Static Extraction of Sound Hierarchical Object Graphs

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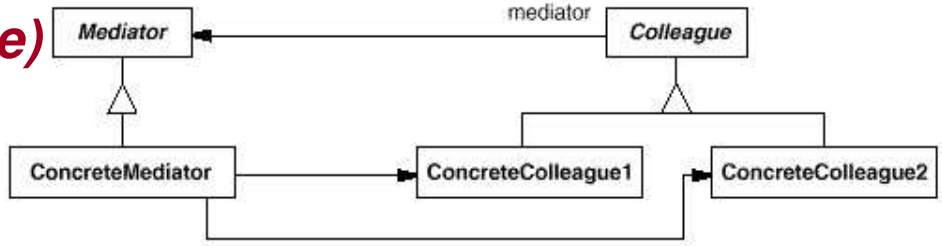
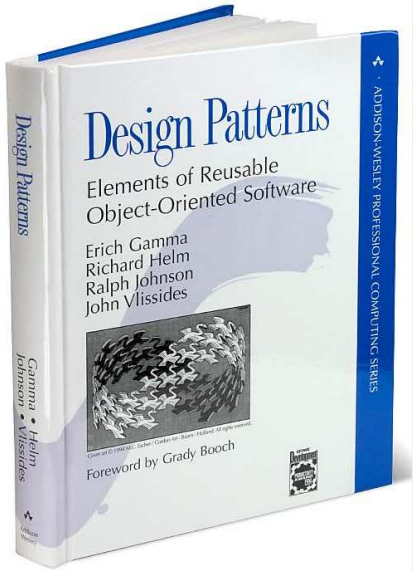
Structure

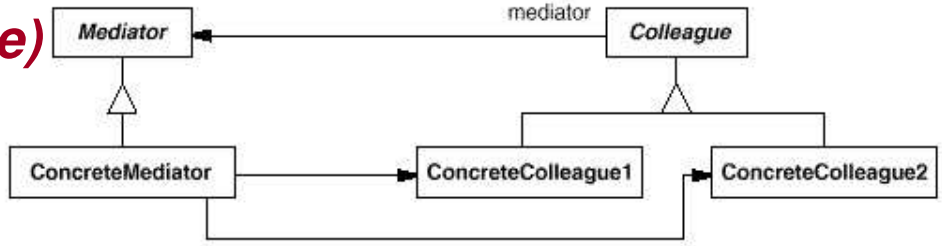
Class Diagram (Type structure)





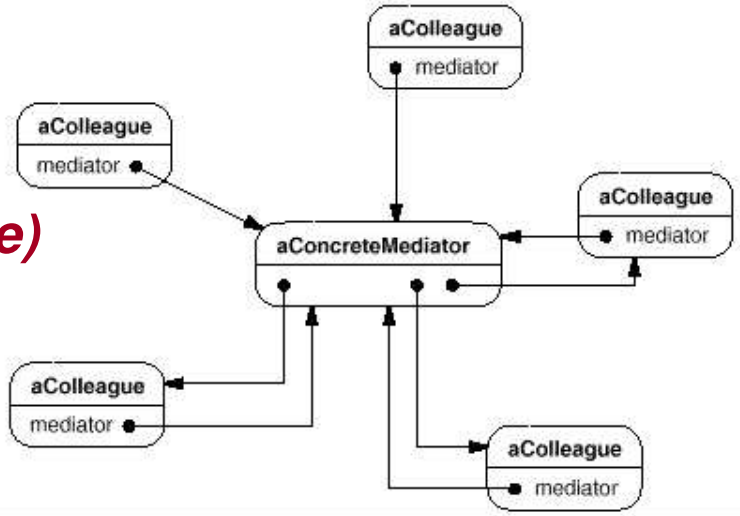
Structure

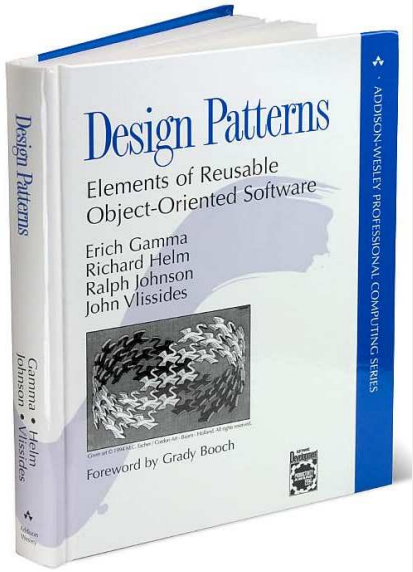
Class Diagram (Type structure)



A typical object structure might look like this:

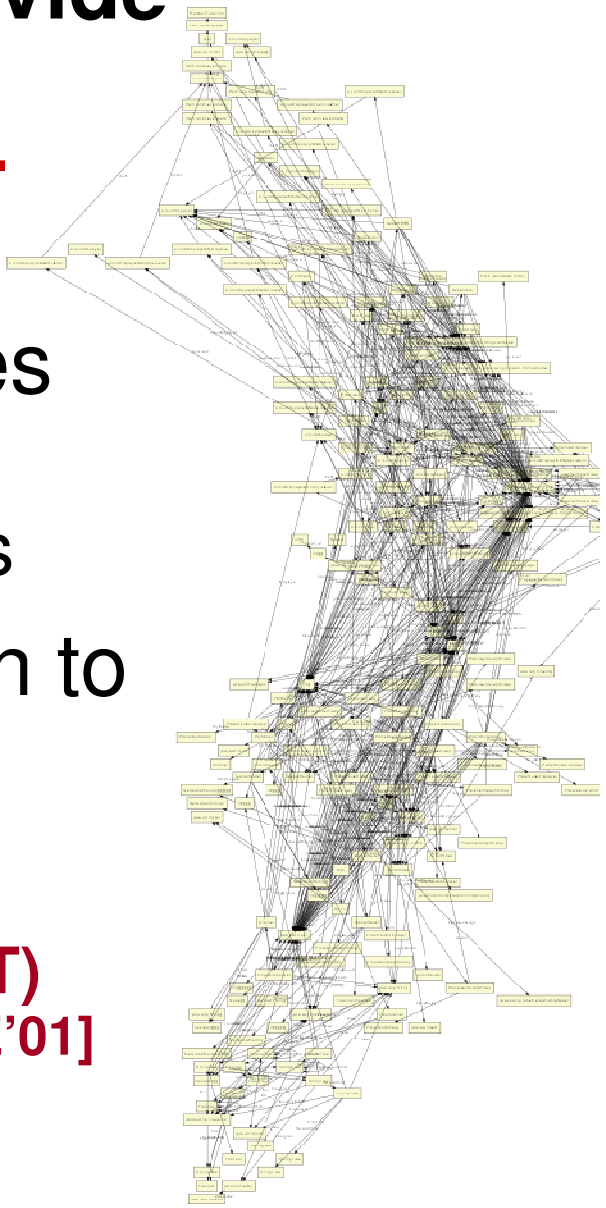
Object diagram (Instance structure)





Flat object graphs do not provide architectural abstraction

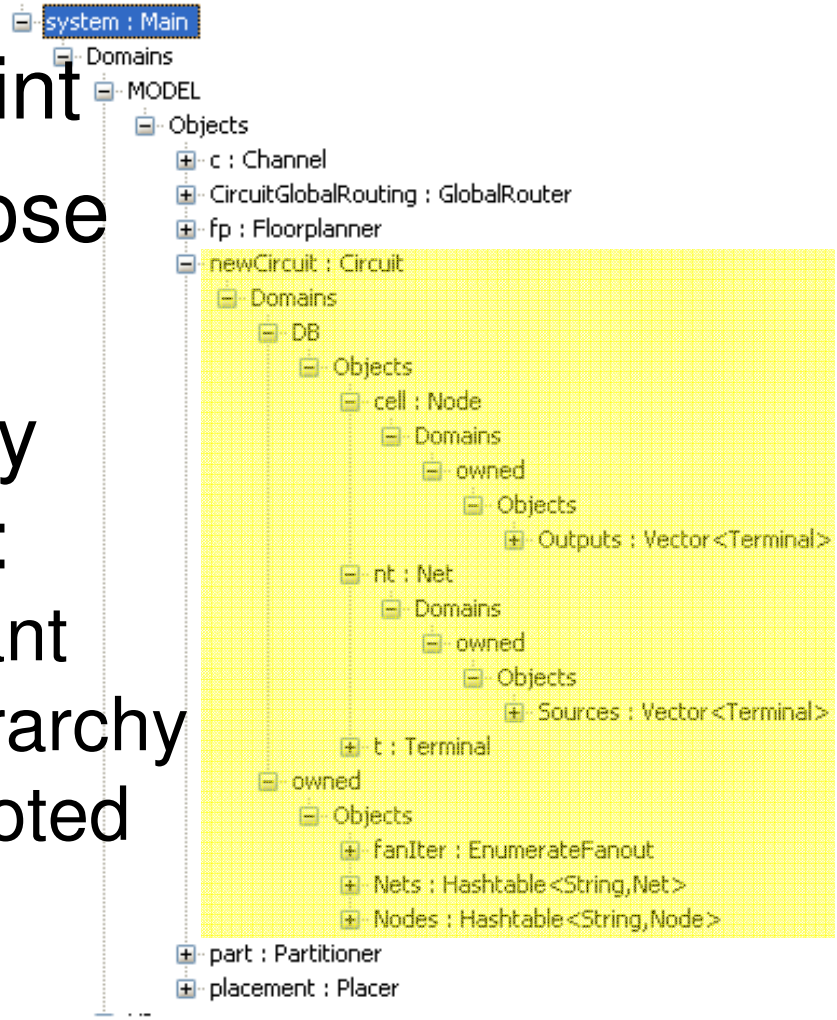
- Low-level objects mixed with architecturally significant ones
  - Show plethora of objects
  - No scale-up to large programs
- Require graph summarization to get readability [Mitchell, ECOOP'06]



Output of WOMBLE (MIT)
[Jackson and Waingold, TSE'01]
on 8,000-line system.

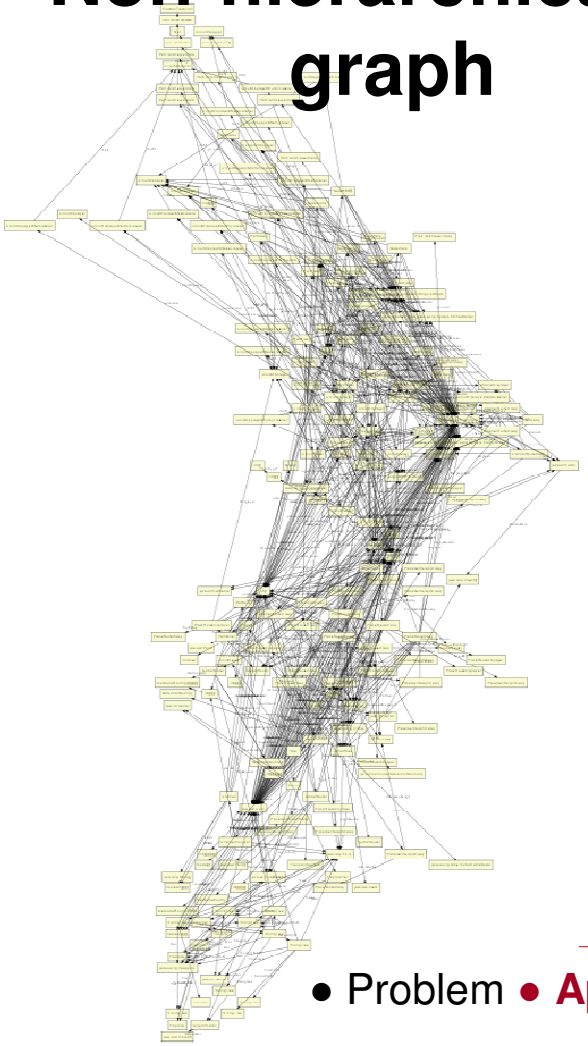
Use hierarchy to convey architectural abstraction

- Pick top-level entry point
- Use ownership to impose conceptual hierarchy
- Convey **abstraction** by **ownership hierarchy**:
  - Architecturally significant objects near top of hierarchy
  - Low-level objects demoted further down

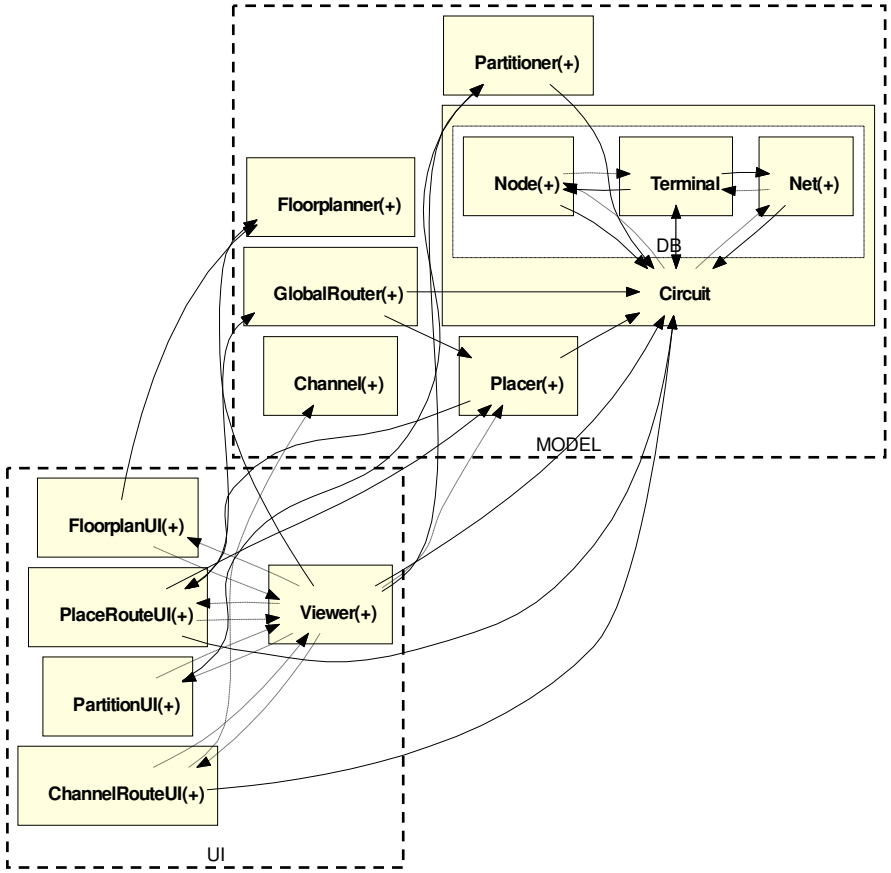


Collapse objects based on ownership (and types) to achieve abstraction

Non-hierarchical graph



Hierarchical graph



Central difficulty

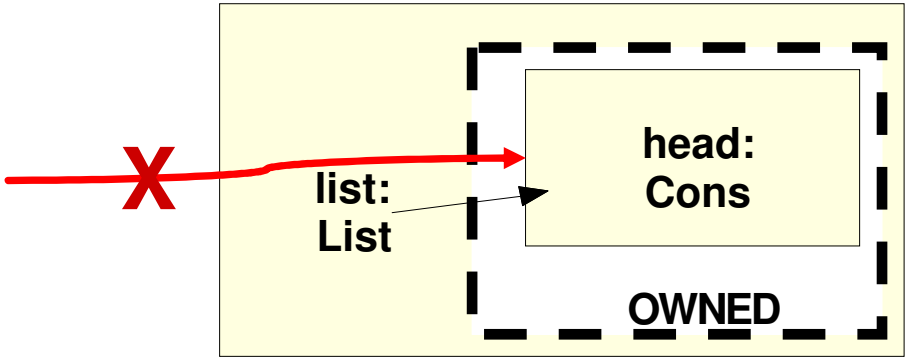
Architectural hierarchy not readily observable in program written in general purpose programming language

Core result

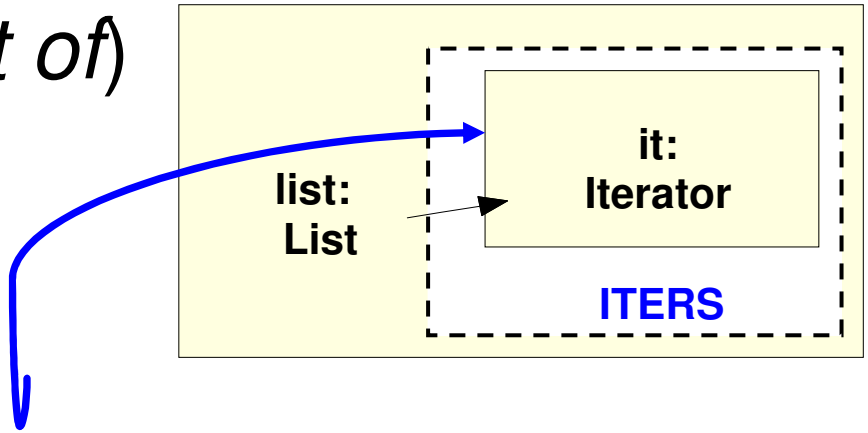
Leverage ownership type annotations to extract **hierarchical** object graph using **static analysis**

Annotations specify design intent

- Strict encapsulation (owned by)



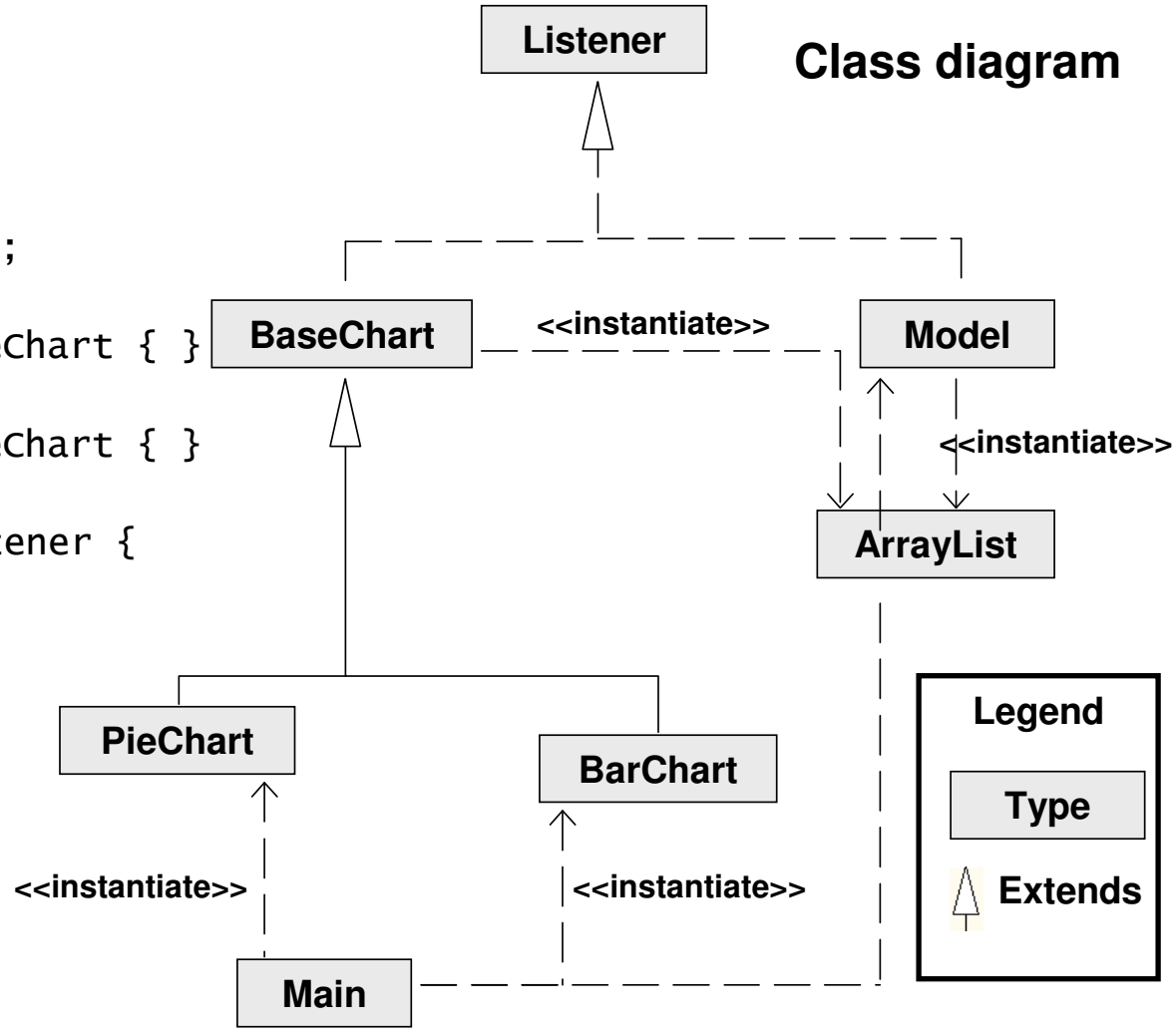
- Logical containment (conceptually *part of*)



