CSE 401 – Compilers

Compiler Backend Survey

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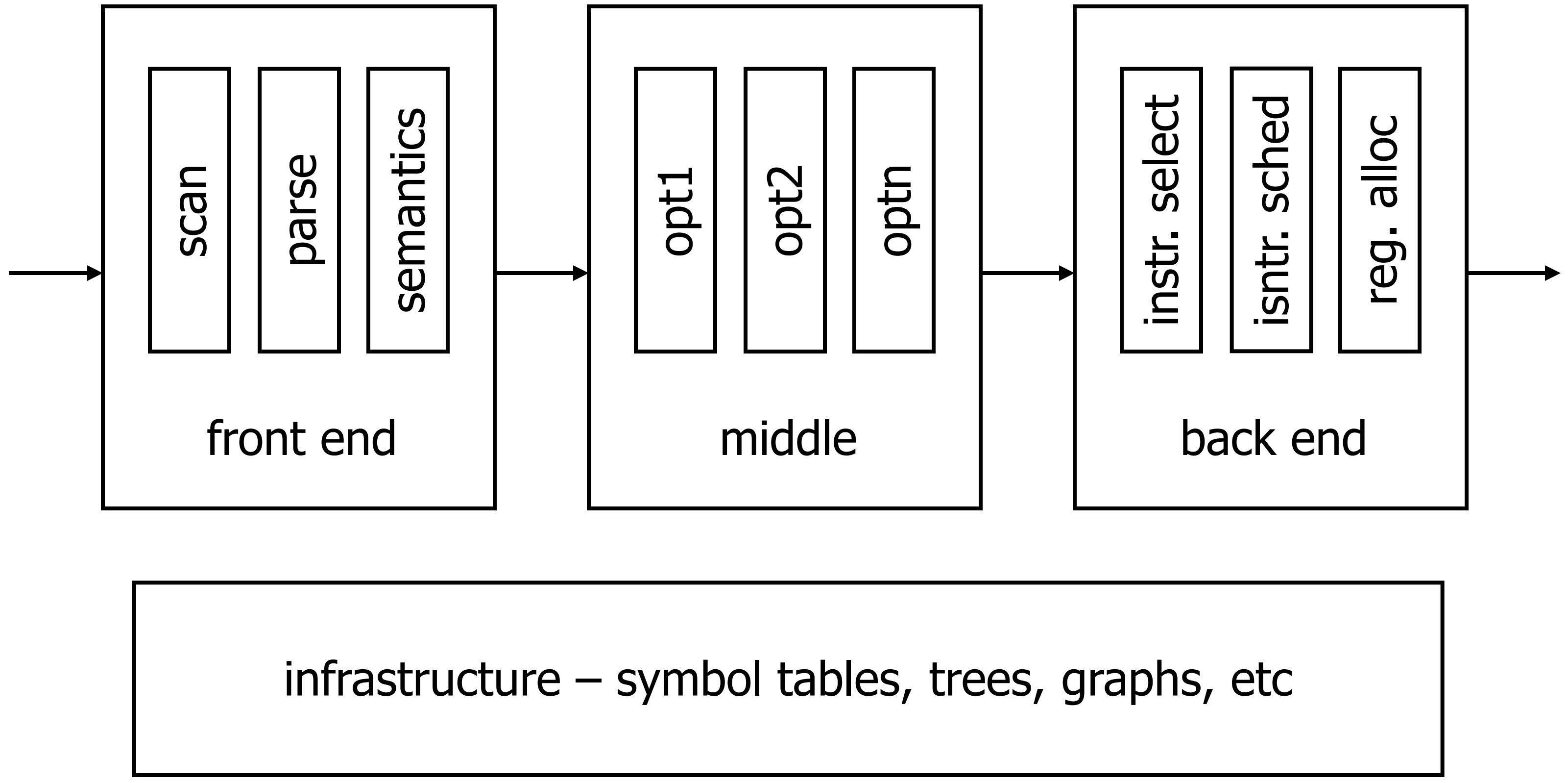
Agenda

- A survey of the major pieces of the back end of the compiler
  - Instruction selection
  - Instruction scheduling
  - Register allocation
- And three particularly neat algorithms
  - Instruction selection by tree pattern matching
  - Instruction list scheduling
  - Register allocation by graph coloring

Compiler Organization



Big Picture

- Compiler consists of lots of fast stuff followed by hard problems
  - Scanner: O(n)
  - Parser: O(n)
  - Analysis & Optimization: ~ O(n log n)
  - Instruction selection: fast or NP-Complete
  - Instruction scheduling: NP-Complete
  - Register allocation: NP-Complete

IR for Code Generation

- Assume a low-level RISC-like IR
  - 3 address, register-register instructions + load/store

    r1 <- r2 op r3
  - Could be tree structure or linear
  - Expose as much detail as possible
- Assume “enough” (i.e., ∞) registers
  - Invent new temporaries for intermediate results
  - Map to actual registers later

Overview Instruction Selection

- Map IR into assembly code
- Assume known storage layout and code shape
  - i.e., the optimization phases have already done their thing
- Combine low-level IR operations into machine instructions (take advantage of addressing modes, etc.)

A Simple Low-Level IR (1)

- What’s important for us is to get a feel for the level of detail involved; the specifics don’t matter as much
- Expressions:
  - CONST(i) – integer constant i
  - TEMP(t) – temporary t (i.e., register)
  - BINOP(op,e1,e2) – application of op to e1,e2
  - MEM(e) – contents of memory at address e
    - Means value when used in an expression
    - Means address when used on left side of assignment
  - CALL(f,args) – application of function f to argument list args

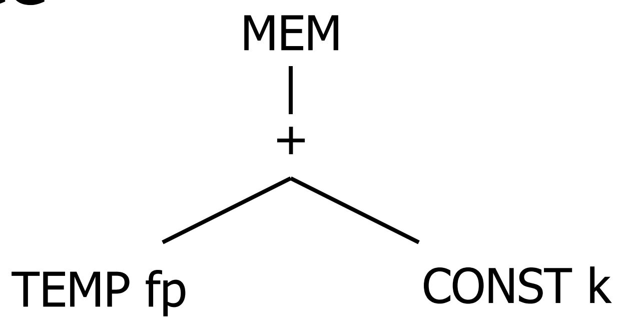
Simple Low-Level IR (2)

- Statements
  - MOVE(TEMP t, e) – evaluate e and store in temporary t
  - MOVE(MEM(e1), e2) – evaluate e1 to yield address a; evaluate e2 and store at a
  - EXP(e) – evaluate expressions e and discard result
  - SEQ(s1,s2) – execute s1 followed by s2
  - NAME(n) – assembly language label n
  - JUMP(e) – jump to e, which can be a NAME label, or more compex (e.g., switch)
  - CJUMP(op,e1,e2,t,f) – evaluate e1 op e2; if true jump to label t, otherwise jump to f
  - LABEL(n) – defines location of label n in the code

