Graph Coloring
Register Allocation

Register Allocation

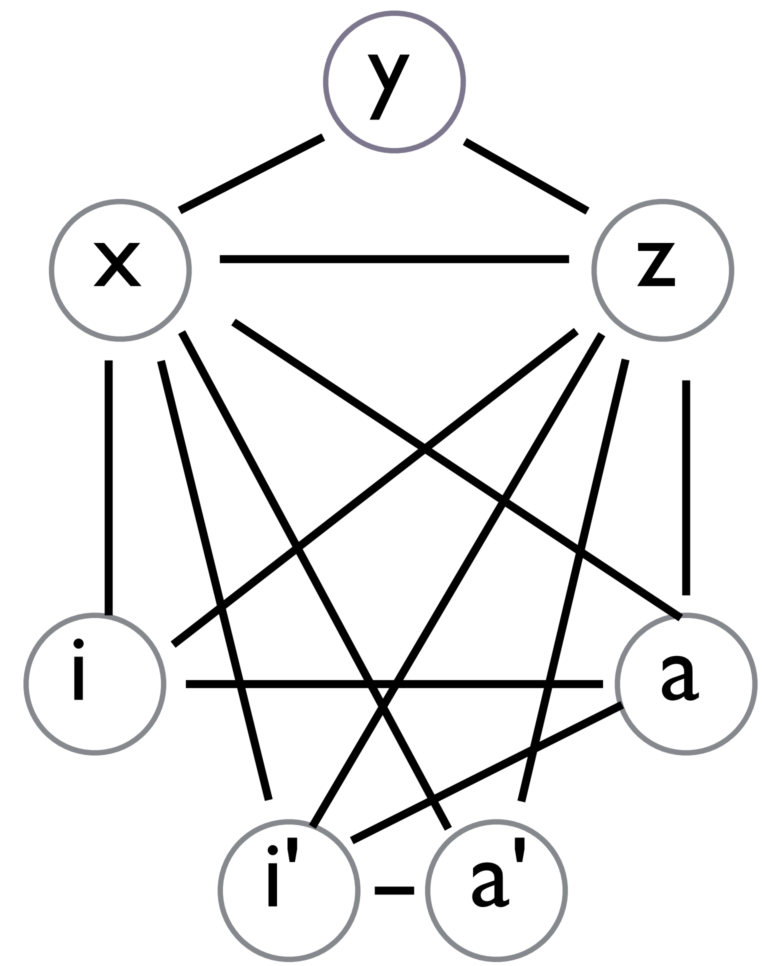
3(.5) Steps

1. **Liveness analysis**: identify when each variable's value is needed in the program
2. **Conflict analysis**: identify which variables interfere with each other
3. **Graph Coloring**: assign variables to registers so that interfering registers are assigned different registers.
    1. Spilling: if necessary, assign some variables to stack slots

Example

```
def f(x,y,z):
  def loop(i,a):
    if i == 0:
      a * z
    else:
      let i' = i - 1 in
      let a' = a + x in
      icall(loop; i', a')
  end
  icall(loop; y, 0)
```

Interference Graph



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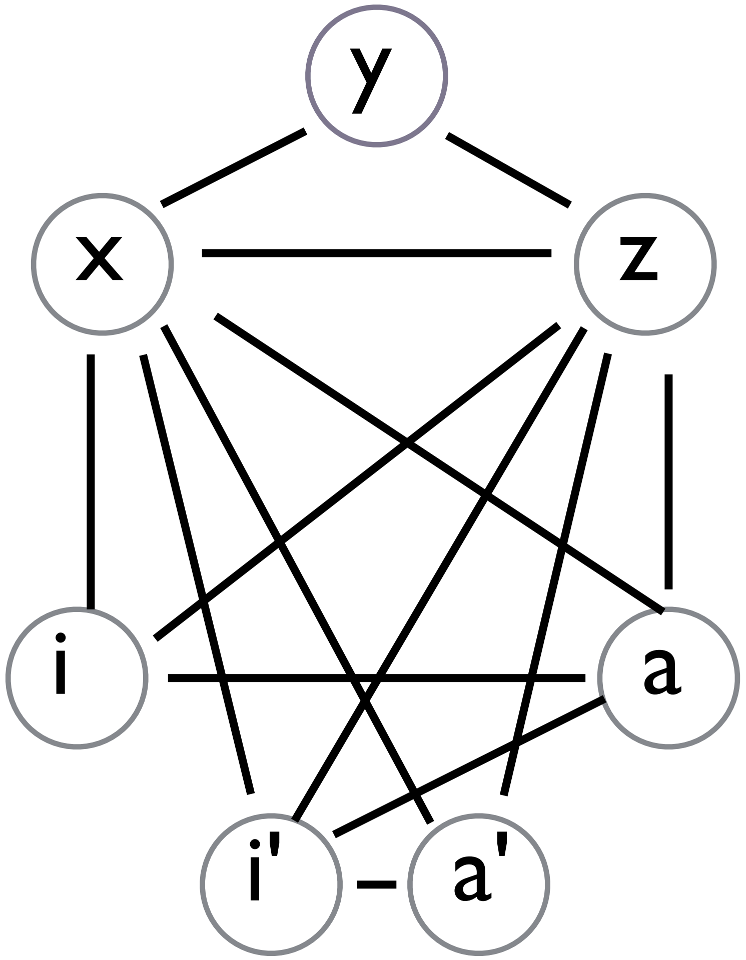

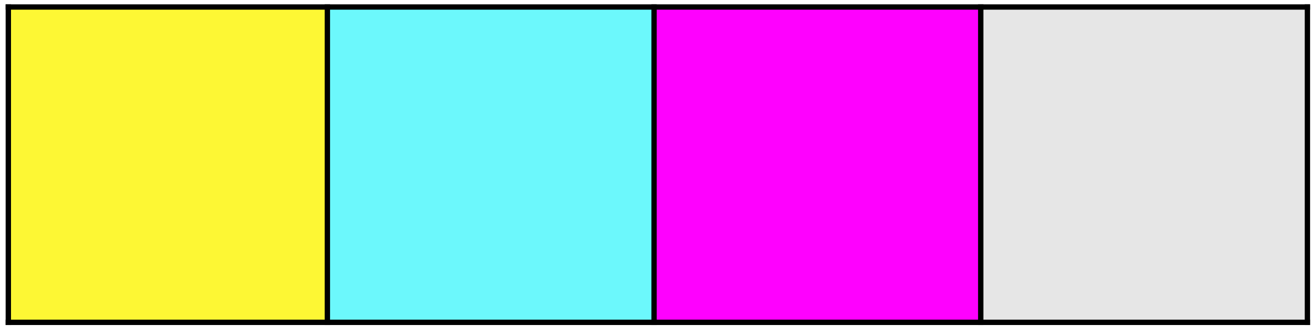

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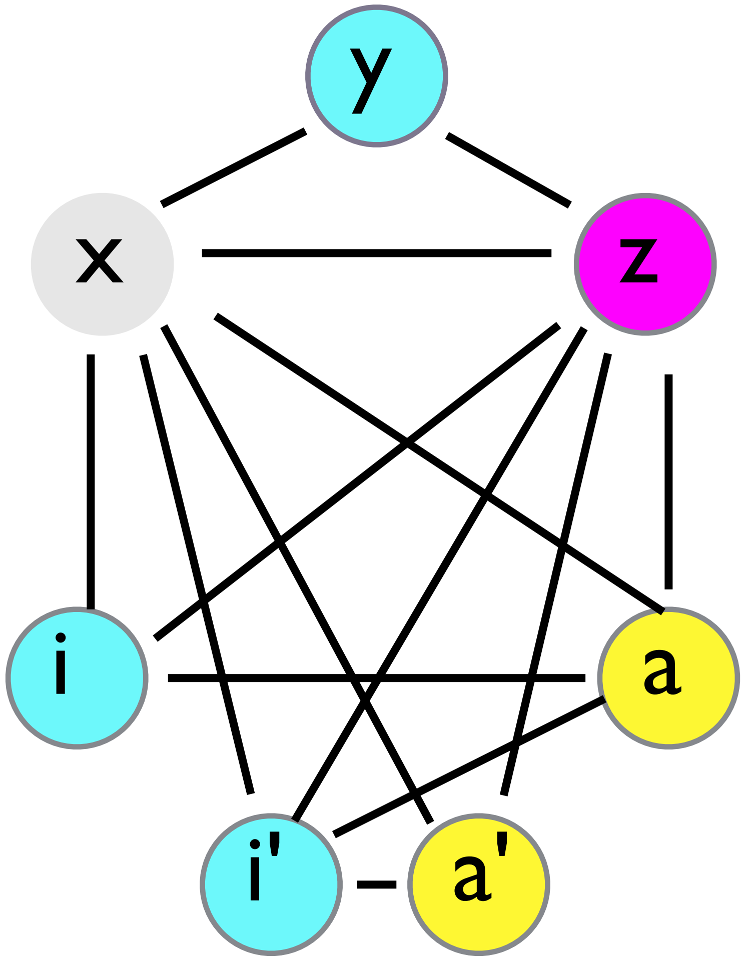

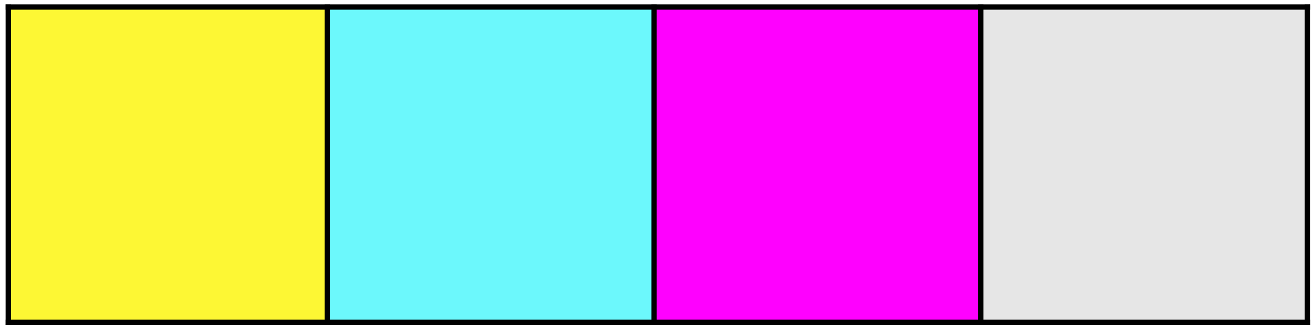

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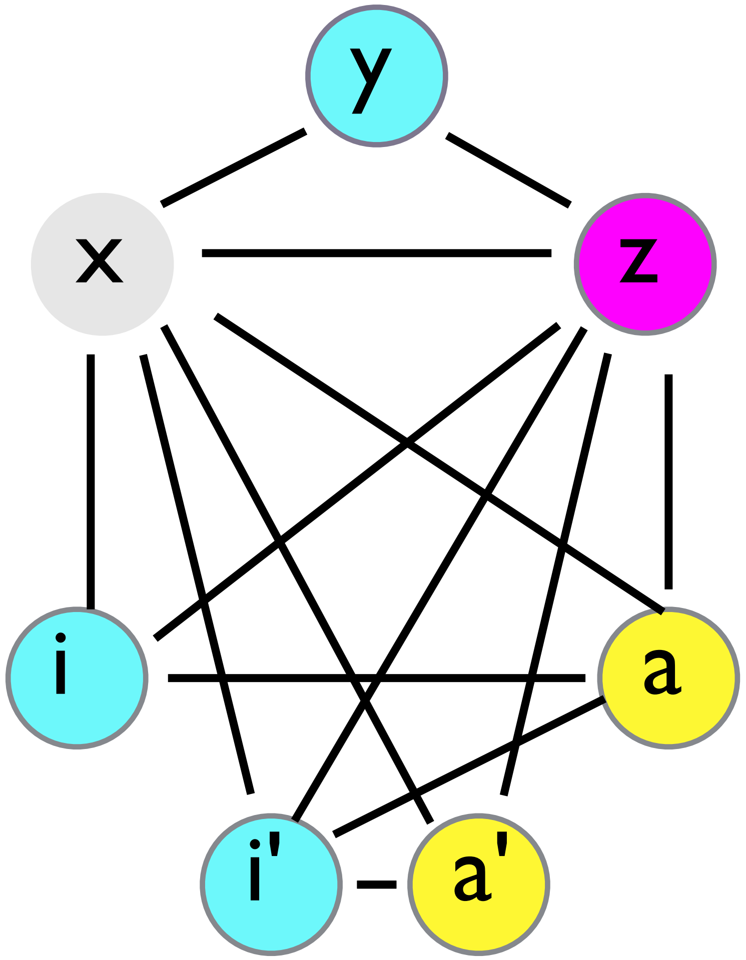

rax	rsi	rdx	rdi

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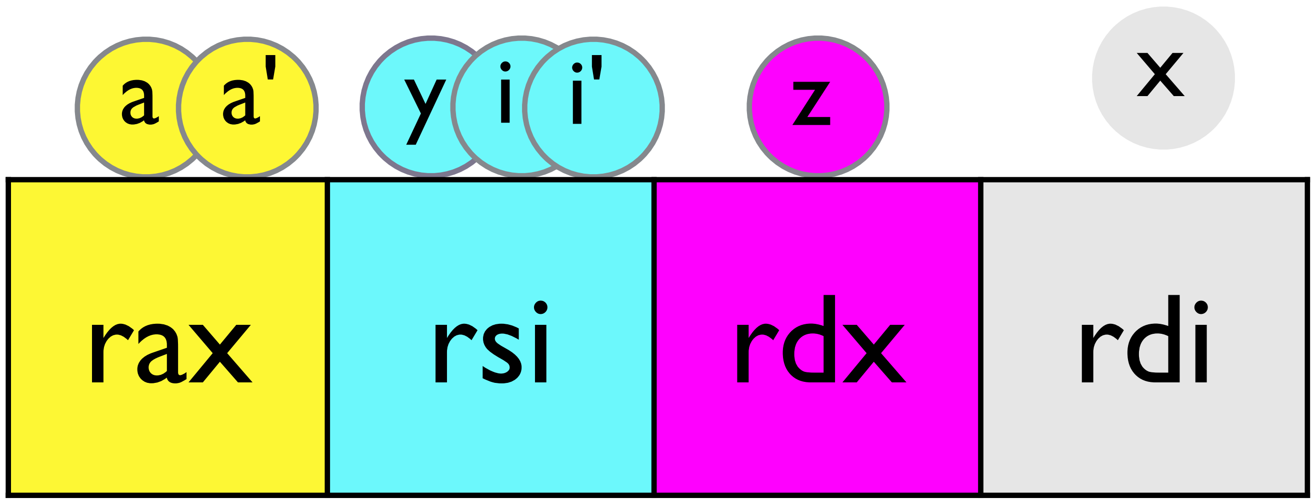

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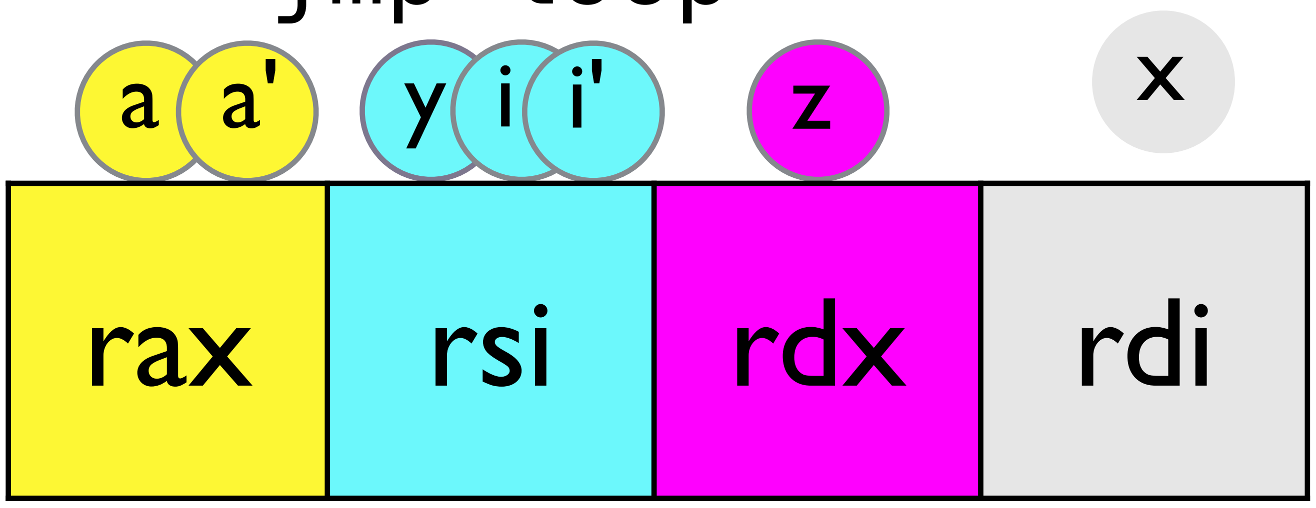
```
f:
  mov rax, 0
loop:
  cmp rsi, 0
  jne els
  imul rax, rdx
  ret
els:
  sub rsi, 1
  add rcx, rdi
  jmp loop
```



Graph Coloring Register Allocation

Given our register conflict graph, want to assign a register to each variable so that no interfering variables are assigned the same register.

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- think of each register as a "color" and we want to paint each node so that no adjacent nodes are the same color.

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Efficient algorithm for graph coloring -> efficient algorithm for graph coloring!

Graph Coloring is Hard

Determining a whether a graph is k-colorable is NP-complete for k > 2.

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Does that mean register allocation is NP-hard?

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So register allocation of their language is NP complete.

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So register allocation of their language is NP complete.

- But our programs are more restrictive: Functional/SSA form...we'll come back to this

Chaitin's Algorithm

- Intuition:
  - Suppose we are trying to k-color a graph and find a node with fewer than k edges.
  - If we delete this node from the graph and color what remains, we can find a color for this node if we add it back in.
  - Reason: With fewer than k neighbors, some color must be left over.
- Algorithm:
  - Find a node with fewer than k outgoing edges.
  - Remove it from the graph.
  - Recursively color the rest of the graph.
  - Add the node back in.
  - Assign it a valid color.

Chaitin's Algorithm

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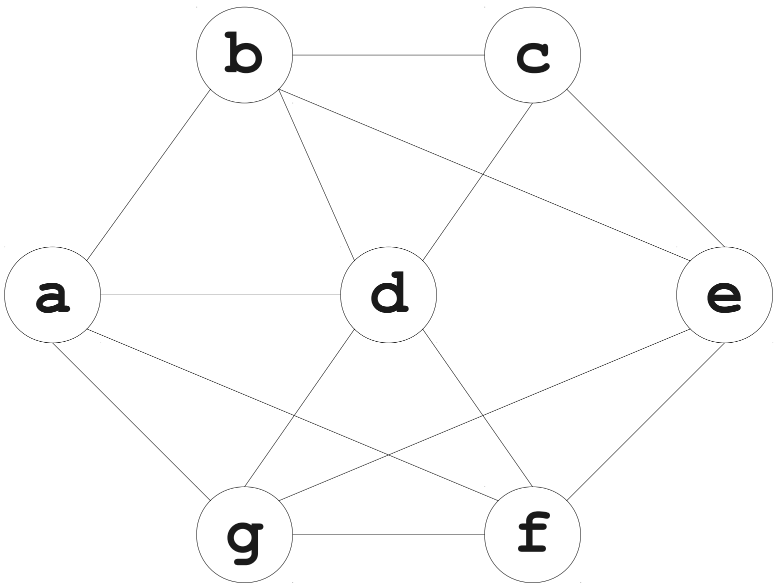

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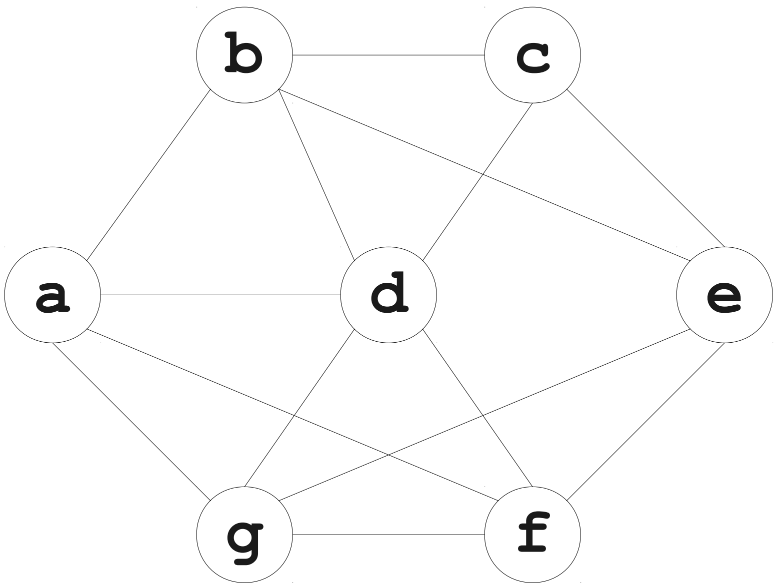

Registers

R_0	R_1	R_2	R_3

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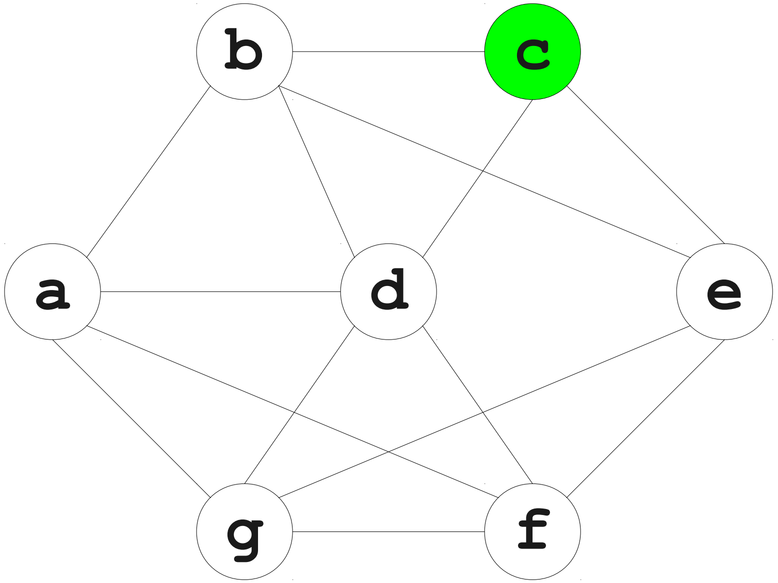

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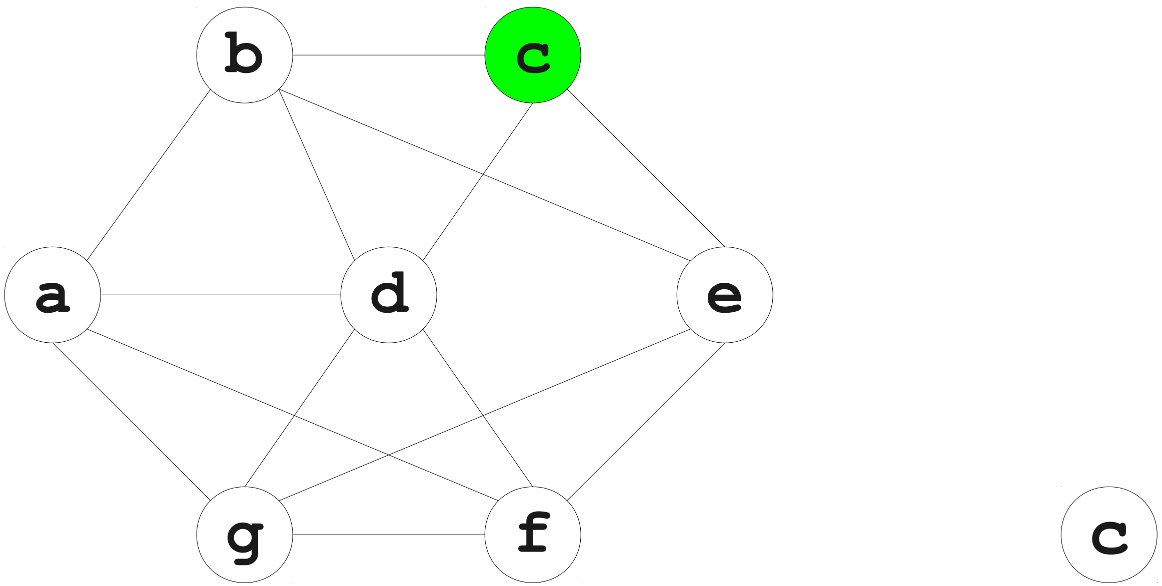

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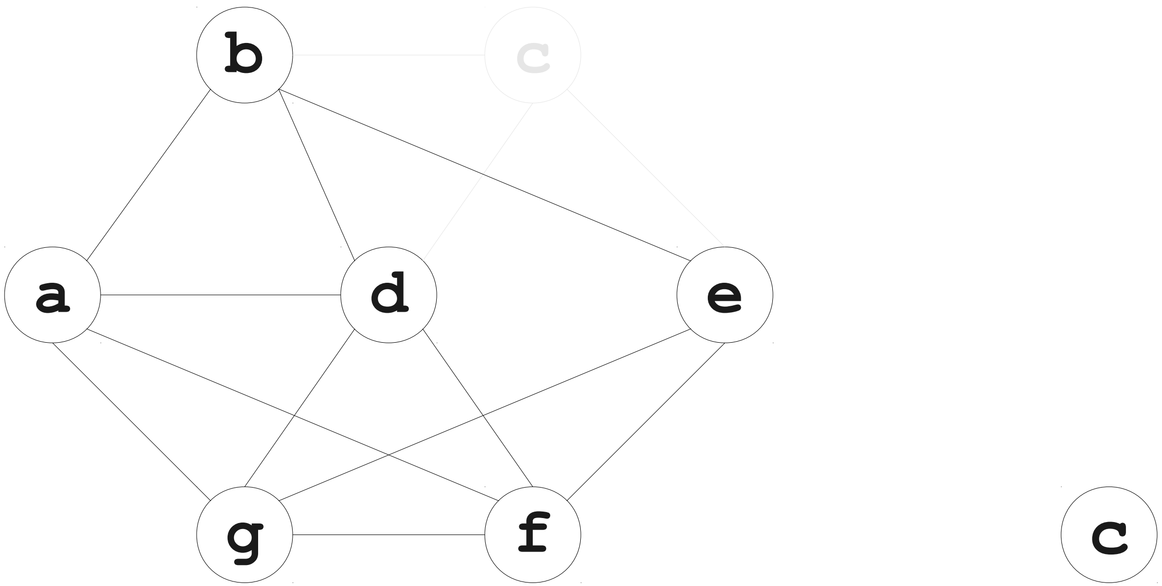

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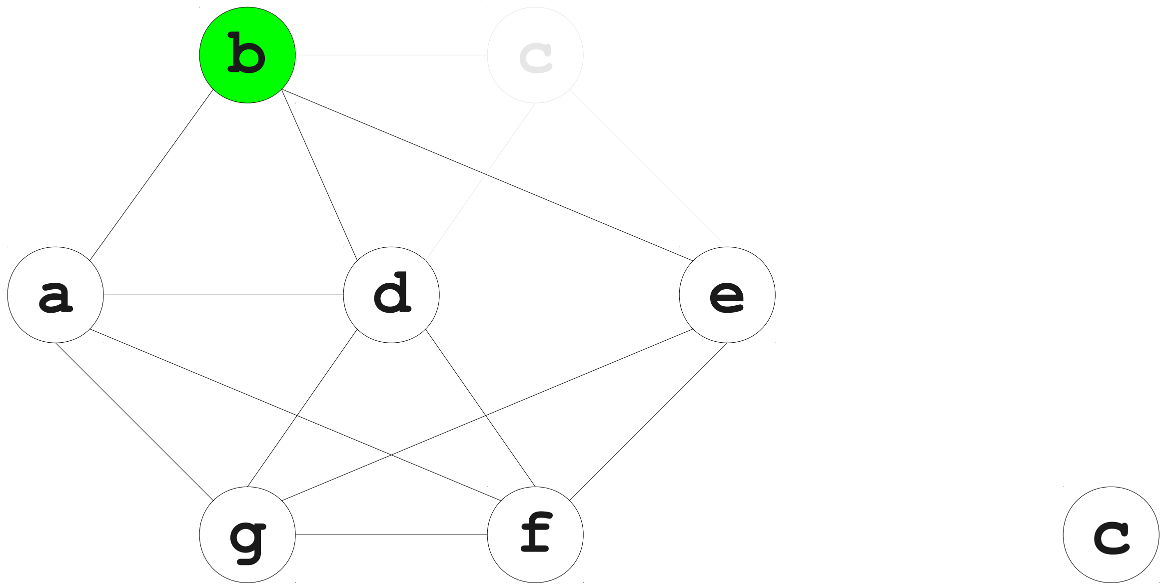

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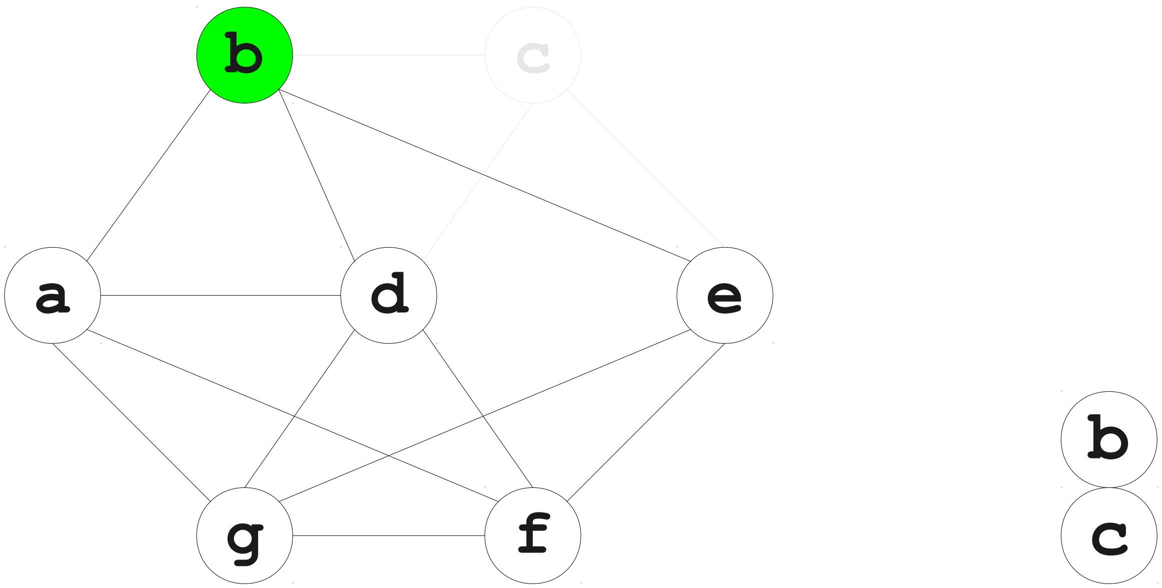

