Pointer analysis

Pointer Analysis

- Outline:
  - What is pointer analysis
  - Intraprocedural pointer analysis
  - Interprocedural pointer analysis
    - Andersen and Steensgaard

Pointer and Alias Analysis

- Aliases: two expressions that denote the same memory location.
- Aliases are introduced by:
  - pointers
  - call-by-reference
  - array indexing
  - C unions

Useful for what?

- Improve the precision of analyses that require knowing what is modified or referenced (eg const prop, CSE …)
- Eliminate redundant loads/stores and dead stores.

```
x := *p;
...
y := *p; // replace with y := x?
```

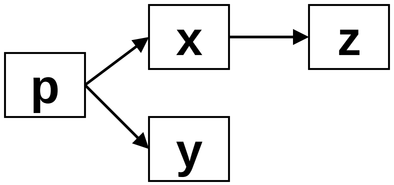
```
*x := ...;
// is *x dead?
```

- Parallelization of code
  - can recursive calls to quick_sort be run in parallel? Yes, provided that they reference distinct regions of the array.
- Identify objects to be tracked in error detection tools

```
x.lock();
...
y.unlock(); // same object as x?
```

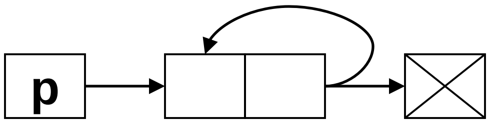
Kinds of alias information

- Points-to information (must or may versions)
  - at program point, compute a set of pairs of the form p **!** x, where p points to x.
  - can represent this information in a **points-to graph**



- Alias pairs
  - at each program point, compute the set of of all pairs (e_1,e_2) where e_1 and e_2 must/may reference the same memory.

- Storage shape analysis
  - at each program point, compute an abstract description of the pointer structure.



Intraprocedural Points-to Analysis

- Want to compute may-points-to information

- Lattice: $D = 2^{\{x \to y \mid x \in Var,\ y \in Var\}}$

$$\sqcup = \cup$$

$$\sqsubseteq = \subseteq$$

$$\bot = \emptyset$$

$$\top = \{x \to y \mid x \in Var,\ y \in Var\}$$

Flow functions

in

`x := k`

out

$F_{x\ :=\ k}(in) = in - \{x \to *\}$

in

`x := a + b`

out

$F_{x\ :=\ a+b}(in) =$

Flow functions

in

`x := y`

out

$F_{x := y}(in) =$ $in - \{x \to *\} \cup \{x \to t \mid y \to t \in in\}$

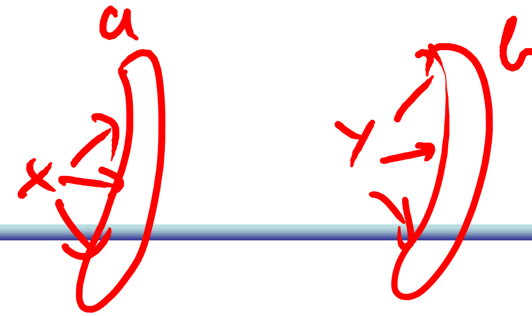
in

`x := &y`

out

$F_{x := \&y}(in) =$

Flow functions



in

```
x := *y
```

out

$F_{x\ :=\ *y}(in) =$ $in - \{x \to *\} \cup \{x \to t \mid \exists z.\ y \to z \in in \wedge z \to t \in in\}$

in

```
*x := y
```

out

$F_{*x\ :=\ y}(in) =$ $in \cup \{a \to b \mid x \to a \in in,\ y \to b \in in\}$

Intraprocedural Points-to Analysis

- Flow functions:

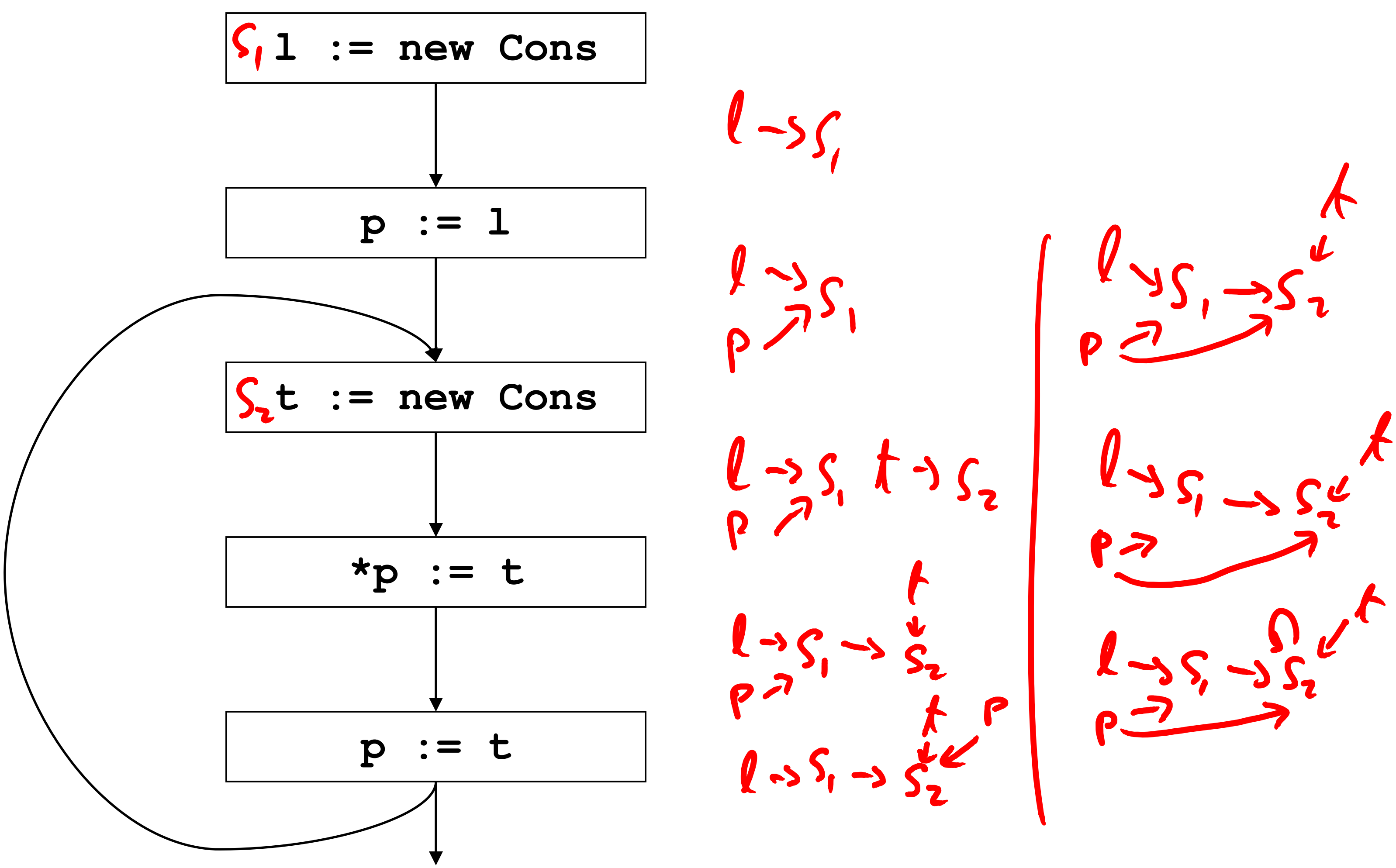
$$
\begin{aligned}
kill(x) &= \bigcup_{v \in Vars} \{(x, v)\} \\
F_{x:=k}(S) &= S - kill(x) \\
F_{x:=a+b}(S) &= S - kill(x) \\
F_{x:=y}(S) &= S - kill(x) \cup \{(x, v) \mid (y, v) \in S\} \\
F_{x:=\&y}(S) &= S - kill(x) \cup \{(x, y)\} \\
F_{x:=*y}(S) &= S - kill(x) \cup \{(x, v) | \exists t \in Vars.[(y, t) \in S \wedge (t, v) \in S]\} \\
F_{*x:=y}(S) &= \textbf{let } V := \{v \mid (x, v) \in S\} \textbf{ in} \\
&\quad S - (\textbf{if } V = \{v\} \textbf{ then } kill(v) \textbf{ else } \emptyset) \\
&\qquad \cup \{(v, t) \mid v \in V \wedge (y, t) \in S\}
\end{aligned}
$$

Pointers to dynamically-allocated memory

- Handle statements of the form: **`x := new T`**
- One idea: generate a new variable each time the new statement is analyzed to stand for the new location:

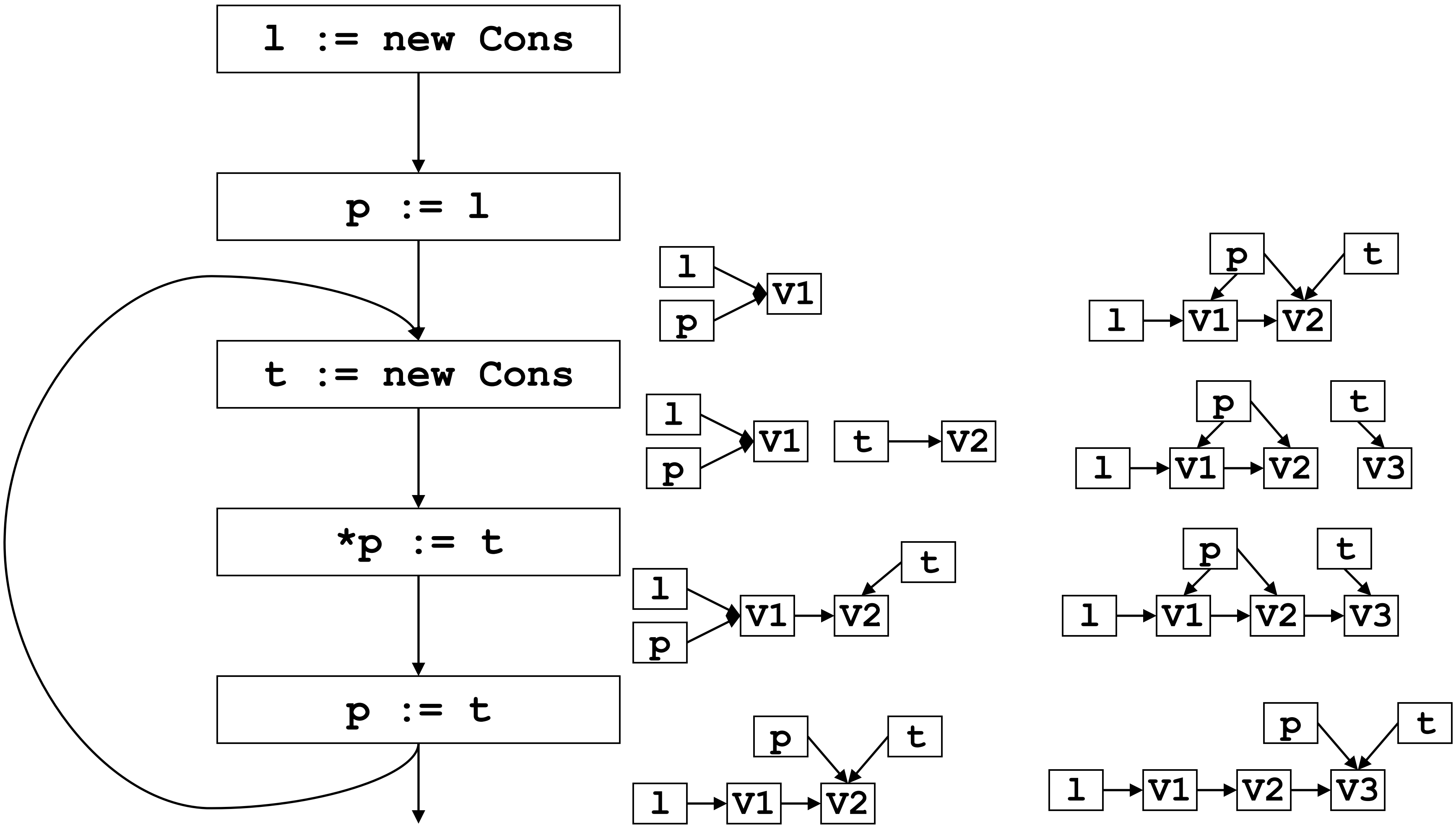
$$F_{x:=new\ \ T}(S) \;=\; S - kill(x) \cup \{(x, newvar())\}$$

Example



S1 l := new Cons
p := l
S2 t := new Cons
*p := t
p := t
l → S1
l → S1
p
l → S1 t → S2
p
l → S1 → S2
t
p
l → S1 → S2
t p
l → S1 → S2
t
p
l → S1 → S2
t
p
l → S1 → S2
t
p

Example solved



What went wrong?