Low-Level IR Example (1)

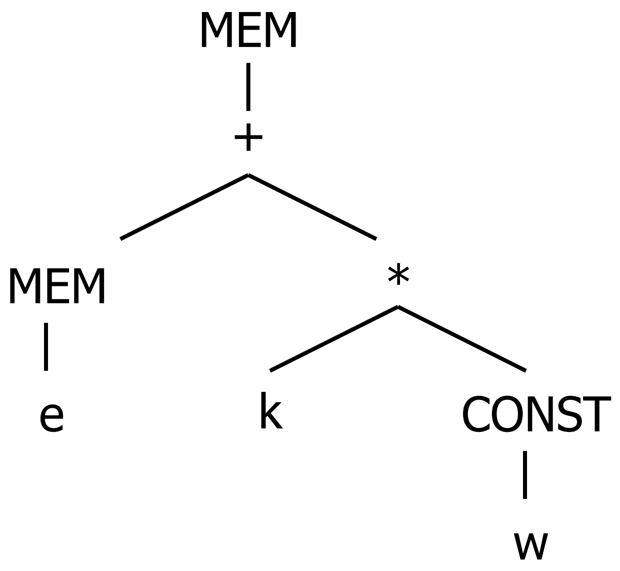
- For a local variable at a known offset k from the frame pointer fp
  - Linear

    MEM(BINOP(PLUS, TEMP fp, CONST k))
  - Tree



Low-Level IR Example (2)

- For an array element e[k], where each element takes up w storage locations



Instruction Selection Issues

- Given the low-level IR, there are many possible code sequences that implement it correctly
  - e.g. to set eax to 0 on x86

    ```
    mov  eax,0          xor  eax,eax
    sub  eax,eax        imul eax,0
    ```

  - Many machine instructions do several things at once – e.g., register arithmetic and effective address calculation

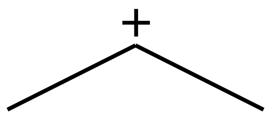
Implementation

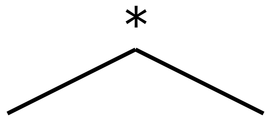
- Goal: find a sequence of machine instructions that perform the computation described by the IR code
- Idea: Describe machine instructions using same low-level IR used for program, then
- Use tree pattern matching to pick machine instructions that match fragments of the program IR tree and use a combination of these up to cover the whole IR code

An Example Target Machine (1)

- Arithmetic Instructions
  - (unnamed) ri
  - ADD ri <- rj + rk
  - MUL ri <- rj * rk
  - SUB and DIV are similar

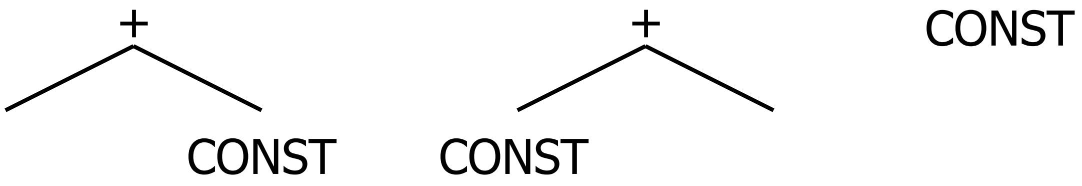
TEMP



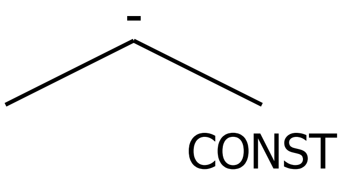


An Example Target Machine (2)

- Immediate Instructons
  - ADDI ri <- rj + c

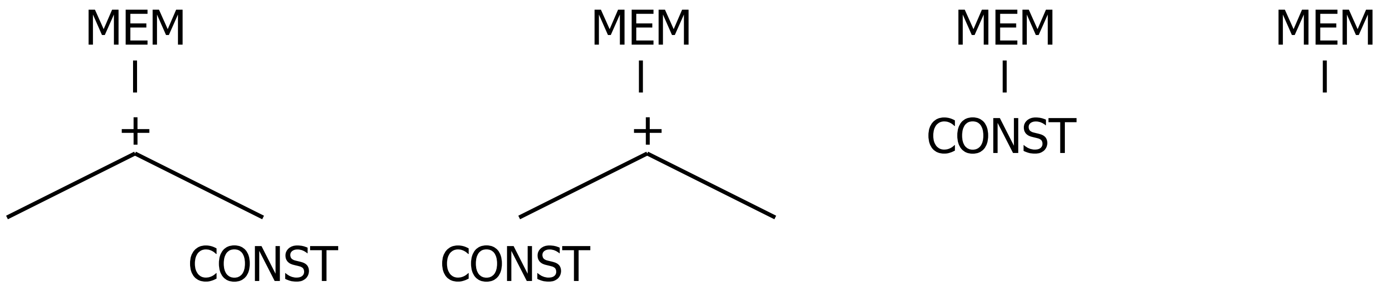


  - SUBI ri <- rj - c



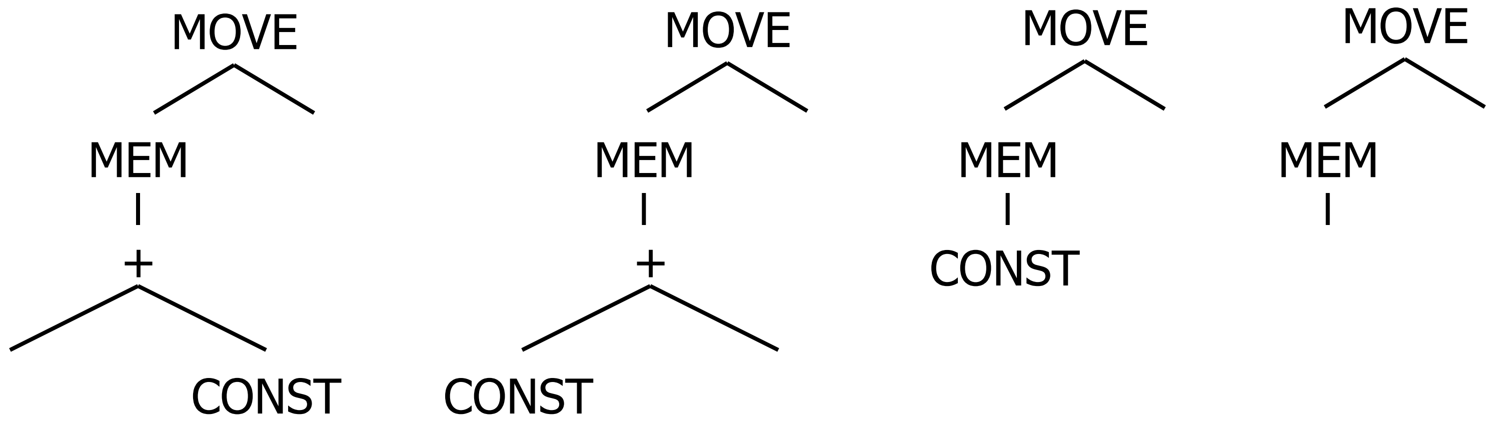
An Example Target Machine (3)

