# CS738: Advanced Compiler Optimizations

# Pointer Analysis

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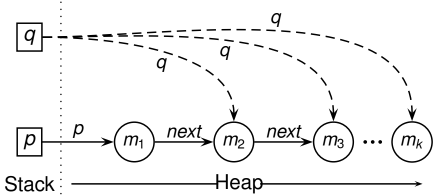
# Why Pointer Analysis?

- Static analysis of pointers & references

| | |
|---|---|
| $S1.$ | $\ldots$ |
| $S2.$ | $q = p;$ |
| $S3.$ | *do* $\{$ |
| $S4.$ | $\quad q = q.next;$ |
| $S5.$ | $\}$ *while* $(\ldots)$ |
| $S6.$ | $\mathbf{p.data} = \mathbf{r1};$ |
| $S7.$ | $q.data = q.data + r2;$ |
| $S8.$ | $\mathbf{p.data} = \mathbf{r1};$ |
| $S9.$ | $r3 = p.data + r2;$ |
| $S10.$ | $\ldots$ |




Superimposition of memory graphs after *do-while* loop

*p* and *q* are definitely not aliases statement S6 onwards.
Statement S8 **is** redundant.

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- Static analysis of pointers & references

```
S1.   ...
S2.   q = p;
S3.   while (...) {
S4.       q = q.next;
S5.   }
S6.   p.data = r1;
S7.   q.data = q.data + r2;
S8.   p.data = r1;
S9.   r3 = p.data + r2;
S10.  ...
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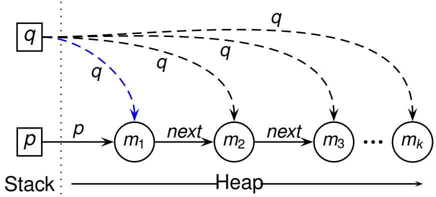


Superimposition of memory graphs after *while* loop

*p* and *q* may be aliases statement S6 onwards.
Statement S8 **is not** redundant.

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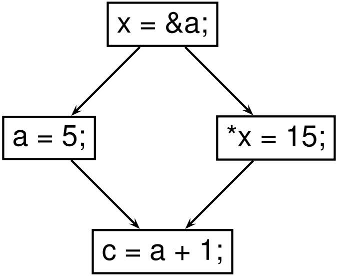


Reaching definitions analysis

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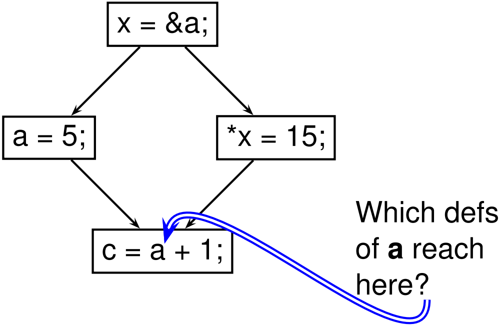


