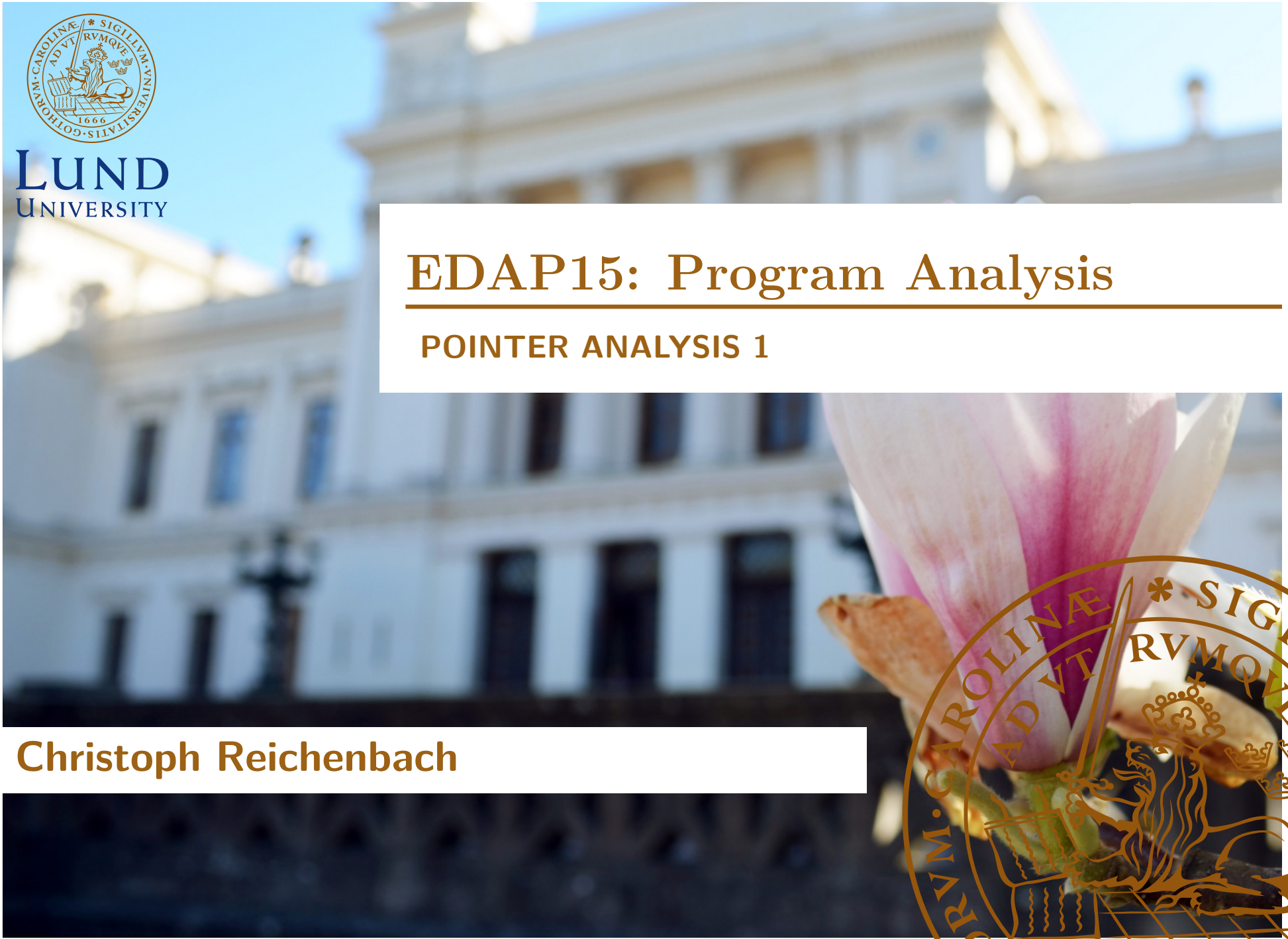


LUND UNIVERSITY

EDAP15: Program Analysis

POINTER ANALYSIS 1

Christoph Reichenbach

Welcome back!

- Lab 2 will be up later today
  - Individual exercise (no group)
- Final homework assignment (lab 4) will require *docker* or *podman*
  - More details soon.

Questions?

Variables and Memory Binding

Teal-2

```
var x := 1;

fun f(y) = {
  var z := y;
  return x + z;
}
```

Java

```
static int x = 1;

static int f(int y) {
  int z = y;
  return x + z;
}
```

- So far: Variables with one of
  - Static memory binding (x)
  - Stack-dynamic memory binding (y, z)
- Key property:
  - Need only track *one* memory binding per **VarDecl**
    - *Static*: Exactly one memory binding per VarDecl
    - *Stack-dynamic*: Zero or more, but only one visible at a time
      Have memory binding iff variable in scope

Heap-Dynamic Memory

- *Heap-Dynamic* memory binding due to:
  - Explicit allocation: **new**, **malloc**
  - Implicit allocation: `[1, 2, 3]` in Teal, Python
- Creates storage locations during execution:
  - Array elements, datastructure fields: also variables!
- Different names can bind to same memory storage location:

Teal

```
var a := [1, 4];
var b := a;
// Different names refer to same memory:
a[1] := 7;
print(b[1]); // prints '7'
// Same name can bind to different memory:
b := [2, 2];
print(b[1]); // prints '2'
```

Teal-2

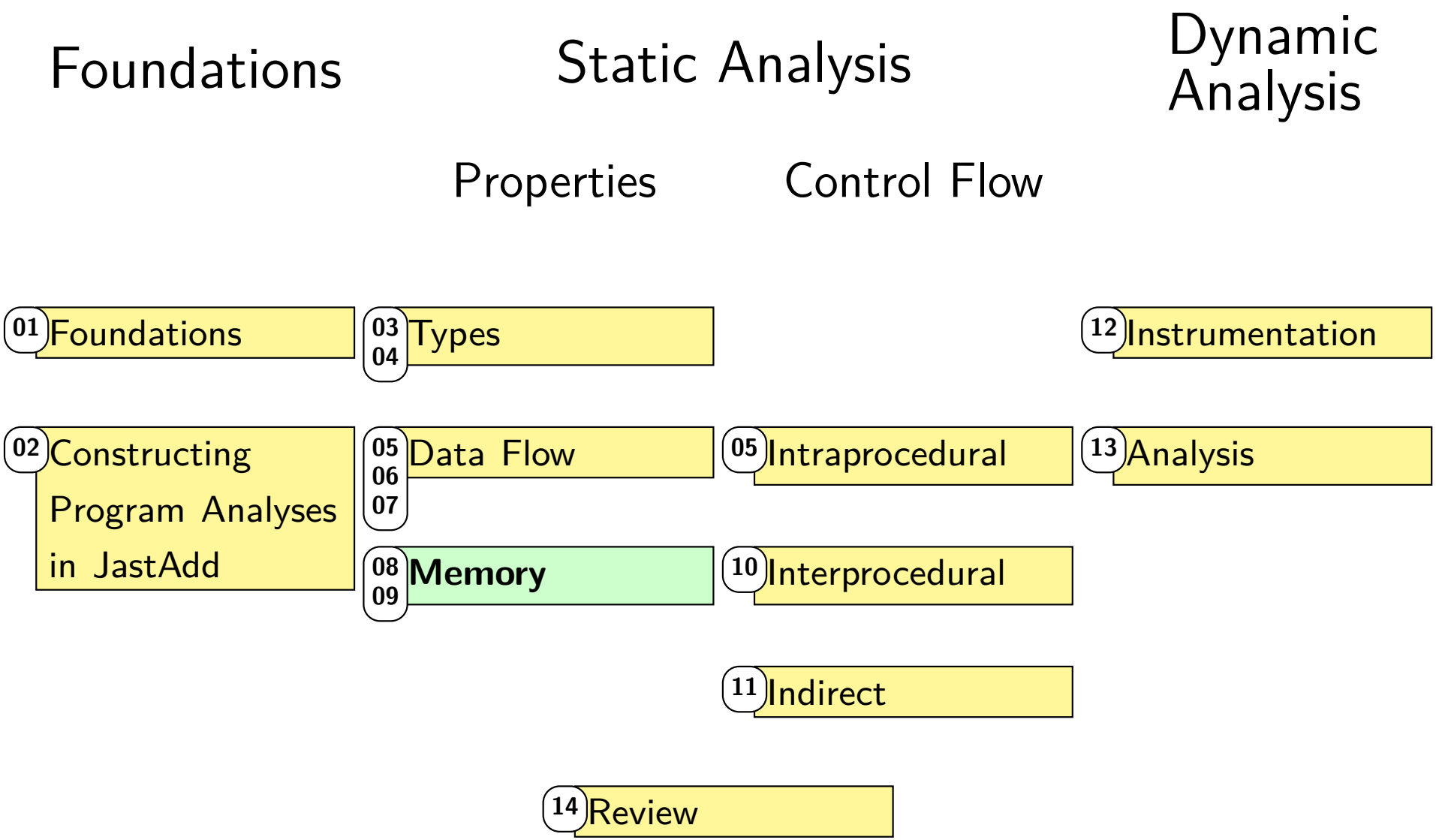
Teal-2

```
type MyType(name: string, value: int);

var x := new MyType("foo", 0);
x.value := 1;
print(x.field);
```

- Teal-2 adds **User-defined types**:
  - Type definition
  - Allocation
  - Assigning to fields
  - Reading from fields

Lecture Overview



Our Memory Modelling Until Now

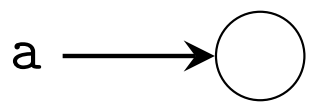
- Our analyses so far have considered:
  - Variables with static memory binding
  - Variables with stack-dynamic memory binding
    - Local variables
    - Parameters

Missing: heap variables!

Example Program

Example

```
a := new();    // ⇐
a.x := null;
b := a;
b.x := new();
a.x.y := 1;
c := new();
c.x := new();
c.x.x := a;
c := a.x;
// A
```



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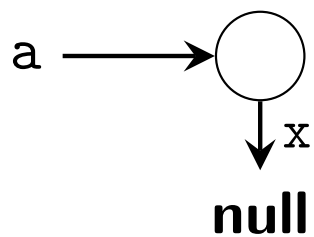

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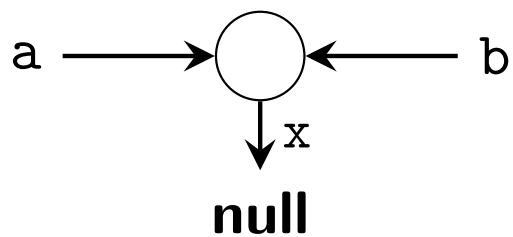

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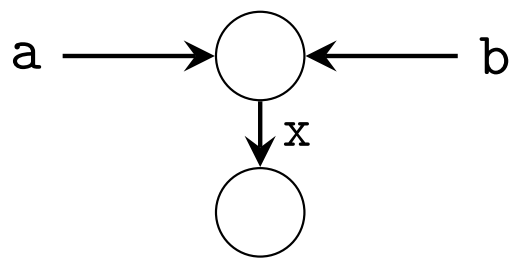

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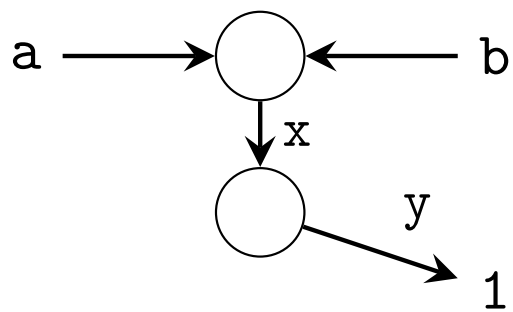

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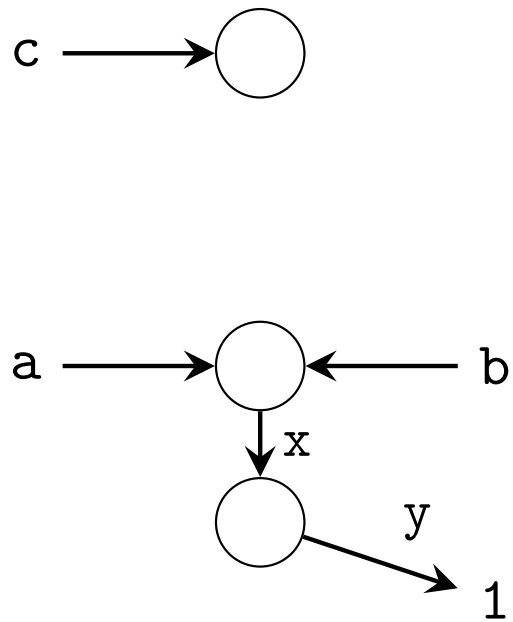

