Pointer analysis

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Pointer Analysis

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

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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

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

- 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?
```

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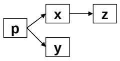
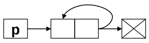
Kinds of alias information

- 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.



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Intraprocedural Points-to Analysis

- Want to compute may-points-to information
- Lattice: $D = 2^{\{x \to y \mid x \in Var, y \in Var\}}$

$\sqcup = \cup$

$\sqsubseteq = \subseteq$

$\bot = \emptyset$

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

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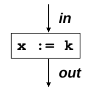
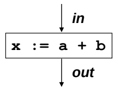
Flow functions



$F_{x := k}(\text{in}) =$



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

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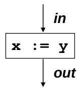
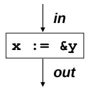
Flow functions



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



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

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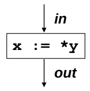
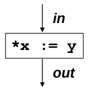
Flow functions



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



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

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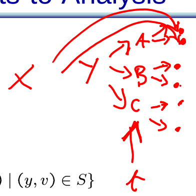
Intraprocedural Points-to Analysis

- Flow functions:



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

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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:

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

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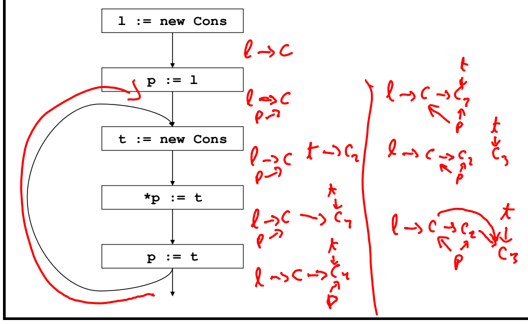
Example



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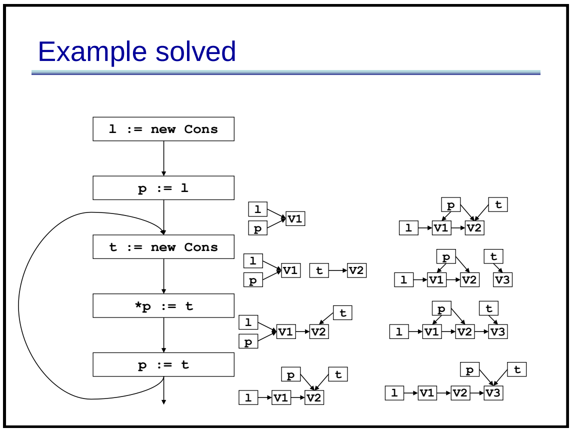

Example solved

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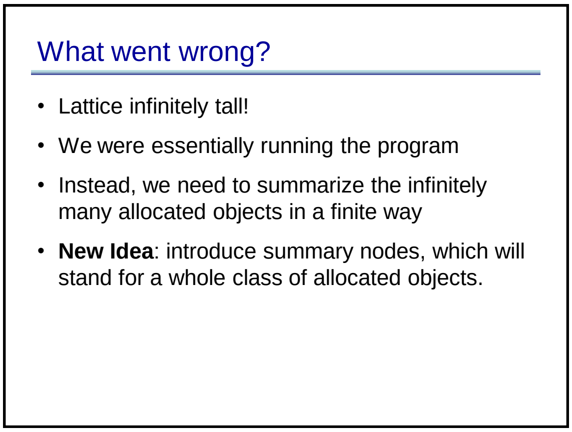

What went wrong?

- 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.

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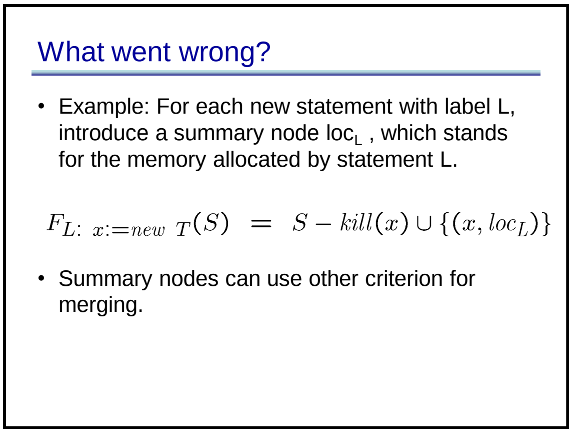

What went wrong?

- 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.

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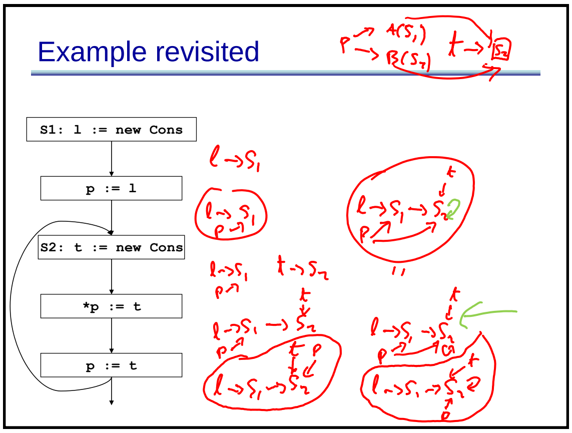

Example revisited

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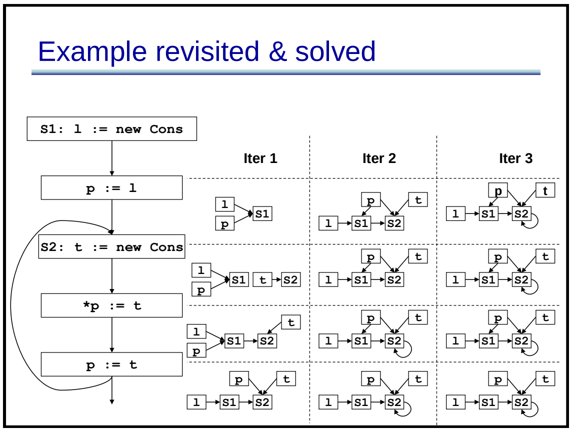

Example revisited & solved

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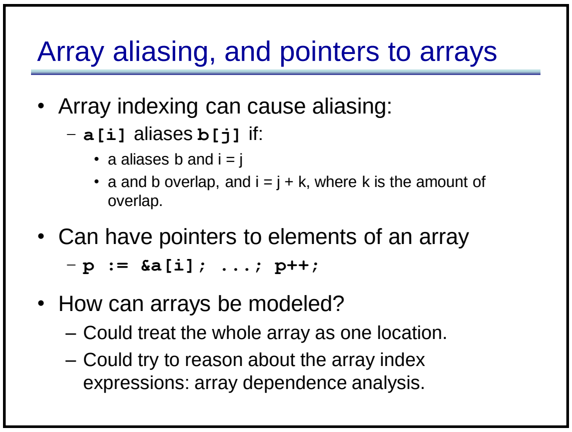

Array aliasing, and pointers to arrays

- 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.

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Fields

- 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.

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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.

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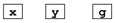
Conservative approximation on entry

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

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

   ...

}
```



