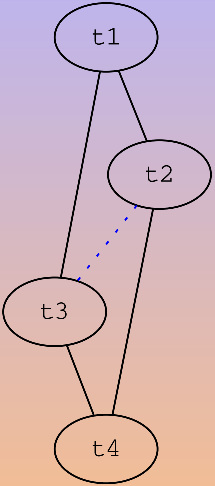

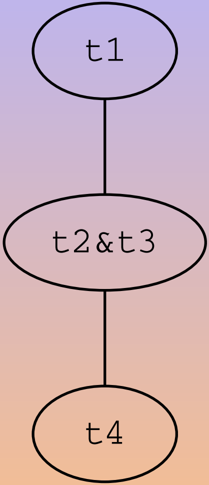

t1 and t4 have one neighbor less!

Yes, But Coalesce Who?

- *Conservative Coalescing*: don't make it harder.
- Coalesce `a` and `b` if

  Briggs: `ab` has fewer than k neighbors of significant degree

  George: every neighbor of `a` is

  - of insignificant degree
  - already interfering with `b`
- George's criterion is well suited for real registers

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- Coalesce `a` and `b` if

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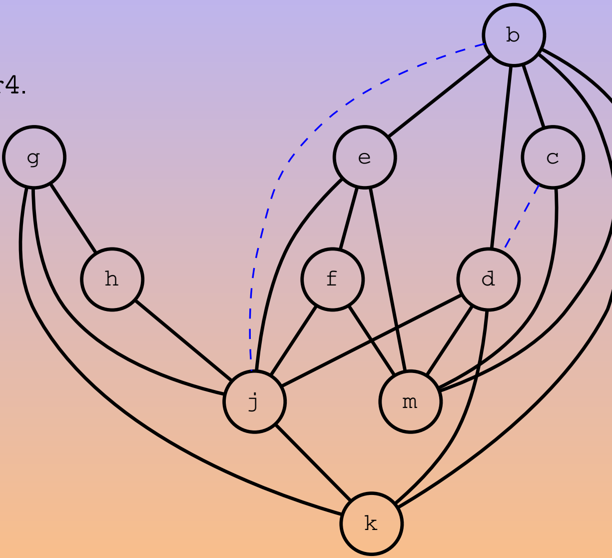
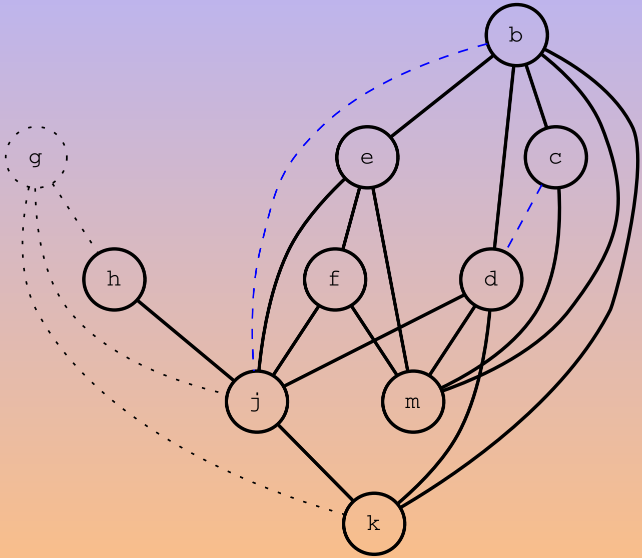
Four registers: `r1`, `r2`, `r3`, `r4`.

```
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
```