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    - Safe approximation of flow-sensitive point-specific information for any point, for any given execution order
  - A statement can not "override" information computed by another statement
    - *NO* Kill component in the flow function
    - If statement *s* kills some data flow information, there is an alternate path that excludes *s*

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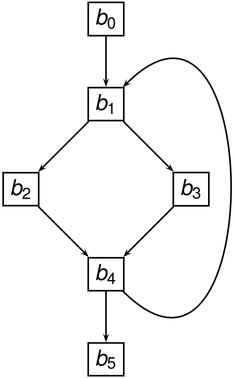
  - A very simple form of pointer analysis
- Side effects analysis
  - Does a procedure modify address / global variable / reference parameter / . . . ?

# Realizing Flow Insensitivity



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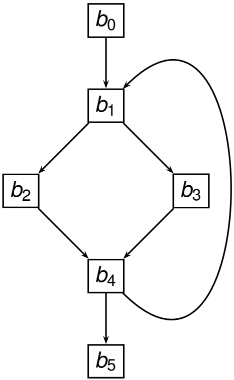


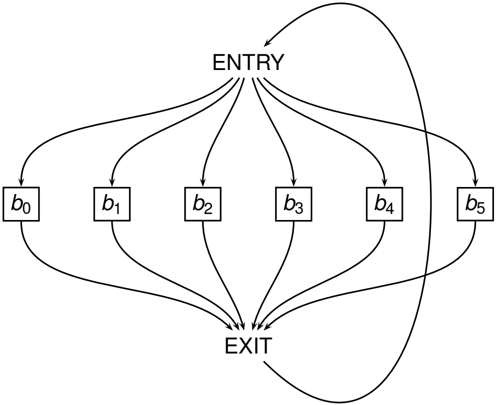

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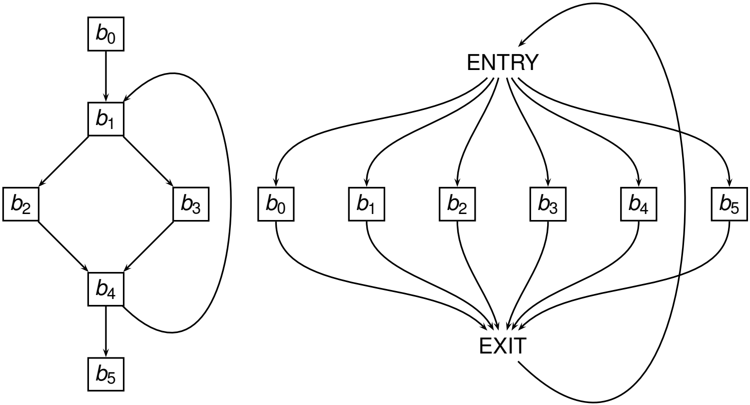


*Allows arbitrary compositions of flow functions in any order* ⇒ *Flow insensitivity*

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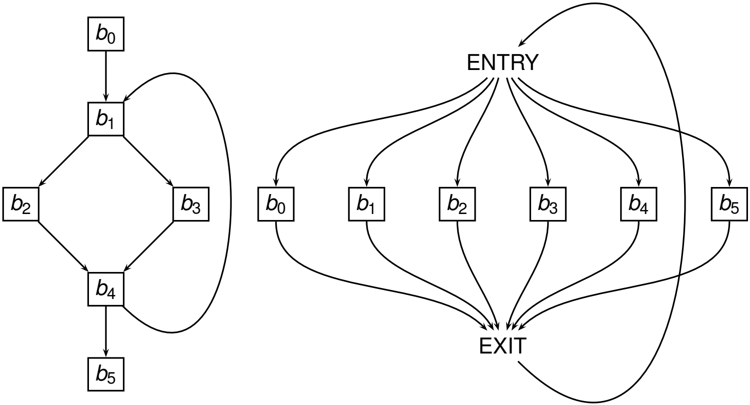


*In practice, dependent constraints are collected in a global repository in one pass and solved independently*

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| Transitive? | No | Must alias: Yes,<br>May alias: No |

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- Subset based analysis

| Program | Constraints | Points-to Graph |
