Pointer Analysis

CS 6340

Introducing Pointers

Example without pointers

[x == 1]

[y == 1]

```
x = 1;
y = x;
assert(y == 1)
```

Same example with pointers

```
x = new Circle();
x.radius = 1;
y = x.radius;
assert(y == 1)
```

Introducing Pointers

Example without pointers

```
x = 1;
[x == 1]
y = x;
[y == 1]
assert(y == 1)
```

Same example with pointers

```
x = new Circle();
x.radius = 1;
[x.radius == 1]
y = x.radius;
[y == 1]
assert(y == 1)
```

Pointer Aliasing

- Situation in which same address referred to in different ways

```
x = new Circle();
x.radius = 1;
[x.radius == 1]
y = x.radius;
[y == 1]
assert(y == 1)
```

```
Circle x = new Circle();
Circle z = ?
x.radius = 1;
[x.radius == 1]
z.radius = 2;
[x.radius == ?]
y = x.radius;
assert(y == 1)
```

May-Alias Analysis

x MAY-ALIAS z?

[x != z]

[x.radius == 1, x != z]

[x.radius == 1]

[y == 1]

```
Circle x = new Circle();
Circle z = new Circle();
x.radius = 1;
z.radius = 2;
y = x.radius;
assert(y == 1)
```

May-Alias Analysis == Pointer Analysis

Must-Alias Analysis

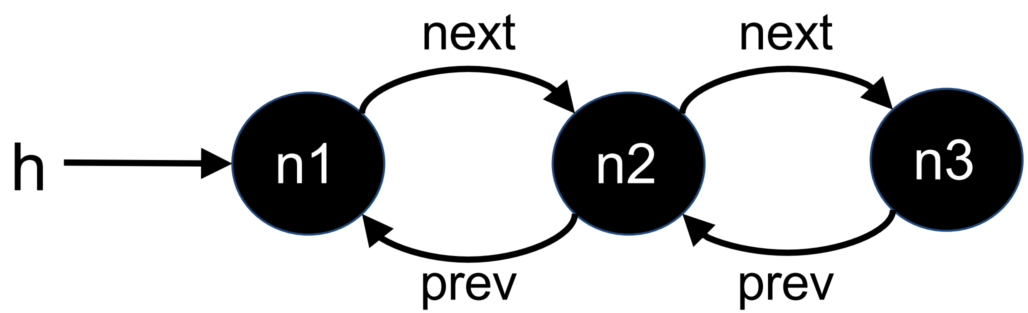
x MUST-ALIAS z?

```
Circle x = new Circle();
Circle z = x;
                          [x == z]
x.radius = 1;
                          [x.radius == 1, x == z]
z.radius = 2;
                          [x.radius == 2]
y = x.radius;
                          [y == 2]
assert(y == 1) y == 2
```

- May-Alias and Must-Alias are dual problems
- Must-Alias more advanced, less useful in practice
- Focus of this Lesson: May-Alias Analysis

Why Is Pointer Analysis Hard?

```
class Node {
  int data;
  Node next, prev;
}

Node h = null;
for (...) {
    Node v = new Node();
    if (h != null) {
        v.next = h;
        h.prev = v;
    }
    h = v;
}
```



h.data
h.next.prev.data
h.next.next.prev.prev.data
h.next.prev.next.prev.data

And many more ...

Approximation to the Rescue

- Pointer analysis problem is undecidable

=> We must sacrifice some combination of:
Soundness, Completeness, Termination

- We are going to sacrifice completeness

=> False positives but no false negatives

What False Positives Mean

x MAY-ALIAS z?

```
Circle x = new Circle();
Circle z = new Circle();
x.radius = 1;
z.radius = 2;
y = x.radius;
assert(y == 1)
```

No

[x != z]

[x.radius == 1, x != z]

[x.radius == 1]

[y == 1]

Yes

[x == z or x != z]

[x.radius == 1, x == z or x != z]

[x.radius == 1 or x.radius == 2]

[y == 1 or y == 2]

False Positive!

Pointer analysis answers questions of form: MayAlias(x, z)?

No => x and z are not aliased in any run

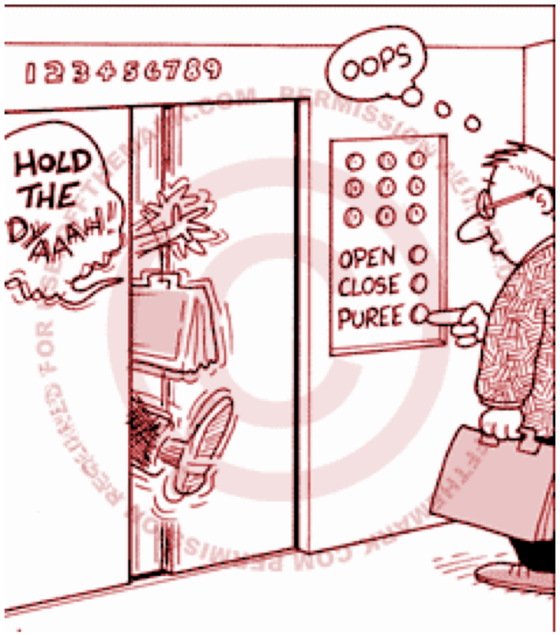
Yes => Can't tell if x and z are aliased in some run

Approximation to the Rescue

- Many sound approximate algorithms for pointer analysis
- Varying levels of precision
- Differ in two key aspects:
  - How to abstract the **heap** (i.e. dynamically allocated data)
  - How to abstract control-flow

Example Java Program

```
class Elevator {
    Object[] floors;
    Object[] events;
}
```

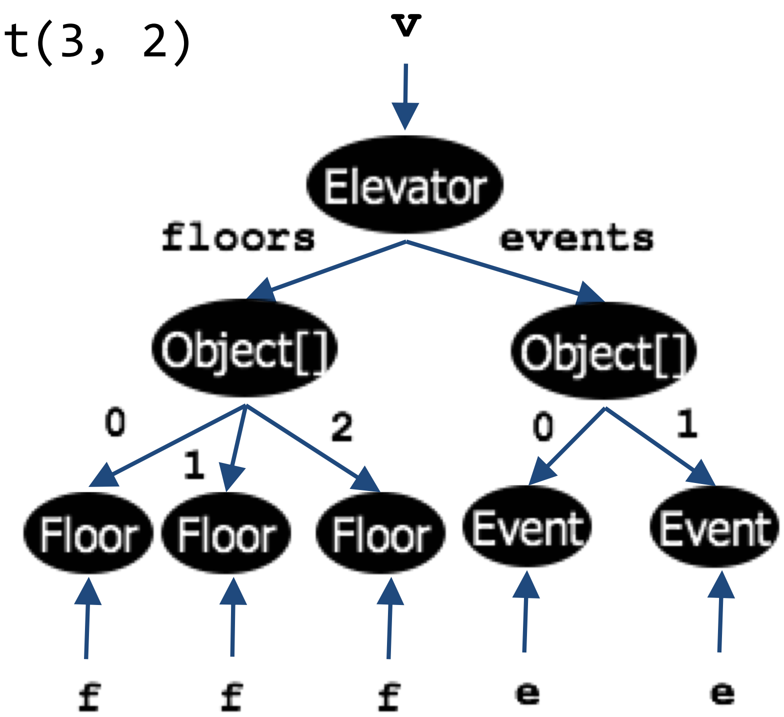



```
void doit(int M, int N) {
   Elevator v = new Elevator();

   v.floors = new Object[M];
   v.events = new Object[N];

   for (int i = 0; i < M; i++) {
       Floor f = new Floor();
       v.floors[i] = f;
   }

   for (int i = 0; i < N; i++) {
       Event e = new Event();
       v.events[i] = e;
   }
}
```