Example: Listener system

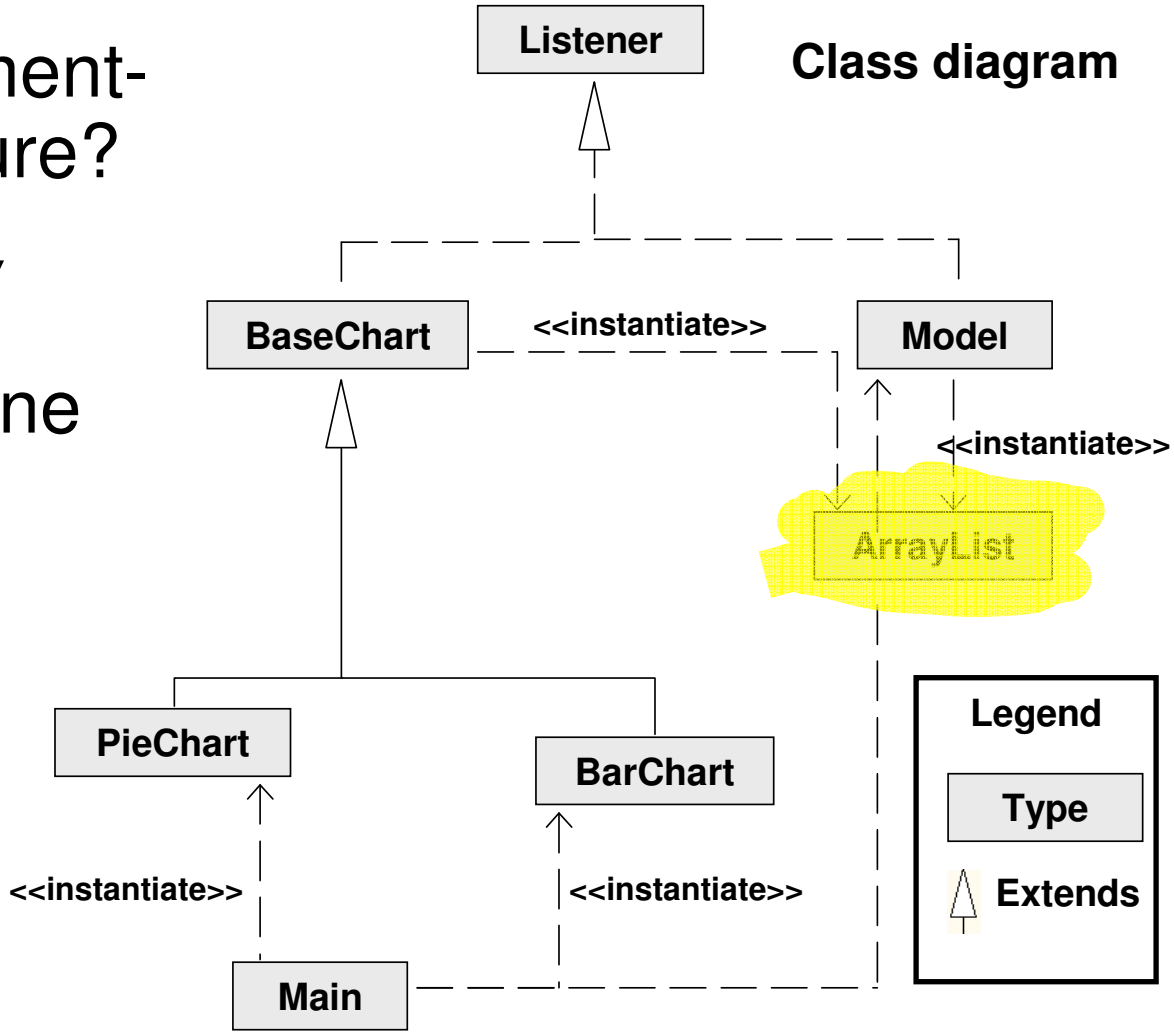
Listeners are hard to understand

```
interface Listener { }

class BaseChart
      implements Listener {
  List< Listener> listeners;
}
class BarChart extends BaseChart { }

class PieChart extends BaseChart { }

class Model implements Listener {
  List<Listener> listeners;
 }

class Main {
  Model model;
  BarChart barChart;
  PieChart pieChart;
}
```



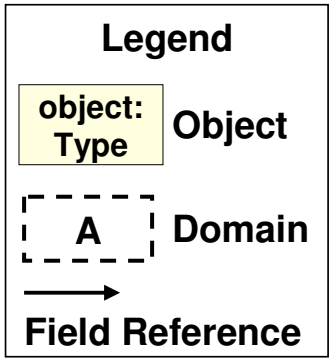
Class diagram leaves unanswered…

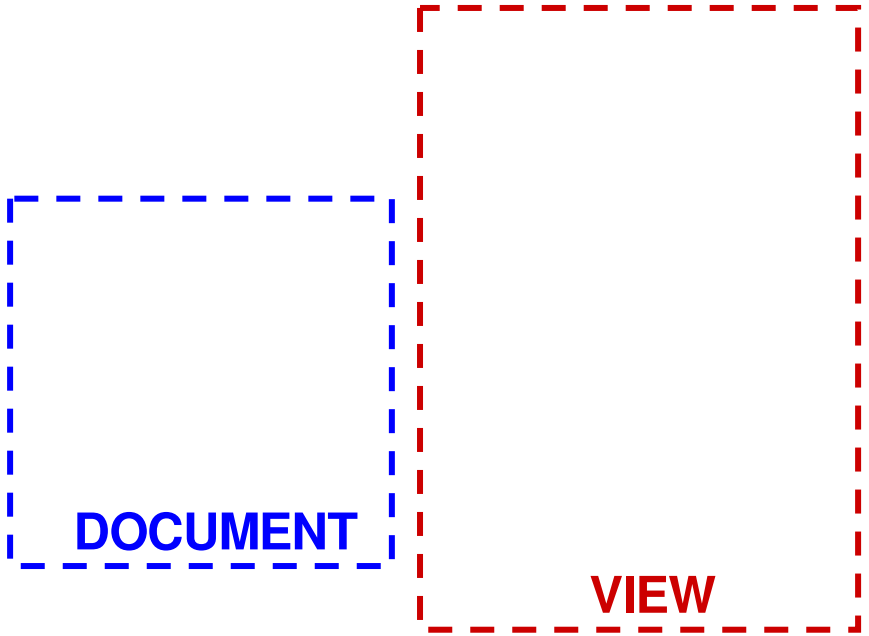
- Is this a Document-View architecture?
- Do `PieChart`, `BarChart`, `Model` share one `Listener`?
- Are different `ArrayList` instances conceptually different?



Object graph complements information in class diagram

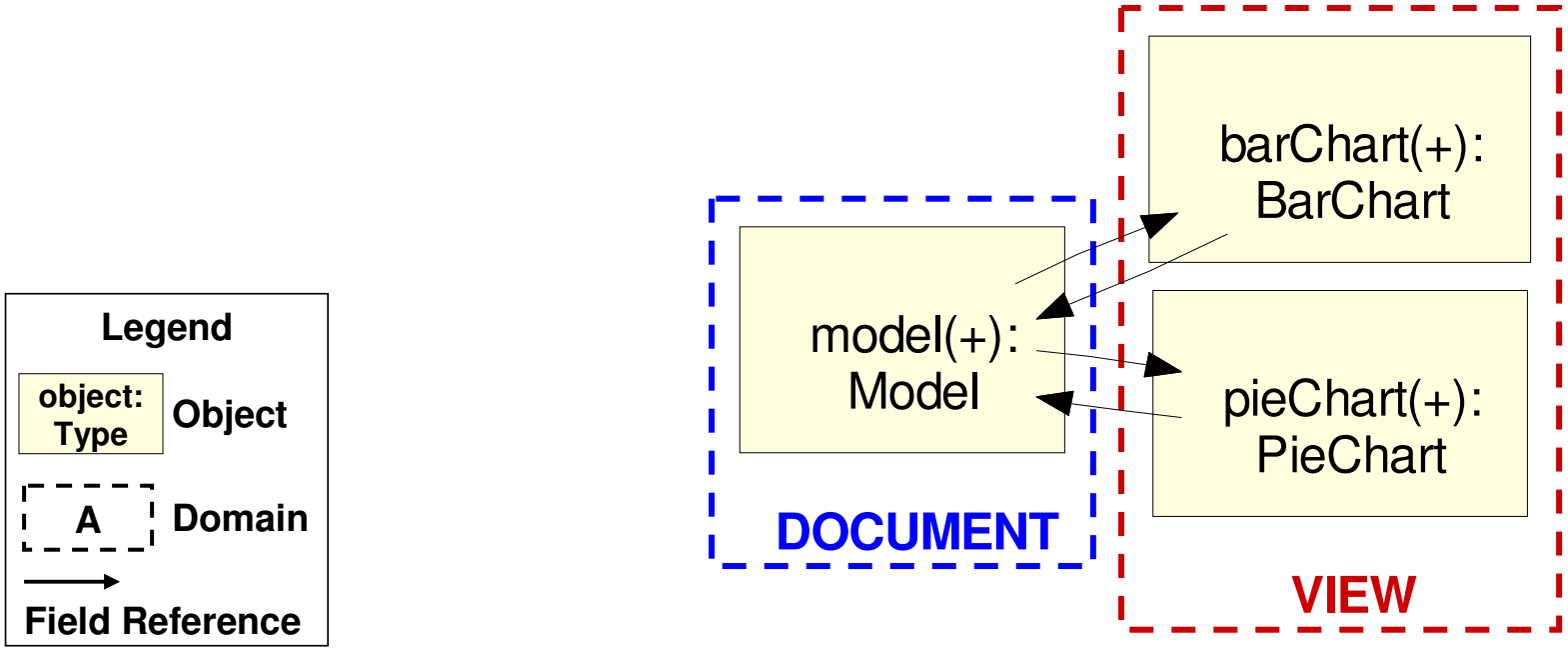
- **Domain** = **conceptual** group of objects
  - E.g., Document-View architecture





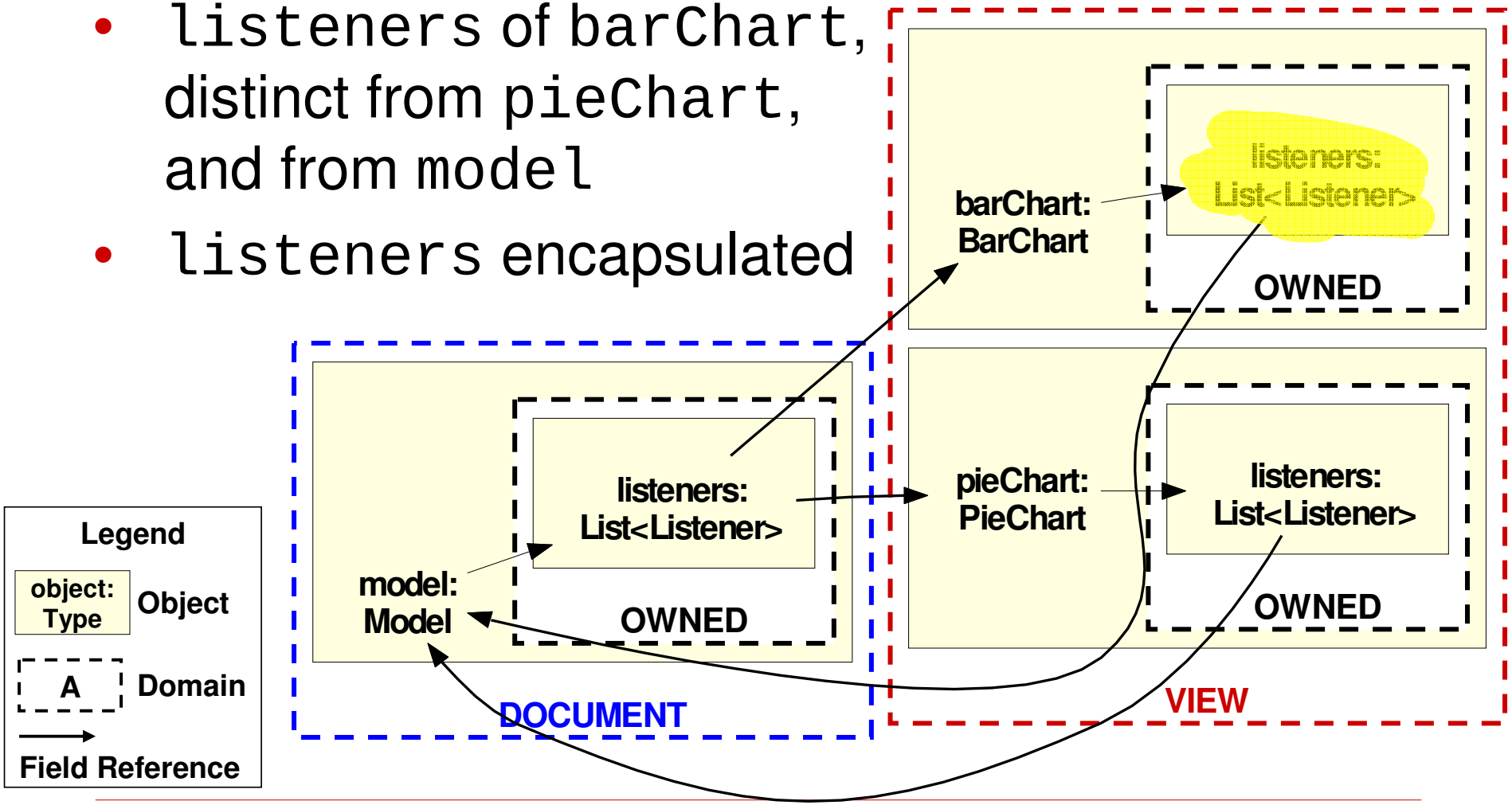
Object graph complements information in class diagram

- Show top-level **objects**
- (+) indicates hidden sub-structure
- Data structures part of other objects



Hierarchy enables expanding level of detail and varying level of abstraction

- `listeners` of `barChart`, distinct from `pieChart`, and from `model`
- `listeners` encapsulated

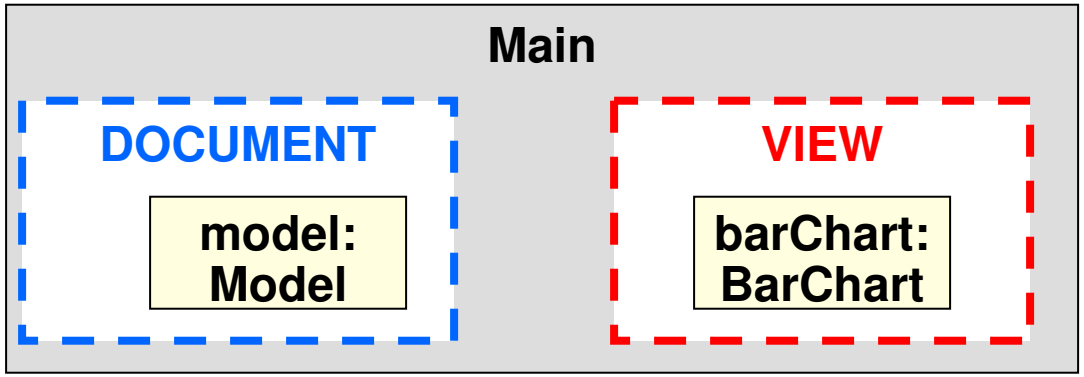


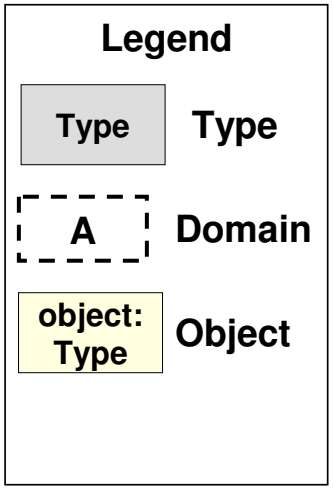
Analysis

Approach combines: (1) type annotations and (2) static analysis

1. Add ownership domain annotations
   [Aldrich and Chambers, ECOOP'04]
   - Typecheck and address warnings
   - Possibly use ownership inference
     [Ma and Foster, OOPSLA'07] [Milanova, IWACO'08] [Aldrich et al., OOPSLA'02]
2. Run static analysis
   - Extract object graph
   - Refine annotations as needed

Group objects into *ownership domains*



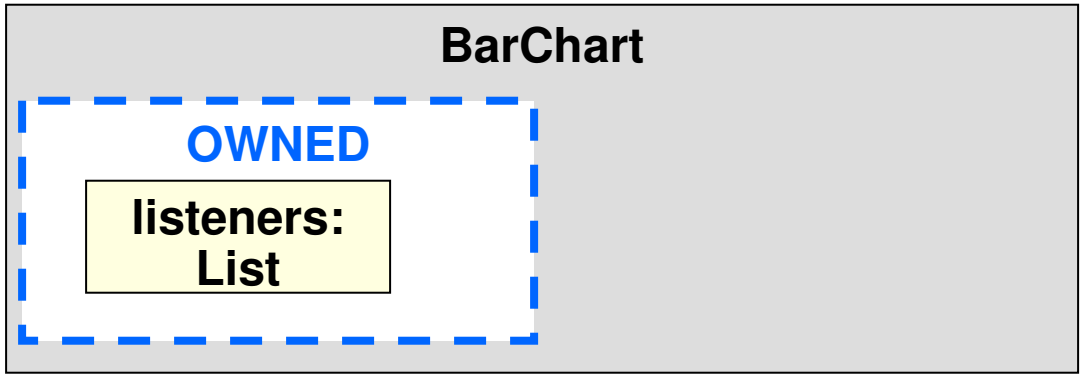


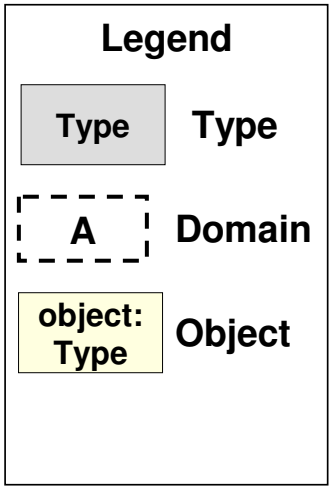

```
class Main {
  domain DOCUMENT, VIEW;
  DOCUMENT Model model;
  VIEW BarChart barChart;
  ...
}
```

