Practical Static Extraction and Conformance Checking of the Runtime Architecture of Object-Oriented Systems

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Software architecture: high-level description of a system's organization

- Communication between stakeholders
- Analyzing quality attributes:
  - Maintainability,
  - Security, performance, reliability …
- Different perspectives or **views**:
  - **Code architecture**
  - **Runtime architecture**
  - **Distinct** but **complementary**
  - Focus today is on **structure**, not **behavior**

Code architecture shows code structure (classes, inheritance, etc.)

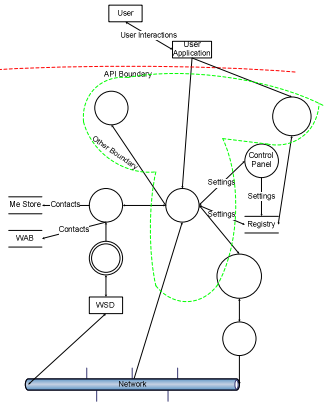
- **Code architecture** represents **static code structure** of system
  - Classes, packages, modules, layers, ..
  - Inherits from class, implements interface
  - Dependencies: imports, calls graphs.
- Impacts qualities like **maintainability**
- **Mature** tool support

Runtime architecture shows objects (instances) and relations between them

- **Runtime architecture** models **runtime structure** as runtime components and potential runtime interactions
  - Runtime component = sets of **objects**
  - Runtime interaction = e.g., points-to relation
- Impacts qualities such as **security**, performance, reliability, …
- **Immature** tool support

Analyze quality attribute, assuming architecture reflects all communication

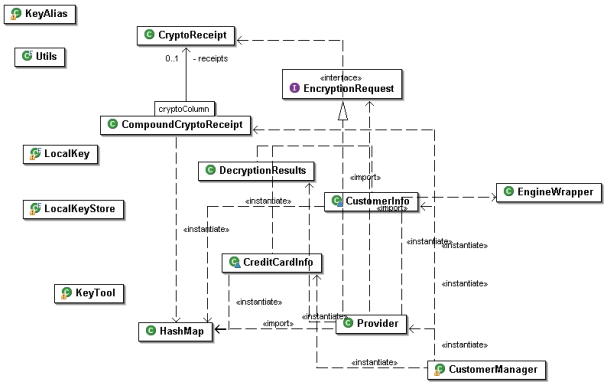
- Microsoft uses **threat modeling** and claims **50% reduction** in vulnerabilities
- Security experts review hand-drawn diagrams (Vista has 1,400 diagrams)
- **Checking conformance** of implementation to architecture not addressed
- Potential security violations



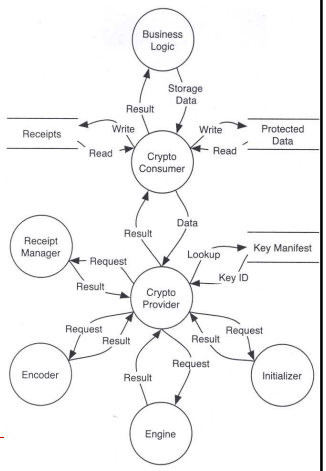
Redacted diagram for Windows Vista™ subsystem

Security analysis requires runtime architecture, not code architecture

Class diagram

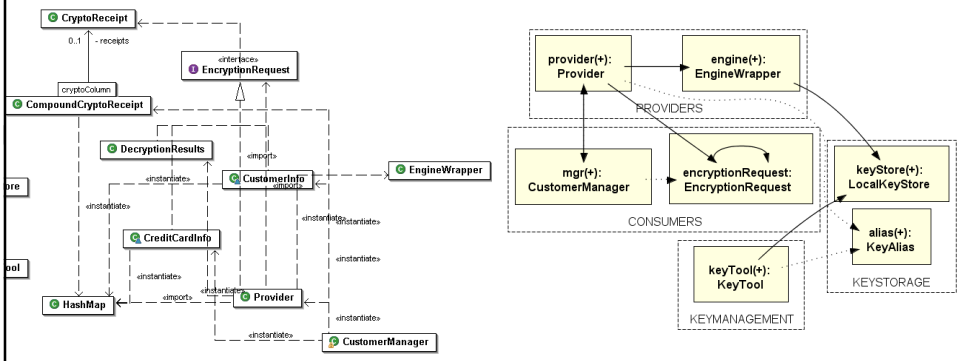


DFD



Security analysis requires runtime architecture, not code architecture

Class diagram **Object diagram**

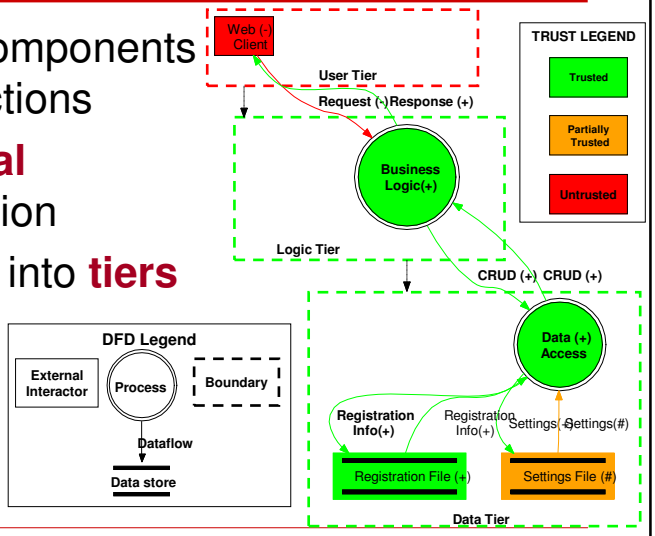


Disclaimer: security architecture

- Threat modeling uses a Data Flow Diagram (DFD) with security annotations
- This presentation uses a different architectural style: a security architecture shows **points-to (not data flow) connectors**, has no explicit data stores or external interactors, and uses more general boundaries that are tiers.

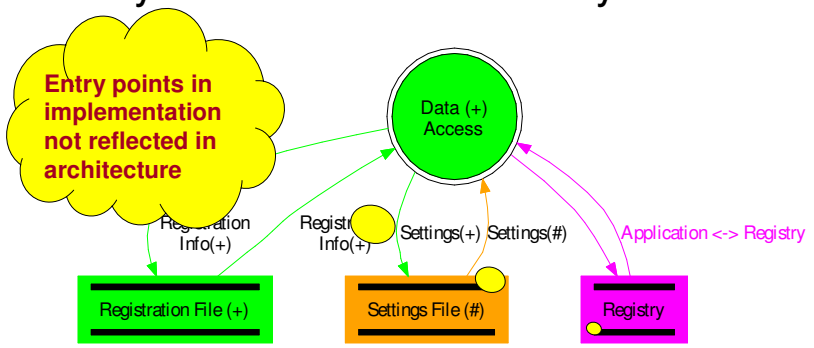
Example security runtime architecture

- **Runtime** components and connections
- **Hierarchical** decomposition
- Partitioning into **tiers**



Some analyses must consider worst case of possible communication

- Results valid only if model is **sound**
- **Sound**: reveal all objects and relations that may exist at runtime – in any run

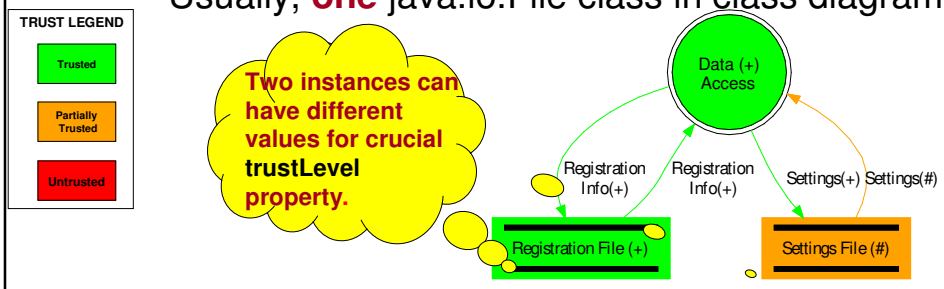


Architectural extraction's key property: soundness

- *Definition: a runtime architecture is **sound** if it represents all runtime components and all possible interactions between those components.*
- Informal Visio diagram often unsound

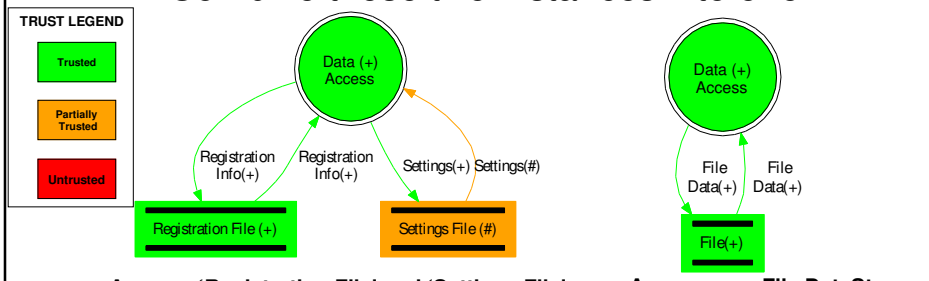
Runtime structure distinguishes between different instances of the same class

- **Different instances** usually have different architectural **properties**
  - Here, **trustLevel** = **Full** vs. **Partial**
  - Usually, **one** java.io.File class in class diagram



Aliasing or state sharing is a challenge in representing a runtime architecture

- Impacts **architectural properties**
  - Settings File (**trustLevel** = **Partial**)
  - vs. Registration File (**trustLevel** = **Full**)
  - Combine these two instances into one?



Assume 'Registration File' and 'Settings File' distinct, with different values for trustLevel.

Assume one File DataStore, with one value for trustLevel.

Other key property: aliasing soundness

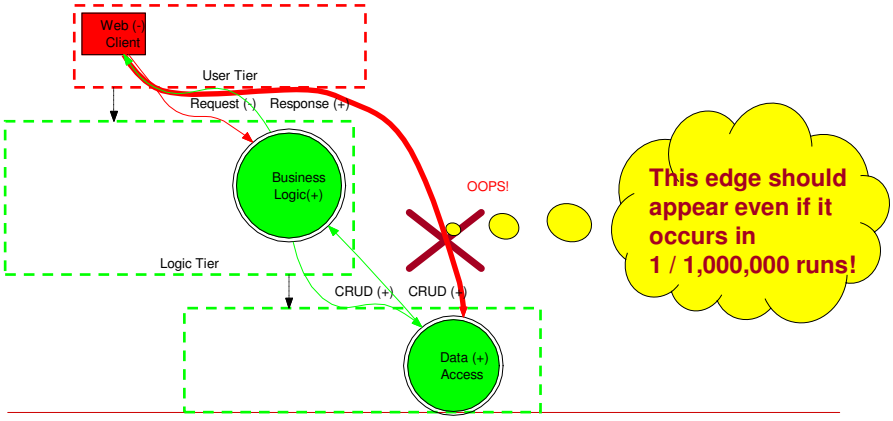
- *Definition: an architecture is sound w.r.t. aliasing if no one runtime entity appears as two "components" in the architecture*
- Otherwise, could assign two different values of **trustLevel** architectural property for one true runtime entity

Architectural extraction: state-of-the-art

- Using **static** analysis still open problem
  - Can capture **all possible** executions
  - Extract low-level **non-architectural** views
  - Analyses often unscalable
- Using **dynamic** analysis
  - Analyze one or more program runs
  - May **miss important objects** or **relations** that arise only **in other** program runs
  - E.g., security analysis must handle **worst**, not typical, possible runtime communication

Two components should communicate only if architecture allows them to do so

- E.g., prohibit **direct comunication** between certain components, **for all program runs**



Checking structural conformance of system to target architecture

- Key property: **communication integrity**

  Definition: each component in the implementation may only communicate directly with the components to which it is connected in the architecture.

  [Moriconi et al., TSE'95] [Luckham and Vera, TSE'95]
- Informal diagrams **omit** communication; confirmed by experience at Microsoft

  [Murphy et al.,TSE'01] [Aldrich et al., ICSE'02]

Previous work to ensure conformance of runtime architecture has drawbacks

- **Runtime monitoring**
  - Cannot check all possible program runs
- **Code generation**
  - Hard to use for **existing systems**
  - More general to **extract-abstract-check**
- **Language-based solutions**

  ArchJava [Aldrich et al., ECOOP'02]
  - Restrictions on object references
  - Require re-engineering **existing systems**
- **Library-based solutions**

Today, you will learn SCHOLIA

SCHOLIA: **s**tatic **c**onformance **h**ecking of **o**bject-based structura**l** v**i**ews of **a**rchitecture.

Scholia are annotations inserted on the margin of an ancient manuscript.
The approach supports existing, i.e., legacy systems, and uses annotations.