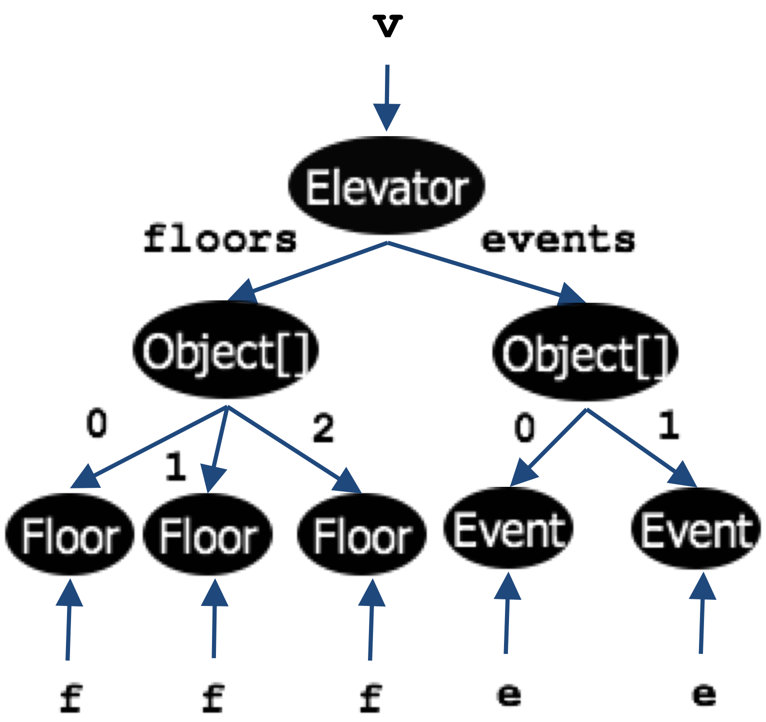
A Run of the Program

```
void doit(int M, int N) {
   Elevator v = new Elevator();

   v.floors = new Object[M];
   v.events = new Object[N];

   for (int i = 0; i < M; i++) {
       Floor f = new Floor();
       v.floors[i] = f;
   }

   for (int i = 0; i < N; i++) {
       Event e = new Event();
       v.events[i] = e;
   }
}
```

doit(3, 2)

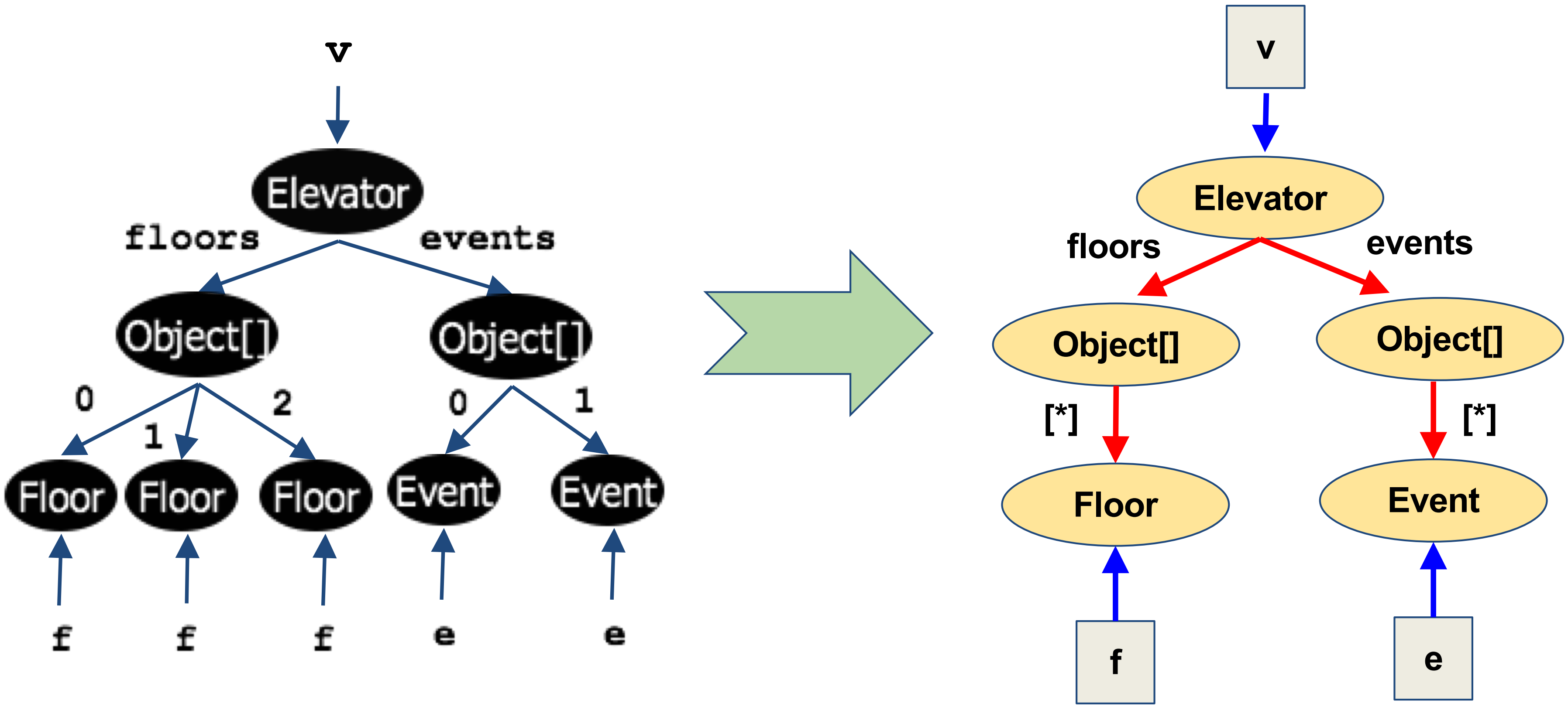


Abstracting the Heap



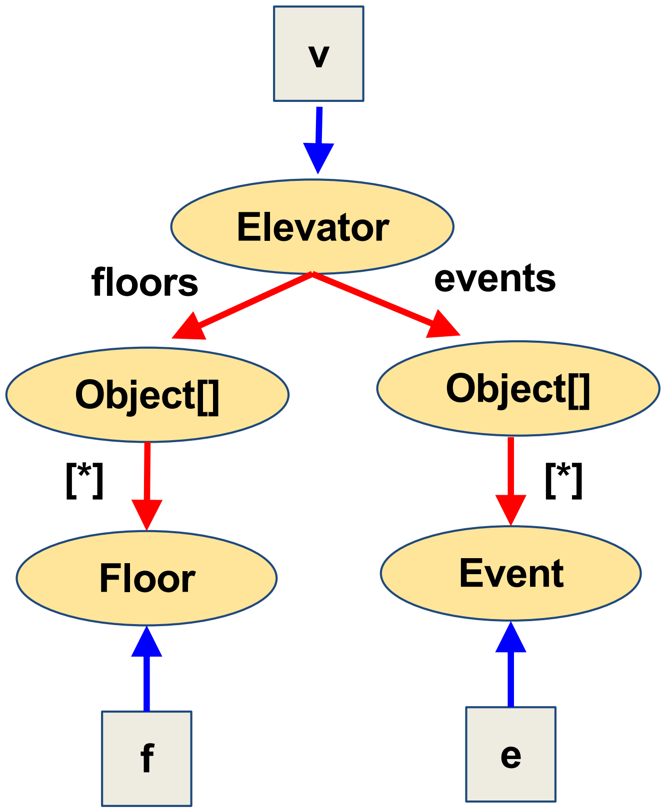

```
void doit(int M, int N) {
   Elevator v = new Elevator();

   v.floors = new Object[M];
   v.events = new Object[N];

   for (int i = 0; i < M; i++) {
       Floor f = new Floor();
       v.floors[i] = f;
   }

   for (int i = 0; i < N; i++) {
       Event e = new Event();
       v.events[i] = e;
   }
}
```