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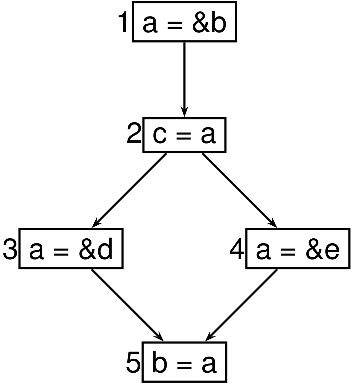


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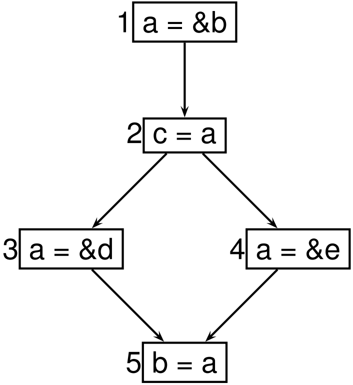


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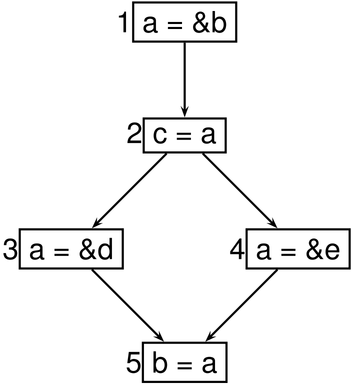


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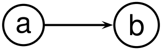

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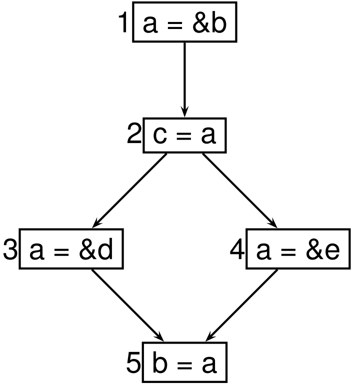


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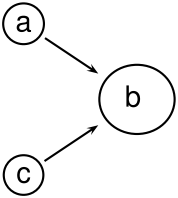

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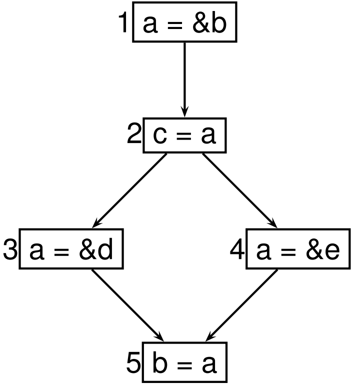


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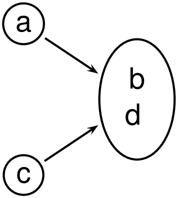

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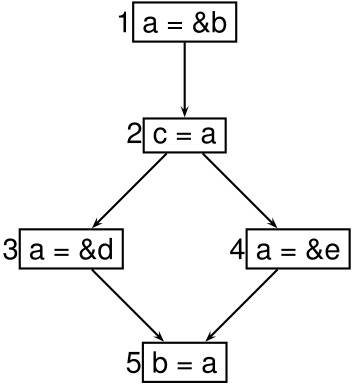


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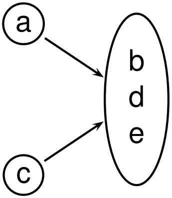

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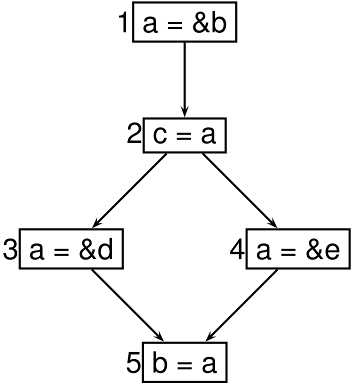


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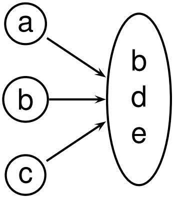

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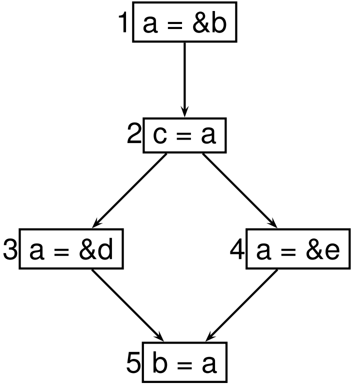


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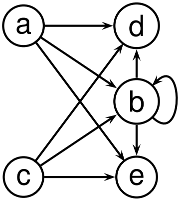

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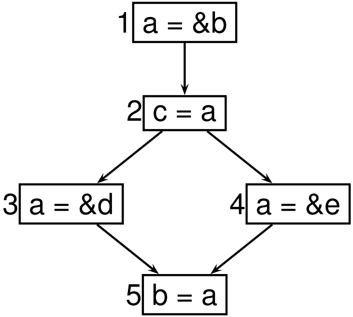