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First entirely static end-to-end approach to guarantee communication integrity for Java

- **SCHOLIA relates** code in widely-used object-oriented language (Java) and a **hierarchical** intended **runtime architecture:**
  - **Extract** instance structure
    - Hierarchy provides abstraction
    - Achieve **soundness**
  - **Abstract** instance structure into architecture
  - **Structurally compare** hierarchical views
  - **Check** conformance
    - Enforce **communication integrity**

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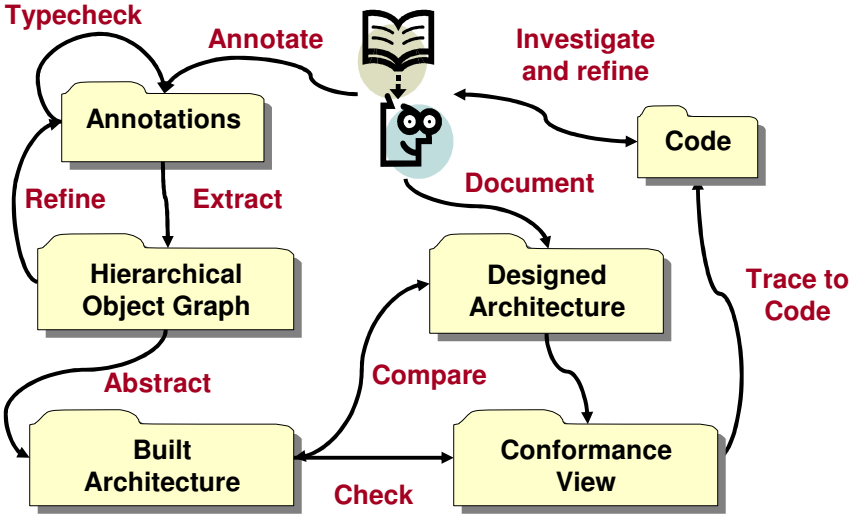
At SCHOLIA's core is the static extraction of architectural runtime structure

- Extract **sound object graph** that conveys **architectural abstraction** by **hierarchy** and by types
  - Uses **static analysis**
  - Achieves **soundness**
  - Relies on **backward-compatible statically type-checkable annotations**
  - Minimally invasive hints about architecture
  - Instead of using new language or library

Conformance checking uses general strategy of extract-abstract-check

- **Extract** instance structure
  - **Add annotations** to code
  - Run **static analysis**
- **Abstract** into **built architecture**
- Document **designed/target** architecture
- **Compare built** and **designed** views
- **Check** conformance

SCHOLIA conformance checking



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Code vs. Execution Structure
Classes Objects
Types Instances
Static Runtime

Illustrated using example

Aphyds, an 8,000-line Java system

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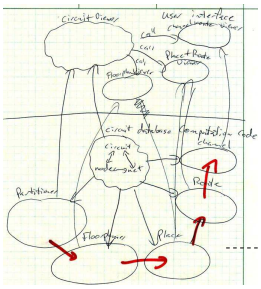
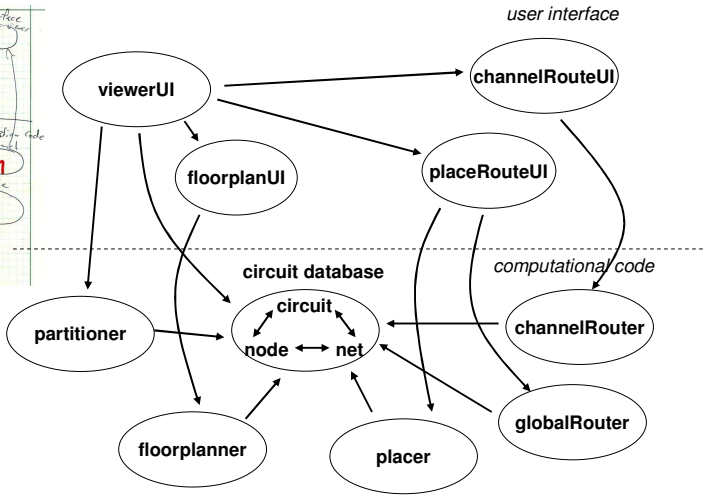
Developer posits a target hierarchical runtime architecture





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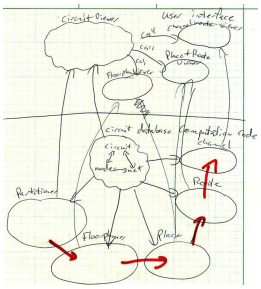
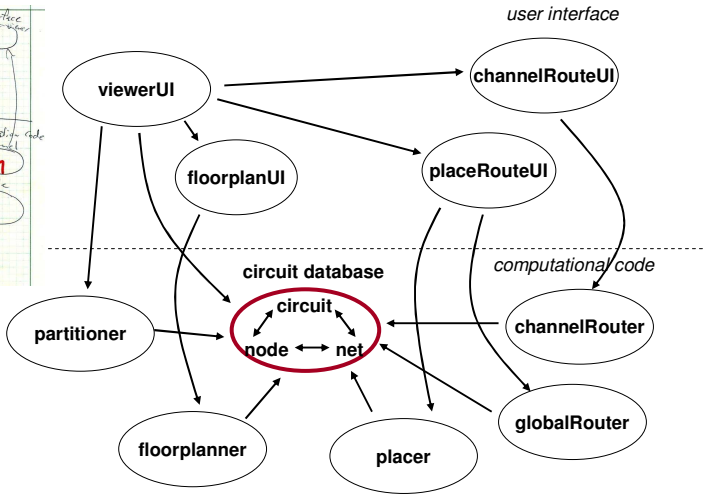
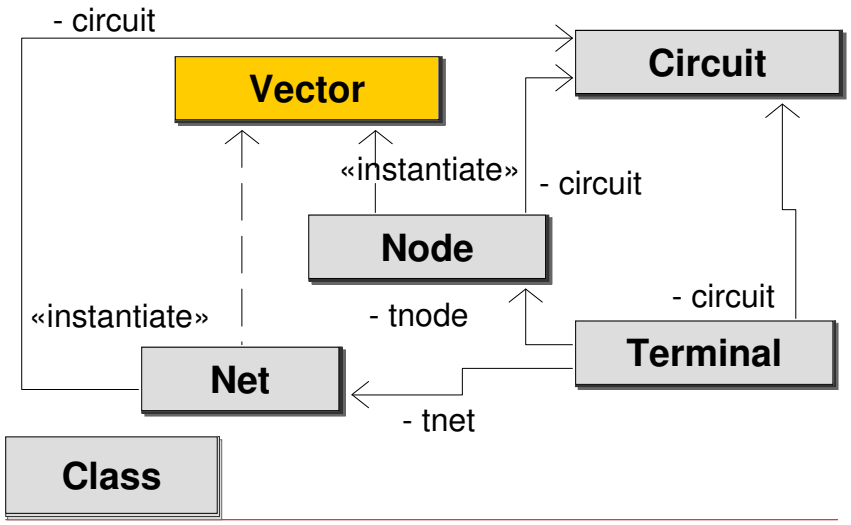




Class diagram shows code structure, e.g., classes, inheritance



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Object diagram shows instance structure, i.e., objects and relations

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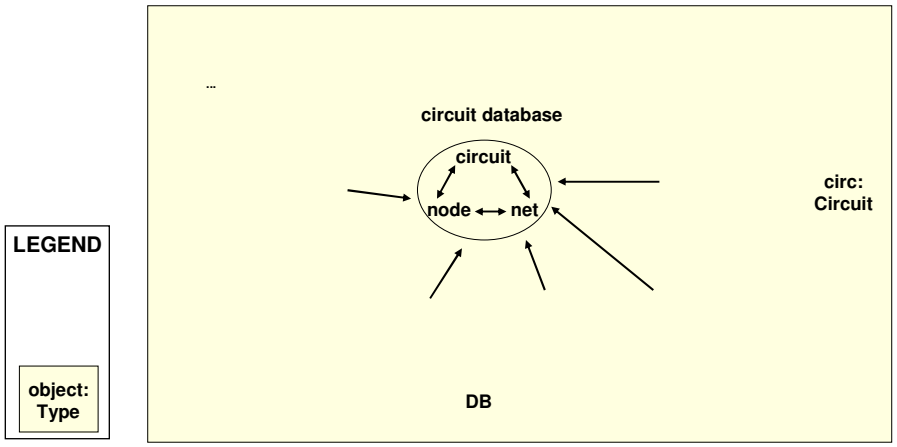
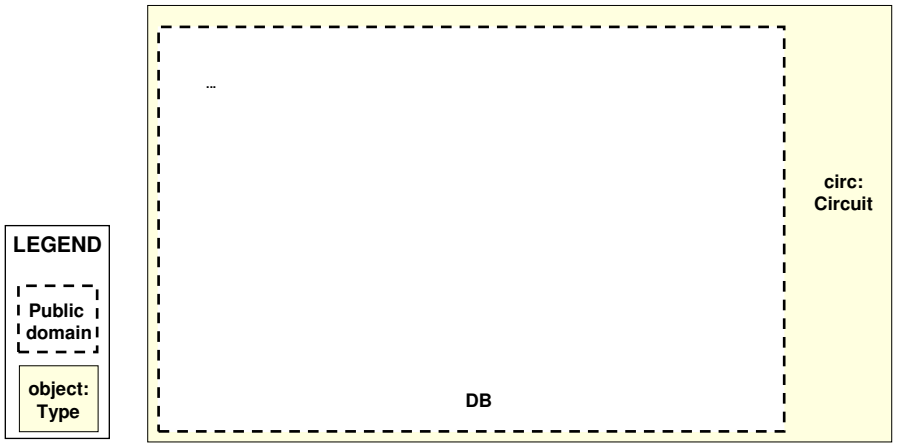
In hierarchical object structure, an object can contain other objects

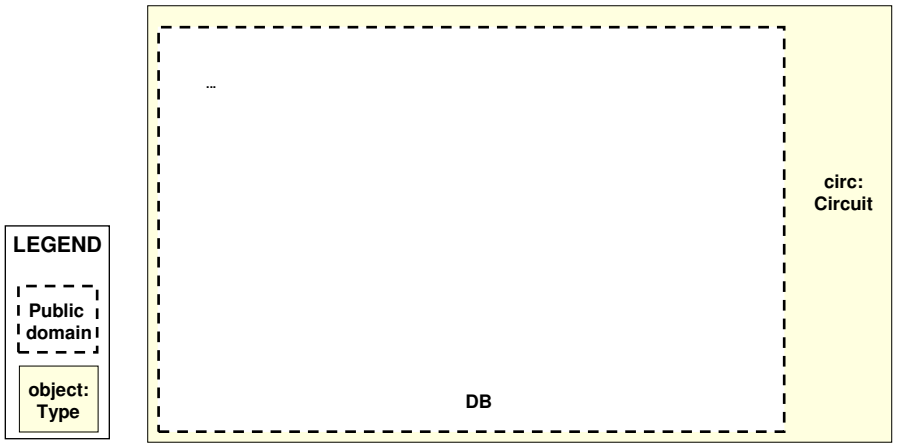


Instead of objects directly owning others, use domains to group related objects



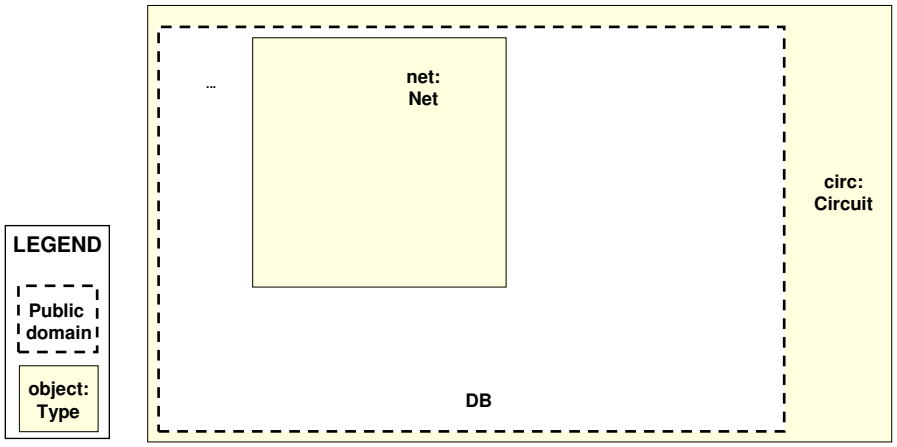
Box nesting indicates "inside"

A public domain in an object defines a conceptual group of contained objects



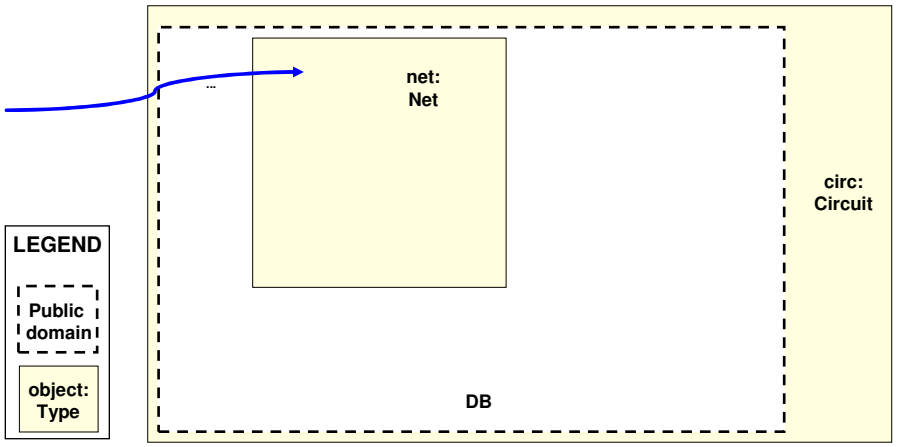
Box nesting indicates "inside"

Placing object 'net' in domain 'DB' inside 'circuit' makes 'net' part of 'circuit'