Result of Heap Abstraction: Points-to Graph



Abstracting Control-Flow

```
void doit(int M, int N) {
   Elevator v = new Elevator();

   v.floors = new Object[M];
   v.events = new Object[N];

   for (int i = 0; i < M; i++) {
       Floor f = new Floor();
       v.floors[i] = f;
   }

   for (int i = 0; i < N; i++) {
       Event e = new Event();
       v.events[i] = e;
   }
}
```



Flow Insensitivity

```
void doit(int M, int N) {
   Elevator v = new Elevator();

   v.floors = new Object[M];
   v.events = new Object[N];

   for (int i = 0; i < M; i++) {
       Floor f = new Floor();
       v.floors[i] = f;
   }

   for (int i = 0; i < N; i++) {
       Event e = new Event();
       v.events[i] = e;
   }
}
```

```
void doit(int M, int N) {
    v = new Elevator

    v.floors = new Object[]
    v.events = new Object[]


    f = new Floor
    v.floors[*] = f



    e = new Event
    v.events[*] = e

}
```

Chaotic Iteration Algorithm

```
graph = empty
repeat:
    for (each statement s in set)
        apply rule corresponding to s on graph
until graph stops changing
```

Kinds of Statements

(statement) s ::= v = new … | v = v2 | v2 = v.f | v.f = v2 | v2 = v[*] | v[*] = v2

(pointer-type variable) v

(pointer-type field) f

Is This Grammar Enough?

v = new … | v = v2 | v2 = v.f |
v.f = v2 | v2 = v[*] | v[*] = v2

```
v.events = new Object[]    ⇒    tmp = new Object[]
                                v.events = tmp

v.events[*] = e            ⇒    tmp = v.events
                                tmp[*] = e
```

Example Program in Normal Form

```
void doit(int M, int N) {
    v = new Elevator


    v.floors = new Object[]
    v.events = new Object[]


    f = new Floor
    v.floors[*] = f


    e = new Event
    v.events[*] = e

}
```

```
void doit(int M, int N) {
    v = new Elevator

    tmp1 = new Object[]
    v.floors = tmp1
    tmp2 = new Object[]
    v.events = tmp2

    f = new Floor
    tmp3 = v.floors
    tmp3[*] = f

    e = new Event
    tmp4 = v.events
    tmp4[*] = e
}
```

QUIZ: Normal Form of Programs

v = new … | v = v2 | v2 = v.f |
v.f = v2 | v2 = v[*] | v[*] = v2

Convert each of these two expressions to normal form:

```
v1.f = v2.f
```

```
v1.f.g = v2.h
```

QUIZ: Normal Form of Programs

v = new … | v = v2 | v2 = v.f |
v.f = v2 | v2 = v[*] | v[*] = v2

Convert each of these two expressions to normal form:

```
v1.f = v2.f
```

⇒

```
tmp = v2.f
v1.f = tmp
```

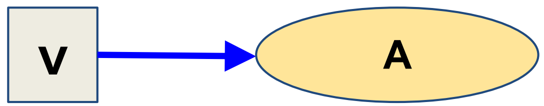
```
v1.f.g = v2.h
```

⇒

```
tmp1 = v1.f
tmp2 = v2.h
tmp1.g = tmp2
```

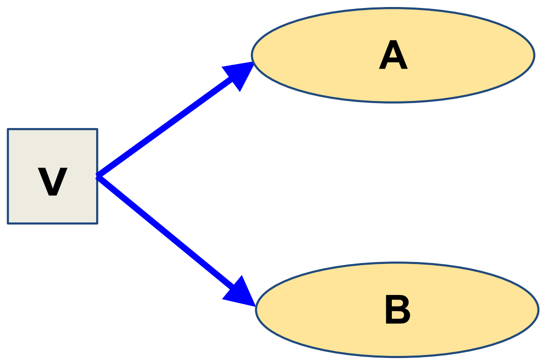
Rule for Object Allocation Sites

Before:



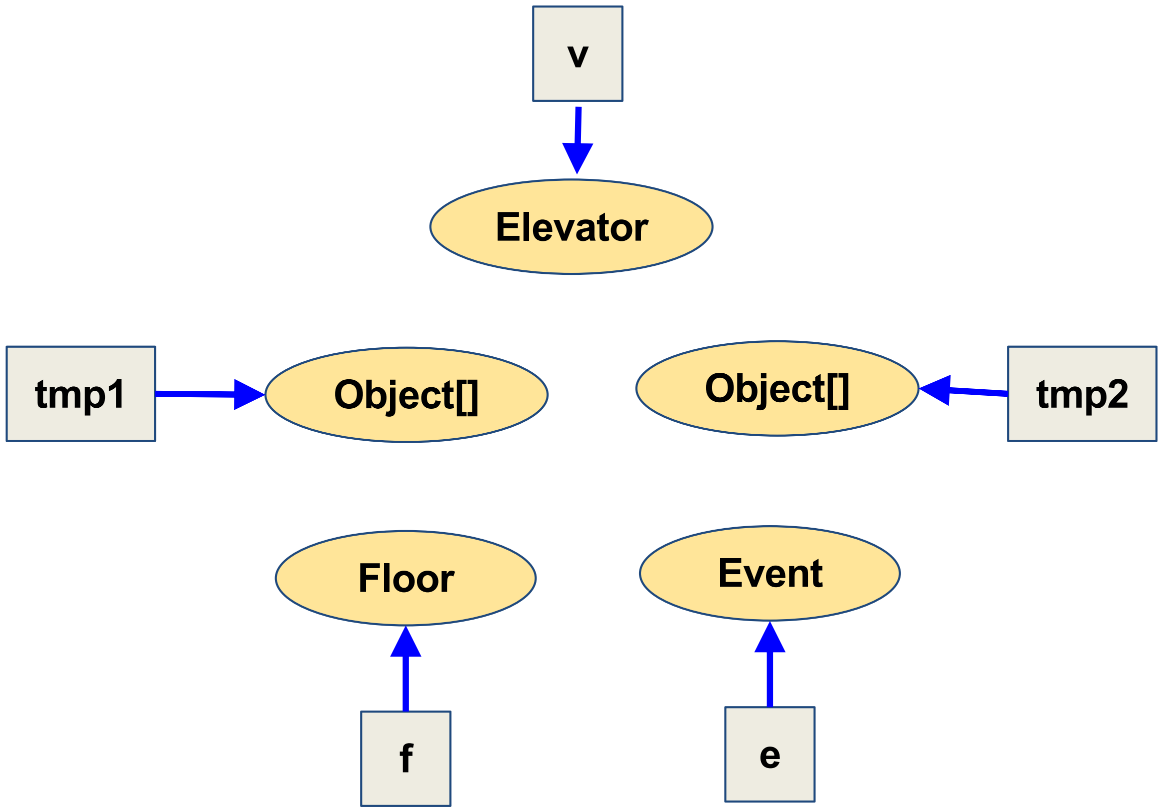

```
v = new B
```

After:

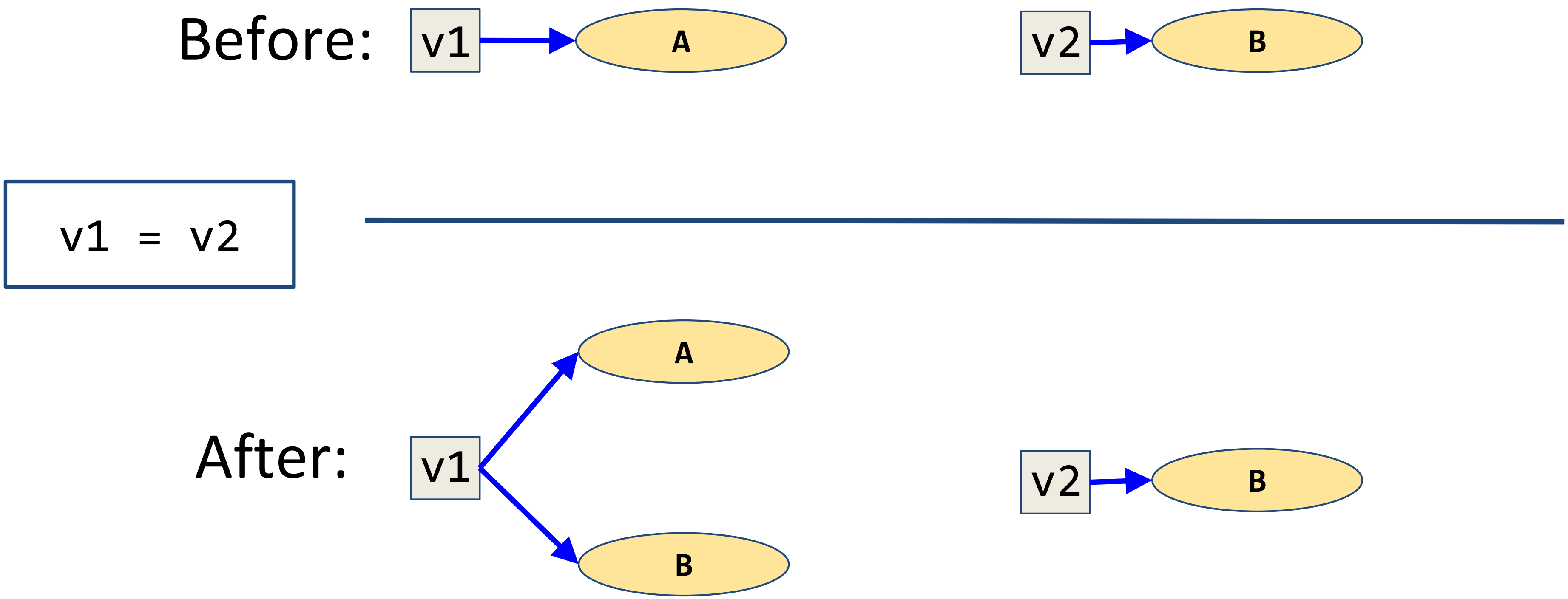


Rule for Object Allocation Sites: Example

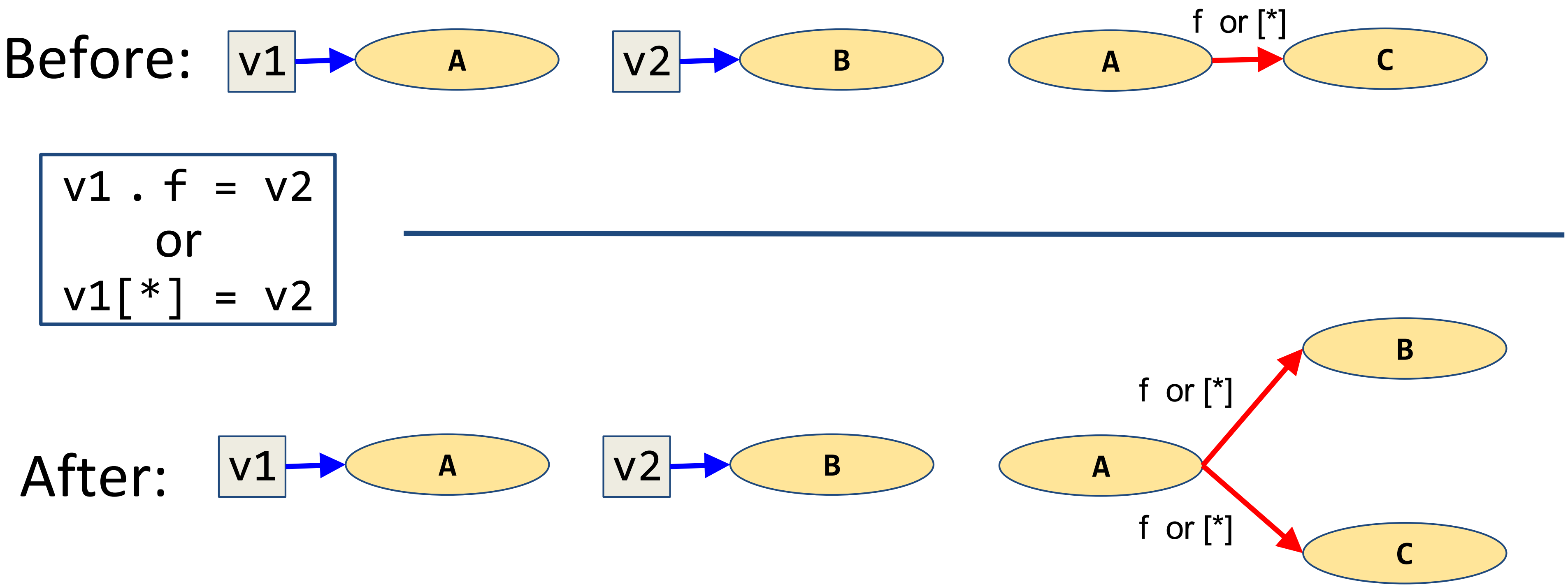
```
void doit(int M, int N) {
    v = new Elevator

    tmp1 = new Object[]
    v.floors = tmp1
    tmp2 = new Object[]
    v.events = tmp2

    f = new Floor
    tmp3 = v.floors
    tmp3[*] = f

    e = new Event
    tmp4 = v.events
    tmp4[*] = e
}
```