- Lattice infinitely tall!
- We were essentially running the program
- Instead, we need to summarize the infinitely many allocated objects in a finite way
- **New Idea**: introduce summary nodes, which will stand for a whole class of allocated objects.

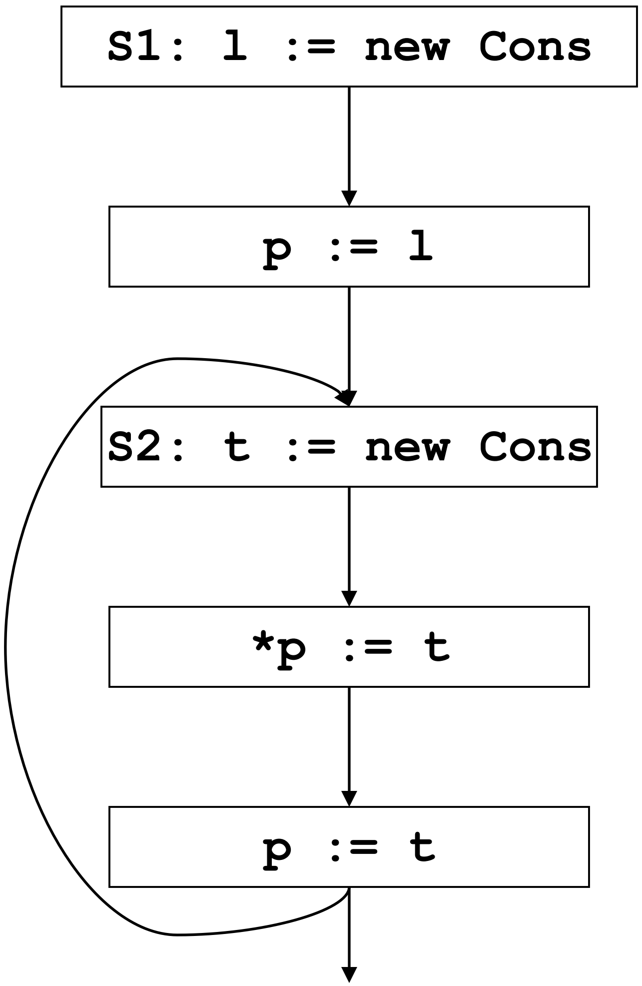
What went wrong?

- Example: For each new statement with label L, introduce a summary node loc_L , which stands for the memory allocated by statement L.

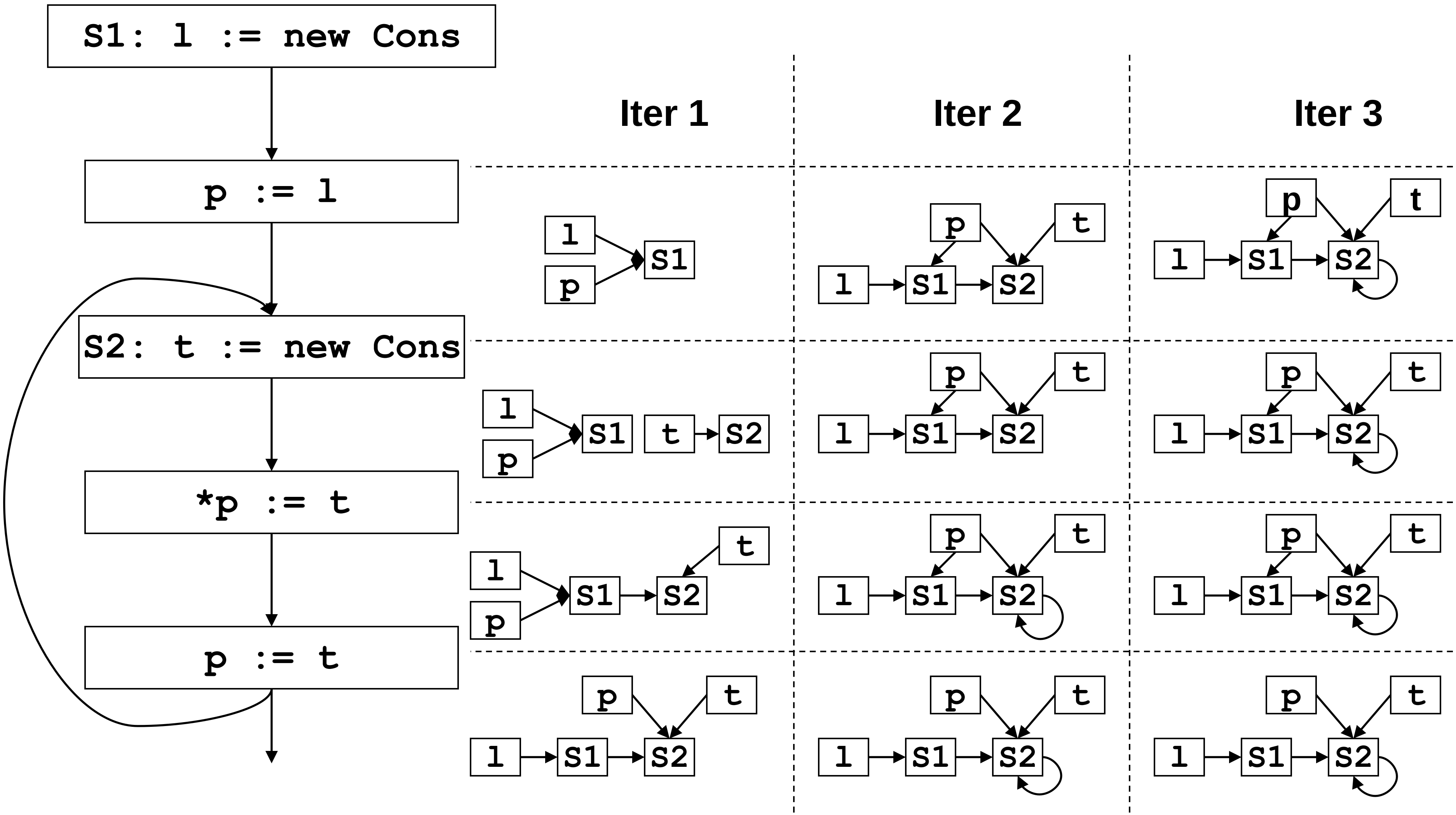
$$F_{L:\ x:=new\ T}(S) \ = \ S - kill(x) \cup \{(x, loc_L)\}$$

- Summary nodes can use other criterion for merging.

Example revisited



Example revisited & solved



Array aliasing, and pointers to arrays

- Array indexing can cause aliasing:
  - **`a[i]`** aliases **`b[j]`** if:
    - a aliases b and i = j
    - a and b overlap, and i = j + k, where k is the amount of overlap.
- Can have pointers to elements of an array
  - **`p := &a[i]; ...; p++;`**
- How can arrays be modeled?
  - Could treat the whole array as one location.
  - Could try to reason about the array index expressions: array dependence analysis.

Fields

foo.n := ...   n := ...

- Can summarize fields using per field summary
  - for each field F, keep a points-to node called F that summarizes all possible values that can ever be stored in F

- Can also use allocation sites
  - for each field F, and each allocation site S, keep a points-to node called (F, S) that summarizes all possible values that can ever be stored in the field F of objects allocated at site S.

Summary

- We just saw:
  - intraprocedural points-to analysis
  - handling dynamically allocated memory
  - handling pointers to arrays
- But, intraprocedural pointer analysis is not enough.
  - Sharing data structures across multiple procedures is one the big benefits of pointers: instead of passing the whole data structures around, just pass pointers to them (eg C pass by reference).
  - So pointers end up pointing to structures shared across procedures.
  - If you don’t do an interproc analysis, you’ll have to make conservative assumptions functions entries and function calls.

Conservative approximation on entry

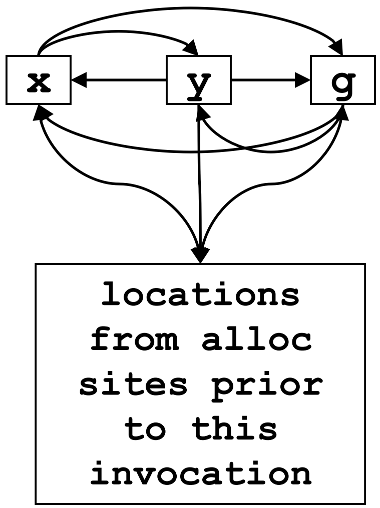
- Say we don't have interprocedural pointer analysis.
- What should the information be at the input of the following procedure:

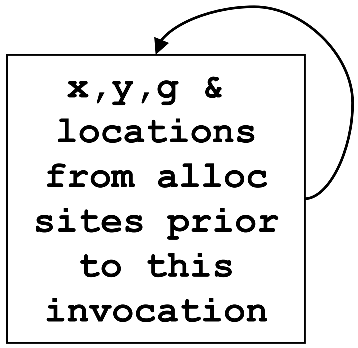
```
global g;                          x    y    g
void p(x,y) {

   ...

}
```

Conservative approximation on entry

- Here are a few solutions:

```
global g;
void p(x,y) {

    ...

}
```



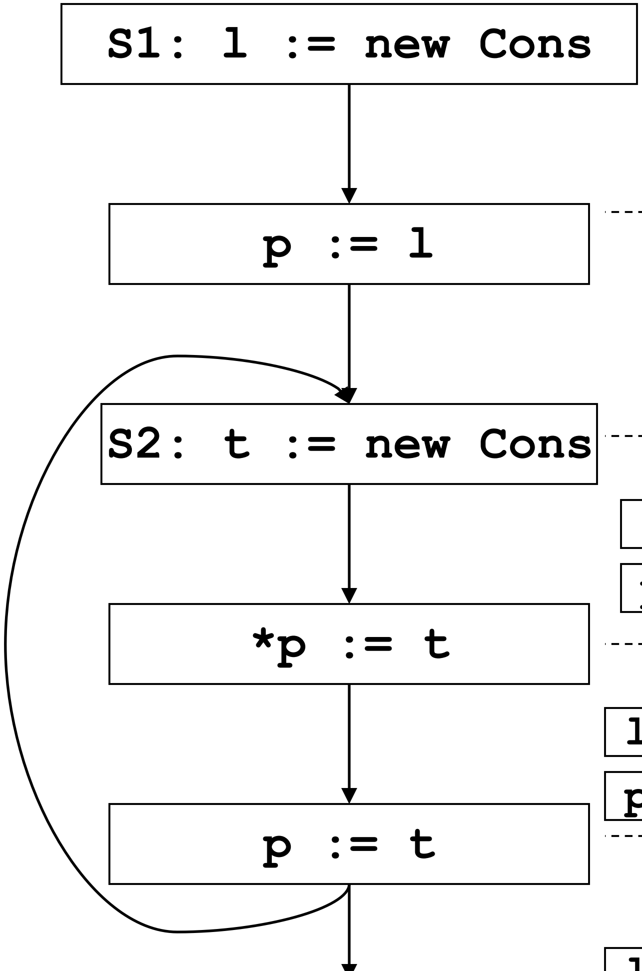


- They are all very conservative!
- We can try to do better.