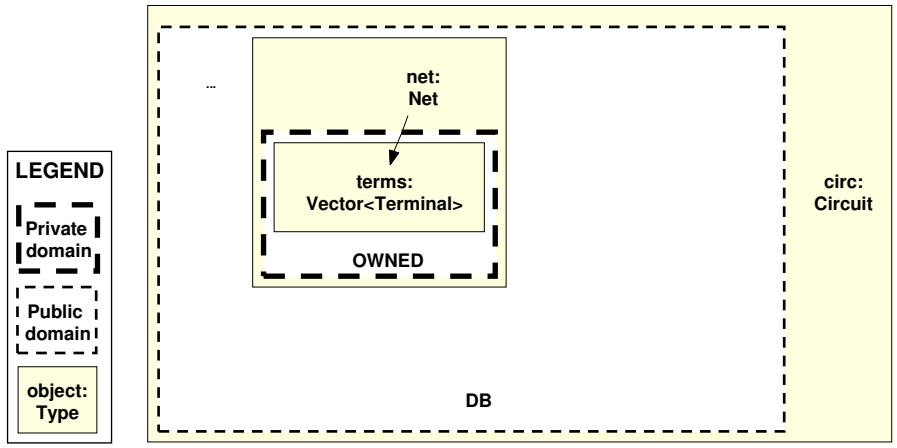
Box nesting indicates "inside"

Any object that can reference ‘circuit’ can also reference ‘net’ inside ‘DB’ domain



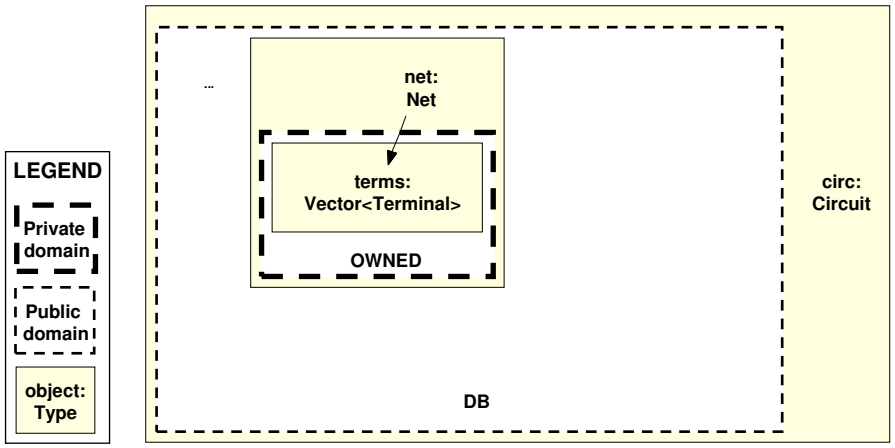
Thin border indicates logical containment

Each object can have domains, e.g., ‘net’ has ‘OWNED’ domain and ‘terms’ inside it



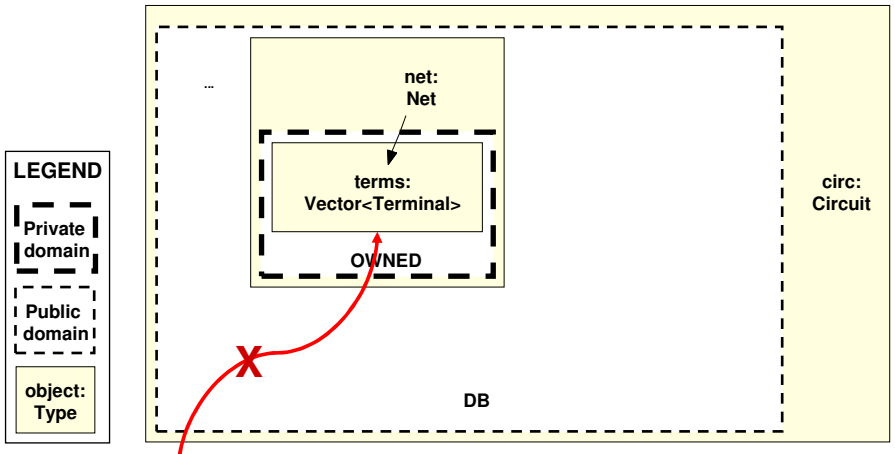
Box nesting indicates “inside”

A private domain defines a strict encapsulation or ownership model



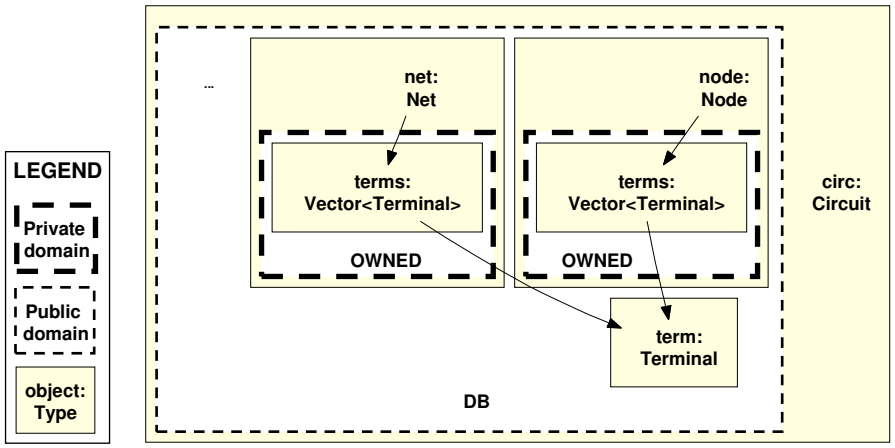
'terms' is in private domain of 'net'

'terms' is strictly encapsulated inside 'net' and cannot be leaked/aliased to outside



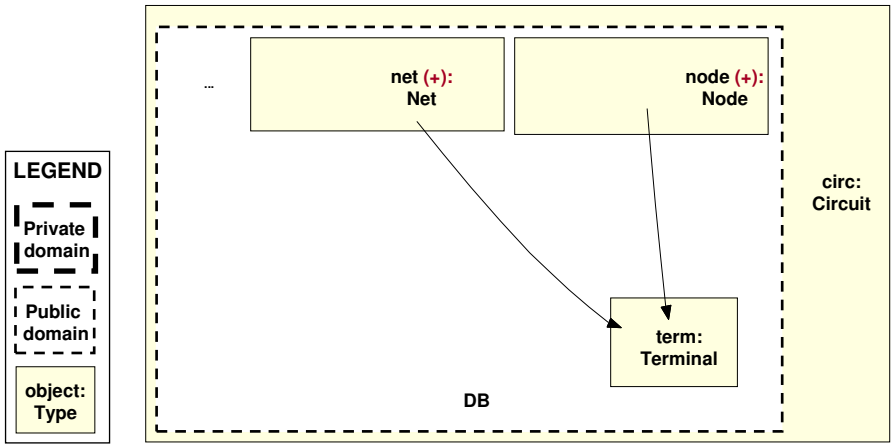
Thick border indicates strict encapsulation

Unlike class diagram, object diagram shows distinct 'Vector' instances



But 'terms' Vectors can share other objects

Hierarchy allows varying abstraction level, by collapsing or expanding objects



(+) indicates collapsed sub-structure

Central difficulty

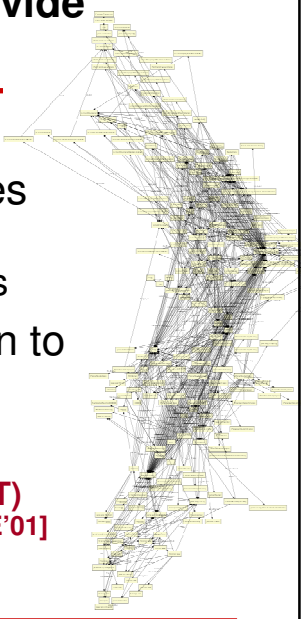
Architectural **hierarchy** not readily observable in program written in general purpose programming language

All previous static analyses extract non-hierarchical abstractions

- Object graph analyses
  - 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
- Related static analyses
  - Points-to analysis [e.g., Milanova et al., TOSEM'05]
  - Shape analysis [e.g., Sagiv et al., POPL'99]

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]



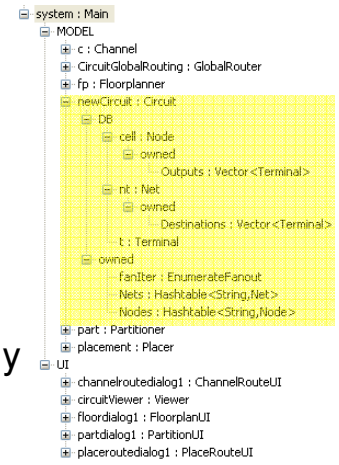
Output of WOMBLE (MIT)
[Jackson and Waingold, TSE'01]
on 8,000-line system.

Key insight

Add **ownership annotations** and leverage them using **static analysis**

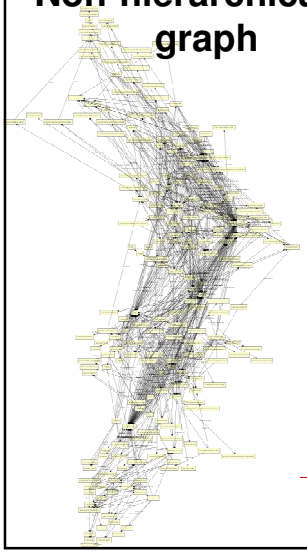
Use hierarchy to convey architectural abstraction

- 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

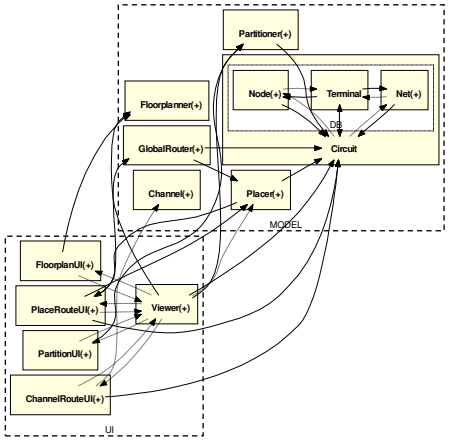


Collapse objects based on ownership (and types) to achieve abstraction

Non-hierarchical graph



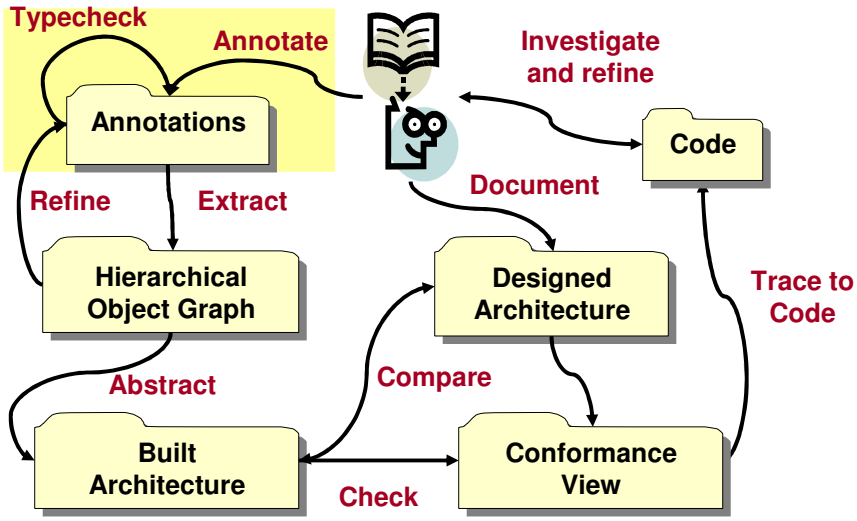
Hierarchical graph



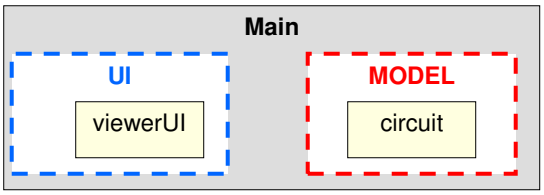
Step 1

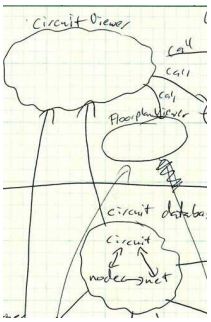
Add and check ownership domain annotations

SCHOLIA conformance checking



Group objects into *ownership domains*





```
class Main {
  domain UI, MODEL;

  UI Viewer viewerUI;
  MODEL Circuit circuit;
  ...
}
```

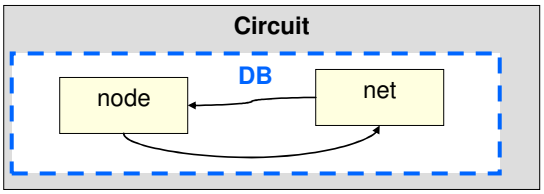
object: Type — Object

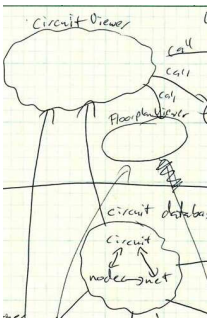
Type — Type

Declarations are simplified

- Ownership domain = conceptual group of objects
- Each object **in exactly one domain**

Domains can be declared inside each class





```
class Circuit {
  domain DB;

  DB Node node;
  DB Net net;
  ...
}
```

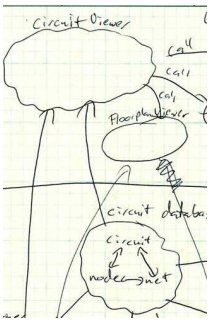
object: Type — Object

Type — Type

Declarations are simplified

Aphyds: concrete annotations

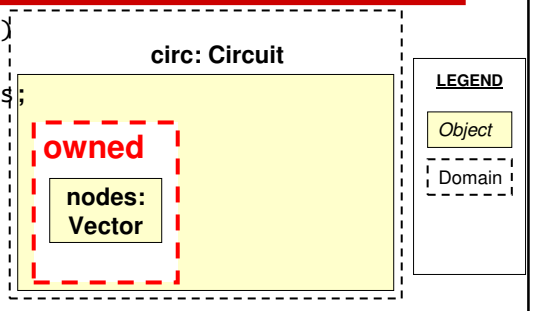
```
@Domains({"UI", "MODEL"})
class Main {
  @Domain("UI") Viewer viewerUI;
  @Domain("MODEL") Circuit circuit;
  ...
}
```