- Load
  - LOAD ri <- M[rj + c]



An Example Target Machine (4)

- Store
  - STORE M[rj + c] <- ri



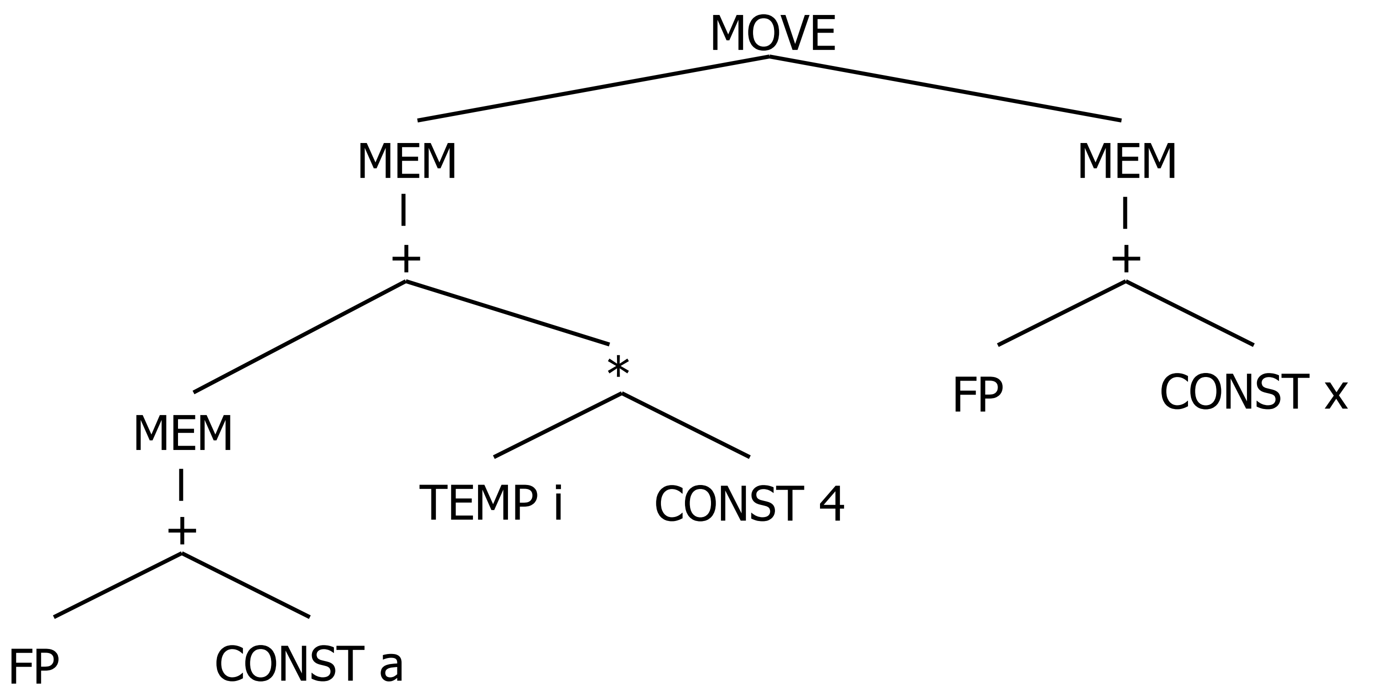
Tree Pattern Matching (1)

- Goal: Tile the low-level tree with operation (instruction) trees
- A *tiling* is a collection of <node,op> pairs
  - node is a node in the tree
  - op is an operation tree
  - <node,op> means that op could implement the subtree at node

Tree Pattern Matching (2)

- A tiling "implements" a tree if it covers every node in the tree and the overlap between any two tiles (trees) is limited to a single node
  - If <node,op> is in the tiling, then node is also covered by a leaf in another operation tree in the tiling – unless it is the root
  - Where two operation trees meet, they must be compatible (i.e., expect the same value in the same location)

Example – Tree for a[i]:=x



Generating Tilings

- Two common algorithms
  - Maximal munch:
    - Top-down tree walk.
    - Find largest tile that fits each node
  - Dynamic programming:
    - Assign costs to nodes in tree = cost of node + subtrees
    - Try all possible combinations bottom-up and pick cheapest

Generating Code

- Given a tiled tree, to generate code
  - Postorder treewalk; node-dependant order for children
  - Emit code sequences corresponding to tiles in order
  - Connect tiles by using same register name to tie boundaries together

Overview
Instruction Scheduling

- Reorder instructions to minimize execution time
  - hide latencies – processor function units, memory/cache stalls
  - Originally invented for supercomputers (60s)
  - Now important everywhere
    - Even non-RISC machines, i.e., x86
    - Even if processor reorders on the fly
- Assume fixed program at this point

Latencies for a Simple Example Machine

Operation	Cycles
LOAD	3
STORE	3
ADD	1
MULT	2
SHIFT	1
BRANCH	0 TO 8

Example: w = w*2*x*y*z;

- Simple schedule

```
1  LOAD     r1 <- w
4  ADD      r1 <- r1,r1
5  LOAD     r2 <- x
8  MULT     r1 <- r1,r2
9  LOAD     r2 <- y
12 MULT     r1 <- r1,r2
13 LOAD     r2 <- z
16 MULT     r1 <- r1,r2
18 STORE    w <- r1
21 r1 free
     2 registers, 20 cycles
```

- Loads early

```
1  LOAD     r1 <- w
2  LOAD     r2 <- x
3  LOAD     r3 <- y
4  ADD      r1 <- r1,r1
5  MULT     r1 <- r1,r2
6  LOAD     r2 <- z
7  MULT     r1 <- r1,r3
9  MULT     r1 <- r1,r2
11 STORE    w <- r1
14 r1 is free
     3 registers, 13 cycles
```

Algorithm Overview

- Build a precedence graph P of instructions, labeled with priorities (usually number of cycles on critical path to the end)
- Use list scheduling to construct a schedule, one cycle at a time
  - At each cycle
    - Chose a ready operation and schedule it
    - Update ready queue
- Rename registers to avoid false dependencies and conflicts

Precedence Graph

- Nodes *n* are operations
- Attributes of each node
  - type – kind of operation
  - delay – latency
- If node n2 uses the result of node n1, there is an edge e = (n1,n2) in the graph