Rule for Object Copy

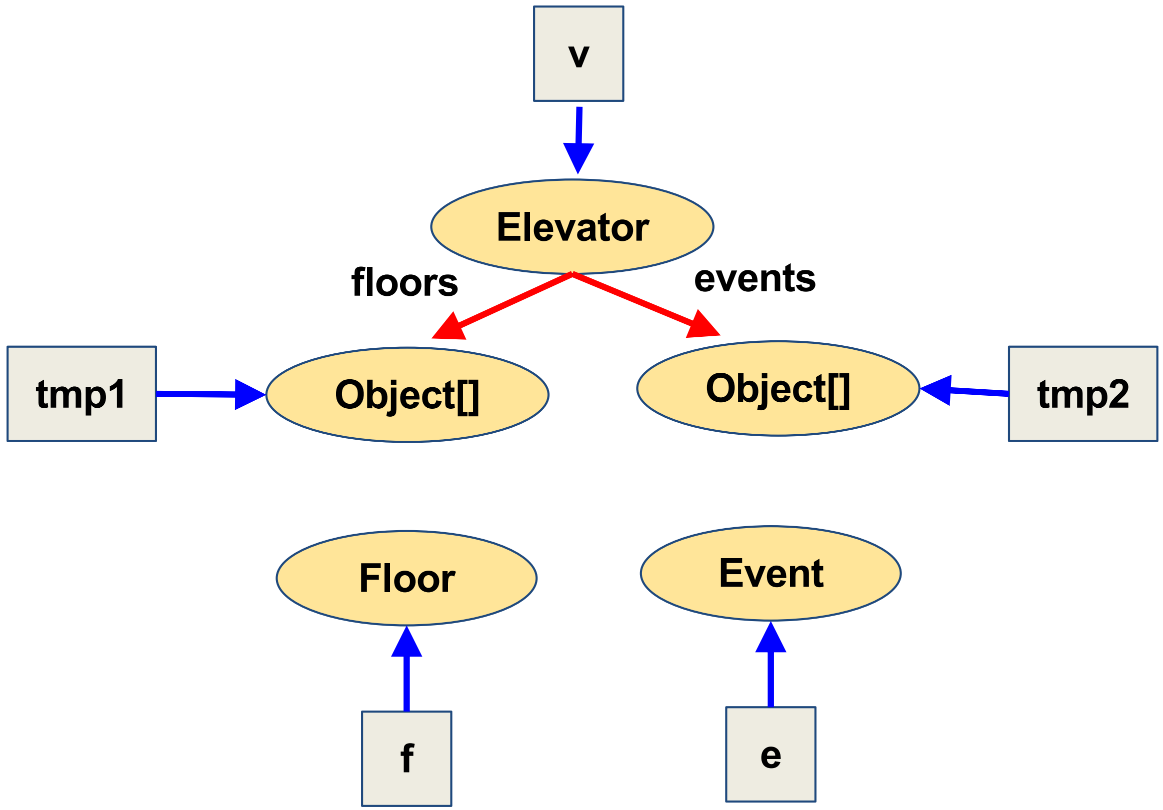


Rule for Field Writes

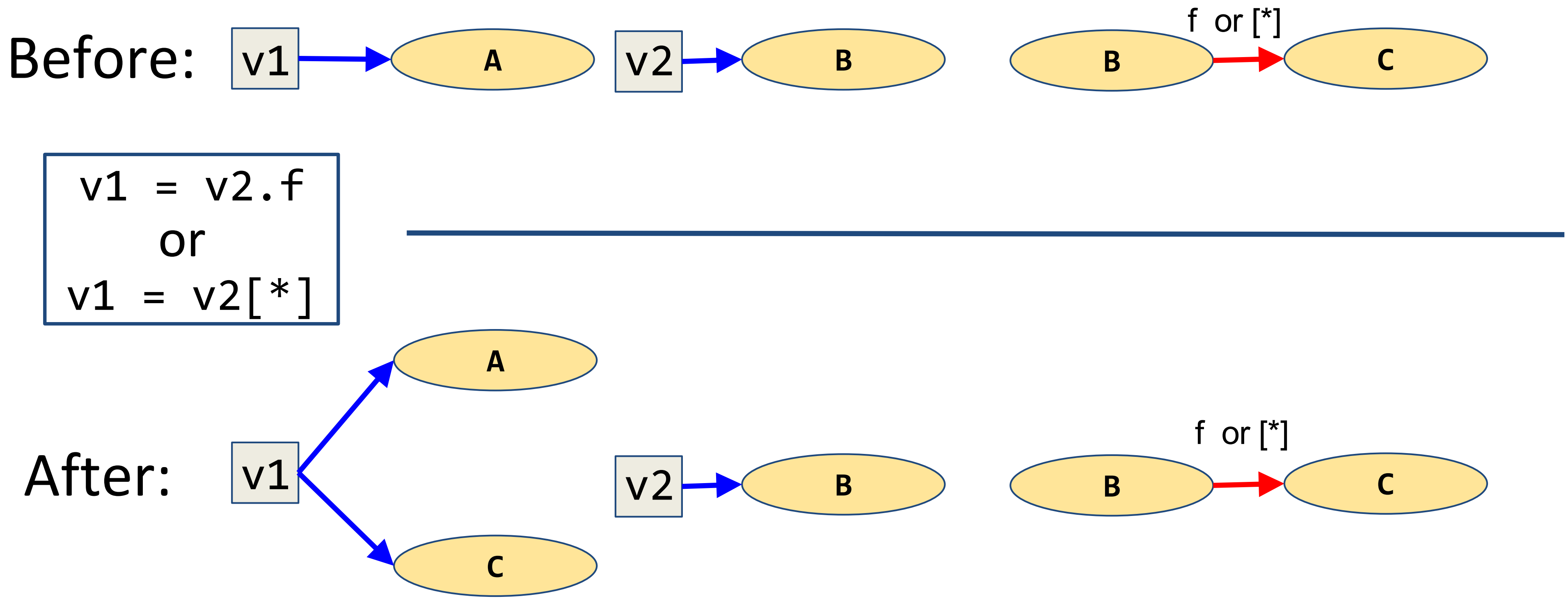


Rule for Field Writes: Example

```
void doit(int M, int N) {
    v = new Elevator

    tmp1 = new Object[]
    v.floors = tmp1
    tmp2 = new Object[]
    v.events = tmp2

    f = new Floor
    tmp3 = v.floors
    tmp3[*] = f

    e = new Event
    tmp4 = v.events
    tmp4[*] = e
}
```

