# Pointer Analysis
## Lecture 2

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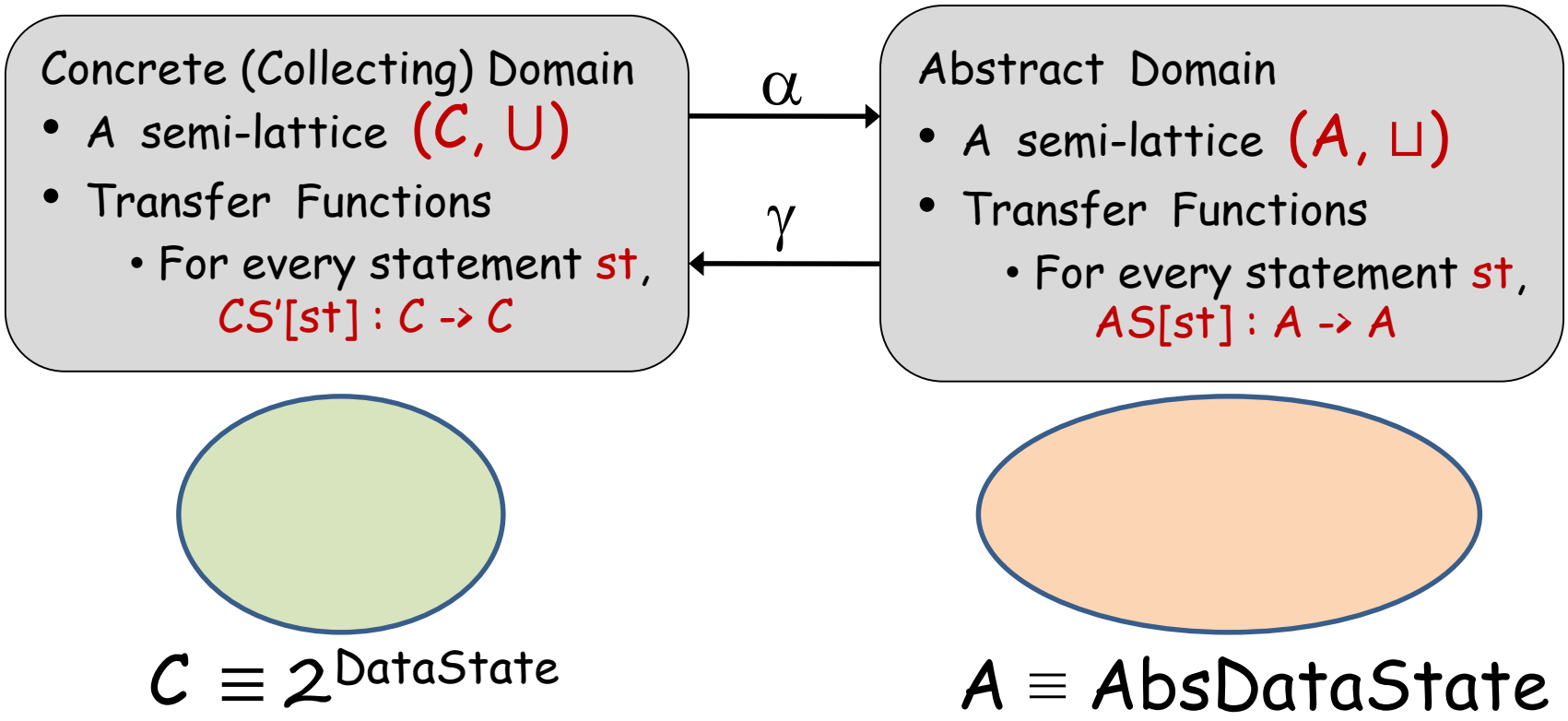
# Correctness and precision of Algorithm A