- Tools use **existing language support for annotations** (available in Java 1.5, C#, …)
- Annotations do not change runtime semantics

Circuit: private domain

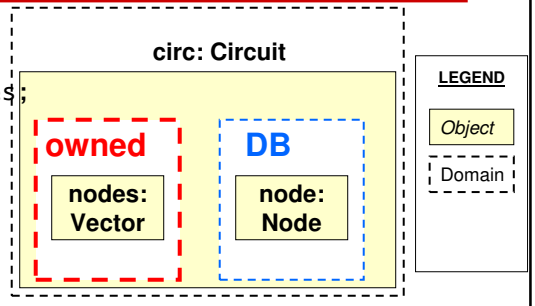
```
@Domains({"owned",          })
class Circuit {
 @Domain("owned") Vector nodes;

}
```



- Each object has one or more domains
  - E.g., Circuit declares domains **owned** and **DB**
- Each object is in exactly one domain
  - E.g., nodes in domain **owned**

Circuit: public domain

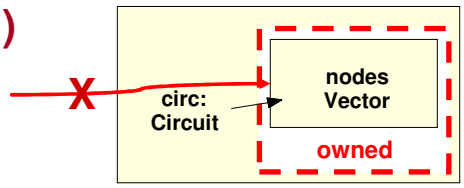
```
@Domains({"owned", "DB"})
class Circuit {
 @Domain("owned") Vector nodes;

 @Domain("DB") Node node;
}
```



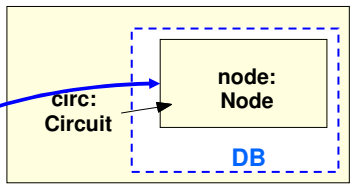
- Each object has one or more domains
  - E.g., Circuit declares domains **owned** and **DB**
- Each object is in exactly one domain
  - E.g., nodes in domain **owned**; node in domain **DB**

Strict encapsulation vs. logical containment

(1) Strict encapsulation (private domain)

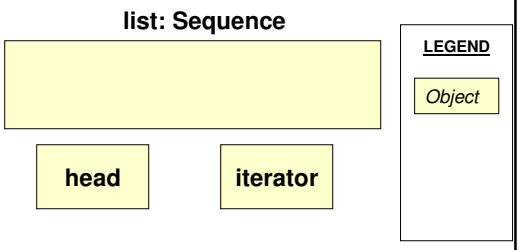


(2) Logical containment (public domain)



Example #2: Sequence

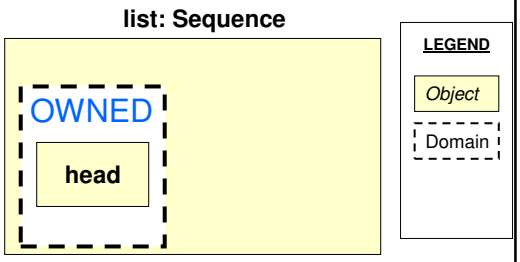
```
class Sequence {
                  Cons head;

 public
 Iterator iterator() {
    return new Iterator(head);
  }
}
```



- Sequence has private state (head)
  - Should not be accessible to outside
- Sequence has iterators that are accessible to outside
  - Can also access private state

Sequence: private domain

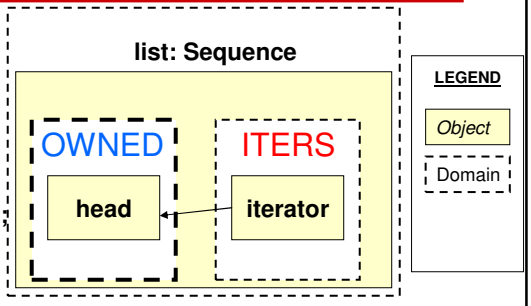
```
@Domains({"OWNED"          })
class Sequence {
 @Domain("OWNED") Cons head;

 public
 Iterator iterator() {
    return new Iterator(head);
  }
}
```



- Sequence has private state (head)
  - Should not be accessible to outside; in private domain
- Sequence has iterators that are accessible to outside
  - Can also access private state

Sequence: public domain

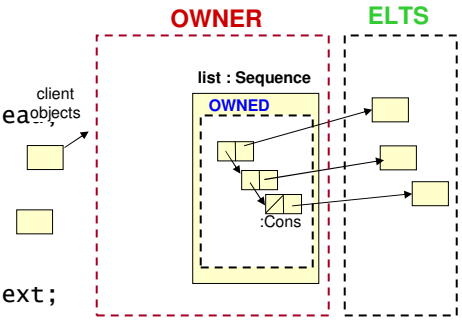
```
@Domains({"OWNED", "ITERS"})
class Sequence {
 @Domain("OWNED") Cons head;

 public @Domain("ITERS")
 Iterator iterator() {
    return new Iterator(head);
  }
}
```



- Sequence has private state (head)
  - Not accessible to outside; in private domain **OWNED**
- Sequence has iterators that are accessible to outside
  - Can also access private state; in public domain **ITERS**

Sequence: ownership domain parameters

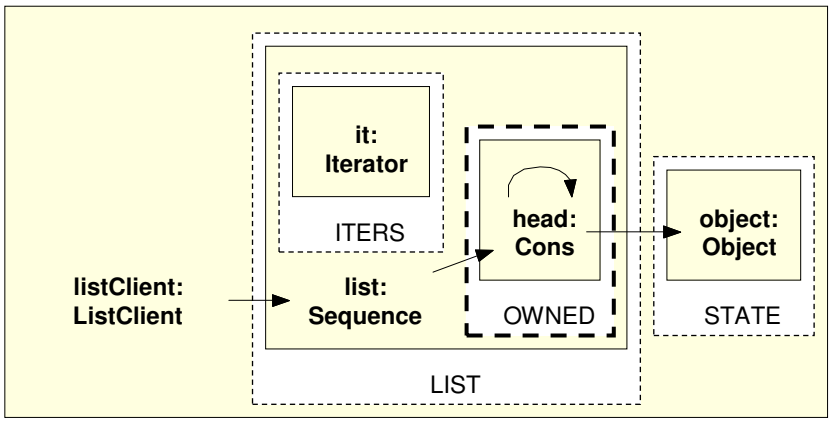
```
@Domains({"OWNED", "ITERS"})
@DomainParams({"ELTS"})
class Sequence {
  @Domain("OWNED<ELEMS>") Cons head;
…
}
@DomainParams({"ELTS"})
class Cons {
   @Domain("ELTS") Object obj;
   @Domain("OWNER<ELTS>") Cons next;
}
```



- To share objects across domains
- Add domain parameter to hold elements in list

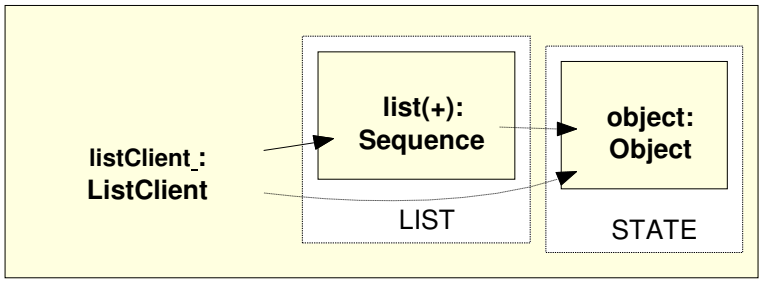
Sequence object graph

- Expand the sub-structure of ‘list’



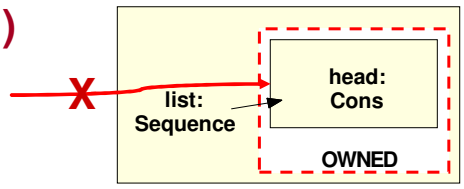
Sequence object graph (continued)

- Collapse the sub-structure of ‘list’

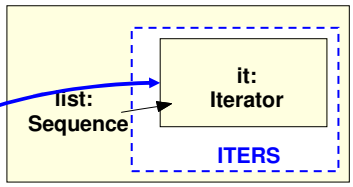


Strict encapsulation vs. logical containment

(1) Strict encapsulation (private domain)



(2) Logical containment (public domain)



Demo: checking Sequence annotations

- Cannot return head of Sequence
  - Head of list in **private domain**
  - **Stronger than making field private**
- Cannot nullify head of list
  - Stronger than Java visibility (e.g., **private**)
- Iterate over list
  - Iterator in **public domain ITERS**

Annotation tool support

- Use **Java 1.5 annotations**
- Typechecker uses Eclipse JDT
- Warnings in Eclipse's **problem window**

Annotation language summary

- `@Domains`: declare domains
- `@DomainParams`: declare *formal* domain parameters
- `@DomainLinks`: declare domain link specifications
- `@DomainInherits`: specify parameters for supertypes
- `@DomainReceiver`: specify annotation on receiver
- `@Domain`: specify object annotation, *actual* domain parameters and (optionally) array parameters
  "annotation<domParam, …> [arrayParam, …]"

Special annotations

- **lent:** temporary alias within method
- **shared:** shared persistently or globally
- **unique:** unaliased object, e.g.,
  - newly created object
  - passed linearly from one domain to another

Annotation language

- Each object defines conceptual groups (*ownership domains)* for its state

  @Domains: declare domains

```
@Domains({"owned"}) // Private domain
class Sequence {
...
}
```

- Each object is declared in a domain

  @Domain: declare domain for given object

```
@Domain("owned") Vector v; // declare in 'owned' domain
```

  ↳ means instance encapsulated within object

Annotation language (continued)

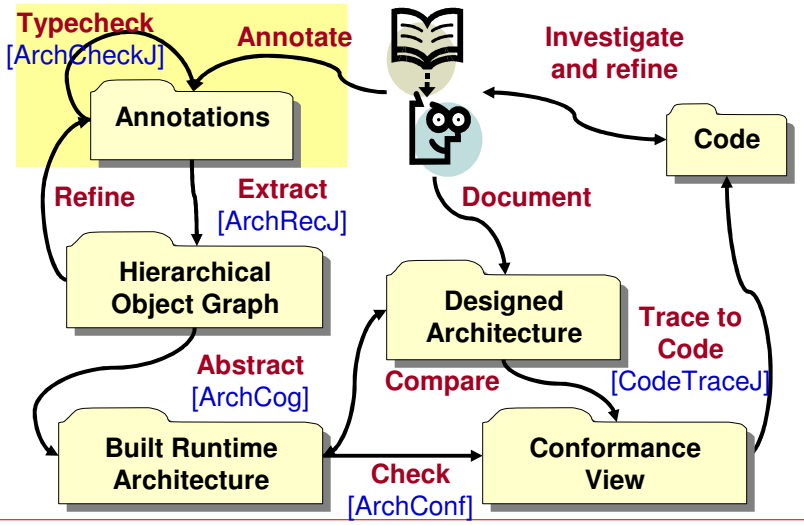
- **@DomainParams:** declare *formal* domain parameters on a type
- **@Domain:** declare domain for object
  - Optionally specify *actual* domains using the parameter order in **@DomainParams**
- Similar to Java 1.5 generics
  - Declare formal type parameter
    `class ArrayList<T> {...`
  - Bind formal type parameter to actual type
    `ArrayList<String> seq;`

Annotation language (continued)

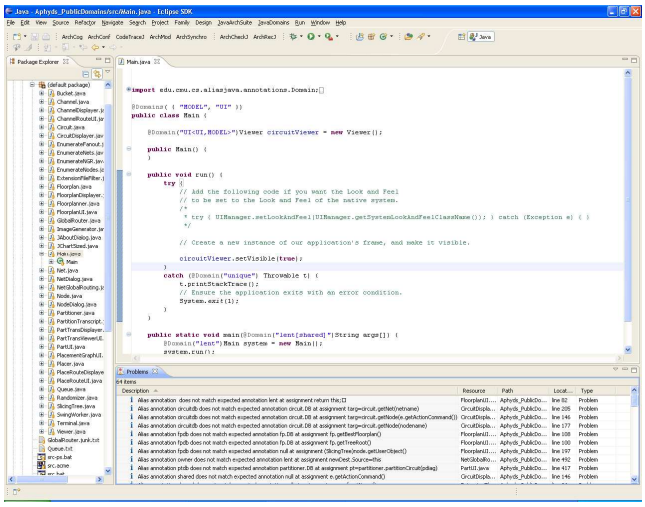
- **@DomainInherits:** bind current type's formal parameters to parameters of supertypes

```
@DomainParams({"elems"})
@DomainInherits({"Iterator<elems>"})
class SeqIterator extends Iterator {
...

}

// Again, similar to Java Generics...
class SeqIterator<T> extends Iterator<T> {
...

}
```

SCHOLIA: use ArchCheckJ



SCHOLIA ArchCheckJ on Aphyds



Hands-on Exercises

Getting setup

- Have Java 1.5 or later installed
- Install **GraphViz**
  - graphviz-2.20.2.exe in zip file
- Read **setup.html**
- Extract zip file
  - Contains Eclipse 3.4
  - AcmeStudio 3.4.x (build 20090415N)
  - **SCHOLIA** Eclipse plugins
- **Accept license agreement**
  - CMU patent-pending technology
  - Non-commercial, research evaluation OK