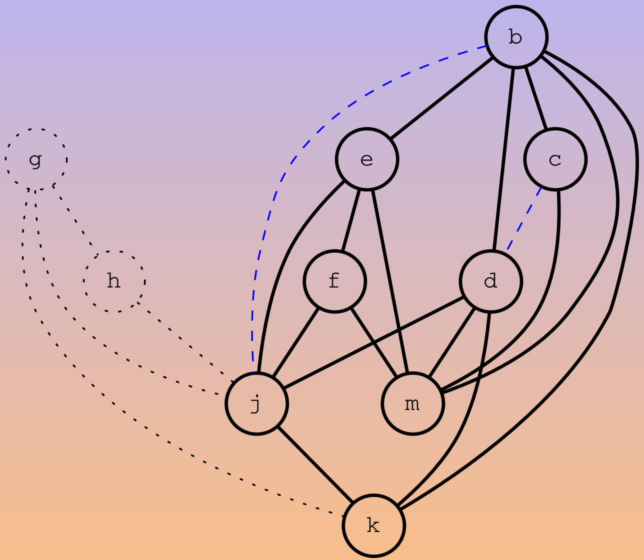


Interference Graph: Simplify 0



g

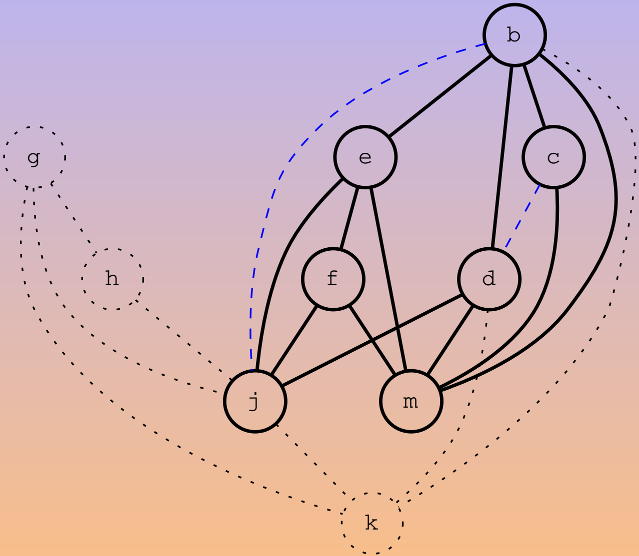
Interference Graph: Simplify 1



h
g

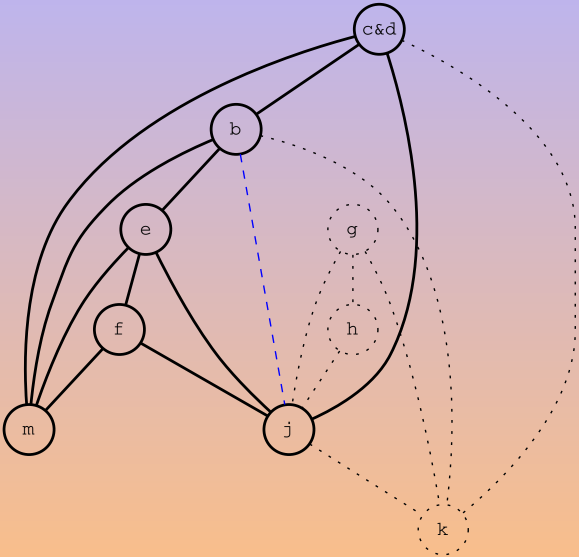
Interference Graph: Simplify 2

k
h
g

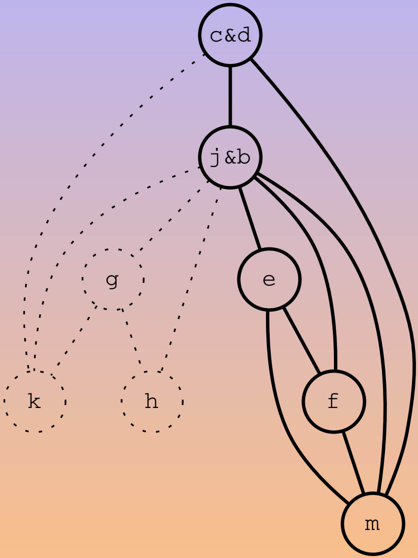


Interference Graph: Simplify 3

c&d
k
h
g

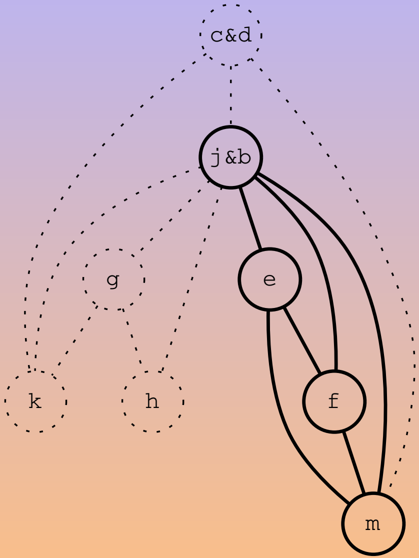


j&b
c&d
k
h
g



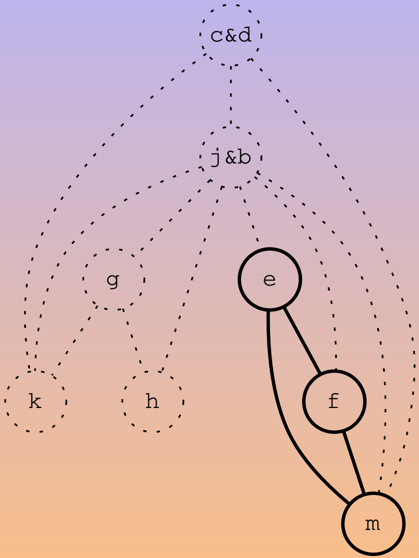
Interference Graph: Simplify 5

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



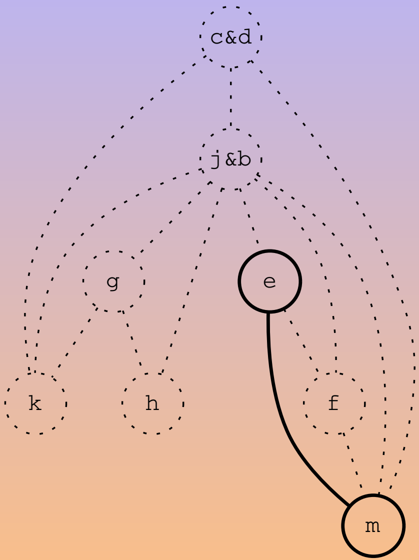
Interference Graph: Simplify 6

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