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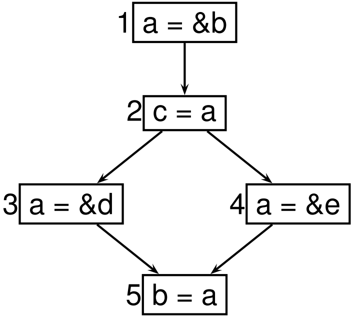


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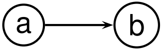

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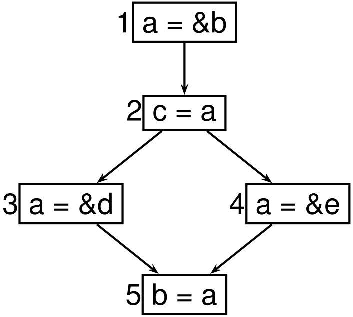


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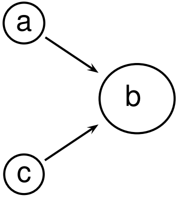

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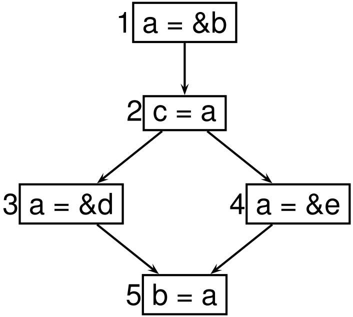


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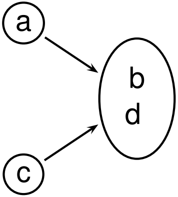

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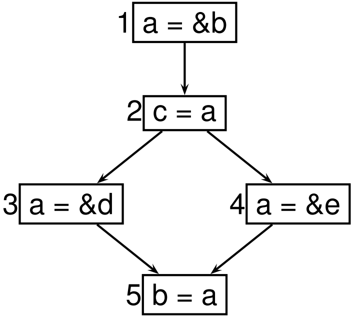


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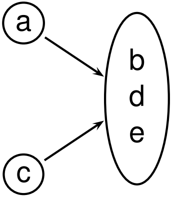

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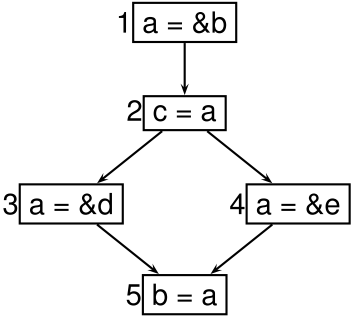


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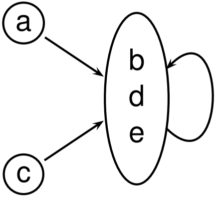

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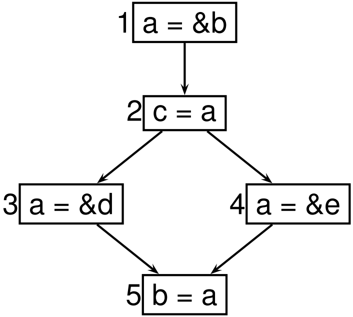


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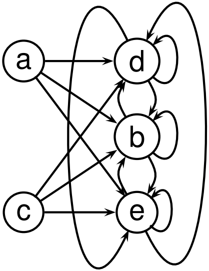
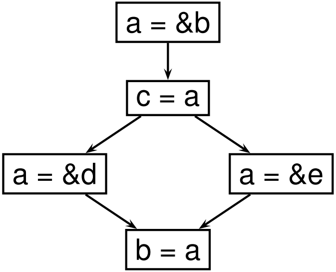
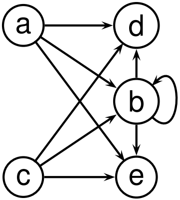
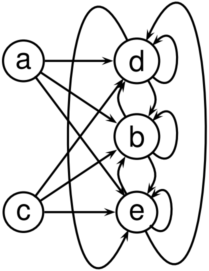


# Comparing Anderson's and Steensgaard's Analyses

| Program | Subset based Points-to Graph | Equality based Points-to Graph |
| --- | --- | --- |
|  |  |  |

# Comparing Anderson's and Steensgaard's Analyses