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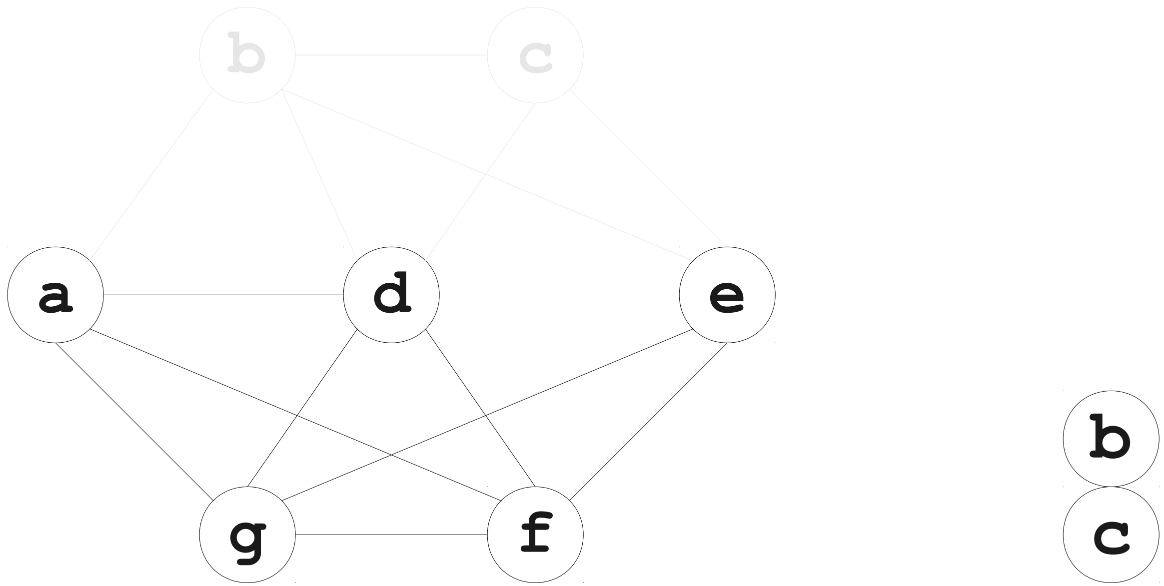

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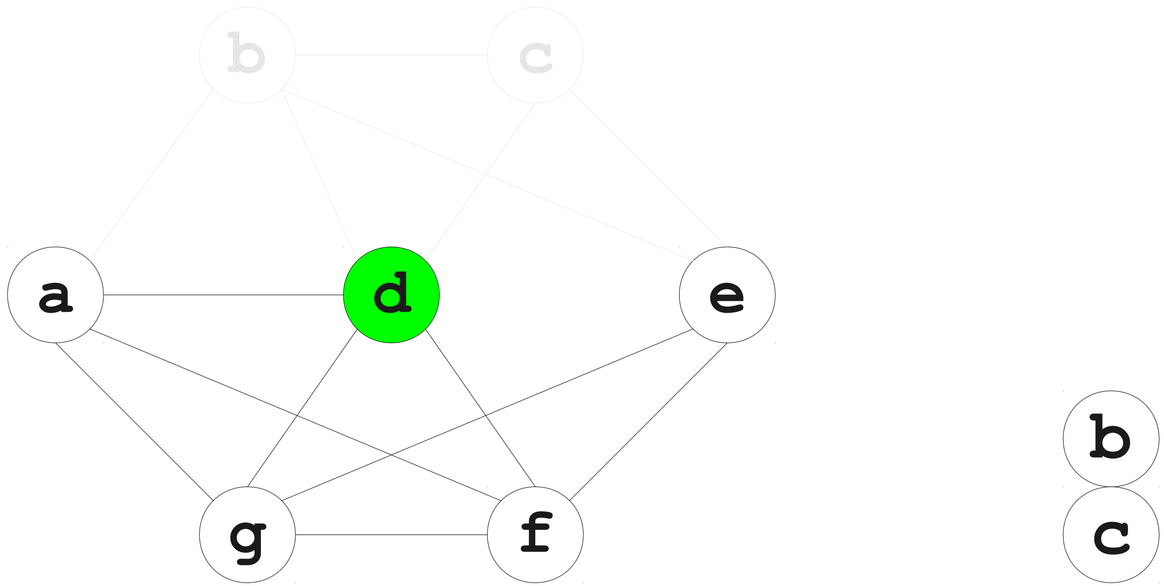

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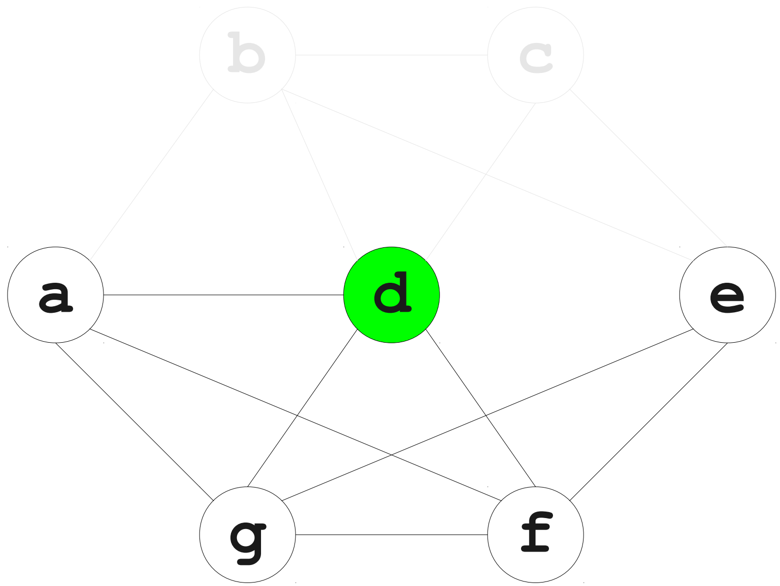

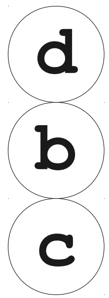

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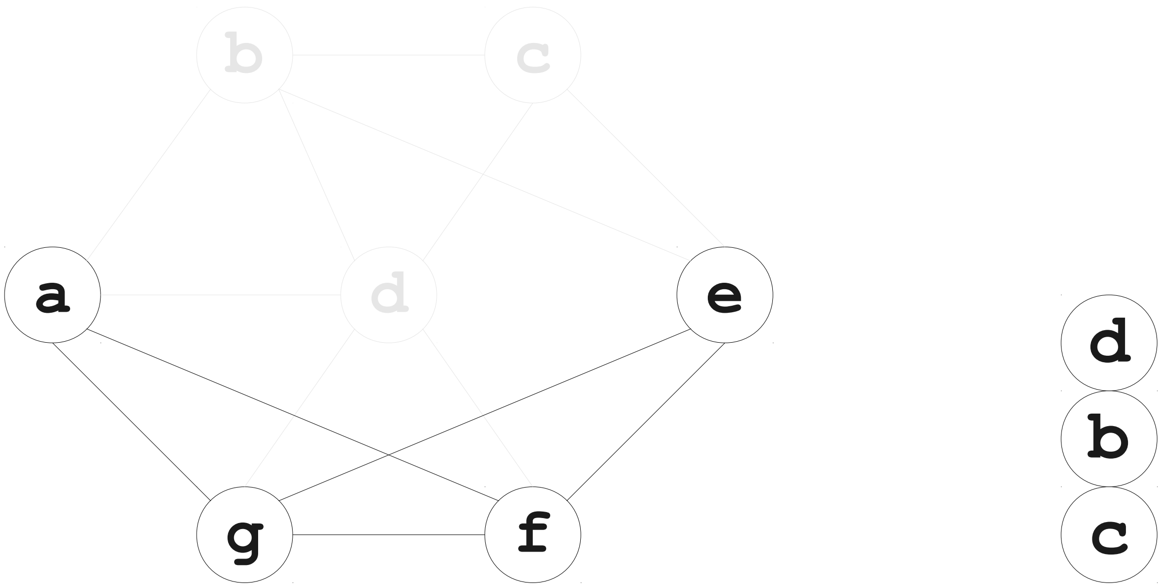

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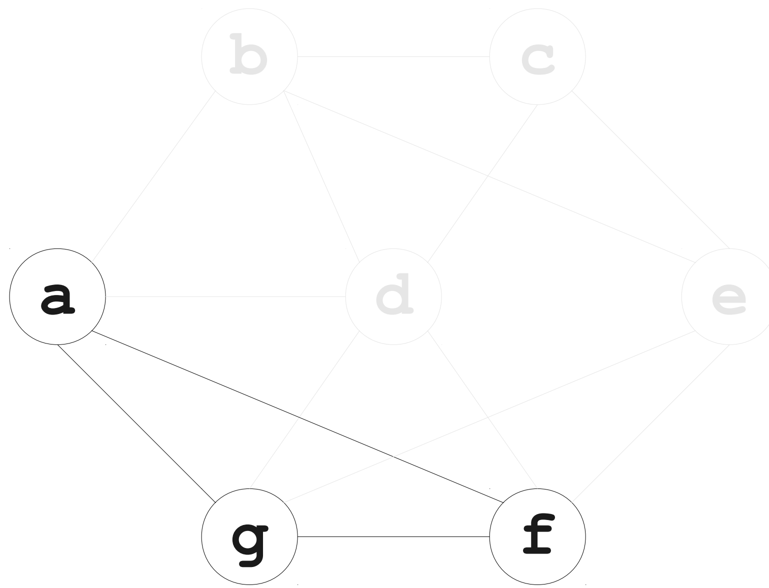

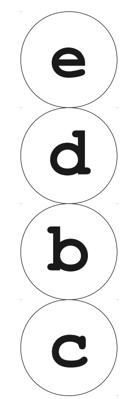

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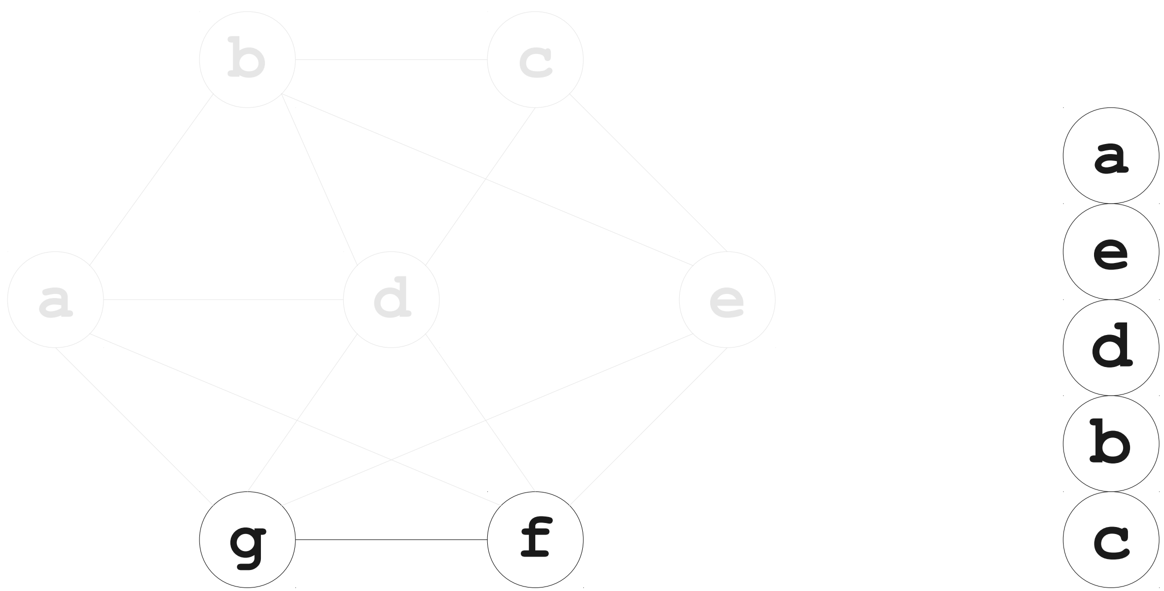

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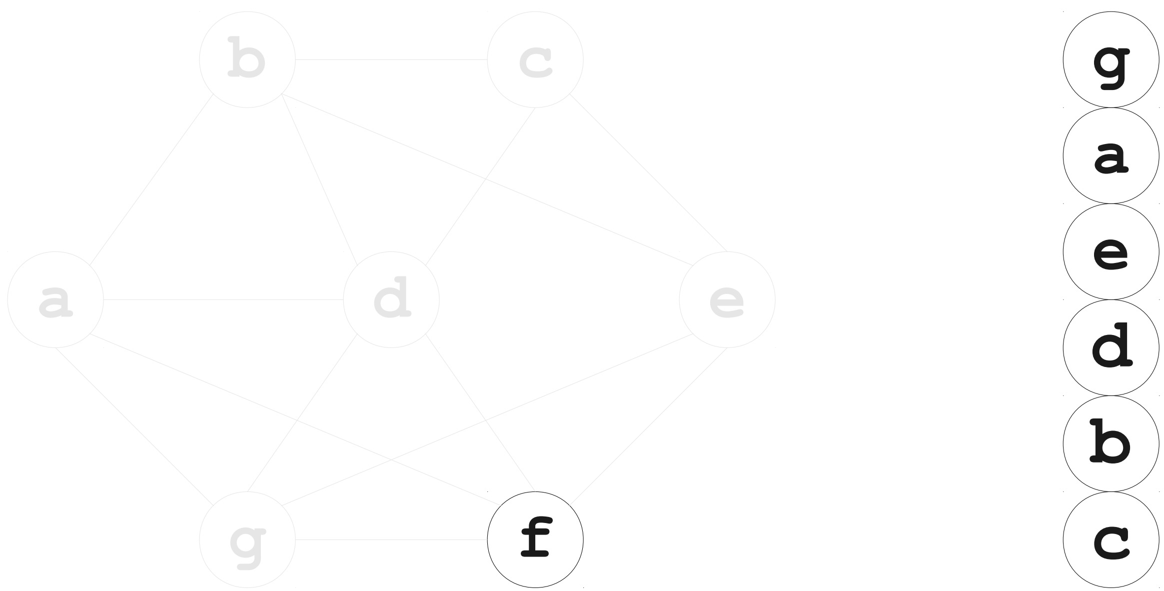

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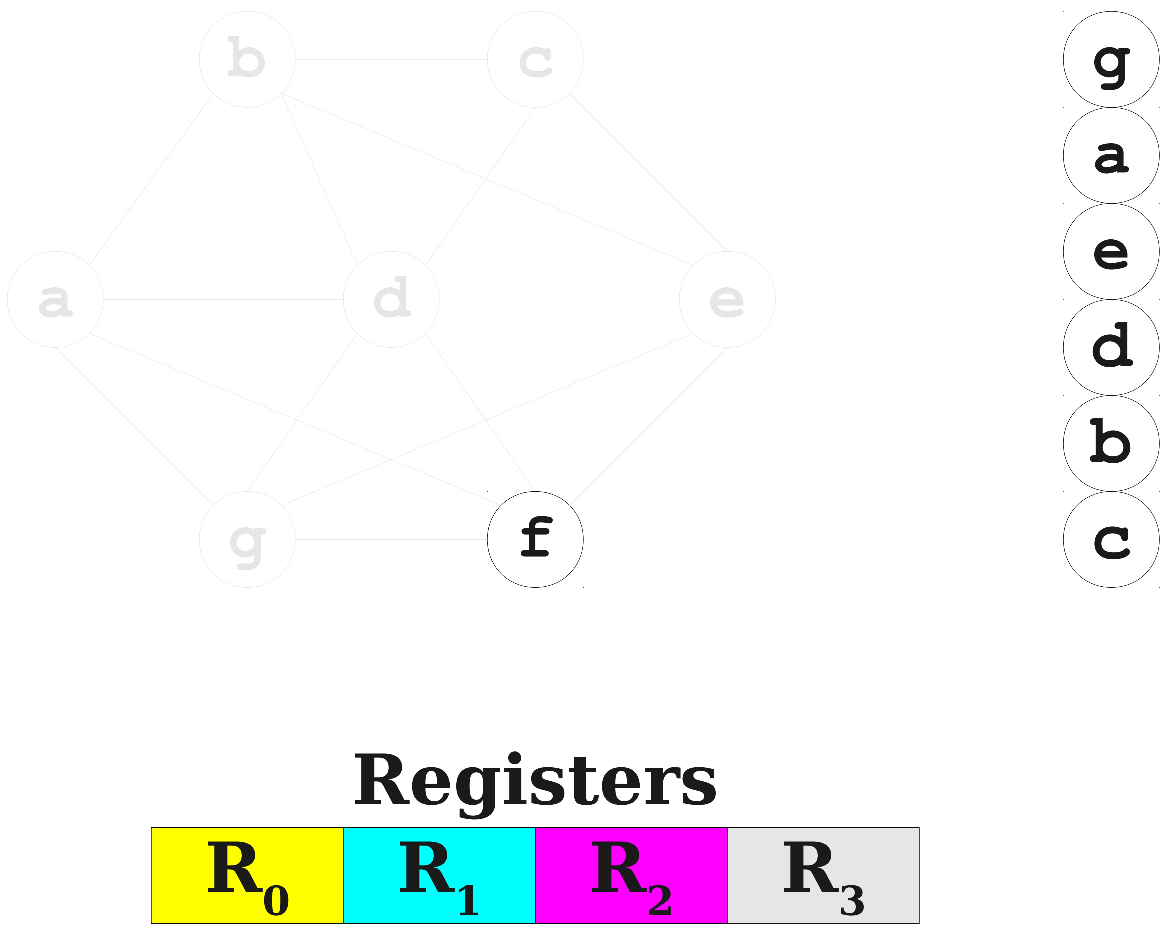

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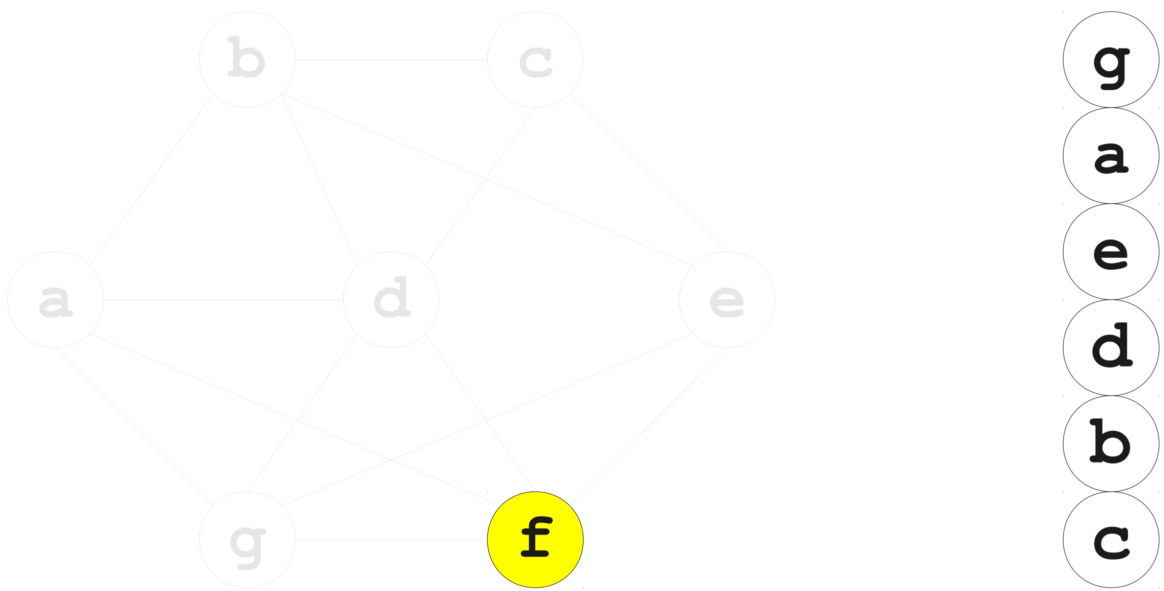

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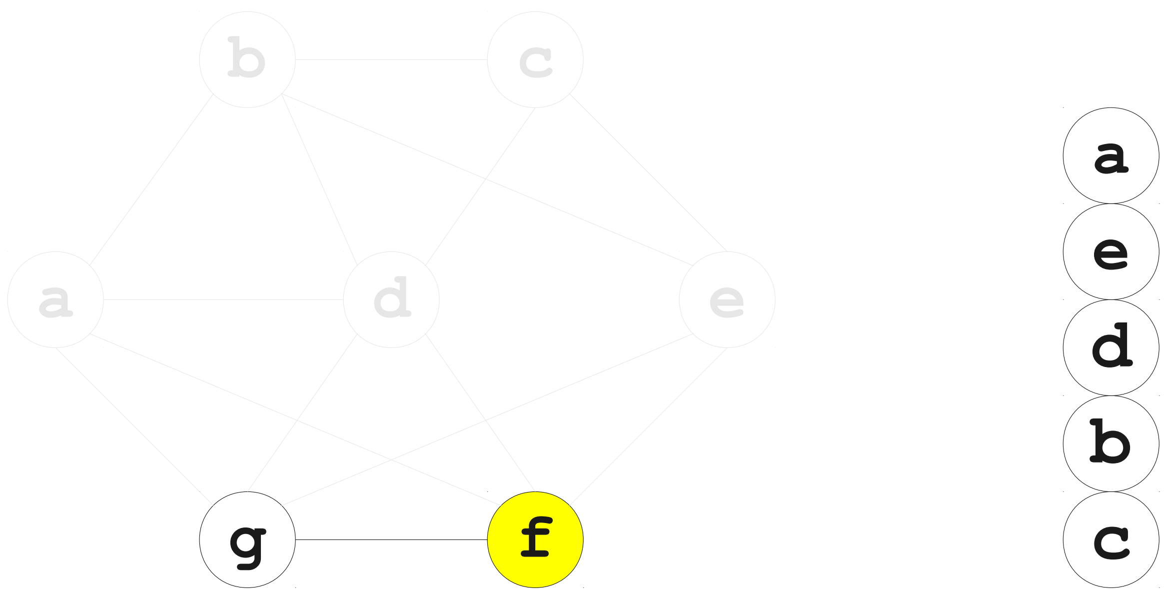

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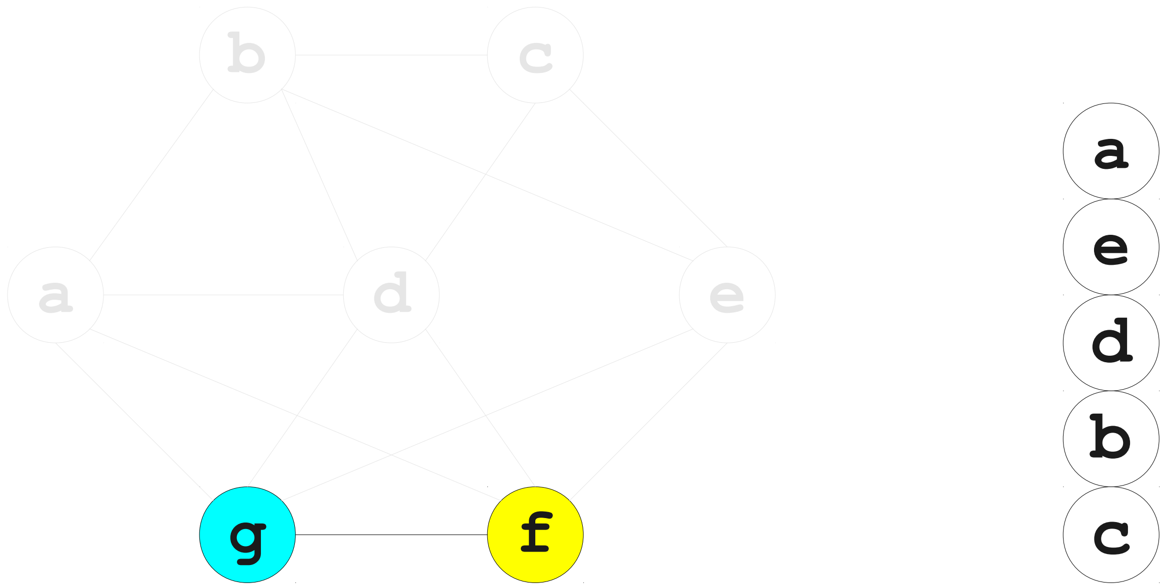

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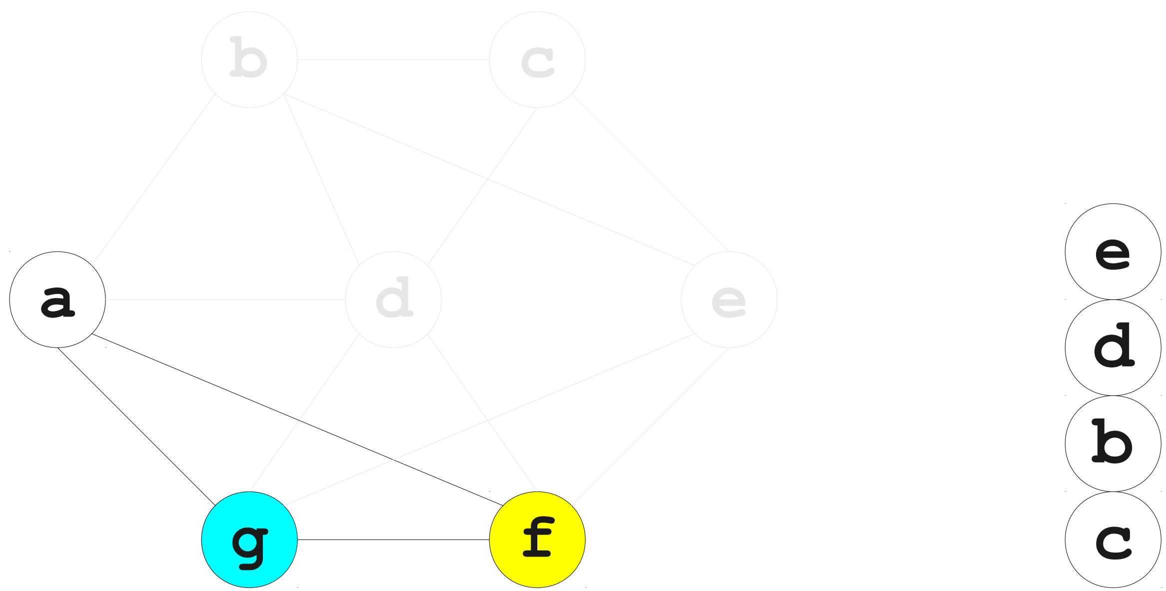

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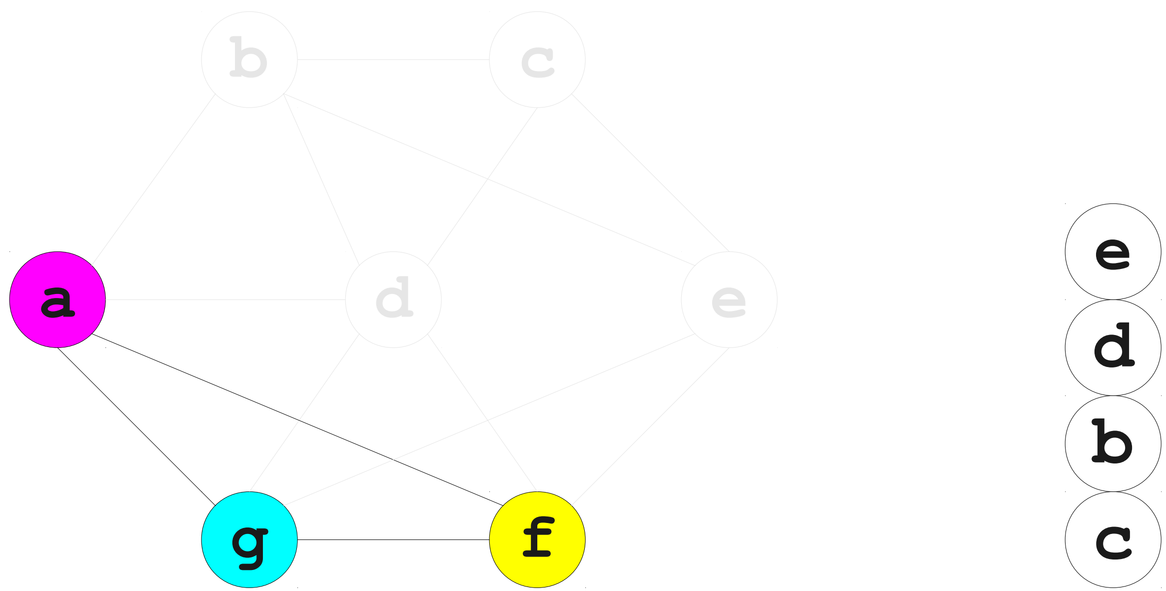

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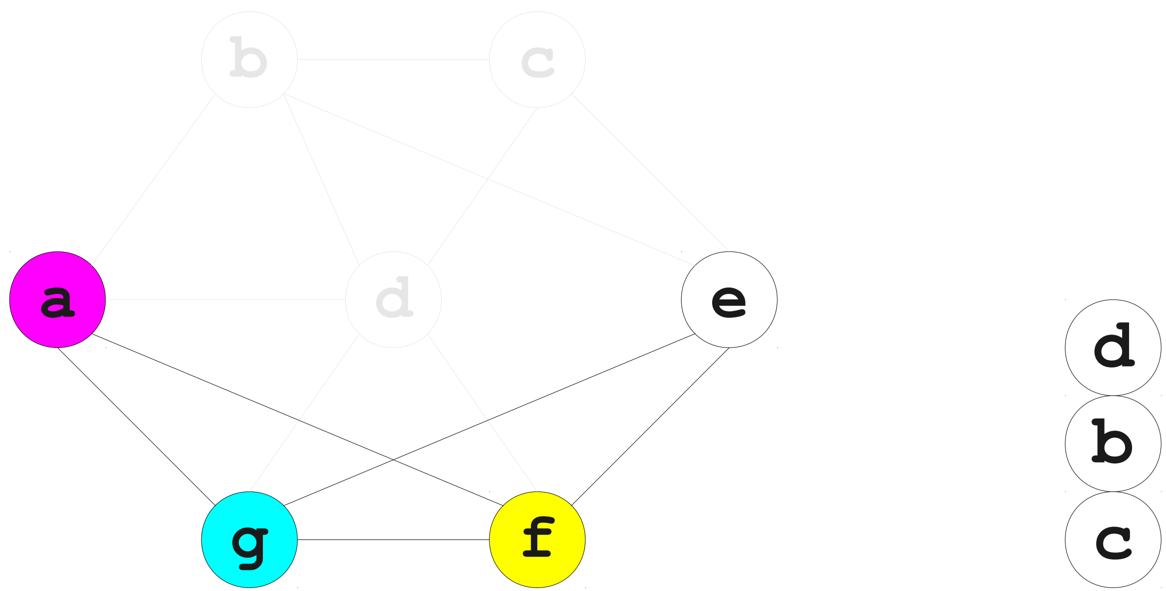

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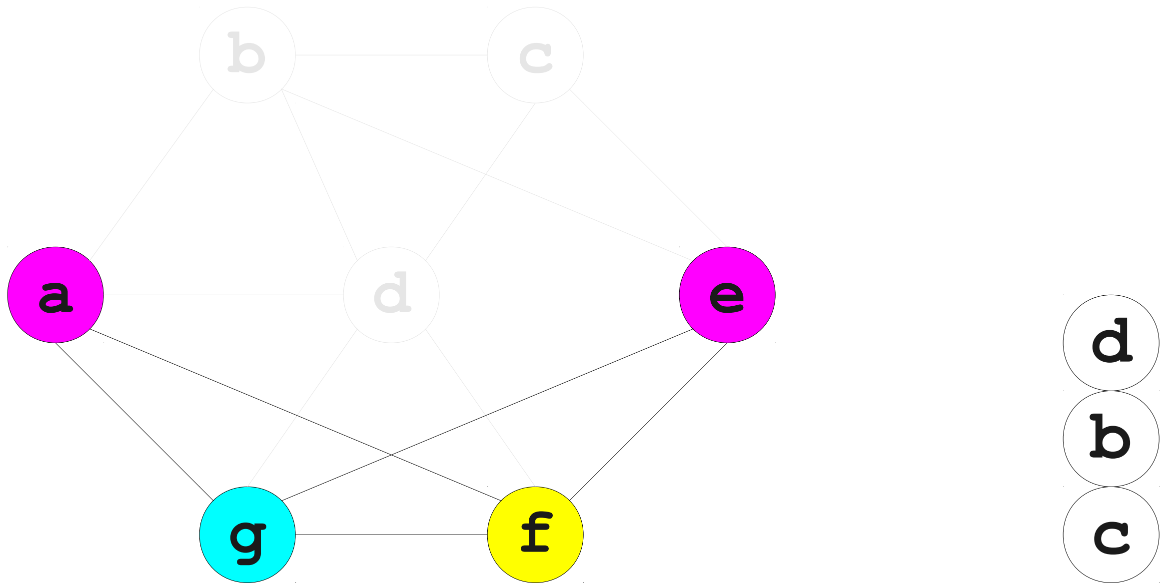