# Enter: The French Recipe (Abstract Interpretation)



# Points-To Analysis (Abstract Interpretation)

$$\alpha(Y) = \lambda p.\ \{x \mid \text{exists } s \text{ in } Y.\ s(p) == x\}$$

$$\gamma(a) = \{(p \to v, q \to w) \mid v \in a(p),\ w \in a(q)\}$$

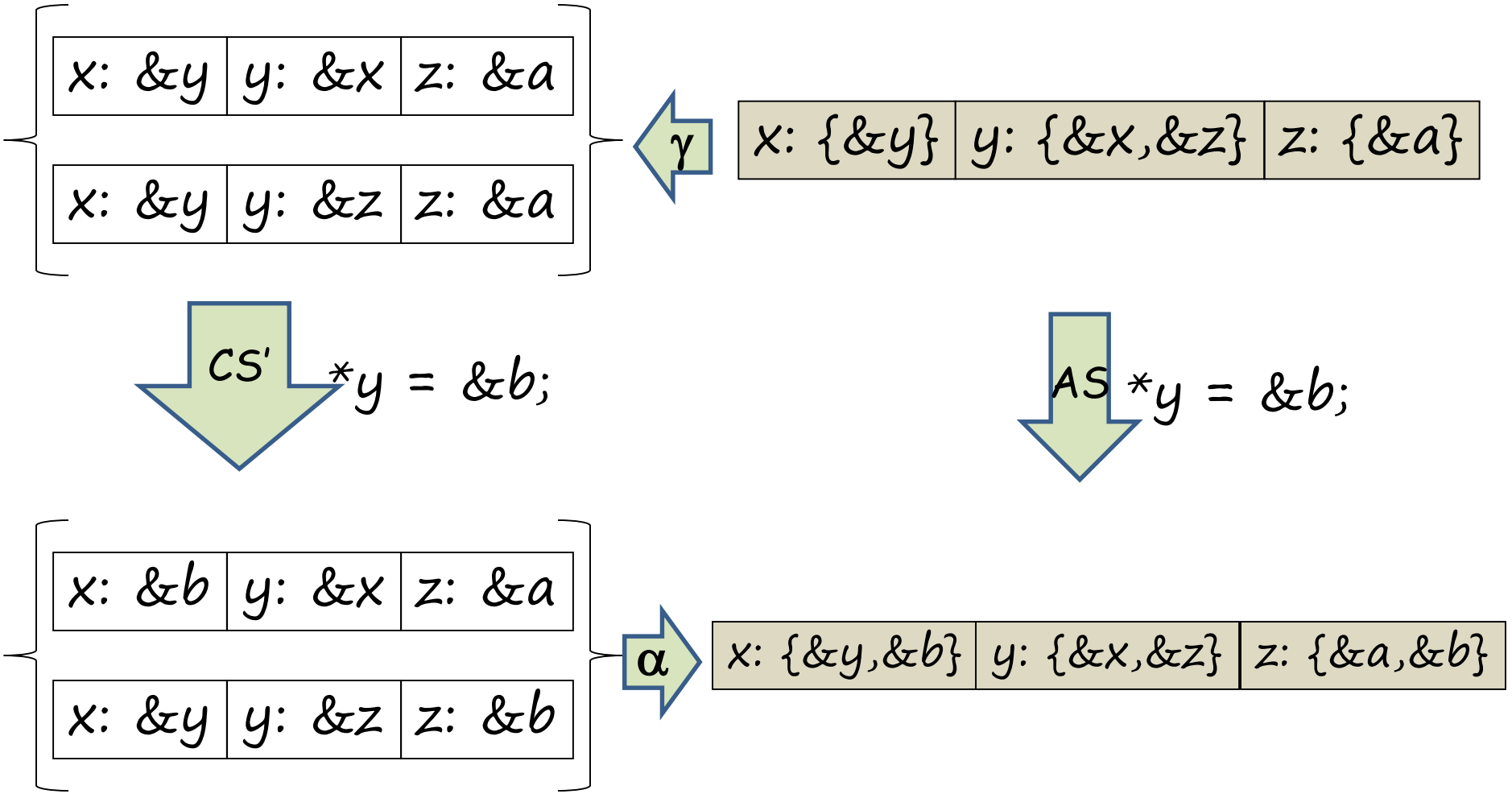
(assuming p, q are the pointer variables in the program)