Example Program

Example

```
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b.x := new();
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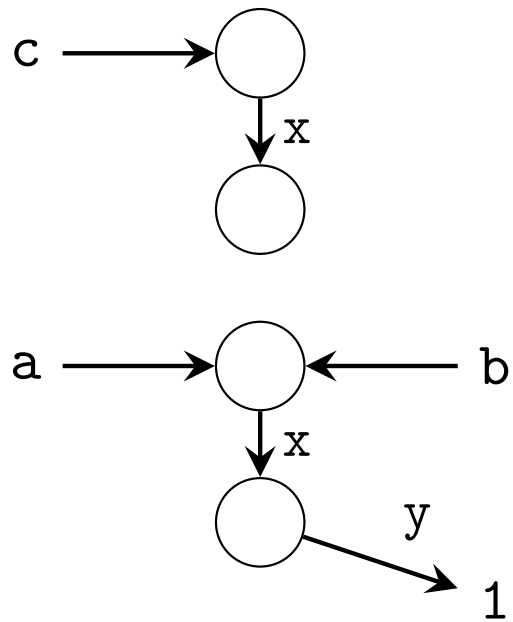
c := new();
c.x := new(); // ⇐
c.x.x := a;
c := a.x;
// A
```



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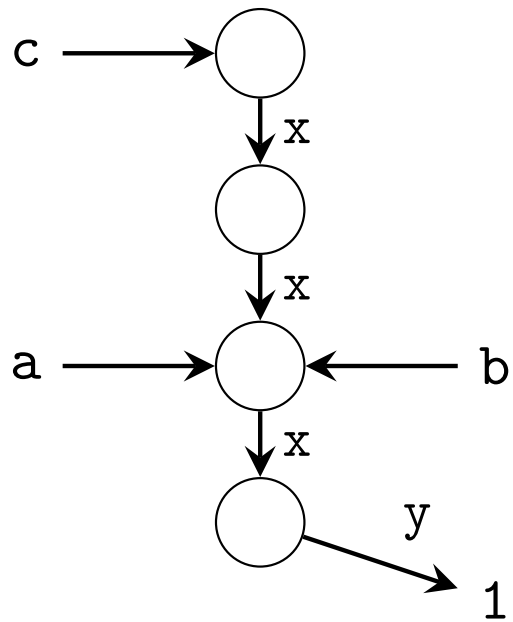
c.x.x := a;    // ⇐
c := a.x;
// A
```



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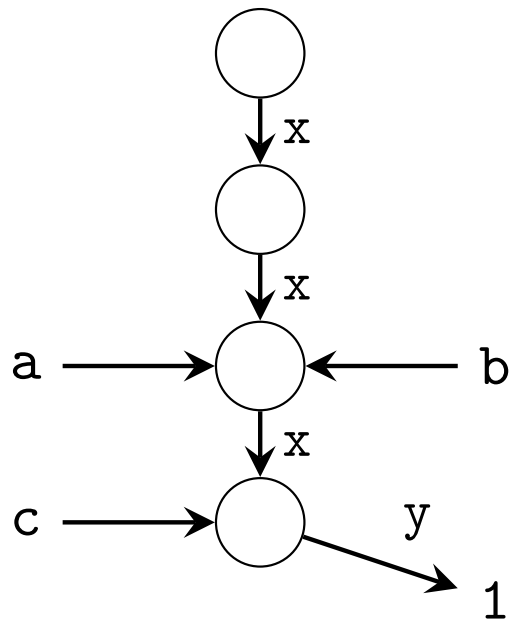
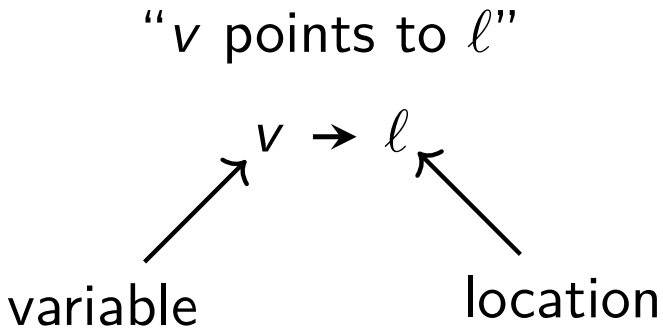
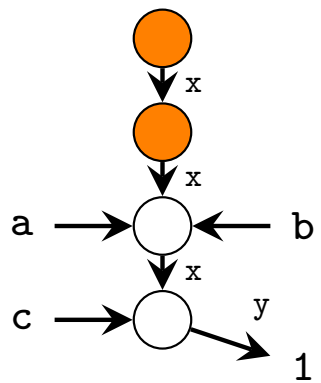


Concrete Heap Graph



- Heap graph connects memory locations
- Represents all heap-allocated objects and their points-to relationships
- Edges labelled with field names
- Some objects not reachable from variables



Aliasing

Example