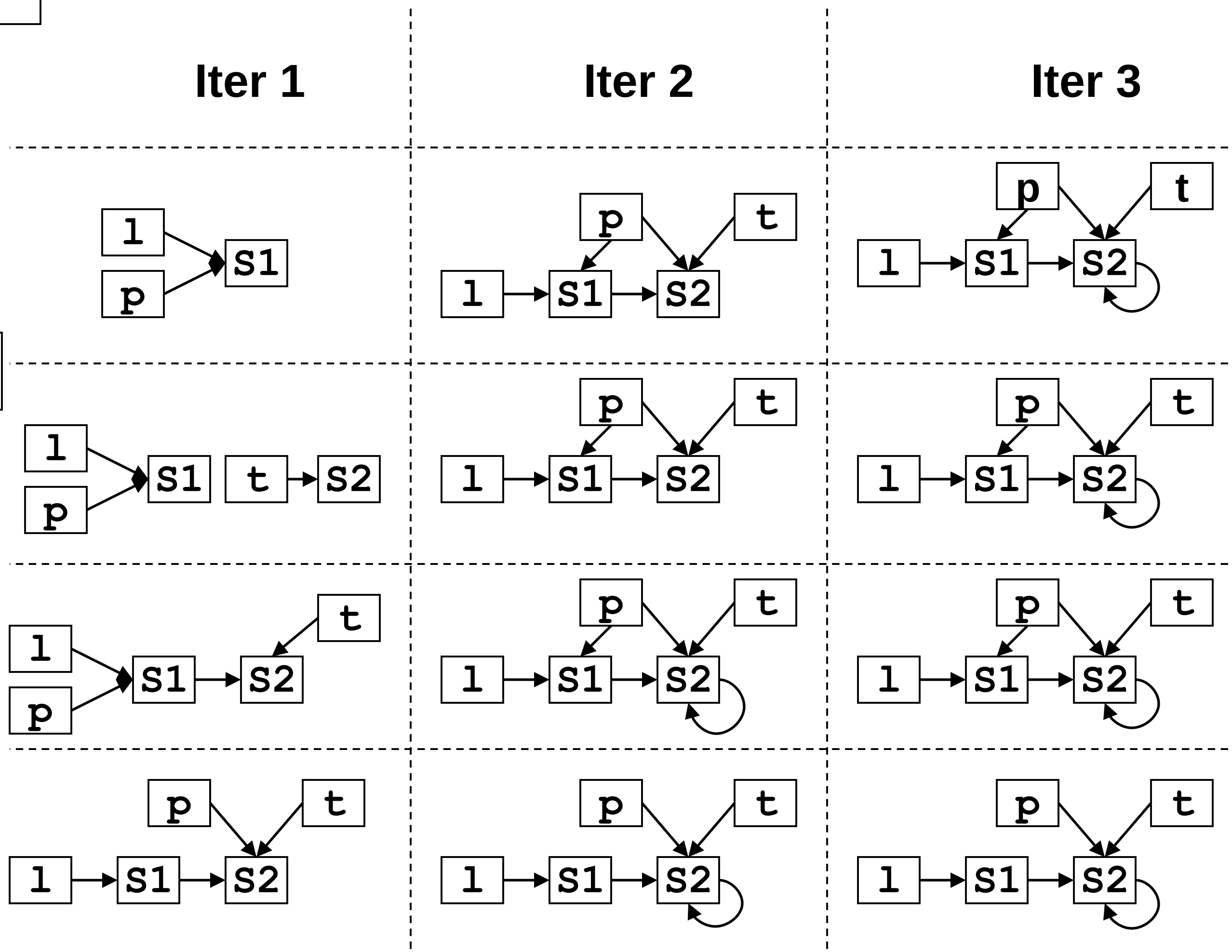
Interprocedural pointer analysis

- Main difficulty in performing interprocedural pointer analysis is scaling
- One can use a top-down summary based approach (Wilson & Lam 95), but even these are hard to scale

Example revisited



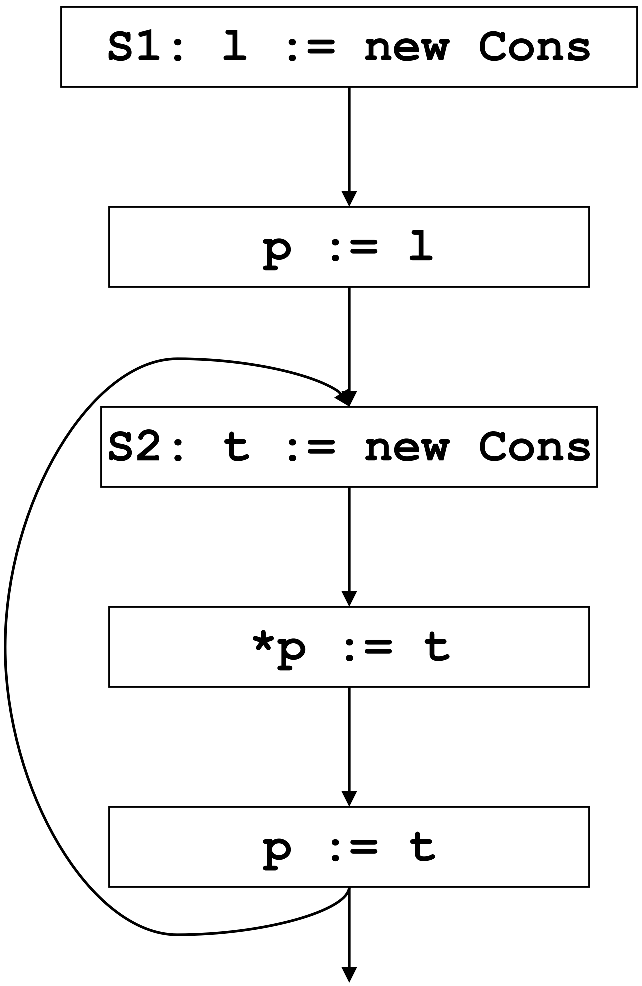
- Cost:
  - space: store one fact at each prog point
  - time: iteration

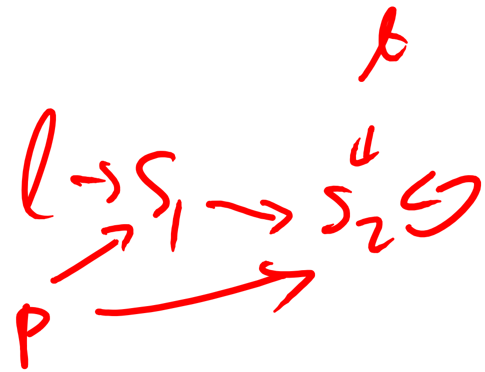


New idea: store one dataflow fact

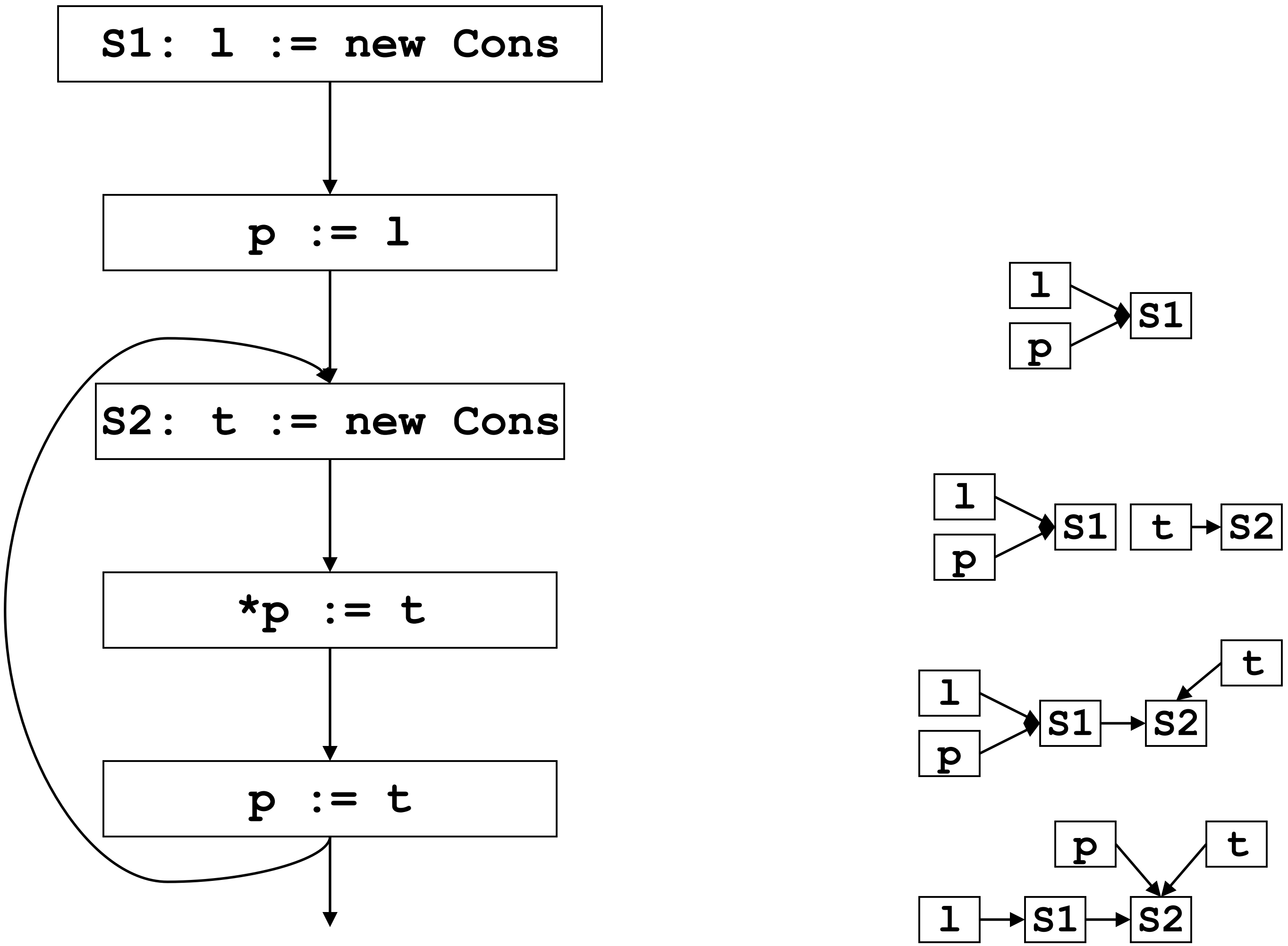
- Store one dataflow fact for the whole program
- Each statement updates this one dataflow fact
  - use the previous flow functions, but now they take the whole program dataflow fact, and return an updated version of it.
- Process each statement once, ignoring the order of the statements
- This is called a flow-insensitive analysis.