```
a = &b;
```

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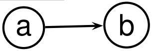

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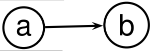


```
b = &c;
```

# Comparing Anderson's and Steensgaard's Analyses

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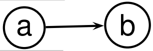


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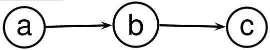

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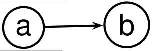


```
b = &c;
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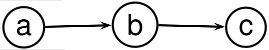
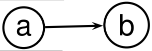



```
d = &e;
```

# Comparing Anderson's and Steensgaard's Analyses

a = &b;

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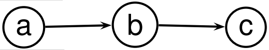


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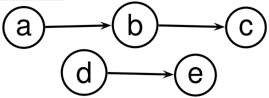

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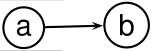


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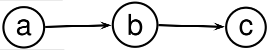


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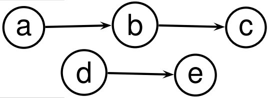


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# Comparing Anderson's and Steensgaard's Analyses

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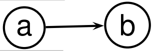
a = &b;
```

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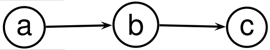


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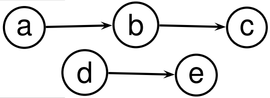


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```
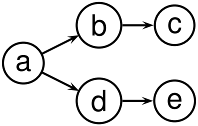
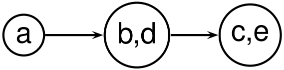

Subset based



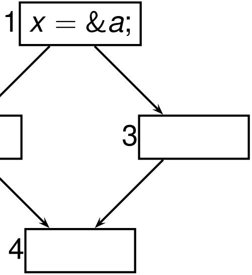

Equality based



# Pointer Indirection Constraints

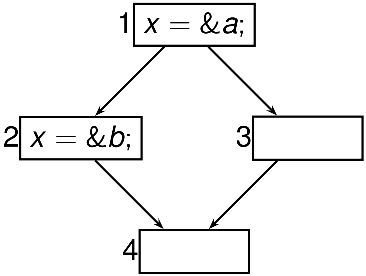
| Stmt | Subset based | Equality based |
|---|---|---|
| a = *b | $P_a \supseteq P_c, \forall c \in P_b$ | MERGE($P_a, P_c$), $\forall c \in P_b$ |
| *a = b | $P_c \supseteq P_b, \forall c \in P_a$ | MERGE($P_b, P_c$), $\forall c \in P_a$ |

# Must Points-to Analysis



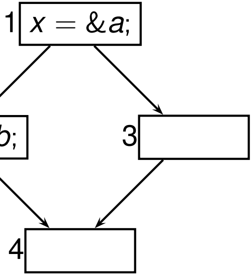

- *x definitely* points-to *a* at various points in the program