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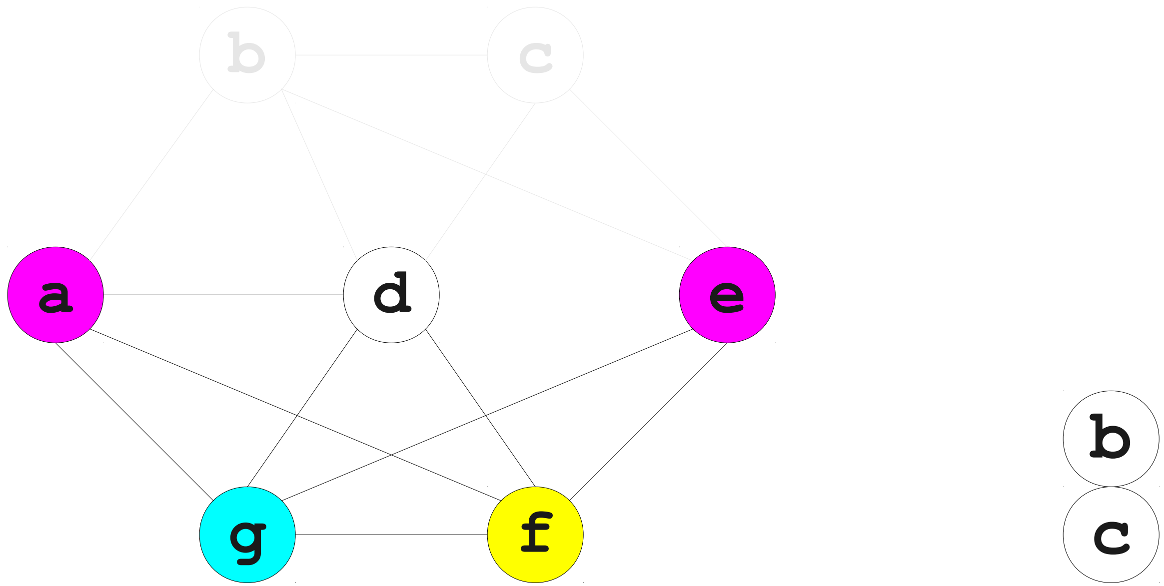

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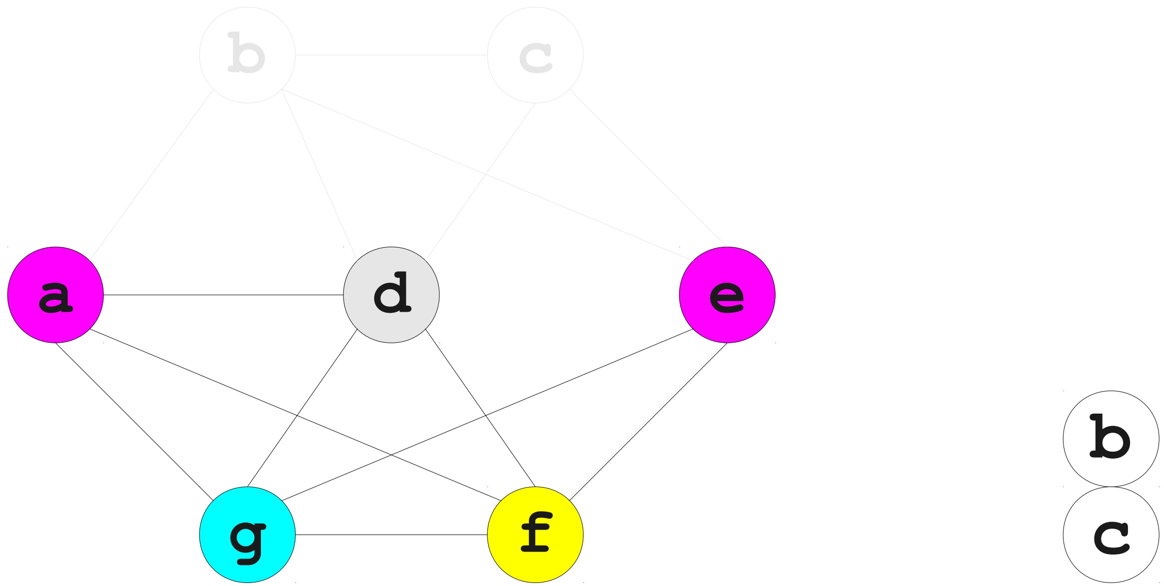

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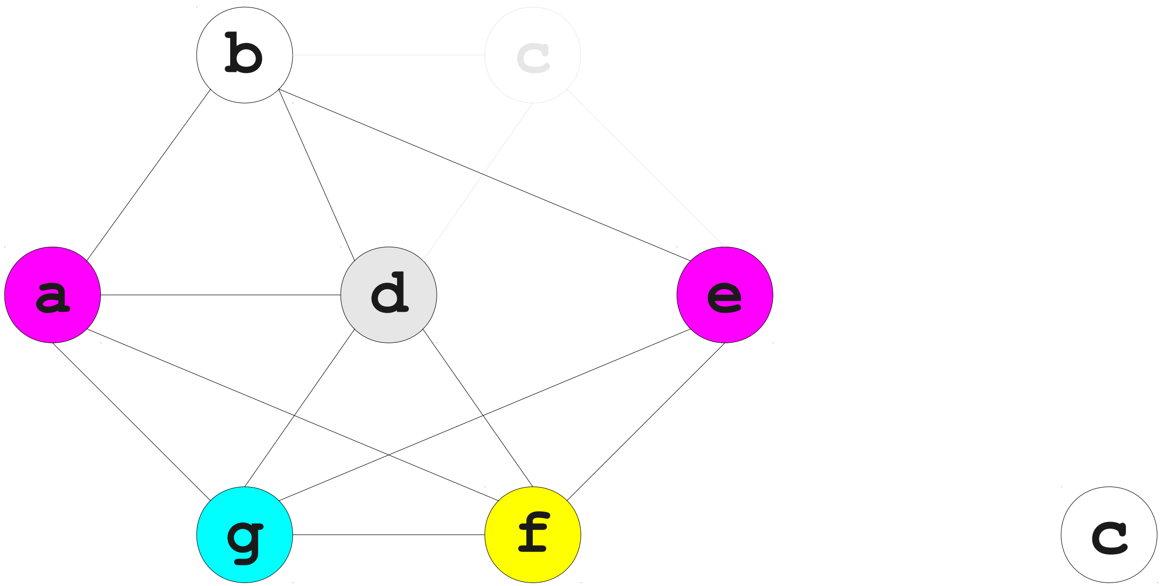

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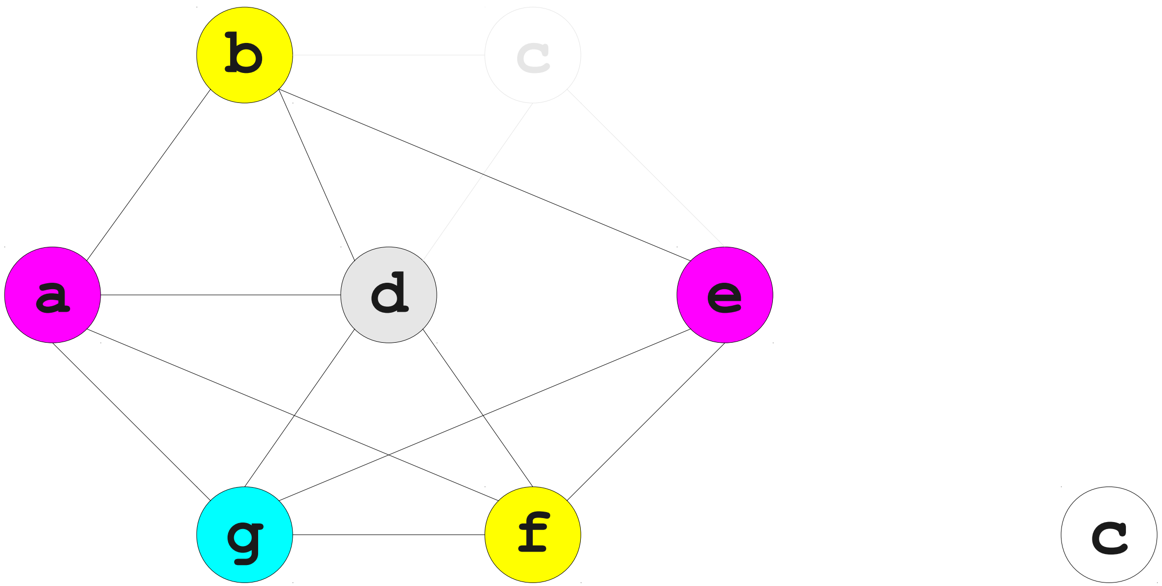

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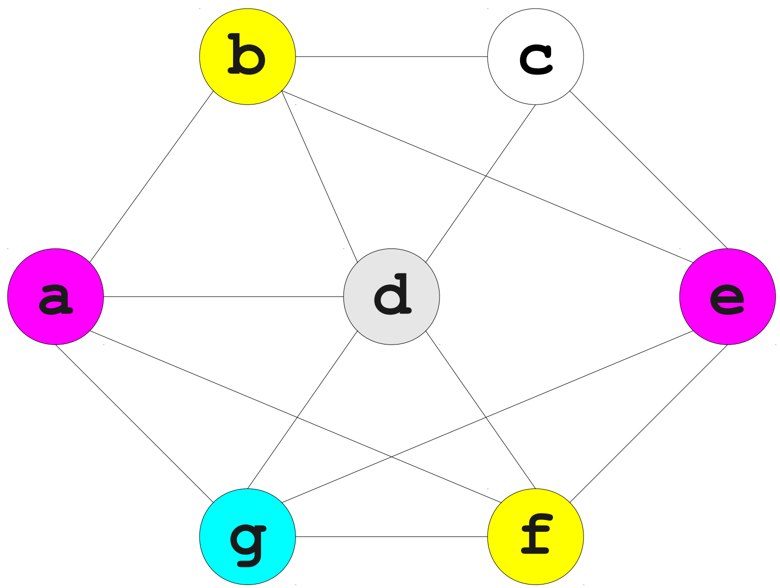

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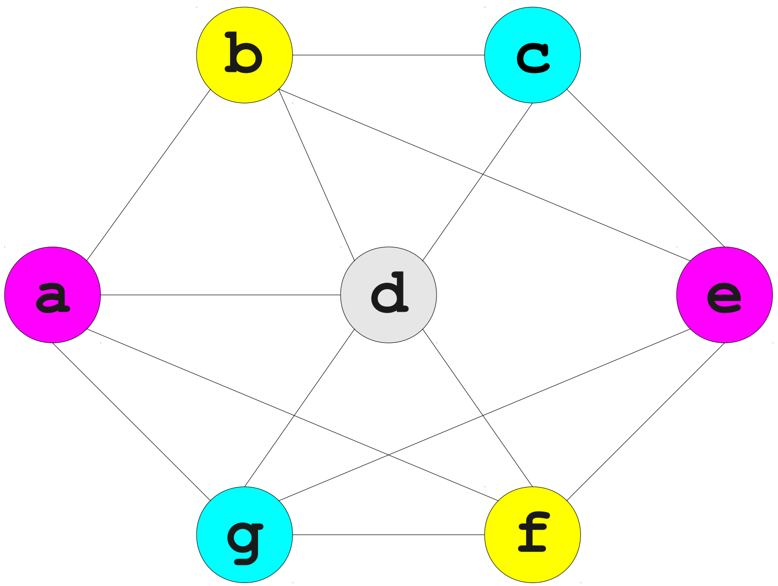

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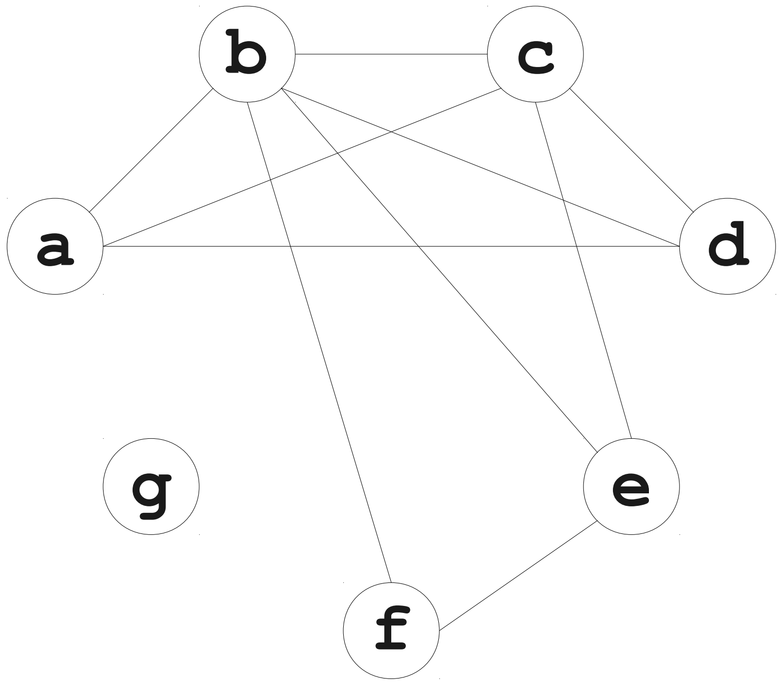
One Problem

- What if we can't find a node with fewer than *k* neighbors?
- Choose and remove an arbitrary node, marking it “troublesome.”
  - Use heuristics to choose which one.
- When adding node back in, it may be possible to find a valid color.
- Otherwise, we have to spill that node.

Chaitin's Algorithm Reloaded



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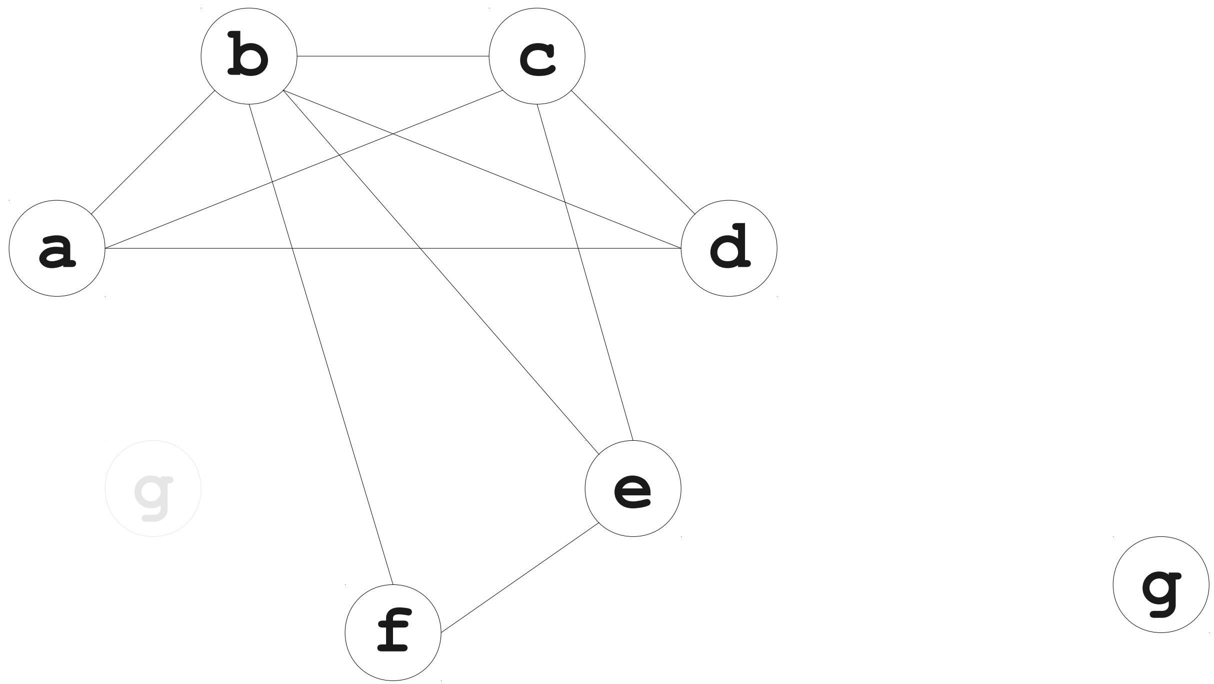

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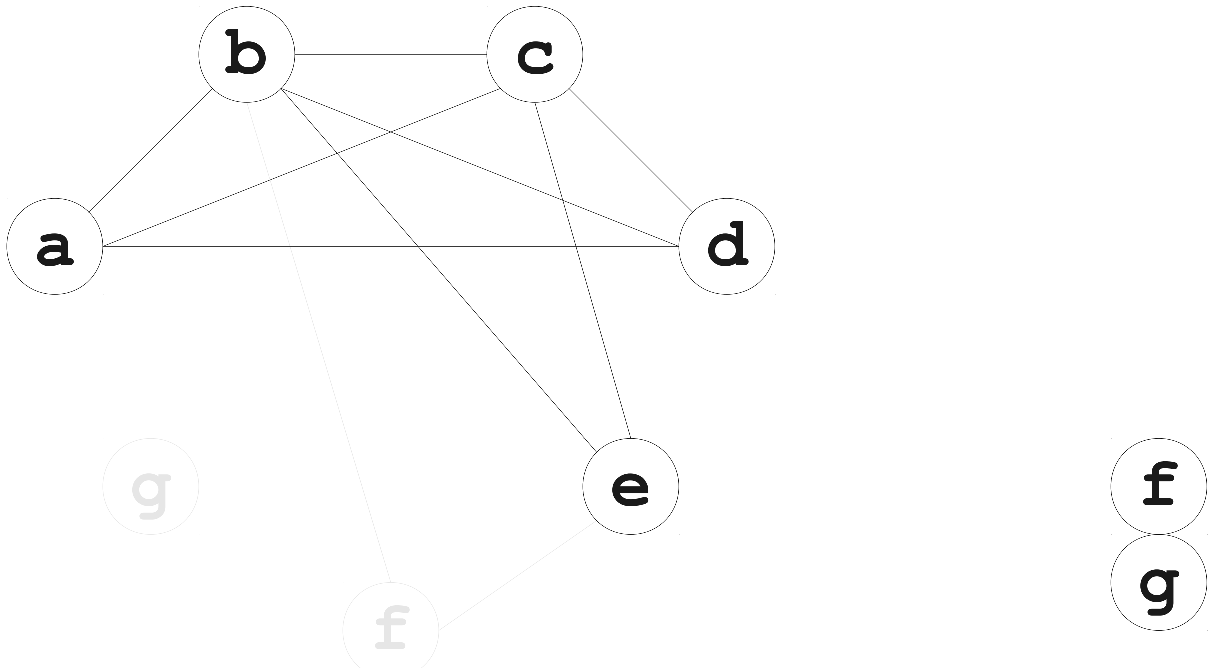

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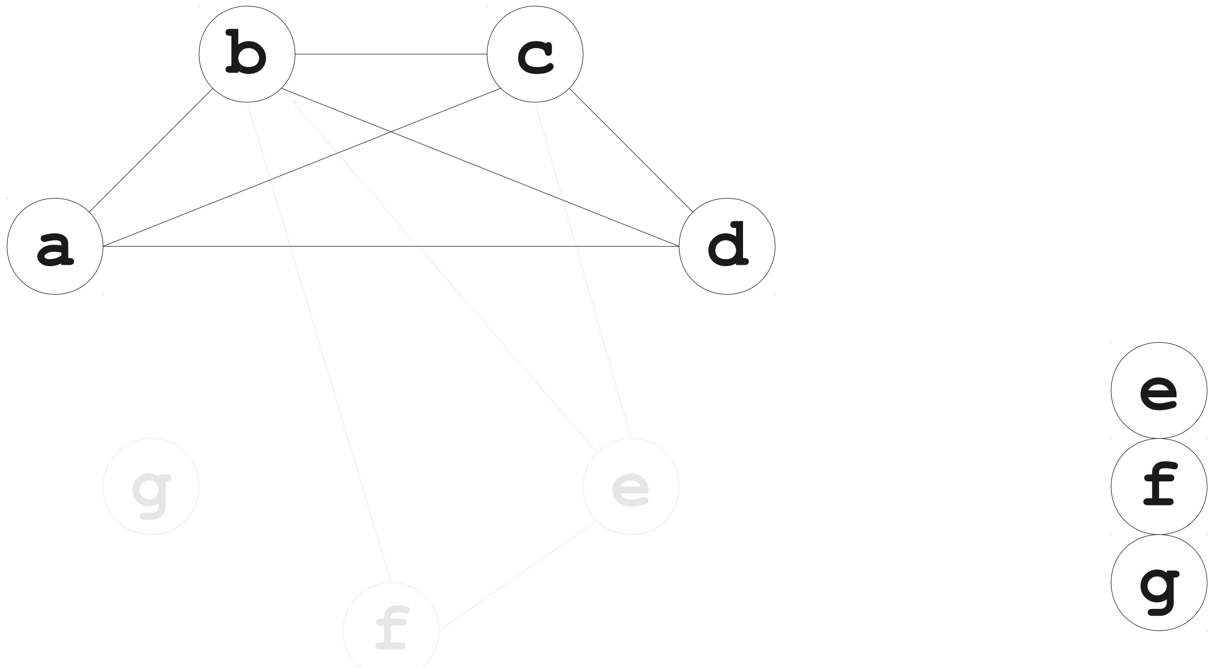

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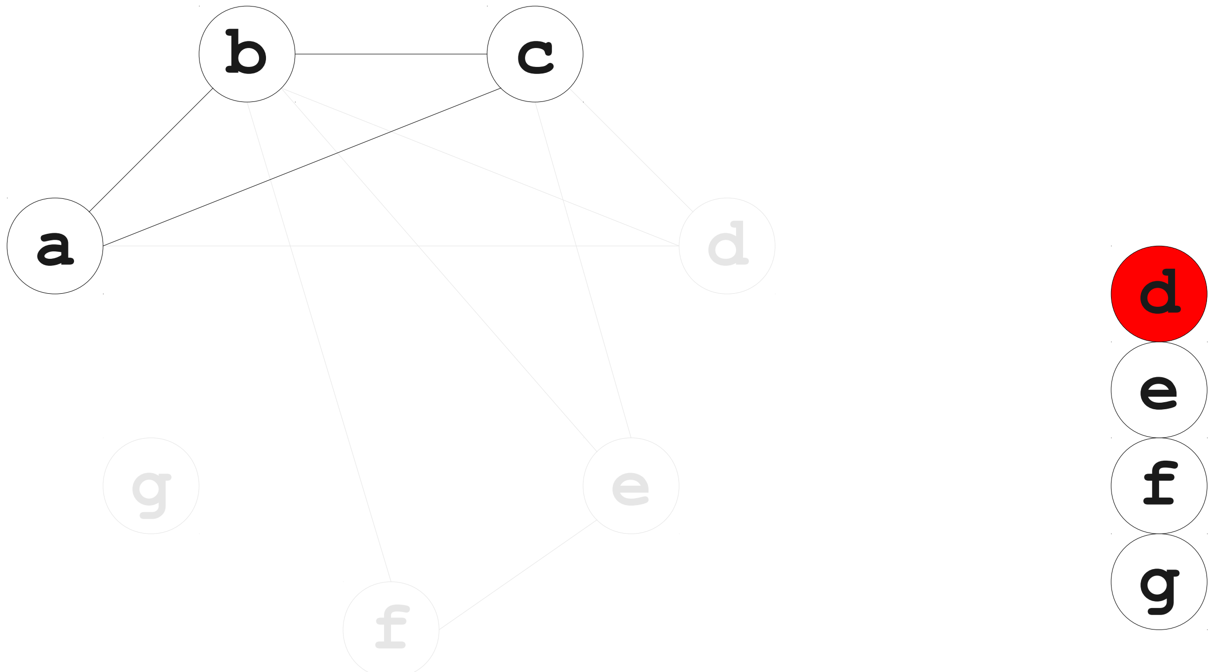

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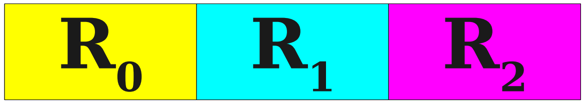

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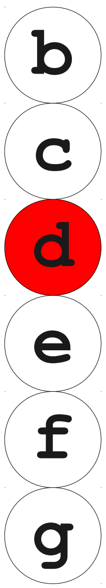

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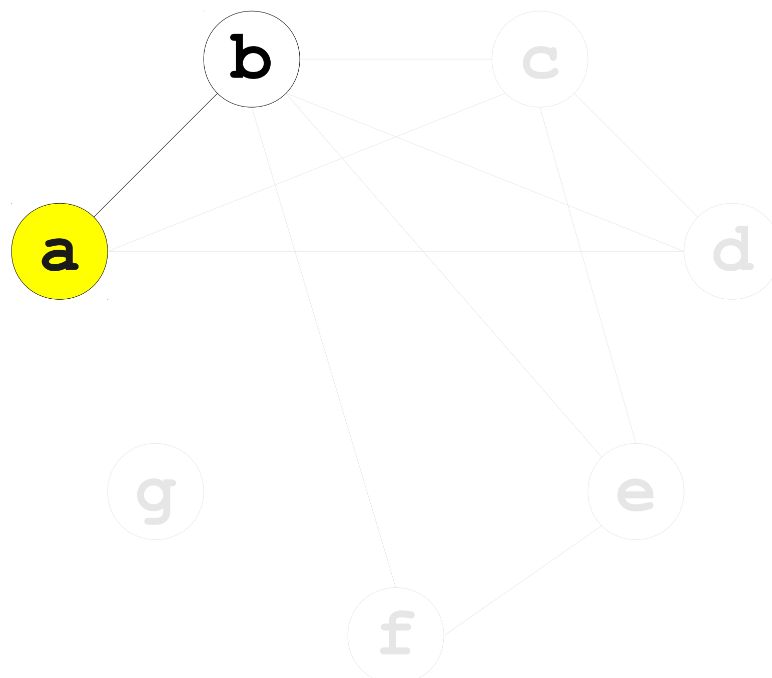

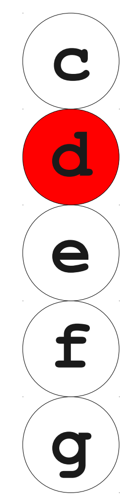

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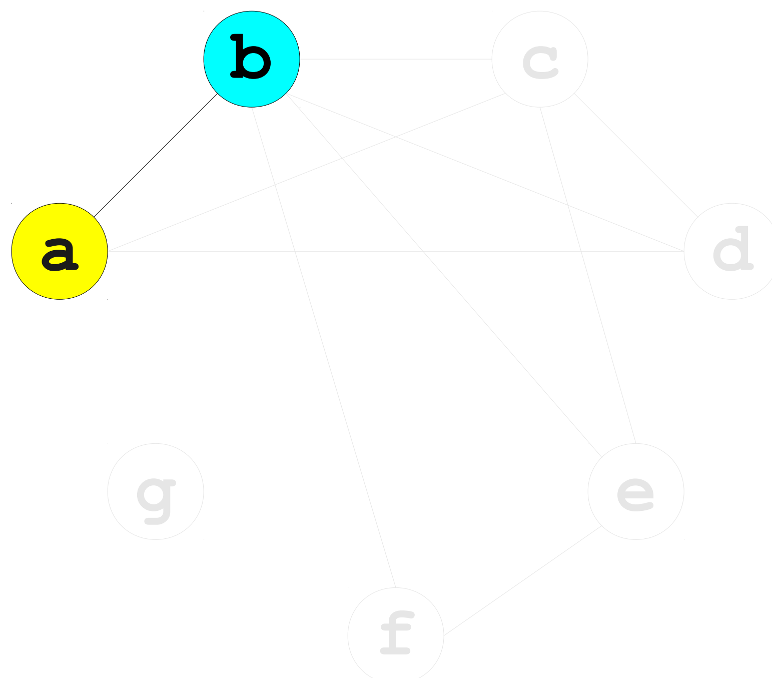

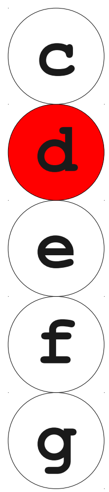

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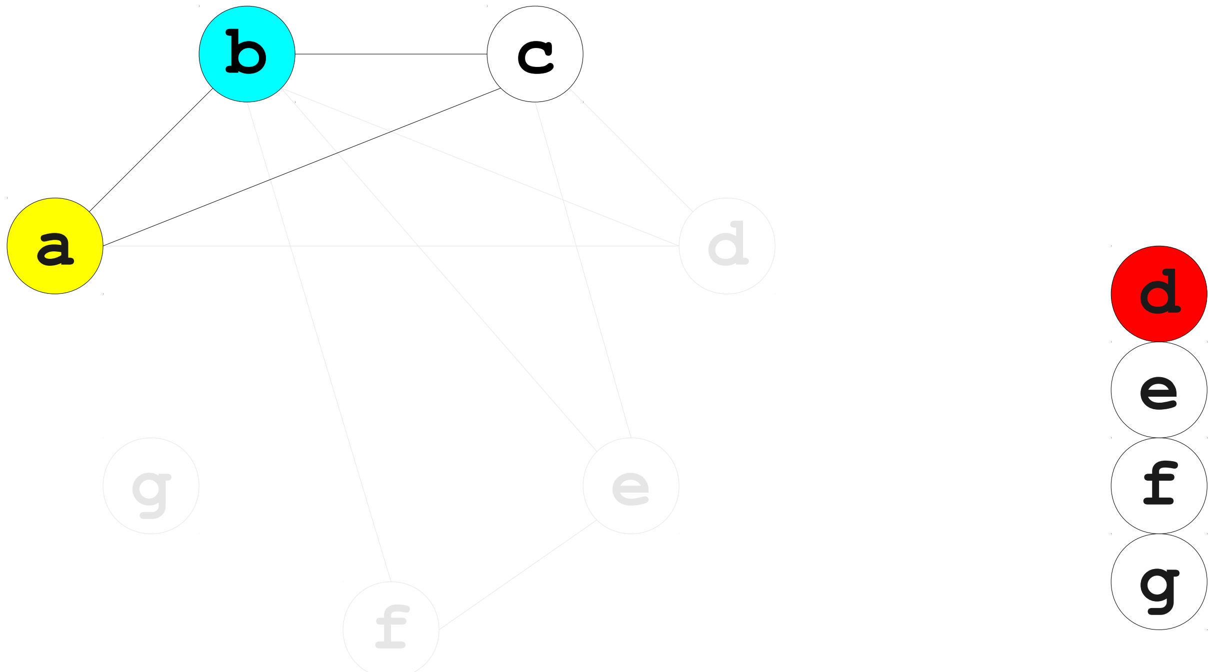

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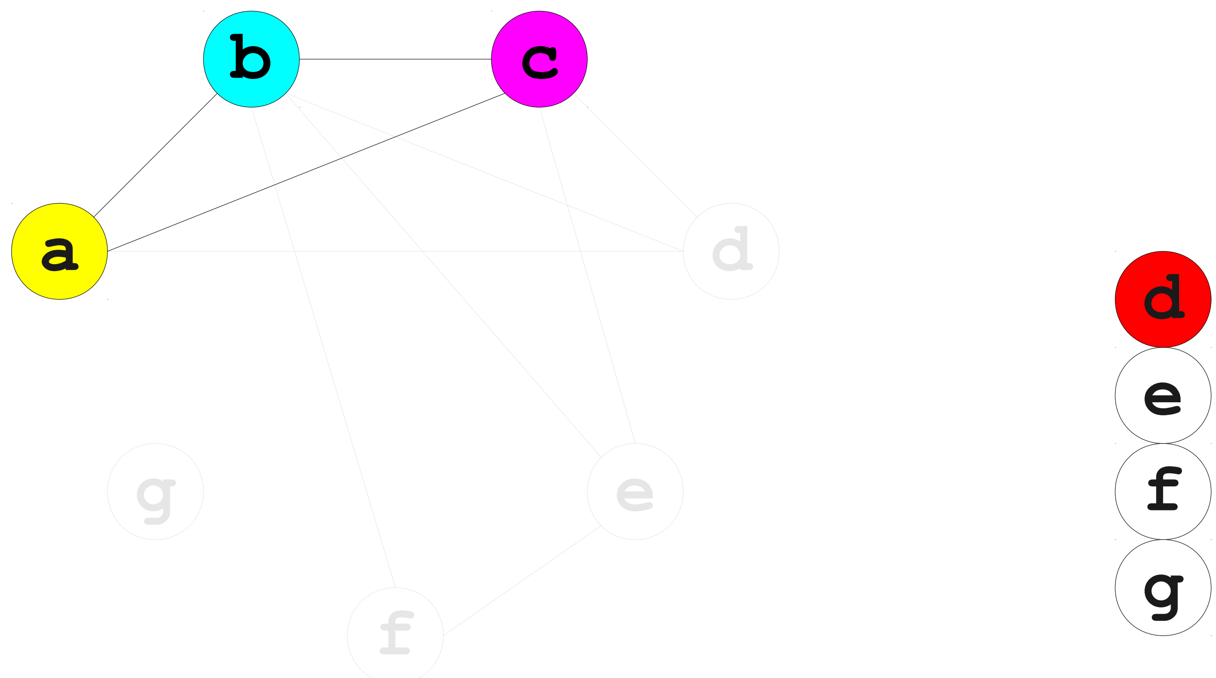