Flow insensitive pointer analysis

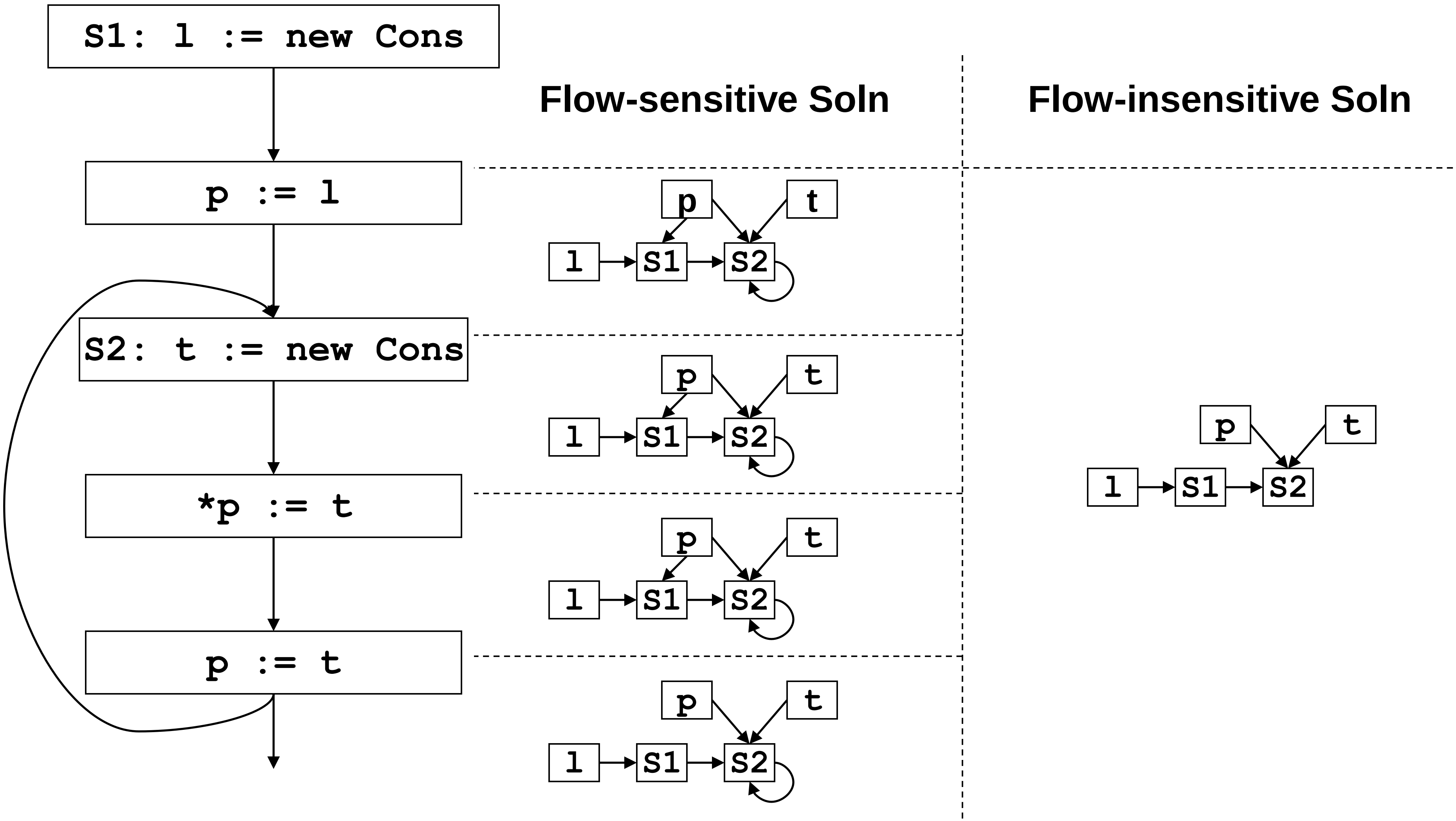




Flow insensitive pointer analysis



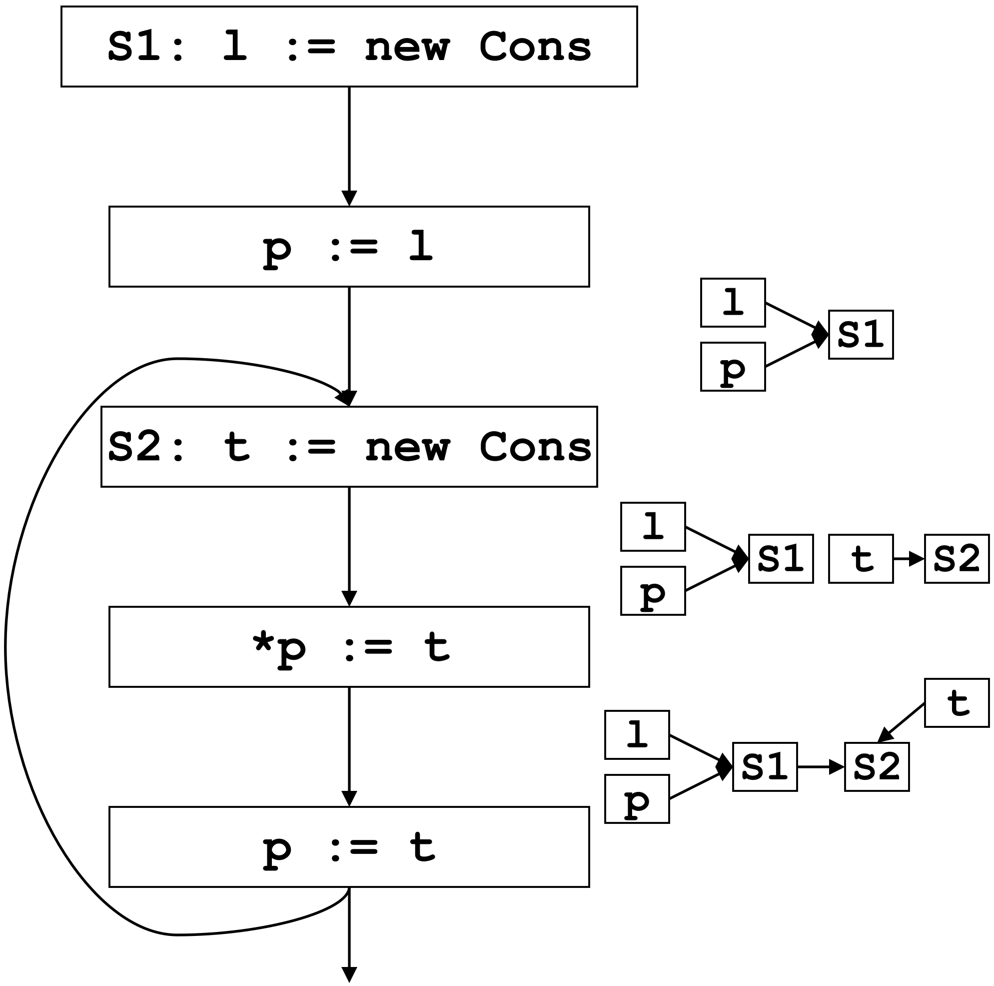
Flow sensitive vs. insensitive



What went wrong?

- What happened to the link between p and S1?
  - Can’t do strong updates anymore!
  - Need to remove all the kill sets from the flow functions.
- What happened to the self loop on S2?
  - We still have to iterate!

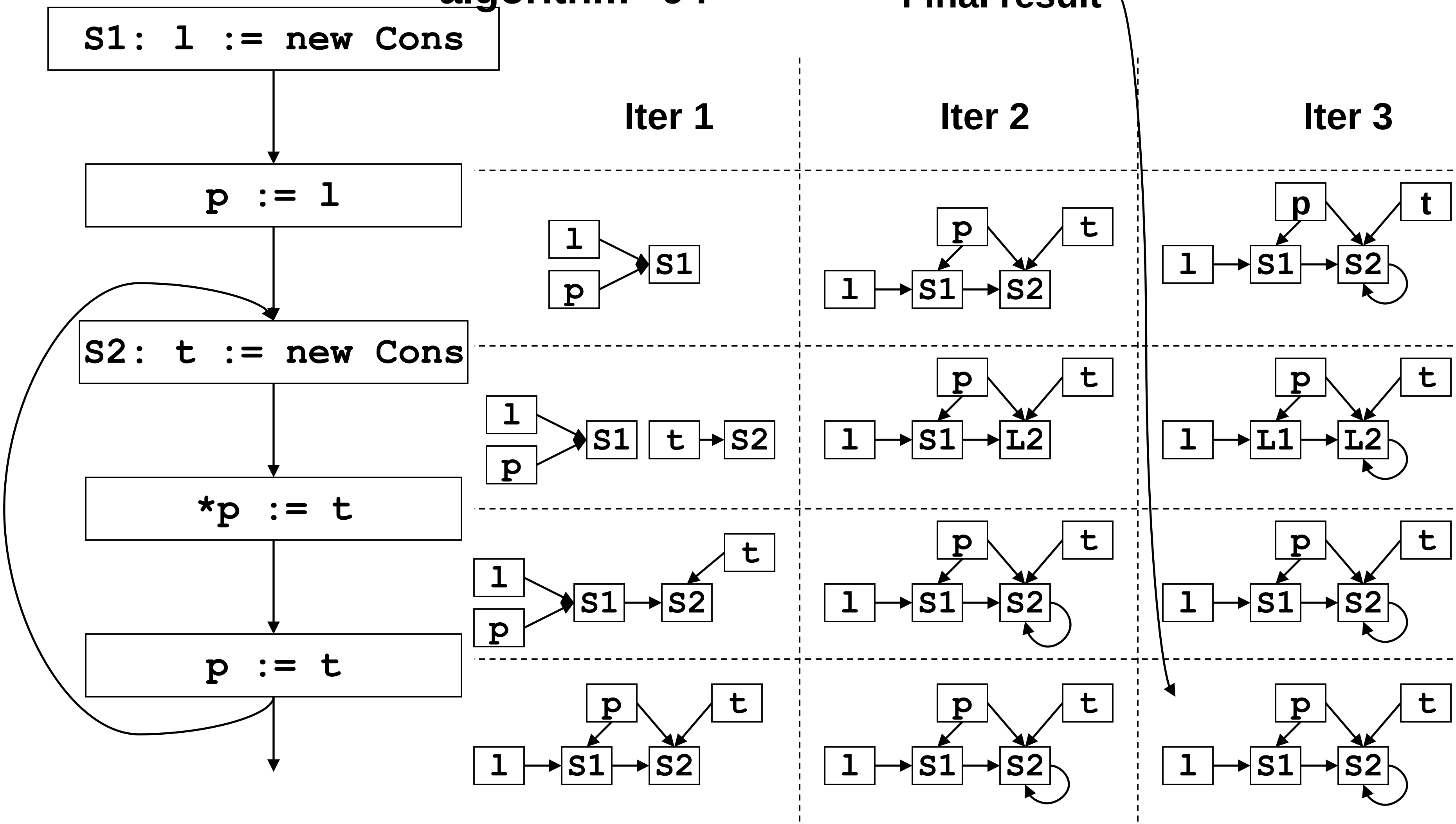
Flow insensitive pointer analysis: fixed



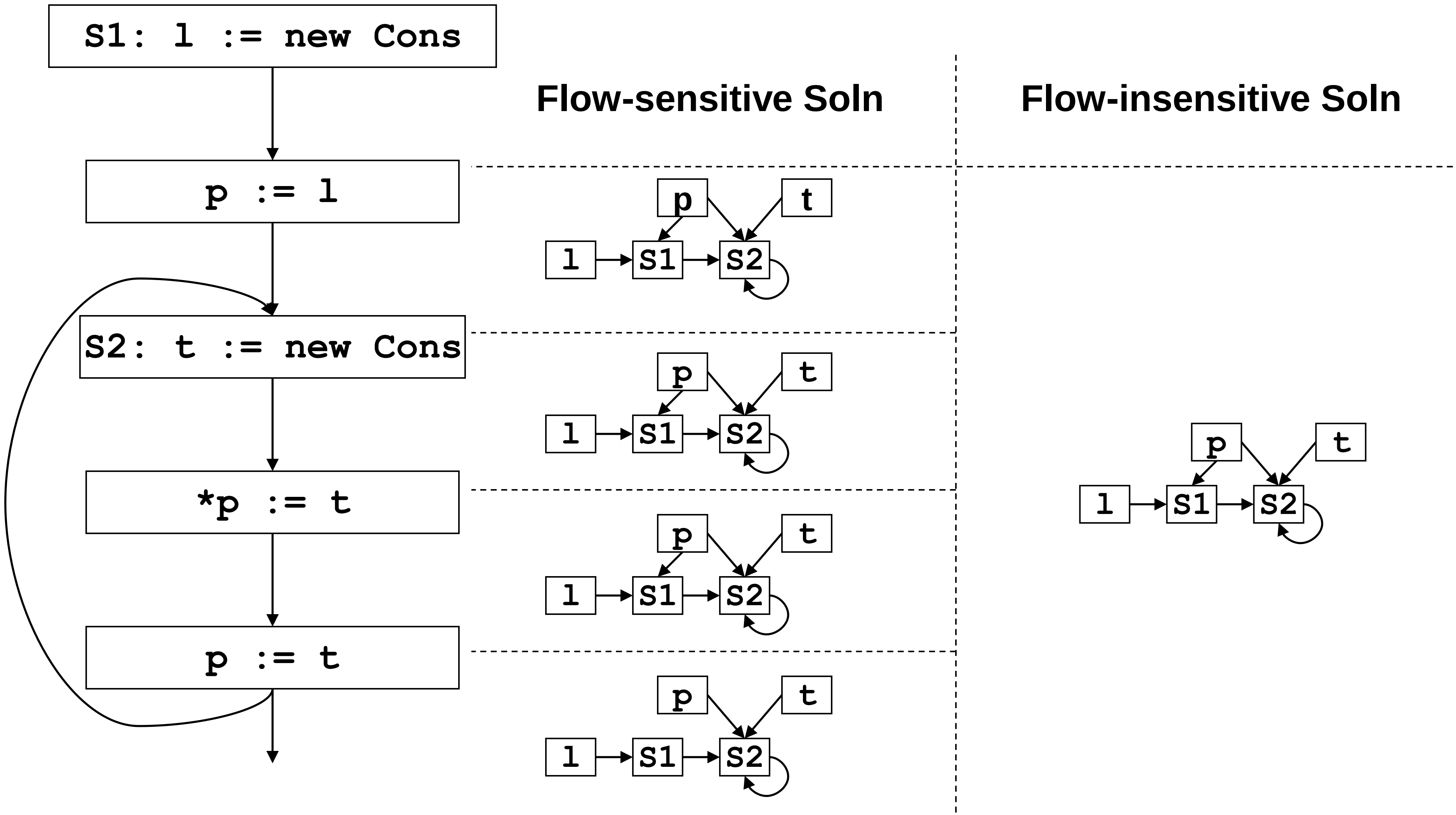
Flow insensitive pointer analysis: fixed