- $x \xrightarrow{D} a$

# May Points-to Analysis




- At OUT of 2, *x* definitely points-to *b*
- At OUT of 3, *x* definitely points-to *a*
- At IN of 4, *x* *possibly* points-to *a* (or *b*)
  - $x \xrightarrow{P} a, x \xrightarrow{P} b$

# May Points-to Analysis

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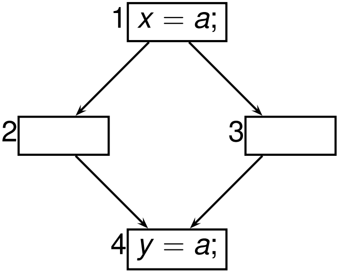
  - $x \xrightarrow{P} \{a, b\}$

# Must Alias Analysis




- $x$ and $a$ always refer to same memory location
- $x \stackrel{D}{\equiv} a$

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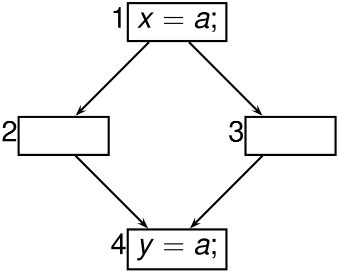
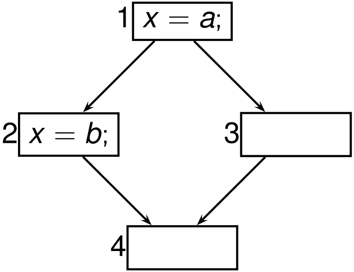



- $x$ and $a$ always refer to same memory location
- $x \stackrel{D}{\equiv} a$
- $x, y$ and $a$ refer to same location at OUT of 4.
- $x \stackrel{D}{\equiv} y \stackrel{D}{\equiv} a$

# May Alias Analysis




- At OUT of 2, $x$ and $b$ are must aliases
- At OUT of 3, $x$ and $a$ are must aliases
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  - $x \overset{P}{\equiv} a$, $x \overset{P}{\equiv} b$

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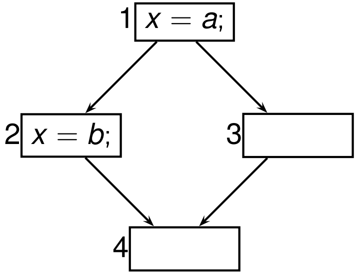


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  - $(x, a), (x, b)$

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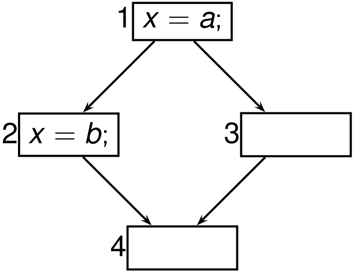


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- If we say: $(x, a, b)$, Is it *Precise?*

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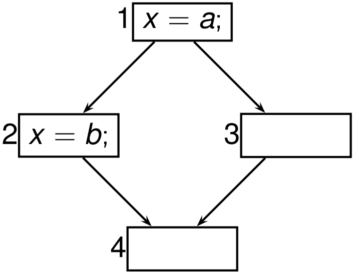


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- If we say: $(x, a, b)$, Is it *Precise? Safe?*

# Must Pointer Analysis

- Makes sense only for Flow Sensitive analysis

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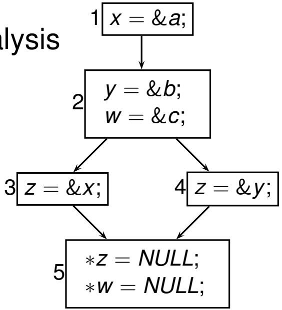

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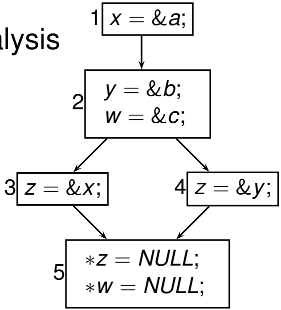


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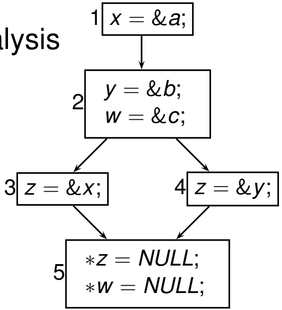


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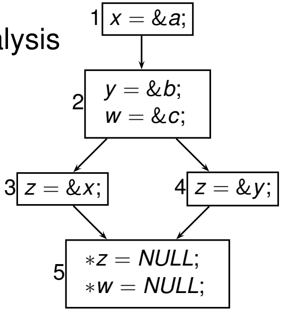


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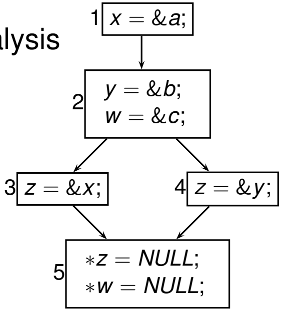


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# Flow Functions for Points-to Analysis

- Basic statements for pointer manipulation