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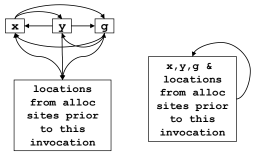
Conservative approximation on entry

- Here are a few solutions:

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

   ...

}
```


x
y
g
locations from alloc sites prior to this invocation
x,y,g & locations from alloc sites prior to this invocation

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

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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

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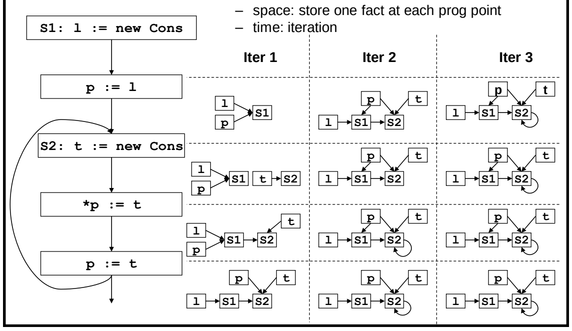
Example revisited

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



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

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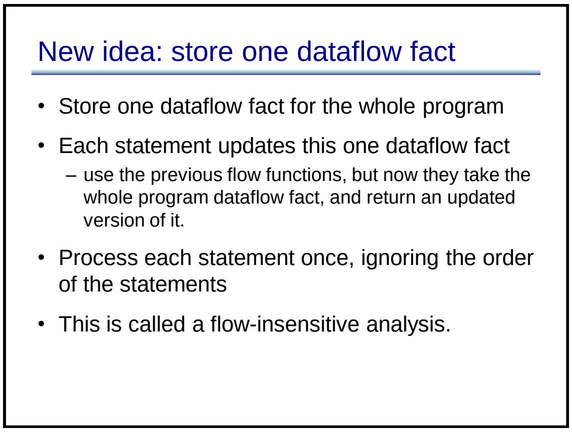

New idea: store one dataflow fact

- 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.

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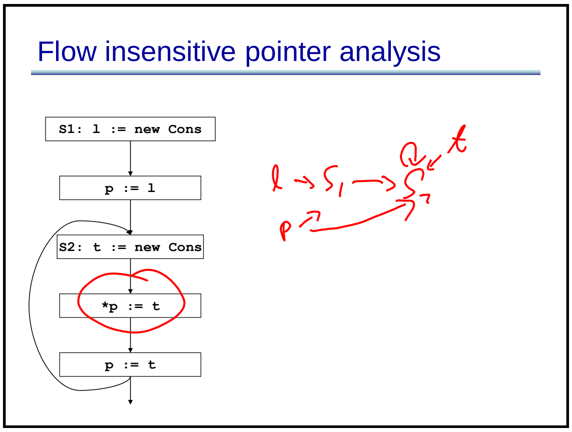

Flow insensitive pointer analysis

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

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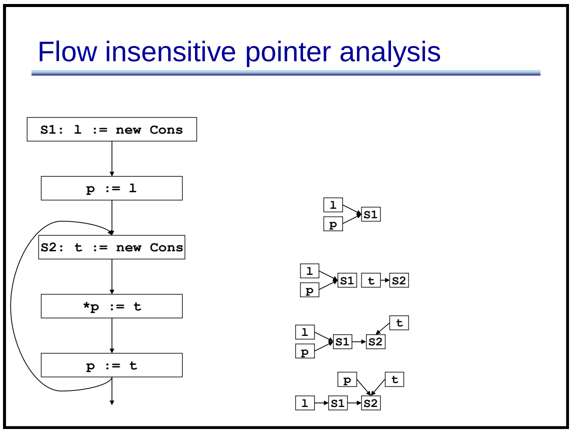

Flow insensitive pointer analysis

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