```
a := new();
a.x := null;
b := a;
b.x := new();
a.x.y := 1;
c := new();
c.x := new();
c.x.x := a;
c := a.x;
// A
```

Aliases at `// A`:

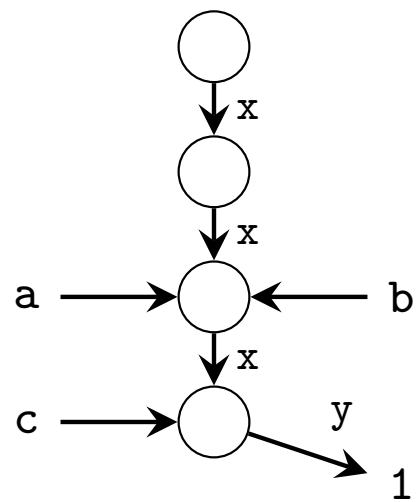
- `a` and `b` represent the same object

$\Rightarrow$ `a` and `b` are *aliased*

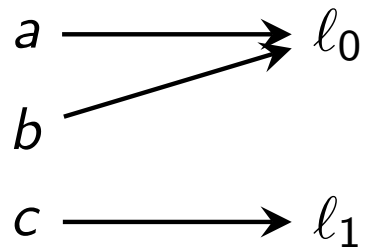
$$\texttt{a} \overset{\textit{alias}}{=\!=} \texttt{b}$$

$\Rightarrow$ `a.x` and `b.x` are *aliased*

- `c` and `a.x` and b.x are *aliased*



Pointer Analysis



- *Points-To Analysis*:
  - Analyse *heap usage*
  - Which *variables* may/must point to which *heap locations*?

$$a \rightarrow \ell_0$$

- *Alias Analysis*:
  - Analyse *address sharing*
  - Compute *equivalence relation* ($\overset{alias}{=\!=}$) between variables
  - Which *pair/set of variables* may/must point to the same address?

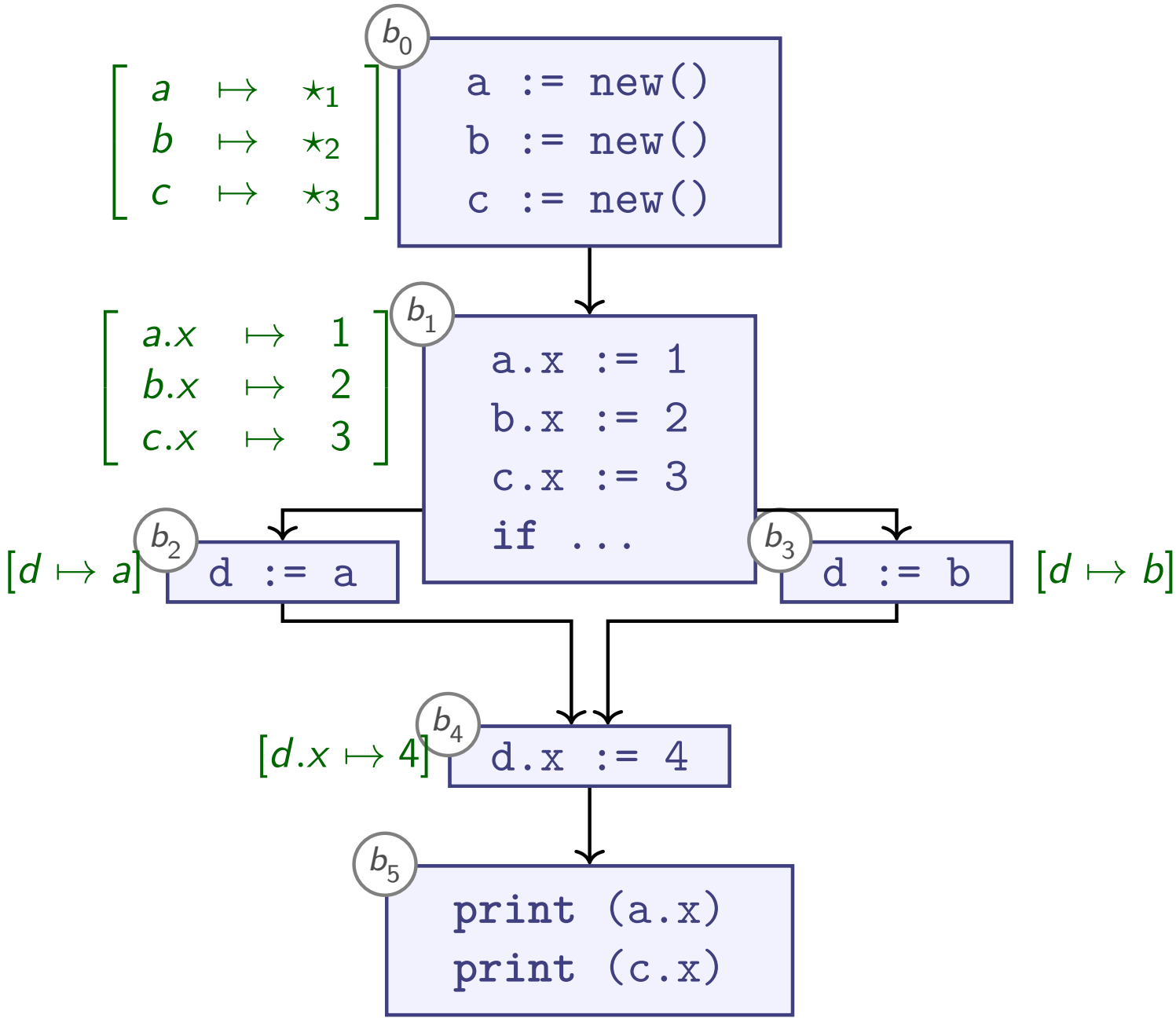
$$a \overset{alias}{=\!=} b$$

Summary: Pointer Analysis

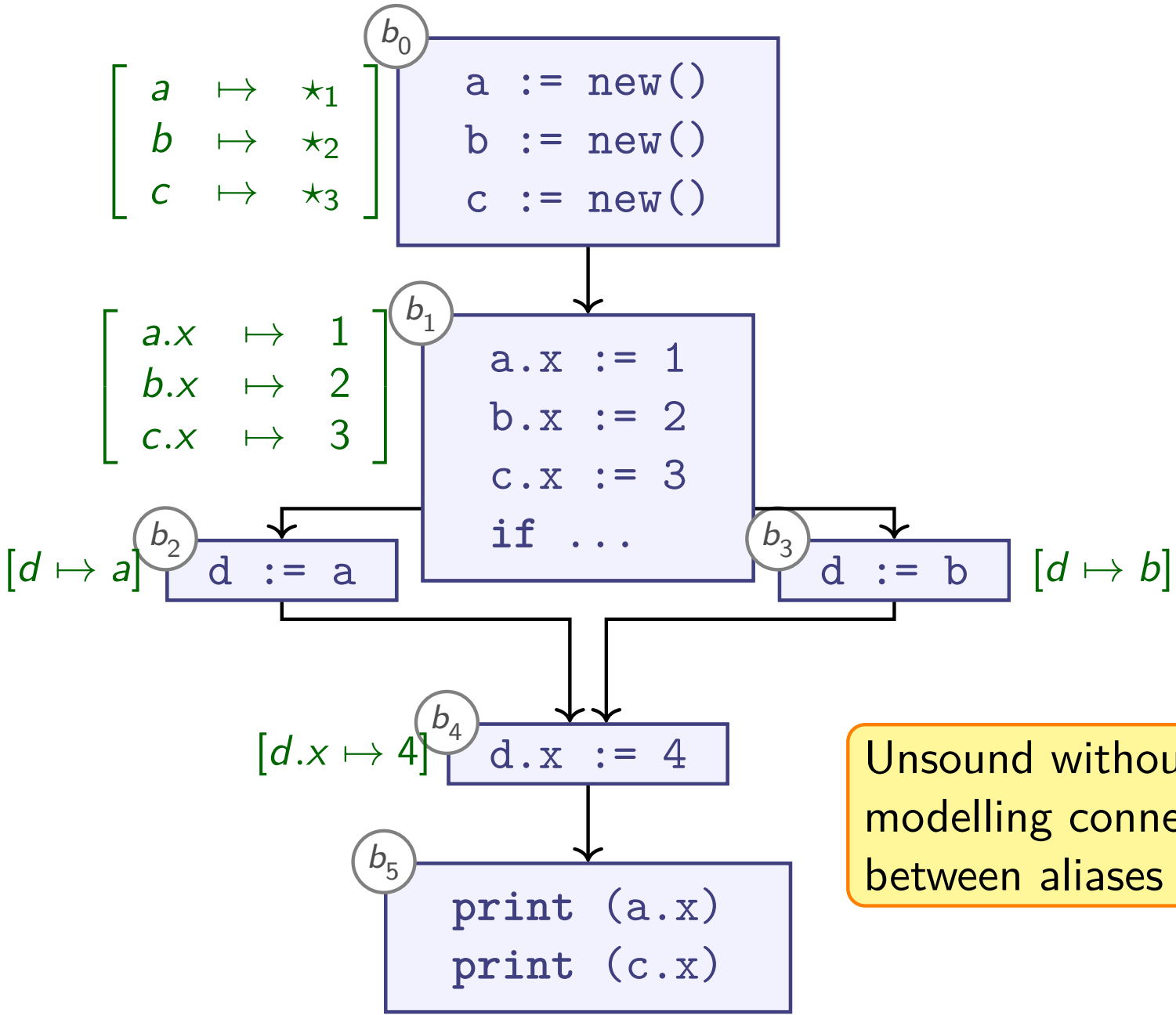
- Class of analyses to model dynamic heap allocation
- **Points-To Analysis**: computes mapping
  - From *variables*
  - To *pointees* (other variables)
  - More general than Alias Analysis
- **Alias Analysis**: computes
  - *Sharing information* between variables
  - Implicitly produced by points-to analysis

$$a \overset{alias}{=\!=} b \iff a \rightarrow \ell \leftarrow b$$

Dataflow with Alias Information

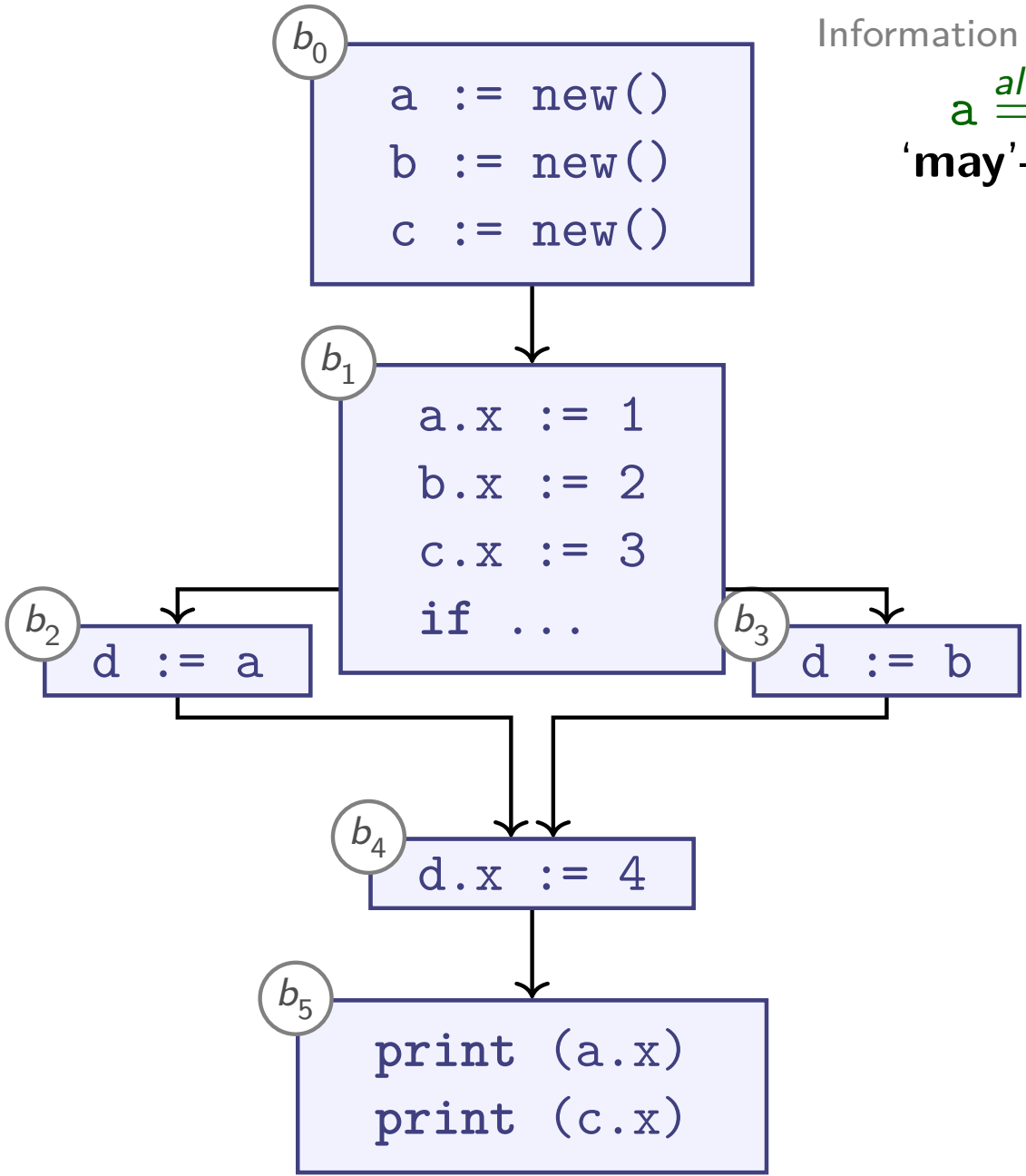


Dataflow with Alias Information



Unsound without modelling connection between aliases

Dataflow with Alias Information

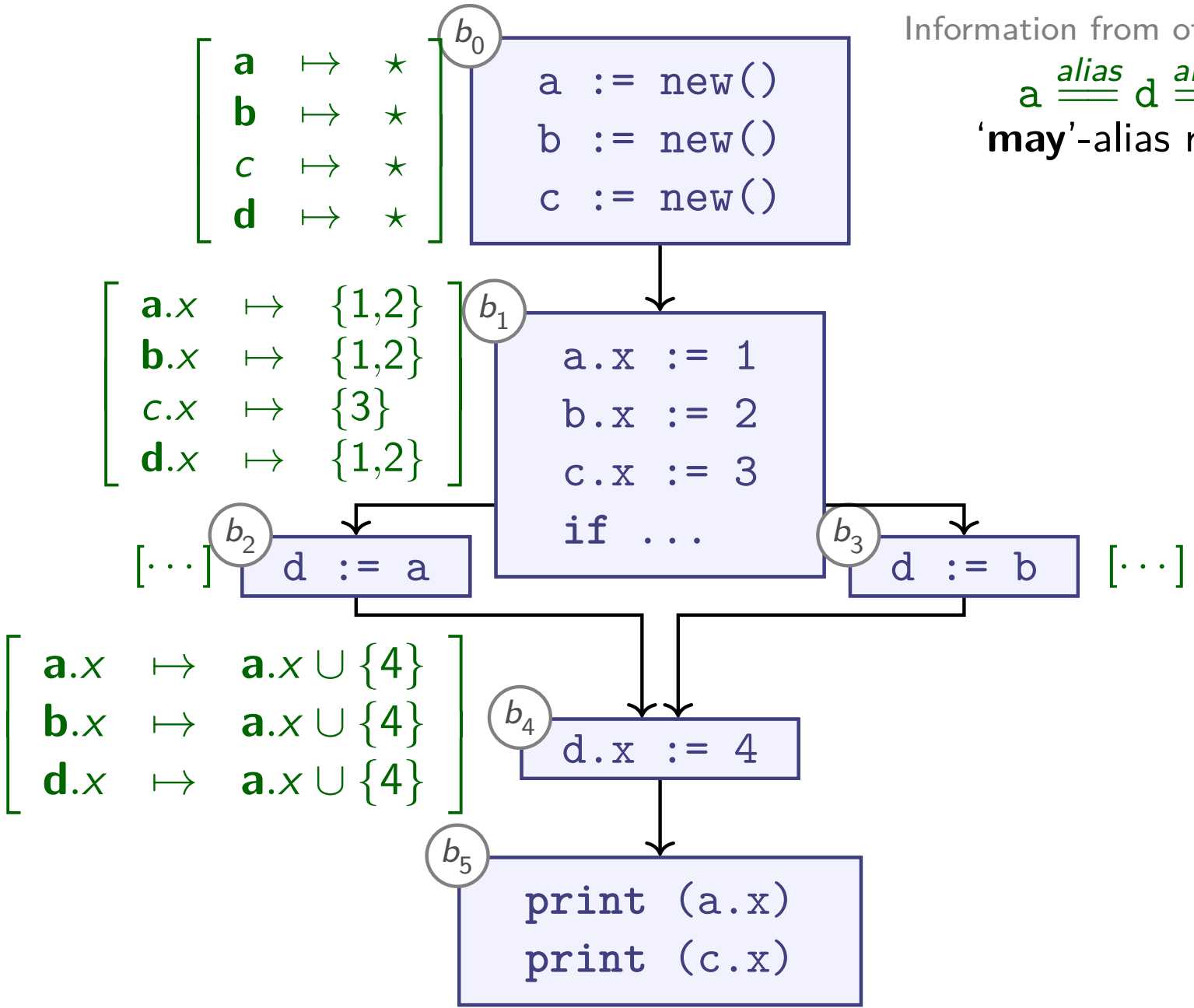


Information from other analysis:

$a \overset{alias}{=\!=} d \overset{alias}{=\!=} b$

'**may**'-alias relation

Dataflow with Alias Information



Information from other analysis:

$\mathtt{a} \overset{alias}{=\!=} \mathtt{d} \overset{alias}{=\!=} \mathtt{b}$

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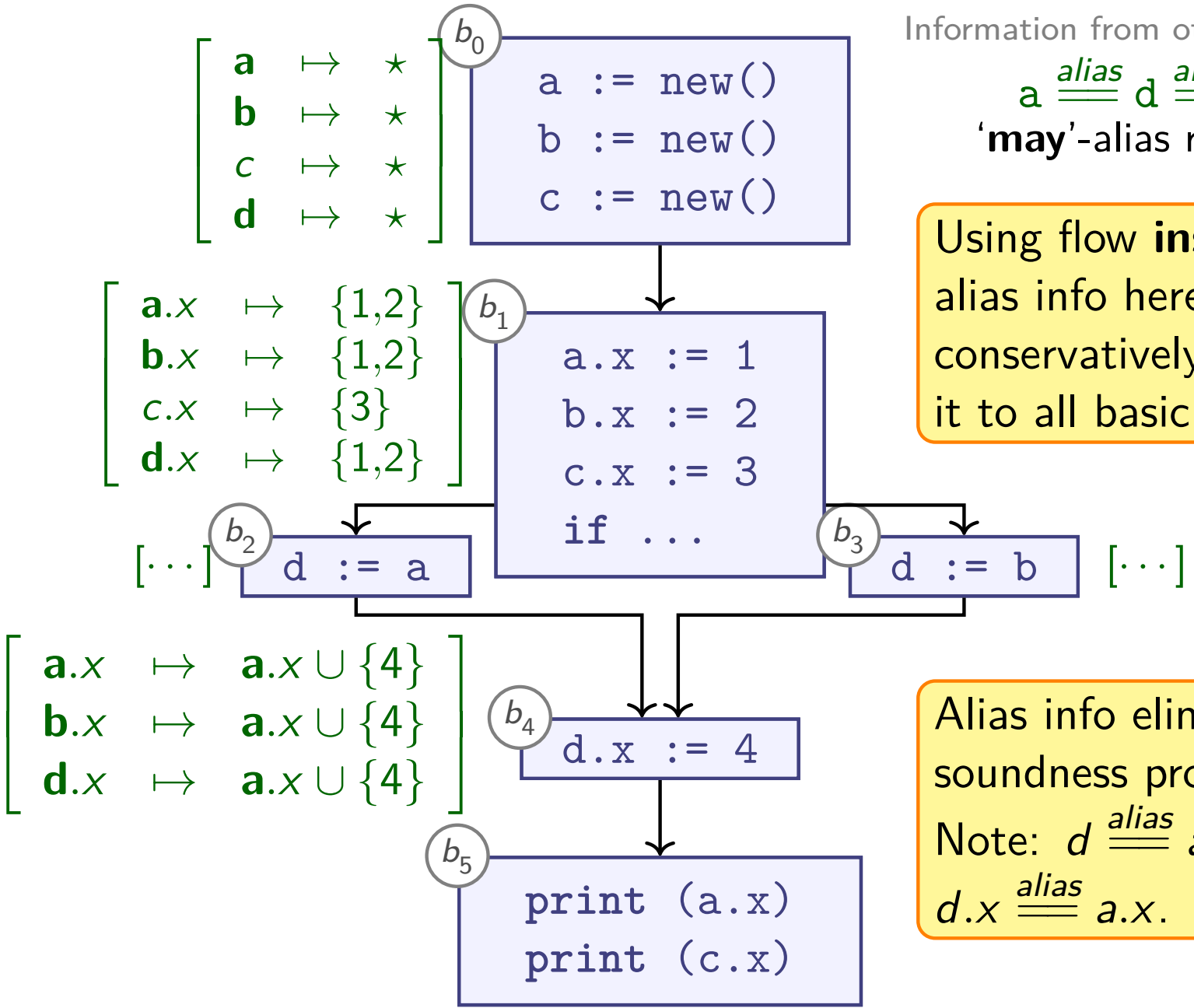
Dataflow with Alias Information



Information from other analysis:

$\mathtt{a} \overset{alias}{=\!=} \mathtt{d} \overset{alias}{=\!=} \mathtt{b}$

'**may**'-alias relation

Using flow **in**sensitive alias info here, so we conservatively apply it to all basic blocks.

Alias info eliminates soundness problem.

Note: $d \overset{alias}{=\!=} a$ implies $d.x \overset{alias}{=\!=} a.x$.

Dataflow + Aliases

- Aliasing affects shared fields:

$$\mathtt{a} \overset{alias}{=\!=} \mathtt{d} \quad \Longrightarrow \quad \mathtt{a}.x \overset{alias}{=\!=} \mathtt{d}.x \text{ for all } x$$

- Use 'may' aliasing knowledge in one of these ways:

1. Multiply *updates* for each alias:

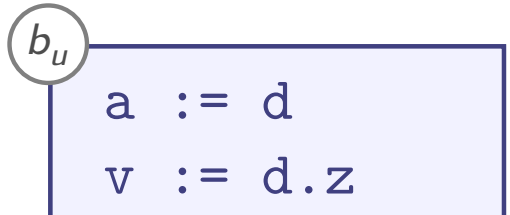
$$\begin{bmatrix} \mathbf{a}.x & \mapsto & \{4\} \\ \mathbf{d}.x & \mapsto & \mathbf{d}.x \cup \{4\} \end{bmatrix}$$

Using MAY alias info means: program *may or may not* not update aliased object.

2. Multiply *reads* for each alias:

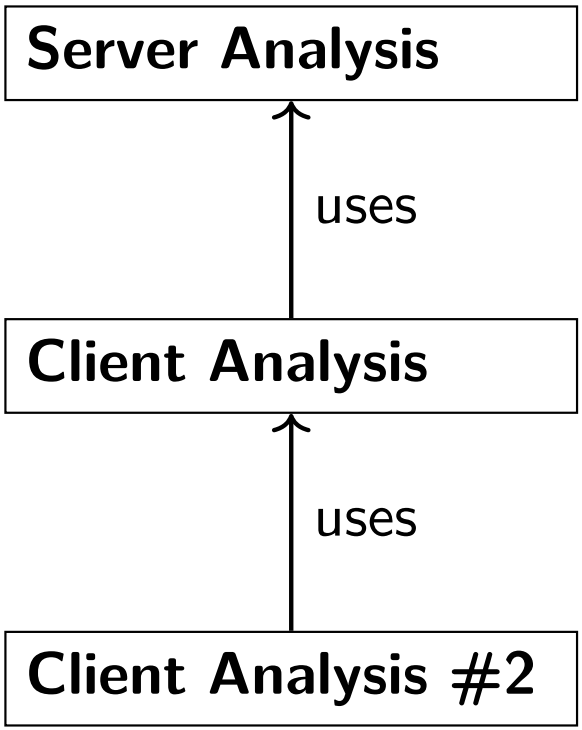
$$\begin{bmatrix} v & \mapsto & \mathbf{a}.x \cup \mathbf{d}.x \end{bmatrix}$$

3. Replace aliased paths by single representative (e.g., **a** represents both **d** and **a**):



$$\begin{bmatrix} v & \mapsto & \mathbf{a}.z \\ \mathbf{a}.x & \mapsto & \mathbf{a}.x \end{bmatrix}$$

Collaboration in Program Analysis



e.g., *Alias*

e.g., *Constant Propagation*

e.g., *Array Out Of Bounds check*

Analyses often form pipeline structures

Summary

- **Analysis client**: user of analysis, often another analysis
  - E.g., *Type analysis* is client of *name analysis*
- **Alias analysis** helps make dataflow analysis more precise
  - Fields inherit aliasing:

$$\mathtt{a} \overset{alias}{=\!=} \mathtt{b} \quad \Longrightarrow \quad \mathtt{a}.x \overset{alias}{=\!=} \mathtt{b}.x \text{ for all } x$$

  - So if $a.x \overset{alias}{=\!=} b.y$, then:
    - $a.x.z \overset{alias}{=\!=} b.y.z$
    - $a.x.z.z \overset{alias}{=\!=} b.y.z.z$
    - $a.x.z.z.z \overset{alias}{=\!=} b.y.z.z.z$ etc.

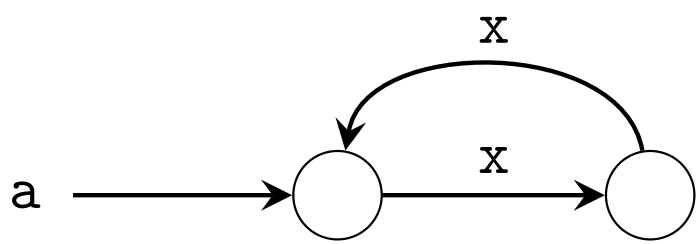
Concrete Heap Graphs (1/3)

Describe heap as a graph:

$$G_{\mathsf{CHG}} = \langle \mathit{MemLoc}, \rightarrow, \overset{\blacksquare}{\rightarrow} \rangle$$

- G_{CHG} describes *actual* heap contents
- *MemLoc* are addressable memory locations
  - *Named* variables (a)
  - *Unnamed* variables (◯)
- Heap size typically 'unbounded for all practical purposes'