Example

- Code

```
a  LOAD      r1 <- w
b  ADD       r1 <- r1,r1
c  LOAD      r2 <- x
d  MULT      r1 <- r1,r2
e  LOAD      r2 <- y
f  MULT      r1 <- r1,r2
g  LOAD      r2 <- z
h  MULT      r1 <- r1,r2
i  STORE     w <- r1
```

Forward vs Backwards

- Backward list scheduling
  - Work from the root to the leaves
  - Schedules instructions from end to beginning of the block
- In practice, compilers try both and pick the result that minimizes costs
  - Little extra expense since the precedence graph and other information can be reused
  - Different directions win in different cases

Overview
Register Allocation

- Map values to actual registers
  - Previous phases change need for registers
- Add code to spill values to temporaries as needed, etc.
- Usually worth doing another pass of instruction scheduling afterwards if spill code inserted

Register Allocation by Graph Coloring

- How to convert the infinite sequence of temporary data references, t1, t2, … into finite assignment register numbers $8, $9, …, $25
- Goal: Use available registers with minimum spilling
- Problem: Minimizing the number of registers is NP-complete … it is equivalent to chromatic number – minimum colors to color nodes of graph so no edge connects same color

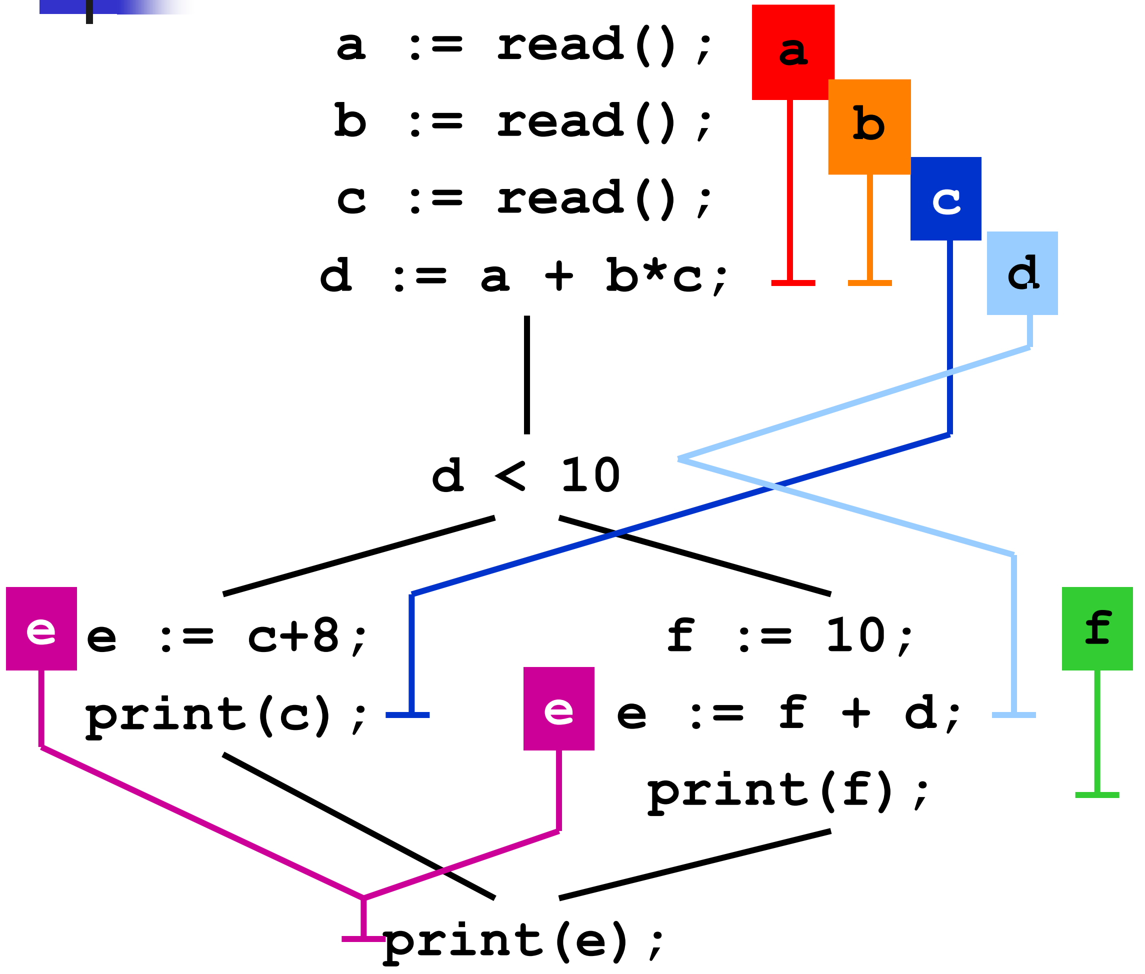
Begin With Data Flow Graph

- procedure-wide register allocation
- only live variables require register storage

dataflow analysis: a variable is live at node N if *the value* it holds is used on some path further down the control-flow graph; otherwise it is dead