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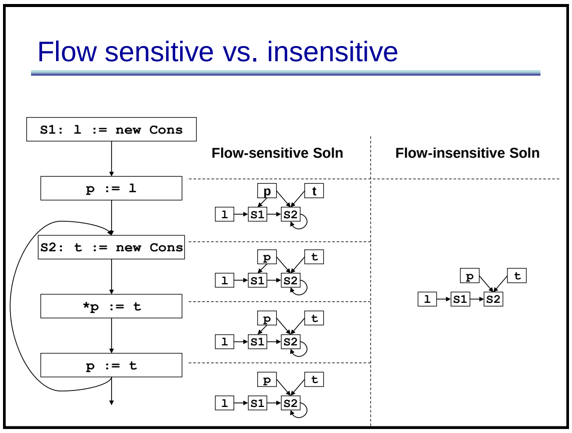

Flow sensitive vs. insensitive

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

Flow-sensitive Soln

Flow-insensitive Soln

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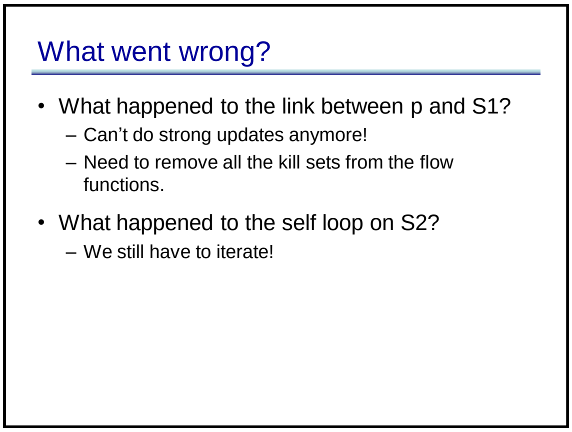

What went wrong?

- 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!

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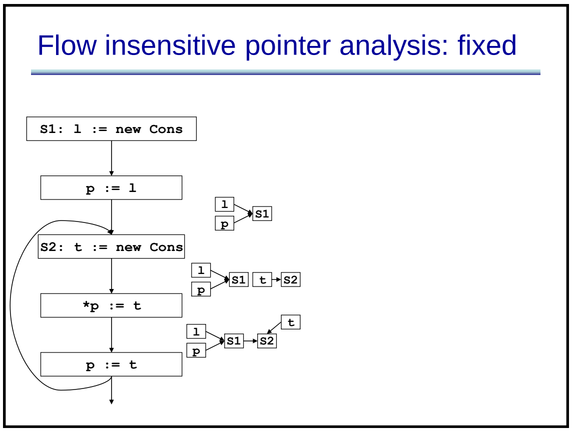

Flow insensitive pointer analysis: fixed

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

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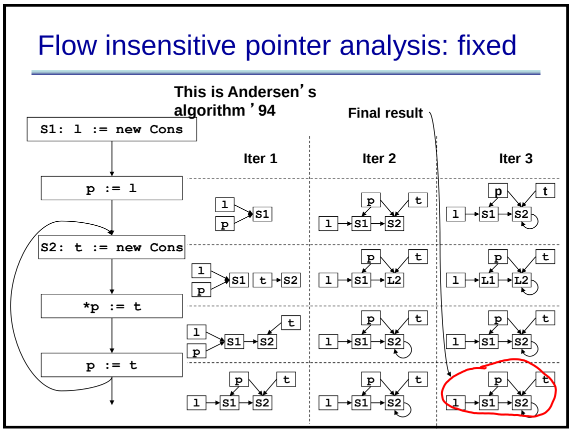

Flow insensitive pointer analysis: fixed

This is Andersen's algorithm '94

Final result

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

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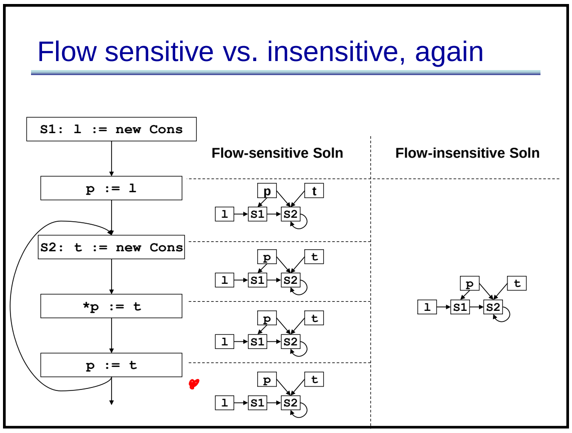

Flow sensitive vs. insensitive, again

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

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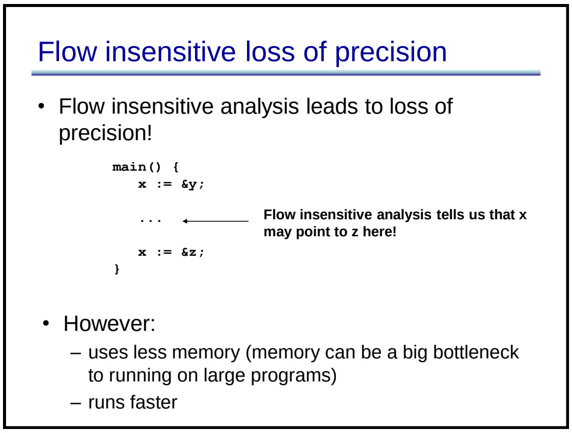

Flow insensitive loss of precision

- 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

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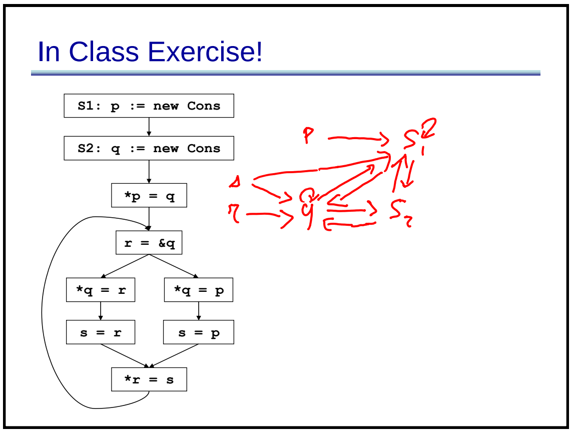

In Class Exercise!