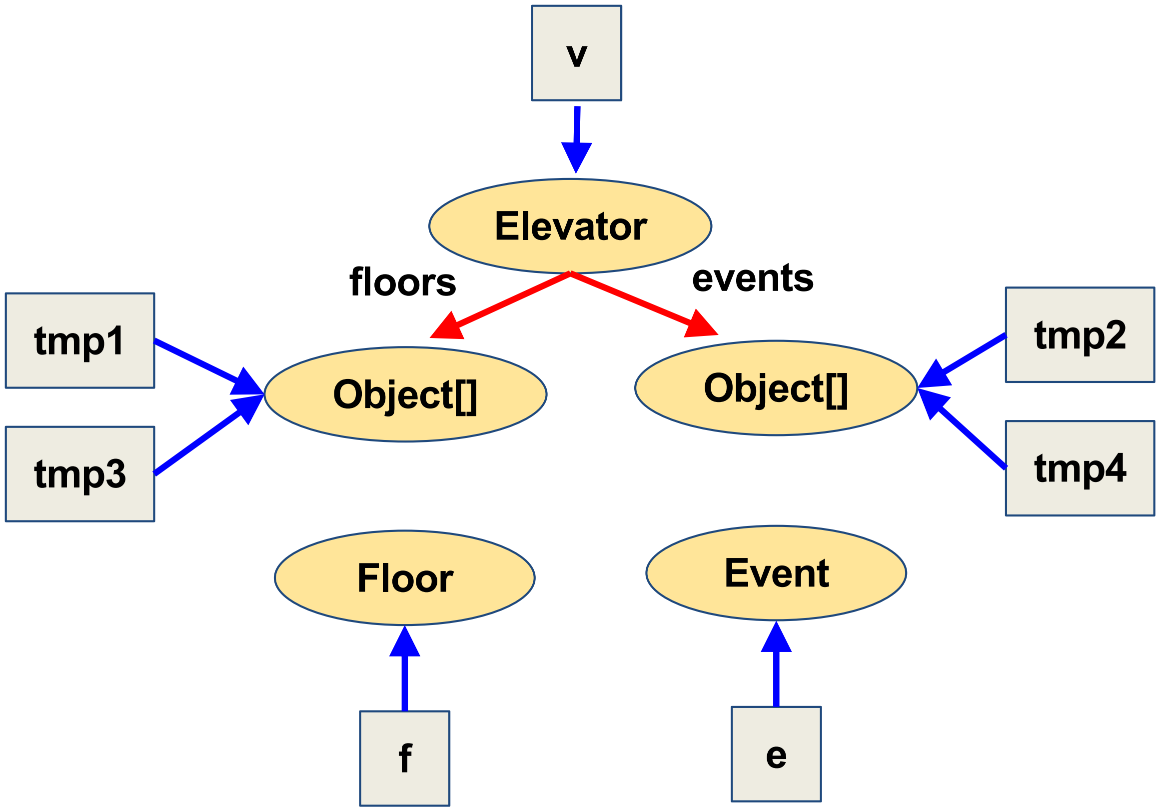


Rule for Field Reads



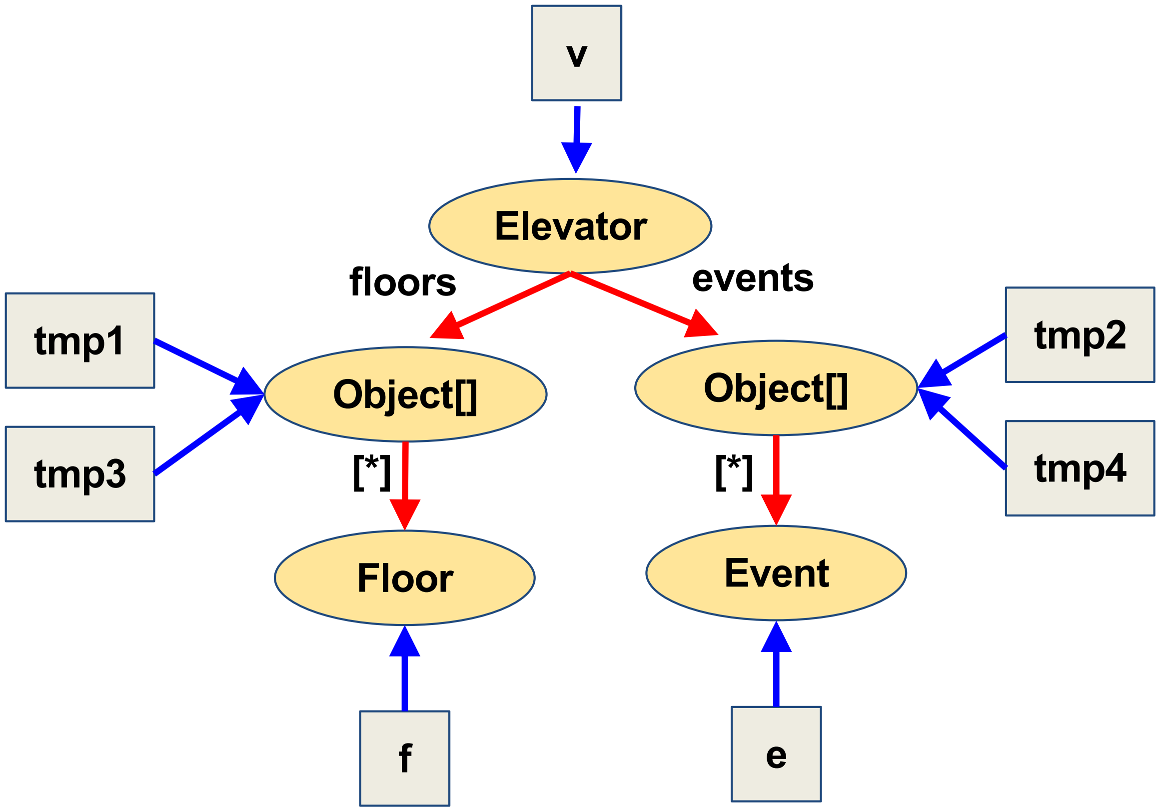
Rule for Field Reads: Example

```
void doit(int M, int N) {
    v = new Elevator

    tmp1 = new Object[]
    v.floors = tmp1
    tmp2 = new Object[]
    v.events = tmp2

    f = new Floor
    tmp3 = v.floors
    tmp3[*] = f

    e = new Event
    tmp4 = v.events
    tmp4[*] = e
}
```



Continuing the Pointer Analysis: Example

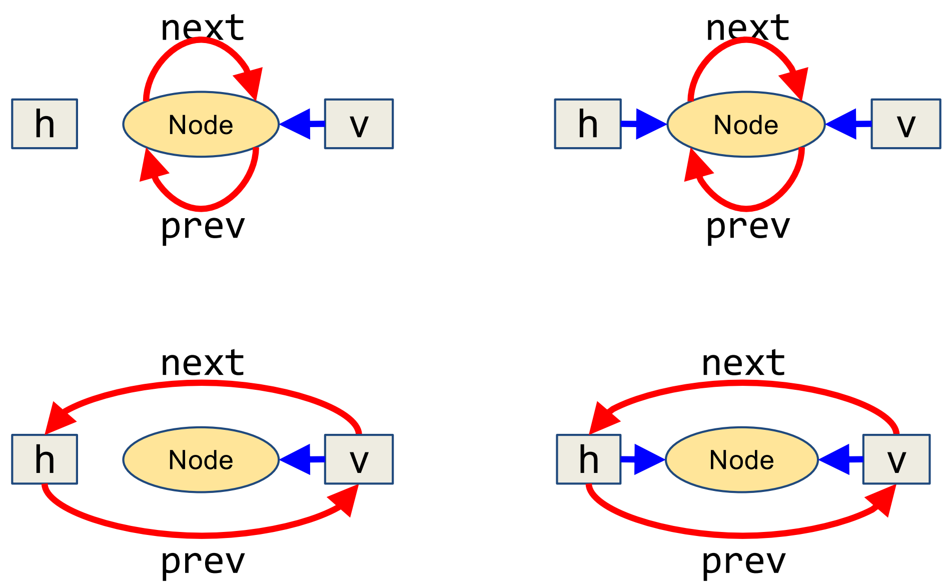
```
void doit(int M, int N) {
    v = new Elevator

    tmp1 = new Object[]
    v.floors = tmp1
    tmp2 = new Object[]
    v.events = tmp2

    f = new Floor
    tmp3 = v.floors
    tmp3[*] = f

    e = new Event
    tmp4 = v.events
    tmp4[*] = e
}
```



QUIZ: Pointer Analysis Example

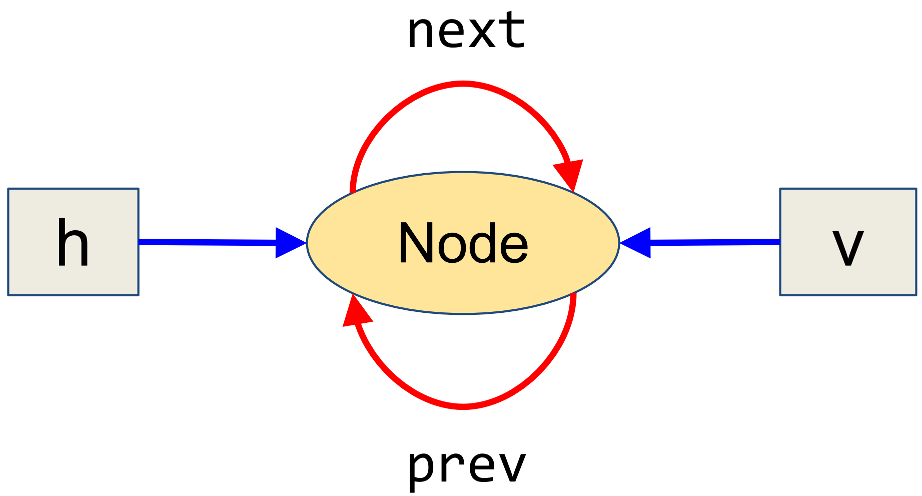
```
class Node {
  int data;
  Node next, prev;
}

Node h = null;
for (...) {
    Node v = new Node();
    if (h != null) {
        v.next = h;
        h.prev = v;
    }
    h = v;
}
```

Choose the points-to graph for the shown program.