Declarations are simplified

- Each object **in exactly one domain**
- No ownership transfer; no multiple ownership

Domains can be declared inside each class

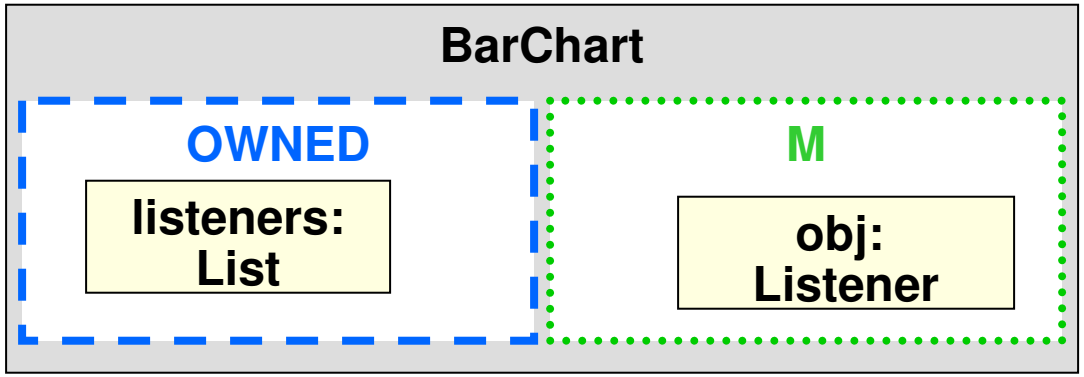





```
class BarChart {
  domain OWNED;
  OWNED List listeners;
  ...
}
```

Declarations are simplified

Domain parameters allow sharing objects




```
class BarChart < M > {
  domain OWNED;
  OWNED List< M Listener> listeners;
}
class Main {
  domain DOCUMENT, VIEW;
  VIEW BarChart<DOCUMENT> barChart;
  ...
}
```

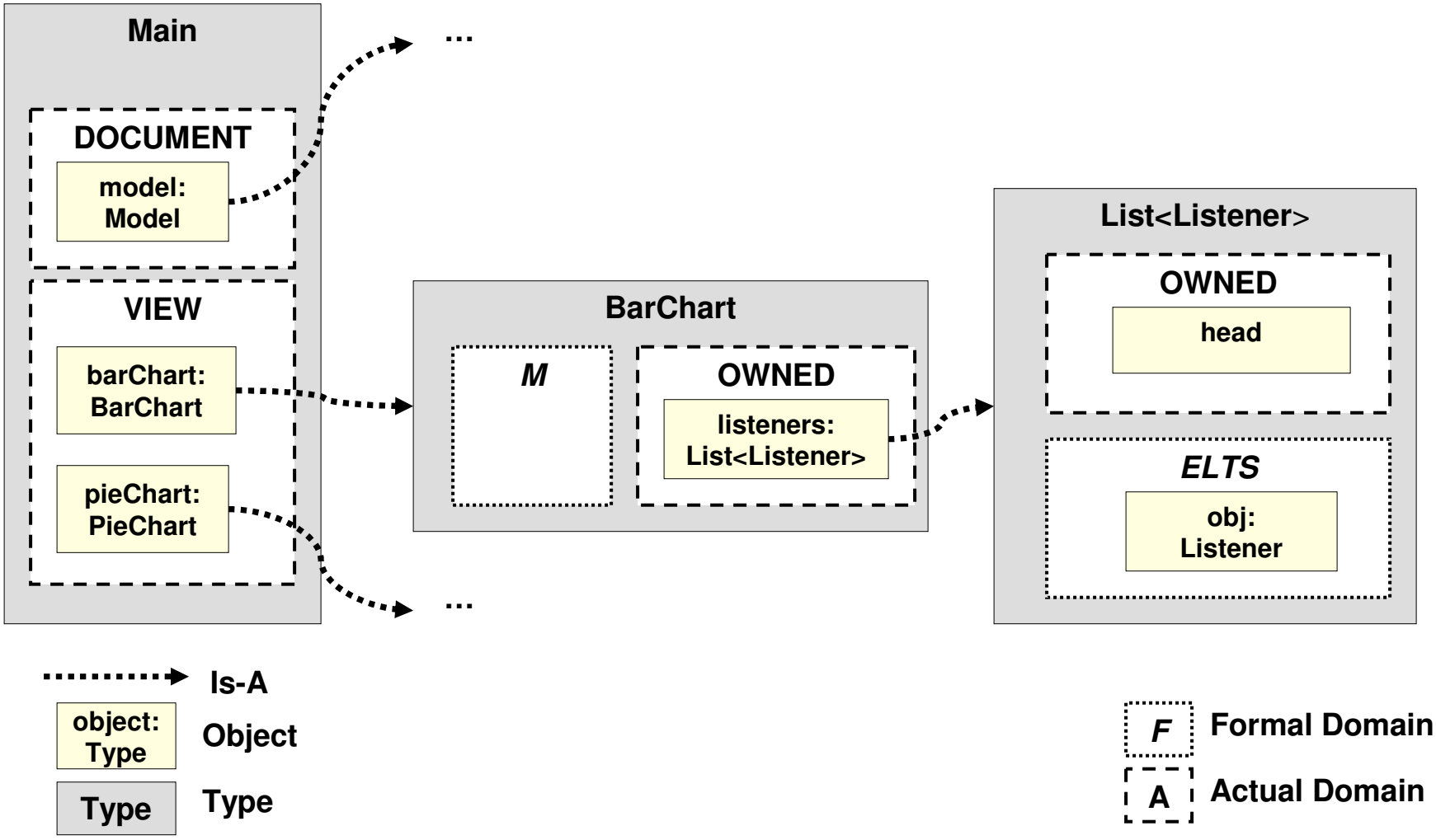
Bind FormalDomain → ActualDomain

BarChart :: M → Main :: DOCUMENT

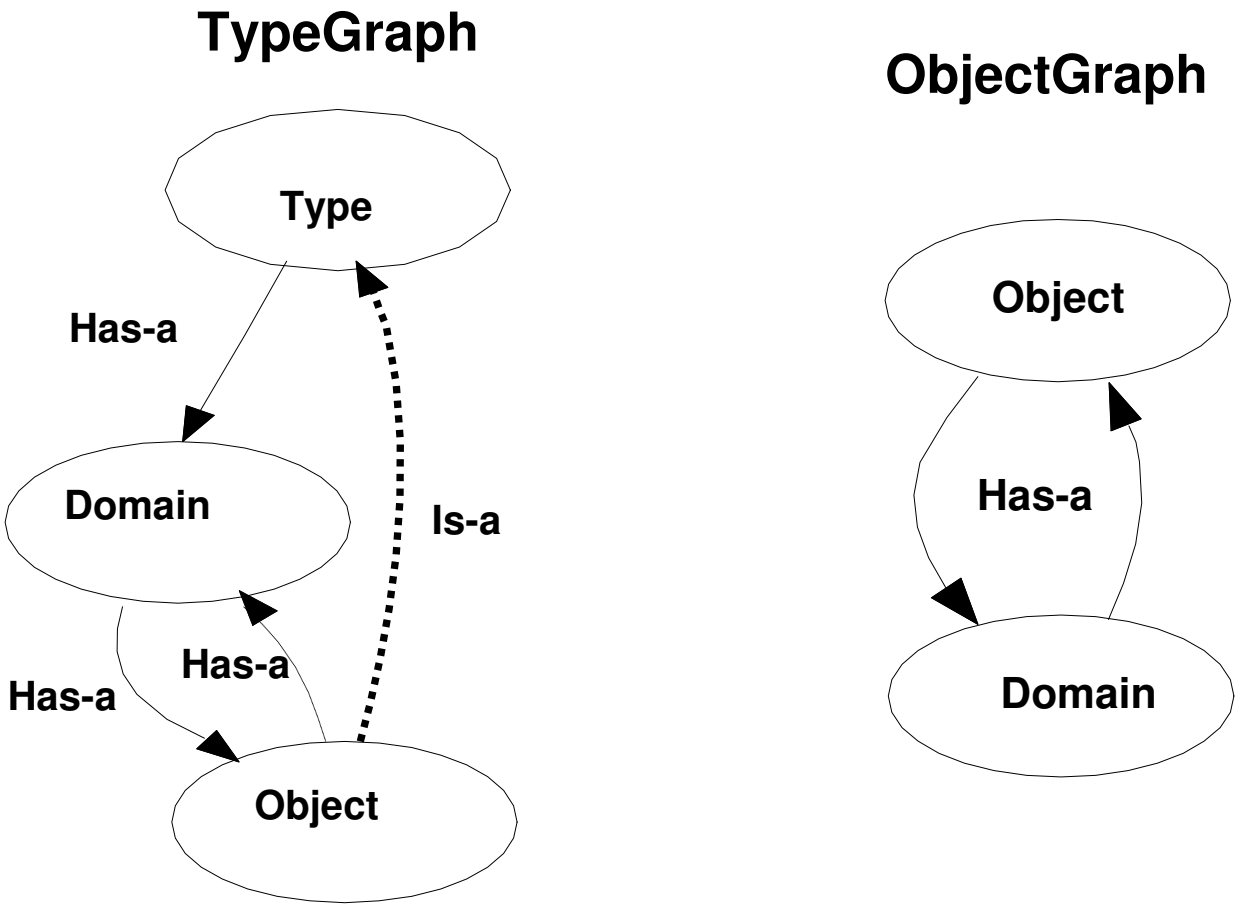
Static analysis to extract object graph

- Build **TypeGraph**
  - Visitor over program's Abstract Syntax Tree
  - Represents type structure of objects in code
- Convert **TypeGraph** to **ObjectGraph**
  - **Instantiates the types** in the TypeGraph
  - Shows only objects and domains

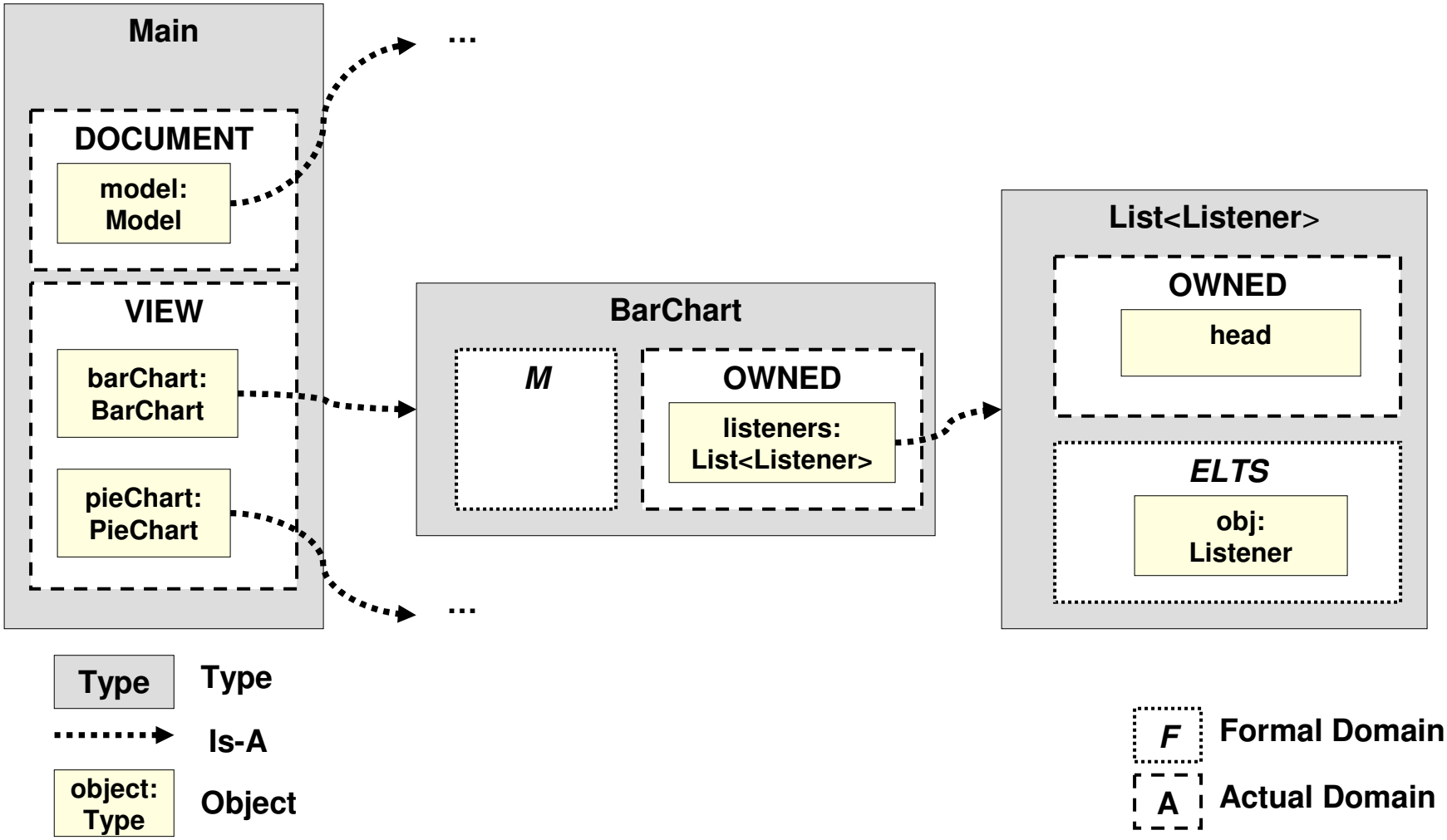
TypeGraph: show types, domains inside types, and objects in domains



Challenge: TypeGraph does not show children objects of a given object



ObjectGraph: instantiate types, starting with root (user selected)