This is Andersen’s algorithm ’94

Final result



Flow sensitive vs. insensitive, again



Flow insensitive loss of precision

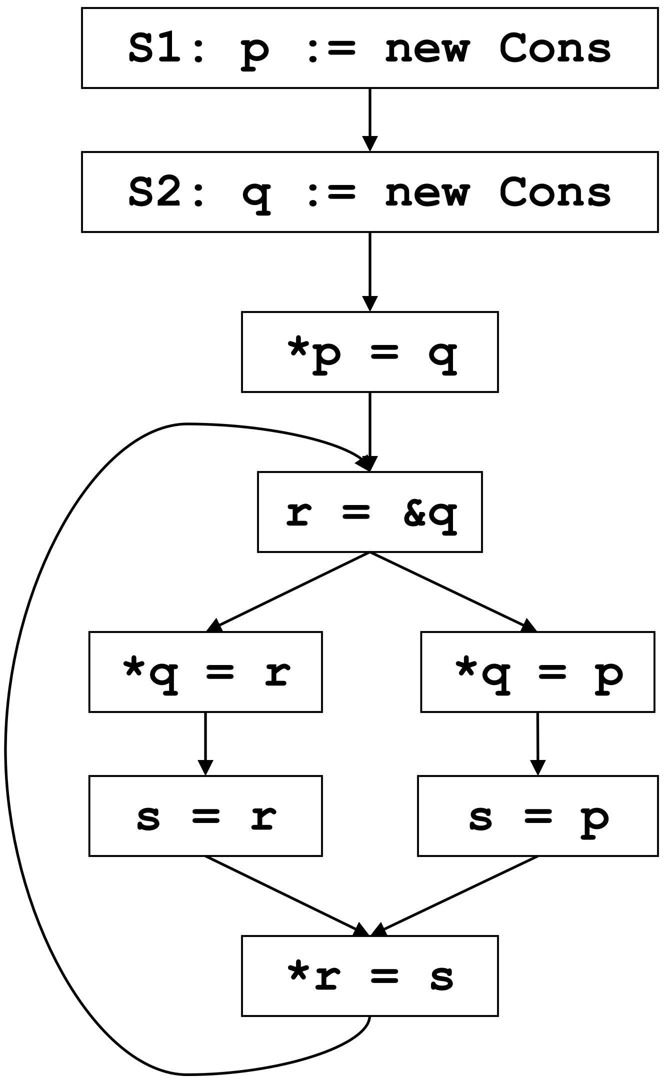
- Flow insensitive analysis leads to loss of precision!

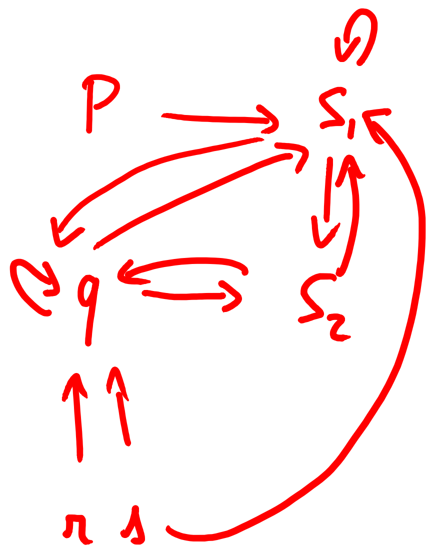
```
main() {
    x := &y;

    ...

    x := &z;
}
```

Flow insensitive analysis tells us that x may point to z here!

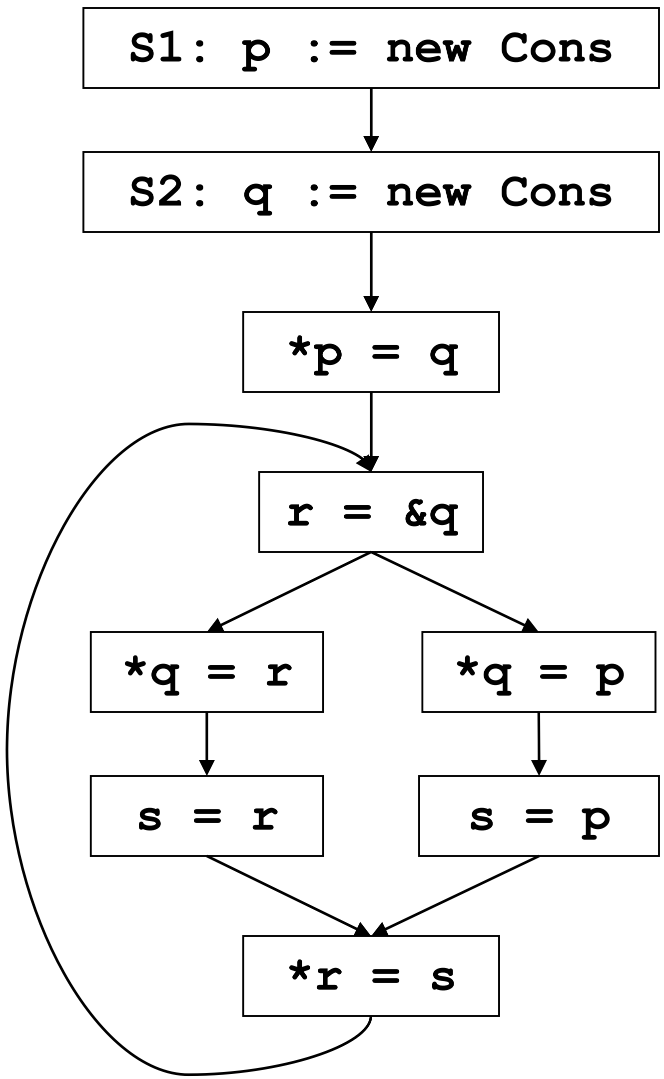
- However:
  - uses less memory (memory can be a big bottleneck to running on large programs)
  - runs faster

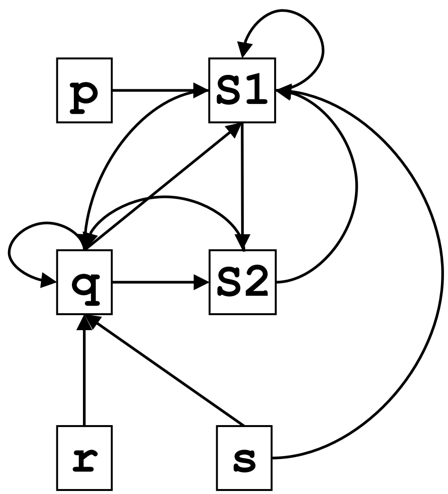
In Class Exercise!



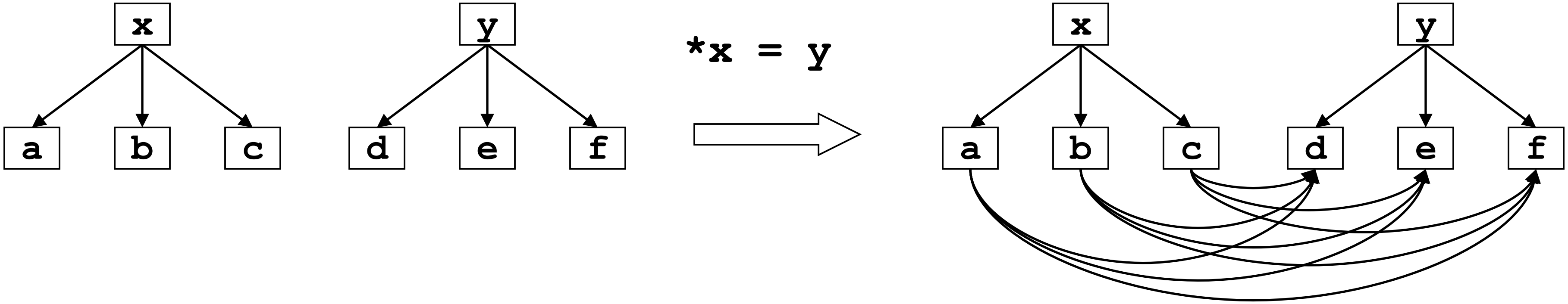


In Class Exercise! solved





Worst case complexity of Andersen

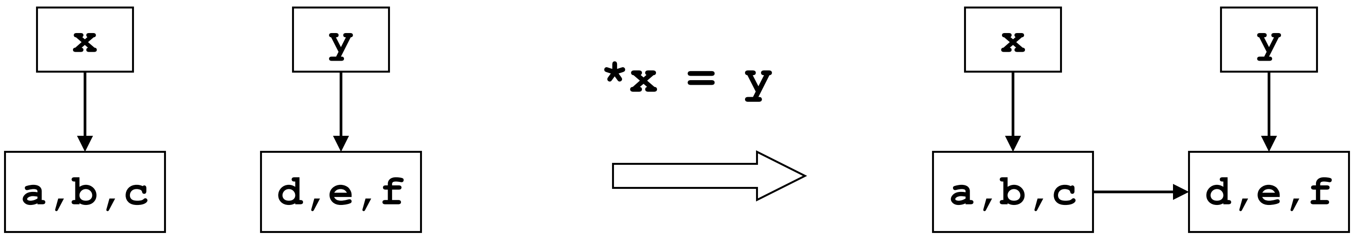


Worst case: N^2 per statement, so at least N^3 for the whole program. Andersen is in

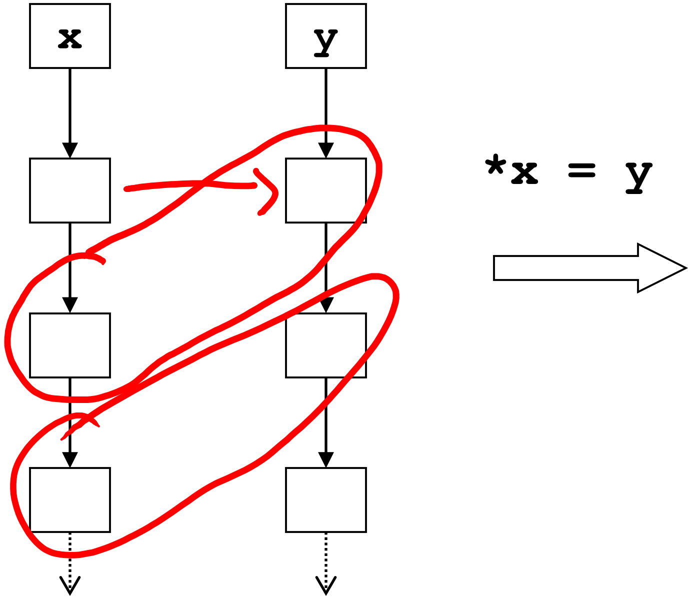
fact $O(N^3)$

New idea: one successor per node

- Make each node have only one successor.
- This is an invariant that we want to maintain.