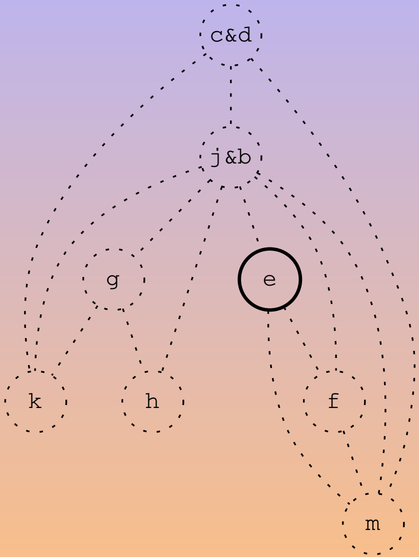
Interference Graph: Simplify 7

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



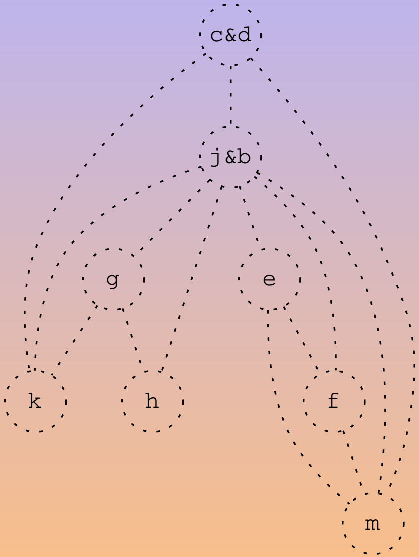
Interference Graph: Simplify 8

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



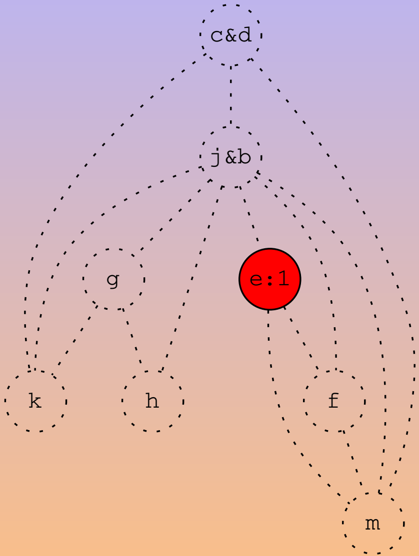
Interference Graph: Simplify 9

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



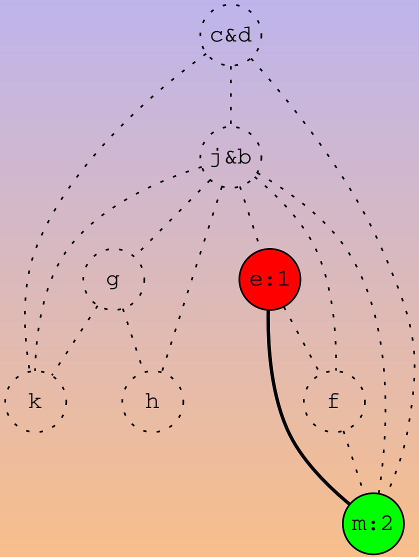
Interference Graph: Simplify 9

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



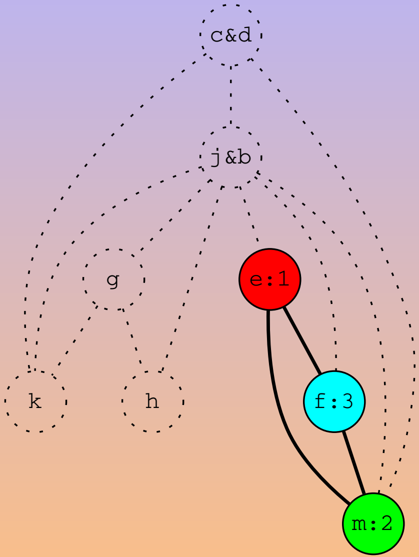
Interference Graph: Simplify 8

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



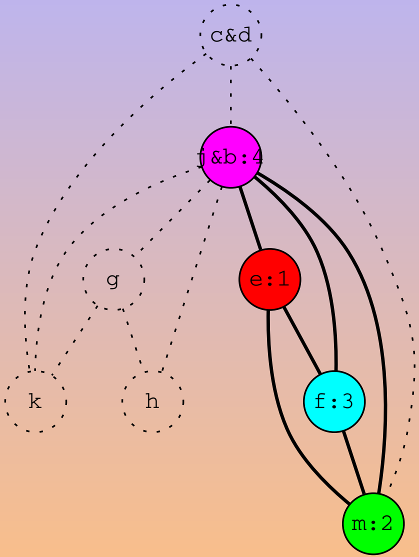