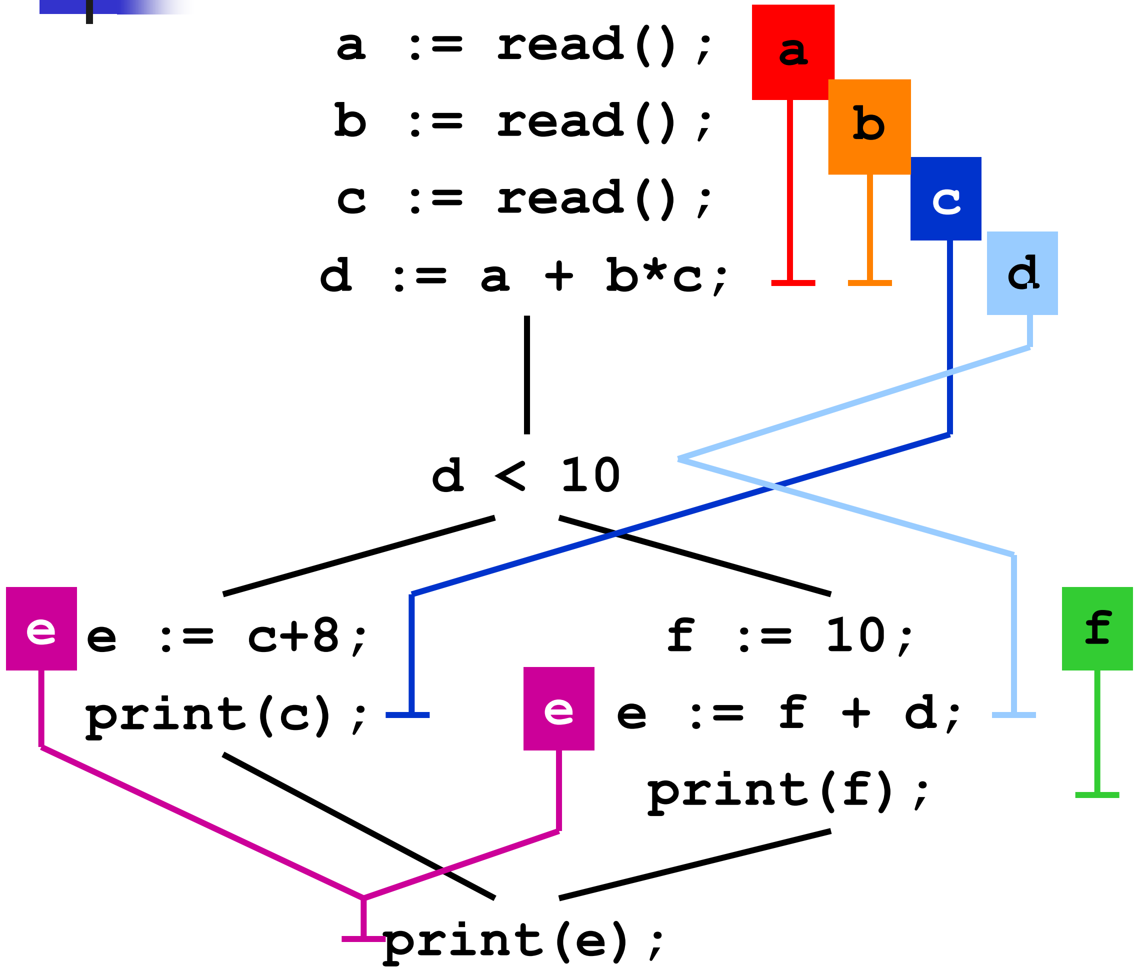
- two variables(values) interfere when their live ranges overlap

Live Variable Analysis

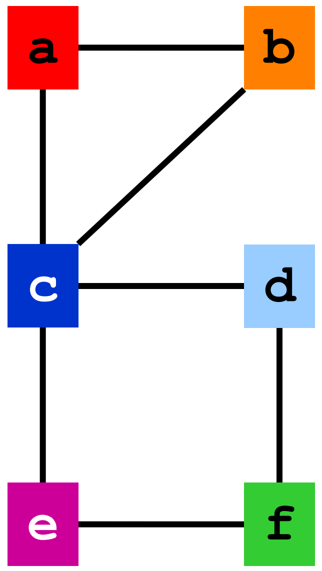


```
a := read();
b := read();
c := read();
d := a + b*c;
if (d < 10 ) then
    e := c+8;
    print(c);
else
    f := 10;
    e := f + d;
    print(f);
fi
print(e);
```

Register Interference Graph



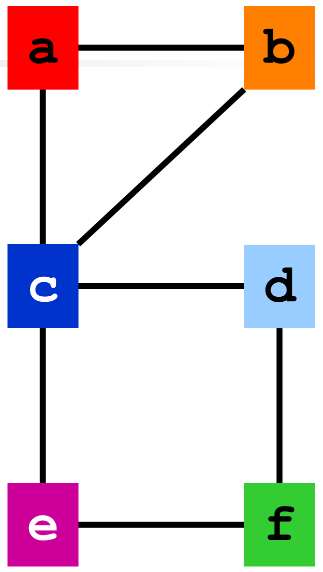
```
a := read();
b := read();
c := read();
d := a + b*c;

d < 10

e := c+8;            f := 10;
print(c);            e := f + d;
                     print(f);

print(e);
```



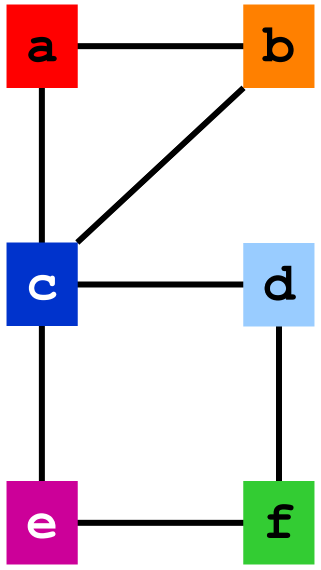
Graph Coloring

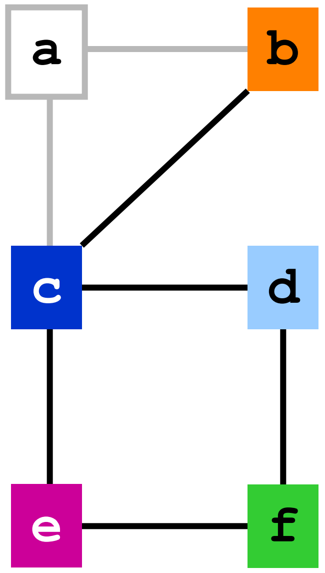
- NP complete problem

- Heuristic: color easy nodes last
  - find node *N* with lowest degree
  - remove *N* from the graph
  - color the simplified graph
  - set color of *N* to the first color that is not used by any of *N*'s neighbors
- Basics due to Chaitin (1982), refined by Briggs (1992)