# Approximating Transformers: Correctness Criterion

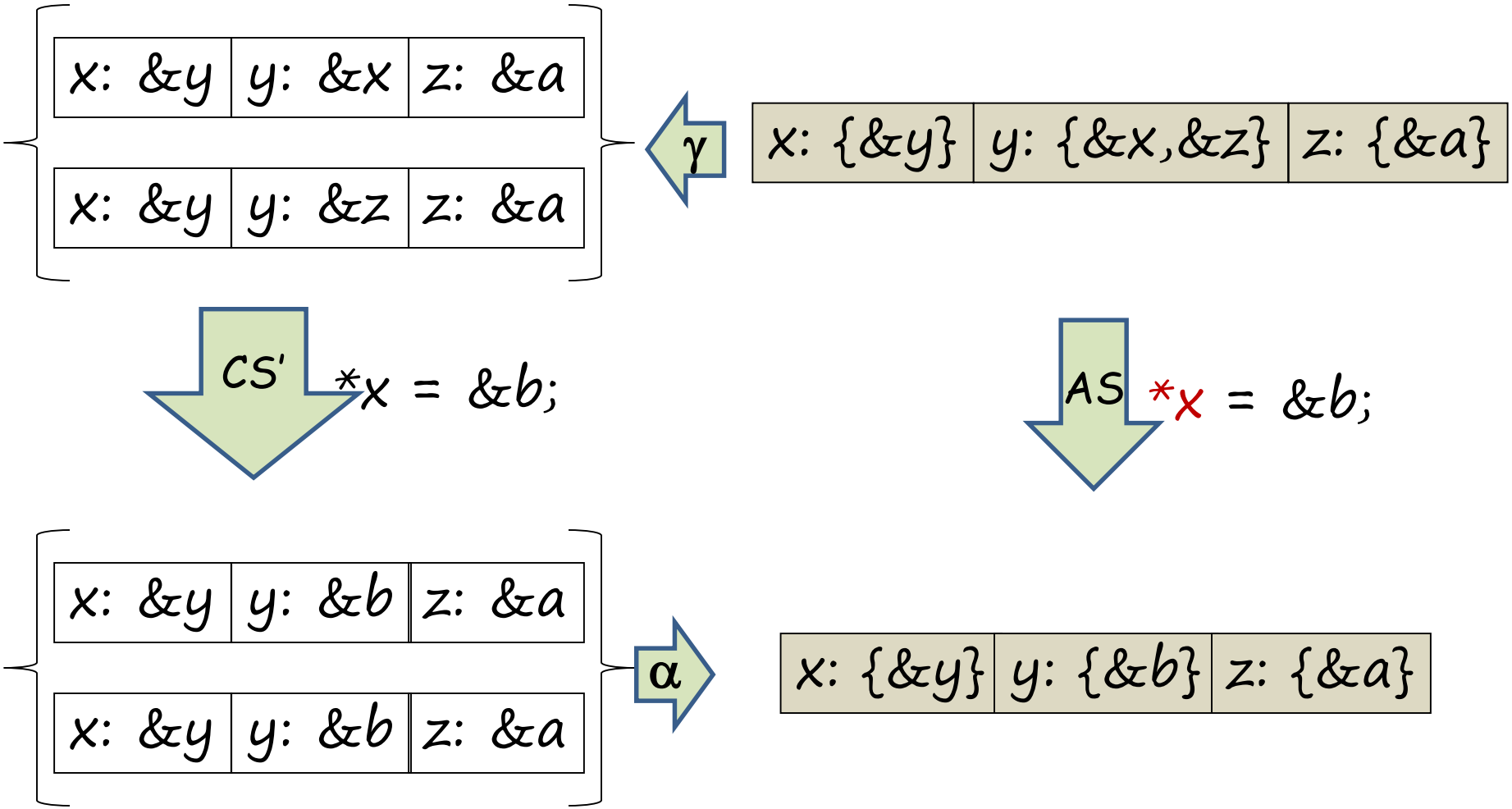
It can be shown that for any statement st, and for any $a1 \in A$