More general case for `*x = y`



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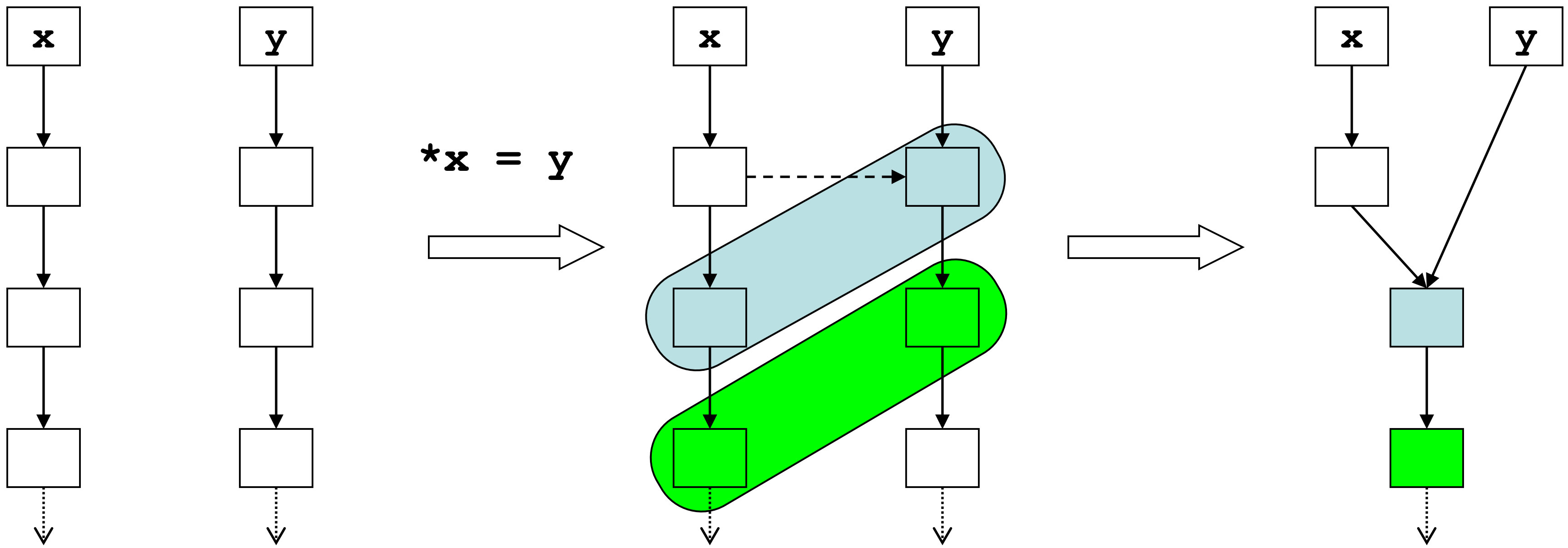
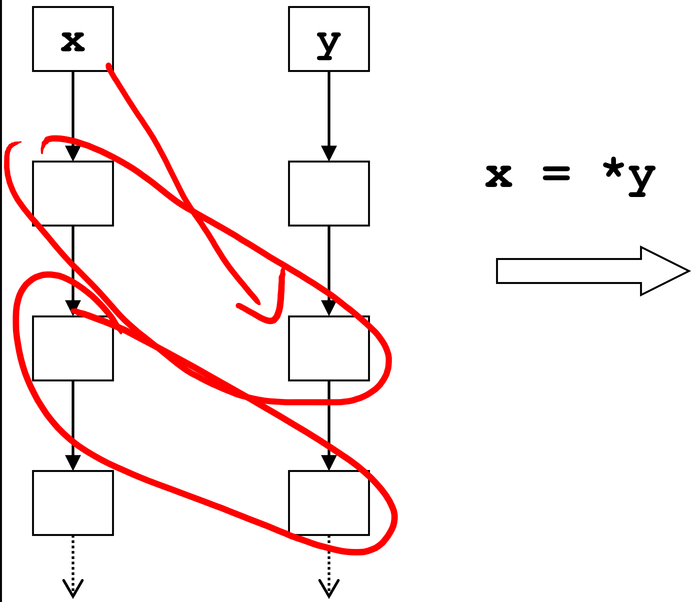


Handling: `x = *y`



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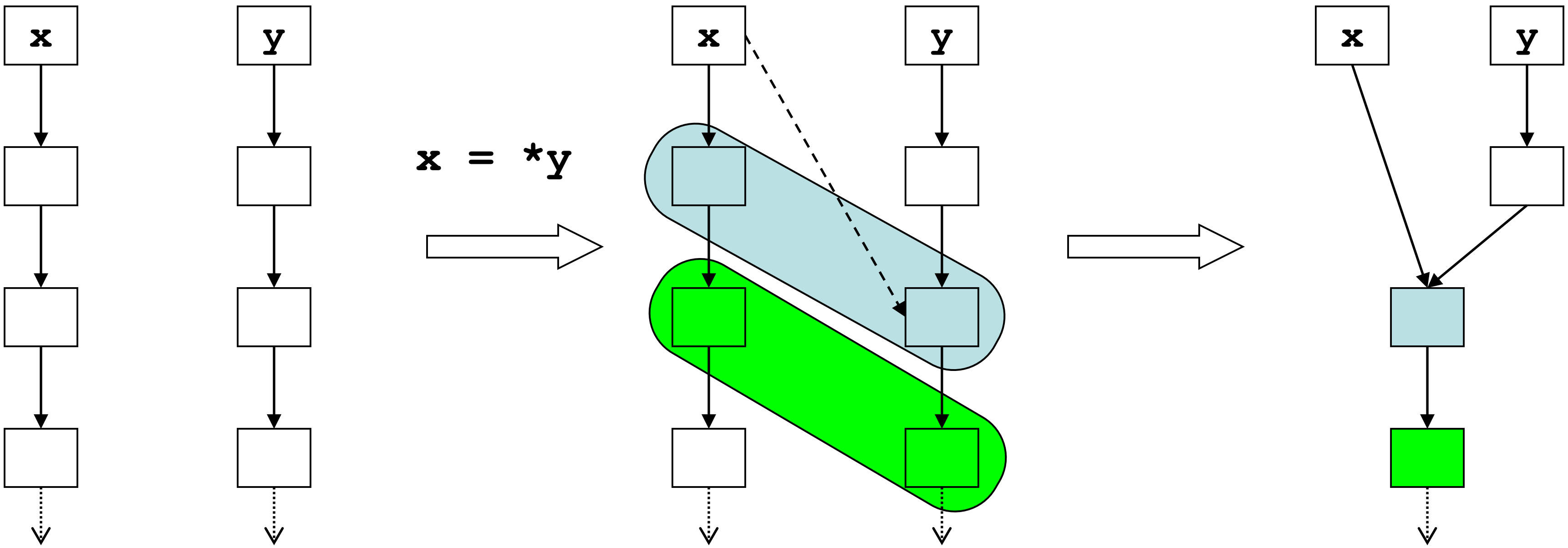
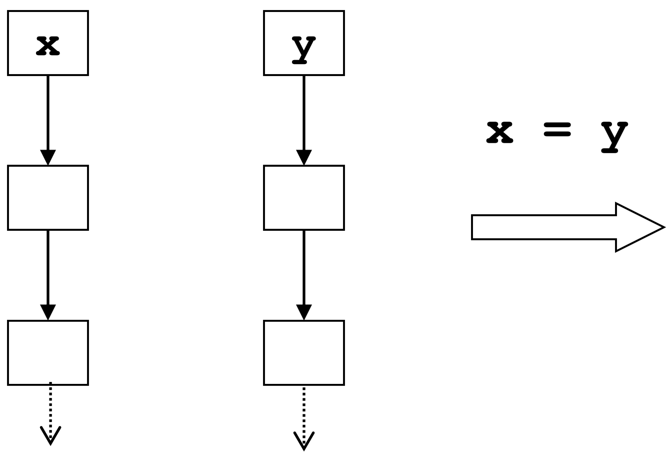
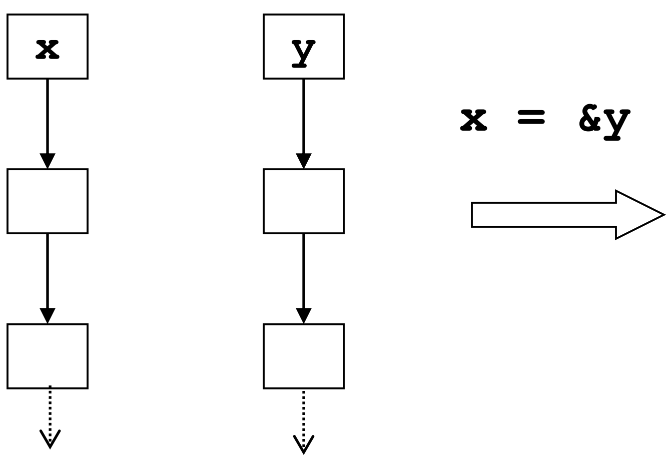


Handling: x = y (what about y = x?)