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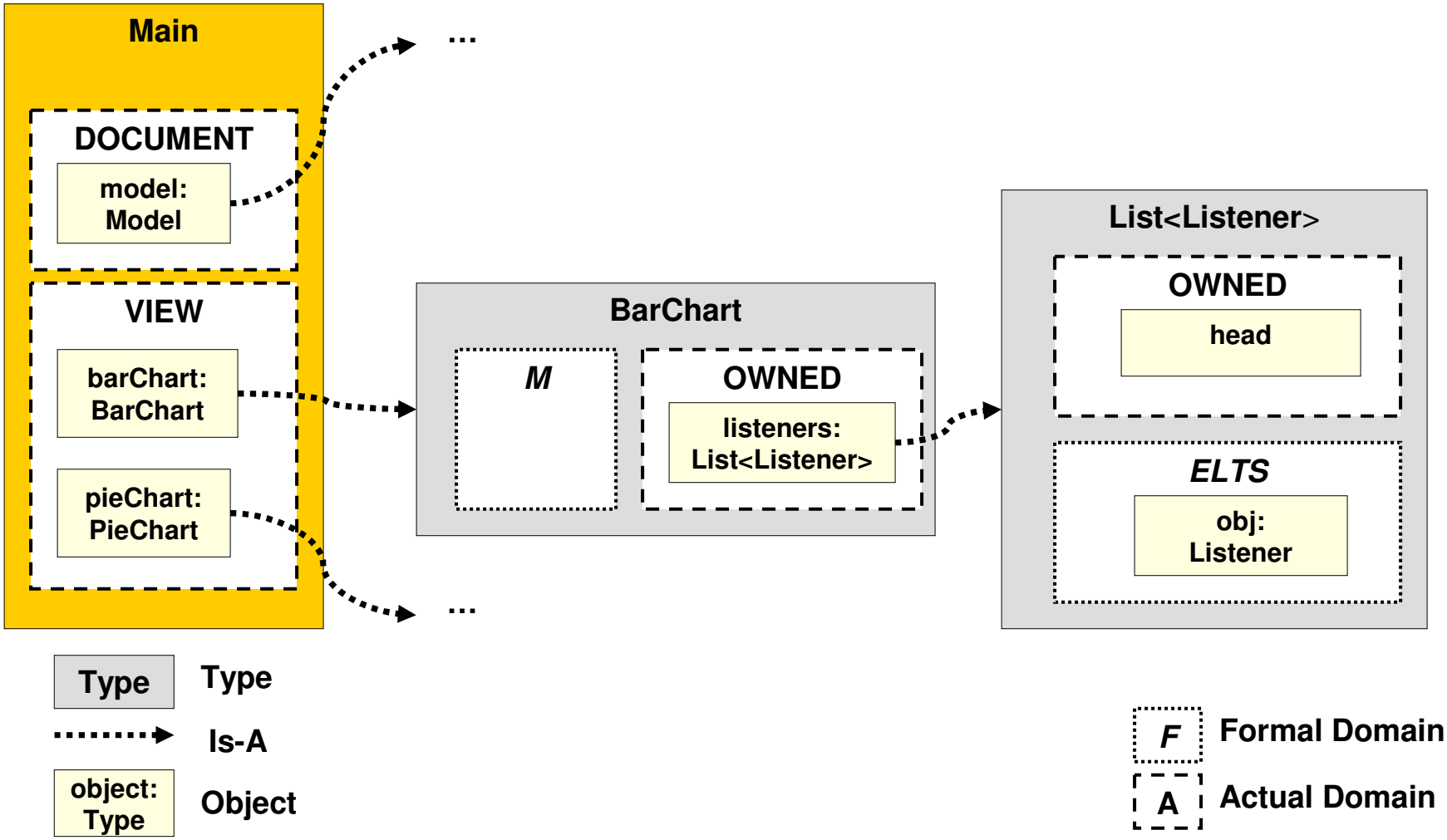
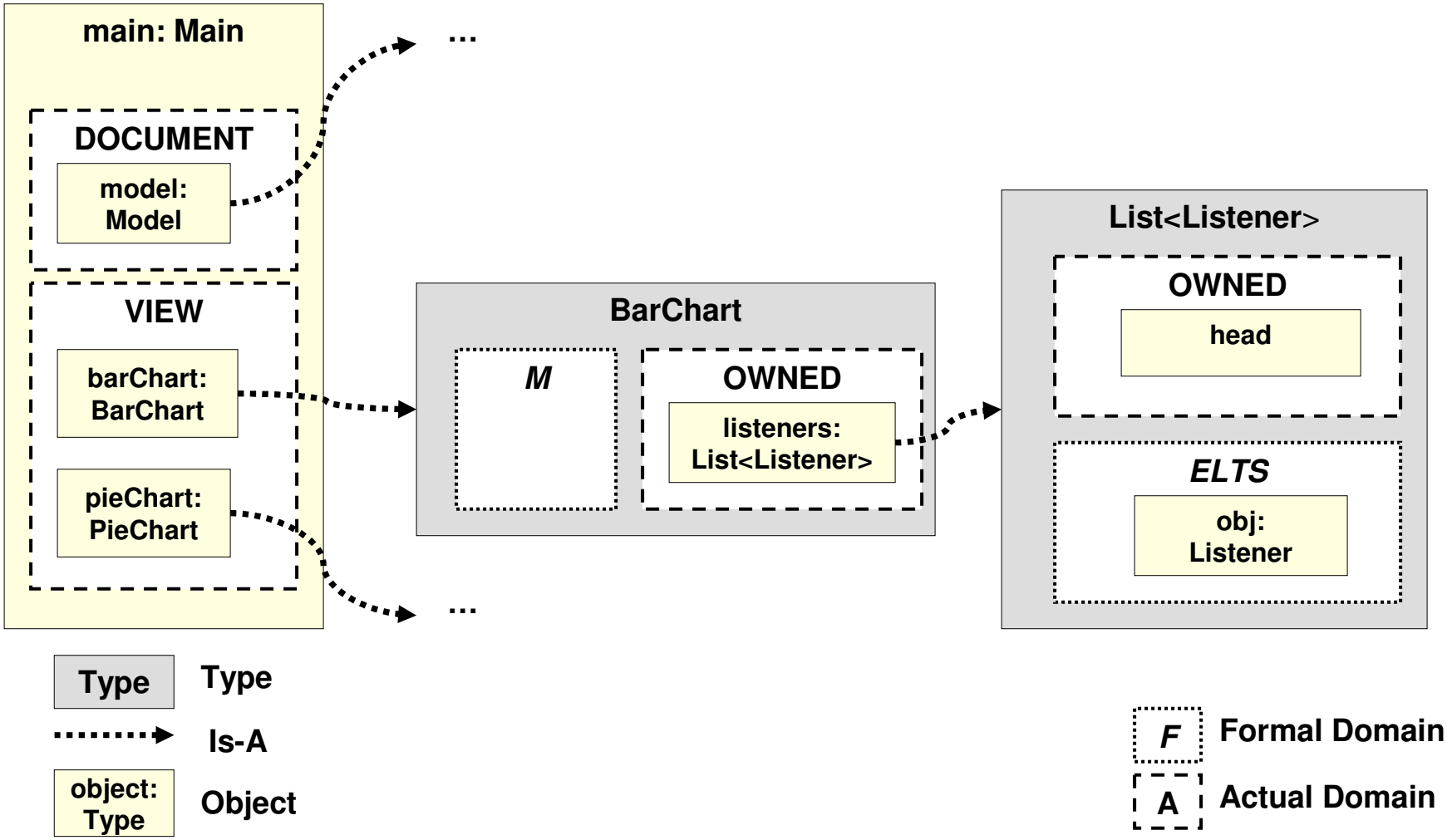
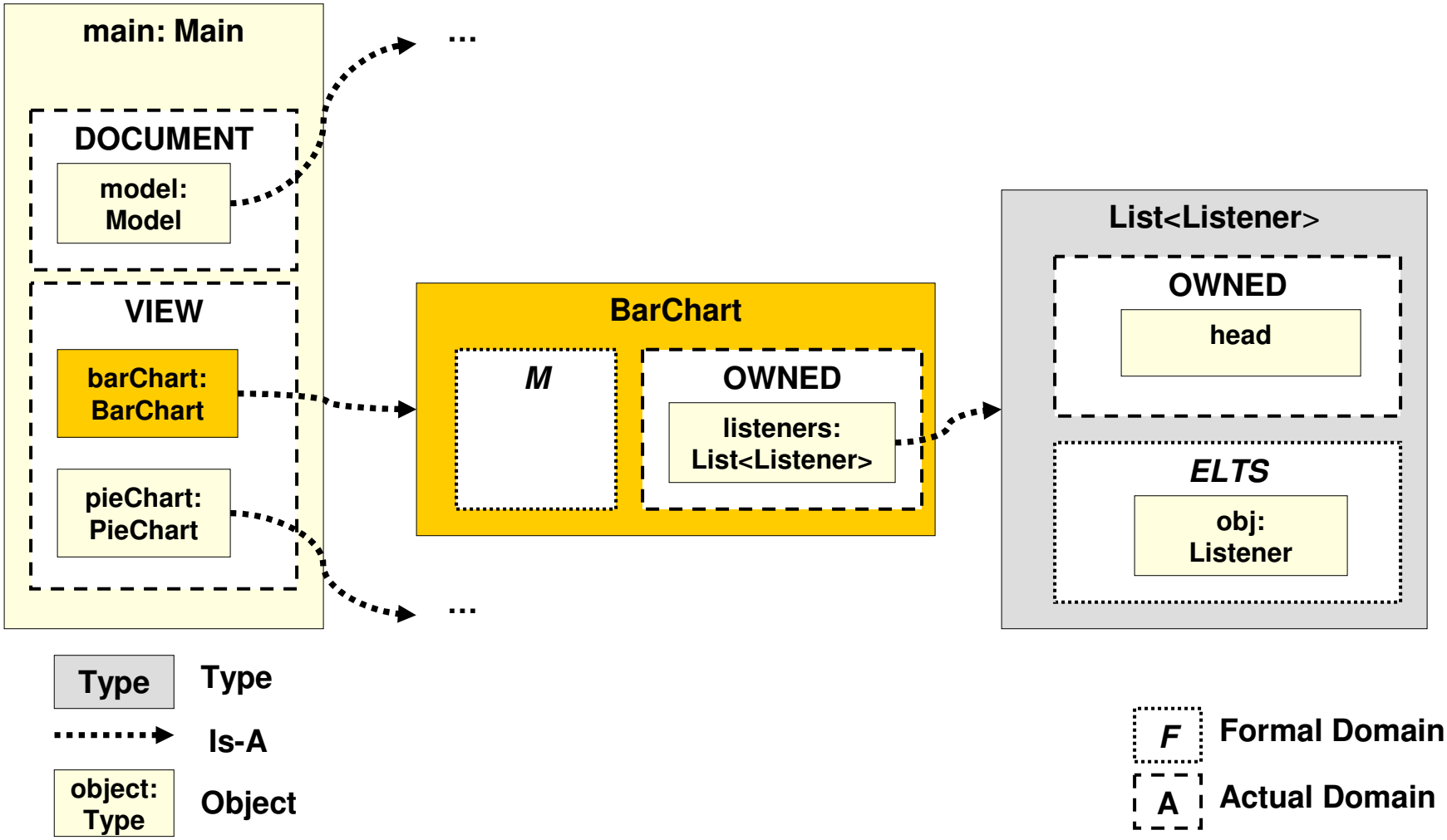


ObjectGraph: instantiate types, starting with root



ObjectGraph: instantiate types, show domains and objects inside domains



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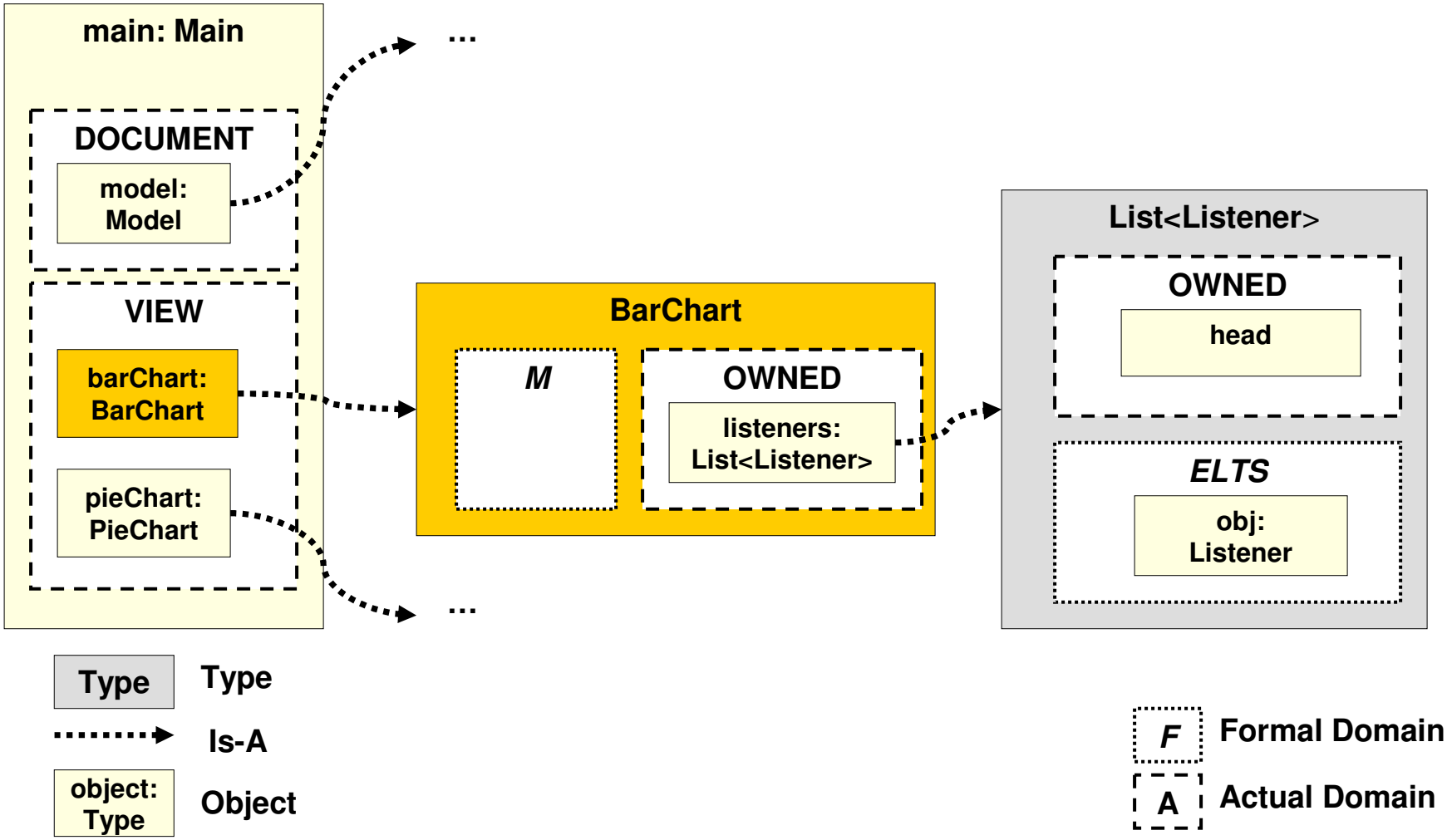

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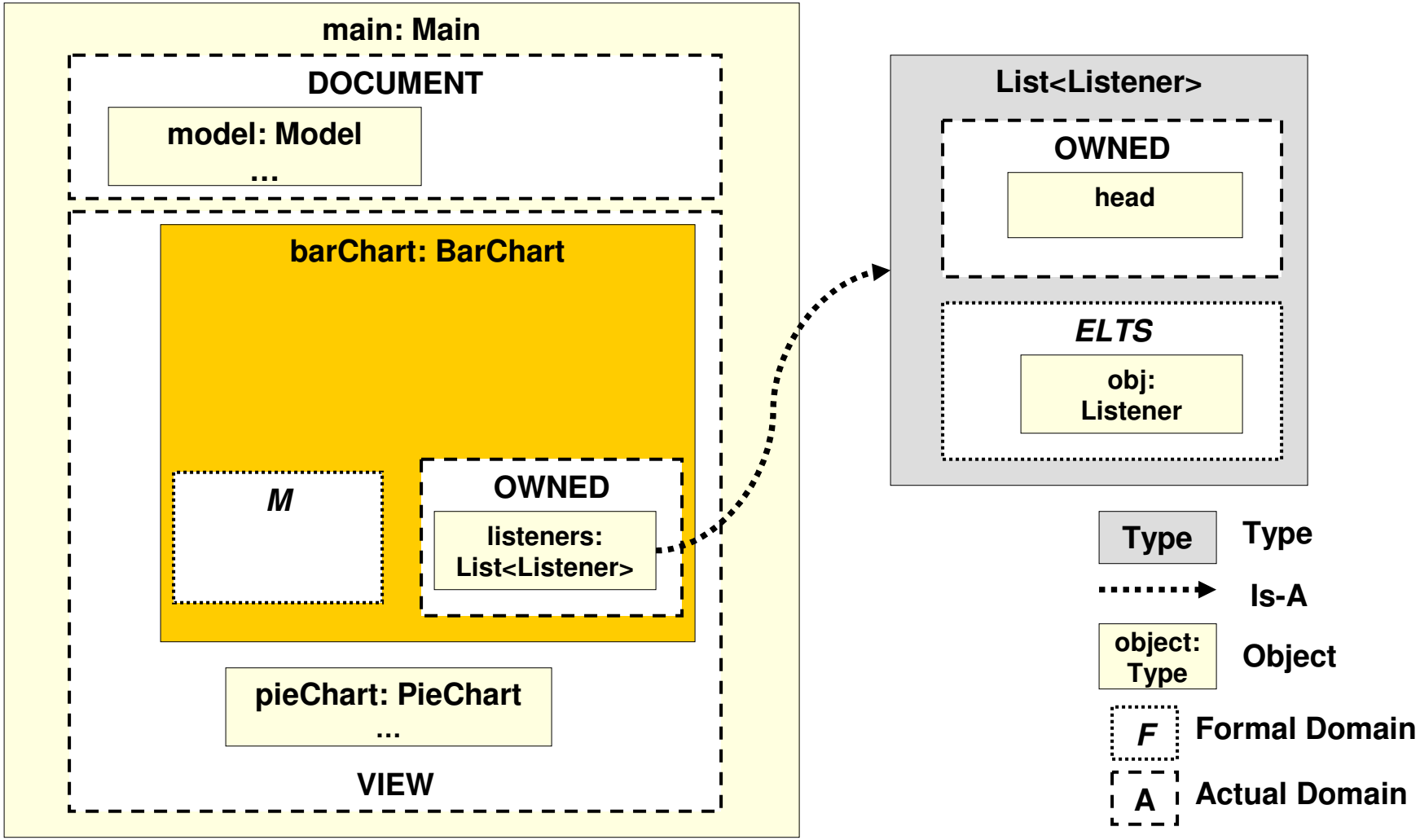

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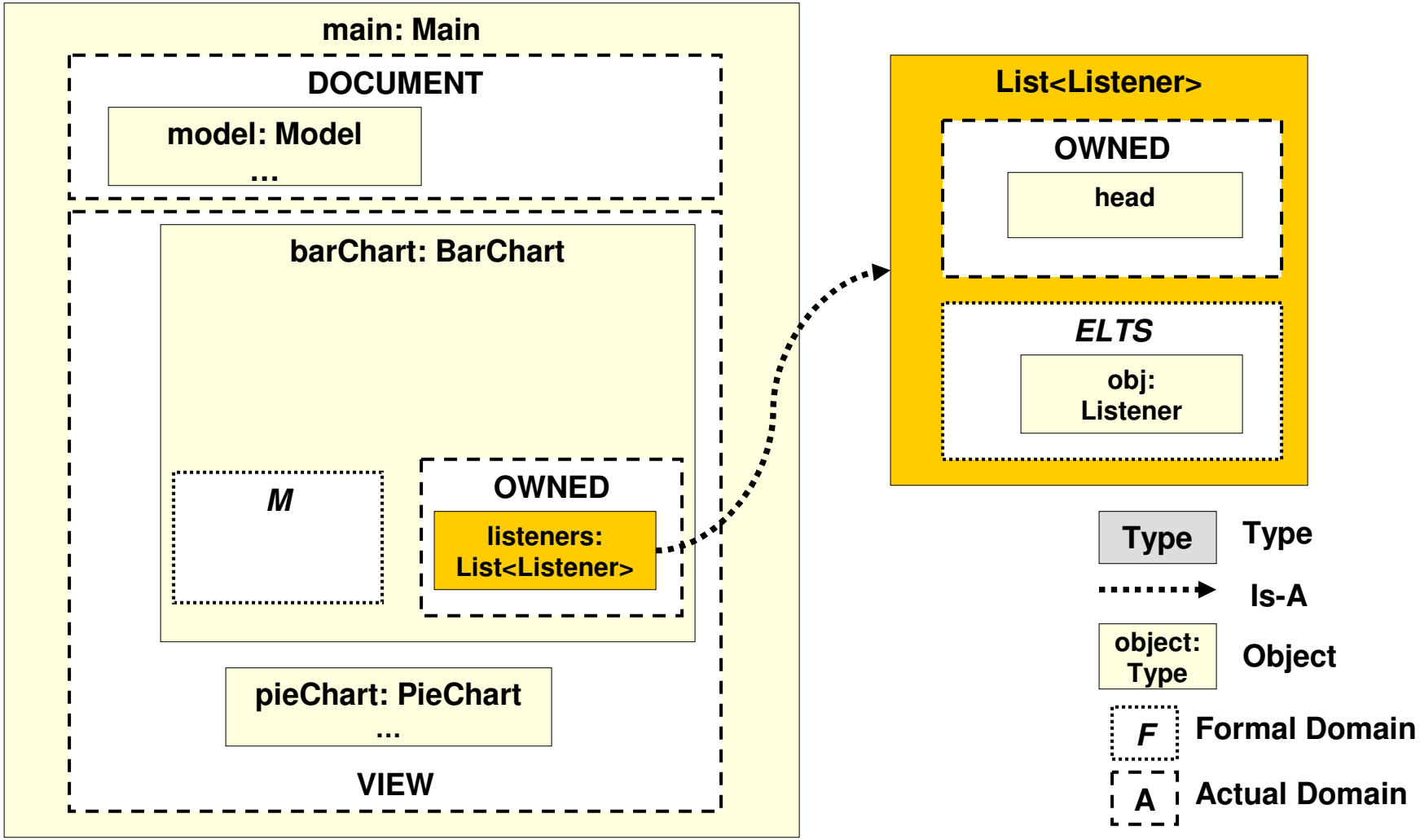

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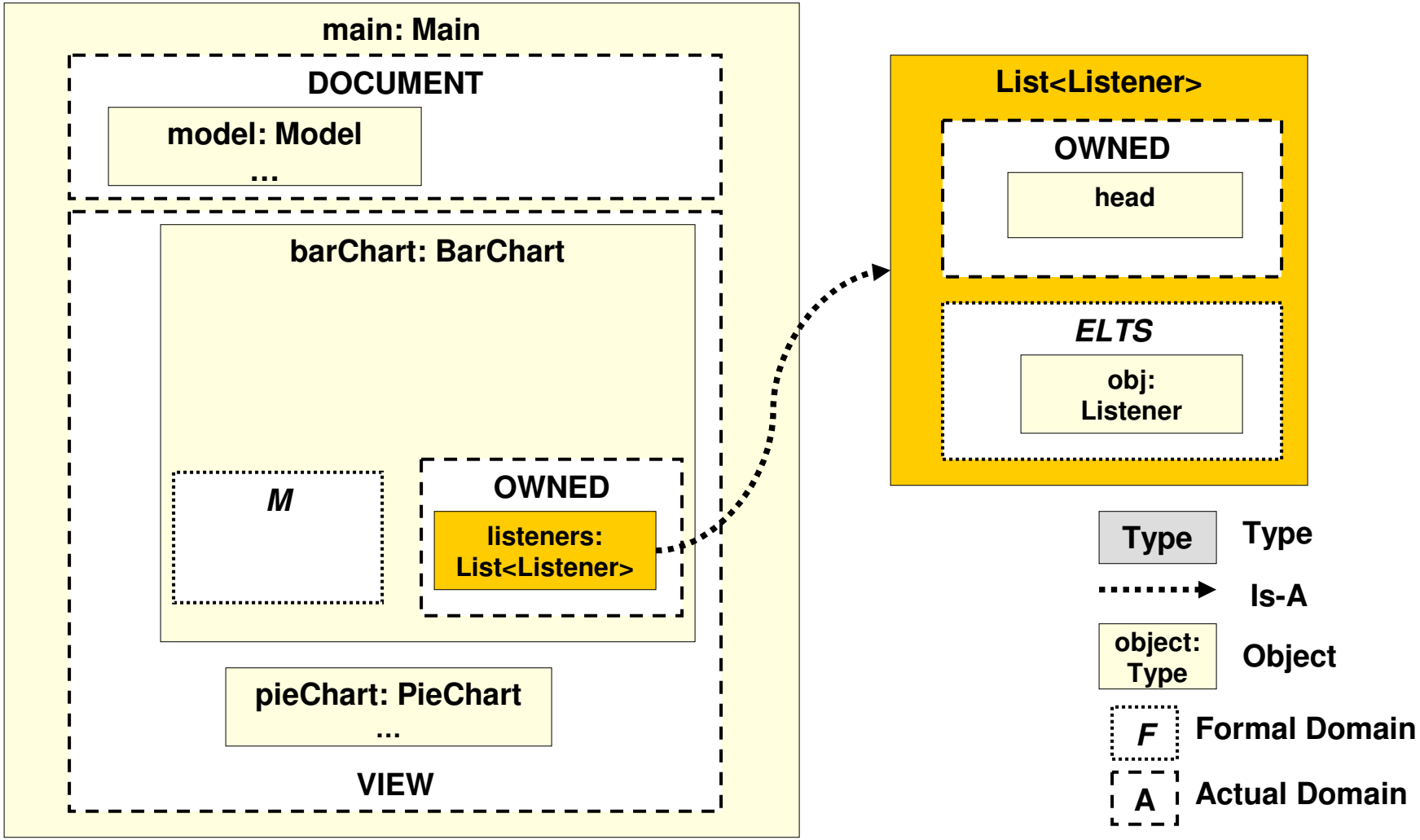