QUIZ: Pointer Analysis Example

```
class Node {
  int data;
  Node next, prev;
}

Node h = null;
for (...) {
    Node v = new Node();
    if (h != null) {
        v.next = h;
        h.prev = v;
    }
    h = v;
}
```



Classifying Pointer Analysis Algorithms

- Is it flow-sensitive?
- Is it context-sensitive?
- What heap abstraction scheme is used?
- How are aggregate data types modeled?

Flow Sensitivity

- How to model control-flow **within** a procedure
- Two kinds: flow-insensitive vs. flow-sensitive
- Flow-insensitive == **weak updates**
  - Suffices for may-alias analysis
- Flow-sensitive == **strong updates**
  - Required for must-alias analysis

Context Sensitivity

- How to model control-flow **across** procedures
- Two kinds: context-insensitive vs. context-sensitive
- Context-insensitive: analyze each procedure once
- Context-sensitive: analyze each procedure possibly multiple times, once per abstract calling context

Heap Abstraction

- Scheme to partition unbounded set of concrete objects into finitely many abstract objects (oval nodes in points-to graph)

- Ensures that pointer analysis terminates

- Many sound schemes, varying in precision & efficiency
  - Too few abstract objects => efficient but imprecise
  - Too many abstract objects => expensive but precise

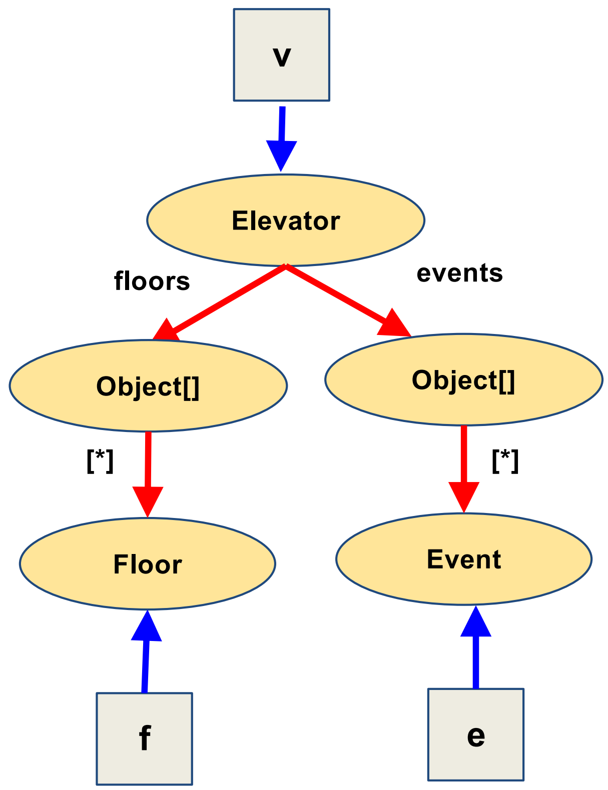
Scheme #1: Allocation-Site Based

One abstract object per **allocation site**

Allocation site identified by:

- **new** keyword in Java/C++
- **malloc**() call in C

Finitely many allocation sites in a program
=> finitely many abstract objects

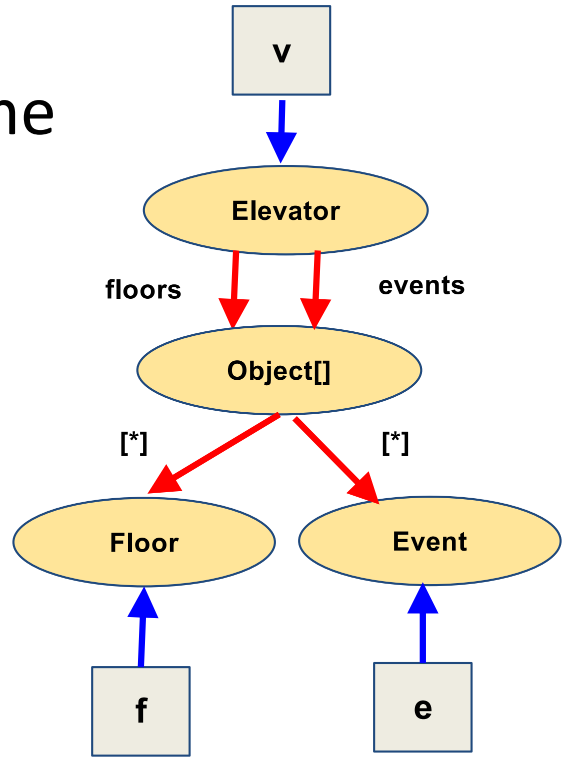


Scheme #2: Type Based

- Allocation-site based scheme can be costly
  - Large programs
  - Clients needing quick turnaround time
  - Overly fine granularity of sites

- One abstract object per type

- Finitely many types in a program
  => finitely many abstract objects

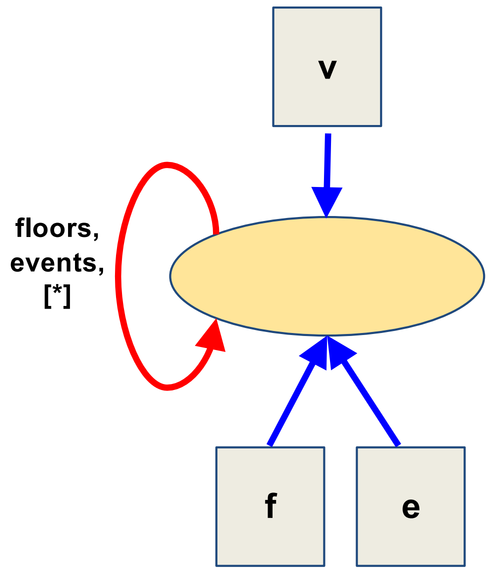


Scheme #3: Heap-Insensitive

Single abstract object representing entire heap

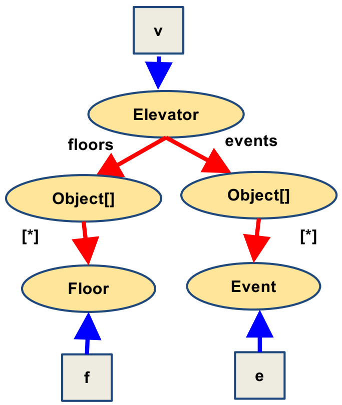
Popular for languages with primarily stack-directed pointers (e.g. C)

Unsuitable for languages with only heap-directed pointers (e.g. Java)