```
a := new Obj();
a.x := new Obj();
a.x.x := a;
```



Concrete Heap Graphs (2/3)

- Direct points-to references:

$$(\rightarrow) \subseteq \mathit{MemLoc} \times \mathit{MemLoc}$$

- Exactly one ℓ' s.th. $\ell \rightarrow \ell'$:
  - For simplicity, assume **null** $\in \mathit{MemLoc}$
- Points-to references via fields:

$$(\overset{\blacksquare}{\rightarrow}) : \mathit{MemLoc} \times \mathit{Field} \rightarrow \mathit{MemLoc}$$

- *Field* labels for record/object fields and array indices:
  - E.g., `x` in '`a.x`' (Java) / '`a->x`' (C/C++)
  - Array indices for 'a[10]' (i.e., $\mathbb{N} \subseteq \mathit{Field}$)

Concrete Heap Graphs (3/3)

- Direct points-to references:

$$(\rightarrow) : \mathit{MemLoc} \rightarrow \mathit{RefLoc} \cup \{\textbf{null}\}$$

- Language difference:
  - **Java/Teal**:
    - Exists *Var*: set of global / local variables and parameters
    - $\mathit{Var} \cap \mathit{RefLoc} = \emptyset$
    - $\mathit{MemLoc} = \mathit{Var} \cup \mathit{RefLoc}$
  - **C/C++**: $\mathit{Var} = \mathit{RefLoc} = \mathit{MemLoc}$
    - Address-of operator (&) allows translating variable into *MemLoc*
    - $\mathit{Var} \subseteq \mathit{RefLoc}$
    - $\mathit{MemLoc} = \mathit{RefLoc}$

Example

Teal-2

```
fun makeList(len) {
  var tail := new N();
  tail.next := null;
  var body := tail;
  while len > 0 {
    var t := body;
    body := new N();
    body.next := t;
    len := len - 1;
  }
  var list := new N();
  list.head := body;
  list.tail := tail;
  return list;
}
```

Example

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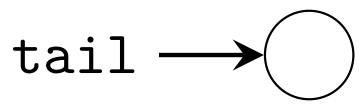

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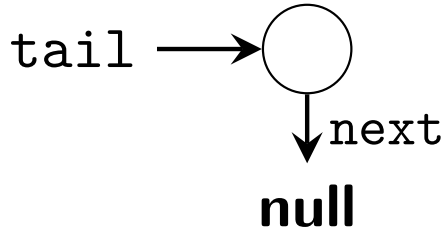

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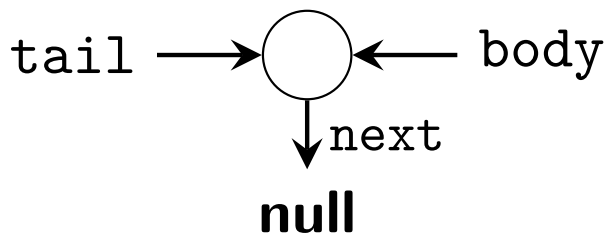

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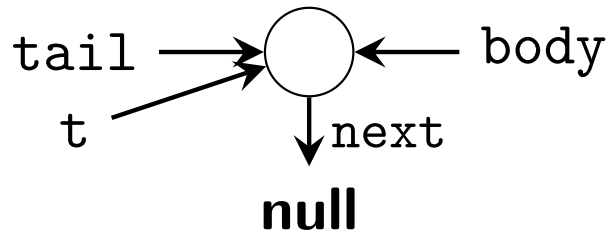

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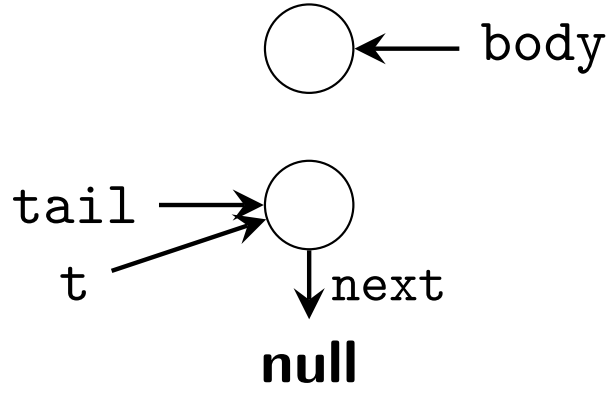

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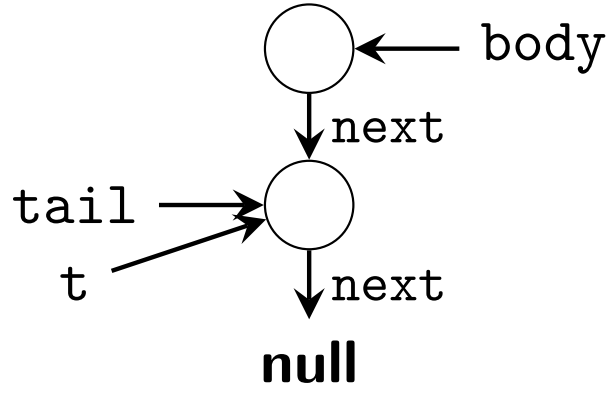

Example

Teal-2

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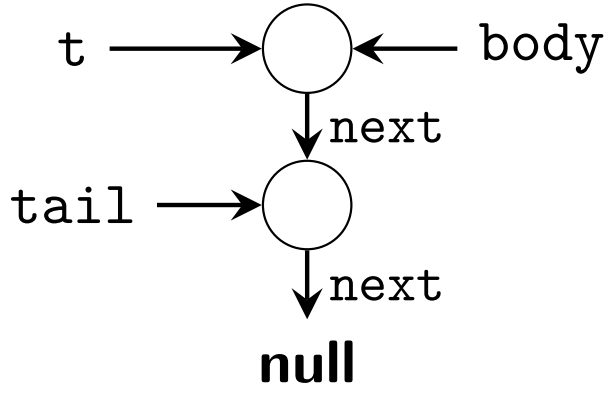
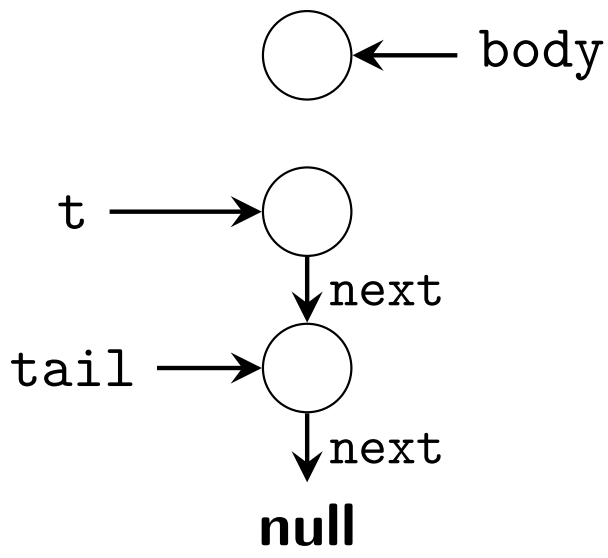
}
```



Example

Teal-2

```
fun makeList(len) {
  var tail := new N();
  tail.next := null;
  var body := tail;
  while len > 0 {
    var t := body;
    body := new N();    //⇐
    body.next := t;
    len := len - 1;
  }
  var list := new N();
  list.head := body;
  list.tail := tail;
  return list;
}
```



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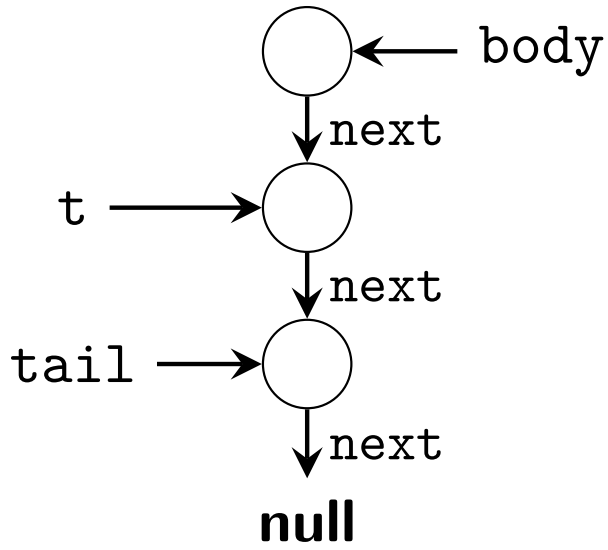