```
S1: p := new Cons
S2: q := new Cons
*p = q
r = &q
*q = r
*q = p
s = r
s = p
*r = s
```

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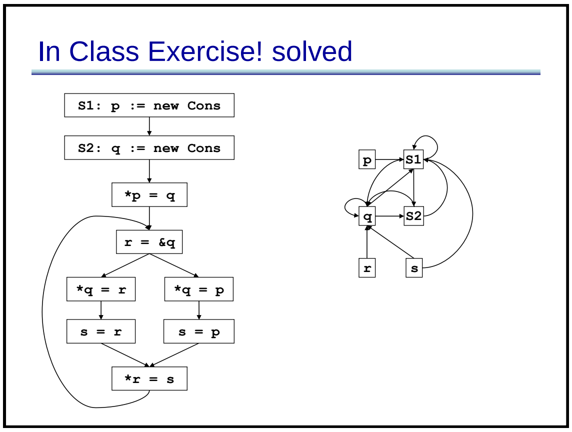

In Class Exercise! solved

```
S1: p := new Cons
S2: q := new Cons
*p = q
r = &q
*q = r
*q = p
s = r
s = p
*r = s
```

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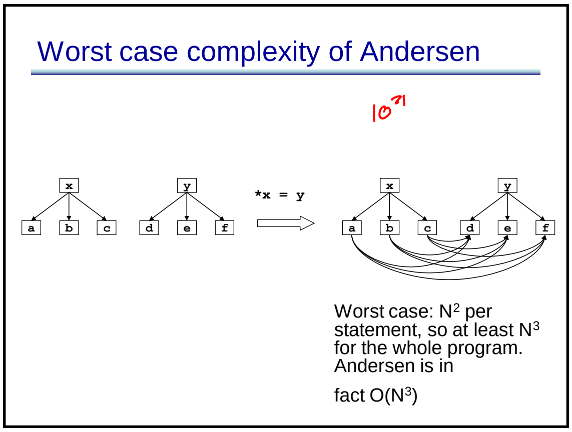

Worst case complexity of Andersen

10^{21}

*x = y

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

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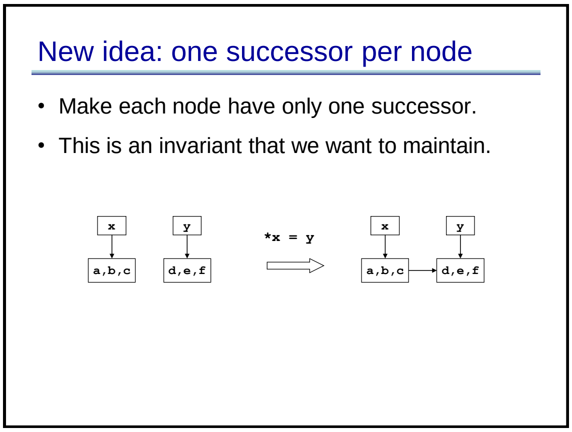

New idea: one successor per node

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

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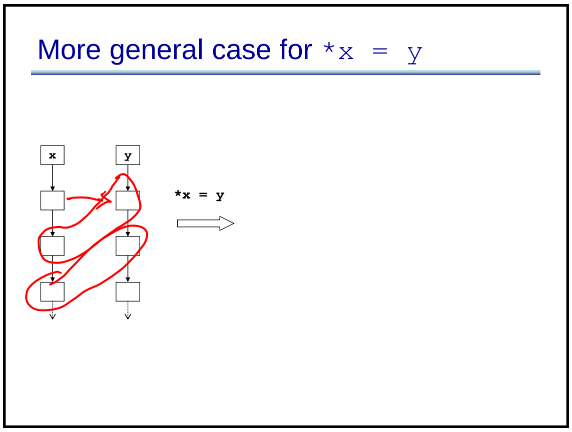