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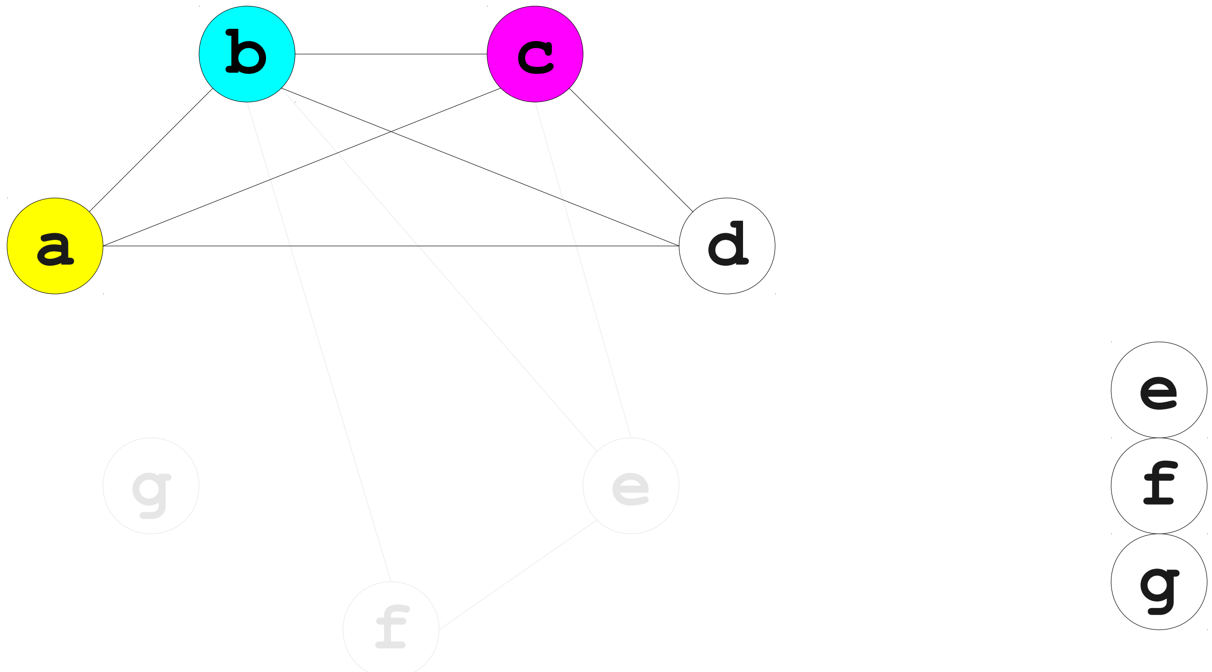

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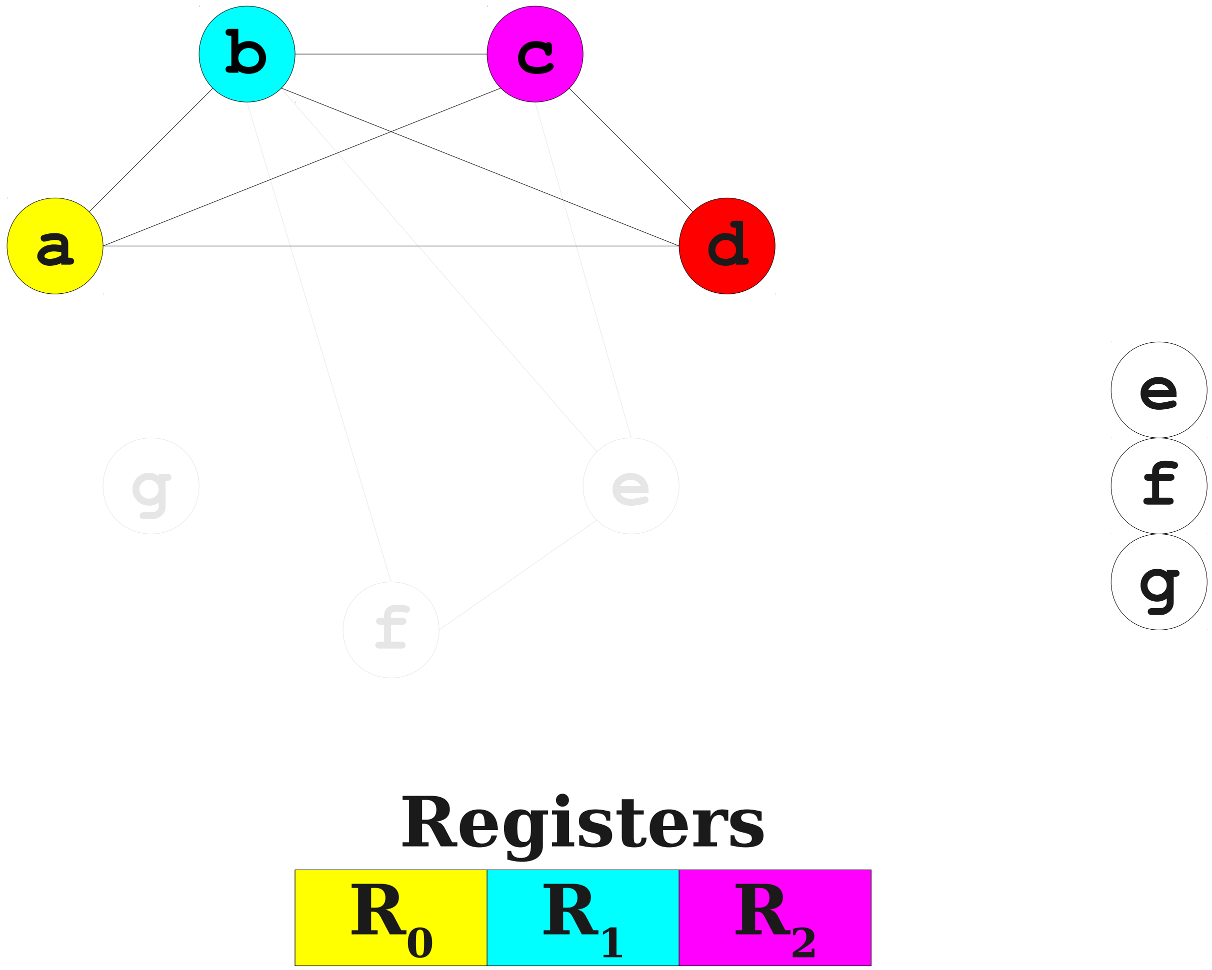

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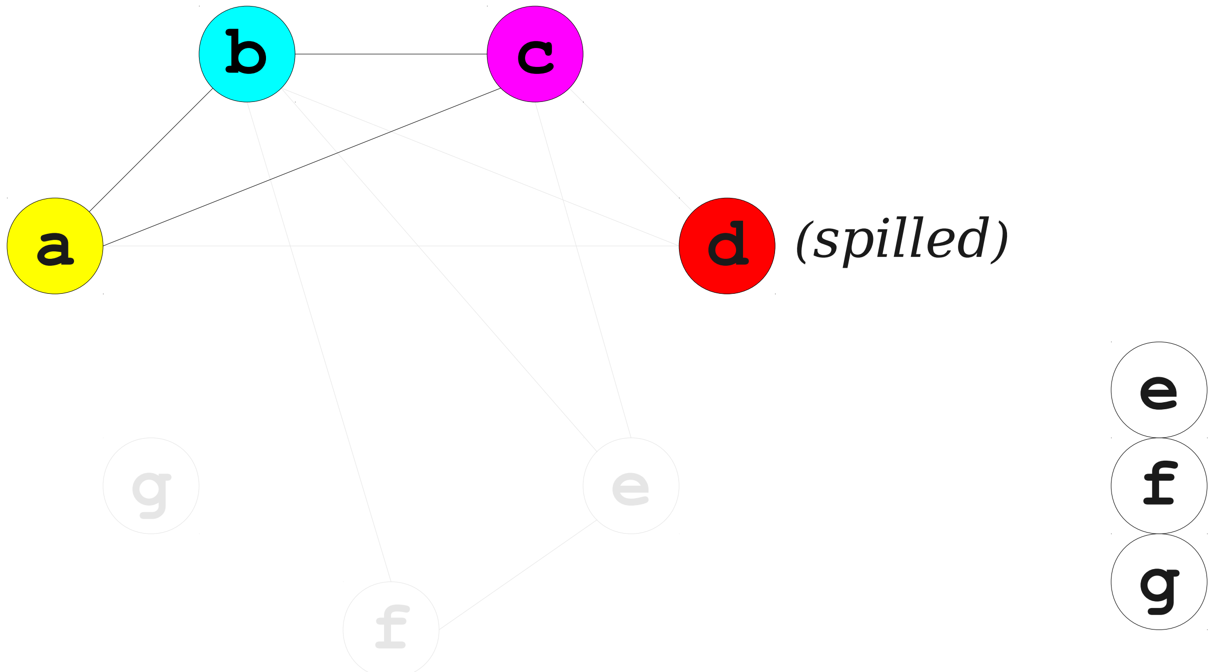

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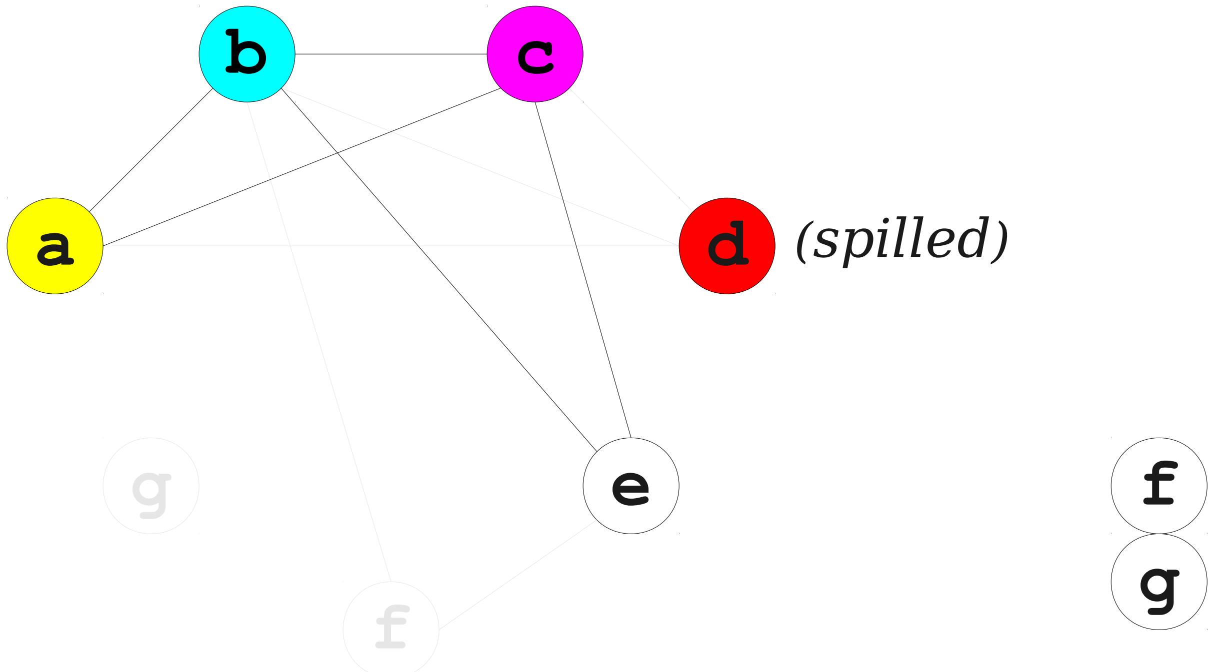

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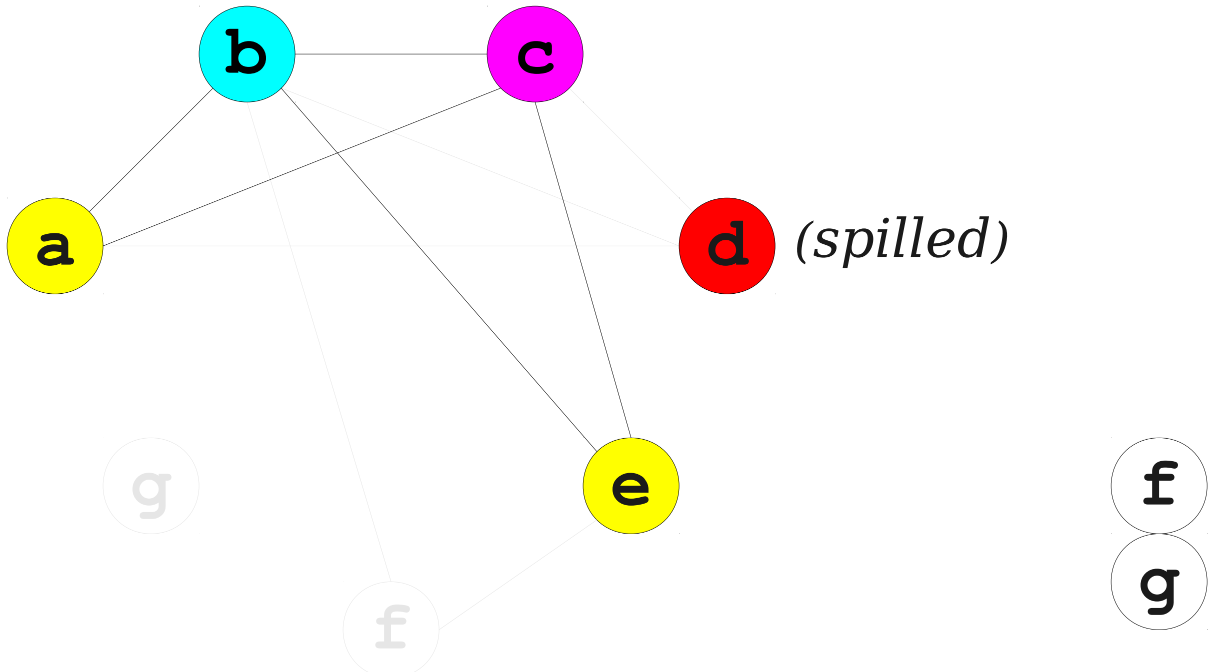
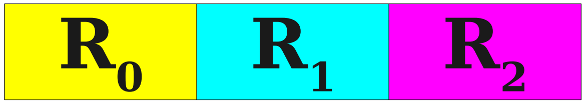


Registers



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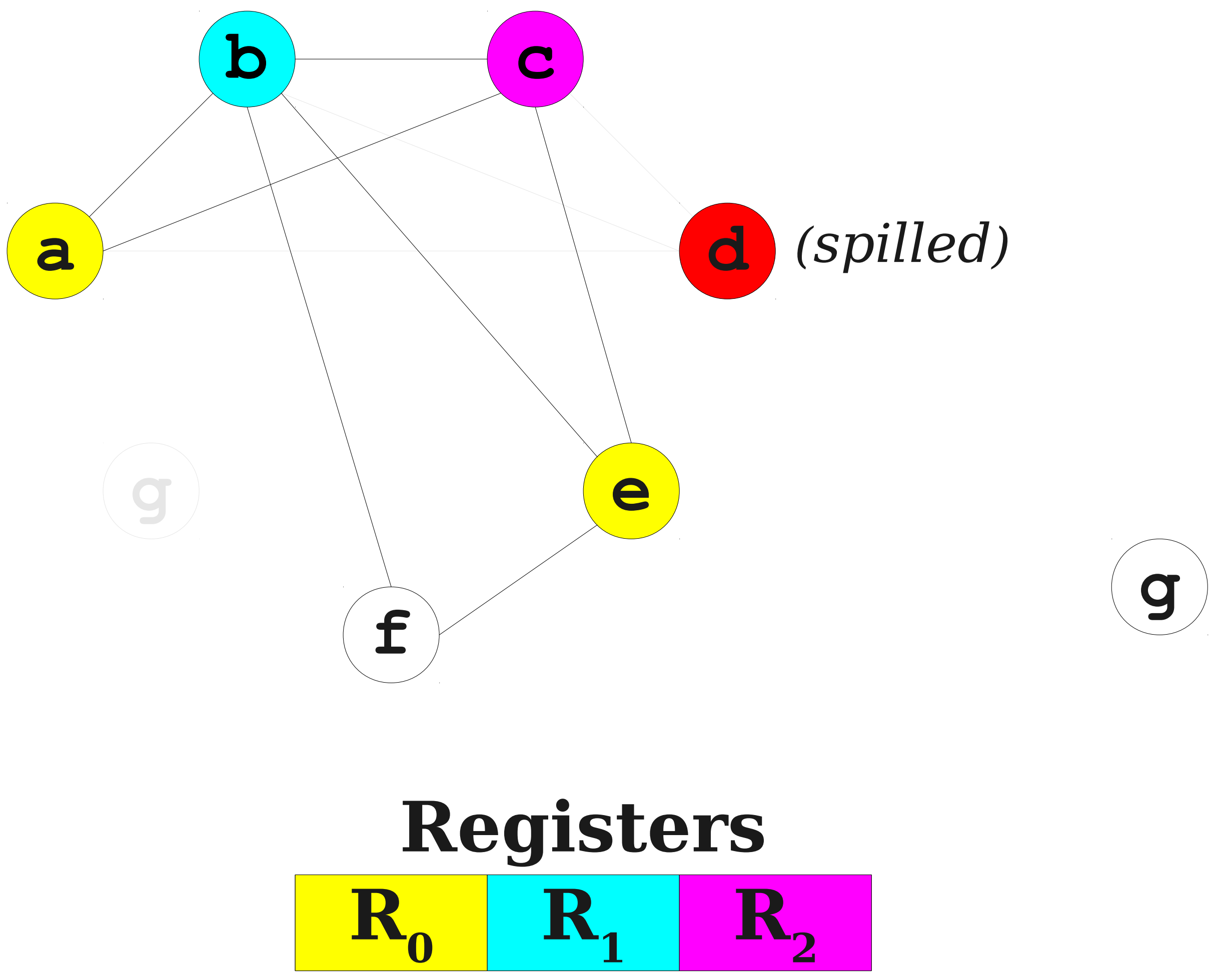

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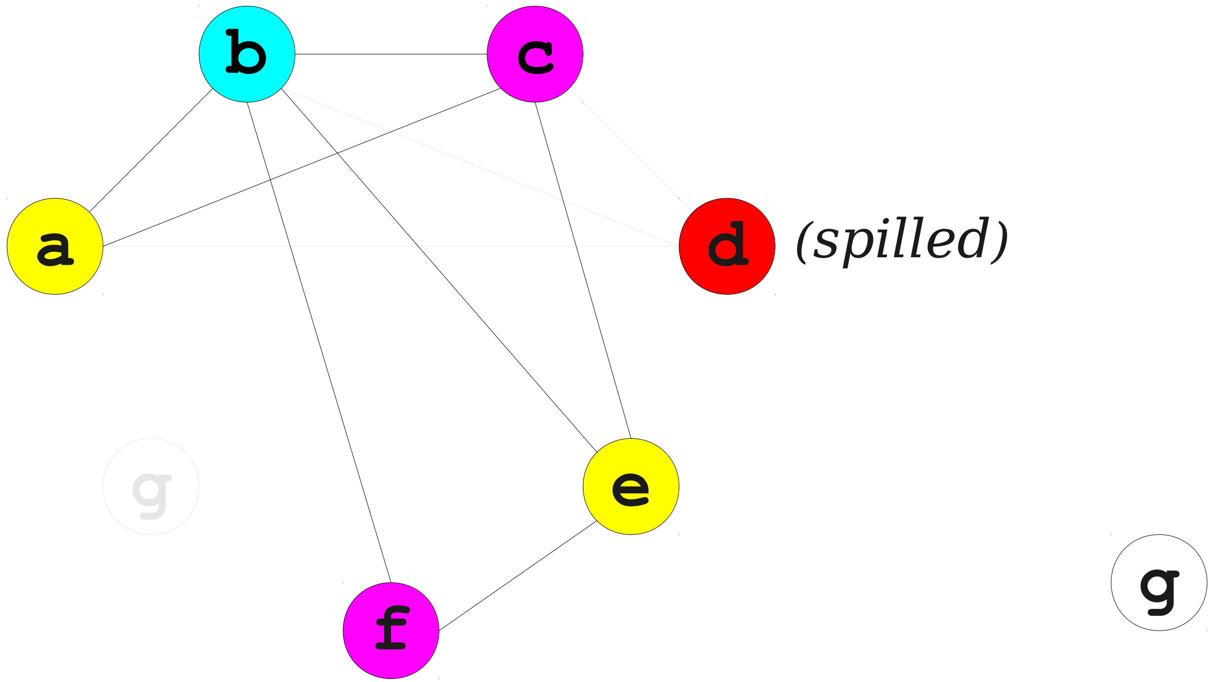

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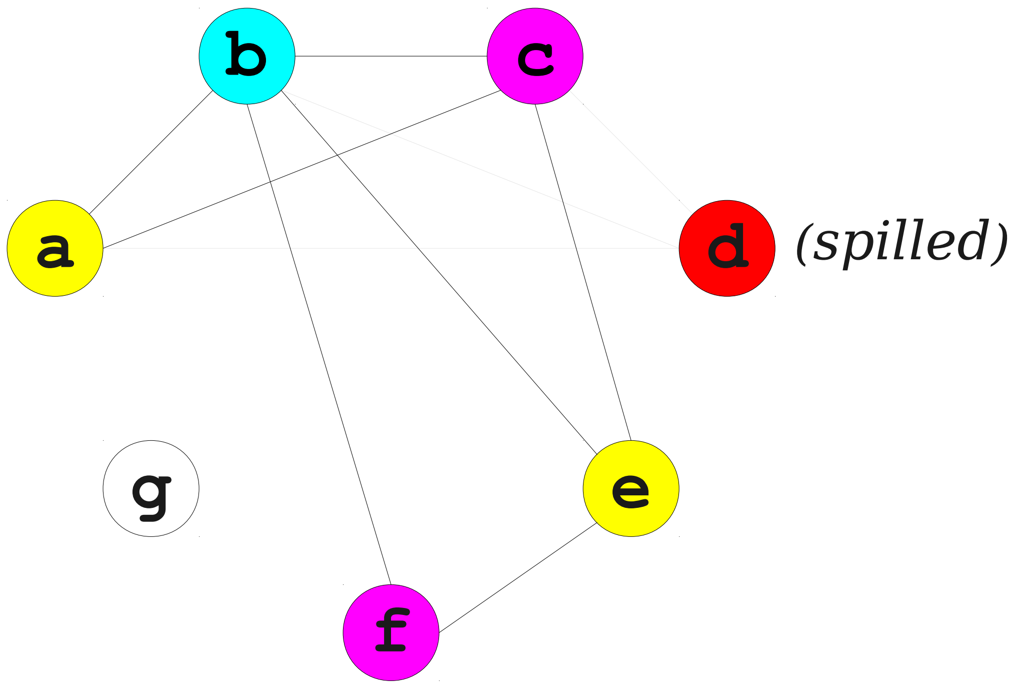

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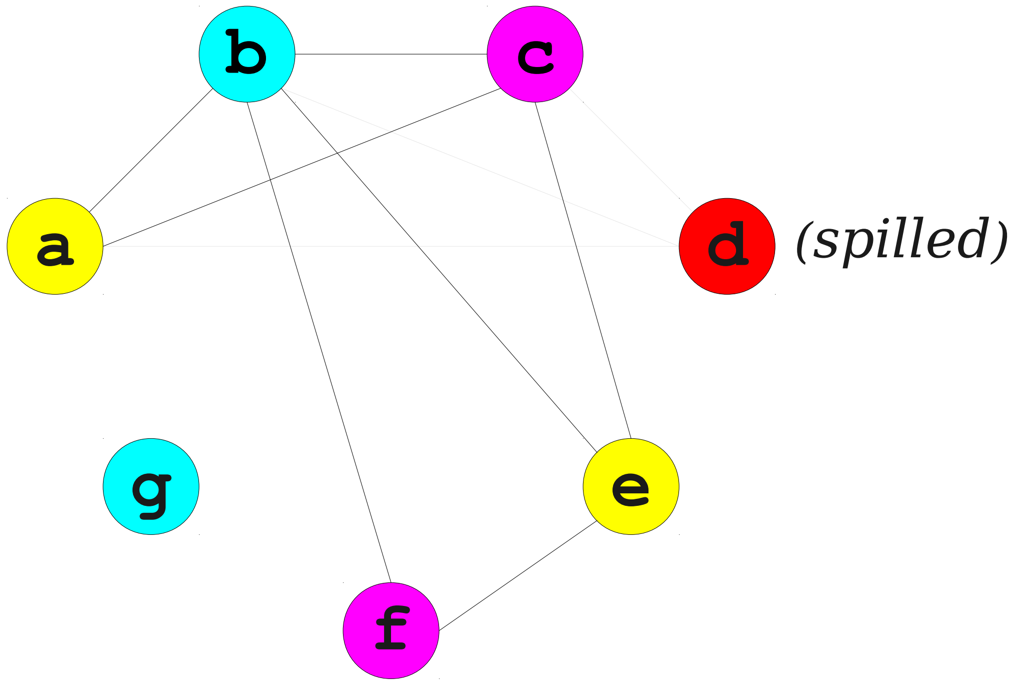

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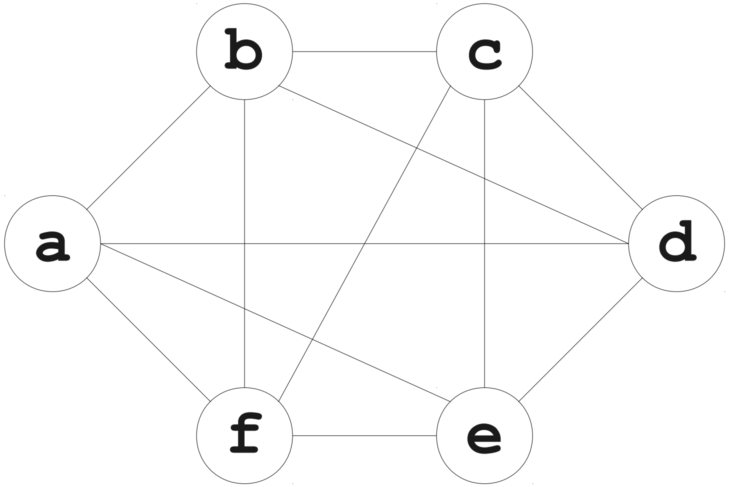

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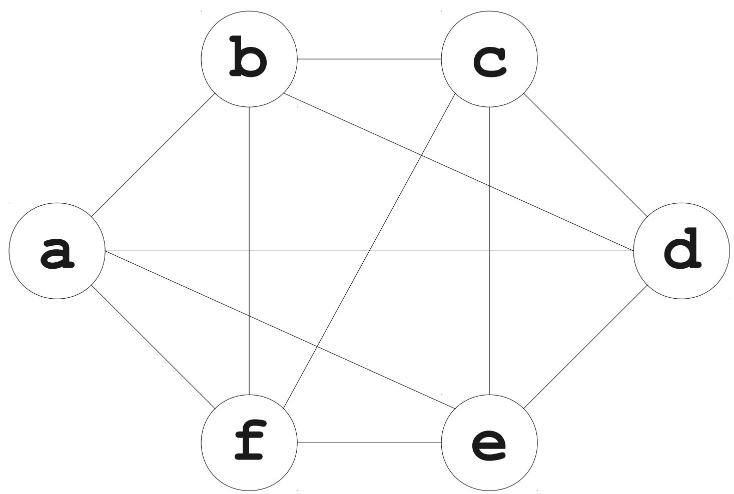

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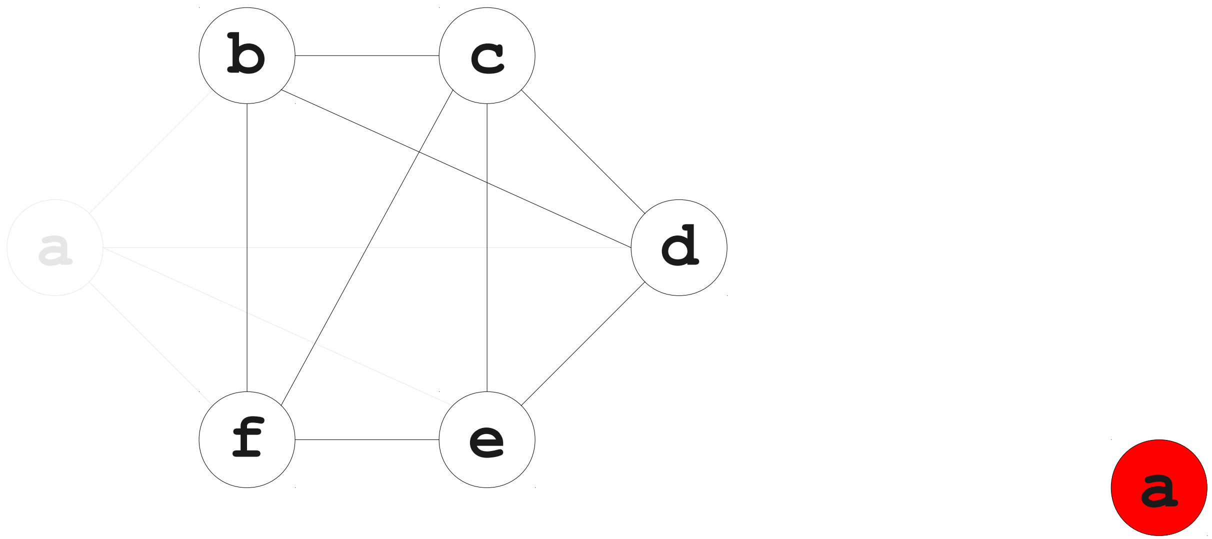

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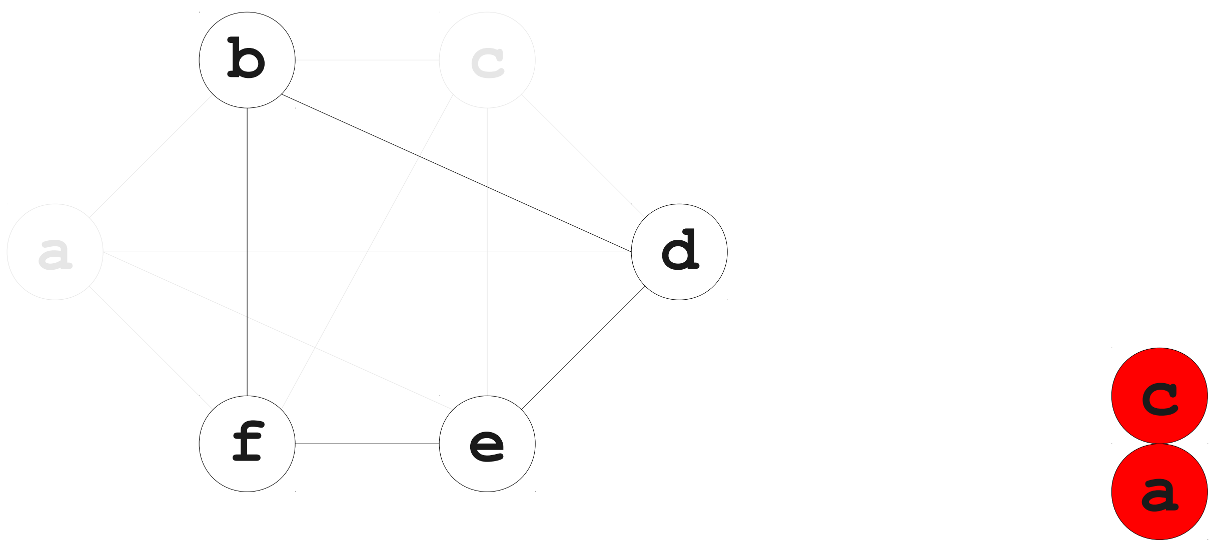