Interference Graph: Simplify 7

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



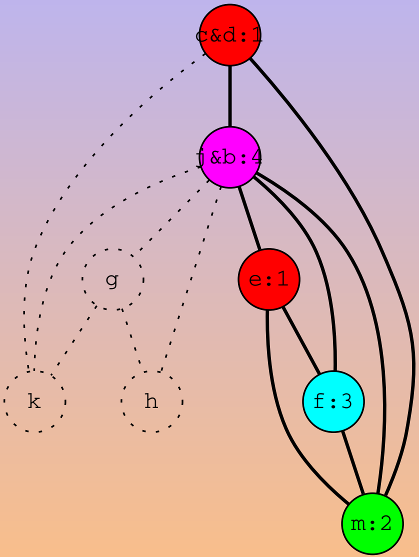
Interference Graph: Simplify 6

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



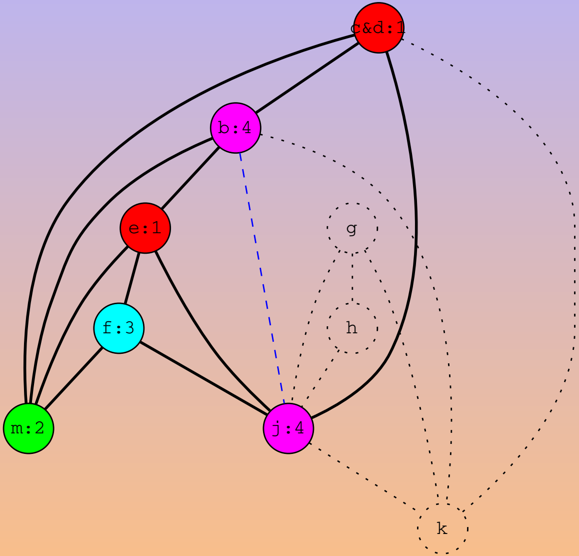
Interference Graph: Simplify 5

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



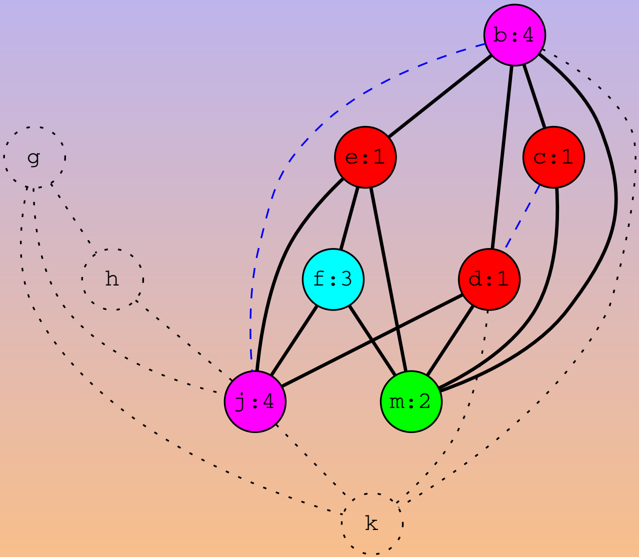
Interference Graph: Simplify 4

j&b
c&d
k
h
g



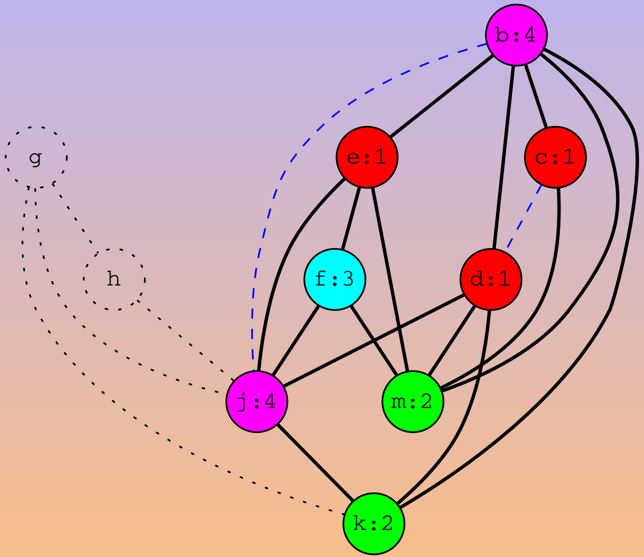
Interference Graph: Simplify 3

c&d
k
h
g

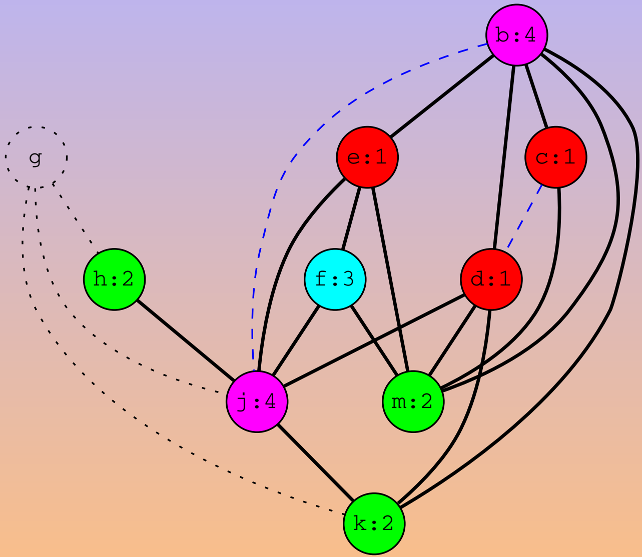


Interference Graph: Simplify 2

k
h
g

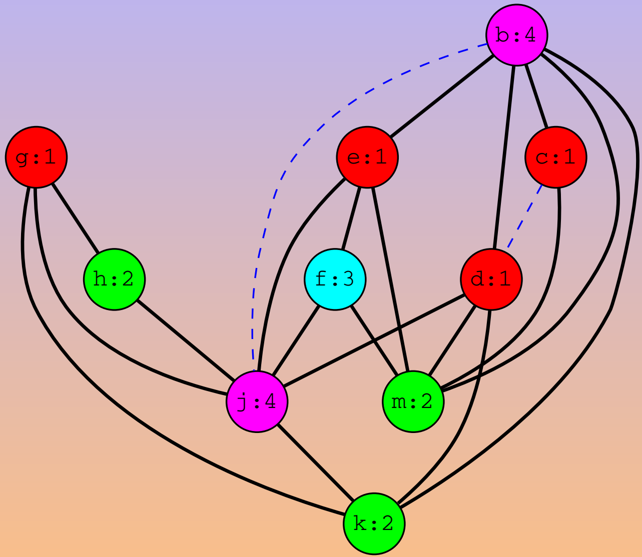


Interference Graph: Simplify 1



h
g

Interference Graph: Simplify 0



g

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

Hard Registers

- 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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Conflicts

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

```
# Routine: fact
l0:                     # def $s0, $s1...
  move $x11, $s0        # def: $x11 use: $s0
  move $x12, $s1        # def: $x12 use: $s1
  ...
l6:
  move $s0, $x11        # def: $s0 use: $x11
  move $s1, $x12        # def: $s1 use: $x12
  ...
                        # use: $fp, $ra, $sp,
                        # ...  $v0, $zero
```