More general case for `*x = y`

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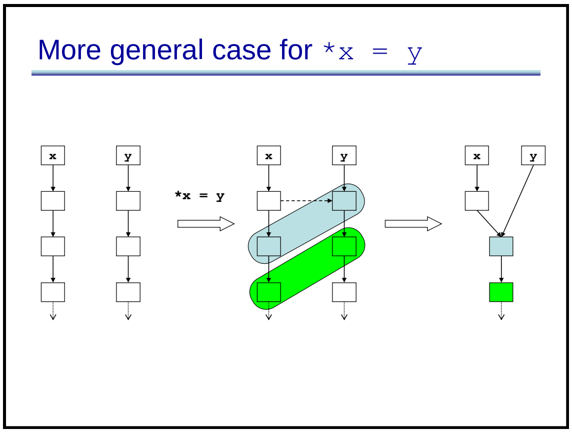
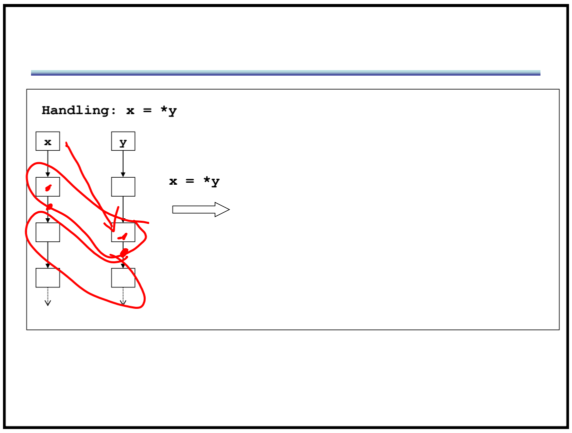


More general case for `*x = y`

40



Handling: x = *y

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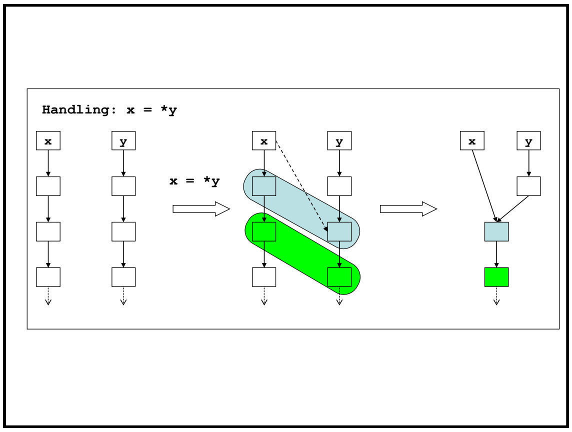

Handling: x = *y

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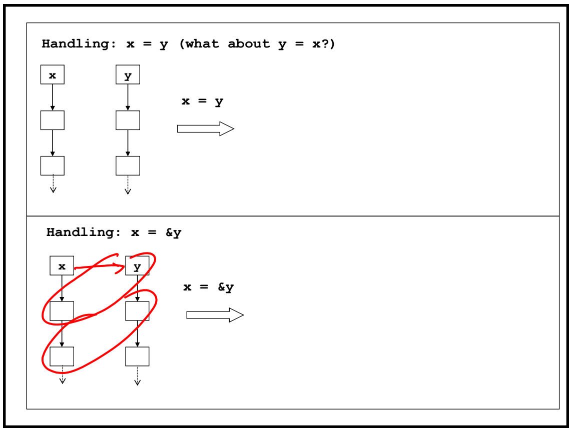

Handling: x = y (what about y = x?)

Handling: x = &y

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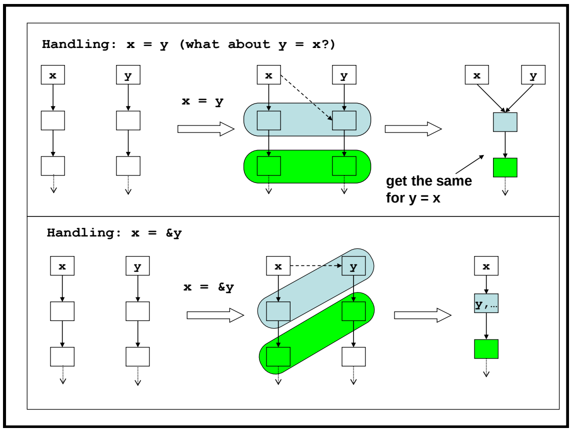

Handling: x = y (what about y = x?)

Handling: x = &y

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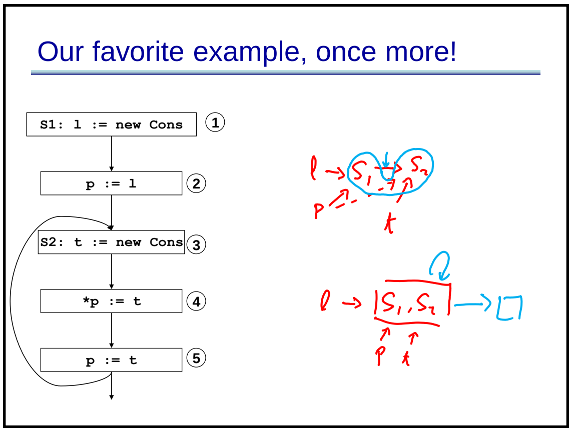

Our favorite example, once more!