Example

Teal-2

```
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  var body := tail;
  while len > 0 {
    var t := body;        //⇐
    body := new N();      //⇐
    body.next := t;       //⇐
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  list.head := body;
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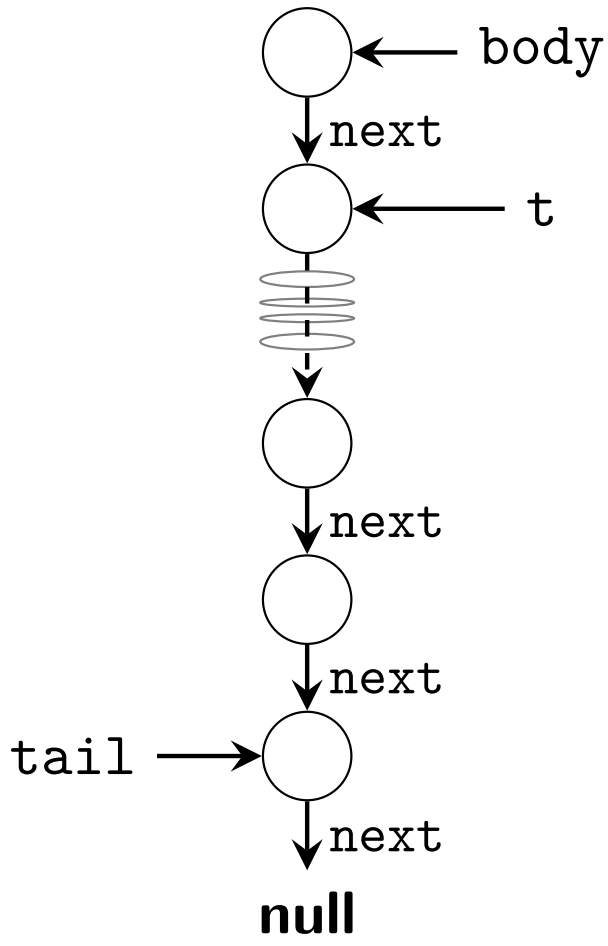

Example

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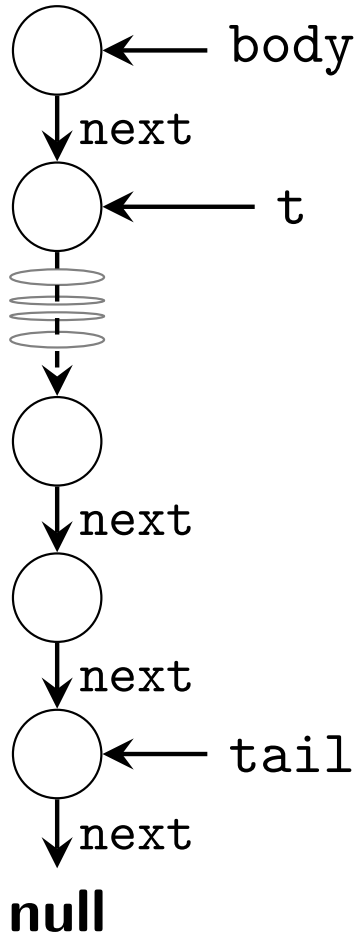

Example

Teal-2

```
fun makeList(len) {
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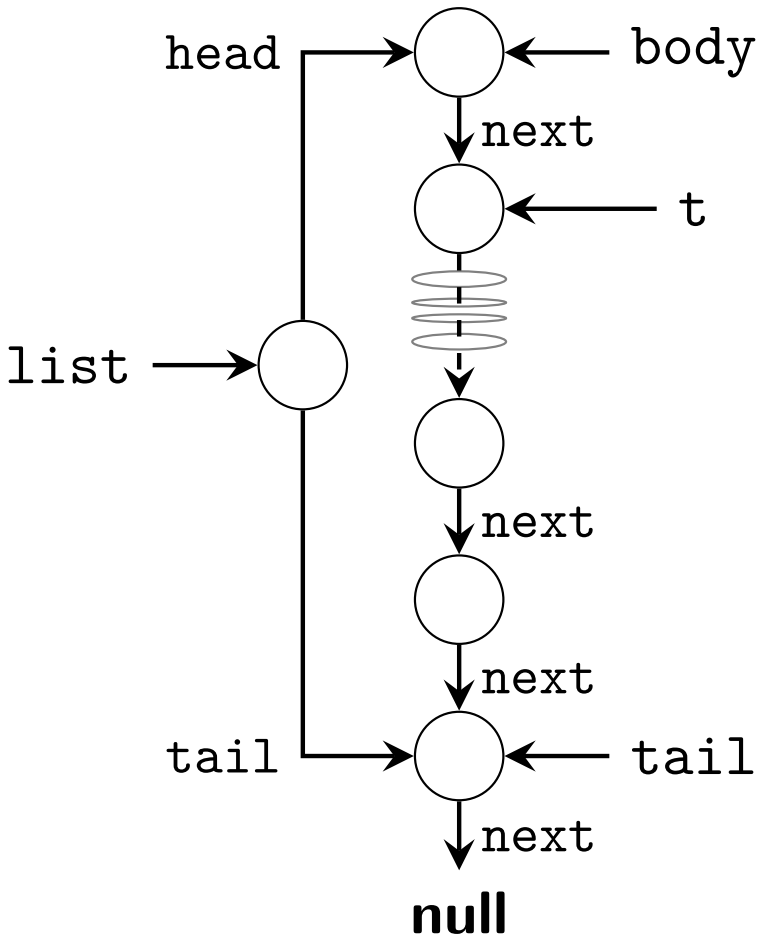
len > 1:



Example

Teal-2

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  }
  var list := new N();
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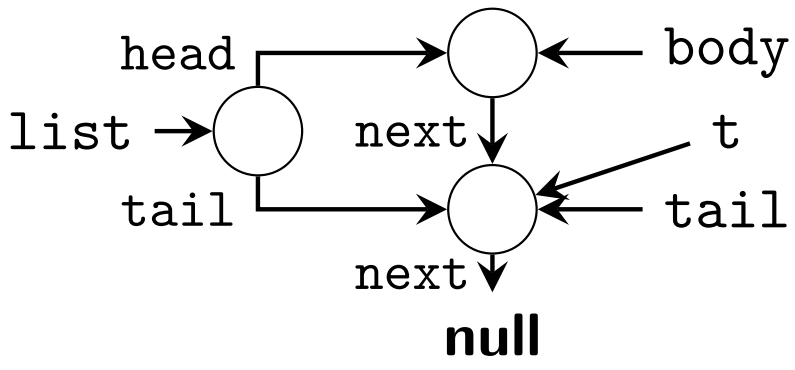
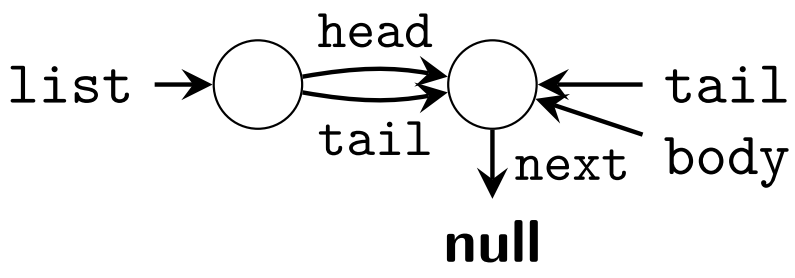
}
```

`len = 1:`



`len = 0:`



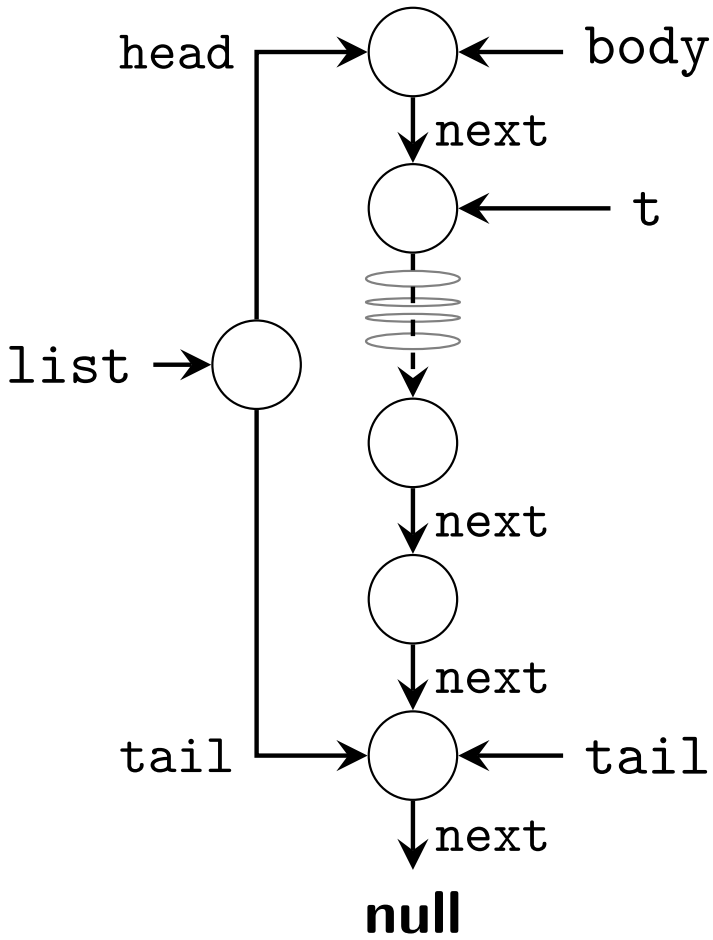
Managing Heap Graphs

- **Challenge**: Size of Concrete Heap Graphs is unbounded
- Different parameters $\Longrightarrow$ different Concrete Heap Graphs

- **Store-less heap models**:
  - Hide heap locations
  - Model heap via *access paths*

`list.head.next.next`

Store-less Model



- Access path-based equivalences:
  - **Must**: `list.tail` $\overset{alias}{=\!=}$ `tail`
  - **Must**: `list.head` $\overset{alias}{=\!=}$ `body`
  - **Must**: `body.next` $\overset{alias}{=\!=}$ `t`
  - **May**: `body.next`$\star$ $\overset{alias}{=\!=}$ `tail`
- Use *regular expressions* to denote repetition
- `body.next`$\star$ $\overset{alias}{=\!=}$ `tail` means:

$$\begin{aligned} \texttt{body} &\overset{alias}{=\!=} \texttt{tail} \\ \texttt{body.next} &\overset{alias}{=\!=} \texttt{tail} \\ \texttt{body.next.next} &\overset{alias}{=\!=} \texttt{tail} \\ &\ldots \end{aligned}$$

- For **May** or **Must** information

Summary

- **Concrete Heap Graph** (CHG) describes actual heap layout during execution
- CHG is unbounded, must summarise to analyse
- **Store-less Models**:
  - Use **access paths** to describe memory locations
  - Common in alias analysis

Managing Heap Graphs

- **Challenge**: Size of Concrete Heap Graphs is unbounded
- Different parameters $\Longrightarrow$ different Concrete Heap Graphs

- **Store-less heap models**:
  - Hide heap locations
  - Model heap via *access paths*

`list.head.next.next`

- **Store-based heap models**:
  - Keep heap locations explicit
  - Introduce *Summary nodes* that can describe multiple CHG nodes

Store-based Model

- Concrete Heap Graph (CHG): graph of the program's reality

$$G_{\mathsf{CHG}} = \langle \mathit{MemLoc}, \rightarrow, \overset{\blacksquare}{\rightarrow} \rangle$$

- Abstract Heap Graph (AHG): approximation of program's reality

$$G_{\mathsf{AHG}} = \langle \mathcal{P}(\mathit{MemLoc}), \rightarrowtriangle, \overset{\blacksquare}{\rightarrowtriangle} \rangle$$

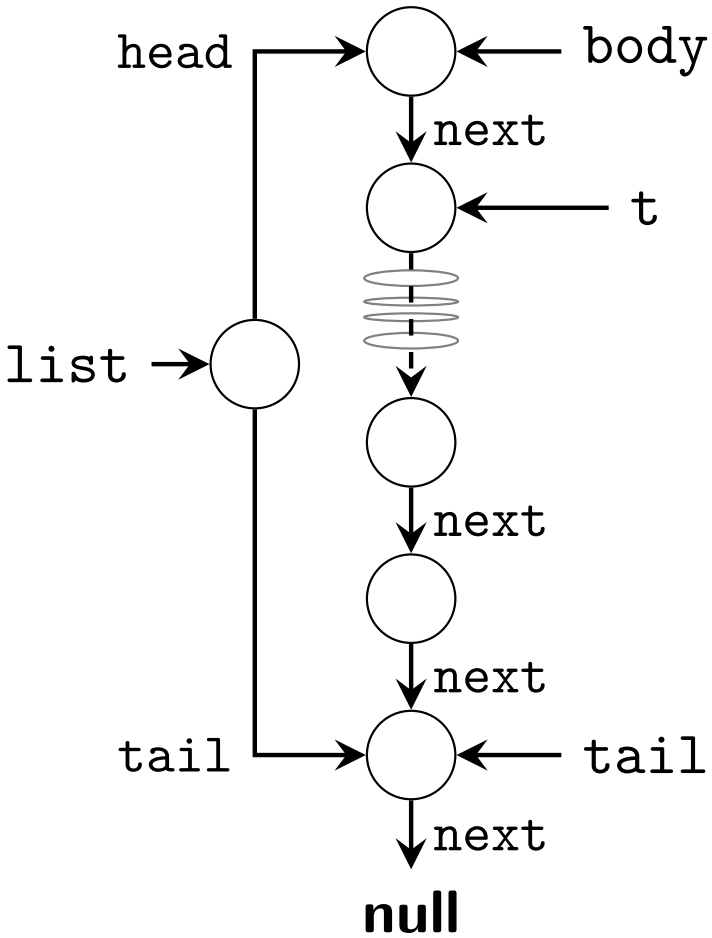
$$\begin{array}{rcl} (\rightarrowtriangle) & : & \mathcal{P}(\mathit{MemLoc}) \rightarrow \mathcal{P}(\mathit{MemLoc}) \\ (\overset{\blacksquare}{\rightarrowtriangle}) & : & \mathcal{P}(\mathit{MemLoc}) \times \mathcal{P}(\mathit{Field}) \rightarrow \mathcal{P}(\mathit{MemLoc}) \end{array}$$

- Key idea: AHG is *finite* graph that summarises CHG
- Soundness (**May** analysis) via:

$$\begin{array}{lcllcl} v & \rightarrow & \ell & \text{implies} & \{v\} \cup V' & \rightarrowtriangle & \{\ell\} \cup L' \\ \ell_0 & \overset{f}{\rightarrow} & \ell_1 & \text{implies} & \{\ell_0\} \cup L'_0 & \overset{\{f\} \cup F'}{\rightarrowtriangle} & \{\ell_1\} \cup L'_1 \end{array}$$

- 'Any CHG edge is represented by (at least) one AHG edge'

Summary Nodes and Edges



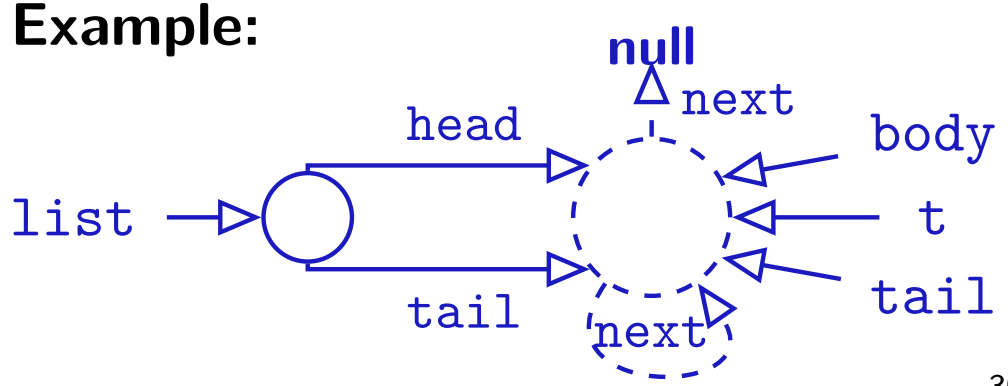
Notation:

- Abstract node $N \subseteq \mathit{MemLoc}$:
  $|N| = 1$: *precise*:
  $|N| > 1$ or variable: *summary*:
- Consider edge $V \rightarrow L$:
  - $|V| = 1$: *precise*:

    $V \longrightarrow L$
  - $|V| > 1$: *summary*:

    $V \dashrightarrow L$
- Analogous for $(\overset{\blacksquare}{\rightarrow} f)$

Example:



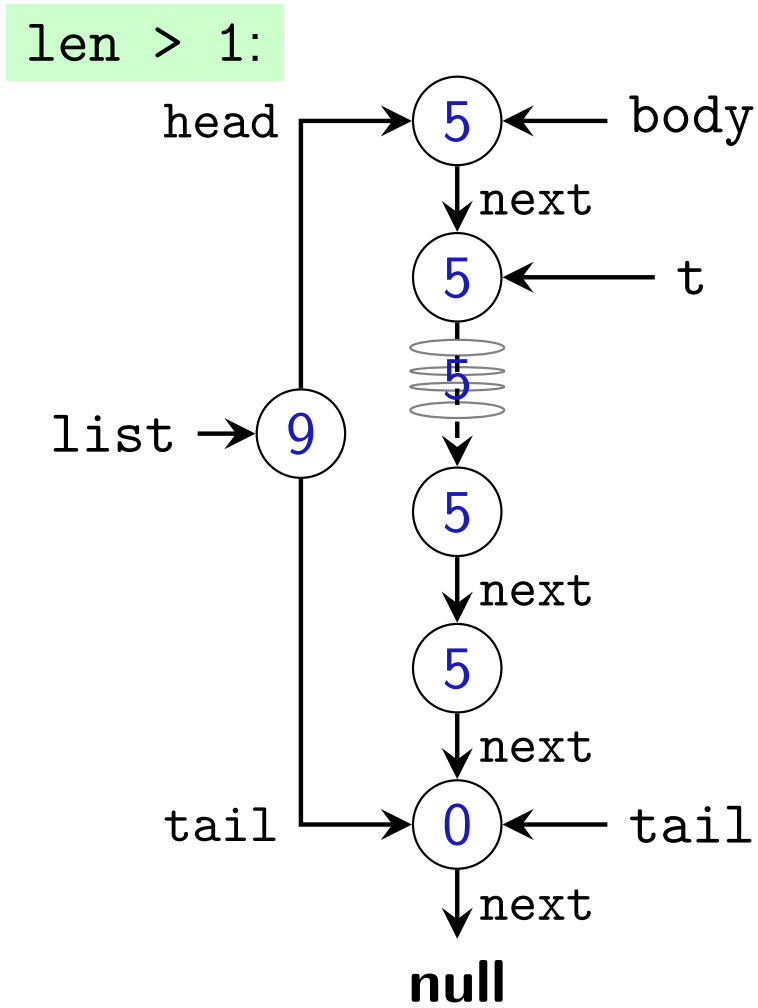
Summary

- **Store-based Models**:
  - Use **Abstract Heap Graph** to summarise *Concrete Heap Graph*
  - Common for finding memory bugs
  - Represents NFA
    - Equivalent to regular expressions

Summaries from Allocation Sites

Teal-2