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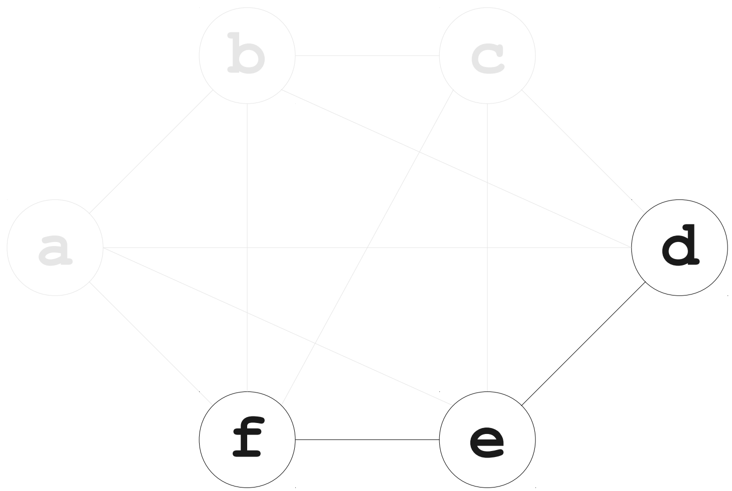

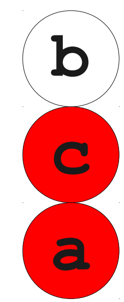

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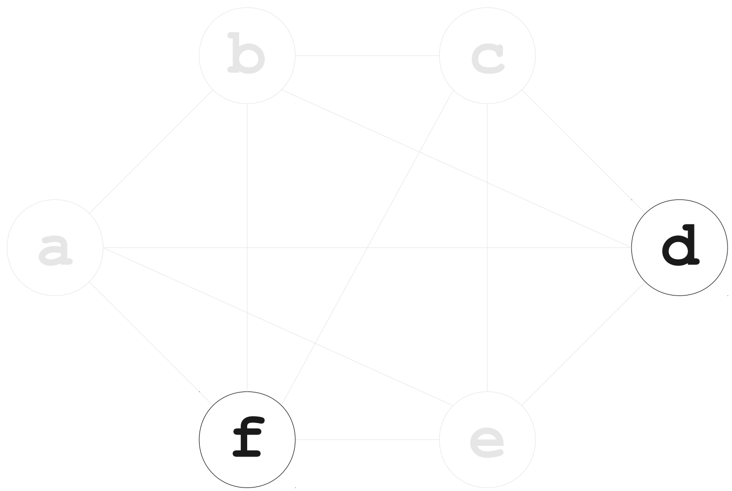

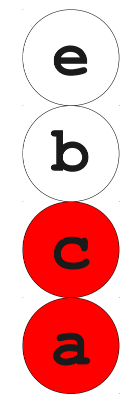

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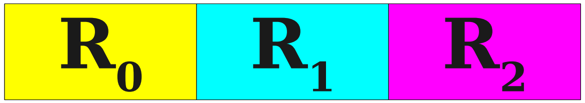

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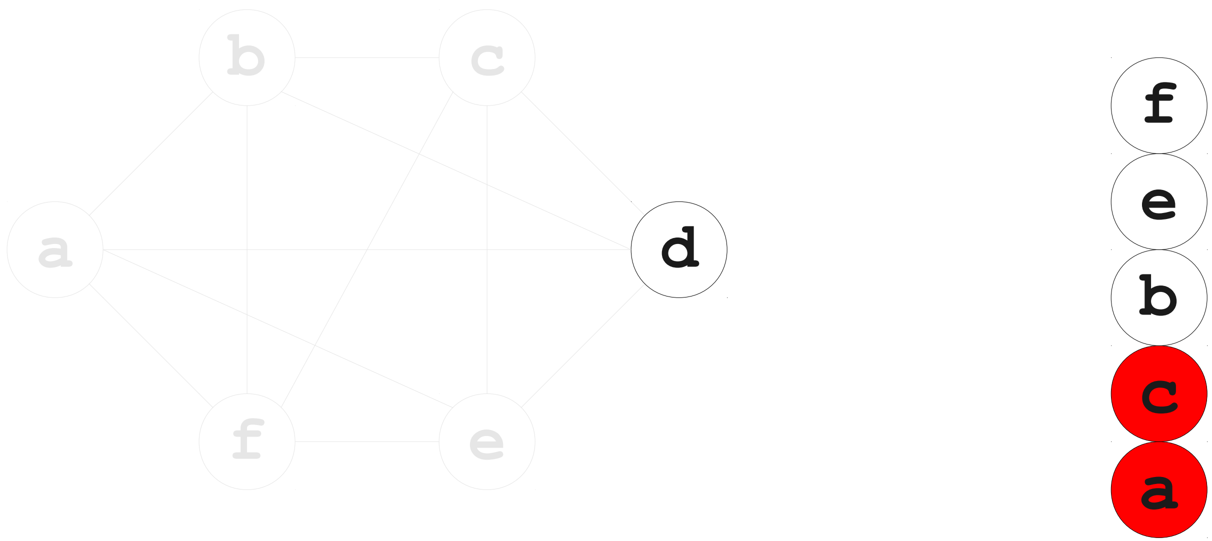

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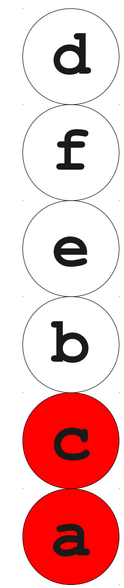

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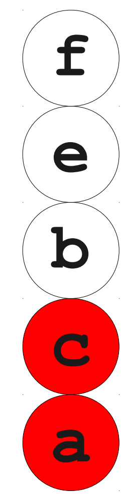

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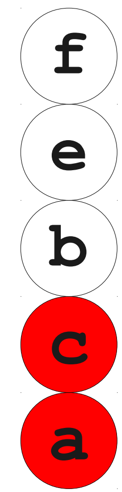

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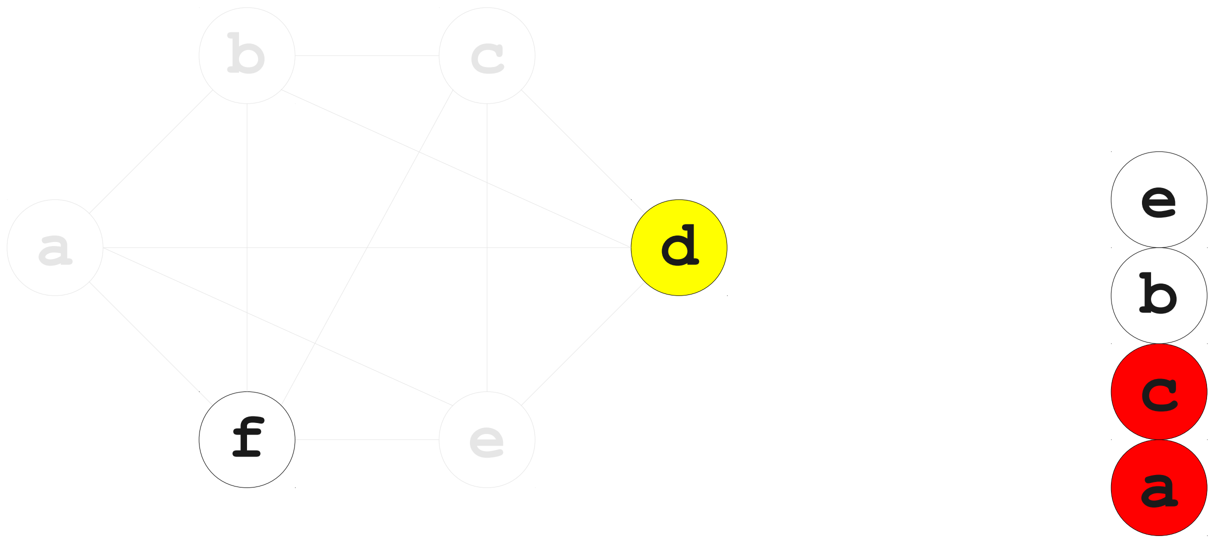

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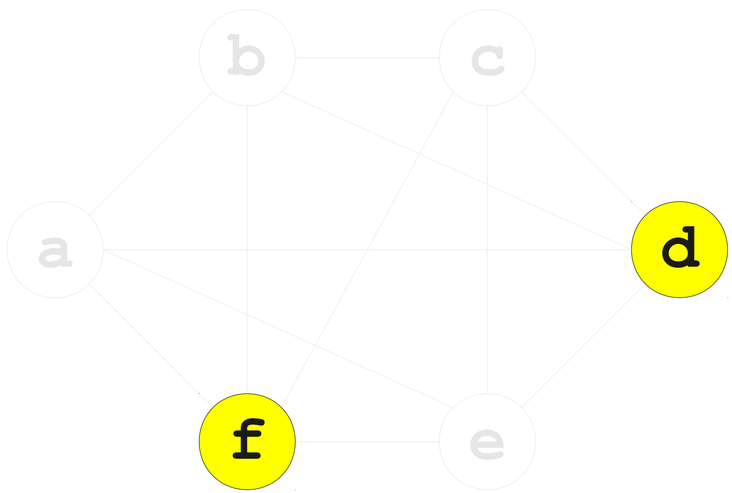

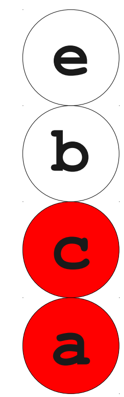

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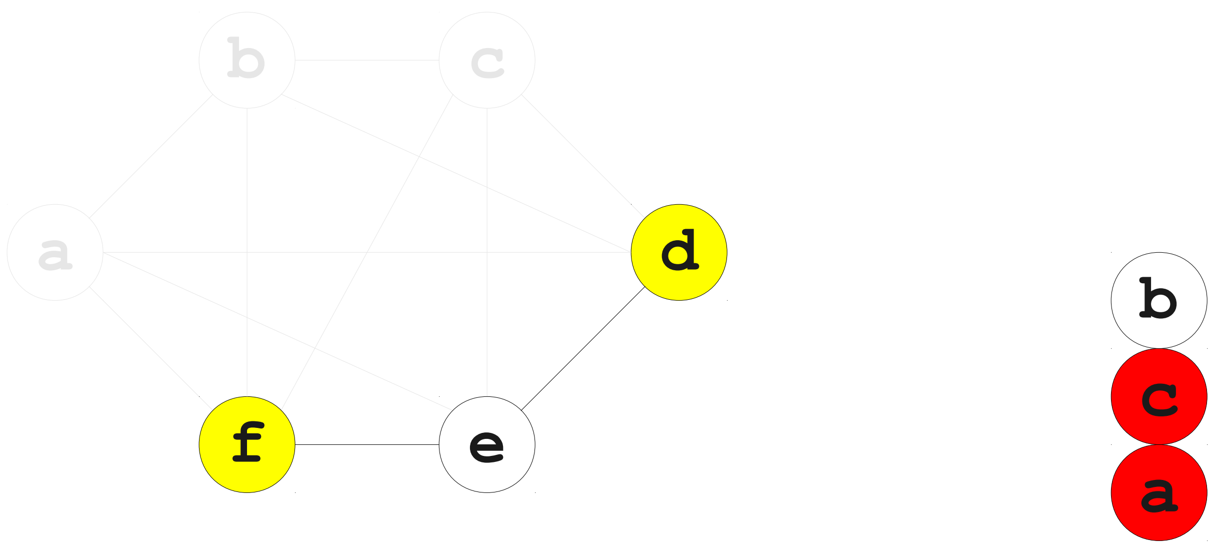

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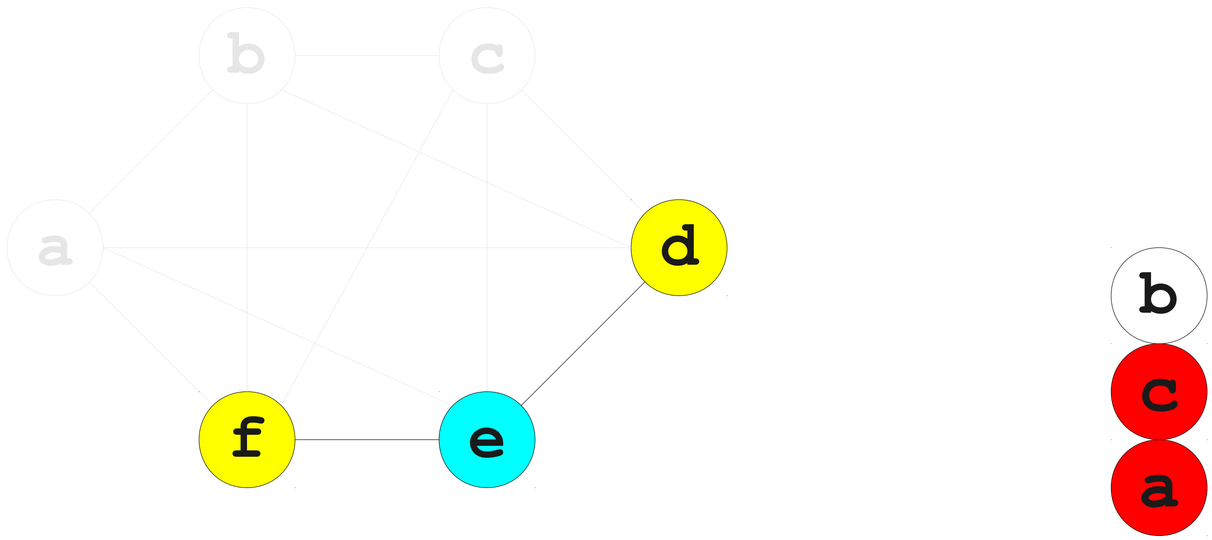

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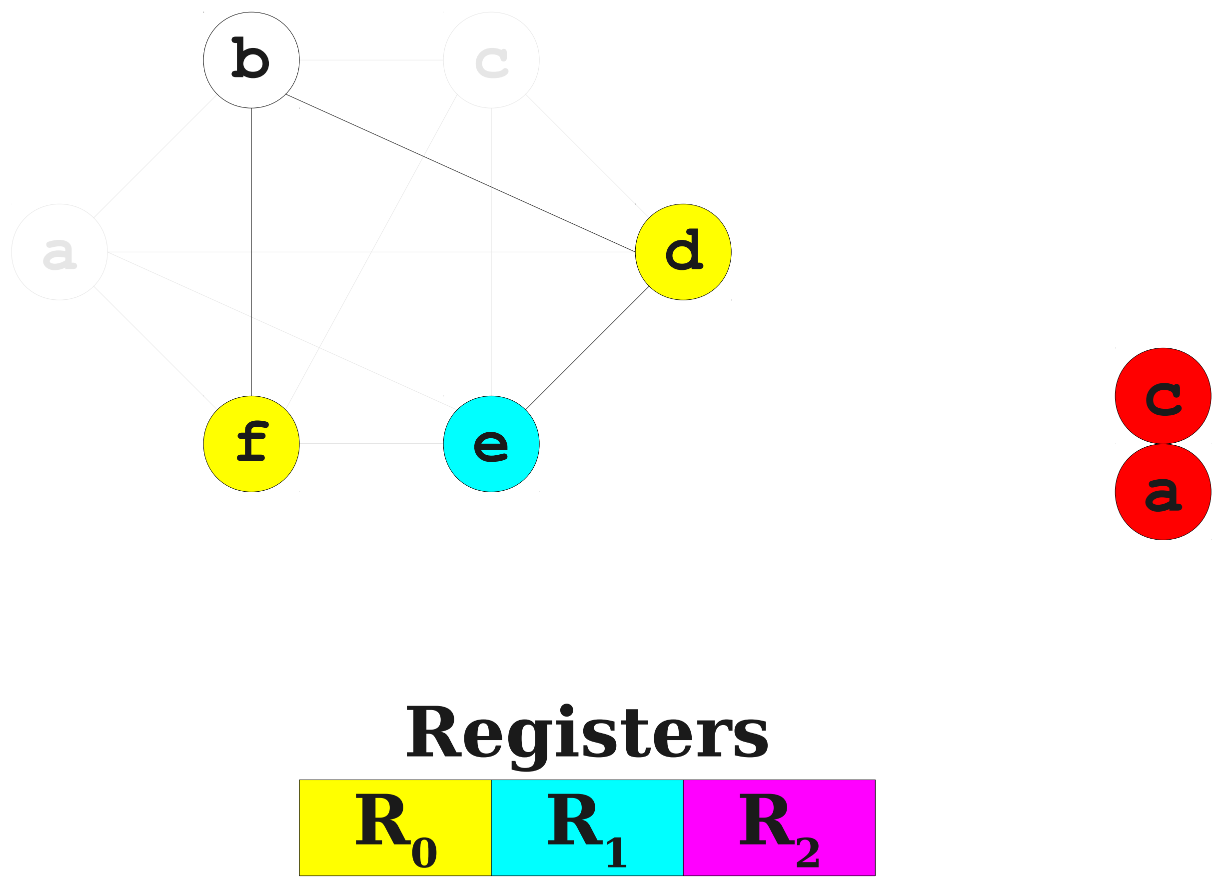

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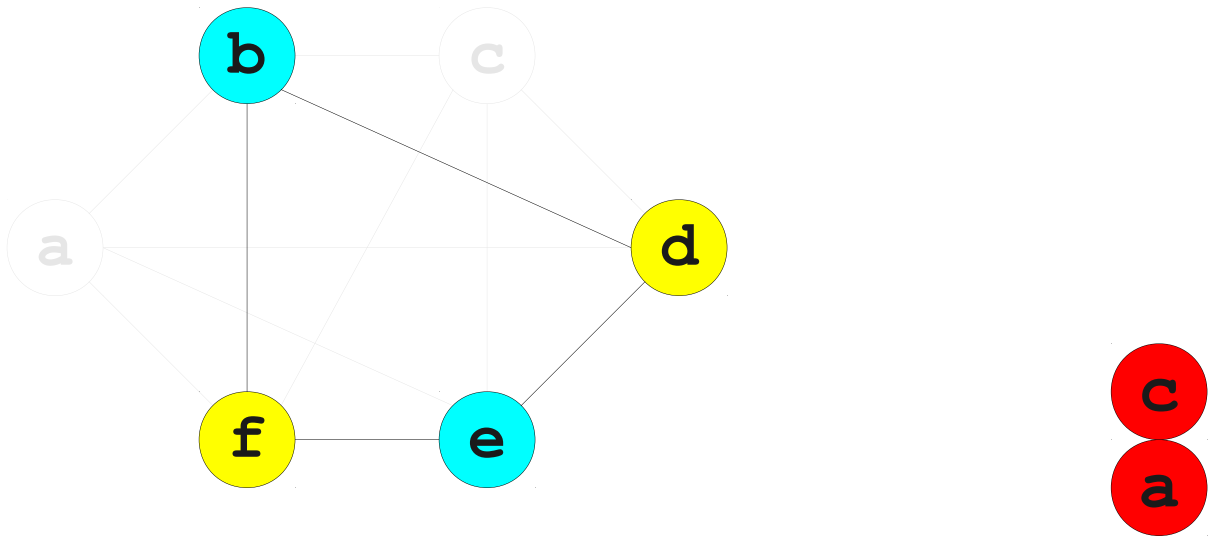

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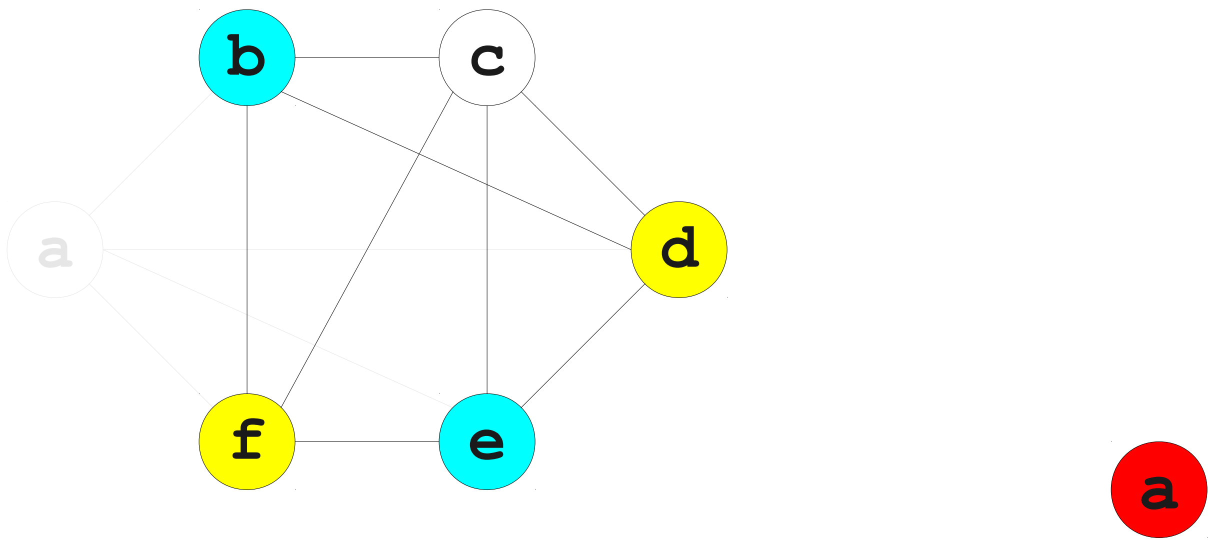

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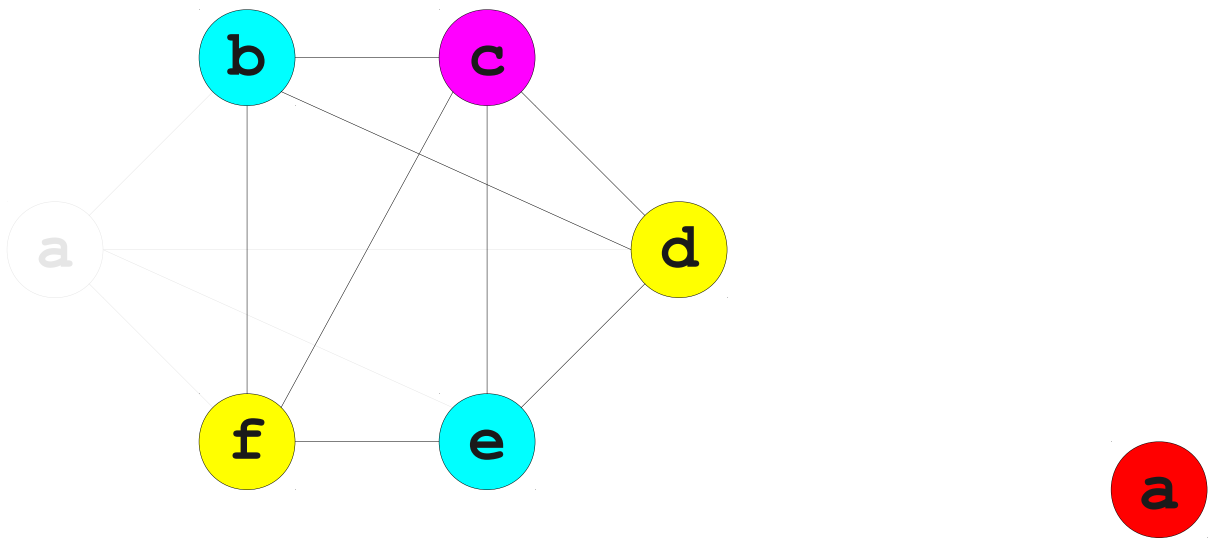

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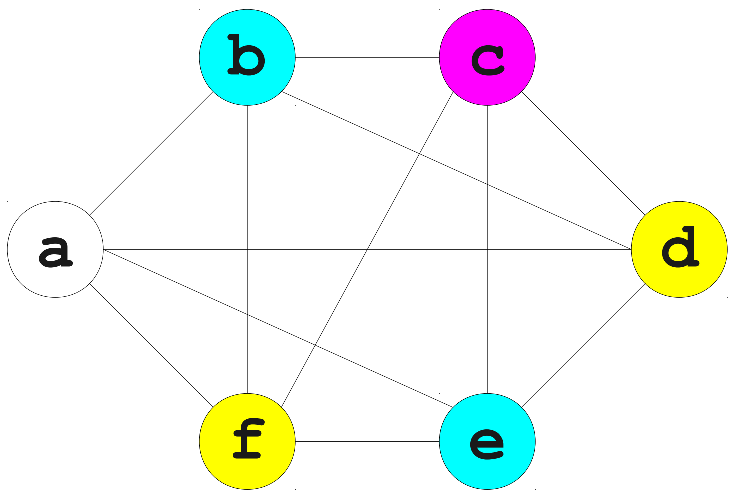

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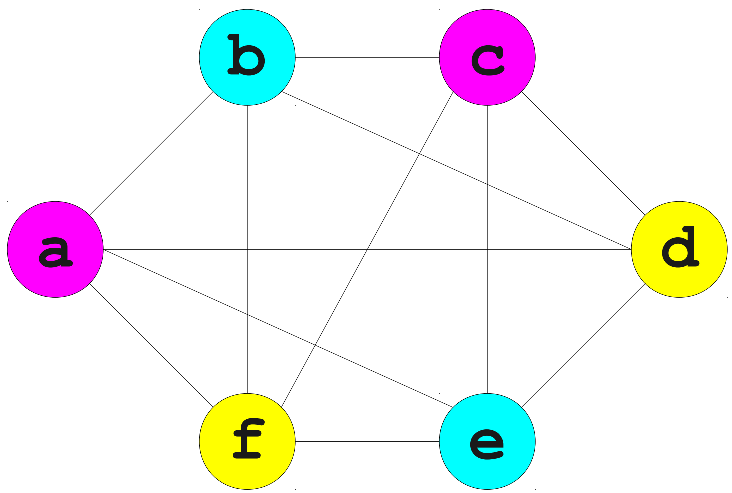

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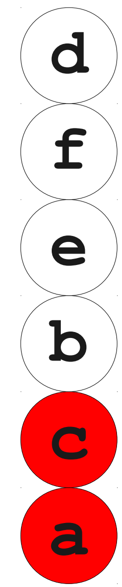

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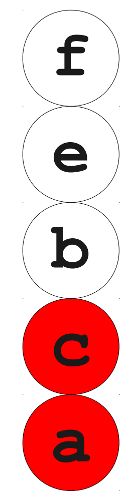

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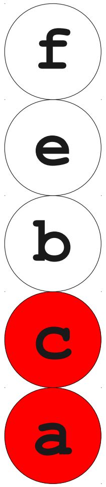

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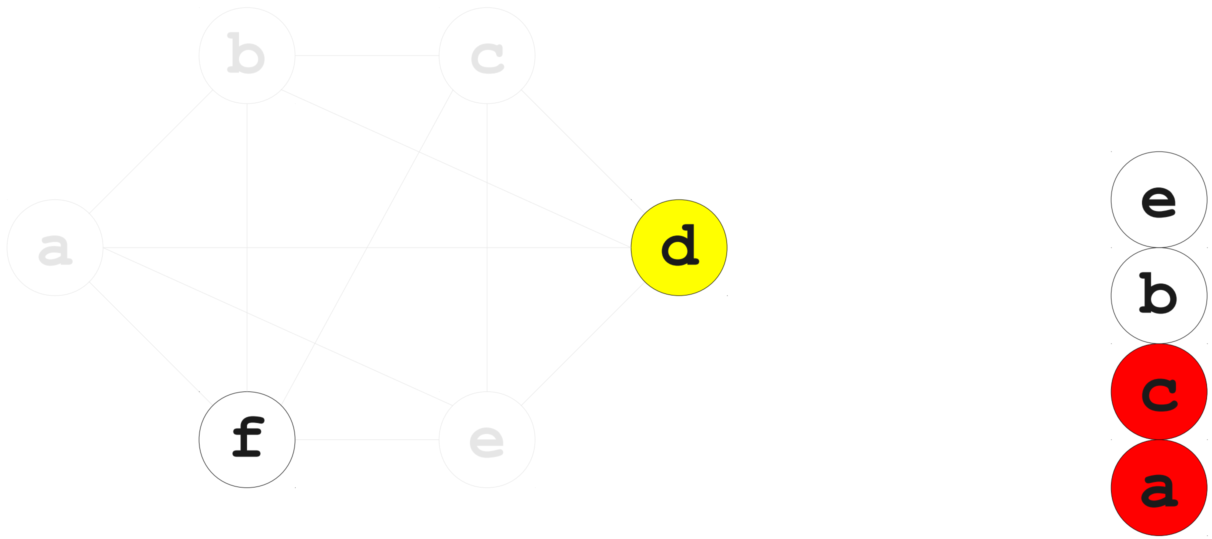

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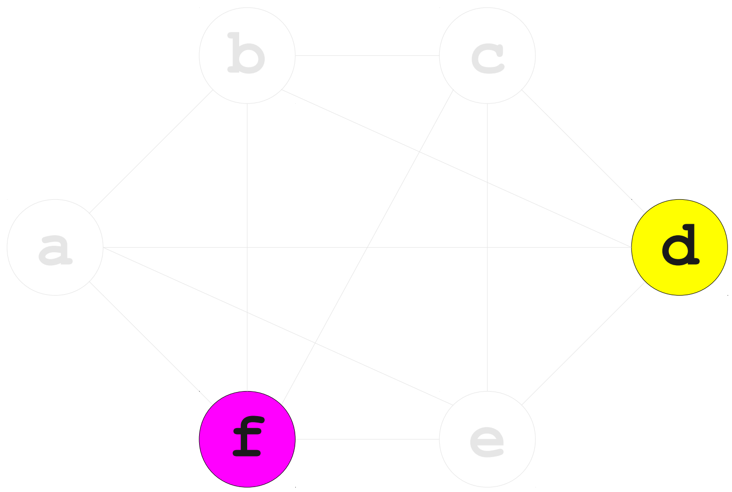