```
S1: l := new Cons  ①
    p := l         ②
S2: t := new Cons  ③
    *p := t        ④
    p := t         ⑤
```

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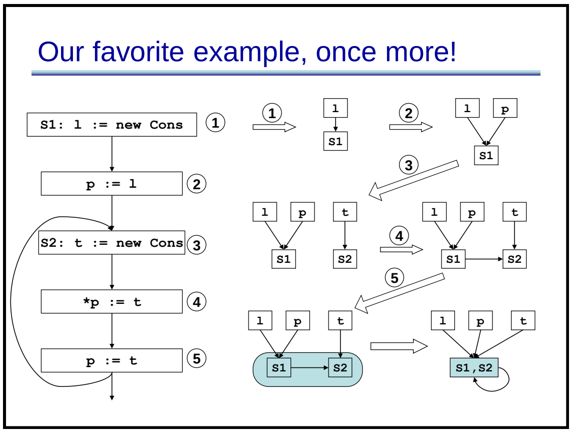

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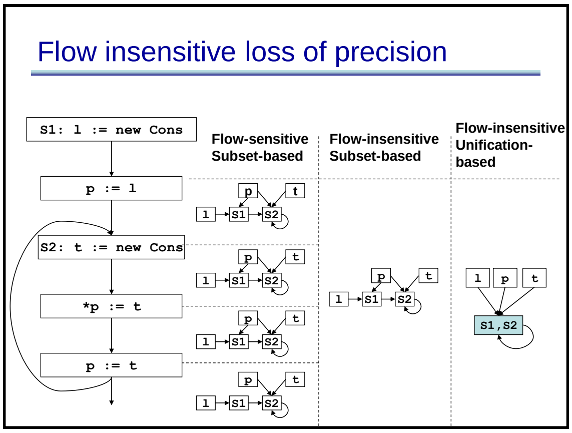

Flow insensitive loss of precision

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

Flow-sensitive Subset-based

Flow-insensitive Subset-based

Flow-insensitive Unification-based

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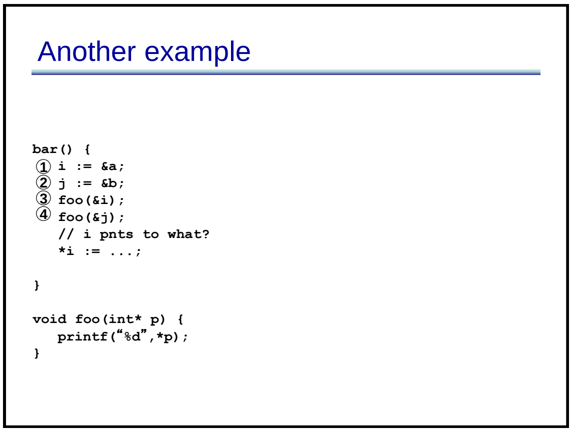

Another example