Handling: x = &y



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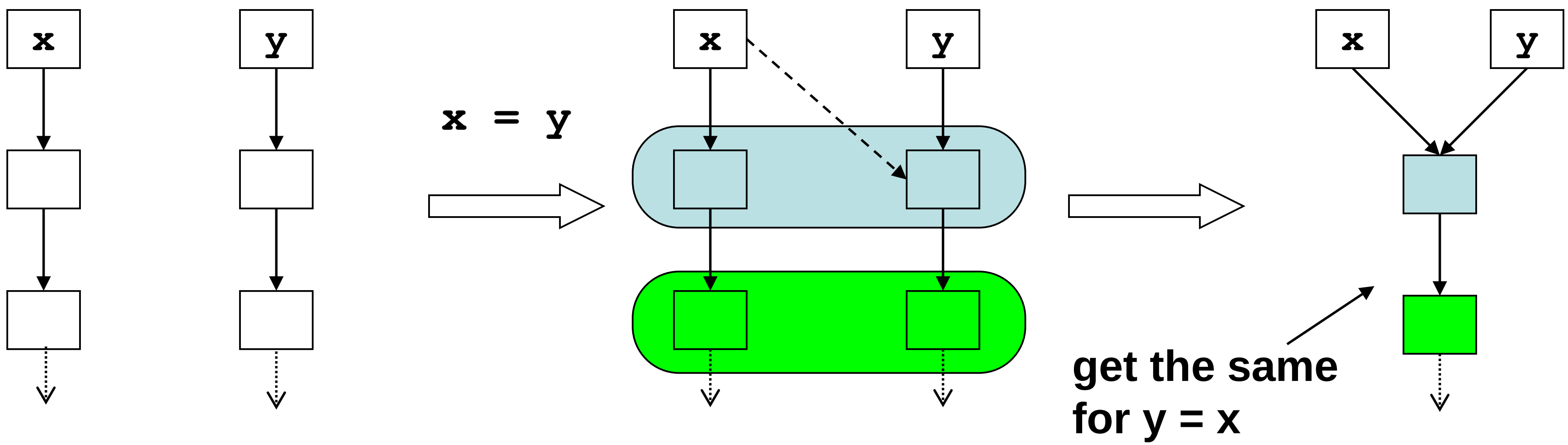
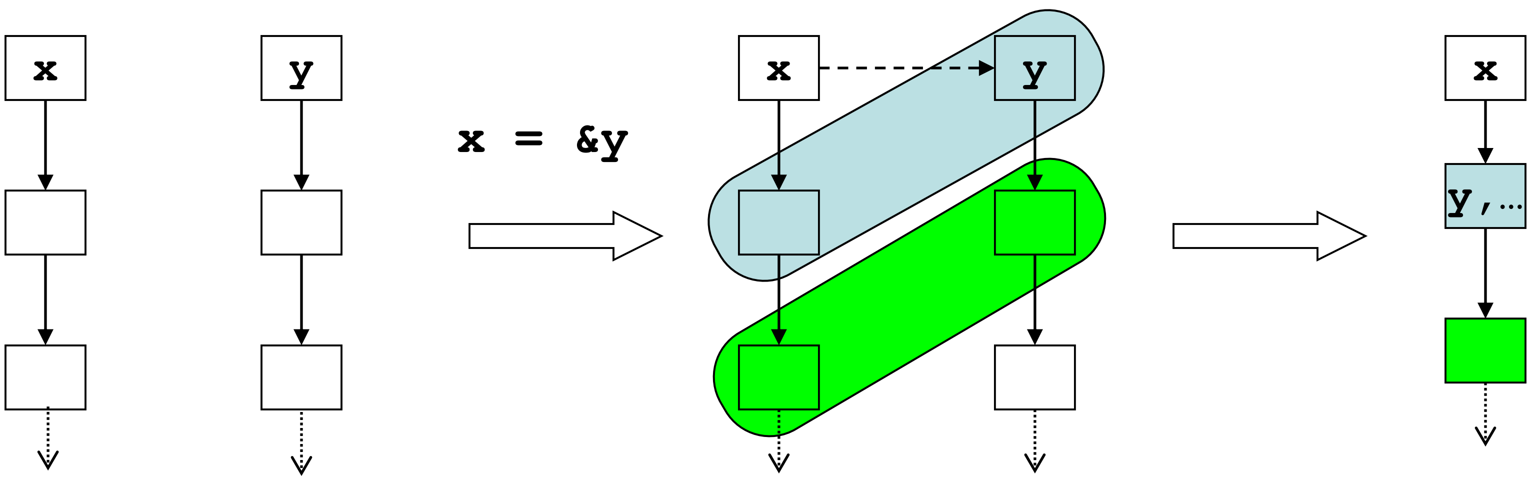
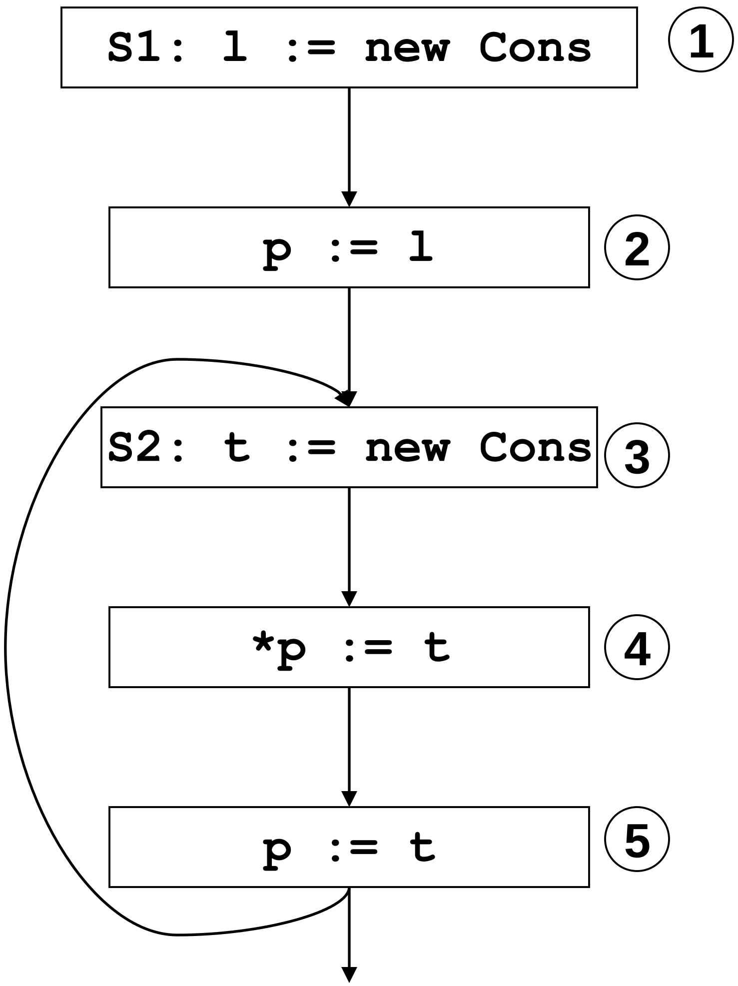
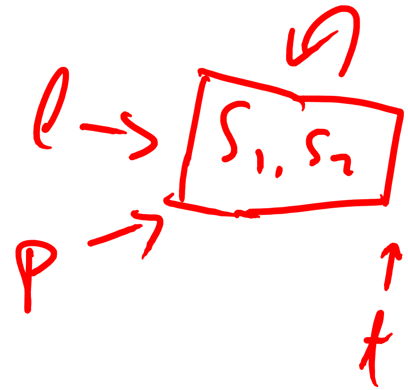


Handling: x = &y



Our favorite example, once more!





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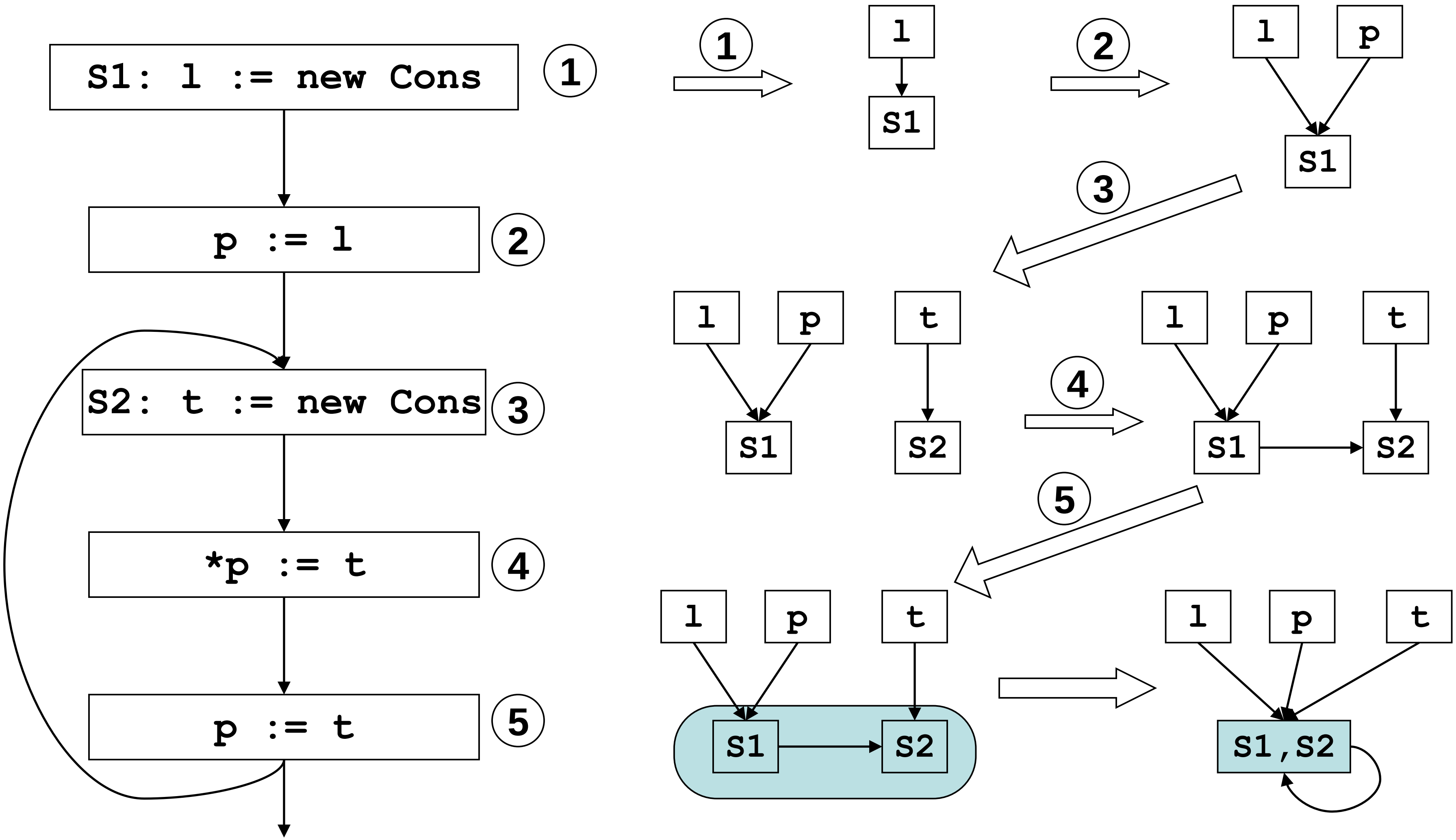
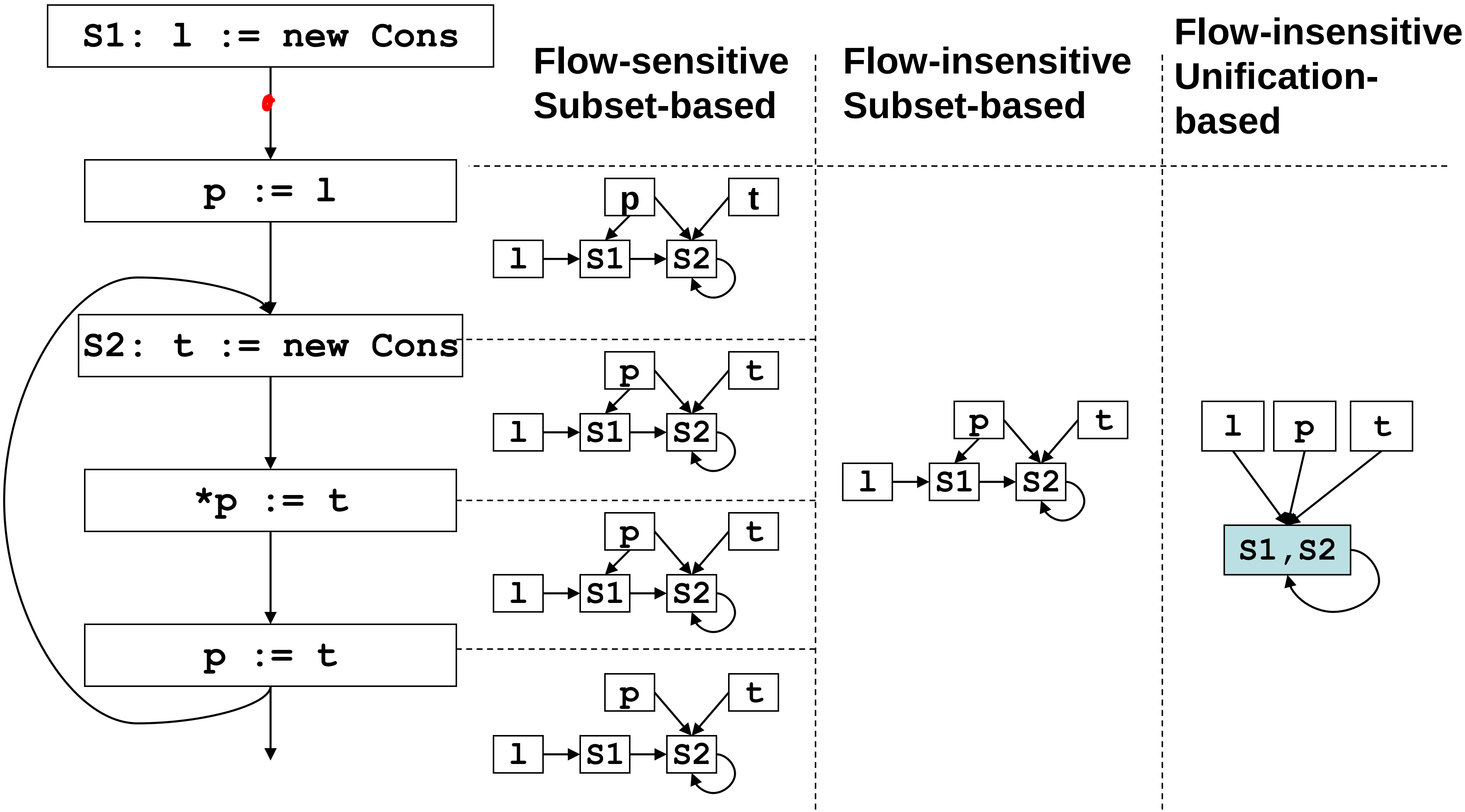