```
fun makeList(len) {
[0]  var tail := new N();
[1]  tail.next := null;
[2]  var body := tail;
[3]  while len > 0 {
[4]    var t := body;
[5]    body := new N();
[6]    body.next := t;
[7]    len := len - 1;
[8]  }
[9]  var list := new N();
[10] list.head := body;
[11] list.tail := tail;
[12] return list;
}
```



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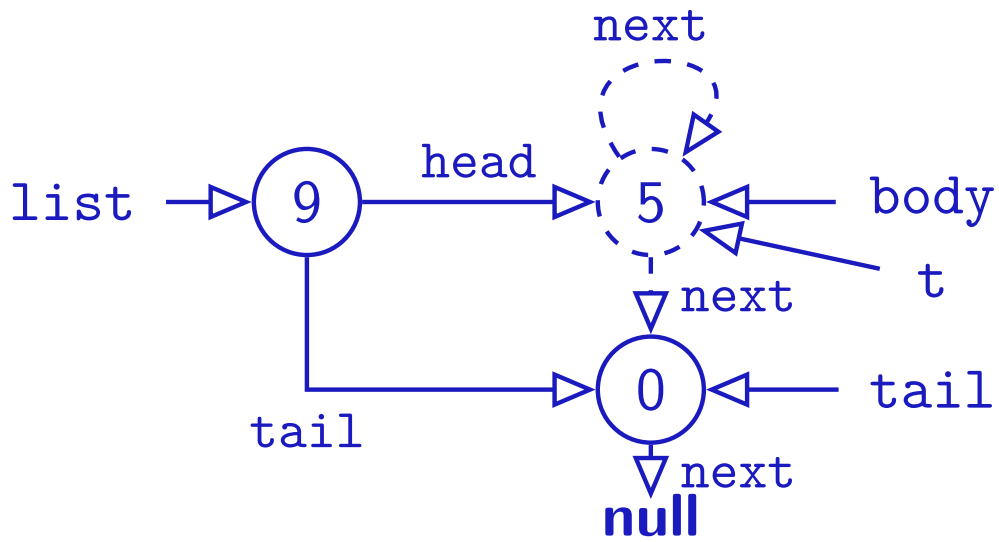

- Summarise *MemLoc* allocated at same program location

Summaries from Allocation Sites

Teal-2

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fun makeList(len) {
[0]   var tail := new N();
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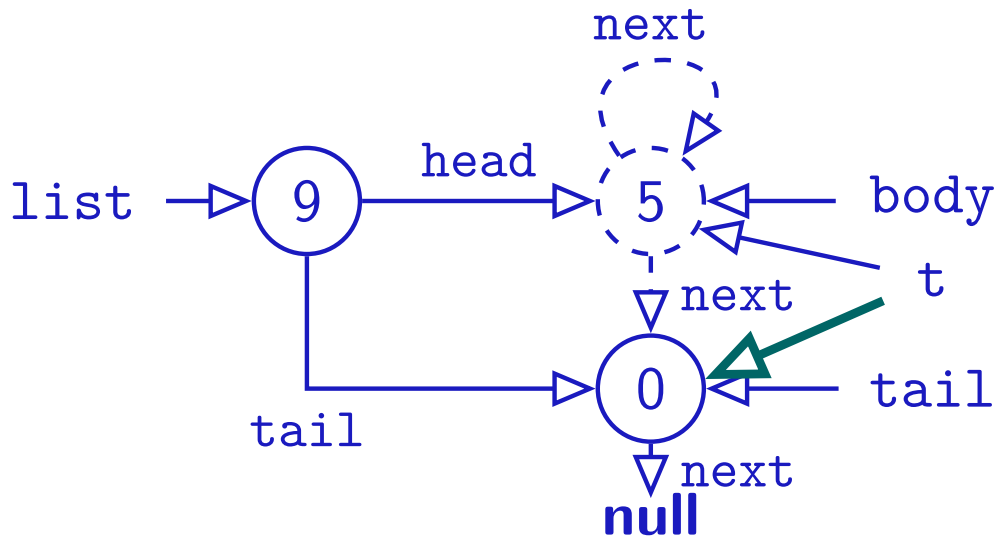
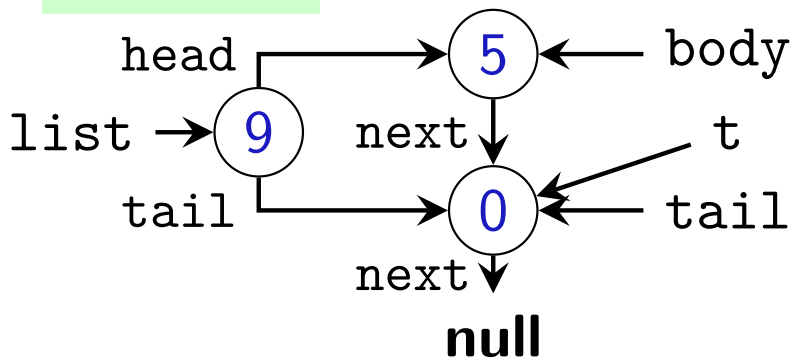


len = 1:



- Summarise *MemLoc* allocated at same program location
- Nodes can have multiple outgoing arrows

Summaries from Allocation Sites

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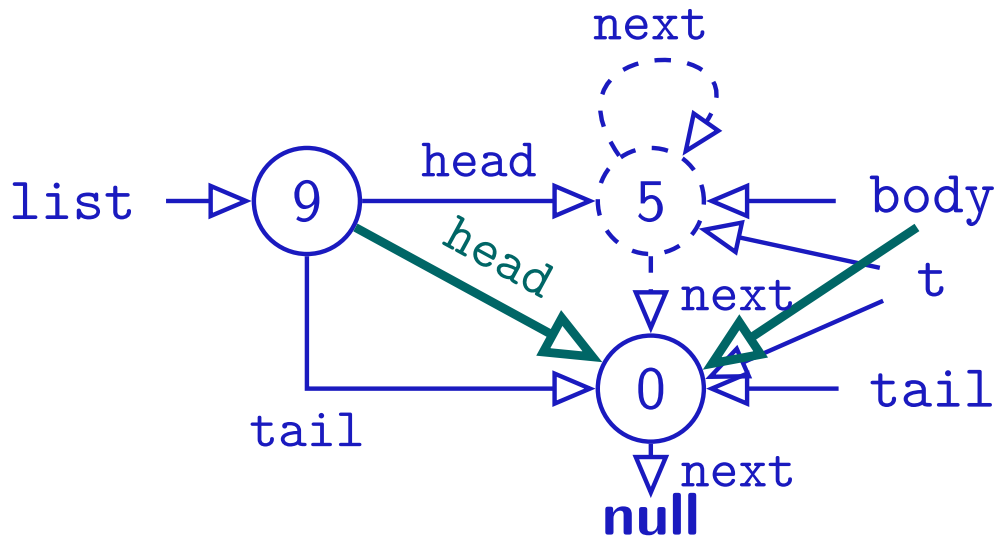
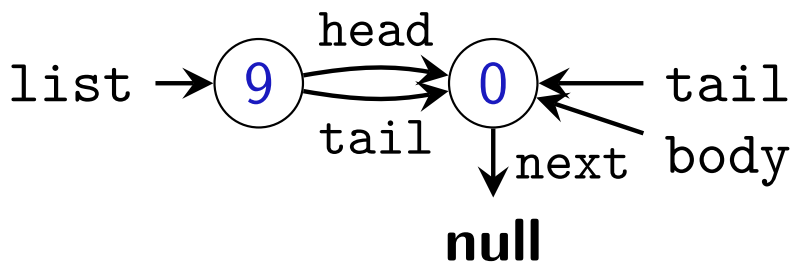


len = 0:



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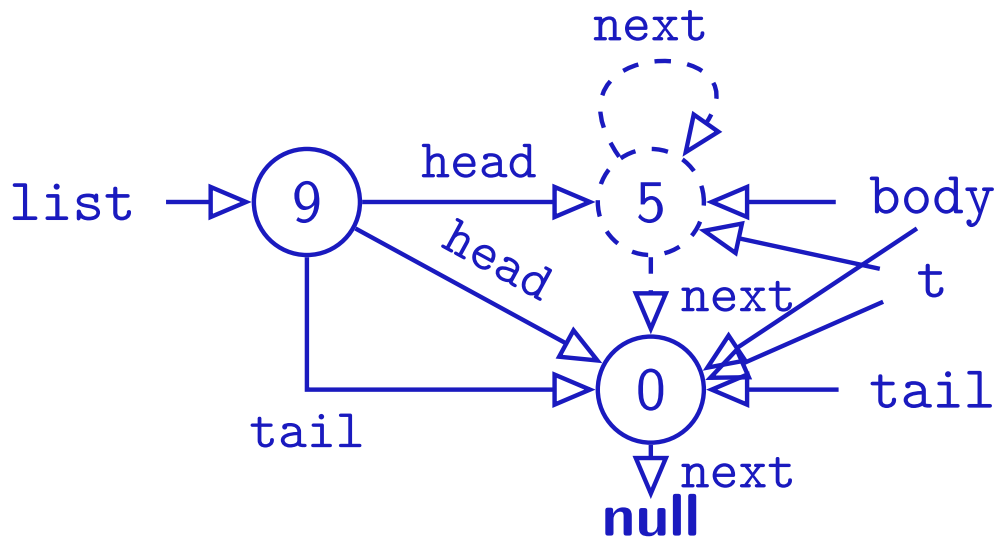


- Summarise *MemLoc* allocated at same program location
- Nodes can have multiple outgoing arrows

Summaries via k-Limiting

- k-Limiting: bound size
- Examples: Limiting...
  - Access path length

    Example (k=3):

    `list.head.next` ⇒ `list.head.next`

    `list.head.next.next` ⇒ `list.head.next`$\star$

    `list.head.next.next.next` ⇒ `list.head.next`$\star$

    `list.head.next.next.val` ⇒ `list.head.(val|next)`$\star$
  - # of ($\rightarrow\!\triangleright$) hops after named variable
  - # of nodes transitively reachable via ($\rightarrow\!\triangleright$) after named variable
  - # of nodes in a loop / function body

  ...

Other Summary Techniques

- General idea: Partition *MemLoc* into finite (manageable!) set
- Summary technique decides how to partition
- Can combine different techniques for increased precision
- Summary techniques distinguish heap nodes by:
  - Allocation site
  - k-limiting
  - How many edges point to the node?
  - Is the node in a cycle?
  - What is the type of the node? (`ArrayList`, `StringTokenizer`, `File`, ...)

  ...

Design Considerations

- Finite representation
- Output should be useful for analysis clients
- Efficient to compute / represent

Summary of Heap Summaries

- *Store-less Models*:
  - Common in alias analysis
- **Store-based Models**:
  - Use **Abstract Heap Graph** to summarise *Concrete Heap Graph*
  - Common for finding memory bugs
  - NFA representation $\mapsto$ regular expressions for Access Paths
- Summarisation techniques:
  - **Allocation-Site Based**: summarise nodes allocated at same point in program
  - k-**Limiting**: Set bound on some property P: no more than k Ps allowed
  - Many combinations / extensions conceivable

Pointer Operations

- Points-to analysis must analyse all pointer operations
- All pointer operations fall into one of the following categories:

Referencing

$$\texttt{a} \rightarrow \ell$$

Create, point to location:

Teal-2