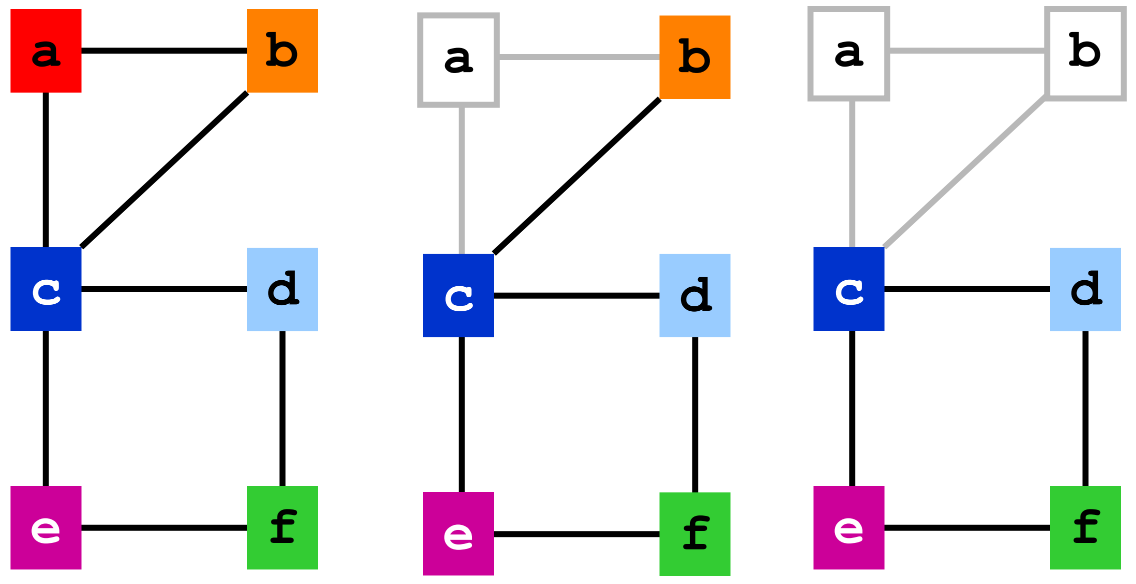


Apply Heuristic

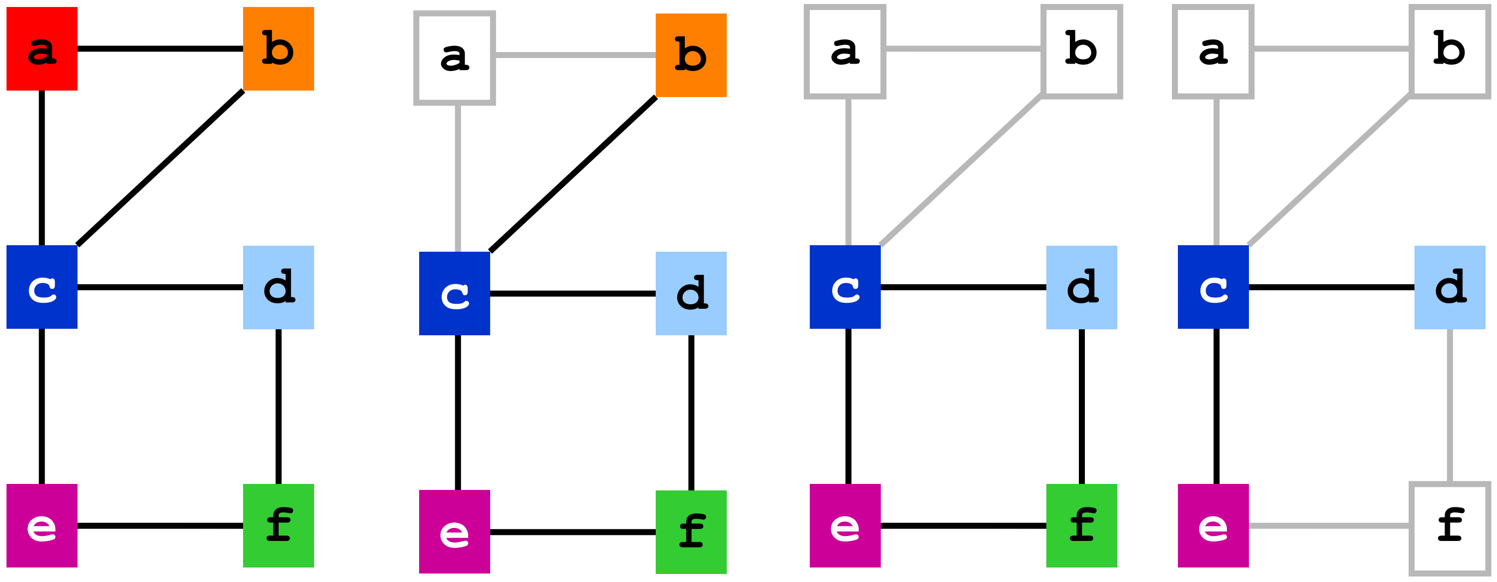




Apply Heuristic



Apply Heuristic



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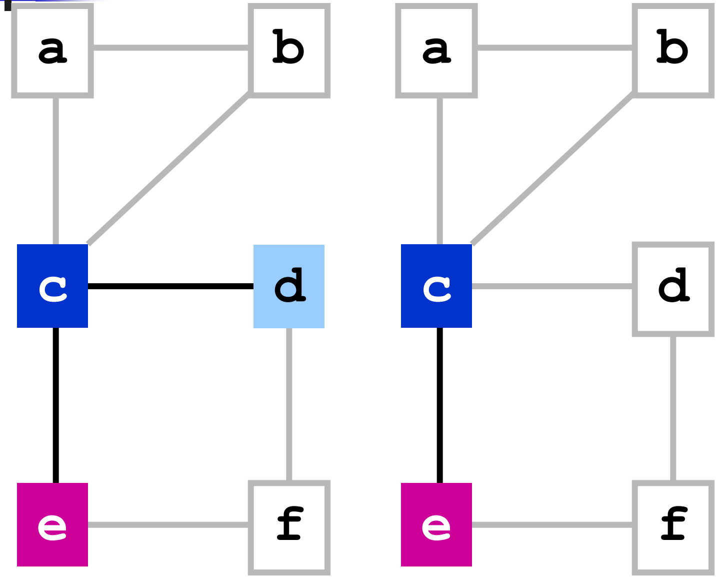

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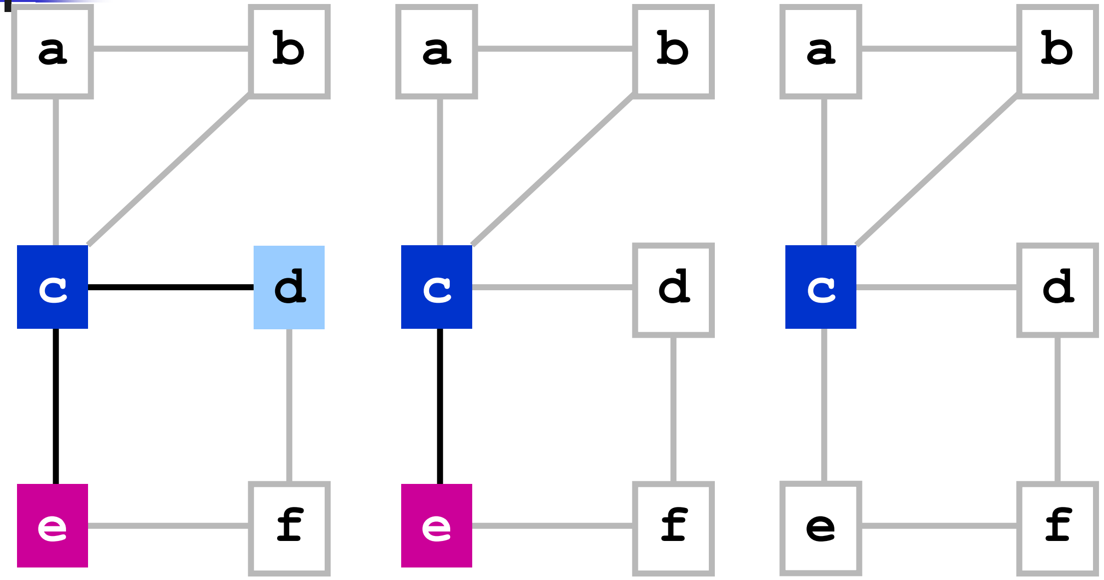