$$AS[st](a1) \geq \alpha(CS[st](\gamma(a1)))$$

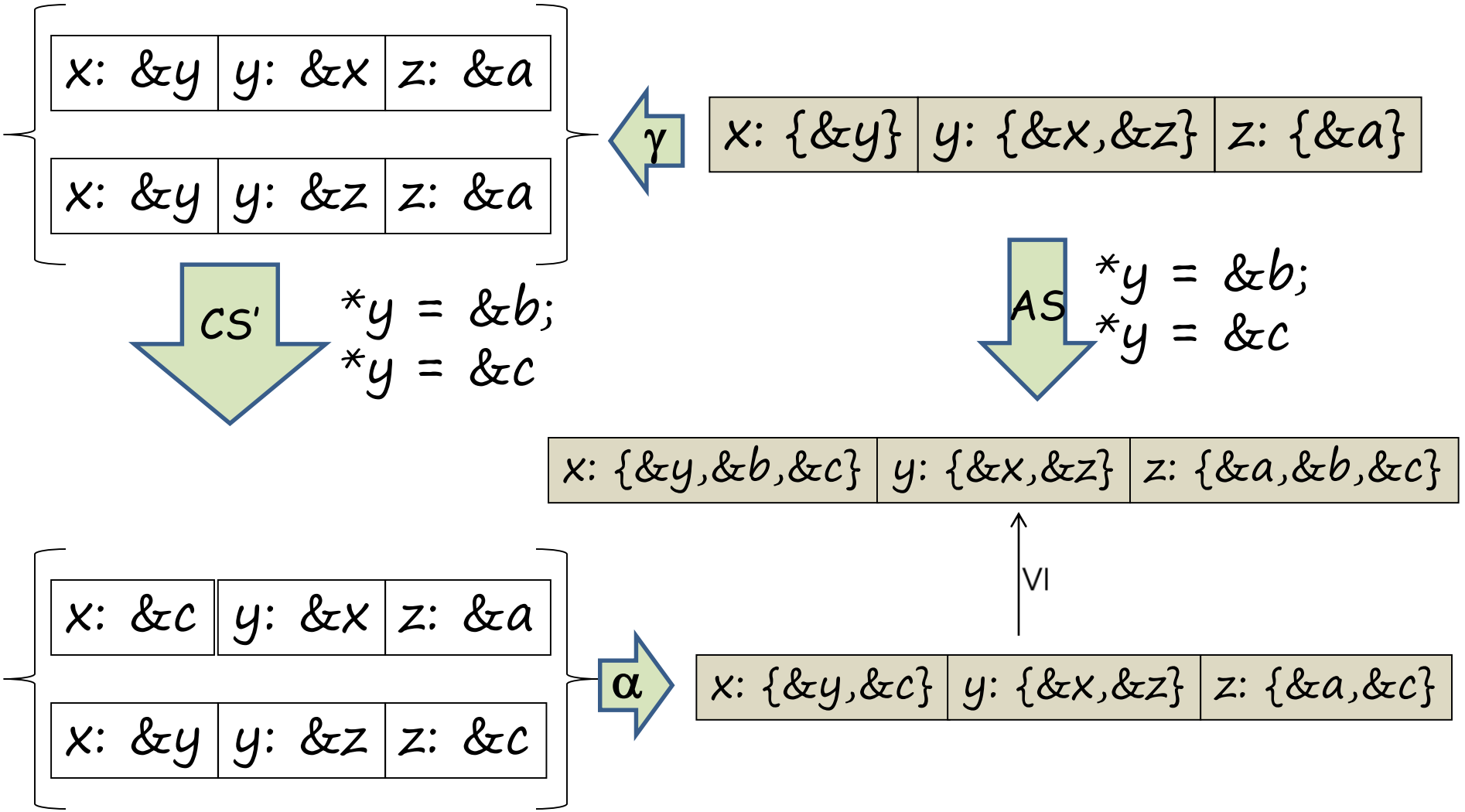
# Transfer function illustration



# Transfer function illustration



# Transfer function illustration



# Is The Precise Solution Computable?

- Claim: The set RS(u) of reachable concrete states (for our language) is precisely computable.
  - (However, Algorithm A is imprecise)

- Note: This is true for any collecting semantics with a finite state space.
- This is true only for restricted language!

# Precise Points-To Analysis: Computational Complexity

- What's the complexity of the least-fixed point computation using the collecting semantics?
- The worst-case complexity of computing reachable states is exponential in the number of variables.
  - Can we do better?
- Theorem: Computing precise may-point-to is PSPACE-hard even if we have only two-level pointers.

# Precise Points-To Analysis: Caveats

- Theorem: Precise may-alias analysis is undecidable in the presence of dynamic memory allocation.
  - Add "x = new/malloc ()" to language
  - State-space becomes infinite

- Digression: Integer variables + conditional-branching involving integer variables also makes any precise analysis undecidable.