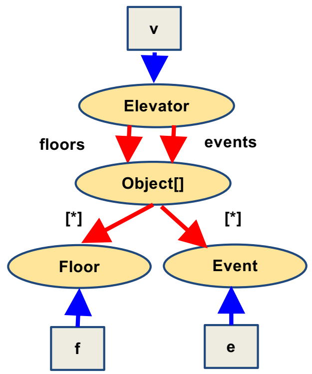


Tradeoffs in Heap Abstraction Schemes

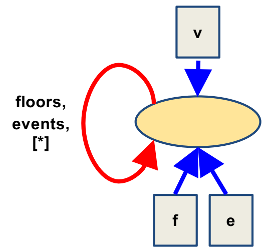
More Precise



Allocation-site based



Type based



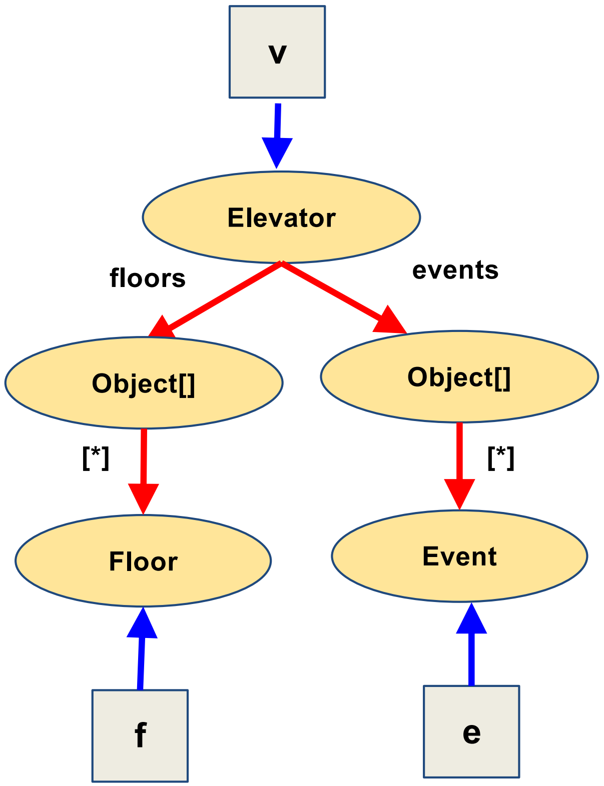
Heap-insensitive

More Efficient

QUIZ: May-Alias Analysis

Do the expression pairs may-alias under these two pointer analyses?

May-Alias?	Allocation-Site Based	Type Based
`e, f`	No	
`v.floors, v.events`		
`v.floors[0], v.events[0]`		
`v.events[0], v.events[2]`	Yes	



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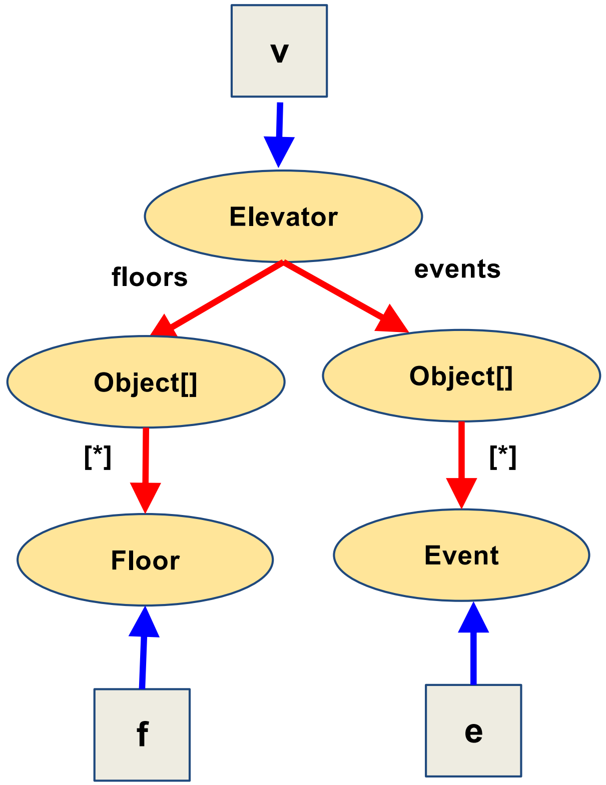
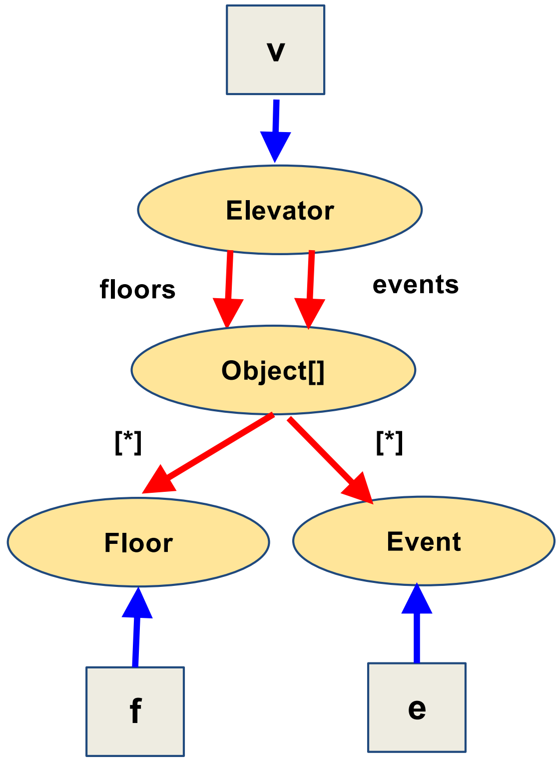


QUIZ: May-Alias Analysis

Do the expression pairs may-alias under these two pointer analyses?

May-Alias?	Allocation-Site Based	Type Based
`e, f`	No	No
`v.floors, v.events`	No	Yes
`v.floors[0], v.events[0]`	No	Yes
`v.events[0], v.events[2]`	Yes	Yes



Modeling Aggregate Data Types: Arrays

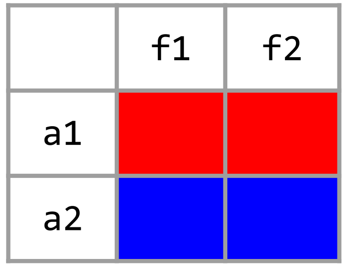
- Common choice: single field [*] to represent all array elements
  - Cannot distinguish different elements of same array

- More sophisticated representations that make such distinctions are employed by array dependence analyses
  - Used to parallelize sequential loops by parallelizing compilers

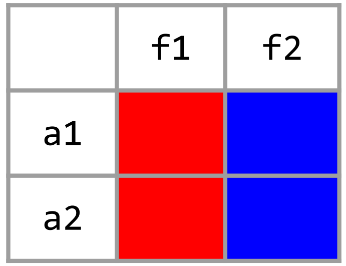
Modeling Aggregate Data Types: Records

Three choices:

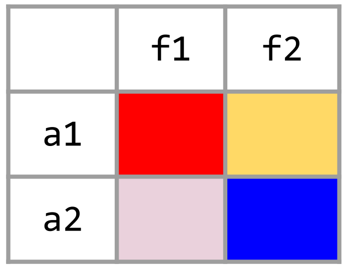
1. Field-insensitive: merge **all** fields of **each** record object



2. Field-based: merge **each** field of **all** record objects



3. Field-sensitive: keep **each** field of **each** (abstract) record object separate



QUIZ: Pointer Analysis Classification

Classify the pointer analysis algorithm we learned in this lesson.

Flow-sensitive?		A. Yes	B. No
Context-sensitive?		A. Yes	B. No
Distinguishes fields of object?		A. Yes	B. No
Distinguishes elements of array?		A. Yes	B. No
What kind of heap abstraction?		A. Allocation-site based	B. Type based

QUIZ: Pointer Analysis Classification

Classify the pointer analysis algorithm we learned in this lesson.

Flow-sensitive?	B	A. Yes	B. No
Context-sensitive?	B	A. Yes	B. No
Distinguishes fields of object?	A	A. Yes	B. No
Distinguishes elements of array?	B	A. Yes	B. No
What kind of heap abstraction?	A	A. Allocation-site based	B. Type based

What Have We Learned?

- What is pointer analysis?
- May-alias analysis vs. must-alias analysis
- Points-to graphs
- Working of a pointer analysis algorithm
- Classifying pointer analyses: flow sensitivity, context sensitivity, heap abstraction, aggregate modeling