Disclaimer

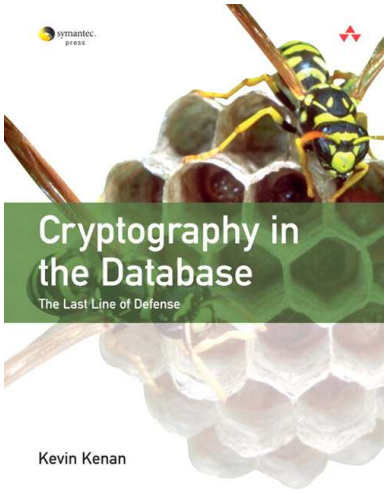
- **Research-Off-The-Shelf (ROTS)** tools
  - Highly specialized
  - Poorly documented
  - Mostly prototypes
- Advice on AcmeStudio
  - **Save early, save often (Ctrl-S)**
  - **Restart often (File Restart)**

Exercise #1: CryptoDB

Add annotations

CryptoDB

- 3-KLOC Java
- Crypto application

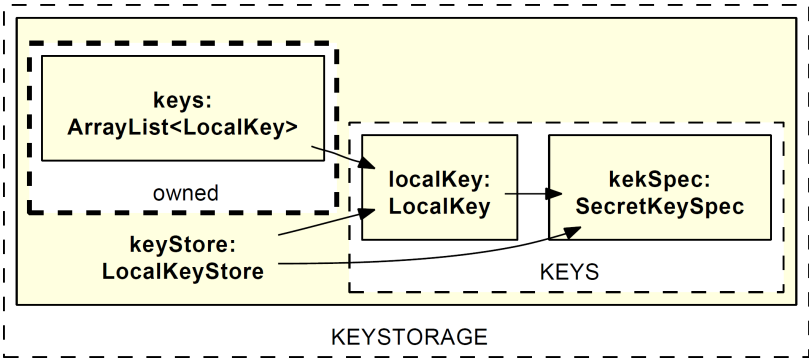


Add annotations and fix warnings

- LocalKeyStore and LocalKey

LocalKeyStore and LocalKey

- Hint: use this as a guide



Exercise #1: CryptoDB

Solution

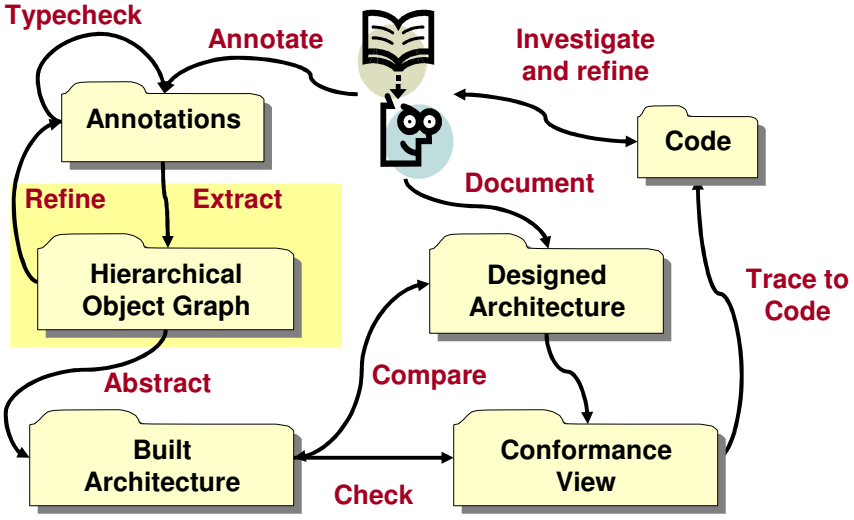
LocalKeyStore, LocalKey annotations

```
class LocalKeyStore {
  private domain OWNED;
  public domain KEYS;
  private OWNED List<KEYS LocalKey> keys;

  public unique List<KEYS LocalKey> getKeys() {
    unique List<KEYS LocalKey> copy = copy(keys);
    return copy;
  }
}
class LocalKey {
 private shared String keyData; // encrypted key
 private shared String keyId; // encrypted key id
 ...
}
```


Step 2

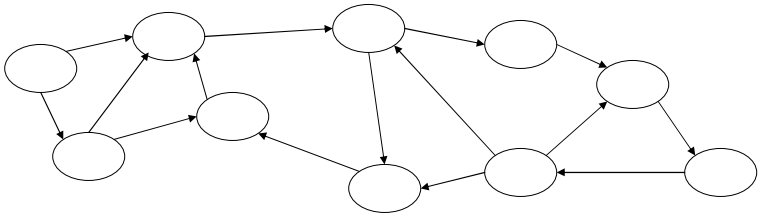
Extract hierarchical object graph using static analysis

SCHOLIA conformance checking



Runtime Object Graph (ROG)

- **Runtime Object Graph (ROG):** graph where
  - A node represents a runtime object,
  - An edge represents a points-to relation



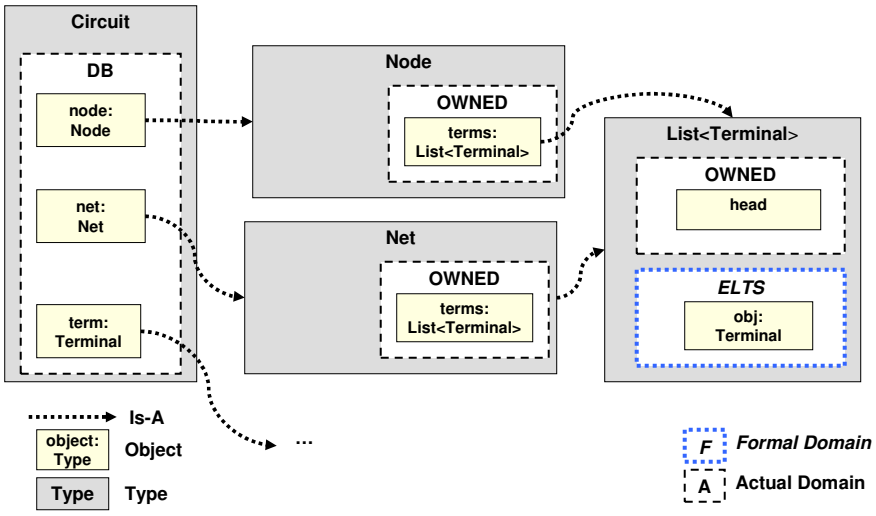
Goal of ObjectGraph static analysis

- Extract **ObjectGraph** that **soundly approximates all possible** Runtime Object Graph (ROG)s
  - Conveys **architectural abstraction** primarily by **ownership hierarchy**
  - Optionally, merges more objects within a domain based on **their declared types**

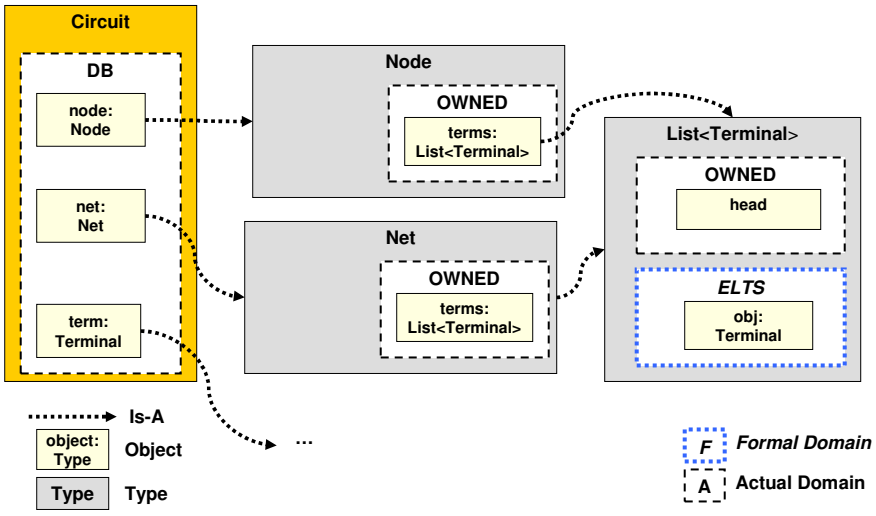
Two phases of the static analysis

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

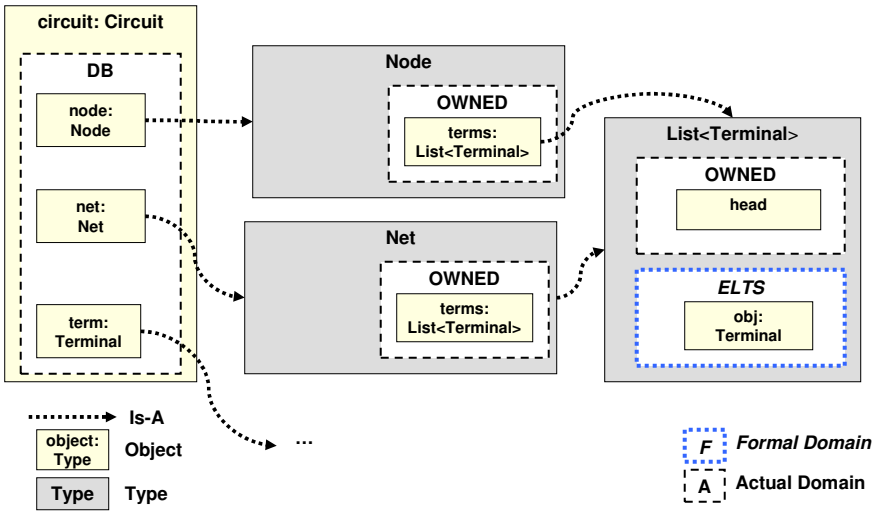
TypeGraph: show types, domains inside types, and objects in domains



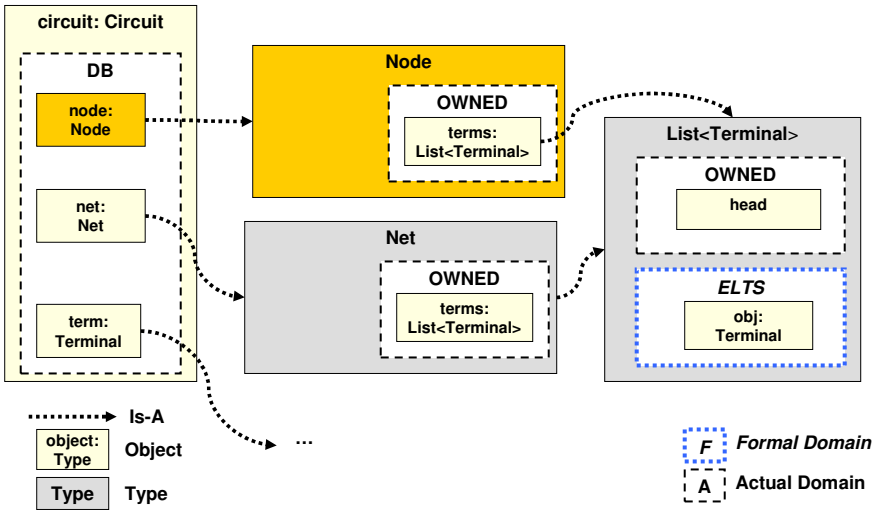
ObjectGraph: instantiate types, starting with root (user selected)



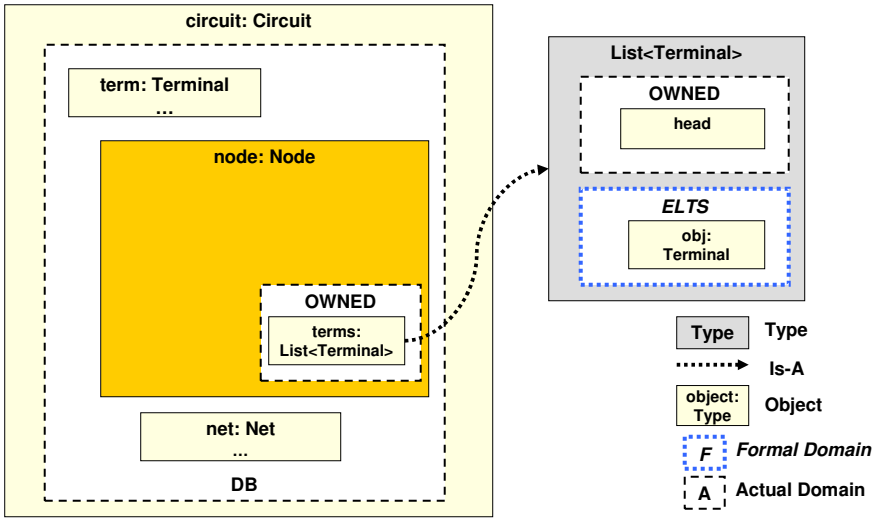
ObjectGraph: instantiate types, starting with root (user selected)



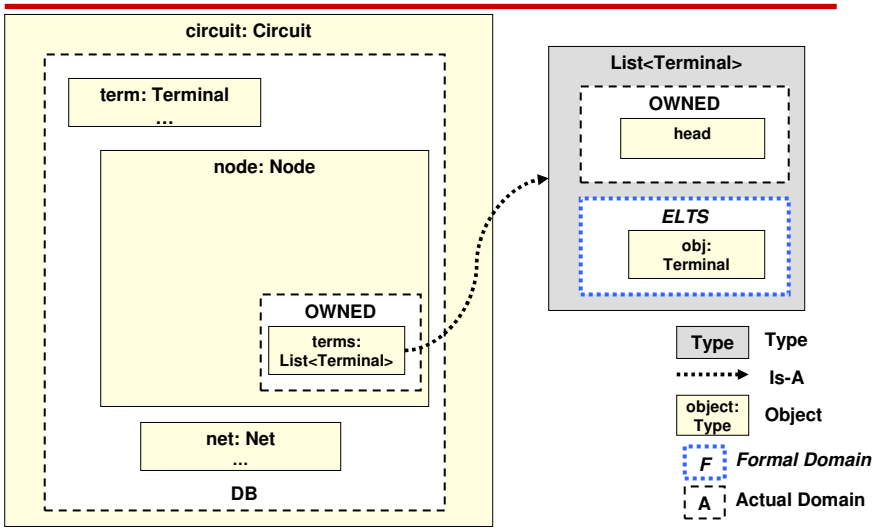
ObjectGraph: instantiate types, show domains and objects inside domains