# Dynamic Memory Allocation

- s: x = new () / malloc ()
- Assume, for now, that allocated object stores one pointer
  - s: x = malloc ( sizeof(void*) )

- Introduce a pseudo-variable $V_s$ to represent objects allocated at statement s, and use previous algorithm
  - treat s as if it were "x = &$V_s$"
  - also track possible values of $V_s$
  - allocation-site based approach

# α in the presence of pseudo variables

$\alpha(Y) = \lambda p.\ \{x \mid$ exist s in Y such that $s(y) = z$ such that:

(p is a normal variable and y is p) OR

(p is $V_r$ and y is an address allocated at site r )

AND

(x is a normal variable and x is z) OR

(x is $V_t$ and z is an address allocated at site t ) $\}$

(For simplicity, assume that the set of all concrete addresses is partitioned upfront among all allocation sites in the program)

# $\gamma$ in the presence of pseudo variables

$\gamma(a) = \{s \mid \forall$ normal variables $p$:

$s(p) = x \wedge x$ is a normal variable $\wedge\ x \in a(p)$, OR

$s(p) = y \wedge y$ is an address allocated at

site $t \wedge V_t \in a(p)$, AND

$\forall$ pseudo-variables $V_r$: $\forall$ addresses $y$ allocated at $V_r$:

$s(y) = x \wedge x$ is a normal variable $\wedge\ x \in a(V_r)$, OR

$s(y) = z \wedge z$ is an address allocated at

site $t \wedge V_t \in a(V_r)\}$

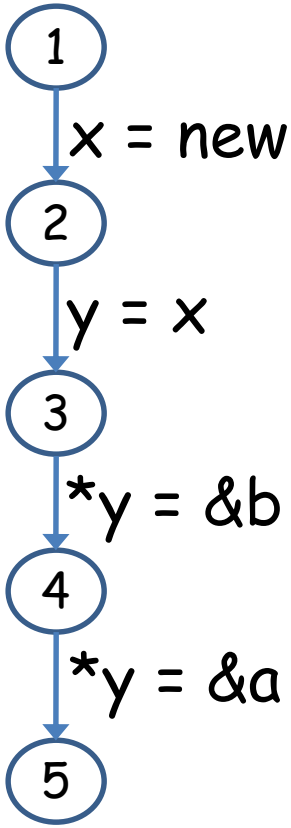
# Dynamic Memory Allocation: Example

```
x = new;

y = x;

*y = &b;

*y = &a;
```



# Example illustrating need for weak updates on summary objects

- Key aspect: $V_s$ represents a set of objects (locations), not a single object
  - referred to as a summary object (node)
  - if x->{$V_s$}, to be safe "*x = .." still needs weak update!

- If example fragment in previous slide is placed in a loop, then solution at vertex 4 would be wrong unless weak-update is adopted.

# Handling structures/objects

- Concrete state maps each variable to a variable or address of an object or null, and for each object o and each field f of o, maps (o,f) to the address of some other object (or to null)
- Let PseudoVar be the set of pseudo-variables, let Var' = Var U PseudoVar U {null}
- Each AbsDataState maps each variable to a subset of Var', and also maps ($V_s$ ,f) to a subset of Var' for each $V_s$ and for each field f in struct allocated at site s

# Handling structures/objects

- Transfer function of an update statement "v->f = w" should perform weak update if v points to a singleton and that element is a pseudo-variable.
  - That is, if v -> $\{V_s\}$ in incoming abstract state, then add points-to set of w to points-to set of $(V_s, f)$