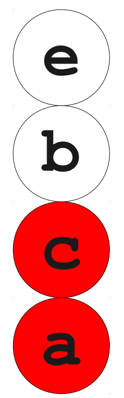

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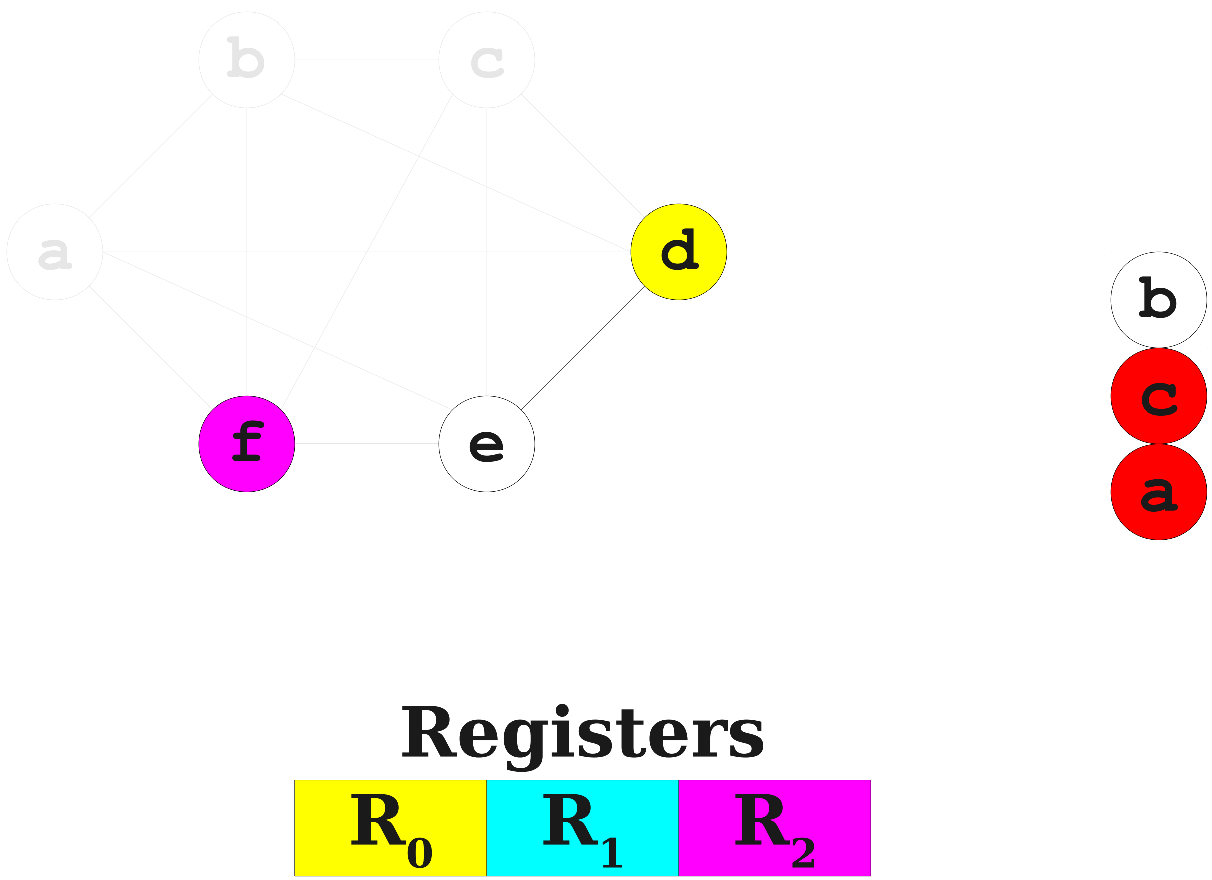

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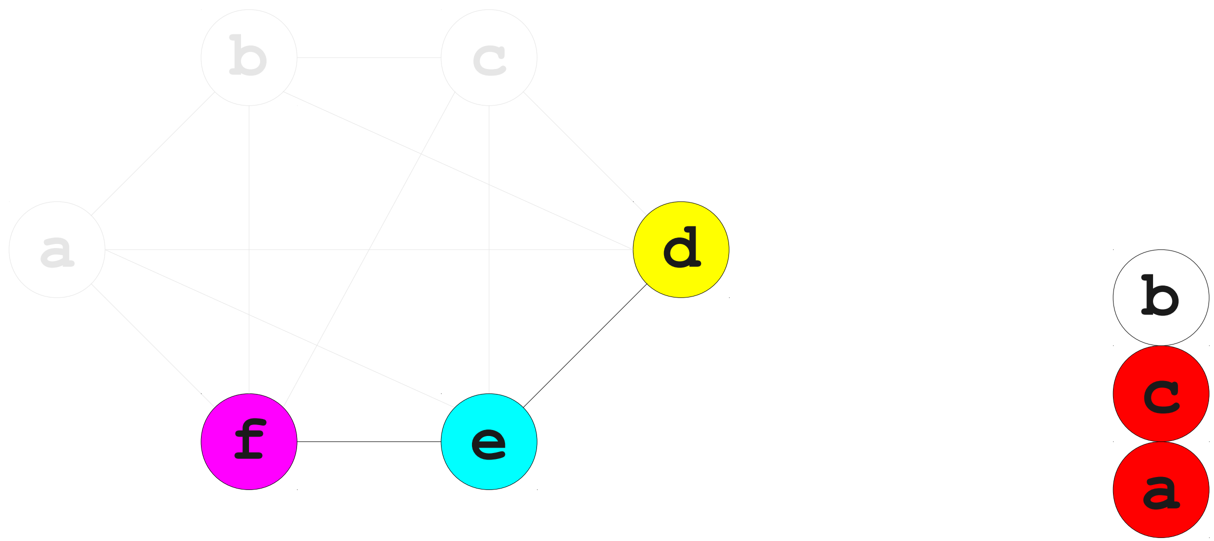

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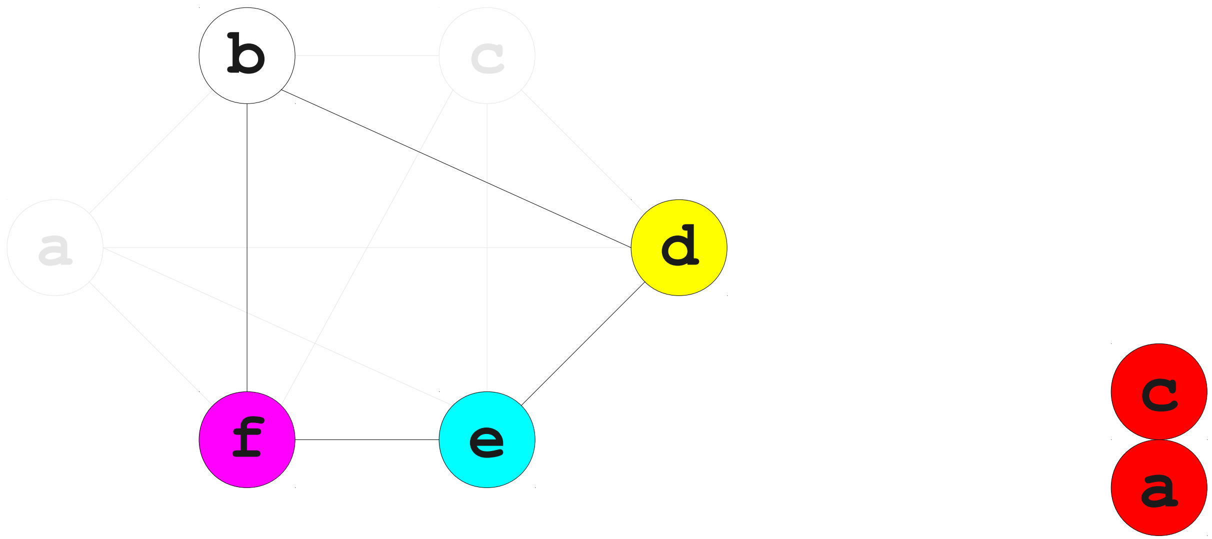

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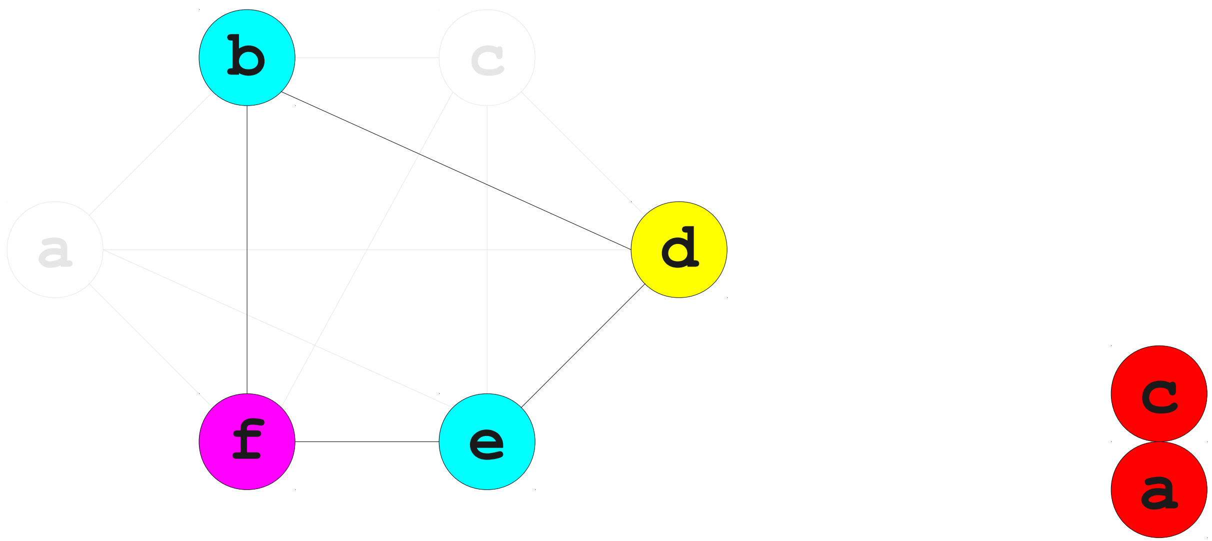

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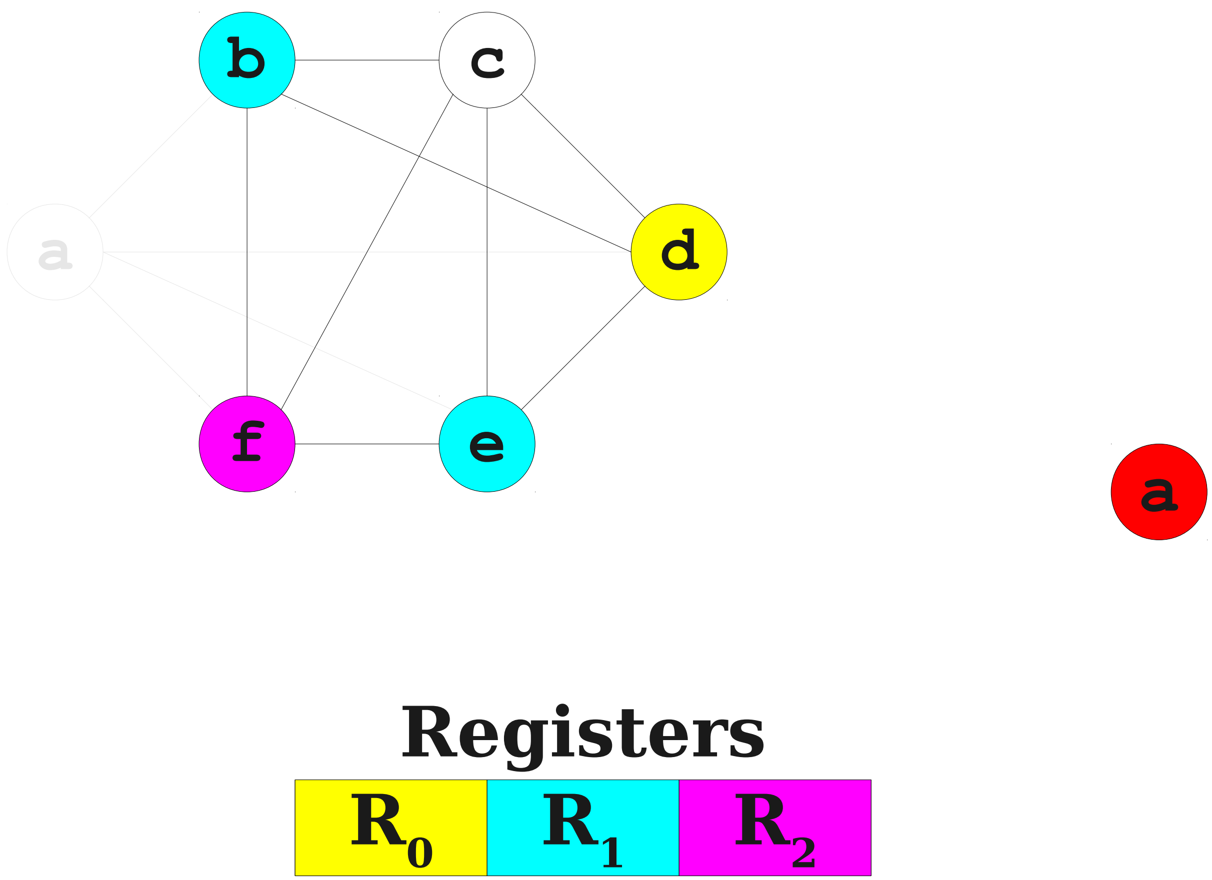

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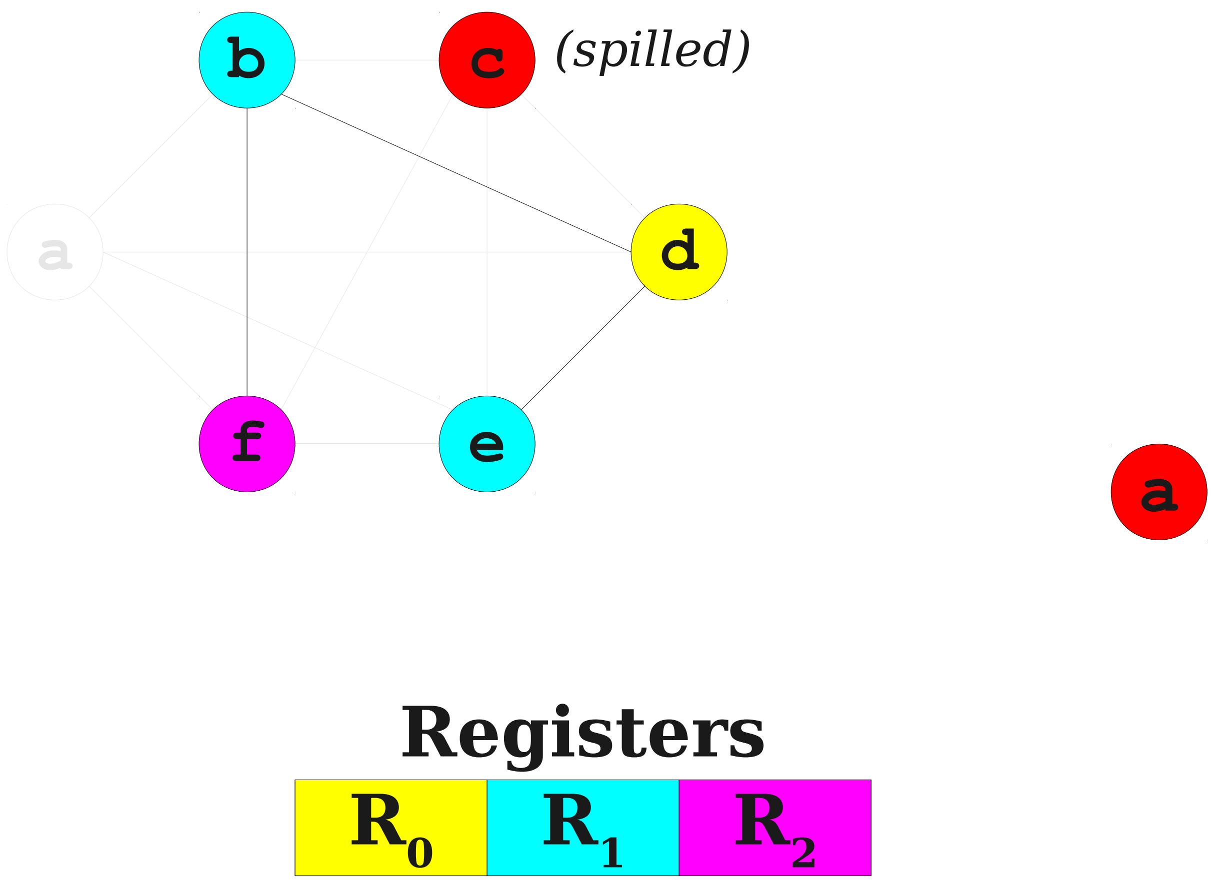

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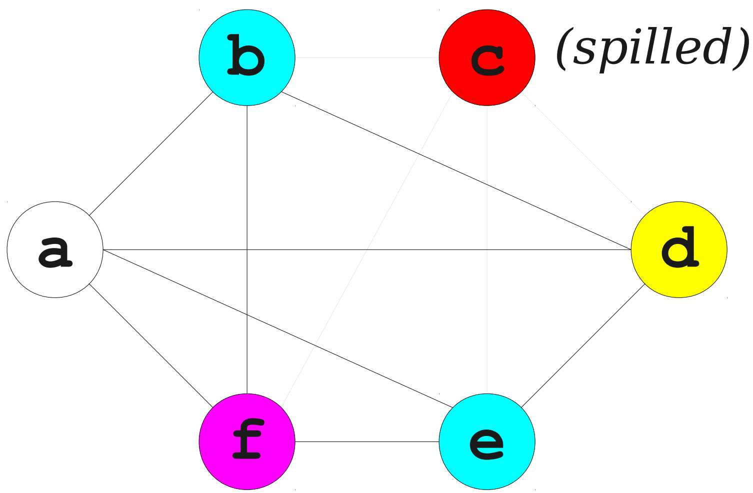

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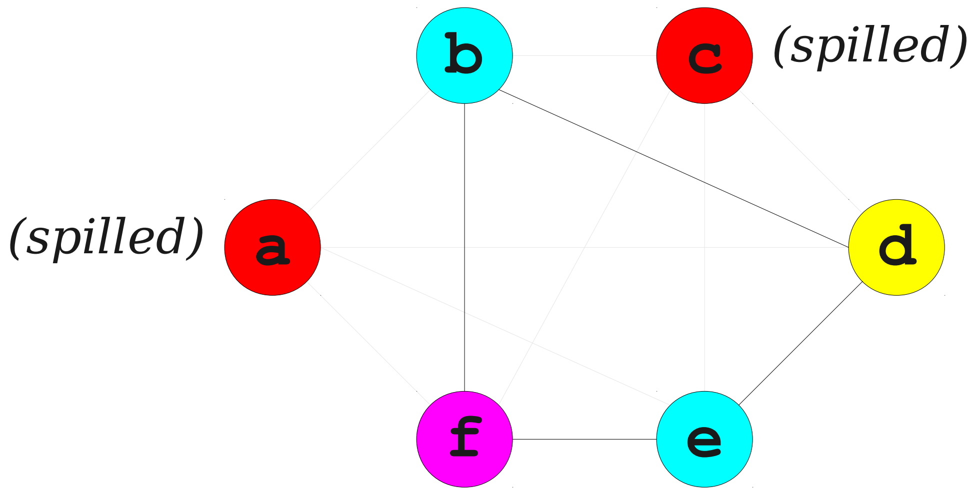

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Chaitin's Algorithm

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- How good the coloring is depends on the order we color the nodes to the graph
  - called the **elimination ordering**
- For every graph, there is a elimination ordering such that Chaitin's algorithm produces an optimal coloring
  - therefore finding this optimal elimination ordering for a general graph is NP-complete

Graph Coloring SSA Programs

Hack et al, "Register Allocation for Programs in SSA-Form", *Compiler Construction* 2006

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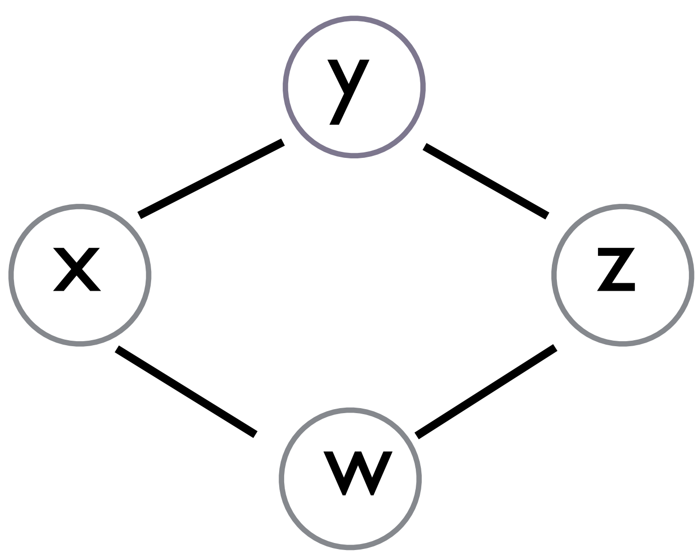
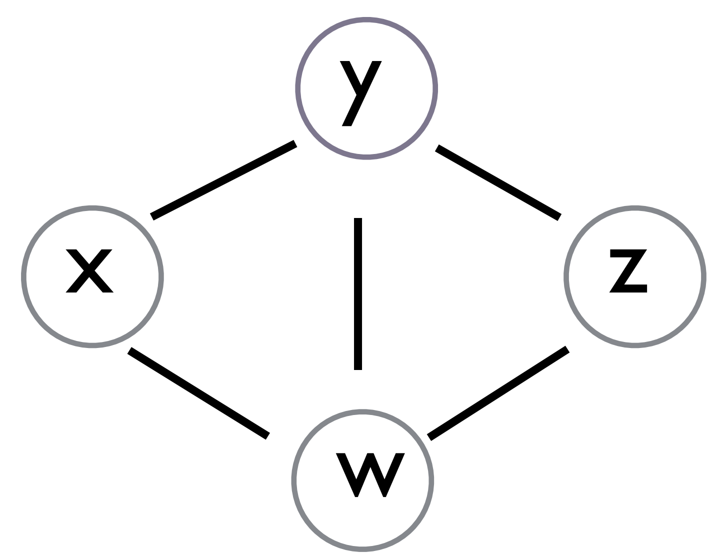
- The interference graphs of an SSA program are all **chordal**
  - Every cycle >= 4 nodes has a **chord**



Not chordal



chordal

Coloring Chordal Graphs

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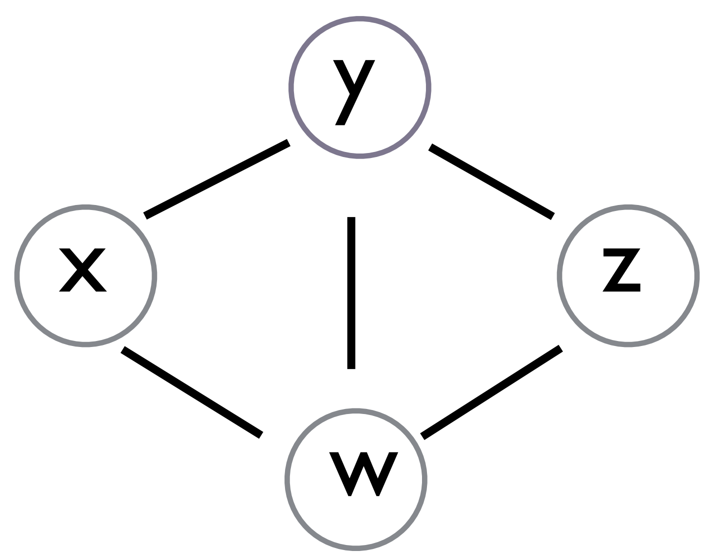

x,y,z,w
not perfect: N(w) non-clique

w,x,y,z
perfect

Every SSA Interference Graph is Chordal

Theorem: A graph is chordal iff it has a **perfect elimination ordering**

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"in-scope" or "dominance" relation

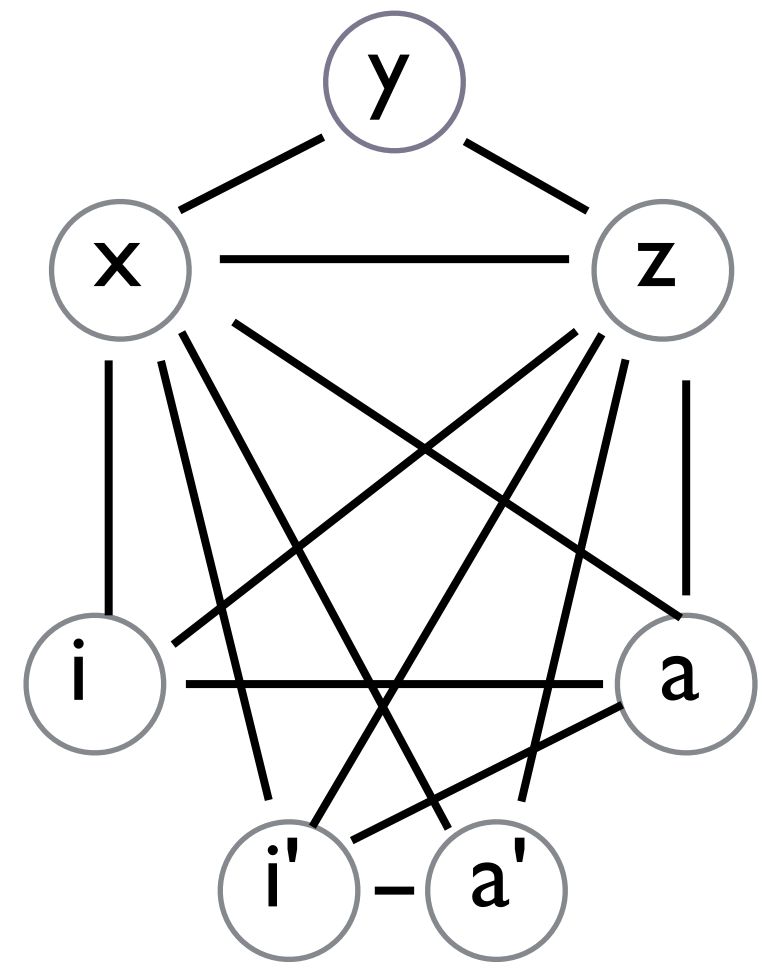
  - a variable x dominates y if is in scope when y is defined (includes simultaneous defs)

- x's definition is "closer to the root" of the AST than y
- easy to compute: pre-order traversal of the nodes

Coloring a Chordal Graph

```
def f(x,y,z):
  def loop(i,a):
    if i == 0:
      a * z
    else:
      let i' = i - 1 in
      let a' = a + x in
      icall(loop; i', a')
  end
  icall(loop; y, 0)
```

Interference Graph



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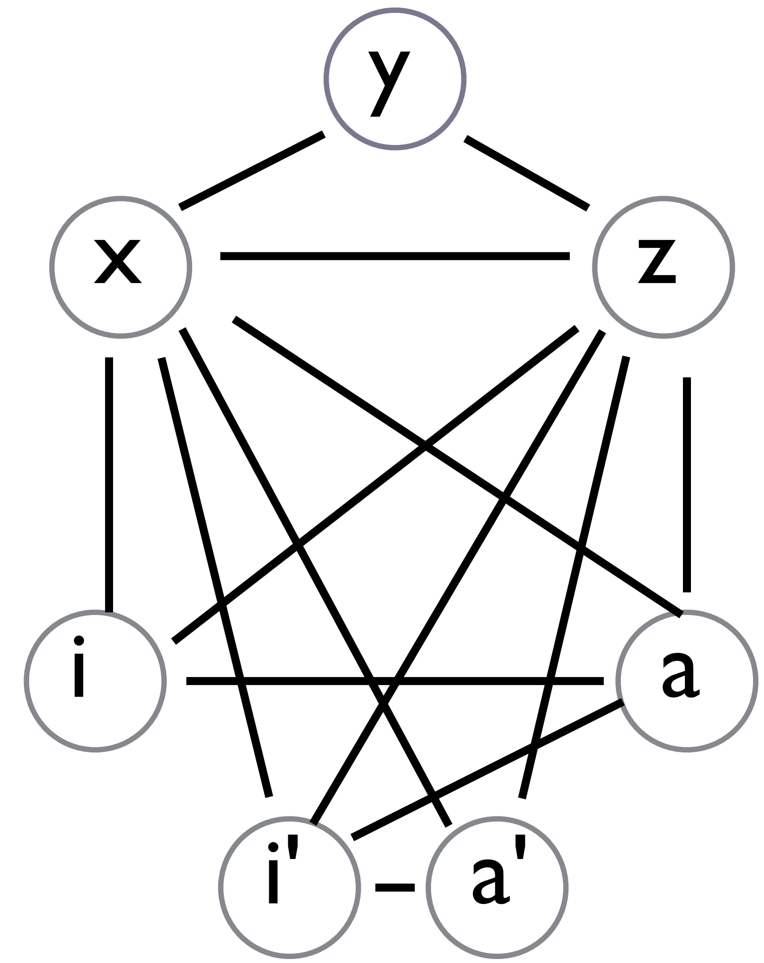

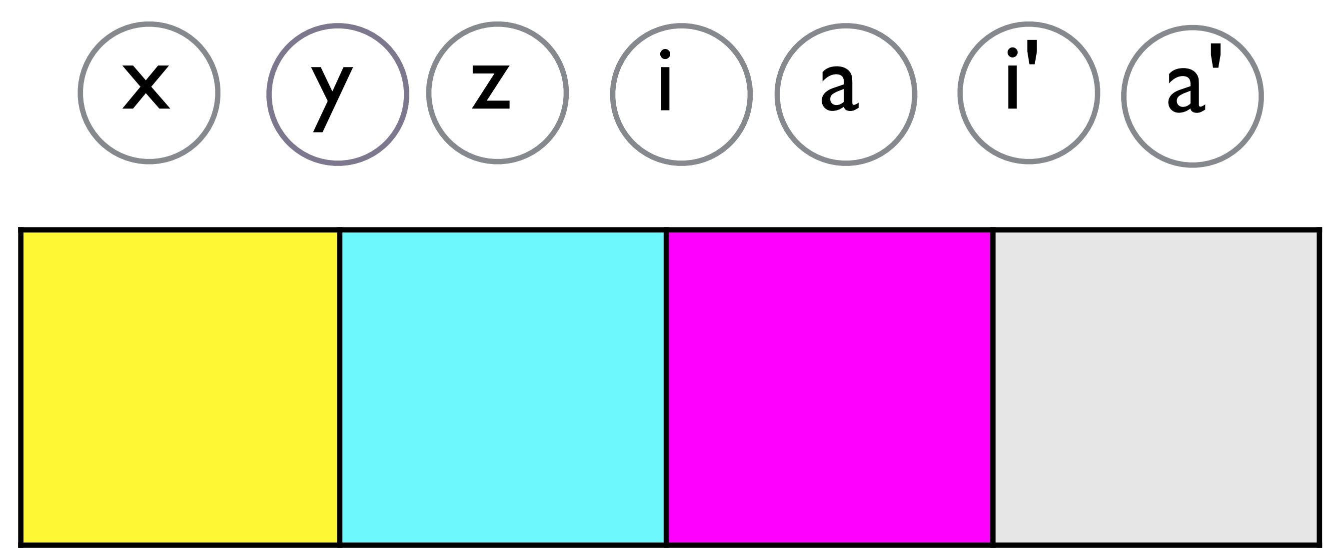

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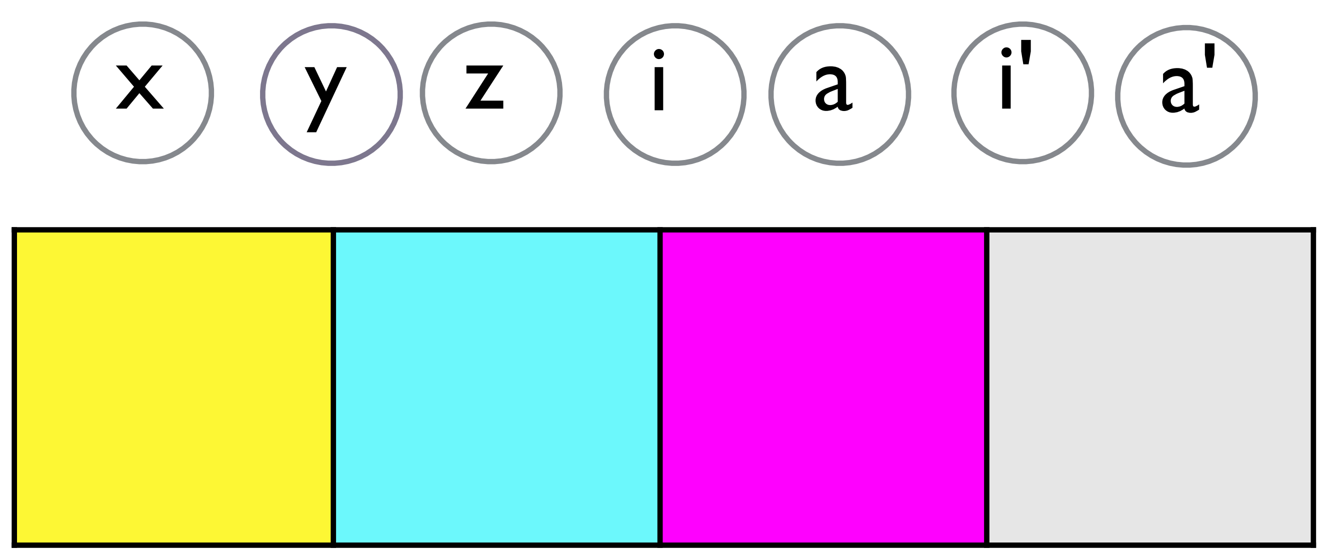