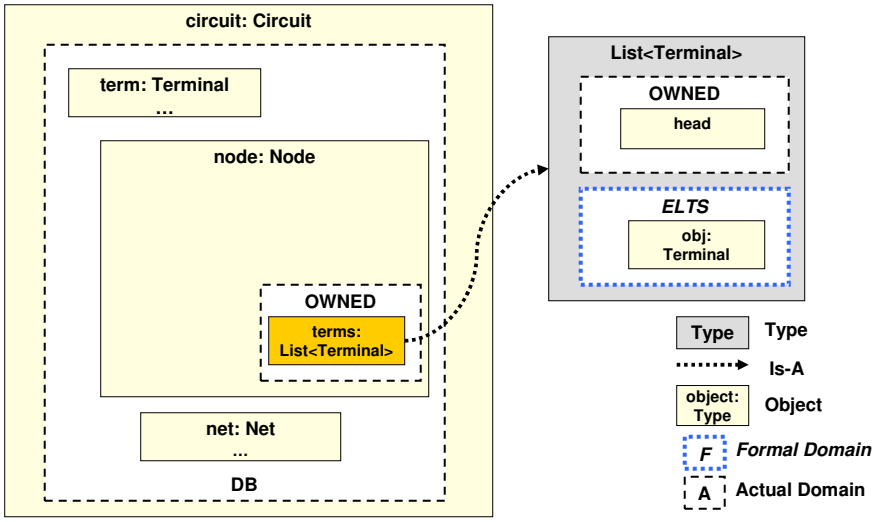
ObjectGraph: instantiate types, show domains and objects inside domains



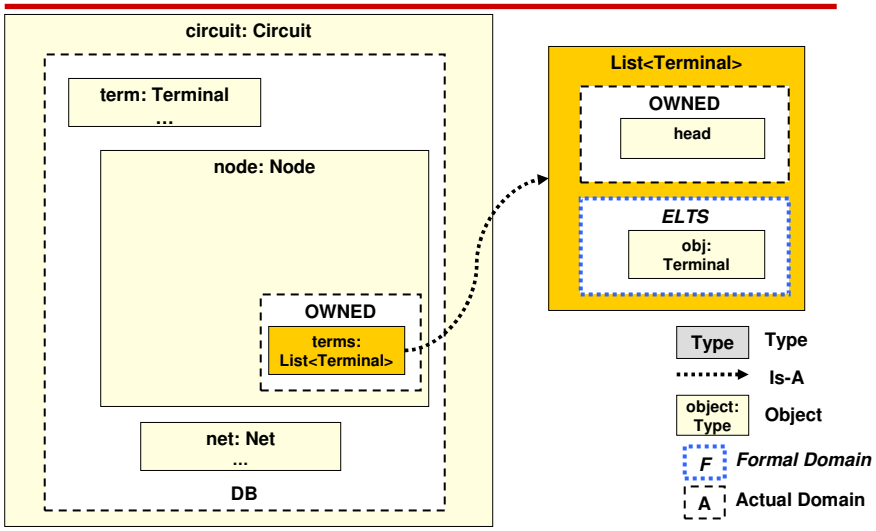
ObjectGraph: instantiate types, show domains and objects inside domains



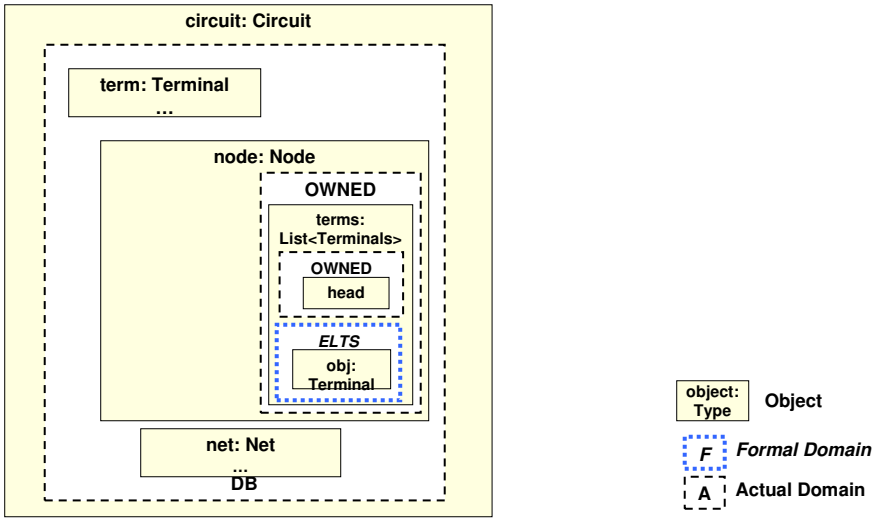
ObjectGraph: instantiate types, show domains and objects inside domains



ObjectGraph: instantiate types, show domains and objects inside domains



ObjectGraph: instantiate types, show domains and objects inside domains

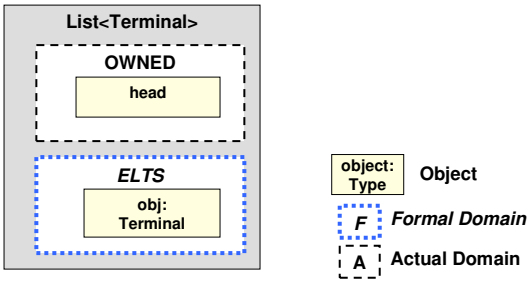


Challenge: unbounded number of objects, based on different executions

- *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)

Challenge: TypeGraph does not show all objects in each domain

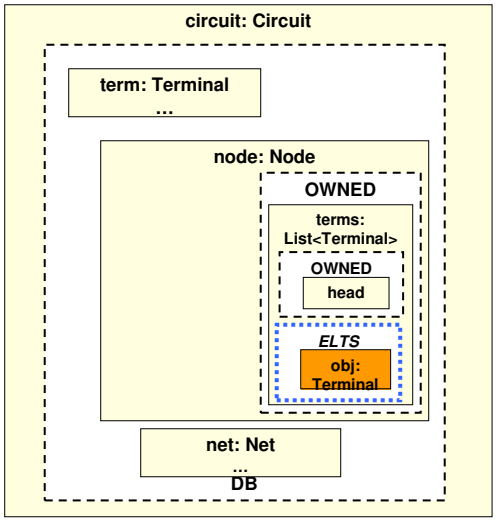
- Reusable or library code often parametric with respect to ownership
  - List does not "own" its elements
  - Takes **domain parameter** *ELTS* for elements



Challenge: TypeGraph does not show all objects in each domain

- At runtime domain parameter bound to other actual 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



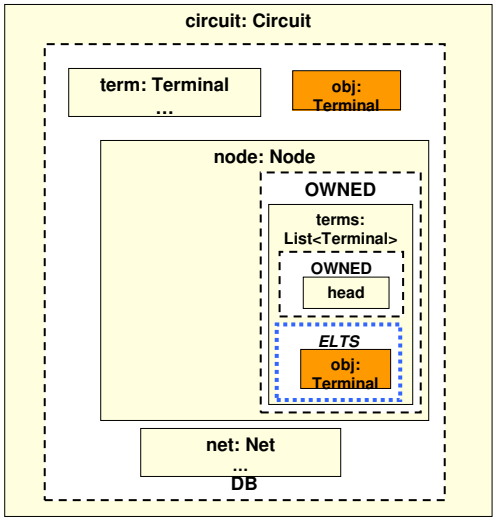

```
class Node<OWNER> {
 domain OWNED;
 // List::ELTS    Node::OWNER
 OWNED List<OWNER Terminal> terms;
}

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 Circuit {
 domain DB;
 // Node::OWNER    Circuit::DB
 DB Node node;
  ...
}

class Node<OWNER> {
 domain OWNED;
 OWNED List<OWNER Terminal> terms;
}
```

object: Type — Object

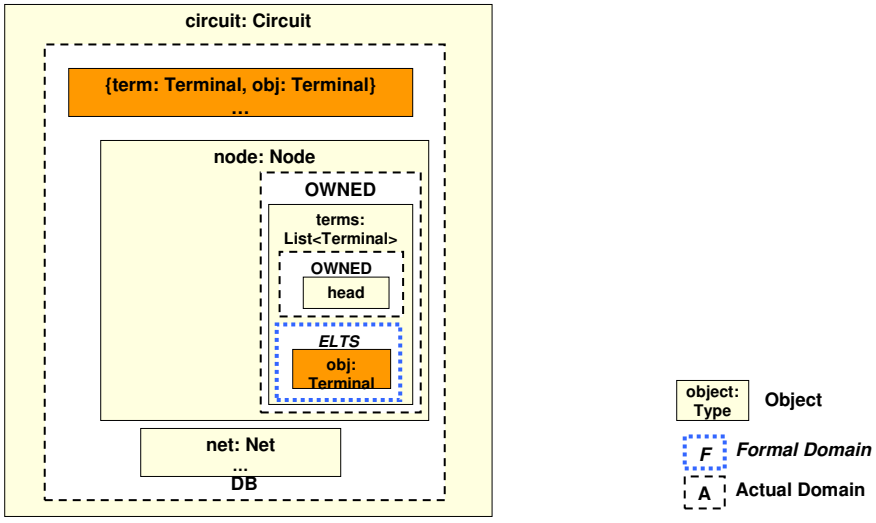
F — Formal Domain

A — Actual Domain

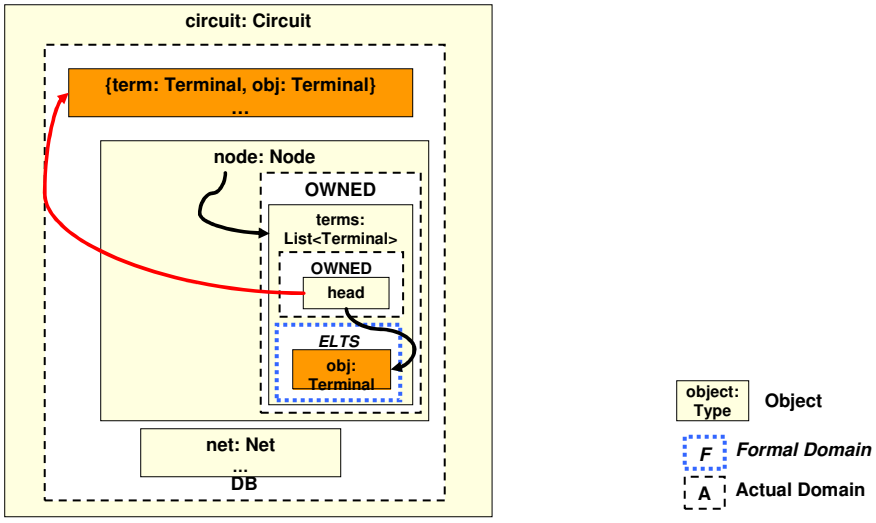
Challenge: TypeGraph does not reflect possible aliasing

- *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 equivalent objects inside a given domain

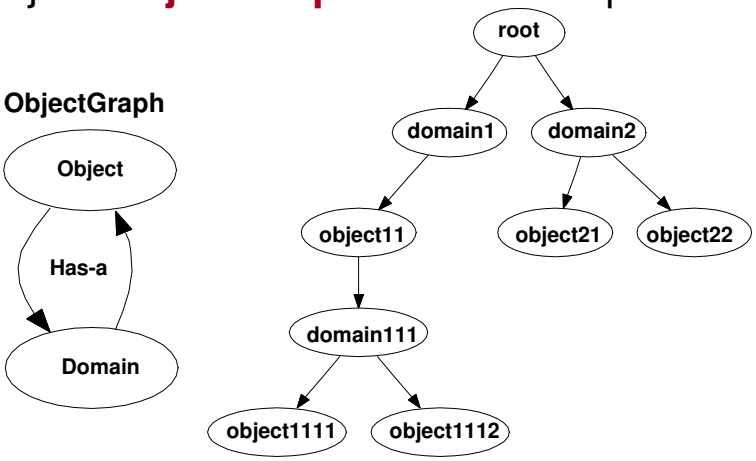


ObjectGraph: add edges to represent points-to relations, incl. to pulled objects



Challenge: ObjectGraph can have cycles

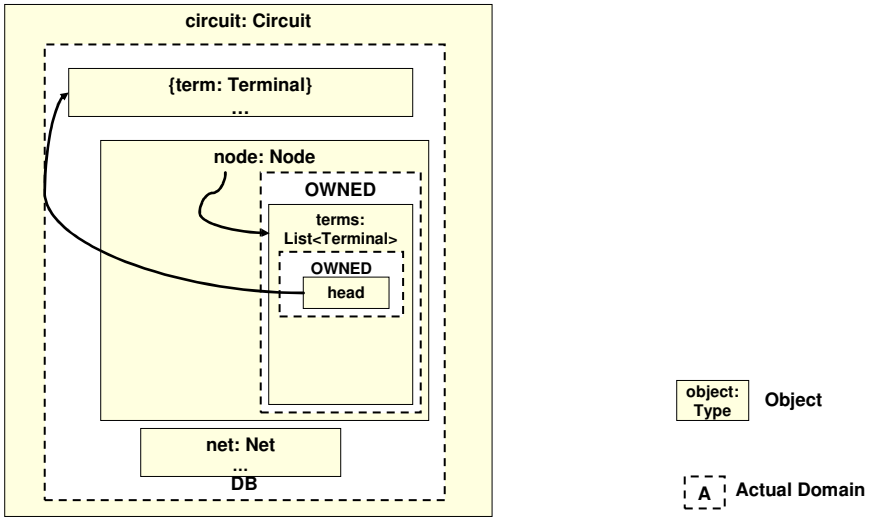
- Project **ObjectGraph** to limited depth