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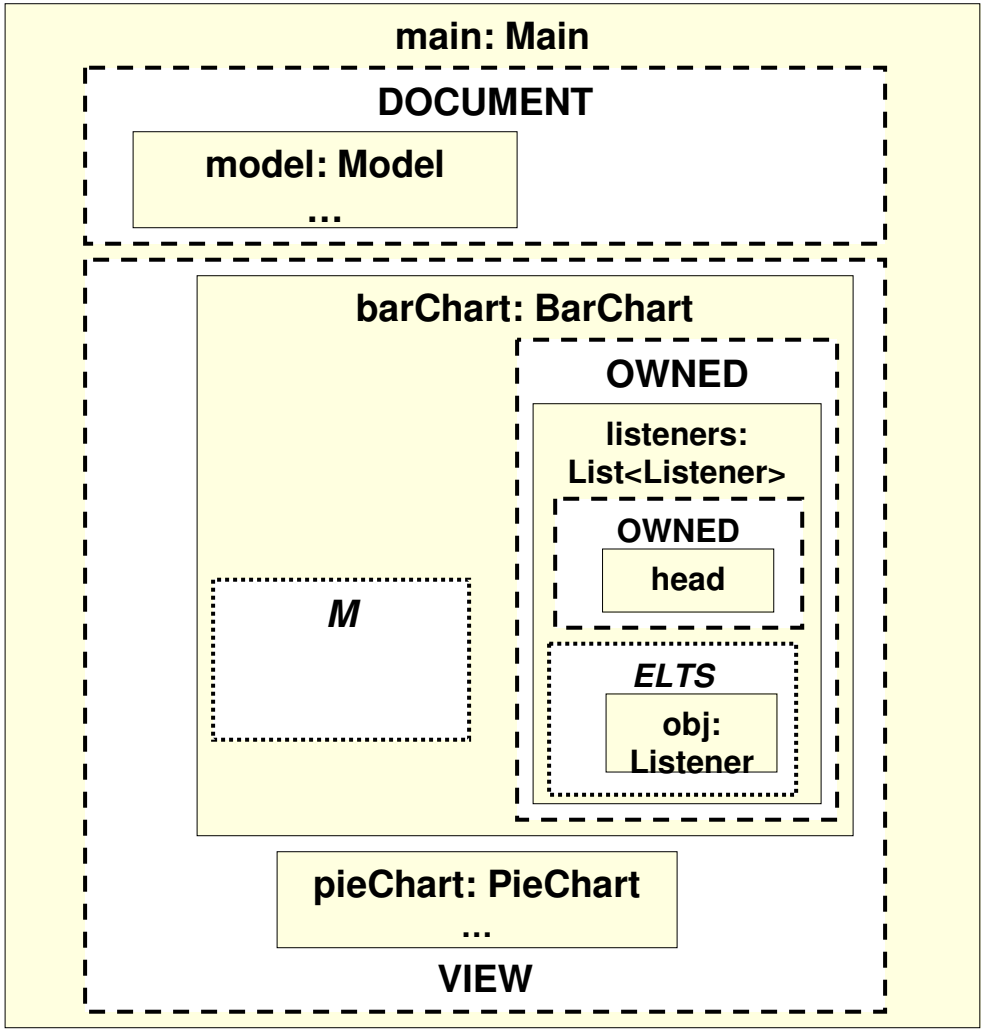
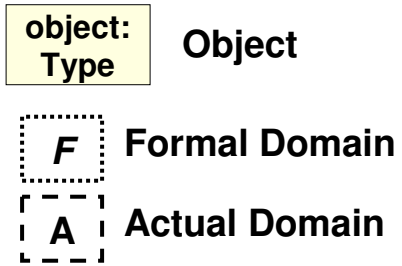


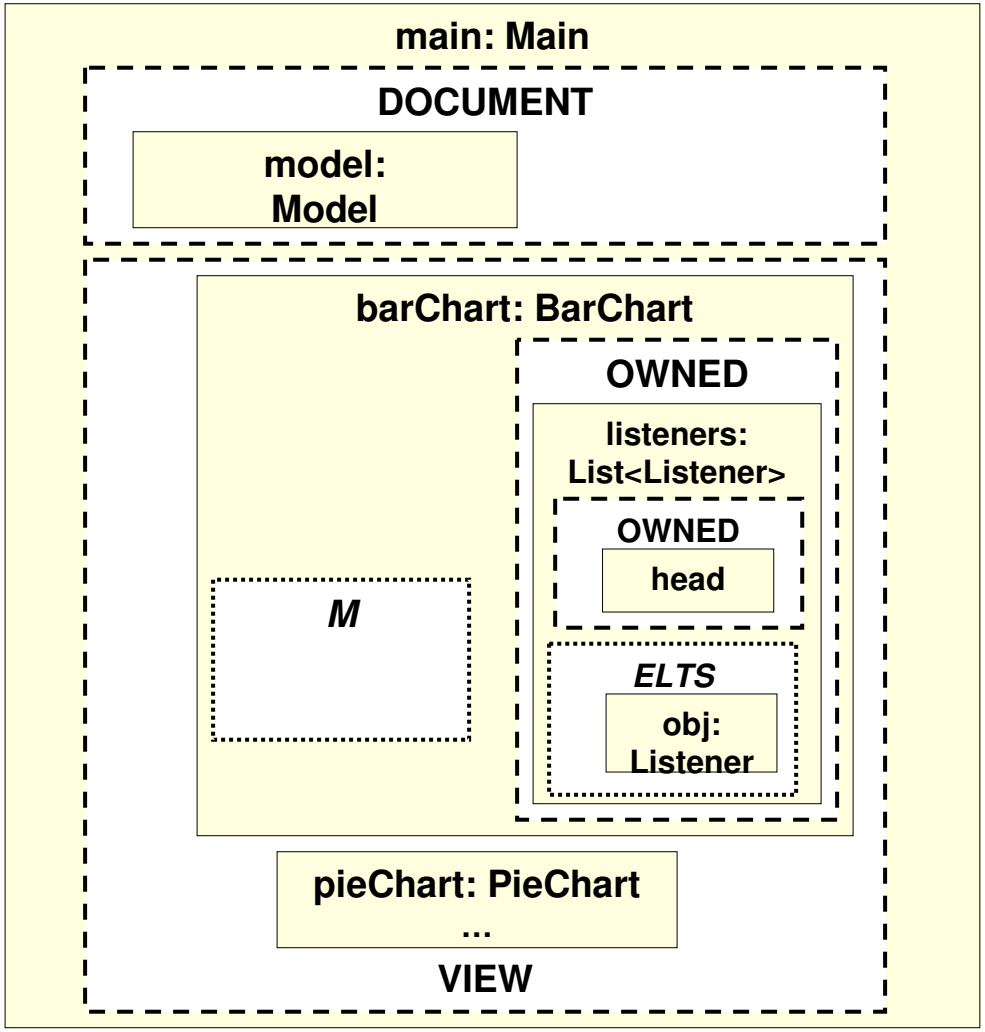


Challenge: unbounded number of objects, based on different executions

- *Invariant: Summarize multiple objects in a domain with one canonical object*

- *Invariant: Merge two objects of the "same type" that are in the same domain*
  - I.e., same declared type, or subtype thereof
  - Or of compatible types (more later)

ObjectGraph: merge equivalent objects inside a given domain



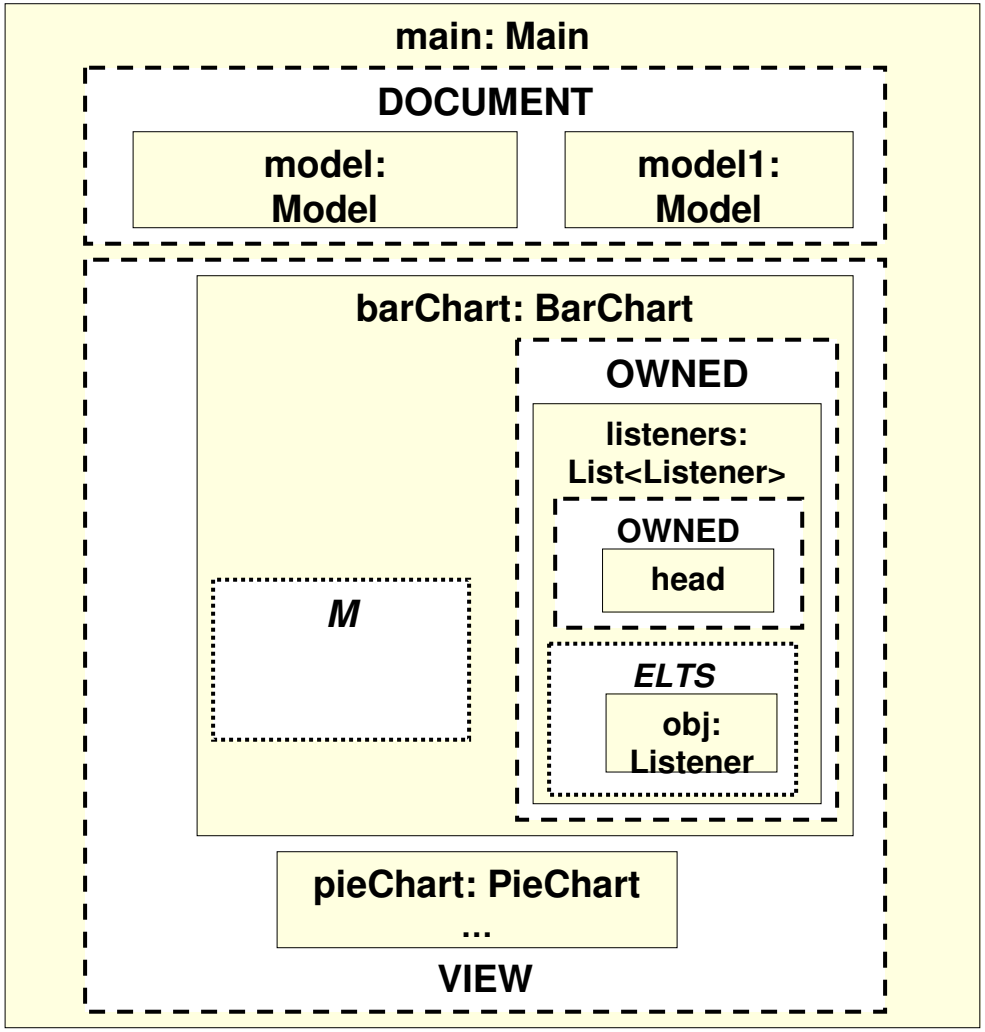

```
class Main {
  domain DOCUMENT, VIEW;

  DOCUMENT Model model;


  ...
}
```

object: Type — Object

F — Formal Domain

A — Actual Domain

ObjectGraph: merge equivalent objects inside a given domain




```
class Main {
  domain DOCUMENT, VIEW;

  DOCUMENT Model model;
  DOCUMENT Model model1;

  ...
}
```

object: Type — Object

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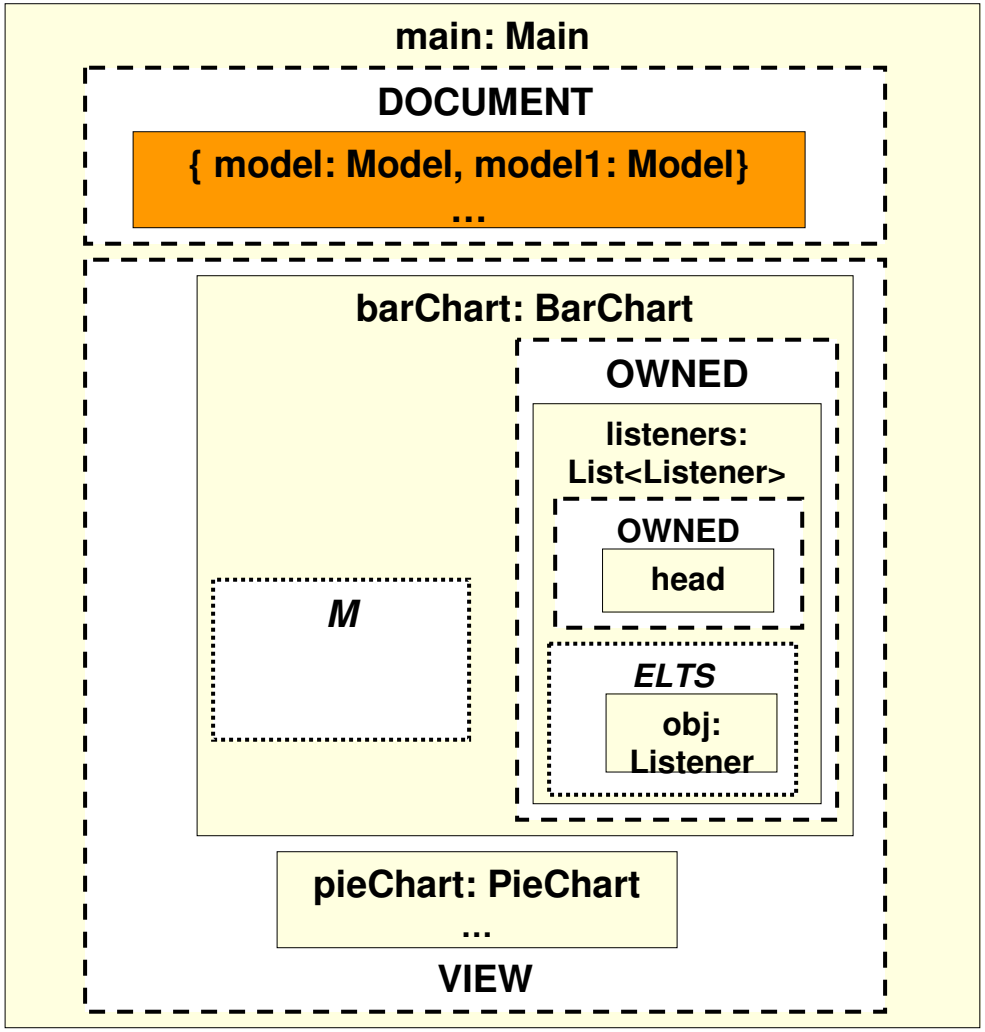
ObjectGraph: merge equivalent objects inside a given domain




```
class Main {
  domain DOCUMENT, VIEW;

  DOCUMENT Model model;
  DOCUMENT Model model1;

  ...
}
```

object: Type — Object

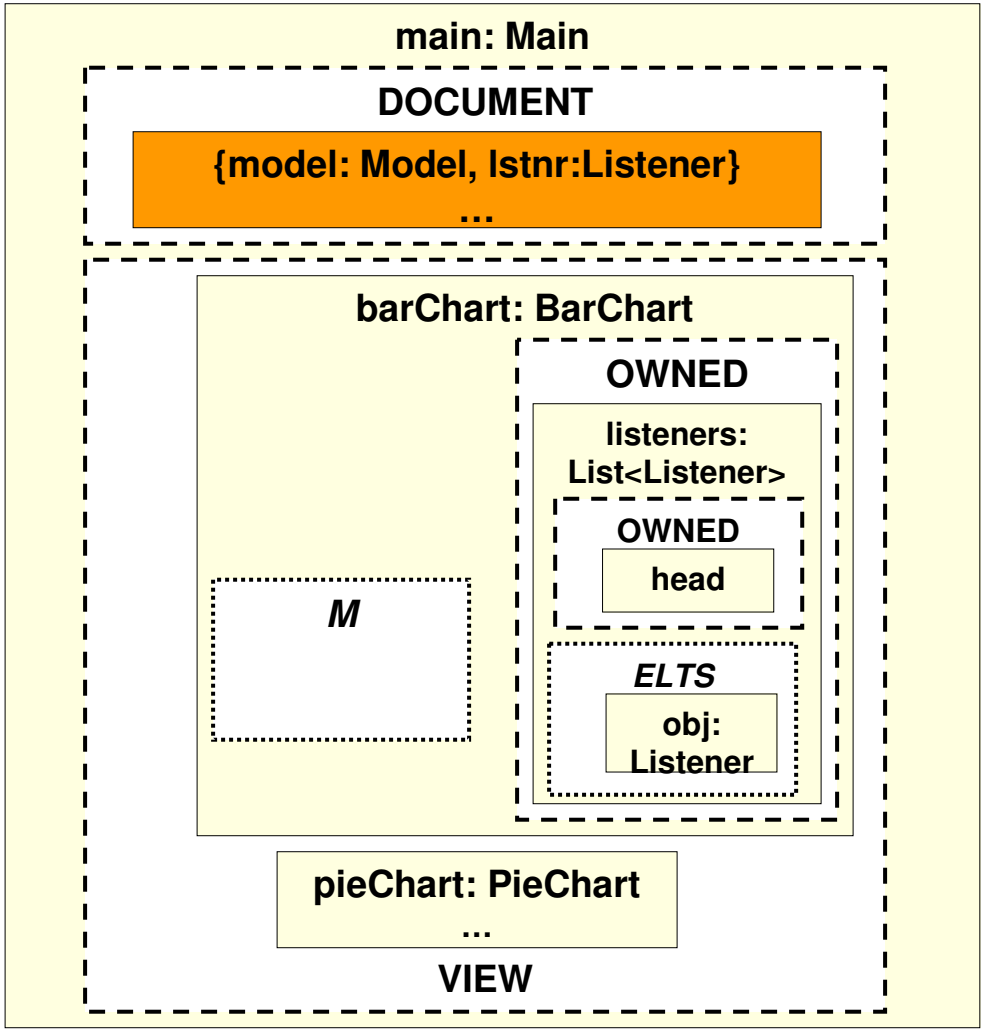
F — Formal Domain

A — Actual Domain

Challenge: TypeGraph does not reflect possible aliasing

- *Invariant: the same object should not appear multiple times in the **ObjectGraph***
- Ownership domain annotations give some precision about aliasing:
  - Two objects in different domains cannot alias
  - Two objects in same domain *may* alias