```
a := new A();
a := [...];
```

Dereferencing

$$\texttt{a} \rightarrow \ell \xrightarrow{f} \ell'$$

Access location:

Teal-2

```
    - read -
...  := a.f;
...  := a[i];
    - write -
a.f := ...;
a[i] := ...;
```

Aliasing

$$\texttt{b} \rightarrow \ell \iff \texttt{a} \rightarrow \ell$$

Copy pointer:

Teal-2

```
a := b;
```

Pointer Operations Across Languages

	C	Java	Teal
Referencing	`a = &b`	`a = new A()`	`a := new A()` `a := [..., b, ...]`
Aliasing	`a = b`	`a = b`	`a := b`

Dereferencing read	`a = b->f`
	`a = b[i]`
	`a = *b`
		`a = b.f`
		`a = b[i]`
			`a := b.f`
			`a := b[i]`

Dereferencing write	`a->f = b`
	`a[i] = b`
	`*a = b`
		`a.f = b`
		`a[i] = b`
			`a.f := b`
			`a[i] := b`

Summary

- Points-to anaysis: compute Abstract Heap Graph by *approximating*

$$v \rightarrow \ell$$

- Analysis must consider:
  - **Referencing**: taking (fresh) location
    - In languages like C/C++, code can also reference locations of stack/global variables
  - **Dereferencing**: accessing object at location
  - **Aliasing**: copying location
- Locations ℓ may model different parts of memory:
  - Static variables: uniquely defined
  - Stack-dynamic variables: zero or more copies (recursion!)
  - Heap-dynamic variables: zero or more copies without variable names attached

Steensgaard's Points-To Analysis

- Fast: $O(n\alpha(n,n))$ over variables in program
  - Sacrifices Precision for speed
  - Developed to deal with large code bases at AT&T
- *Equality-based*
- Intuition:
  Whenever two variables *might* point to the same memory location, treat them as globally equal

B. Steensgaard. 'Points-to analysis in almost linear time.' In Proceecings of POPL '96, pages 32–41. ACM Press, 1996.

Distinguishing Field Names?

- For simplicity, don't distinguish field names:
- `a.`$\square$ instead of `a.f` or `a.g`
- Will discuss consequences of this simplification shortly

Constraint Collection

- 'Points-to-set': $pt(v)$ approximates $\{\ell | v \rightarrow \ell\}$
  - $pt(v) = \{\ell | v \rightarrow\!\triangleright \ell\}$
- For each statement in program:
  - If **Referencing** (`a := new`$_{\ell_b}$ `...`) (allocation site ℓ_b)):

$$\ell_b \in pt(\mathtt{a})$$

  - If **Aliasing** (`a := b`):

$$pt(\mathtt{a}) = pt(\mathtt{b})$$

  - If **Dereferencing read** (`a := b.`$\square$):

$$\text{for each } \ell \in pt(\mathtt{b}) \implies pt(\mathtt{a}) = pt(\ell)$$

  - If **Dereferencing write** (`a.`$\square$ `:= b`):

$$\text{for each } \ell \in pt(\mathtt{a}) \implies pt(\mathtt{b}) = pt(\ell)$$

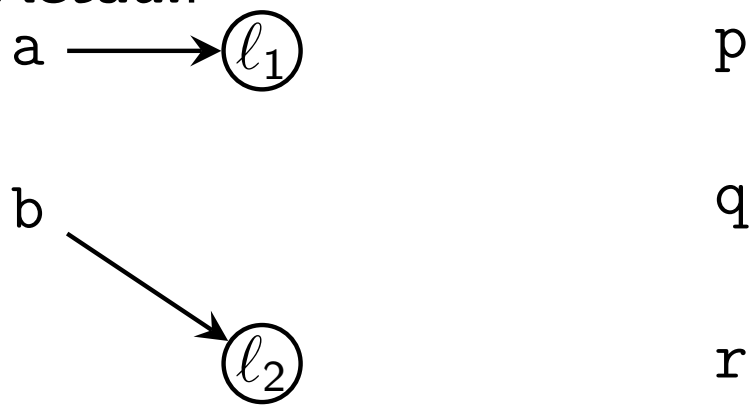
Example

⇒	`x := new`$_{\ell_z}$	$\ell_z \in pt(\mathtt{x})$
	`x := y`	$pt(\mathtt{x}) = pt(\mathtt{y})$
	`x := y.`$\square$	for each $\ell \in pt(\mathtt{y})$ $\implies$ $pt(\mathtt{x}) = pt(\ell)$
	`x.`$\square$ `:= y`	for each $\ell \in pt(\mathtt{x})$ $\implies$ $pt(\mathtt{y}) = pt(\ell)$

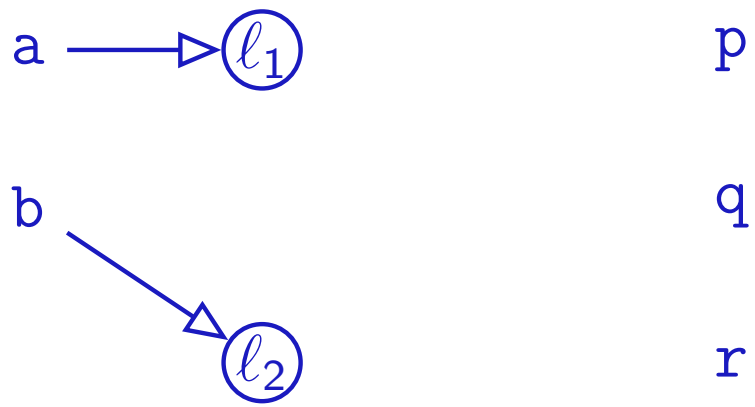
Teal

```
var a := new_ℓ1();
var b := new_ℓ2(); //⇐
a := new_ℓ3();
var p := new_ℓ4();
p.n := a;
var q := new_ℓ6();
q.n := b;
p := q;
var r := q.n;
```

- **Actual**:



- **Steensgaard**:



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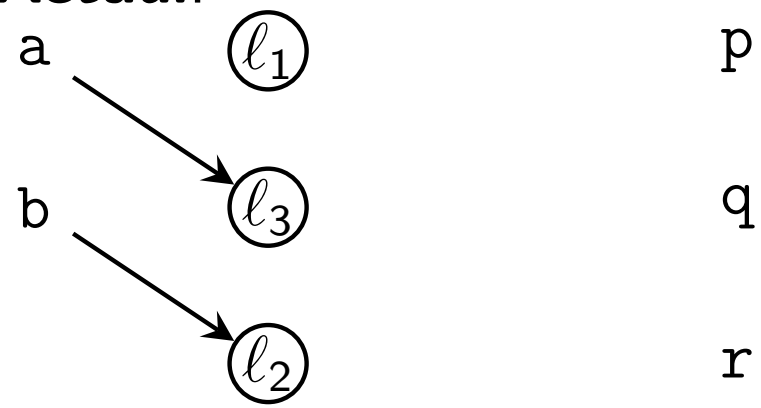
	`x := y`	$pt(\mathtt{x}) = pt(\mathtt{y})$
	`x := y.`$\square$	for each $\ell \in pt(\mathtt{y})$ $\implies$ $pt(\mathtt{x}) = pt(\ell)$
	`x.`$\square$ `:= y`	for each $\ell \in pt(\mathtt{x})$ $\implies$ $pt(\mathtt{y}) = pt(\ell)$

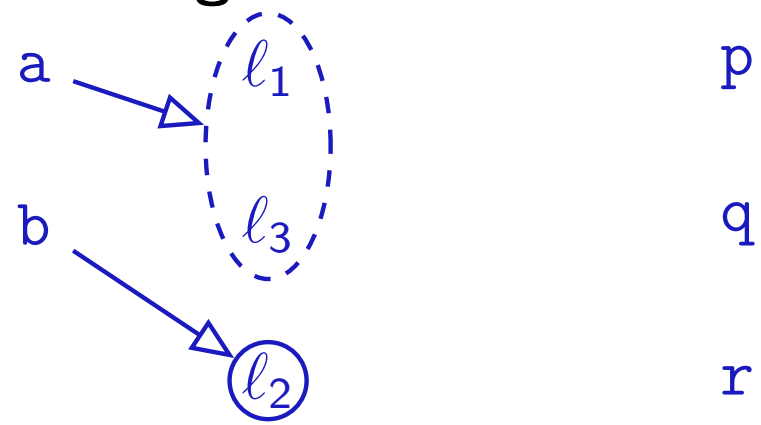
Teal

```
var a := new_ℓ1();
var b := new_ℓ2();
a := new_ℓ3();          //⇐
var p := new_ℓ4();
p.n := a;
var q := new_ℓ6();
q.n := b;
p := q;
var r := q.n;
```

- **Actual**:



- **Steensgaard**:



Example

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	`x := y`	$pt(\mathtt{x}) = pt(\mathtt{y})$
	`x := y.`$\square$	for each $\ell \in pt(\mathtt{y})$ $\implies$ $pt(\mathtt{x}) = pt(\ell)$
$\Rightarrow$	`x.`$\square$ `:= y`	for each $\ell \in pt(\mathtt{x})$ $\implies$ $pt(\mathtt{y}) = pt(\ell)$

Teal