Example [Appel, 1998]

```c
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

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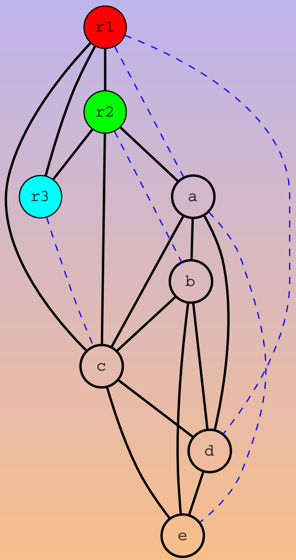
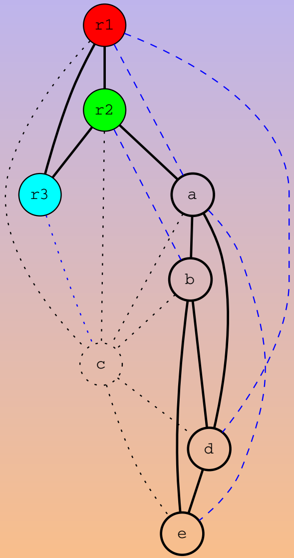
  r3 := c
  return
# liveout: r1, r3
```



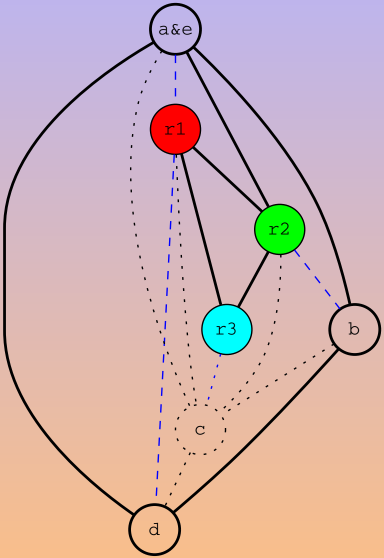
Interference Graph: Simplify 0

c



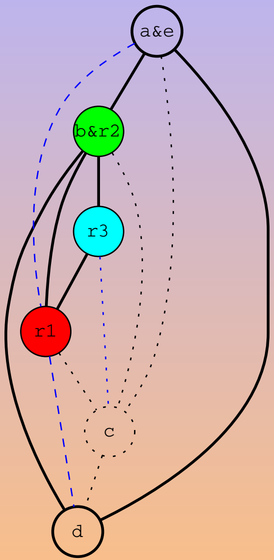
Interference Graph: Simplify 1

a&e
c



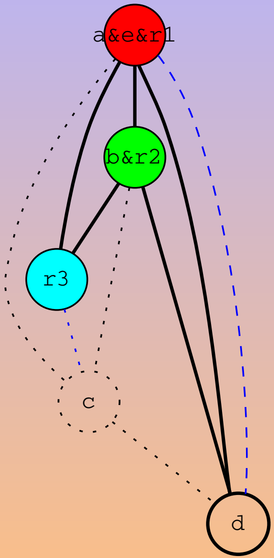
Interference Graph: Simplify 2

b&r2
a&e
c



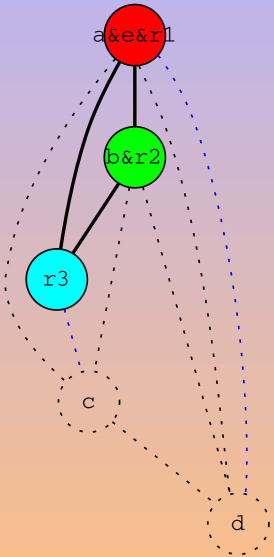
Interference Graph: Simplify 3

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



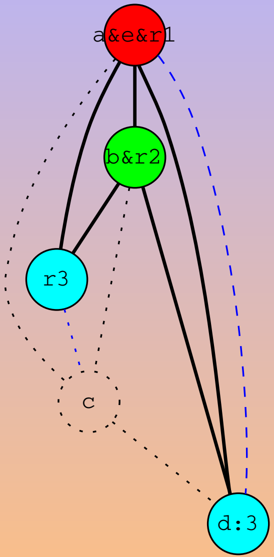
Interference Graph: Simplify 4

d