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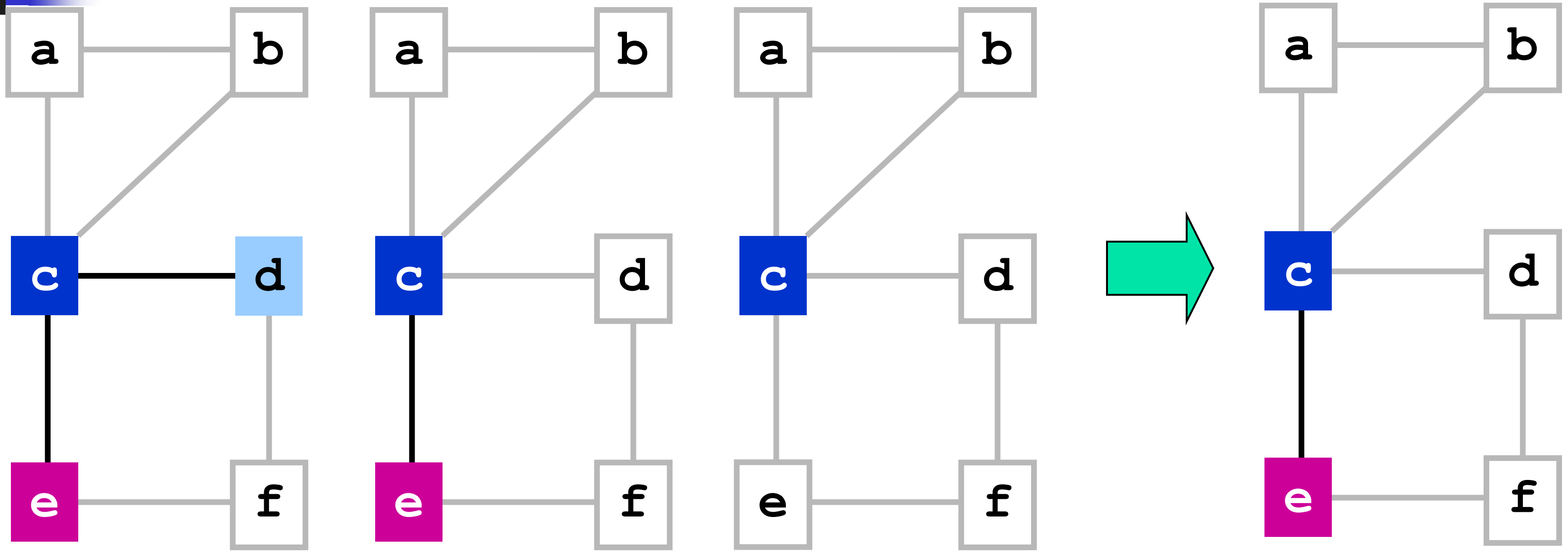

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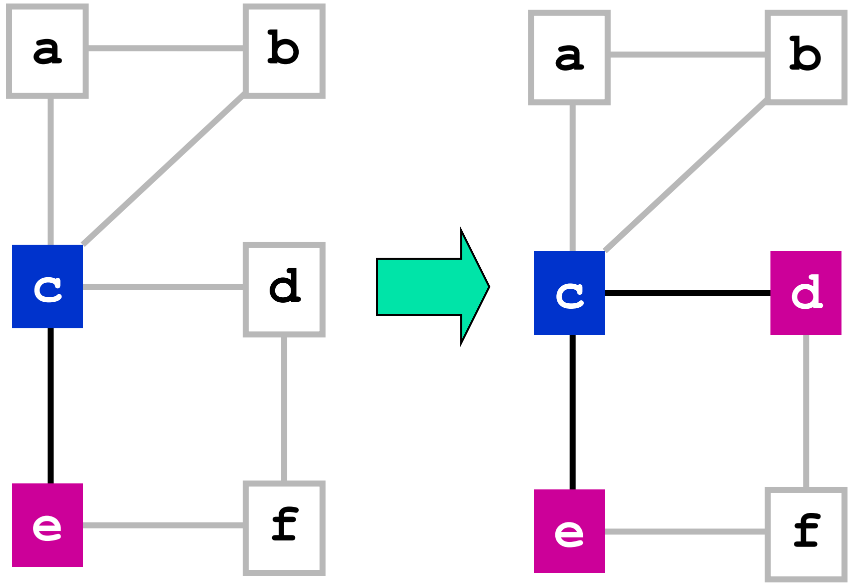

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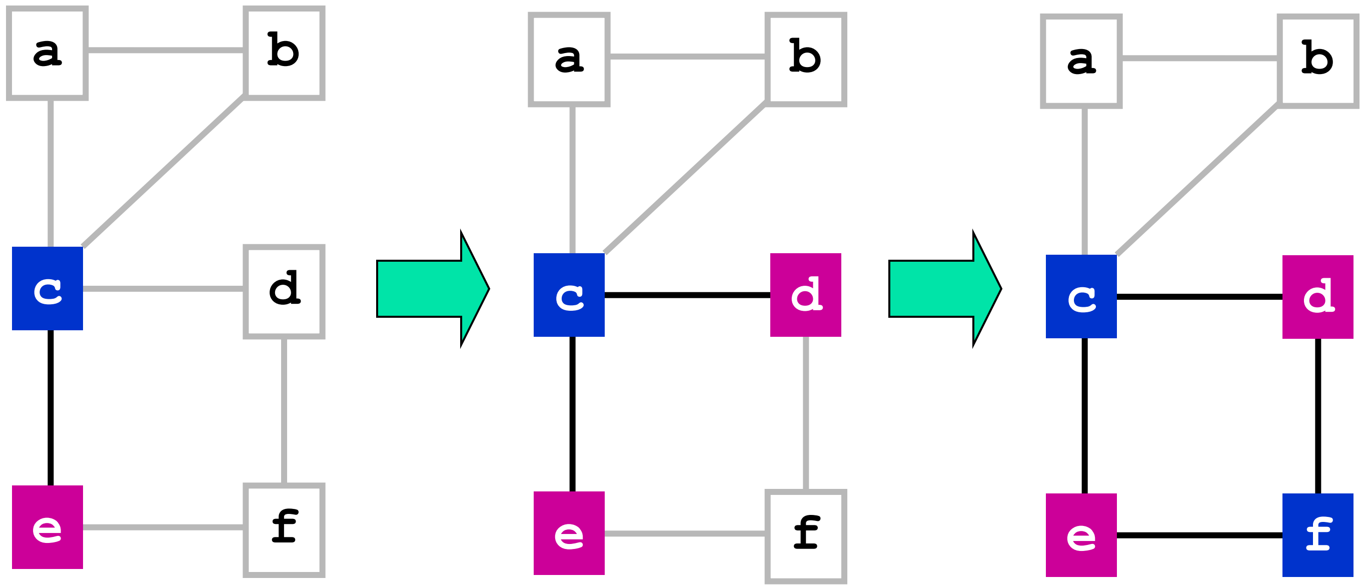