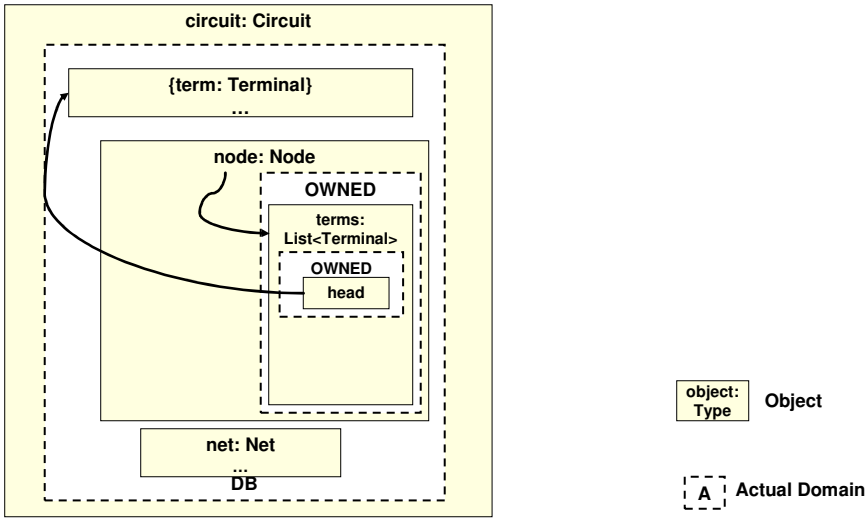
Challenge: objects from elided sub-structures could point to other objects

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

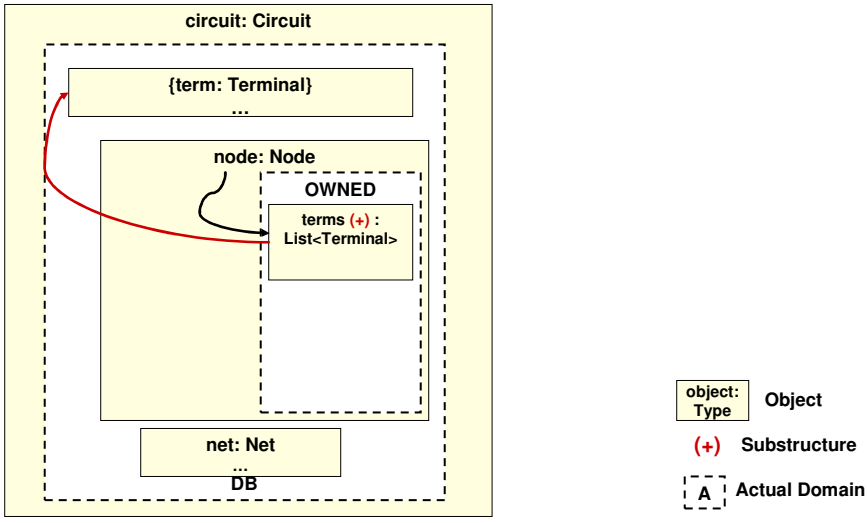
Aphyds: no longer show formal domains, e.g., 'ELTS' inside 'terms'



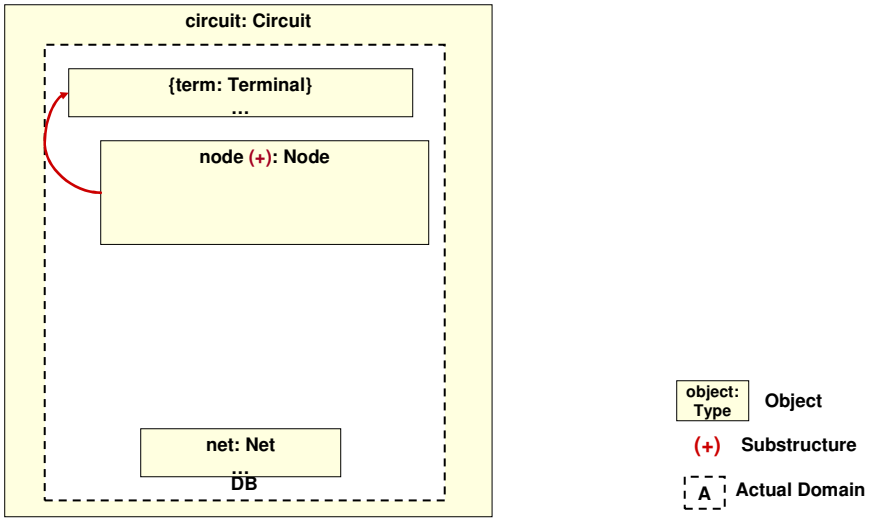
Aphyds: 'node' substructure points to other objects, such as 'term' object



Aphyds: collapsing substructure of 'terms' object causes edge lifting



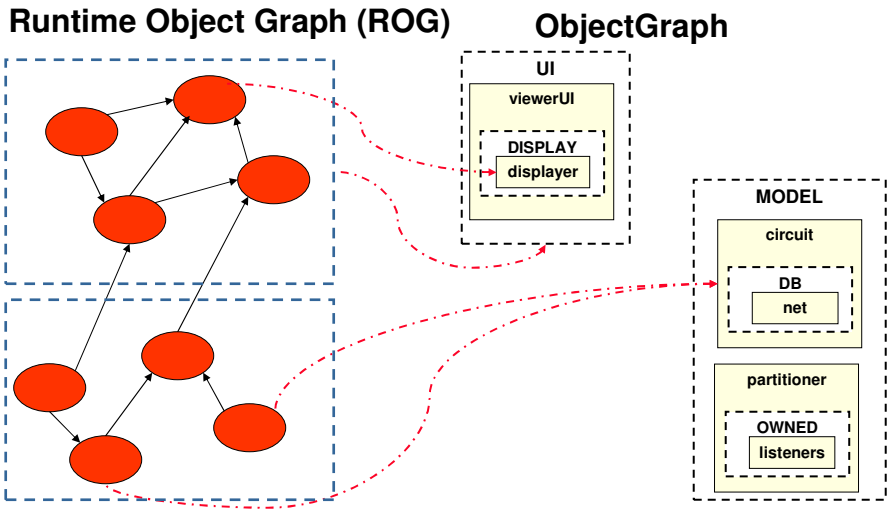
Aphyds: collapsing substructure of 'node' object causes additional edge lifting



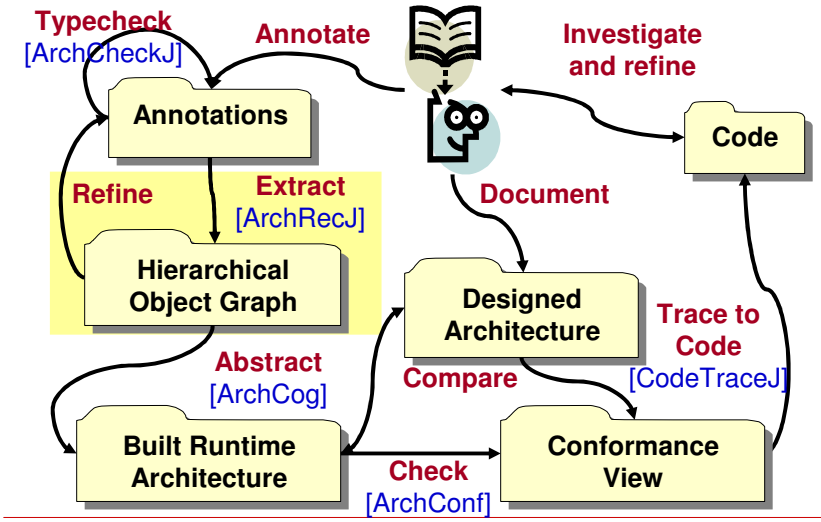
Extraction key property: soundness

- To be **sound**, must **show** all objects and relations that may exist in any run
- **Aliasing soundness**: no one object appears as two "boxes" in object graph

Intuition behind soundness

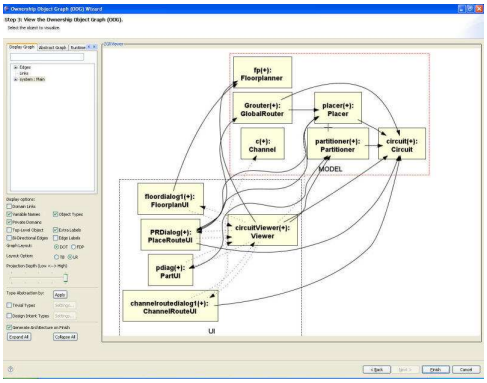


SCHOLIA: use ArchRecJ



SCHOLIA ArchRecJ on Aphyds

- Abstract objects by ownership hierarchy
- Optionally abstract objects by types



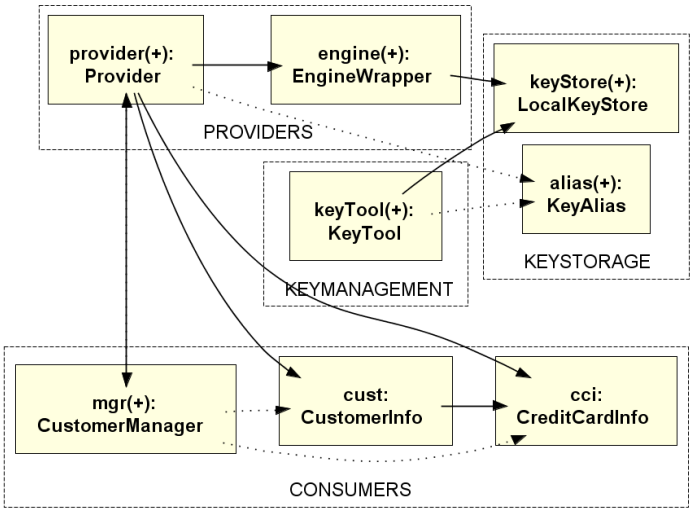
Exercise #2: CryptoDB

Extract object graphs

Exercise #2: CryptoDB

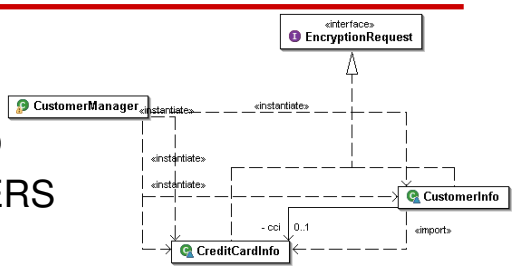
Solution

CryptoDB OOG – no abstraction by types



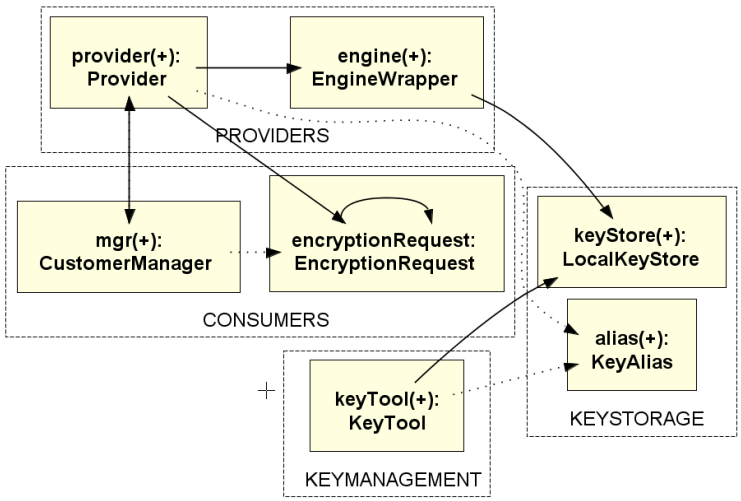
CryptoDB abstraction by types

- Merge CustomerInfo and CreditCardInfo
- Both in CONSUMERS



- Merge objects when they share non-trivial *least upper bound types*
- User configures list of “trivial types“; by default, includes Object, Cloneable, etc.