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  - x = NULL $\Rightarrow$ treat NULL as a special variable
- $OUT = IN - kill \cup gen$
  - with a twist!

# Flow Function: x = y

$$\begin{aligned} \text{May}_{gen} &= \{x \rightarrow p \mid y \rightarrow p \in \text{May}_{IN}\} \\ \text{May}_{kill} &= \bigcup_{p \in Vars} \{x \rightarrow p\} \end{aligned}$$

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\end{aligned}
$$

$$
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$$\text{May}_{gen} = \{p \to p' \mid x \to p \in \text{May}_{IN}, y \to p' \in \text{May}_{IN}\}$$

$$\text{May}_{kill} = \bigcup_{p' \in Vars} \{p \to p' \mid x \to p \in \text{Must}_{IN}\}$$

*Strong update!!*

$$\text{Must}_{gen} = \{p \to p' \mid x \to p \in \text{Must}_{IN}, y \to p' \in \text{Must}_{IN}\}$$

$$\text{Must}_{kill} = \bigcup_{p' \in Vars} \{p \to p' \mid x \to p \in \text{May}_{IN}\}$$

*Weak update!!*

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# Summarizing Flow Functions

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  - $\Rightarrow$ should remove only strong updates
  - $\Rightarrow$ should kill using Must Points-To information
- Must Points-To analysis
  - A points-to pair should be removed if it can be removed along some path
  - $\Rightarrow$ should remove all weak updates
  - $\Rightarrow$ should kill using May Points-To information
- Must Points-To $\subseteq$ May Points-To

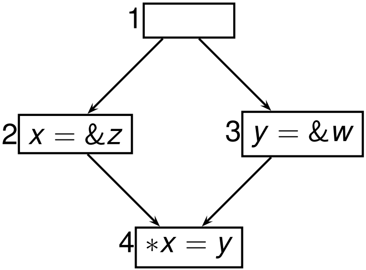
# Safe Approximations for May and Must Points-to

- A pointer variable

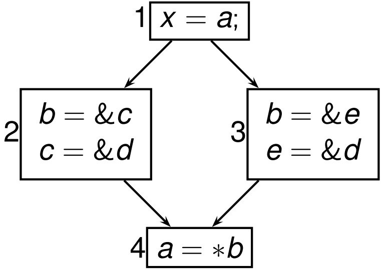
| | **May** | **Must** |
|---|---|---|
| **Points-to** | points to every possible location | points to nothing |
| **Alias** | aliased to every other pointer variable | only to itself |

# Non-Distributivity of Points-to Analysis

**May Information**

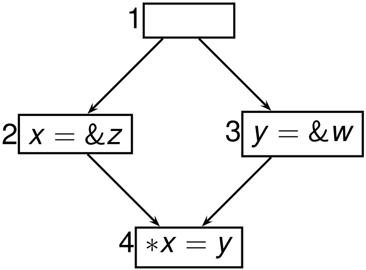



**Must Information**



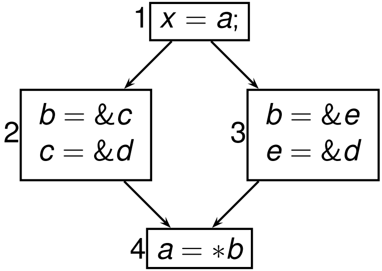
# Non-Distributivity of Points-to Analysis

**May Information**



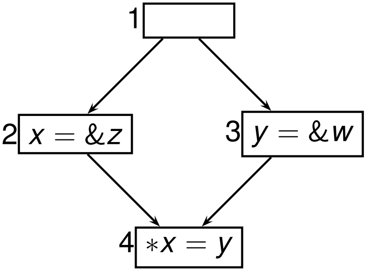

$z \rightarrow w$ is spurious

**Must Information**



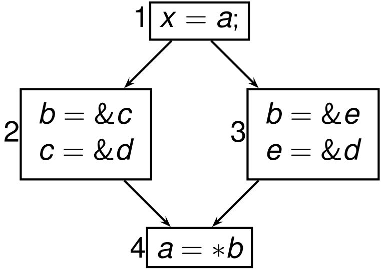
# Non-Distributivity of Points-to Analysis

**May Information**




$z \rightarrow w$ is spurious

**Must Information**




$a \rightarrow d$ is missing