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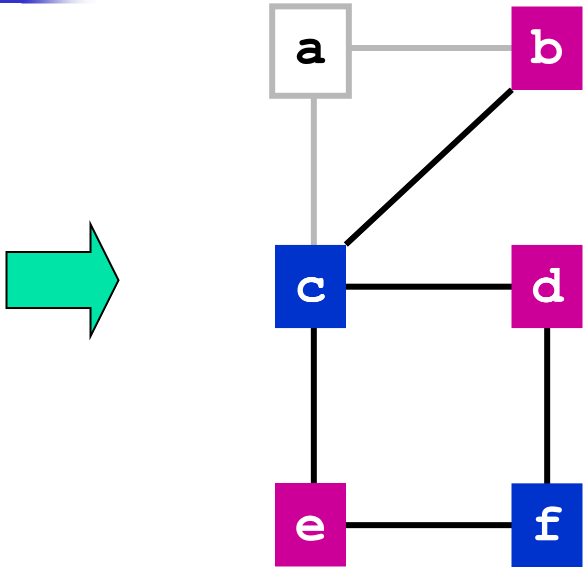

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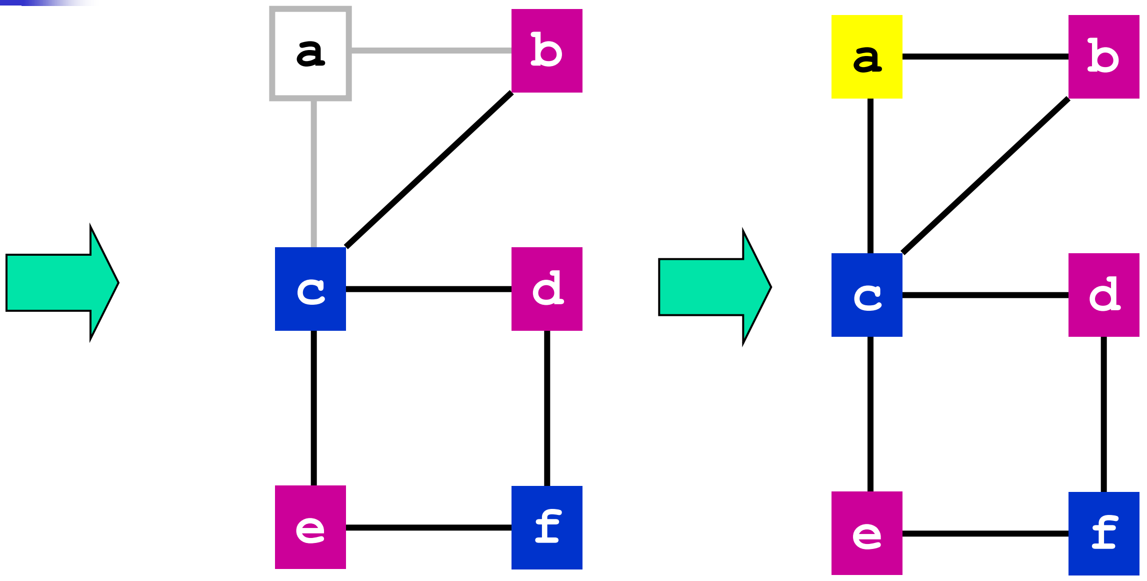
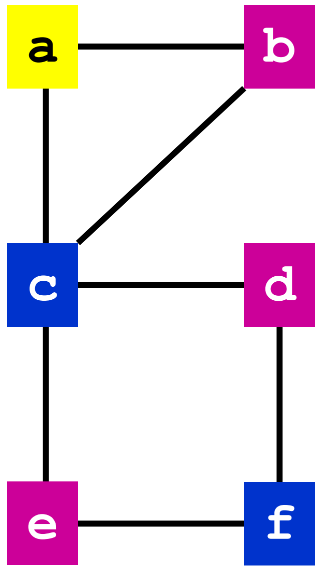


Final Assignment



```
   a  := read();
   b  := read();
   c  := read();
  d  := a + b*c;
if (d < 10 ) then
      e  := c+8;
      print(c);
       else
       f  := 10;
     e  := f + d;
      print(f);
         fi
    print(e);
```

Some Graph Coloring Issues

- May run out of registers
  - Solution: insert spill code and reallocate
- Special-purpose and dedicated registers
  - Examples: function return register, function argument registers, registers required for particular instructions
  - Solution: "pre-color" some nodes to force allocation to a particular register

Exercise

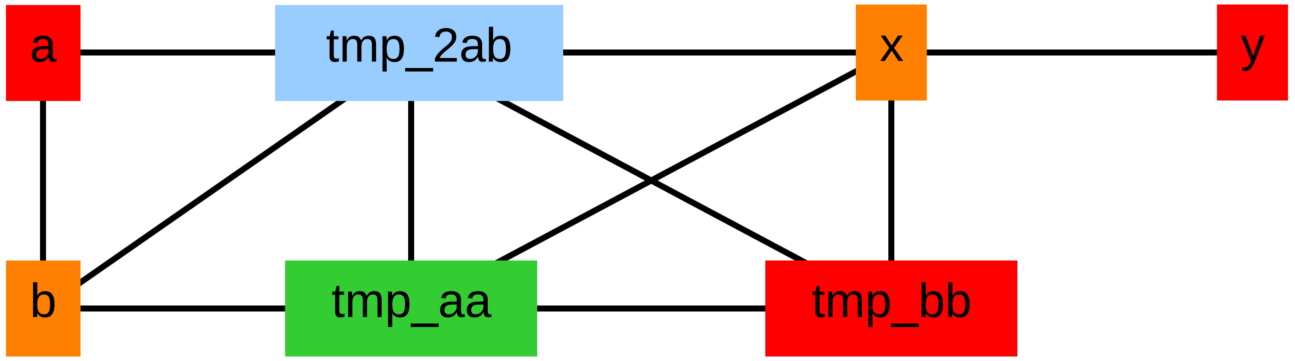
```
{  int tmp_2ab = 2*a*b;
   int tmp_aa = a*a;
   int tmp_bb = b*b;

   x := tmp_aa + tmp_2ab + tmp_bb;
   y := tmp_aa - tmp_2ab + tmp_bb;
}
```

given that a and b are live on entry and dead on exit, and that x and y are live on exit:

(a) construct the register interference graph

(b) color the graph; how many registers are needed?

4 Registers Needed


a
tmp_2ab
x
y
b
tmp_aa
tmp_bb