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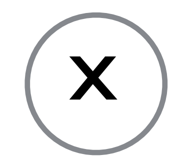

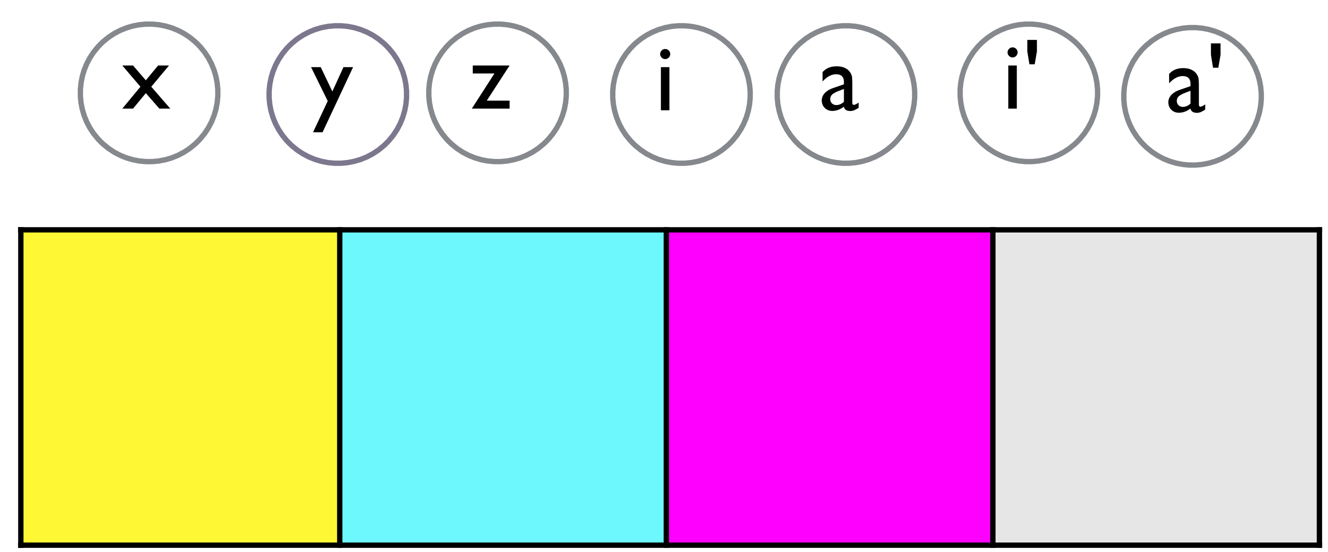

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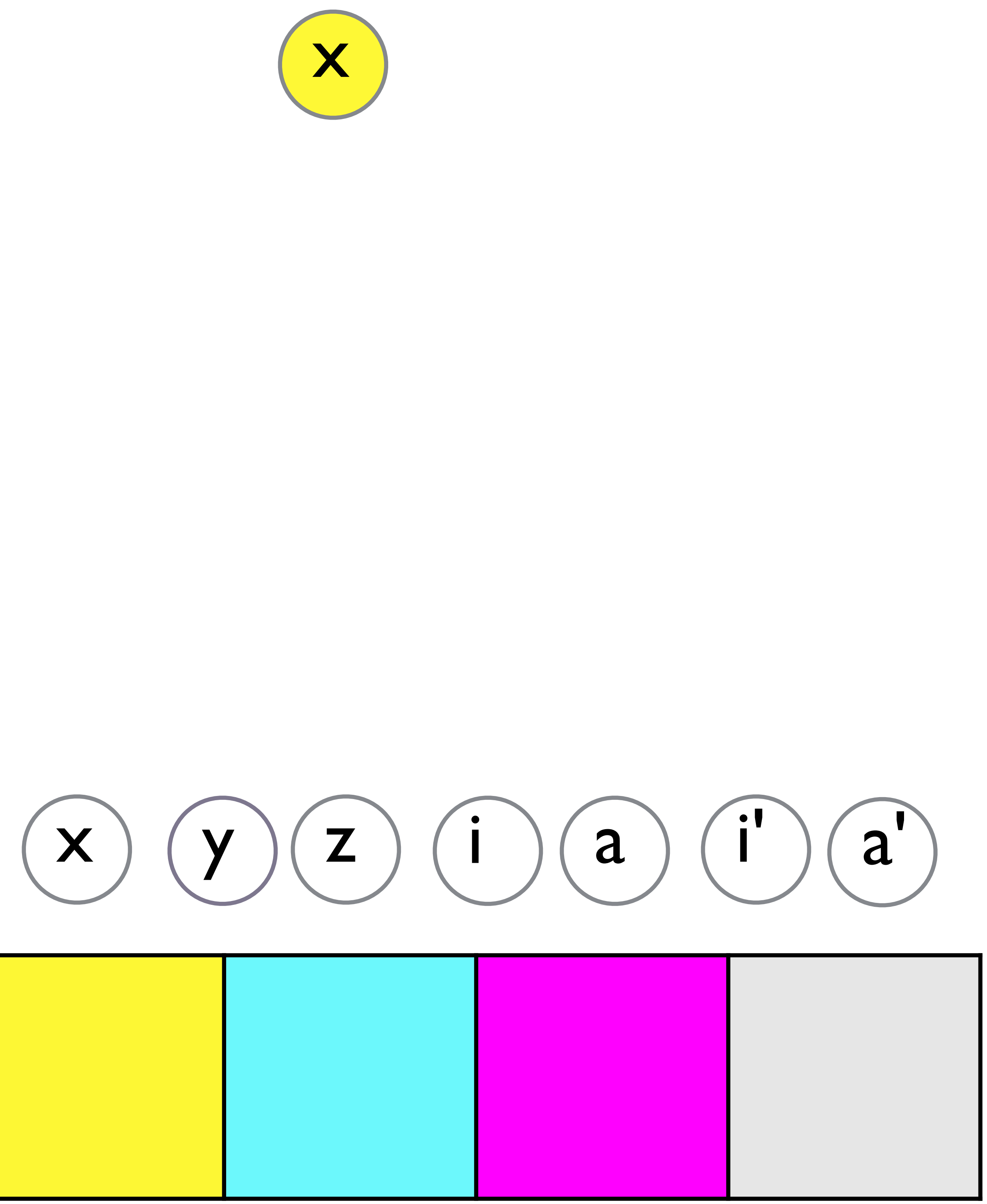

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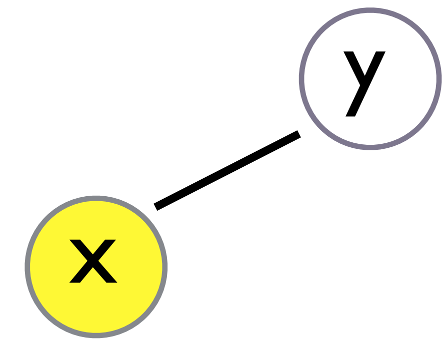

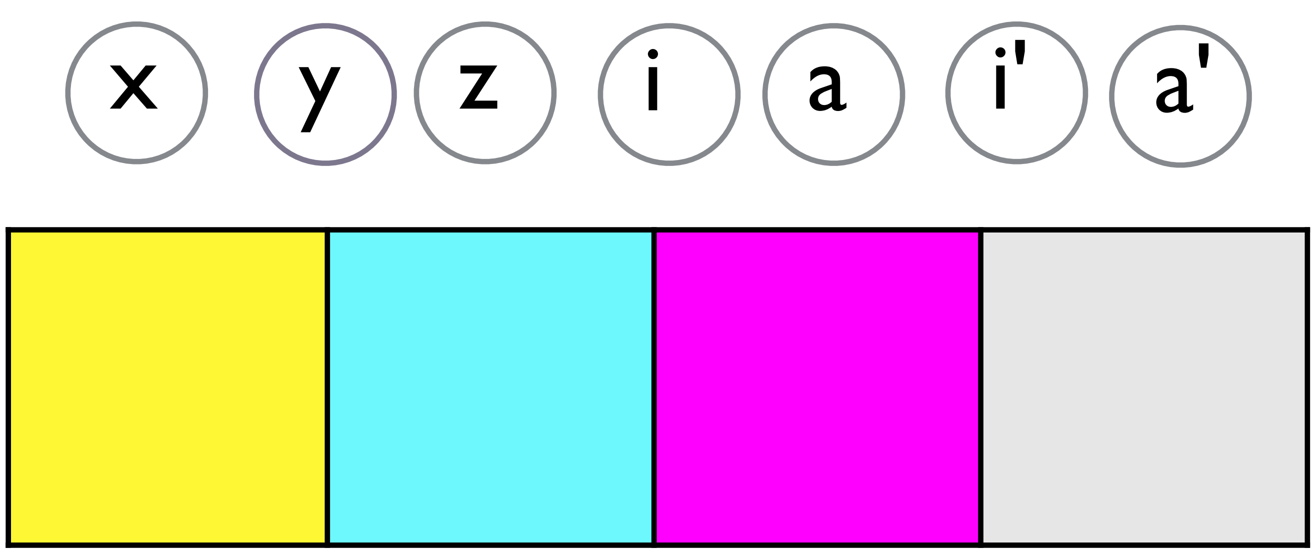

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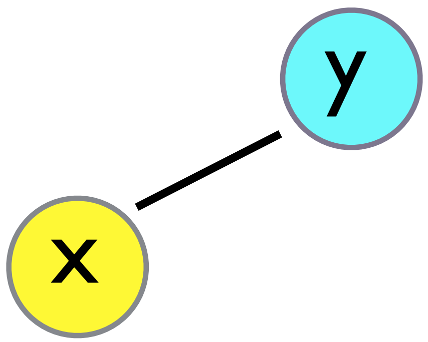

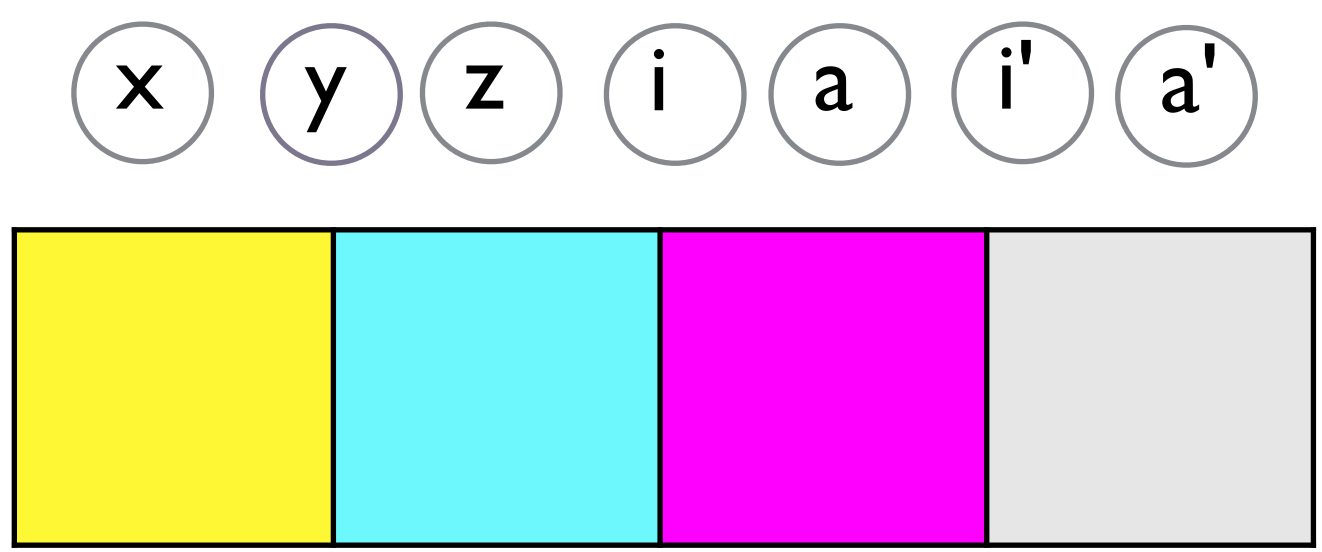

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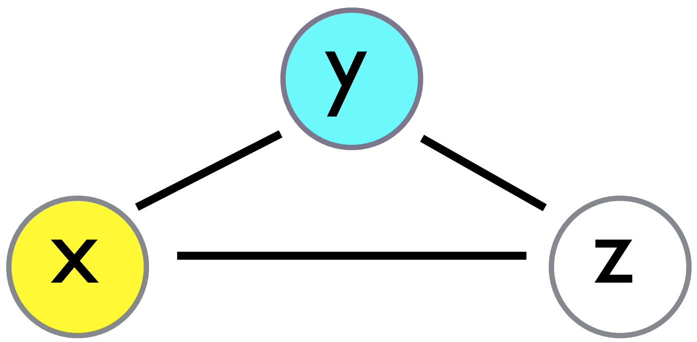

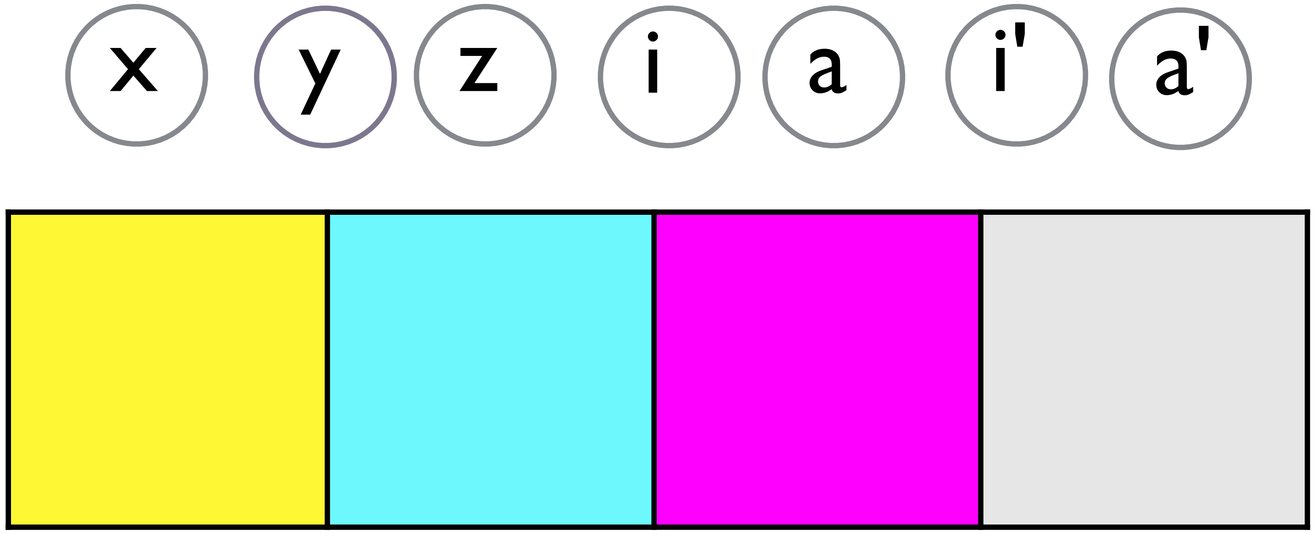

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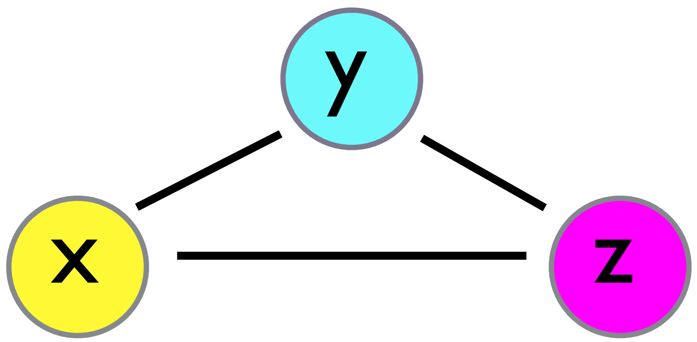

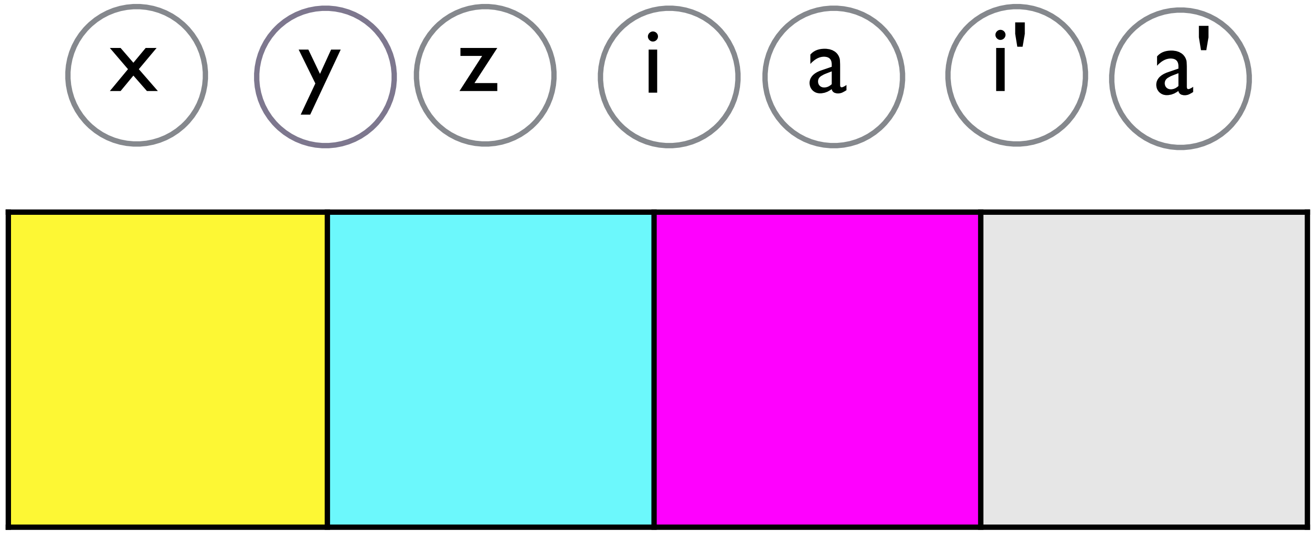

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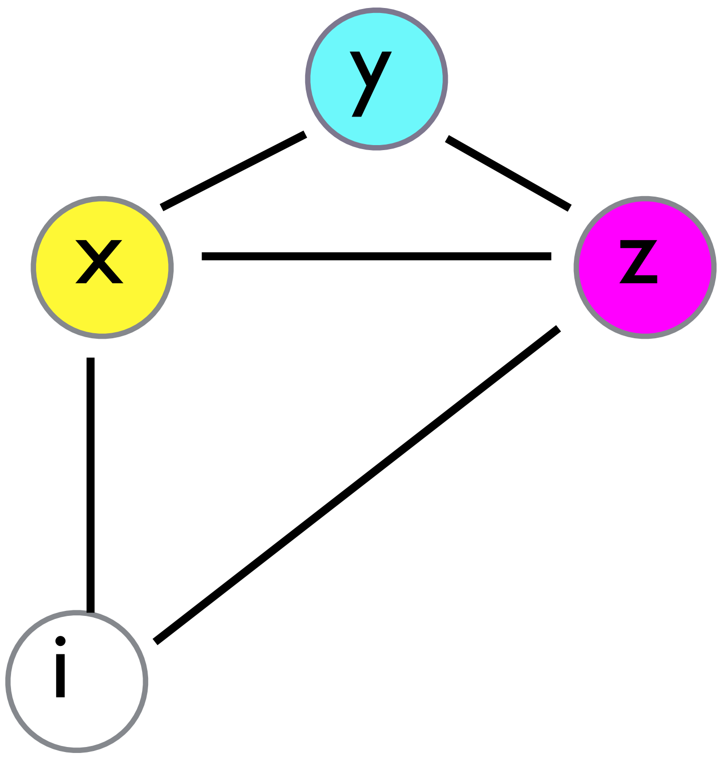

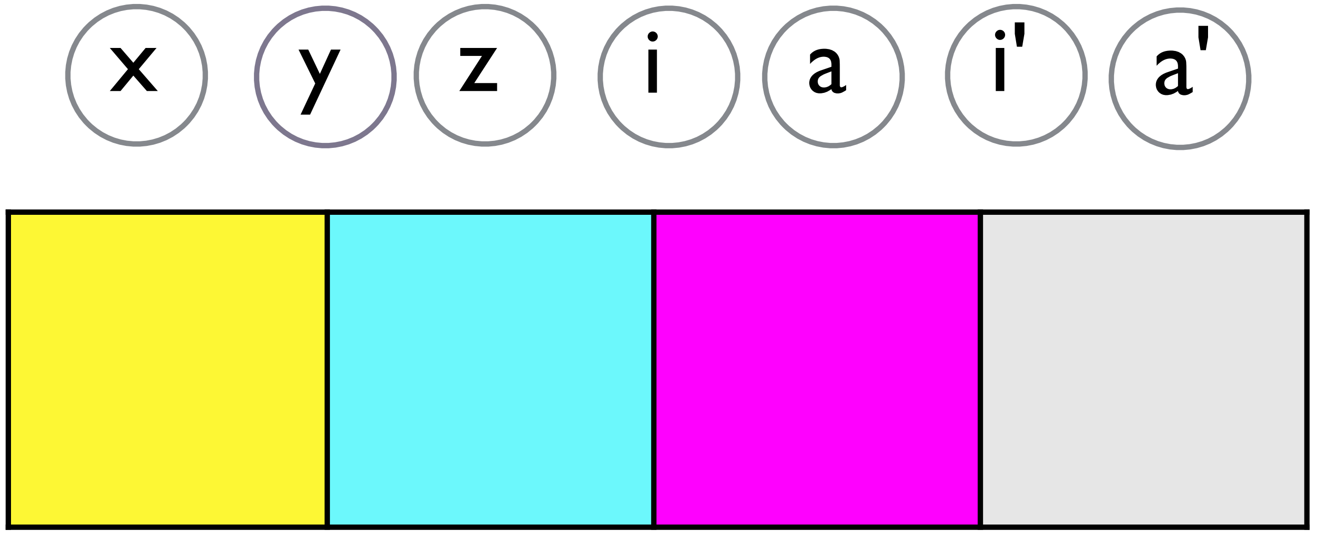

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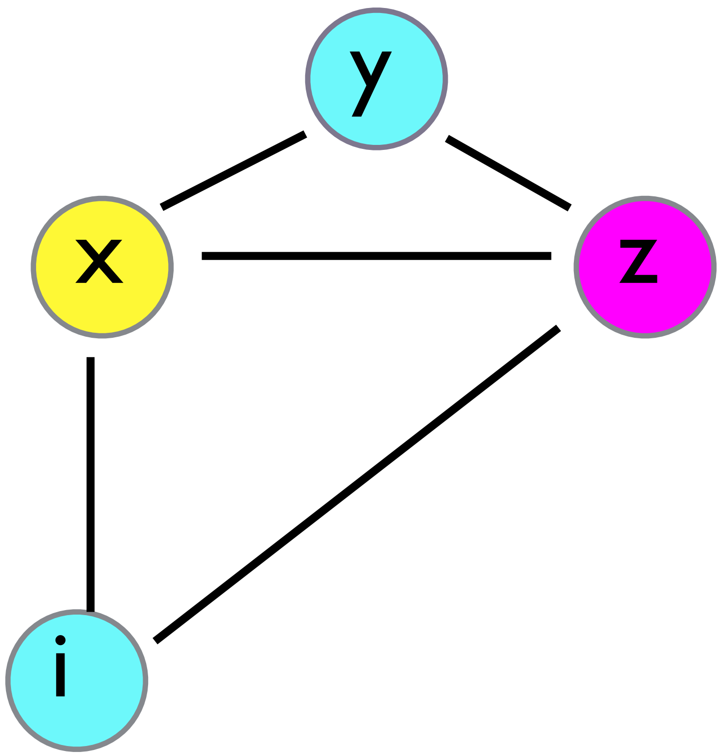

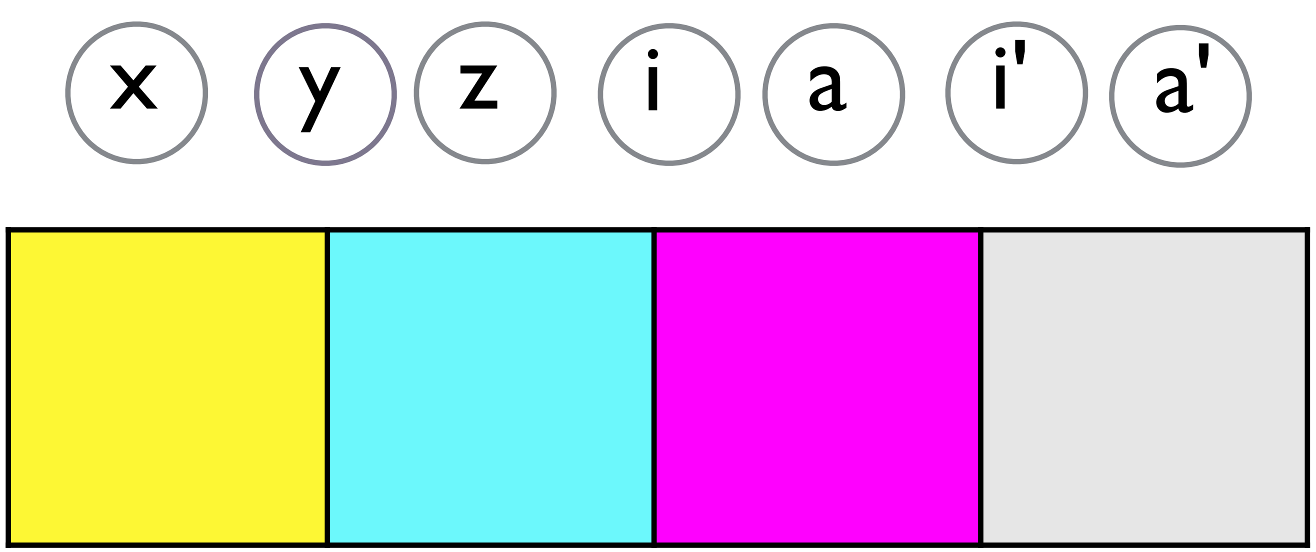

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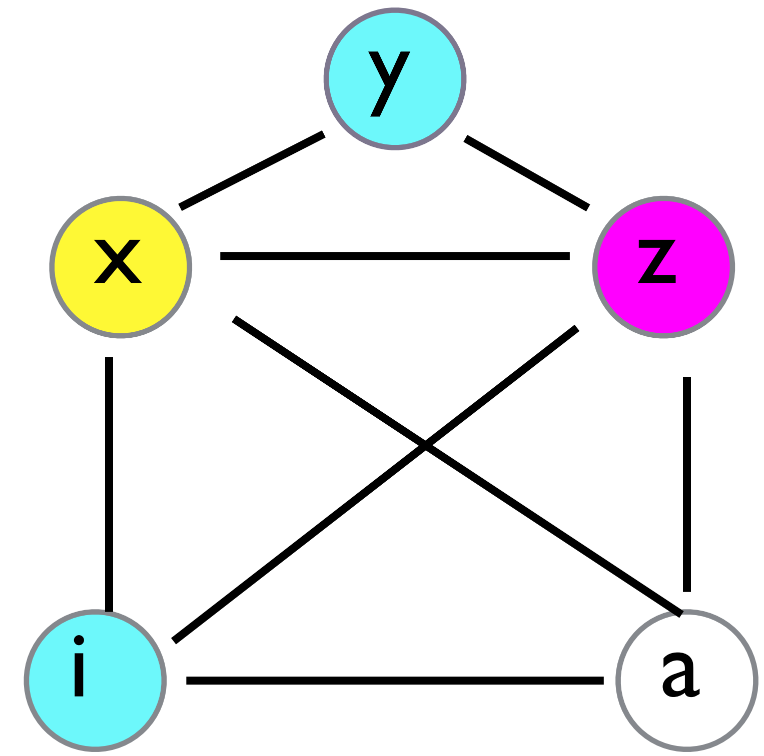

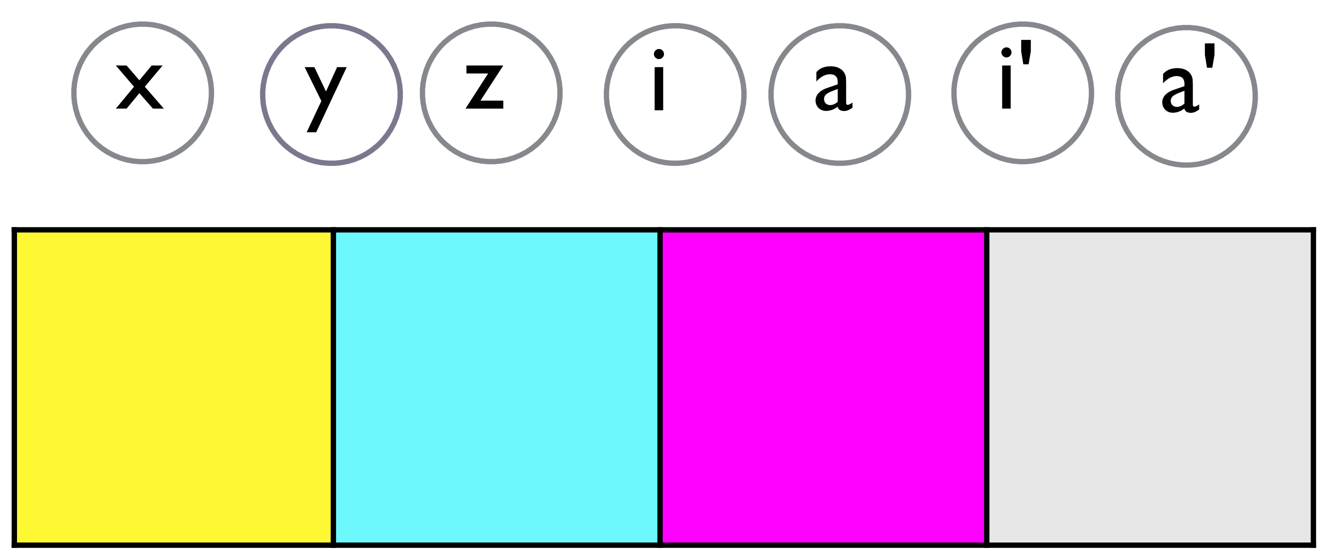

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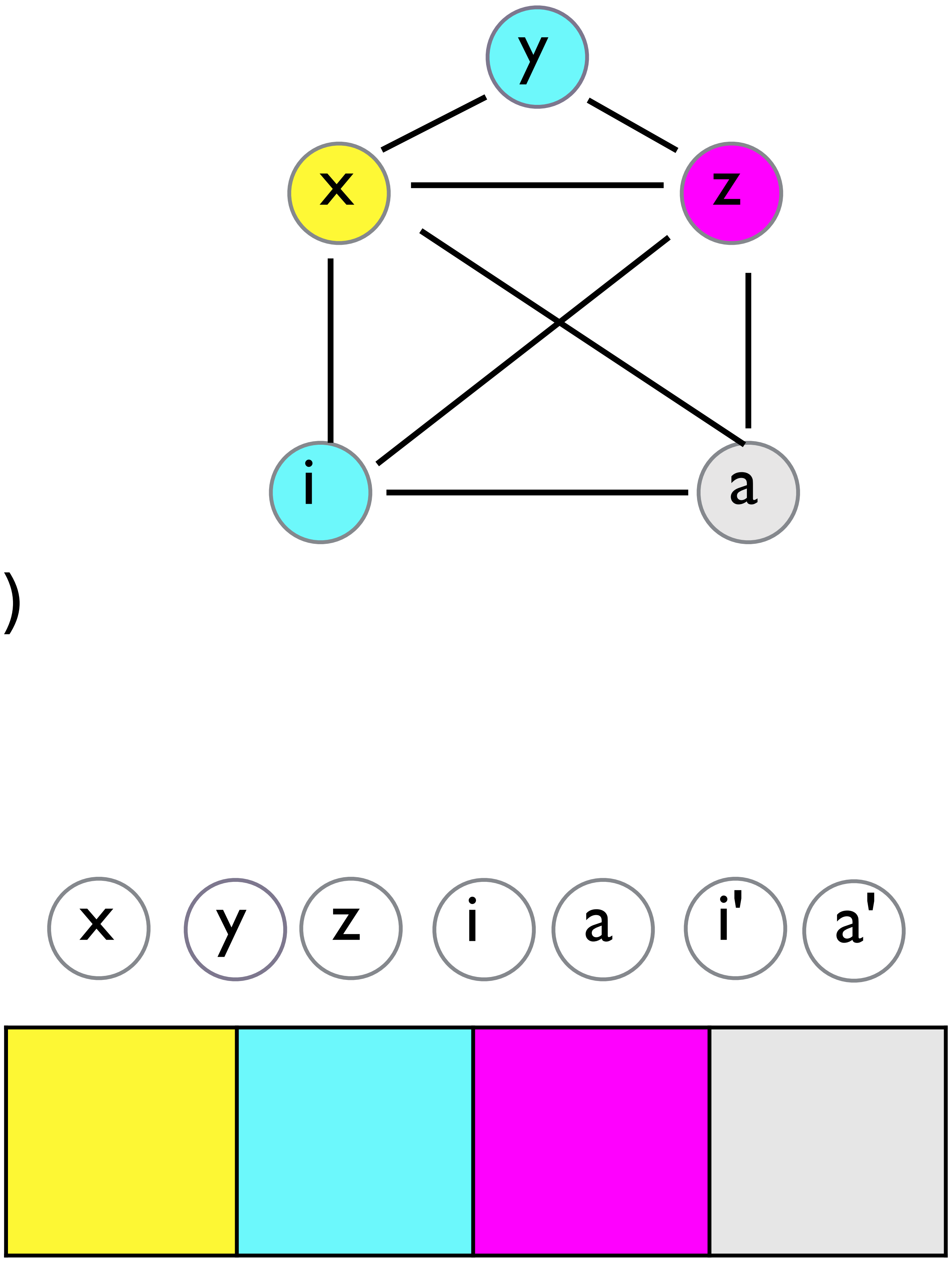