Flow insensitive loss of precision

*l = &x

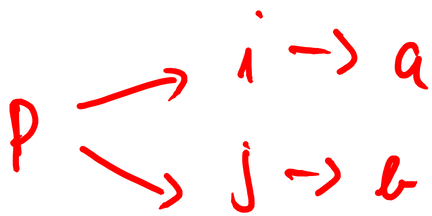


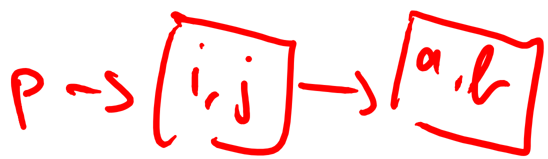
Another example

```
bar() {
 ① i := &a;
 ② j := &b;
 ③ foo(&i);
 ④ foo(&j);
    // i pnts to what?
    *i := ...;

}

void foo(int* p) {
   printf("%d",*p);
}
```





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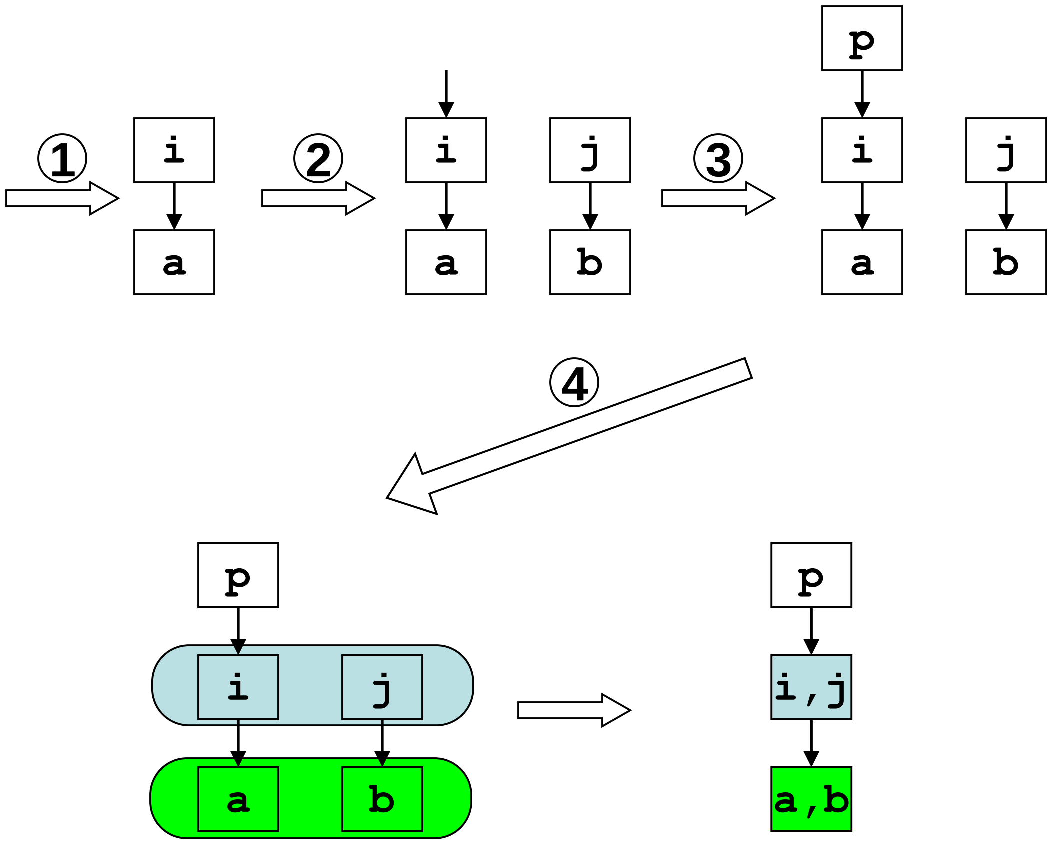


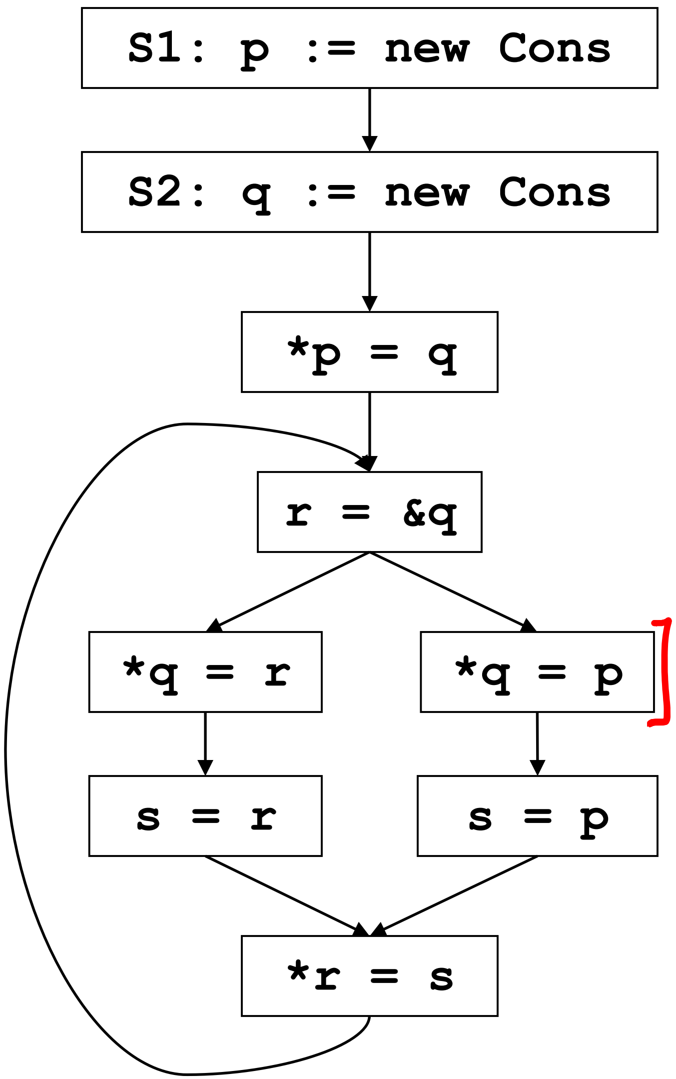
Almost linear time

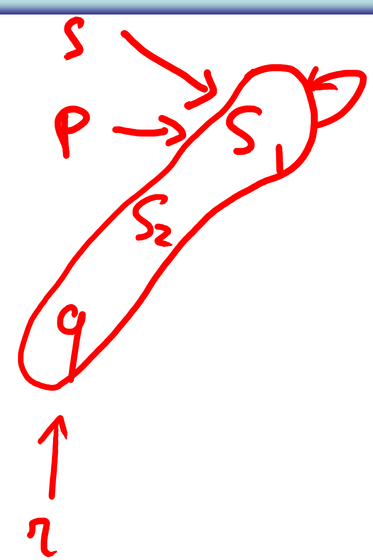
- Time complexity: O(Nα(N, N))

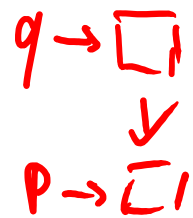
inverse Ackermann function

- So slow-growing, it is basically linear in practice
- For the curious: node merging implemented using UNION-FIND structure, which allows set union with amortized cost of O(α(N, N)) per op. Take CSE 202 to learn more!

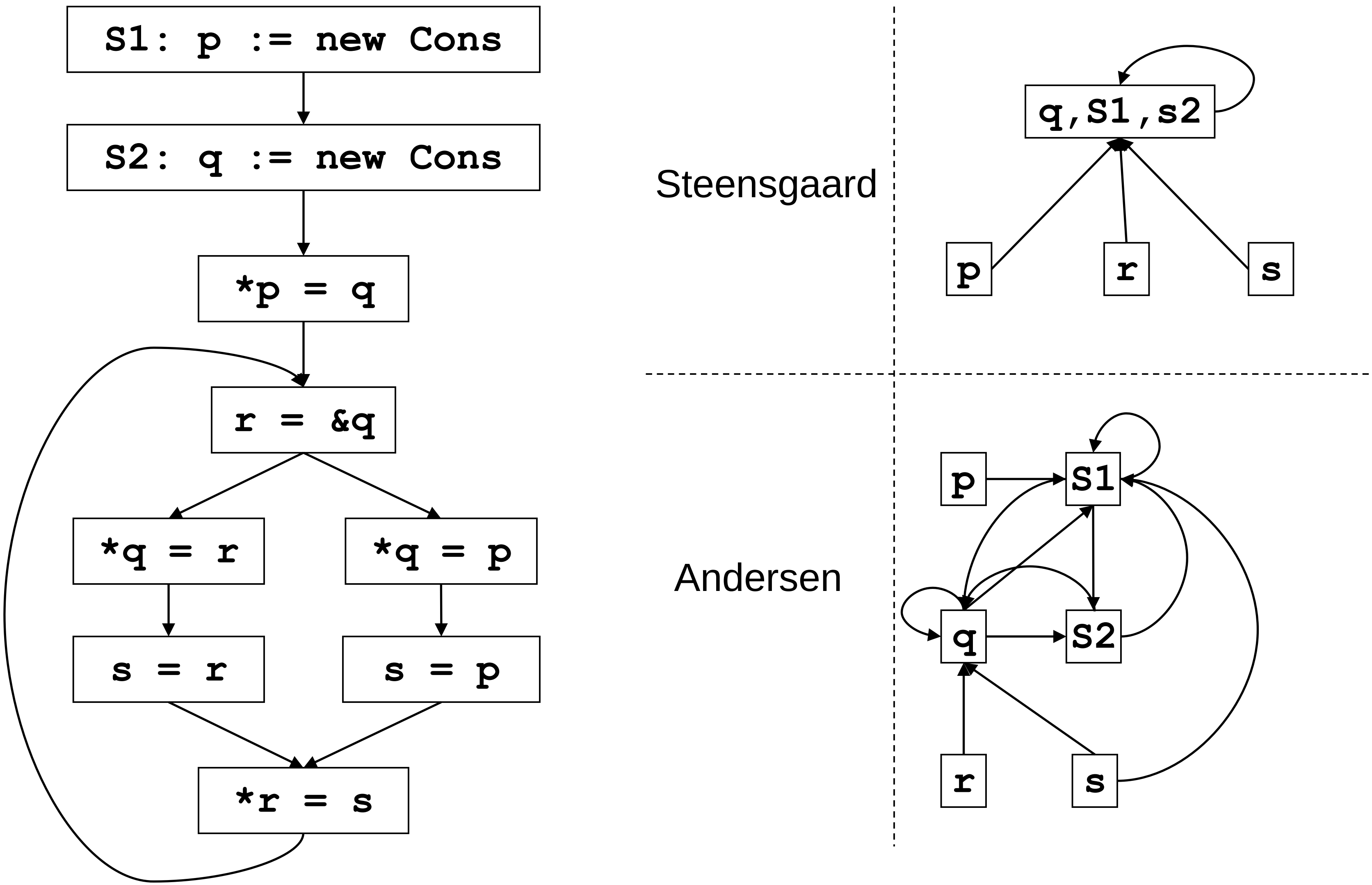
In Class Exercise!







In Class Exercise! solved



Advanced Pointer Analysis

- Combine flow-sensitive/flow-insensitive
- Clever data-structure design
- Context-sensitivity