*a&e&r*1
*b&r*2
a&e
c



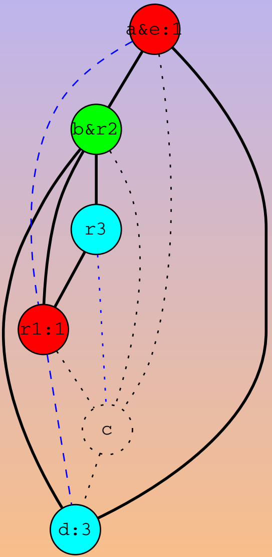
Interference Graph: Simplify 4

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



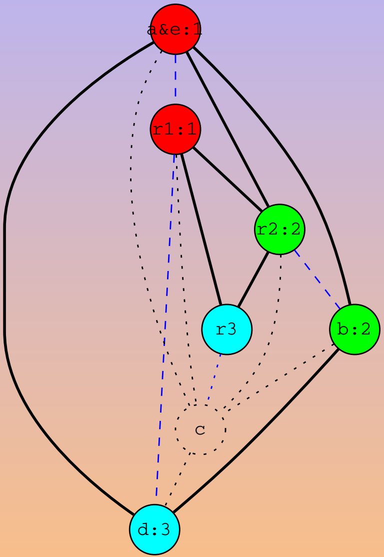
Interference Graph: Simplify 3

$a\&e\&r1$
$b\&r2$
$a\&e$
c



Interference Graph: Simplify 2

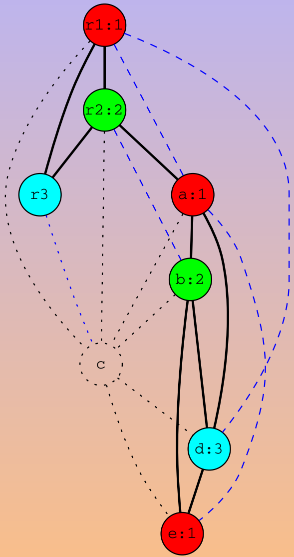
b&r2
a&e
c



Interference Graph: Simplify 1

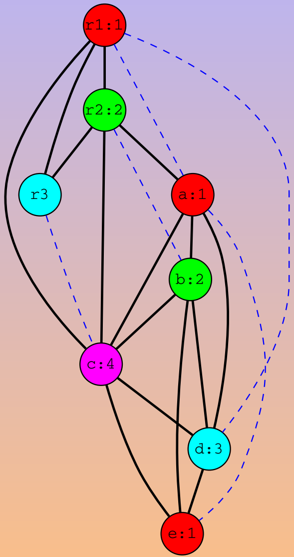
a&*e*

c



Interference Graph: Simplify 0

c



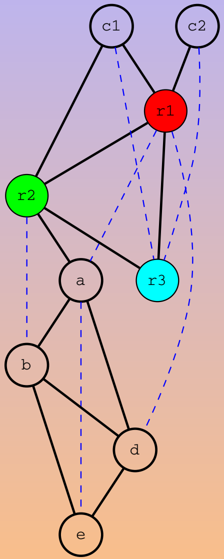
Spilling

```
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
```

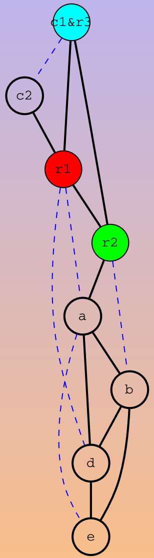
Example

```
enter:
  c1   := r3
  [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
```