ObjectGraph: merge objects, in one domain, that *may* alias, based on types




```
class Main {
  domain DOCUMENT, VIEW;

  DOCUMENT Model model;
  DOCUMENT Listener lstnr;

  ...
}

class Model implements Listener {
  ...
}
```

object: Type — **Object**

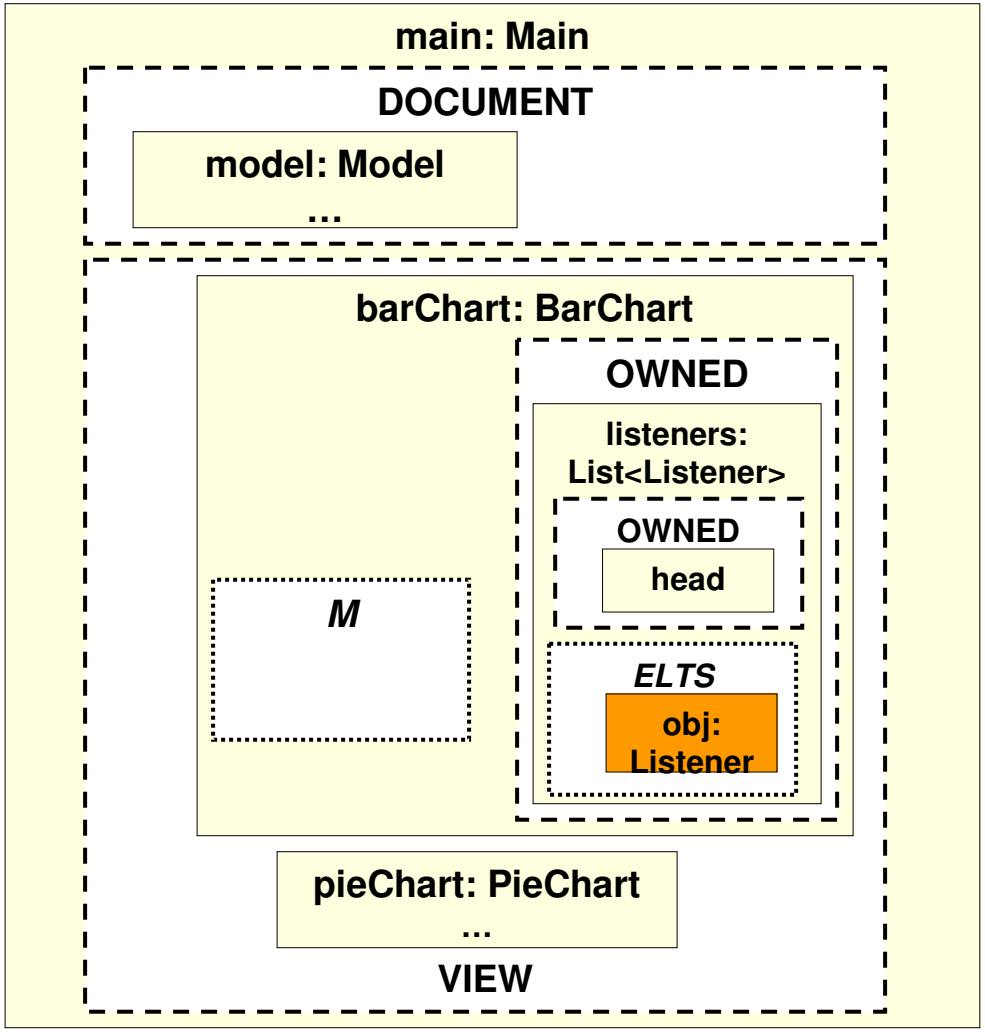
F — **Formal Domain**

A — **Actual Domain**

Challenge: TypeGraph does not show all objects in each domain

- Object can be declared in domain parameter
- Domain parameter bound to other domain
- *Invariant: In the ObjectGraph, each object that is in a given domain must appear where that domain is declared*
- **Pull each object** declared inside formal domain parameter into each domain bound to the formal domain parameter

ObjectGraph: pull objects from formal domains to actual domains



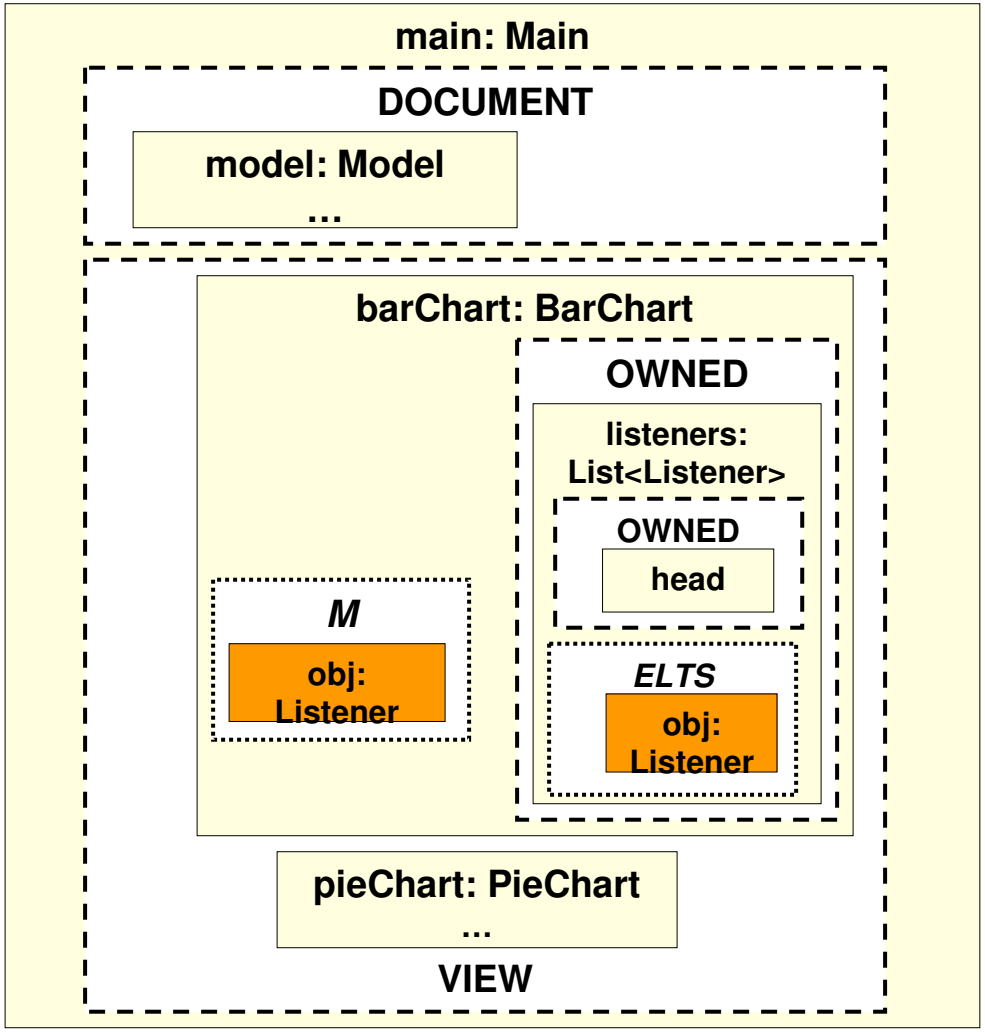

```
class BarChart <M> {
 domain OWNED;

 OWNED List<M Listener> listeners;
}

class List<ELTS T> {
 // ELTS is for List elements
 // T is generic type parameter
 // Virtual field
 ELTS T obj;
}
```

object: Type — Object

F — Formal Domain

A — Actual Domain

ObjectGraph: pull objects from formal domains to actual domains




```
class BarChart <M> {
 domain OWNED;
 // List::ELTS    BarChart::M
 OWNED List<M Listener> listeners;
}

class List<ELTS T> {
 // ELTS is for List elements
 // T is generic type parameter
 // Virtual field
 ELTS T obj;
}
```

object: Type — Object

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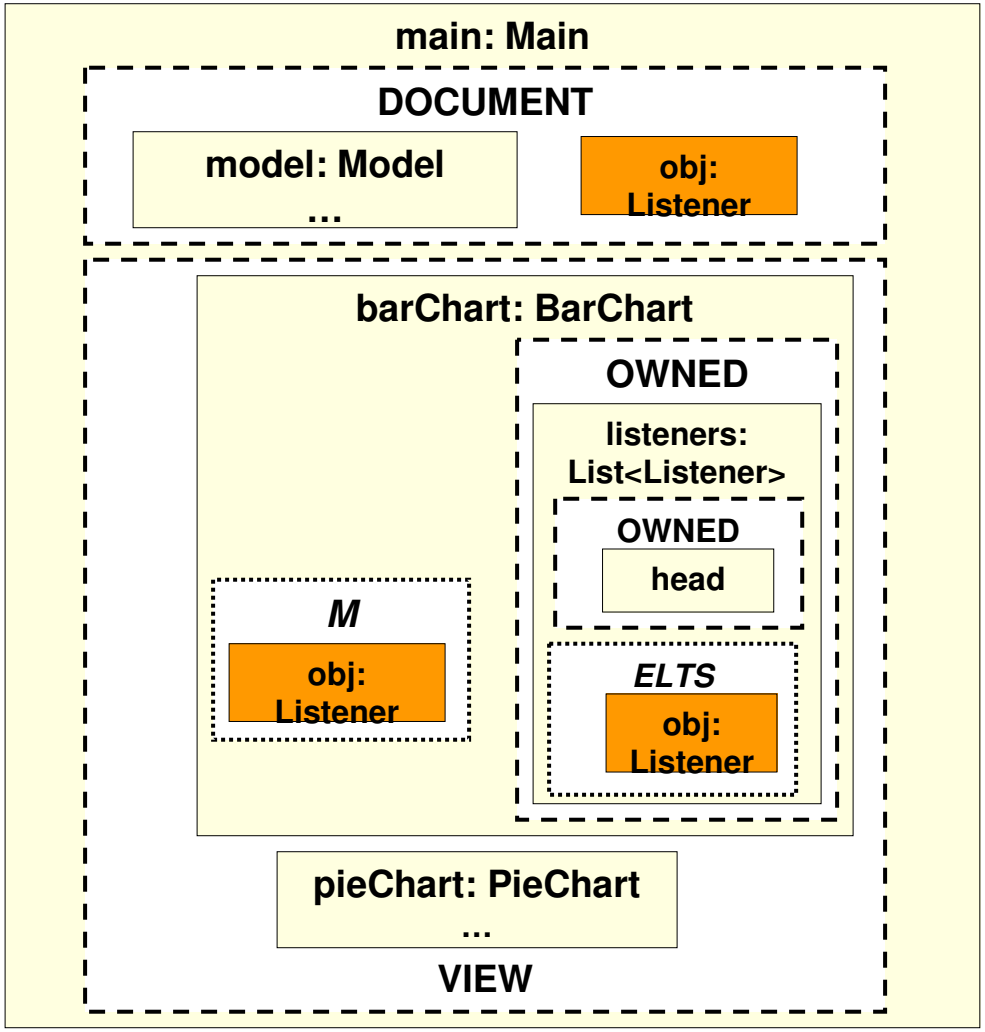
ObjectGraph: pull objects from formal domains to actual domains



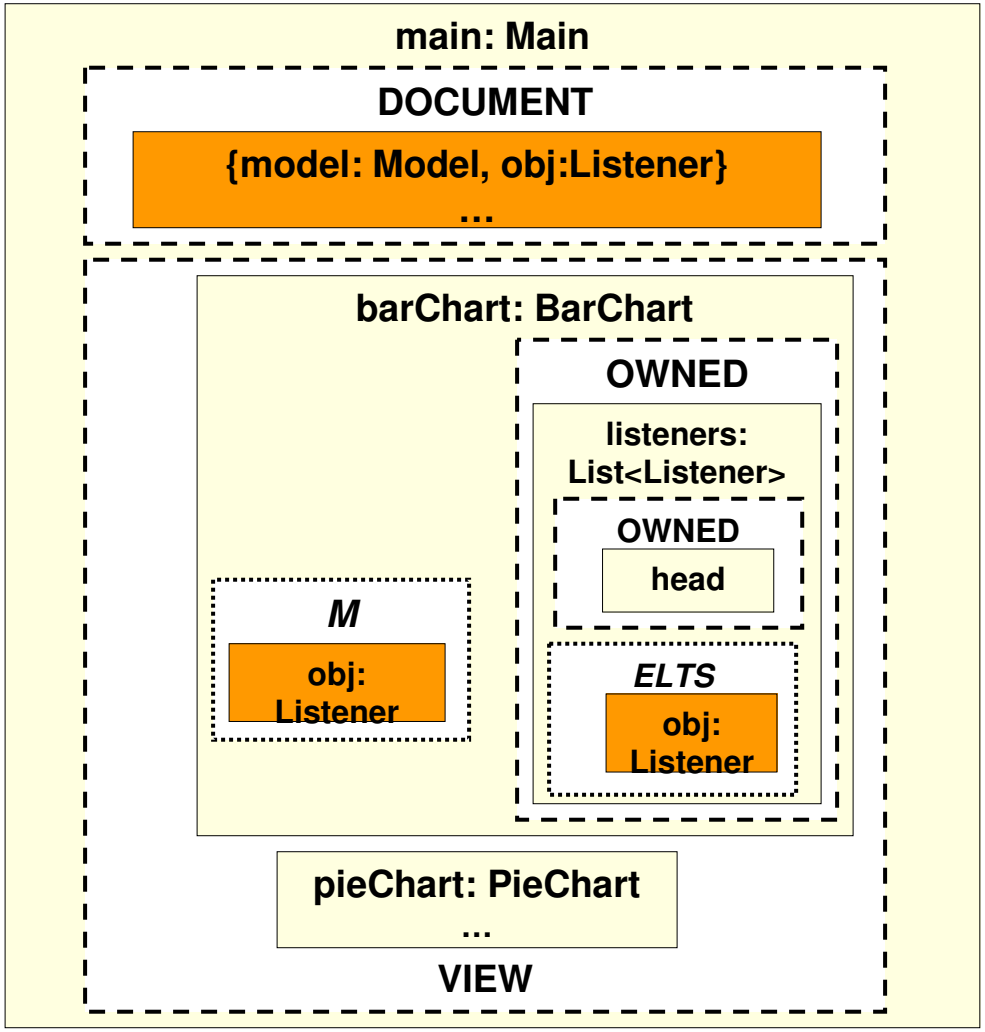

```
class Main {
 domain DOCUMENT, VIEW;
 // BarChart::M    Main::DOCUMENT
 VIEW BarChart<DOCUMENT> barChart;
   ...
}

class BarChart<M> {
 domain OWNED;
 OWNED List<M Listener> listeners;
}
```

object: Type — **Object**

F — **Formal Domain**

A — **Actual Domain**

ObjectGraph: again, merge objects, in one domain, that *may* alias



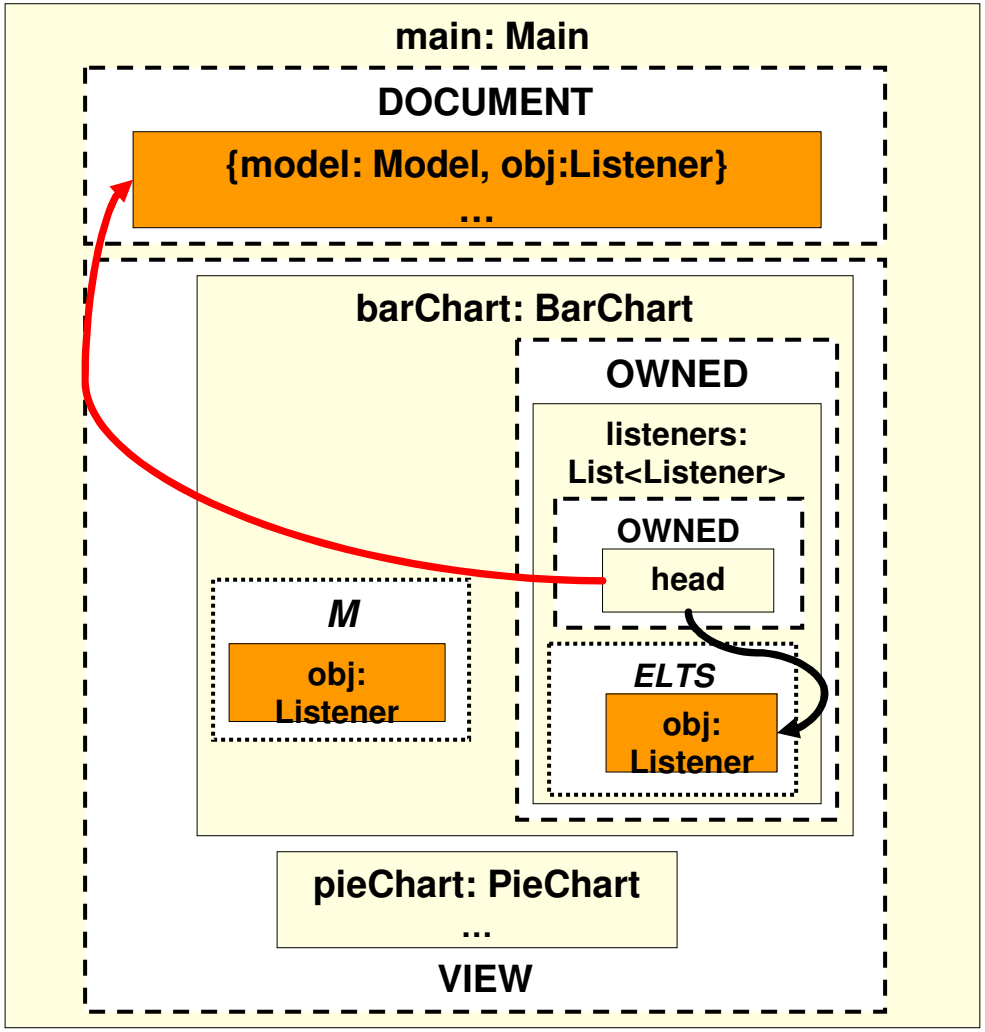

```
class Model implements Listener {
  ...
}
```