```
var a := new_ℓ1();
var b := new_ℓ2();
a := new_ℓ3();
var p := new_ℓ4();
p.n := a;                    //⇐
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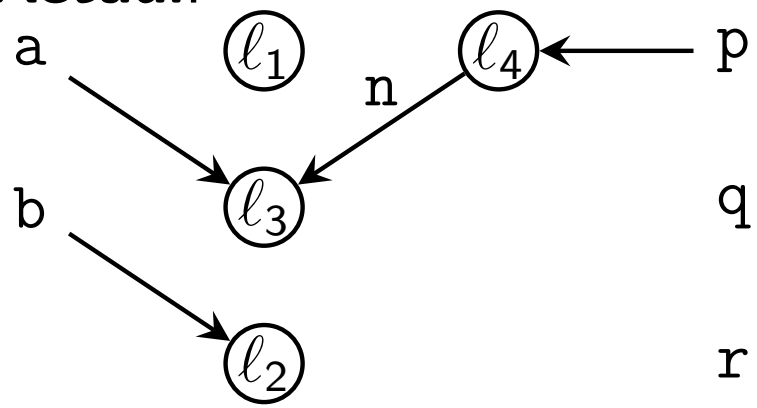
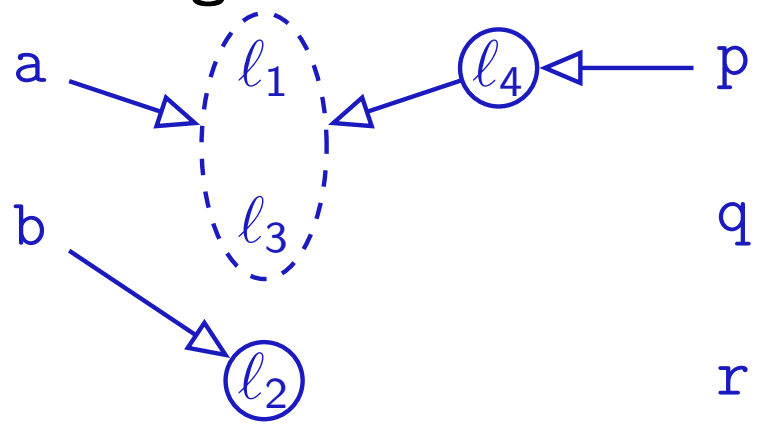
- **Actual**:



- **Steensgaard**:



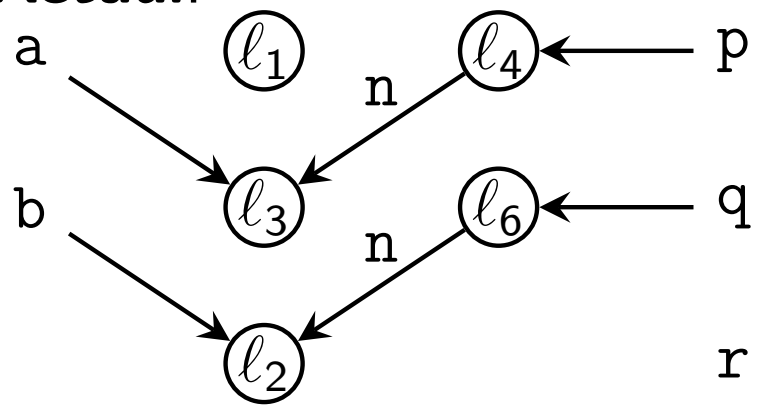
Example

	`x := new`$_{\ell_z}$	$\ell_z \in pt(\mathtt{x})$
	`x := y`	$pt(\mathtt{x}) = pt(\mathtt{y})$
	`x := y.`$\square$	for each $\ell \in pt(\mathtt{y})$ $\implies pt(\mathtt{x}) = pt(\ell)$
$\Rightarrow$	`x.`$\square$ `:= y`	for each $\ell \in pt(\mathtt{x})$ $\implies pt(\mathtt{y}) = pt(\ell)$

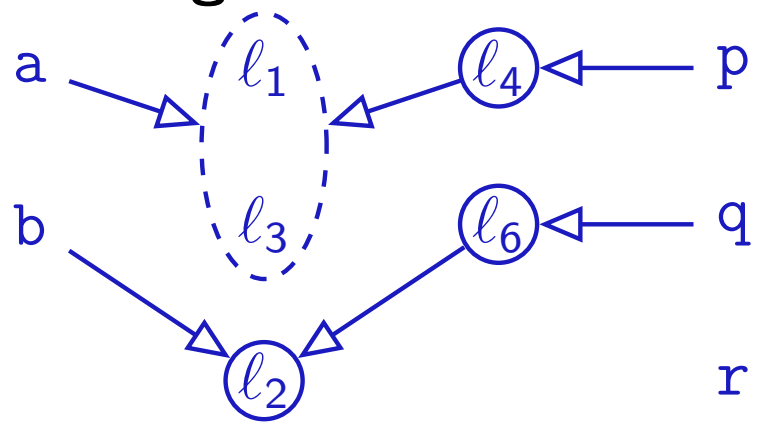
Teal

```
var a := new_ℓ1();
var b := new_ℓ2();
a := new_ℓ3();
var p := new_ℓ4();
p.n := a;
var q := new_ℓ6();
q.n := b;                    //⇐
p := q;
var r := q.n;
```

- **Actual**:



- **Steensgaard**:



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$\Rightarrow$	`x := y`	$pt(\mathtt{x}) = pt(\mathtt{y})$
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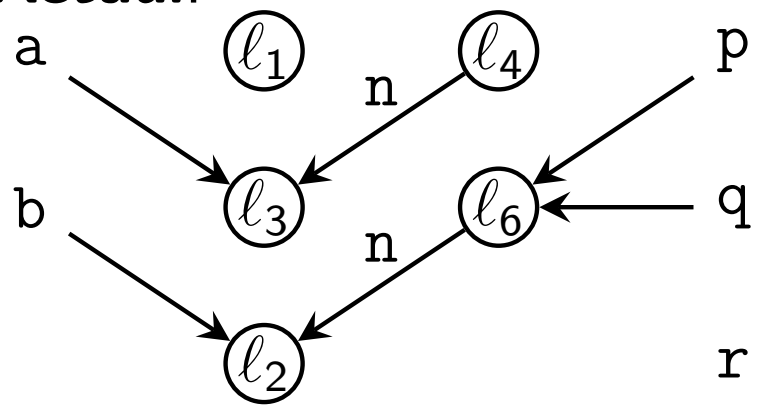
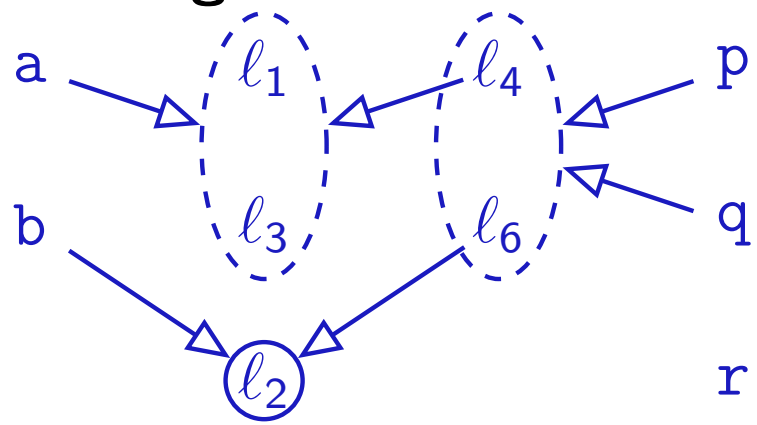
- **Actual**:



- **Steensgaard**:



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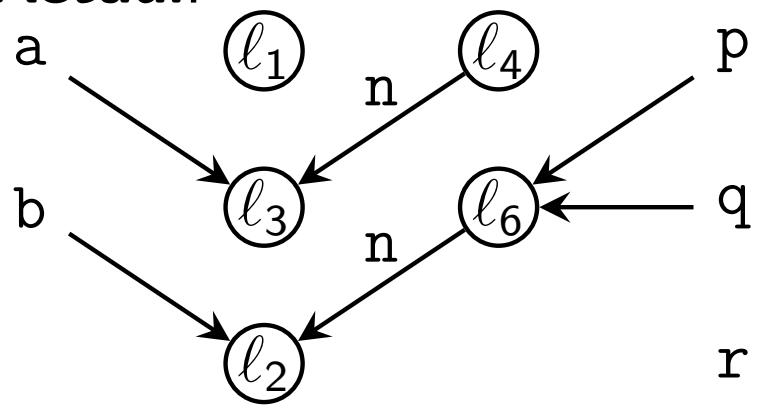
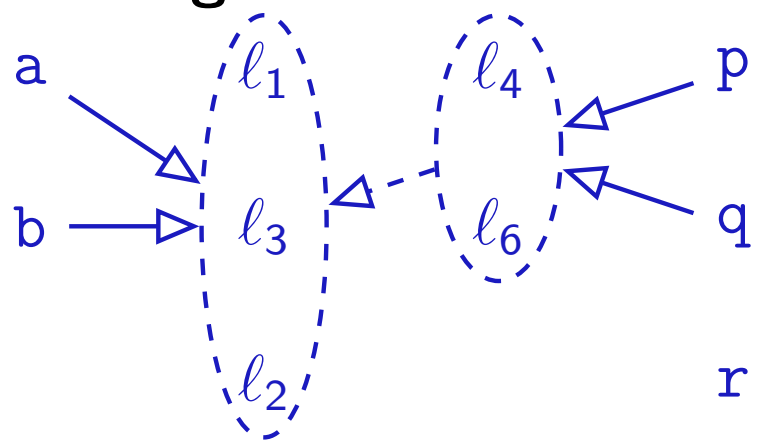
- **Actual**:



- **Steensgaard**:



When merging: 'collapse' children (merge recursively)

Example

	`x := new`$_{\ell_z}$	$\ell_z \in pt(\mathtt{x})$
	`x := y`	$pt(\mathtt{x}) = pt(\mathtt{y})$
$\Rightarrow$	`x := y.`$\square$	for each $\ell \in pt(\mathtt{y})$ $\implies pt(\mathtt{x}) = pt(\ell)$
	`x.`$\square$ `:= y`	for each $\ell \in pt(\mathtt{x})$ $\implies pt(\mathtt{y}) = pt(\ell)$

Teal

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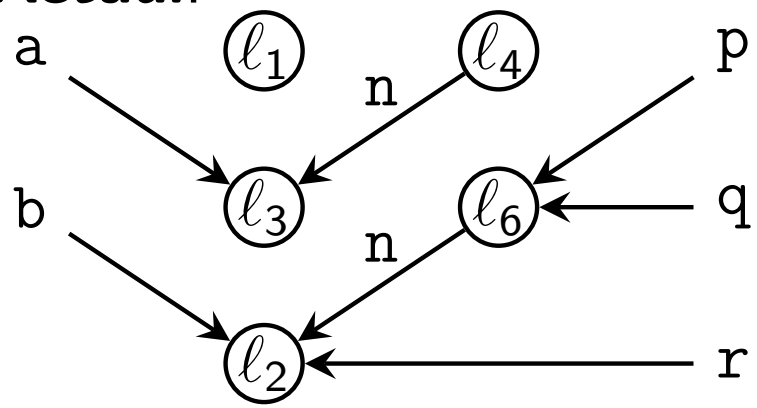
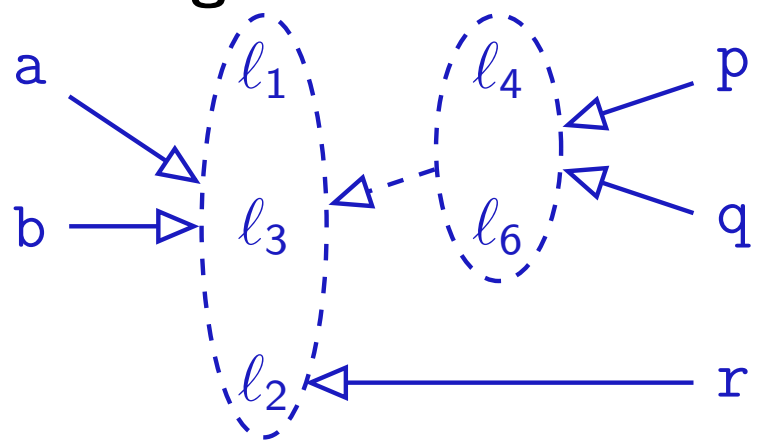
var p := new_ℓ4();
p.n := a;
var q := new_ℓ6();
q.n := b;
p := q;
var r := q.n;      //⇐
```

- **Actual**:



- **Steensgaard**:



When merging: 'collapse' children (merge recursively)

Summary

- Points-to sets $pt(v) = \{\ell \mid v \rightarrowtriangle \ell\}$
  - Partitions abstract heap locations
  - pt thus equivalent to Abstract Heap Graph
- Steensgaard's points-to analysis:
  - special case of *type analysis*
- Steensgaard's analysis in practice:
  - Highly efficient when implemented with Union-Find
  - Less precise than other commonly-used analyses

Outlook

- More pointers on Tuesday
- Lab 2 goes out today
  - Individual exercise (no group)

`https://cs.lth.se/EDAP15`