```
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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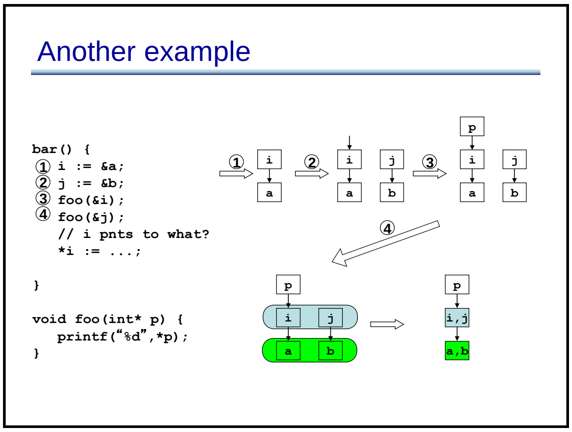

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④ foo(&j);
   // i pnts to what?
   *i := ...;

}

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!

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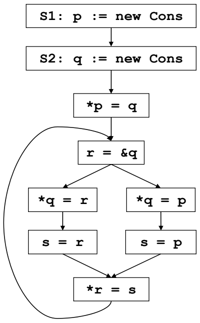
In Class Exercise!



S1: p := new Cons

S2: q := new Cons

*p = q

r = &q

*q = r

*q = p

s = r

s = p

*r = s

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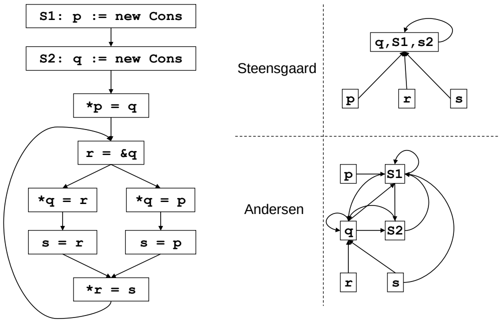
In Class Exercise! solved



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*q = r

*q = p

s = r

s = p

*r = s

Steensgaard

Andersen

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Advanced Pointer Analysis

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

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