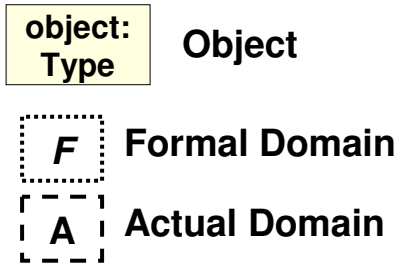
object: Type — Object

F — Formal Domain

A — Actual Domain

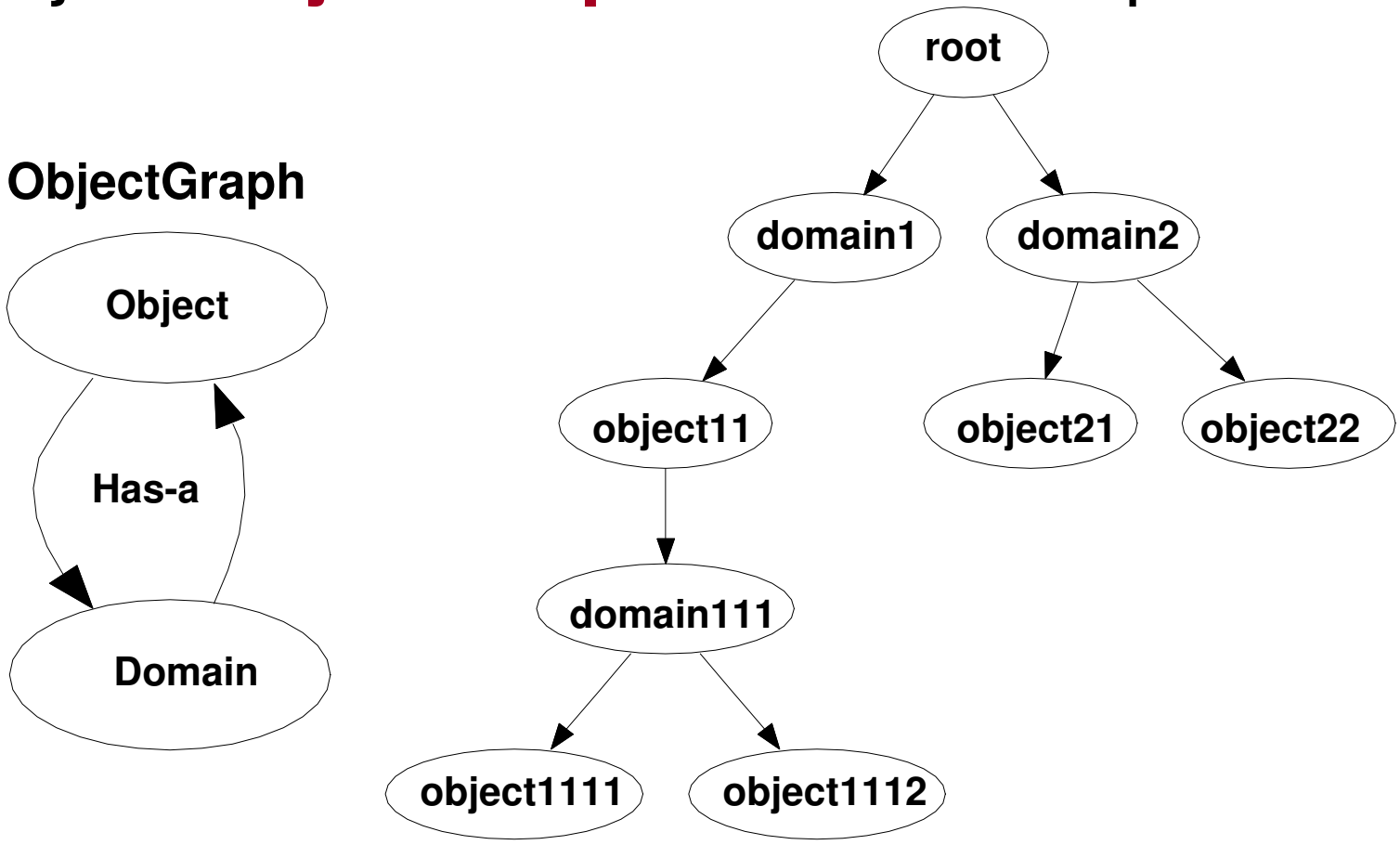
ObjectGraph: add edges to represent points-to relations, incl. to pulled objects





Challenge: ObjectGraph can have cycles

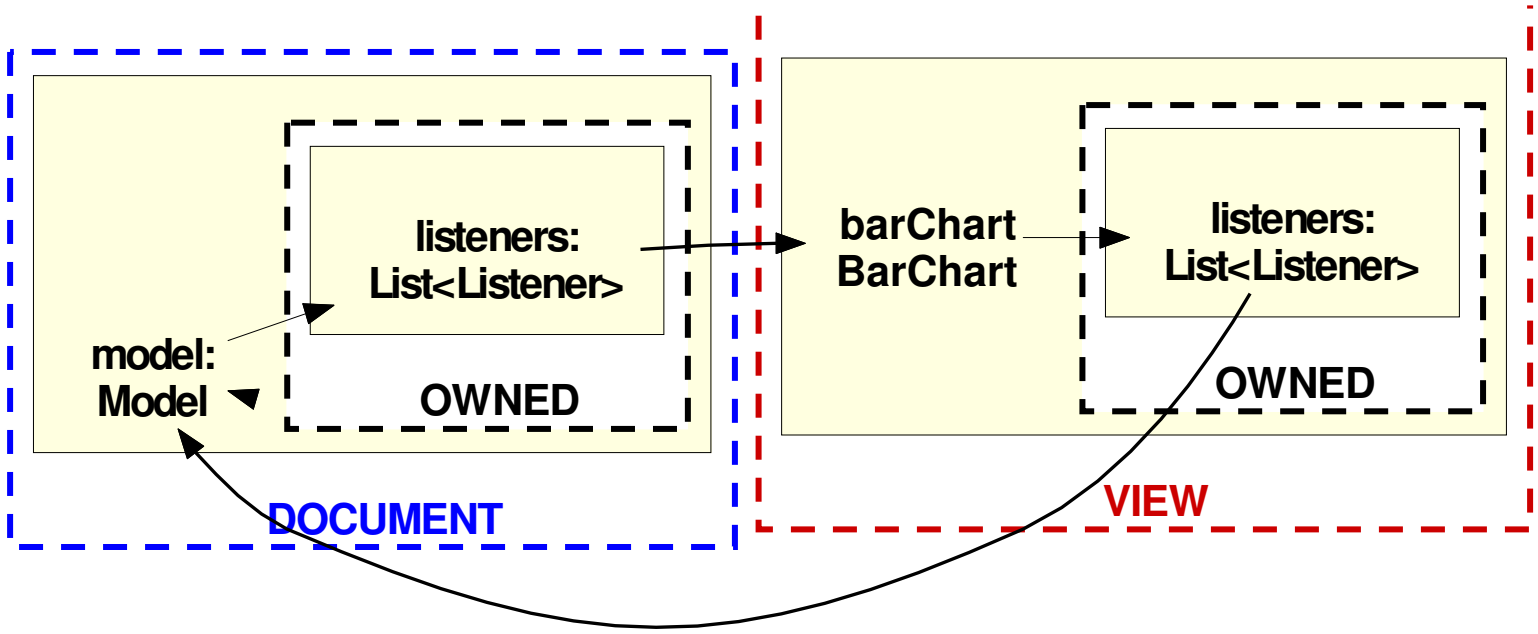
- Project **ObjectGraph** to limited depth



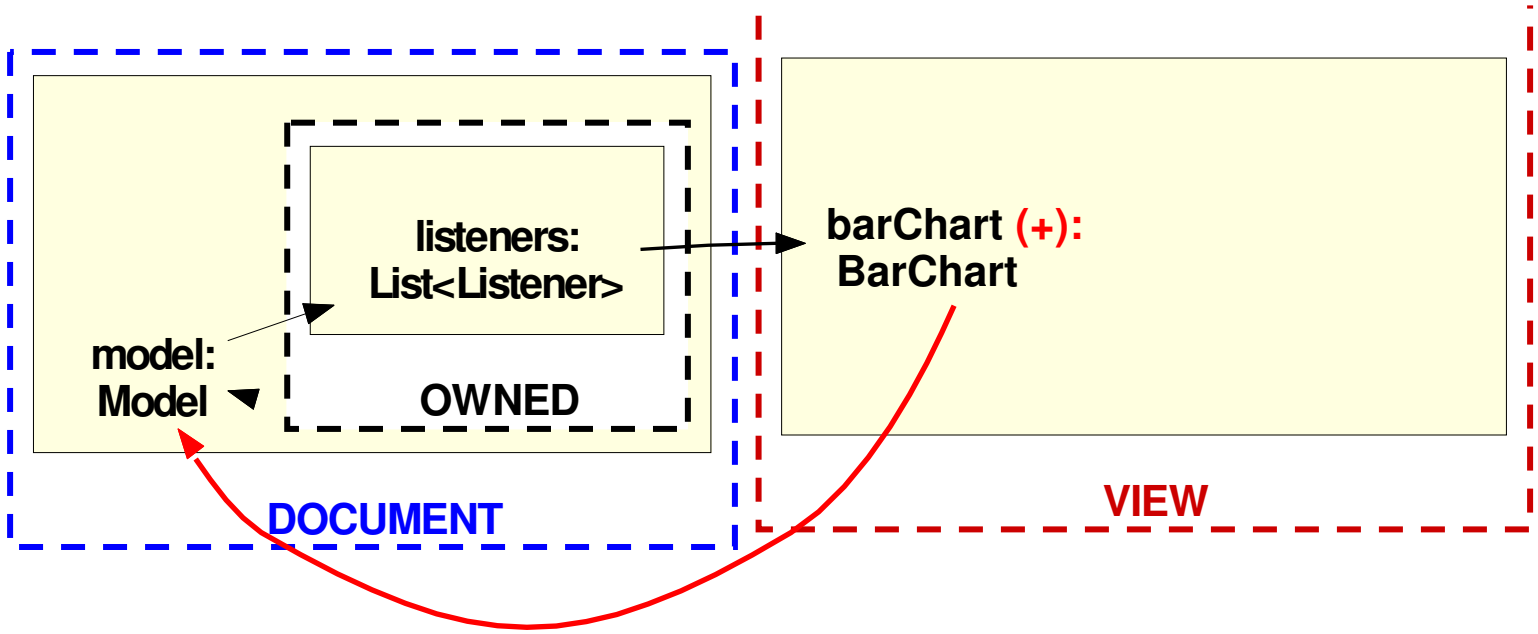
Challenge: edges could be due to sub-objects that point to external objects

- *Invariant: show all object relations, even ones due to objects in sub-structures*
- Lift **edge** to parent object when hidden sub-object points to external objects

Example of edge lifting



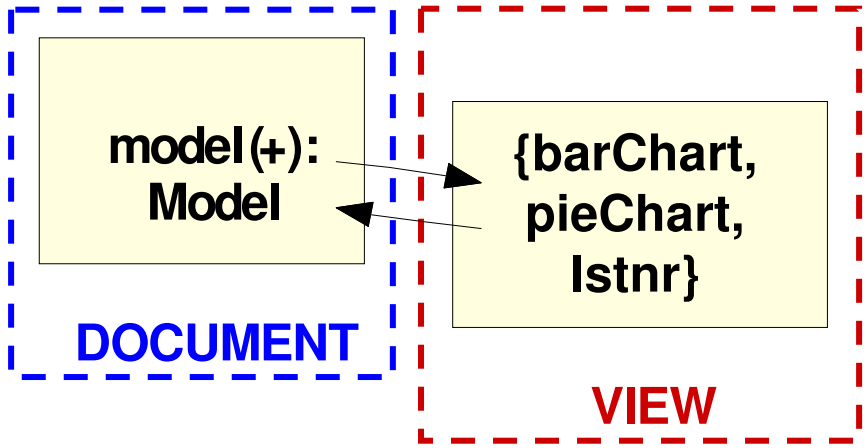
Example of edge lifting



Abstraction by types

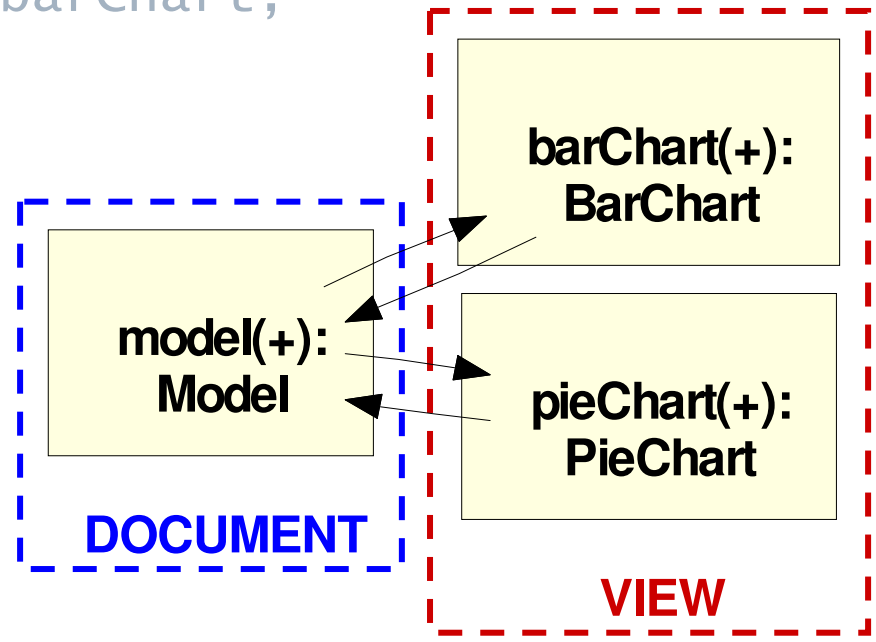
Challenge: using declared types could lead to excessive merging (imprecision)

```
class Main {
  domain DOCUMENT, VIEW;
  DOCUMENT Model model;
  VIEW BarChart barChart;
  VIEW PieChart pieChart;
  VIEW Listener lstnr = barChart;
  ...
}
```



TypeGraph: consider only object allocations (Instantiation-Based View)

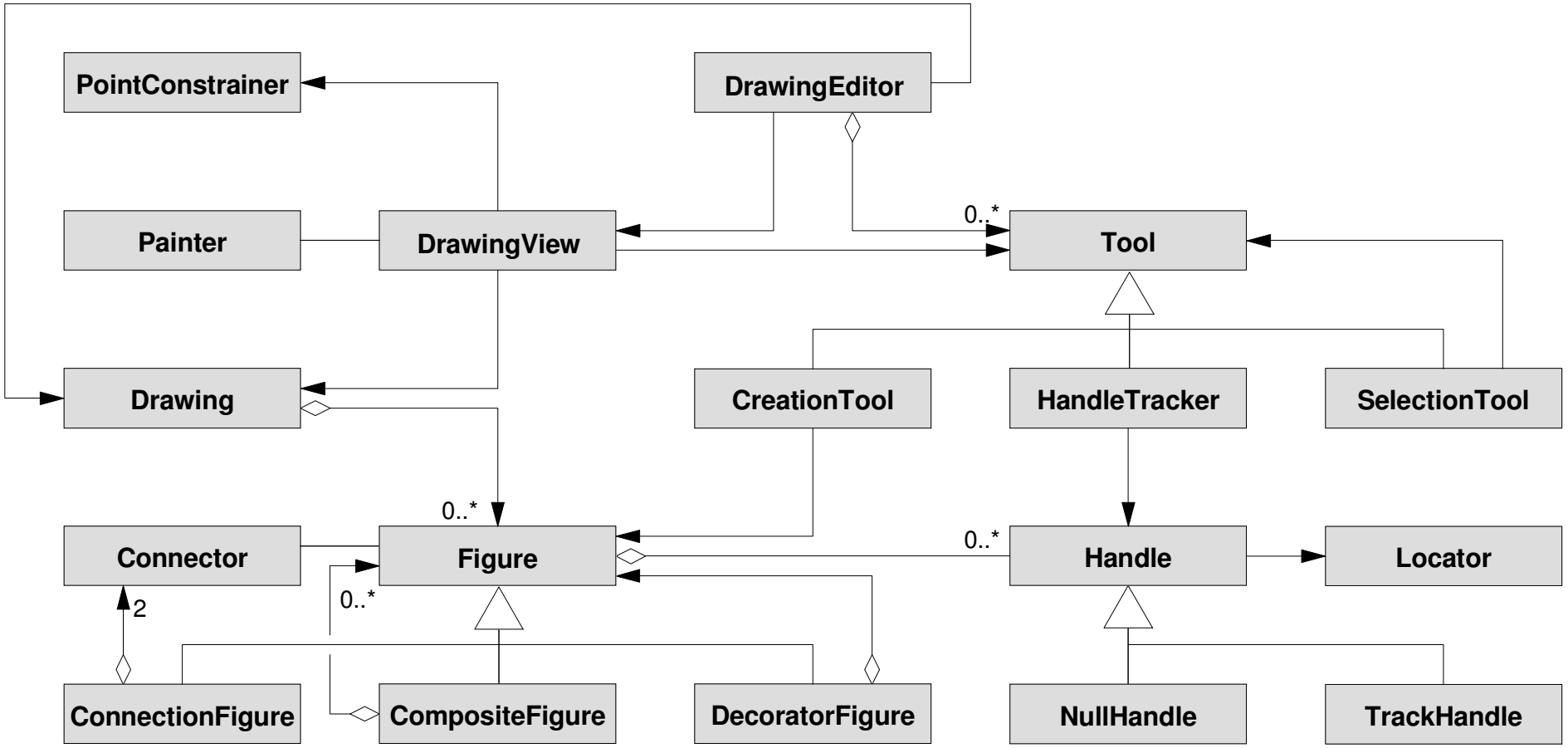
```
class Main {
  domain DOCUMENT, VIEW;
  DOCUMENT Model model = new Model();
  VIEW BarChart barChart = new BarChart();
  VIEW PieChart pieChart = new PieChart();
  VIEW Listener lstnr = barChart;
  ...
}
```



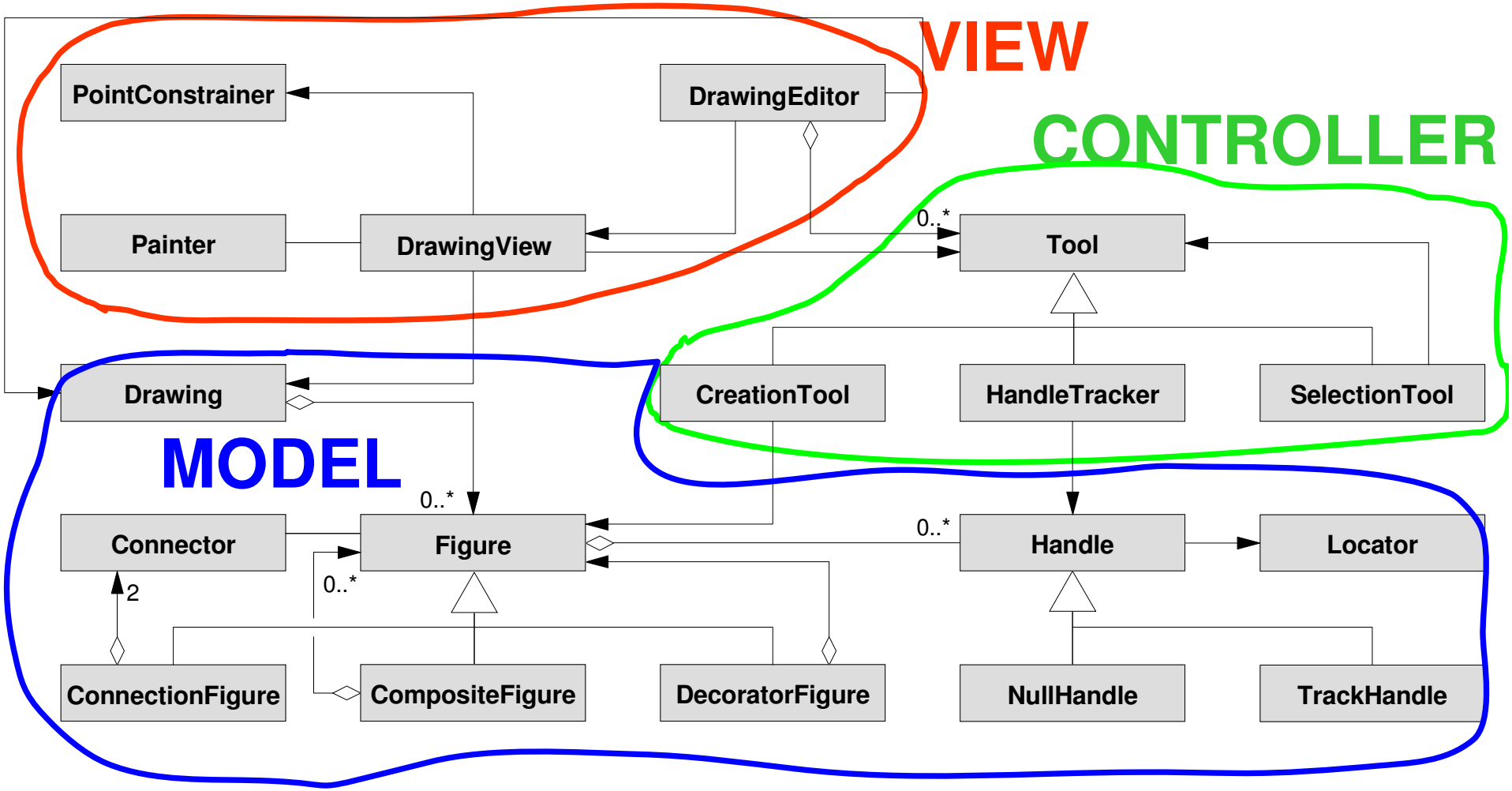
Challenge: maintain abstraction in Instantiation-Based View (IBV)