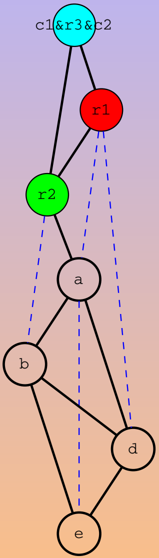
Interference Graph: Simplify 0

$c1\&r3$



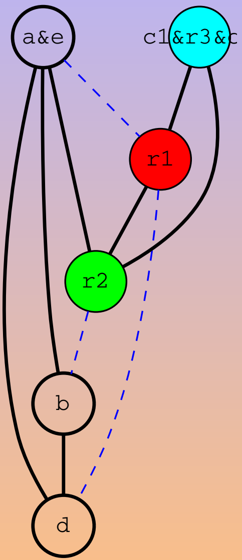
Interference Graph: Simplify 1

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



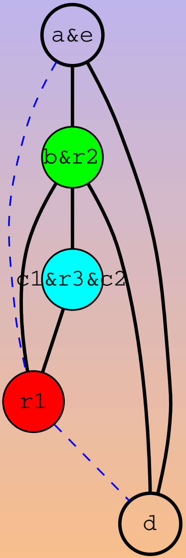
Interference Graph: Simplify 2

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



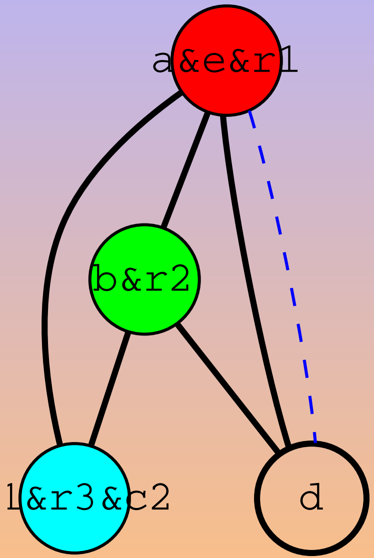
Interference Graph: Simplify 3

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



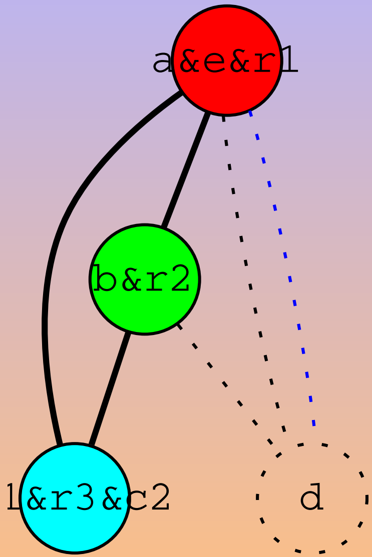
Interference Graph: Simplify 4

$a\&e\&r1$
$b\&r2$
$a\&e$
$c1\&r3\&c2$
$c1\&r3$



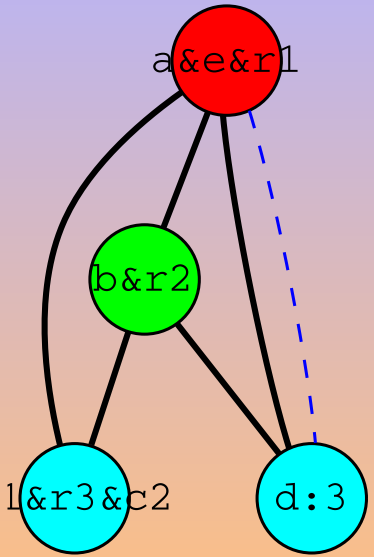
Interference Graph: Simplify 5

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

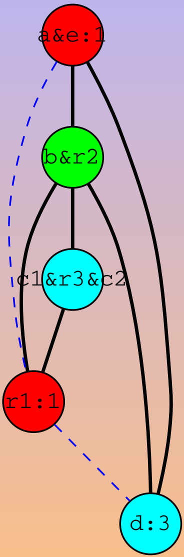


Interference Graph: Simplify 5

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

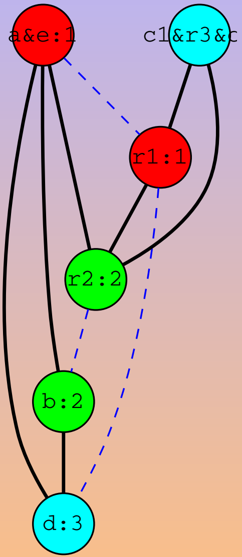


$a\&e\&r1$
$b\&r2$
$a\&e$
$c1\&r3\&c2$
$c1\&r3$



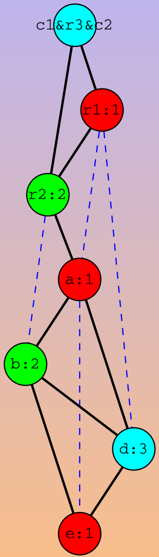
Interference Graph: Simplify 3

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



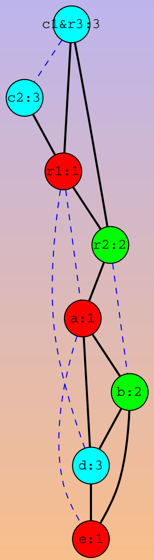
Interference Graph: Simplify 2

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



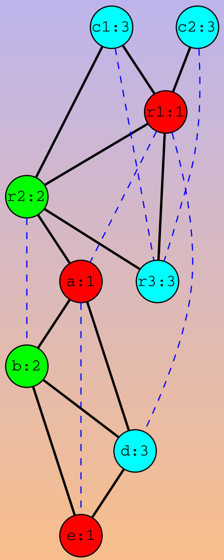
Interference Graph: Simplify 1

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



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

Implementation

- Naive implementation is quadratic
- Lower with heavy use of *worklists*
- Queries on the conflict graph
  - Iterate over neighbors, hence adjacency list
  - 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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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]

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