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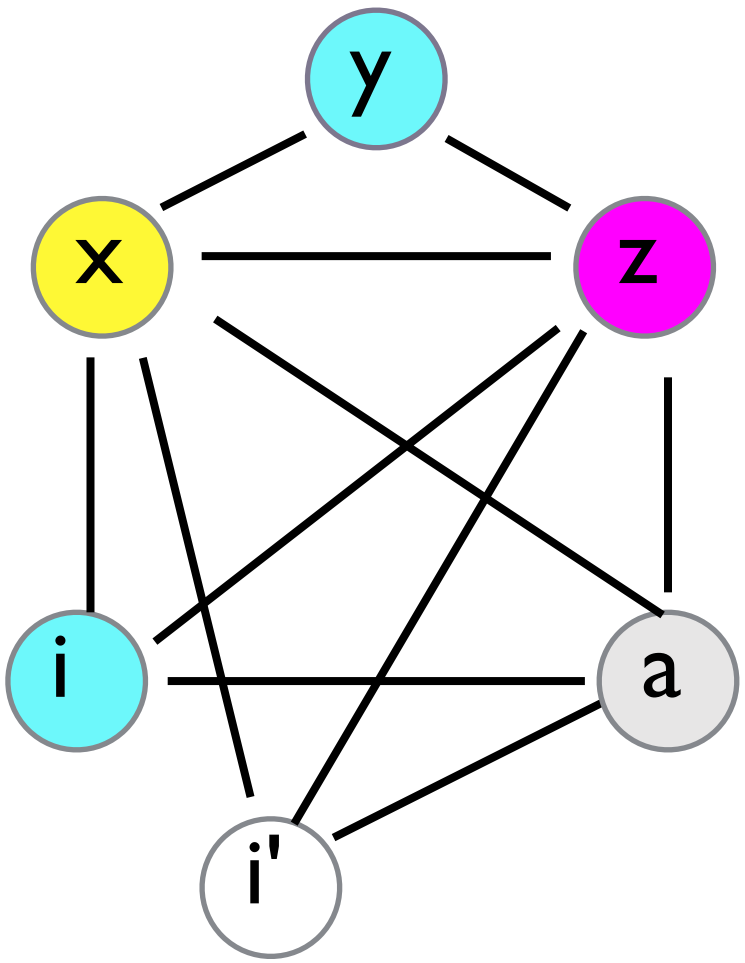

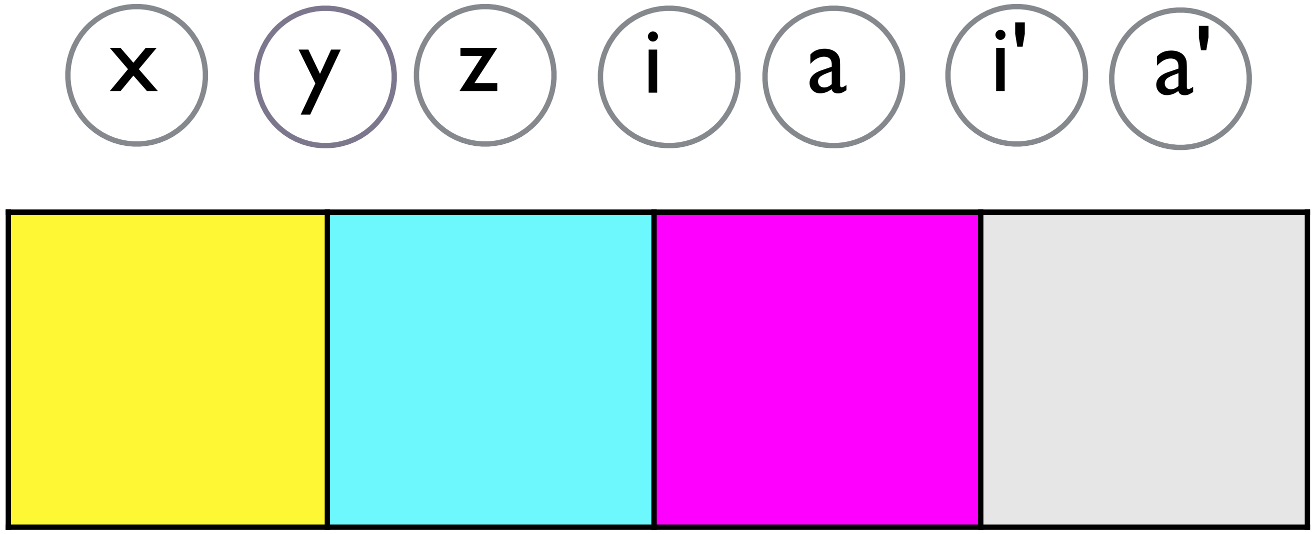

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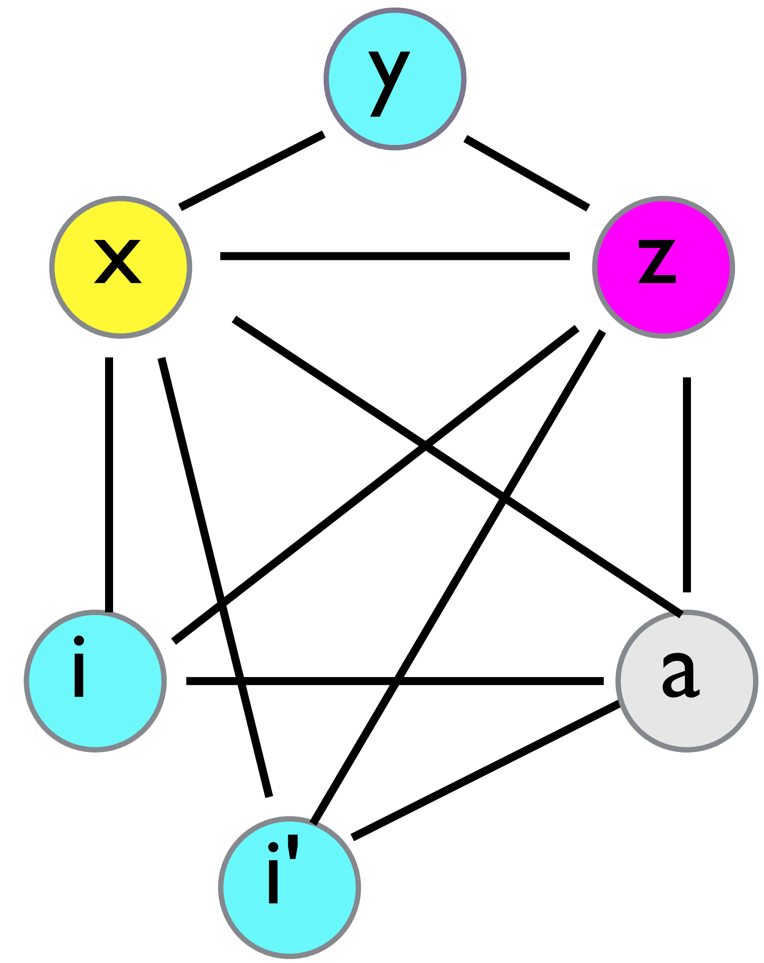

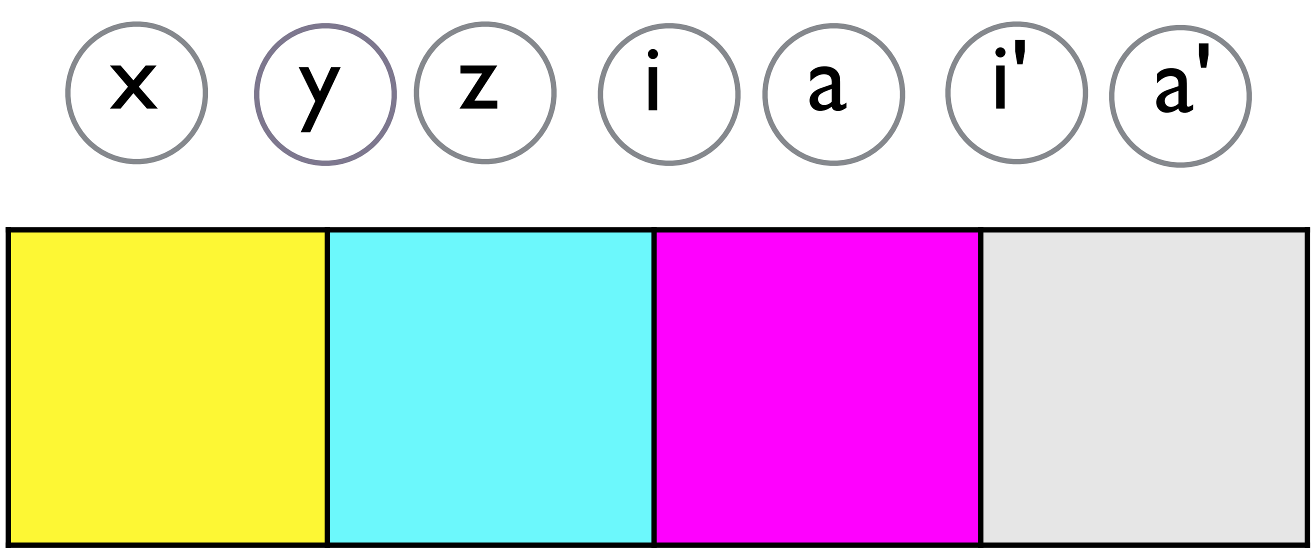

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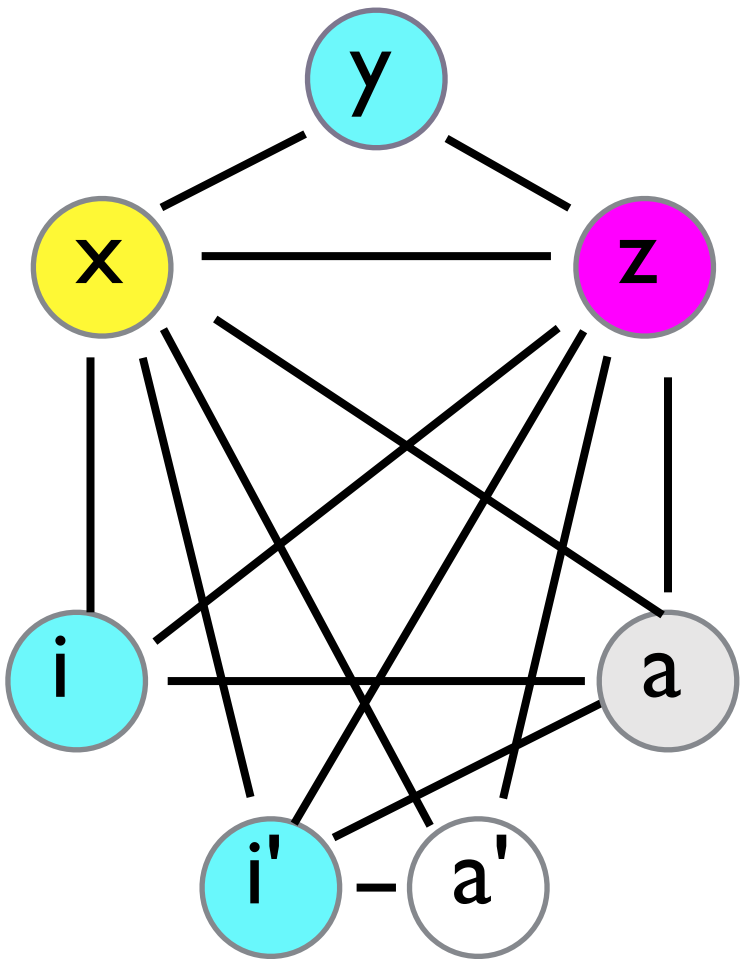

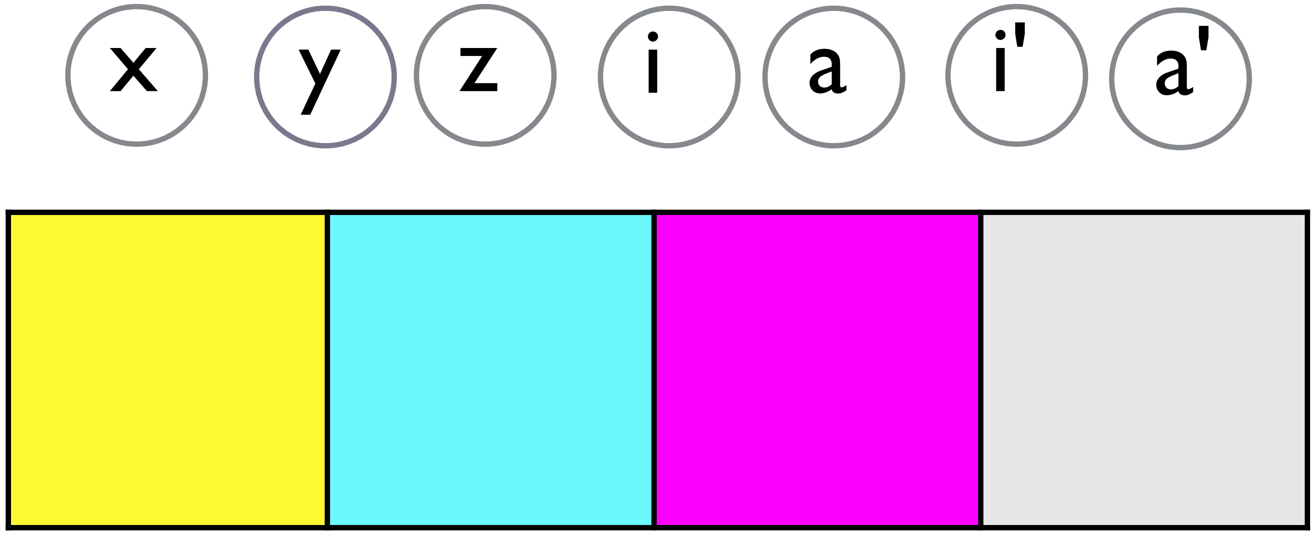

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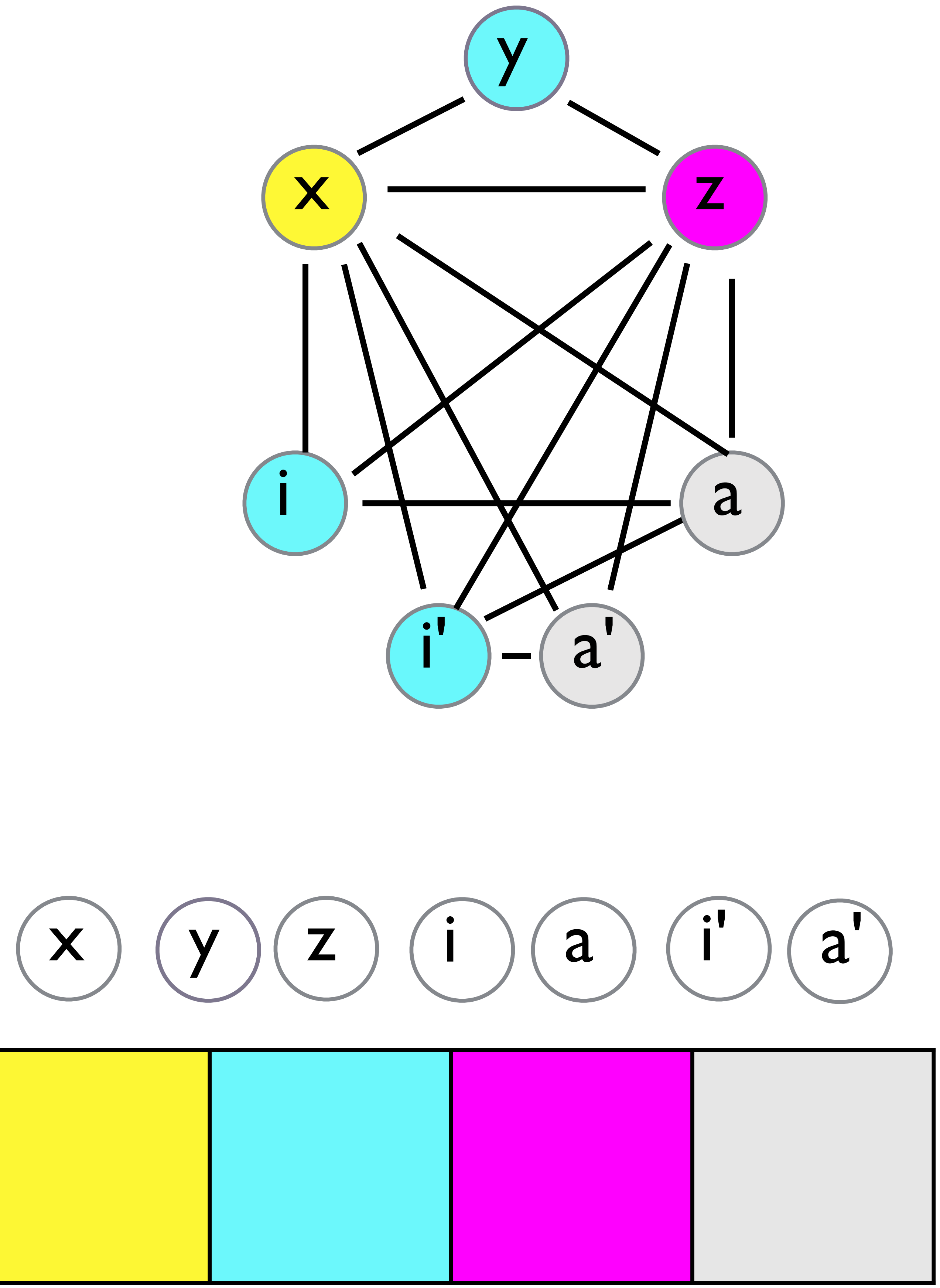

Using Register Assignment

1. For each function definition, we'll run liveness, conflict analysis and register allocation, producing a mapping from variable names to registers/stack offsets.
2. How does your code generation change?

Effects on Codegen

- No longer always put result in RAX: put result in

let x = y * z

in ...

Want the result of y * z to go wherever x is stored, not RAX.

Implementing Local Tail Calls

```
def f(a,b,c): e in
...
local_tail_call(f; [x,y,z])
```

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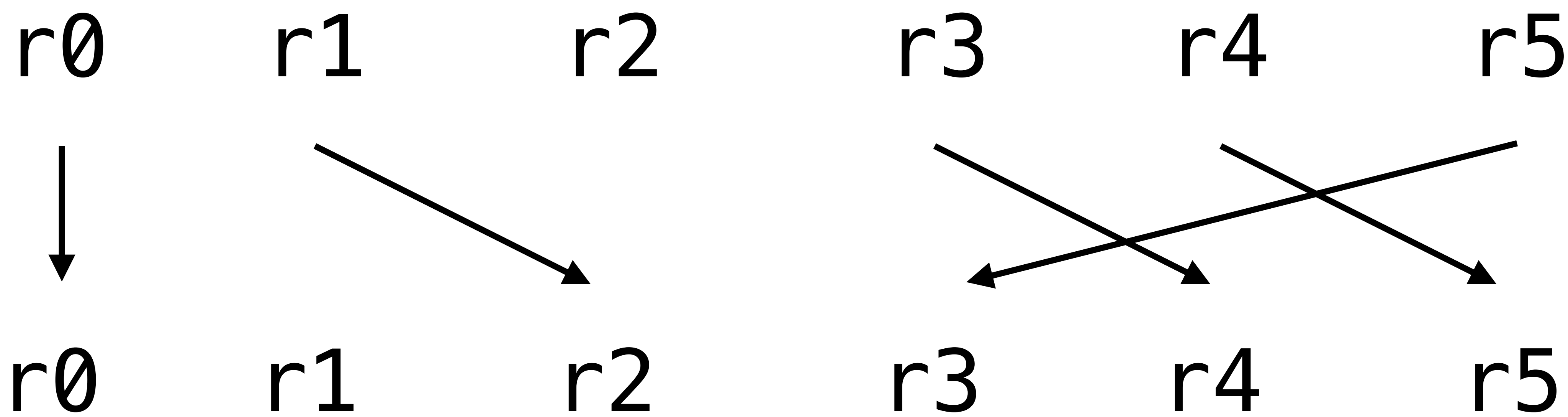
```
mov r_x, r_a
mov r_y, r_b
mov r_z, r_z
jmp f
```

Implementing Local Tail Calls



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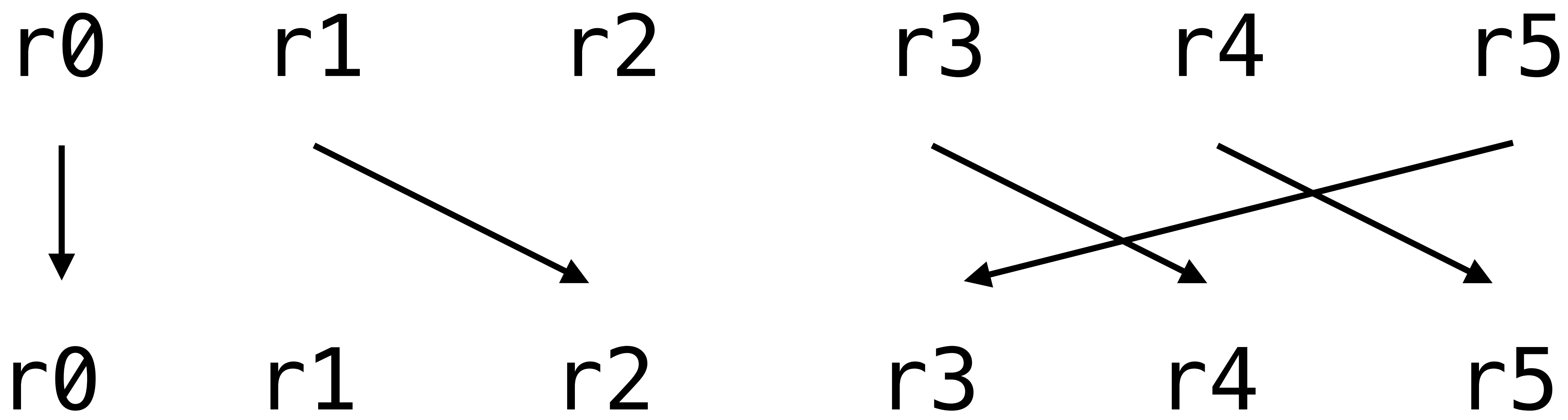

nop

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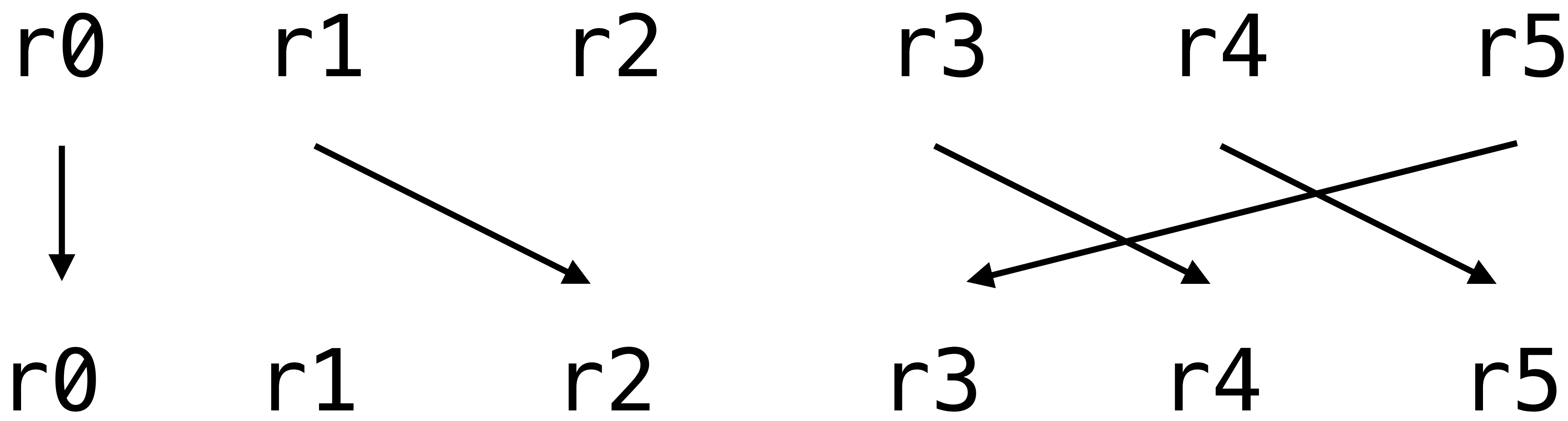


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nop  mov r2, r1
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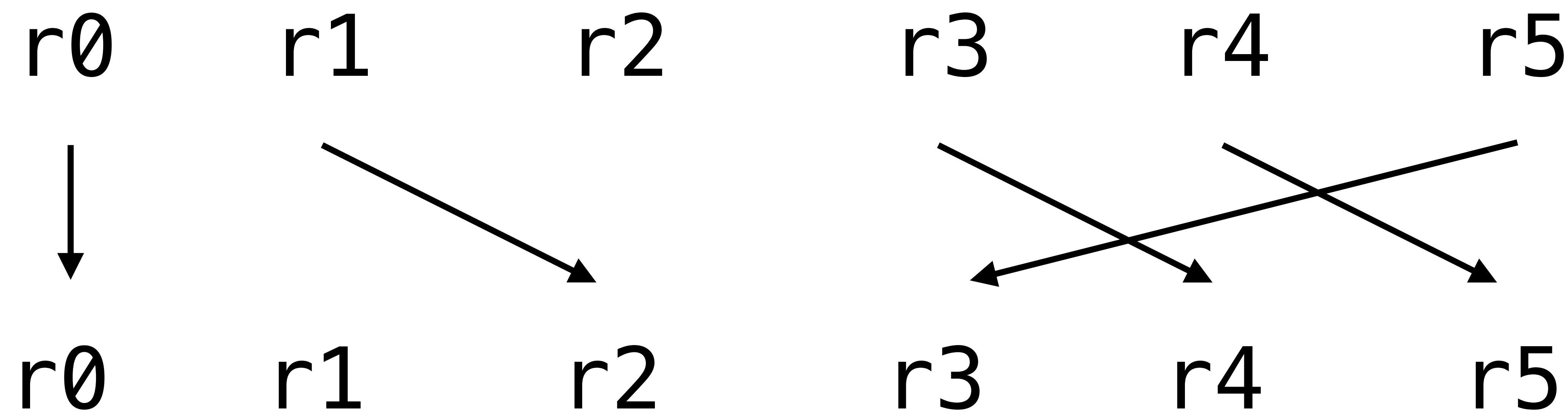


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```
xchg rax, r3
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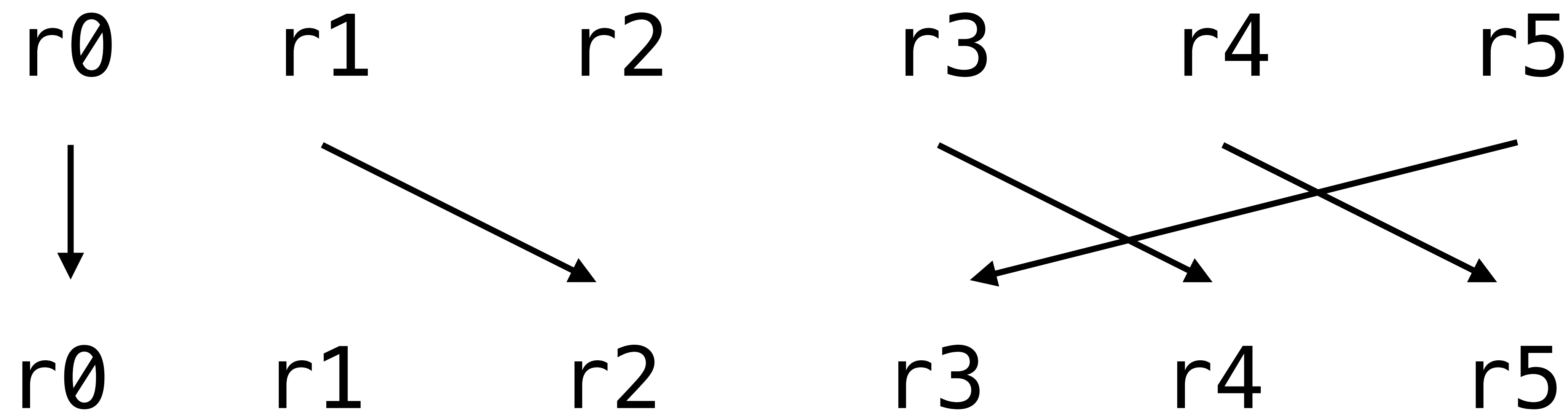


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SSA reg allocation is polytime, but minimizing the resulting number of movs/xchg is NP hard

Register Allocation vs Calling Conventions

Now that we are using registers we need to take care to respect treatment of registers in the calling conventions we use.

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- **volatile** aka **caller-save**: when you make a call, the value of these registers may change when the callee returns
- **non-volatile** aka **callee-save**: when you make a call, the value of these registers will be the same when the callee returns

Volatile/Caller Save registers

volatile aka **caller-save**

let x = ... in

let y = f(z) in

x + y

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- Harder solution: add nodes to interference graph for volatile registers, add conflicts at every non-tail call

Non-volatile/Callee Save registers

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if **y** is stored in a **non-volatile** register, its value must be **restored** when we return

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- Harder solution: treat non-volatiles as "hidden args" of global fundefs, with ret/tail calls as uses.