# Inter-procedural analysis

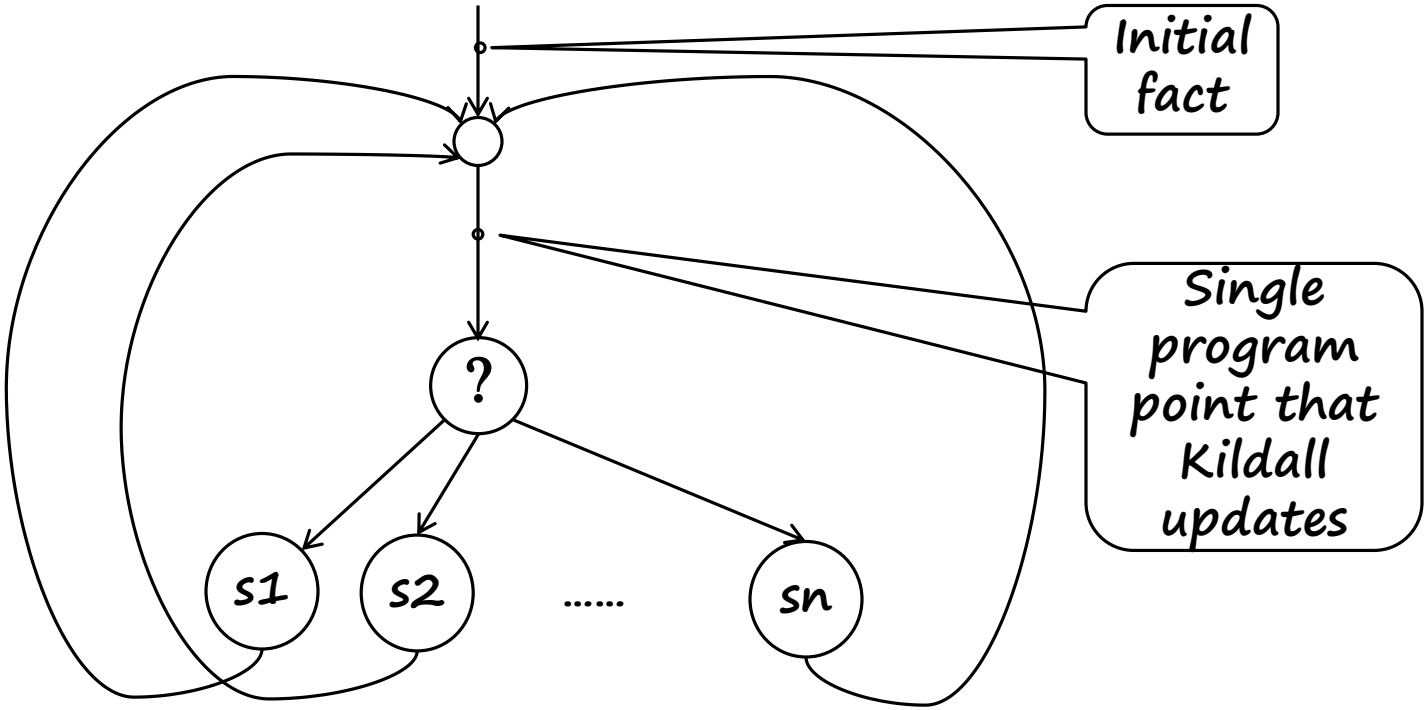
- Context-sensitivity can be achieved using standard techniques
- Indirect (virtual) function call sites need to be resolved to candidate functions using points-to analysis. And points-to analysis needs calls to be resolved! Therefore, the two have to happen hand in hand.

# Andersen's Analysis

- A flow-insensitive analysis
  - computes a single points-to solution, which over-approximates points-to solutions at all program points
  - ignores control-flow – treats program as a set of statements
  - equivalent to collapsing the given program to have a single program point, and then applying Algorithm A on it.

# Andersen's Analysis

If program has statements s1, s2, …, sn, then create collapsed CFG as follows:




After algorithm terminates, final solution at the single program point over-approximates result computed by flow-sensitive analysis at any point

# Example: Andersen's Analysis

```
x = &a;

*x = &w;

y = x;

x = &b;

*x = &t;

z = x;
```

# Notes about Andersen's Analysis

- Strong updates never happen in Andersen's analysis!
  - If x->{y} and y->{w} before we process statement "*x = &z", then even if transfer function returns y->{z}, due to subsequent join, y will point to {w,z} after this step.
- Flow-insensitive style can be adopted for any analysis, not just for pointer analysis

# Why Flow-Insensitive Analysis?

- Reduced space requirements
  - a single points-to solution
- Reduced time complexity
  - no copying of points-to facts
    - individual updates more efficient
  - a cubic-time algorithm
- Scales to millions of lines of code
  - most popular points-to analysis

# Andersen's Analysis: An alternative formulation

1. Introduce a constraint variable $PT_x$ for each program variable x
2. Create a constraint from each assignment statement, as follows:

   x = y: $PT_x \subseteq PT_y$

   *x = y: $PT_v \subseteq PT_y$, forall variables v in $PT_x$

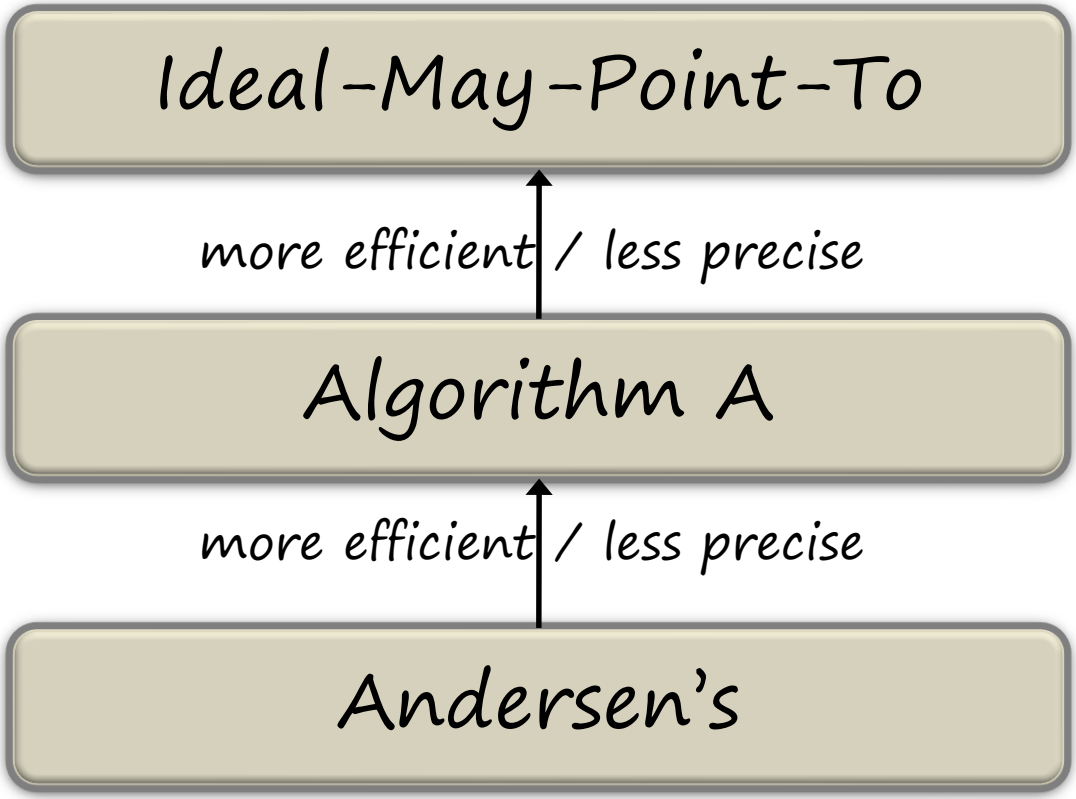
   x = &y: $PT_x \subseteq \{y\}$

   x = *y: $PT_x \subseteq PT_v$, forall variables v in $PT_y$

3. Find least solution to set of all constraints that were generated above. (A solution is a mapping from constraint variables to sets of program variables.) Emit this least solution as the final solution.
   - Note: Solution s1 dominates Solution s2 if for each program variable v, $s2(PT_v) \subseteq s1(PT_v)$

Note: This approach computes exact same result as previous approach that collapses program and then uses Algorithm A.

# May-Point-To Analyses



# Andersen's Analysis: Further Optimizations and Extensions

- Fahndrich et al., Partial online cycle elimination in inclusion constraint graphs, PLDI 1998.
- Rountev and Chandra, Offline variable substitution for scaling points-to analysis, 2000.
- Heintze and Tardieu, Ultra-fast aliasing analysis using CLA: a million lines of C code in a second, PLDI 2001.
- M. Hind, Pointer analysis: Haven't we solved this problem yet?, PASTE 2001.
- Hardekopf and Lin, The ant and the grasshopper: fast and accurate pointer analysis for millions of lines of code, PLDI 2007.
- Hardekopf and Lin, Exploiting pointer and location equivalence to optimize pointer analysis, SAS 2007.
- Hardekopf and Lin, Semi-sparse flow-sensitive pointer analysis, POPL 2009.

# Context-Sensitivity Etc.

- Liang & Harrold, Efficient computation of parameterized pointer information for interprocedural analyses. SAS 2001.
- Lattner et al., Making context-sensitive points-to analysis with heap cloning practical for the real world, PLDI 2007.
- Zhu & Calman, Symbolic pointer analysis revisited. PLDI 2004.
- Whaley & Lam, Cloning-based context-sensitive pointer alias analysis using BDD, PLDI 2004.
- Rountev et al. Points-to analysis for Java using annotated constraints. OOPSLA 2001.
- Milanova et al. Parameterized object sensitivity for points-to and side-effect analyses for Java. ISSTA 2002.

# Applications

- Compiler optimizations
- Verification & Bug Finding
  - use in preliminary phases
  - use in verification itself