- Prevents excessive merging
  - Reduces abstraction
  - Leads to clutter
- Example: JHotDraw
  - 16,000 lines of Java
  - 200 classes
  - Rich inheritance hierarchy
  - Designed by object-oriented design experts

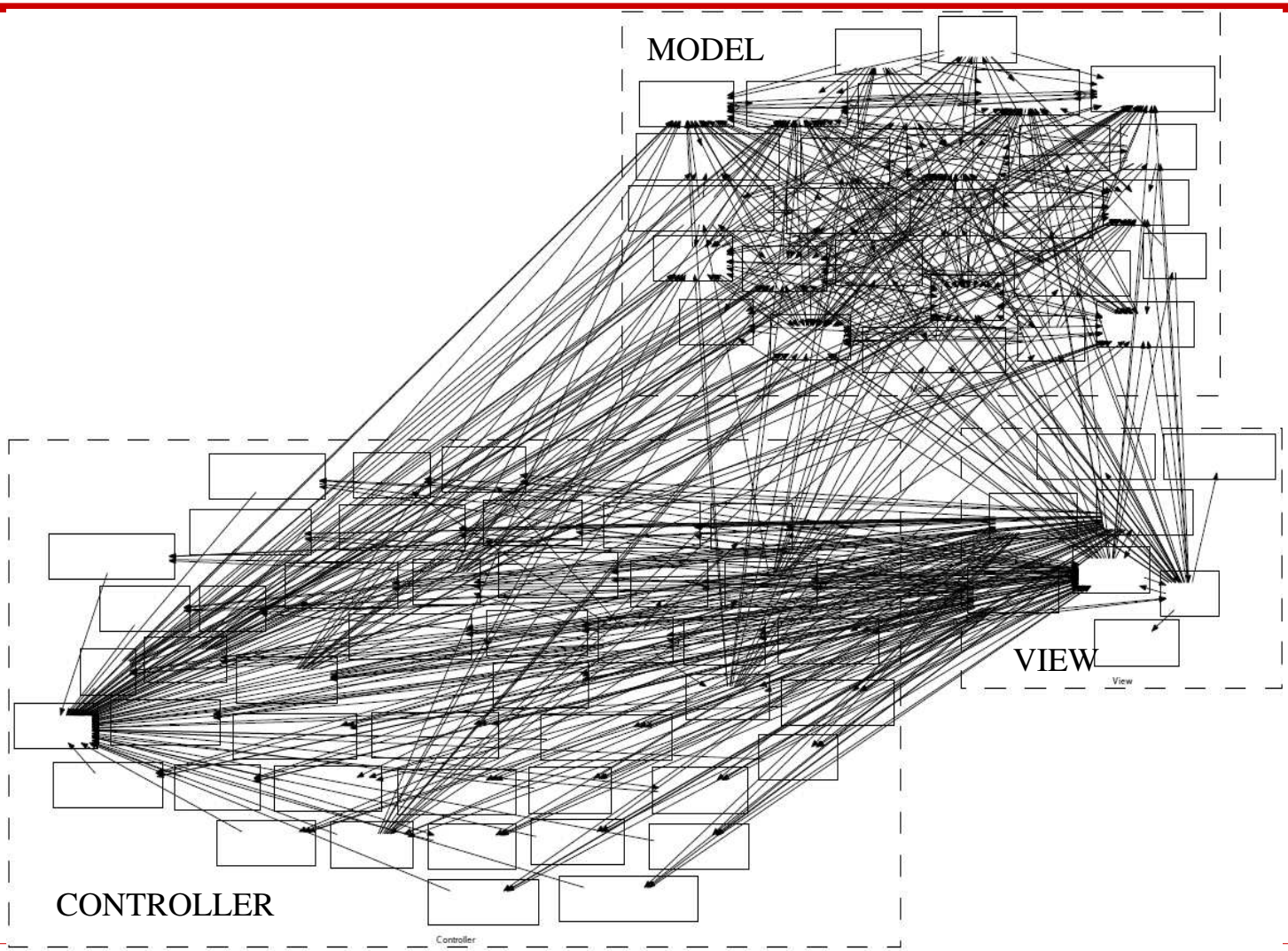
JHotDraw class diagram



Adding annotations to JHotDraw



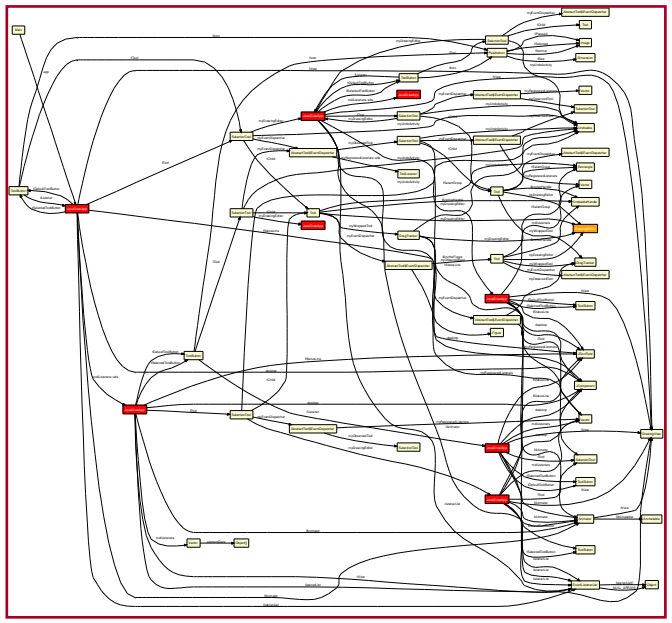
JHotDraw Object Graph (IBV)



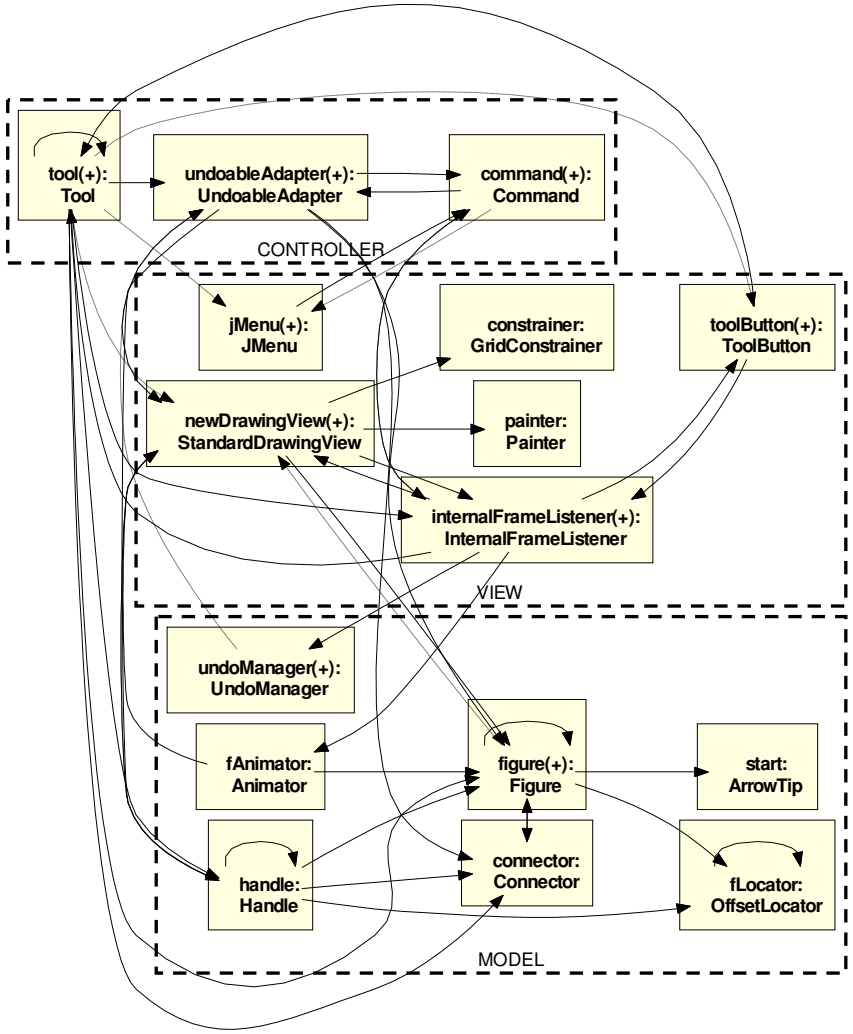
Abstraction by types

- (Optionally) Merge objects, **in a given domain**, based on their declared types
  - Heuristic (can be turned off)
  - Need not apply globally
- Abstract by **trivial types**
  - Merge objects when their types have **non-trivial least upper bound**
  - User configures list of trivial types. By default, includes `Object`, `Serializable`, etc.
- Or abstract by **design intent types**
  - Based on a list of architecturally relevant types, e.g., `Drawing, Figure, …`
  - Works well if type structure carefully designed
- Details in paper

JHotDraw with abstraction by types



Output of WOMBLE
[Jackson and Waingold, TSE'01]

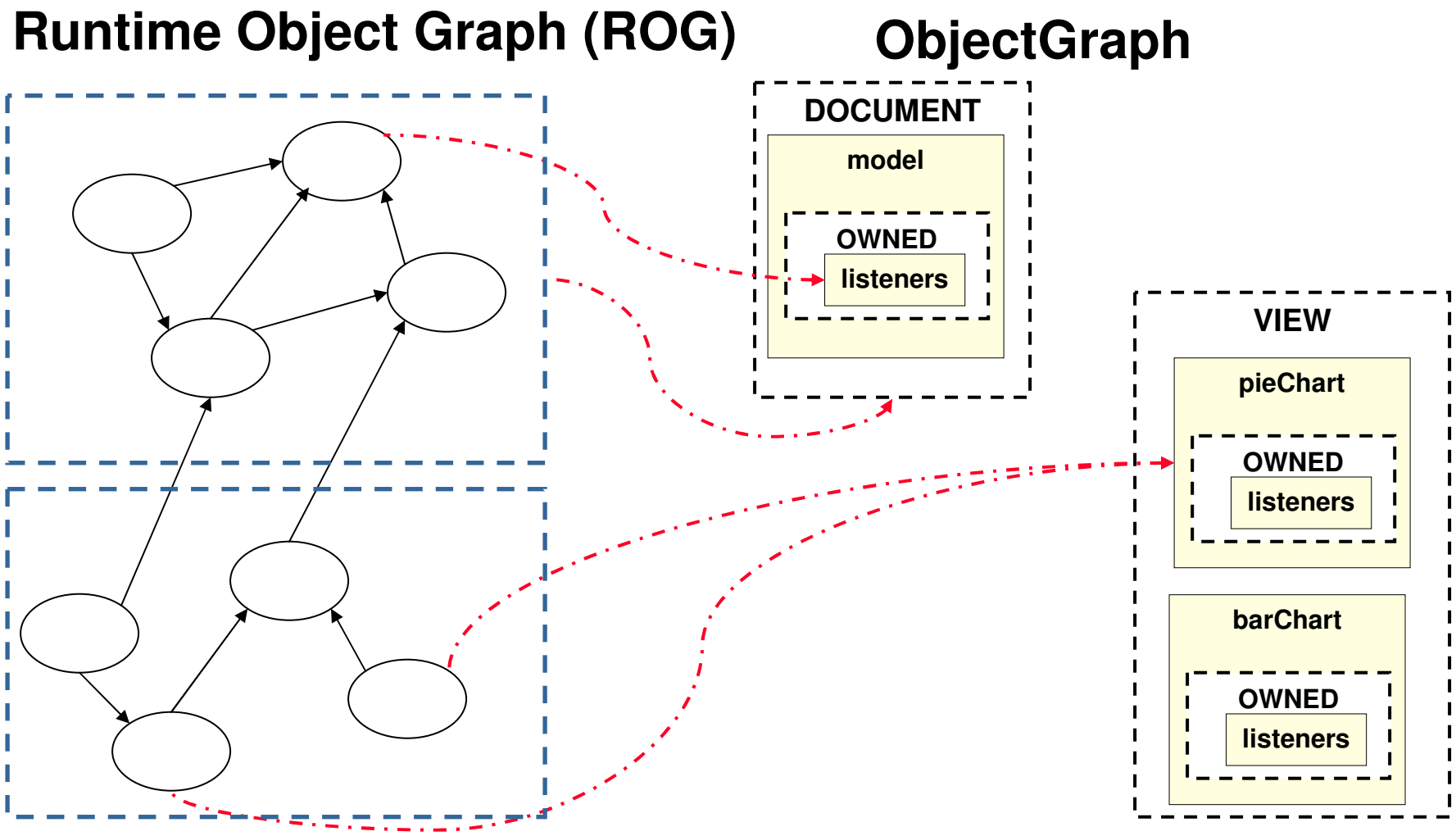


Soundness

Soundness

- Dynamic analysis previously used to infer runtime ownership structure for one or more program runs
- **Static analysis can** describe all possible program runs:
  - For **soundness, show** all objects and relations that may exist in any run
  - Maintain **aliasing soundness**: no one object should appear as two "boxes" in object graph

Intuition behind soundness



Theorem: Object and Domain Soundness

- Each object in a ROG has **exactly one representative** in an ObjectGraph.
- Similarly, each domain in the ROG has exactly one representative in the ObjectGraph.
- Furthermore, mapping is consistent with respect to the ownership relation.

Proving soundness

- Formalization using rewriting rules

Object Rules $\boxed{\Theta \implies \Theta'}$

$$\frac{\mathsf{AbstractObject}(o,\ d,\ t,\ \{b\ldots\})}{\Theta \vdash \mathsf{try}(\{o\},\ d)}\ [\text{R-CONVERT-OBJECT}]$$

$$\frac{\begin{array}{c}\mathsf{RuntimeObject}(\{o_{pull}\ldots\},\ d_{param}) \in \Theta \qquad \mathsf{RuntimeObject}(\{o_{parent}\ldots\},\ d_{parent}) \in \Theta \\ \mathsf{AbstractDomain}(d_{param}, \mathsf{typeof}(o_{parent})) \qquad \mathsf{aparam}(o_{parent}, d_{param}, d_{actual})\end{array}}{\Theta \vdash \mathsf{try}(\{o_{pull}\ldots\},\ d_{actual})}\ [\text{R-PULL-OBJECT}]$$

$$\frac{\Theta \vdash \mathsf{try}(\{o\ldots\},\ d) \qquad \nexists\, o, o_1.(\ \mathsf{RuntimeObject}(\{o_1\ldots\},\ d) \in \Theta\ \wedge\ \vdash \mathsf{compat}(\mathsf{typeof}(o),\ \mathsf{typeof}(o_1))\ )}{\Theta \implies \Theta, \mathsf{RuntimeObject}(\{o\ldots\},\ d)}\ [\text{R-NEW-OBJECT}]$$

$$\frac{\Theta \vdash \mathsf{try}(\{o\ldots\},\ d) \qquad \mathsf{compat}(\mathsf{typeof}(o),\ \mathsf{typeof}(o_1))}{\Theta, \mathsf{RuntimeObject}(\{o_1\ldots\},\ d) \implies \Theta, \mathsf{RuntimeObject}(\{o\ldots\} \cup \{o_1\ldots\},\ d)}\ [\text{R-MERGE-OBJECTS}]$$

$$\frac{\mathsf{compat}(\mathsf{typeof}(o_1),\ \mathsf{typeof}(o_2))}{\Theta, \mathsf{RuntimeObject}(\{o_1\ldots\},\ d), \mathsf{RuntimeObject}(\{o_2\ldots\},\ d) \implies \Theta, \mathsf{RuntimeObject}(\{o_1\ldots\} \cup \{o_2\ldots\}, d)}\ [\text{R-MERGE-EXISTING}]$$

Auxiliary Rules

$$\frac{\mathsf{AbstractObject}(o,\ d,\ t,\ \{d_{param} \mapsto d_{actual}, \ldots\})}{\mathsf{aparam}(o, d_{param}, d_{actual})} \qquad \frac{\mathsf{AbstractObject}(o,\ d,\ t,\ \{b\ldots\})}{\mathsf{typeof}(o) = t}$$

$$\mathsf{compat}(t_1,\ t_2) \text{ iff } t_1 <: t_2 \text{ or } t_2 <: t_1 \text{ or } \mathsf{existsNonTrivialLUB}(t_1,\ t_2) \text{ or } \mathsf{mapToSameDIT}(t_1,\ t_2) \quad [\text{R-AUX-COMPAT}]$$

Proof of Object and Domain Soundness

- Ownership domains formalization
  - Featherweight Domain Java
  - Store typing characterizes any execution of a well-typed program
- Soundness proof relates store typing to extracted ObjectGraph

Future work: Edge Soundness

- Edges in an ObjectGraph soundly abstract all field points-to relations between objects in an ROG.
- If object ℓ_1 has a field reference to object ℓ_2 in a ROG, then there is an edge between the representatives of ℓ_1 and ℓ_2 in the ObjectGraph.

Evaluation

Evaluated on several case studies and a field study (totaling 68 KLOC)

- Research Question: *does an extracted ObjectGraph suffer from too much or too little abstraction on real code?*

System	Size	Comments
JHotDraw	15 KLOC	Designed by object-oriented design experts
HillClimber	15 KLOC	Designed by undergraduates
Aphyds	8 KLOC	Original developer drew architecture
LbGrid	30 KLOC	Part of 250-KLOC commercial system

Related work

- Object graph extraction
  - Without using annotations
    [Jackson and Waingold, ICSE'99,TSE'01]
    [O'Callahan, Ph.D. thesis'01]
  - Using non-ownership annotations
    [Lam and Rinard, ECOOP'03]
  - Some unsound w.r.t. aliasing or inheritance
  - Non-hierarchical object models
- Related static analyses
  - Points-to analysis [e.g., Milanova et al., TOSEM'05]
  - Shape analysis [e.g., Sagiv et al., POPL'99]
  - Precise, but non-hierarchical abstractions

Related work (continued)

- Radical language extensions
  - Specify architectural hierarchy and instances
    ArchJava [Aldrich et al., ECOOP'02]
    JCoBox [Schäfer et al., CoCoME'07]
  - Restrict passing object references
  - Require re-engineering existing systems
- Dynamic ownership analyses
  - Organize objects based on ownership
    [Hill, Noble and Potter, J. Vis. Lang.& Comp.,'02]
  - Infer strict-as-dominator hierarchy
  - Describe structure for few program runs

Summary

- **Static analysis** to extract **hierarchical object graph**
  - Relies on **ownership type annotations**
  - Proved **object/soundness** theorem
- **Evaluated analysis** on real object-oriented code totaling 68 KLOC
  - Achieves adequate precision
  - Sufficient to relate abstracted object graph to a posited target architecture [Tech. report]