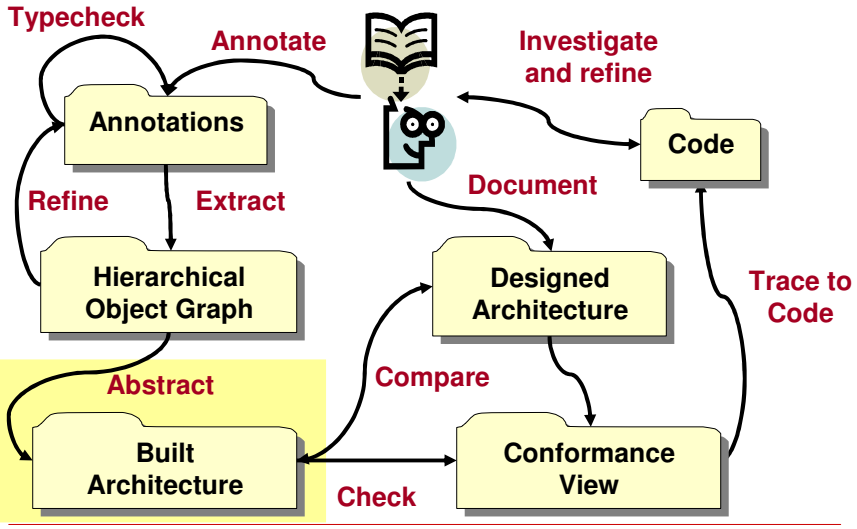
CryptoDB OOG, with abstraction by types



Step 3

Abstract object graph into built architectures

SCHOLIA conformance checking

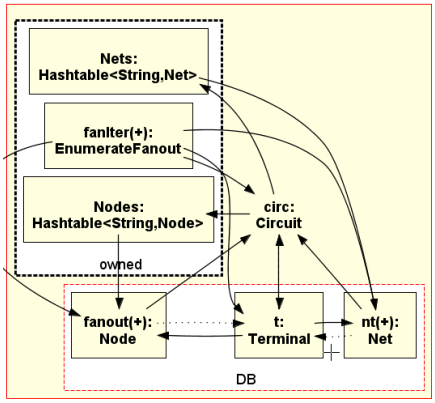


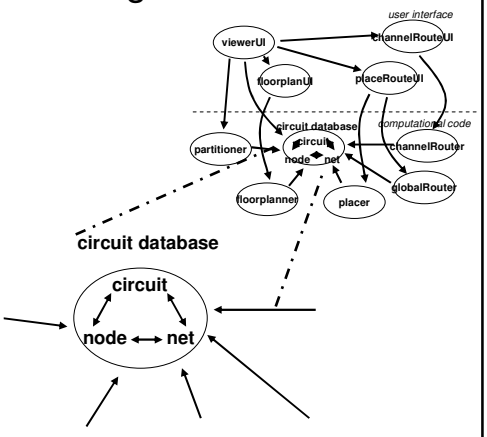
Why need to abstract an object graph?

- Extracted object graph provides architectural abstraction by ownership hierarchy and by types
- May not be isomorphic to architect's intended architecture
- May require further abstraction

Aphyds: object graph vs. target architecture

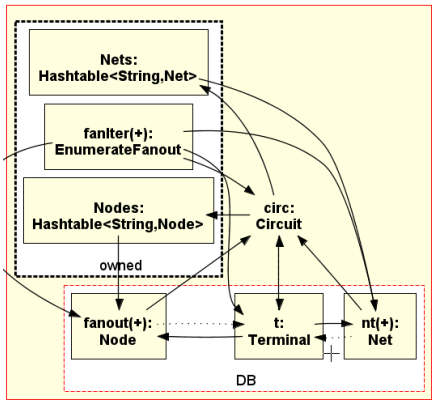
- Object graph
- Target architecture



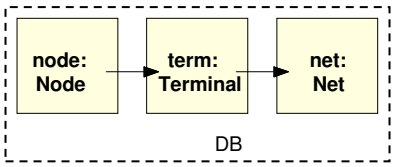


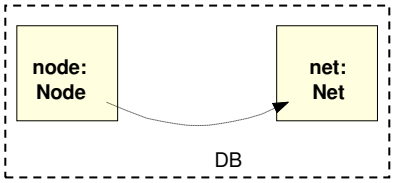
Elide and summarize domains/objects

- **Private domains** hold representation
- **Public domains** hold visible state
- Soundly summarize private domains



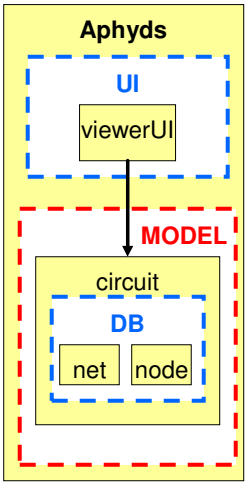
Soundly summarizing elided objects



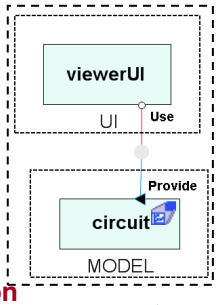


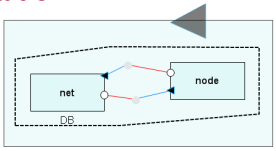
- Eliding object 'term' leads to **summary edge** to show **transitive communication**
- Effectively, abstracts object into **edge**

Represent abstracted object graph in architecture description language



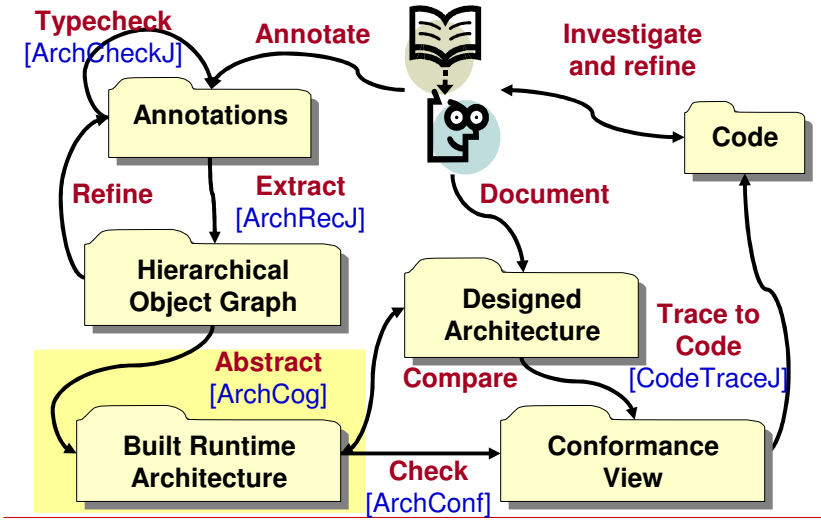
OOG		C&C view
Top-level object	↔	System
Object	↔	Component
Domain	↔	Group
Interface	↔	**Provide** port
Field reference	↔	**Use** port
Object relation	↔	Connector
Substructure	↔	**Representation**





● Annotate ● Extract ● **Abstract** ● Document ● Compare ● Analyze ● Investigate 121

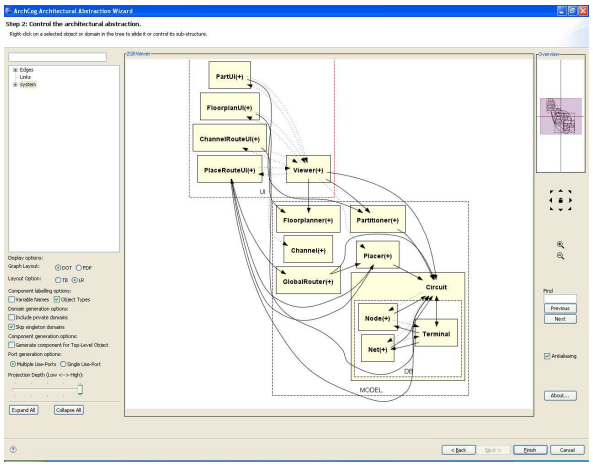
SCHOLIA: use ArchCog



● Annotate ● Extract ● **Abstract** ● Document ● Compare ● Analyze ● Investigate 122

SCHOLIA ArchCog on Aphyds

- Abstract object graph into C&C view
- Control projection depth
- Elide private domains



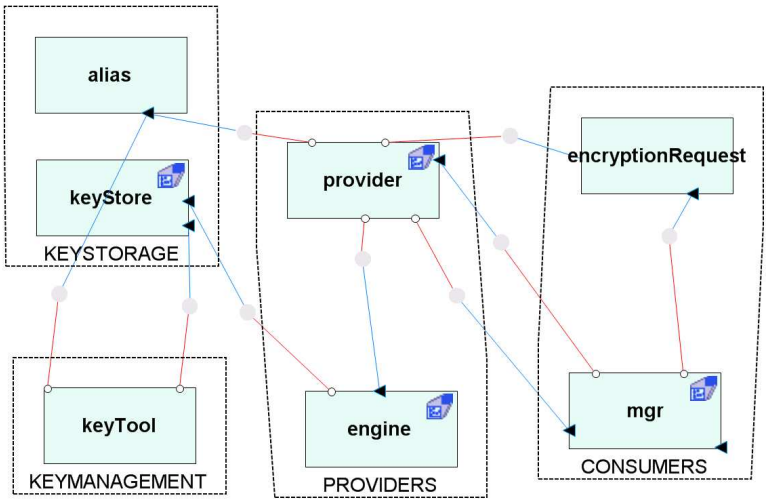
Exercise #3: CryptoDB

Abstract object graph

Exercise #3: CryptoDB

Solution

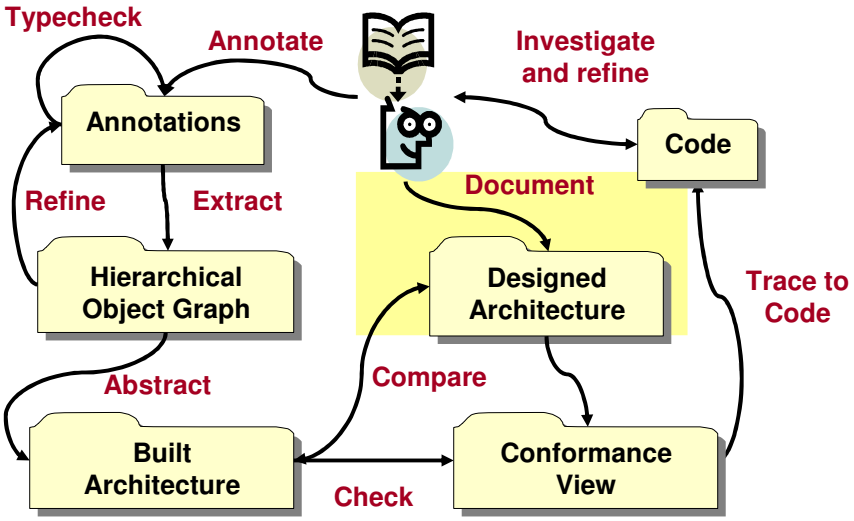
CryptoDB built architecture



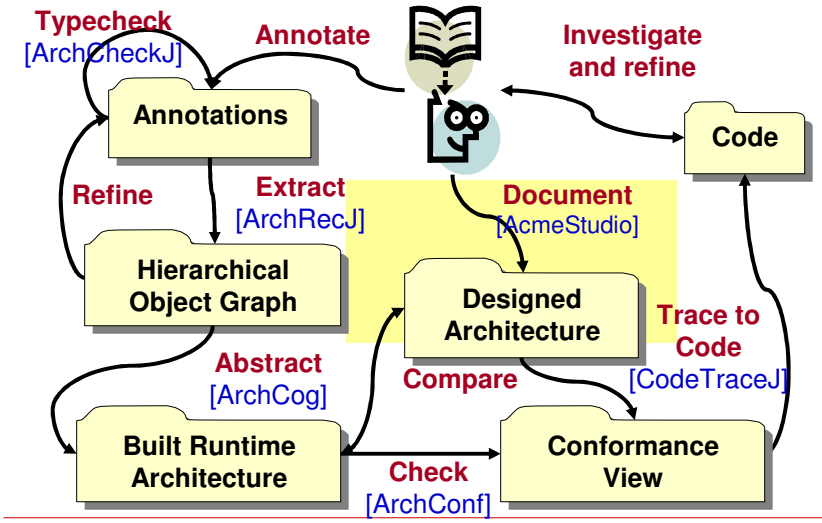
Step 4

Document target architecture

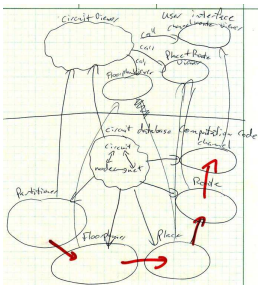
SCHOLIA conformance checking

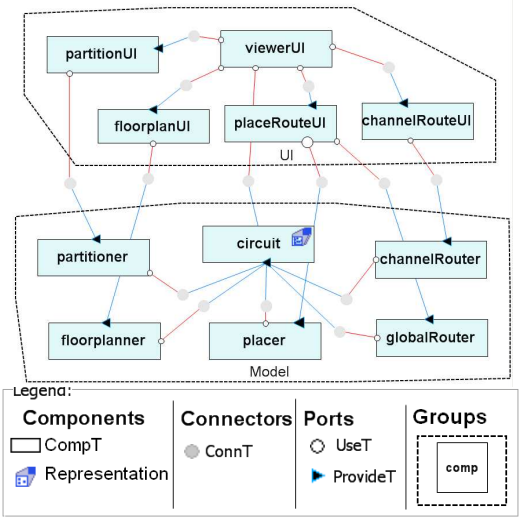


SCHOLIA: use AcmeStudio



Aphyds: document designed architecture in architecture description language



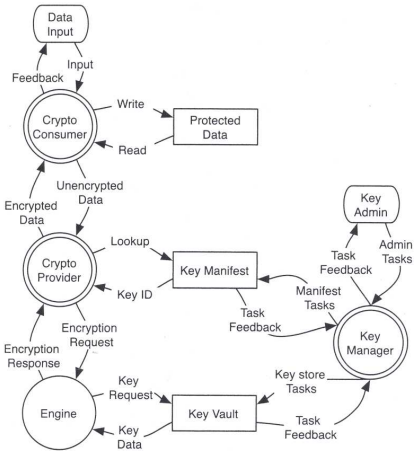


Exercise #4: CryptoDB

Document target architecture

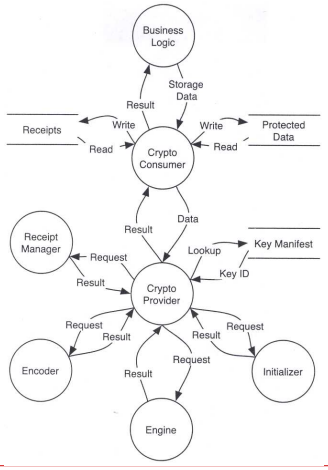
CryptoDB

- DFD Level-1



CryptoDB

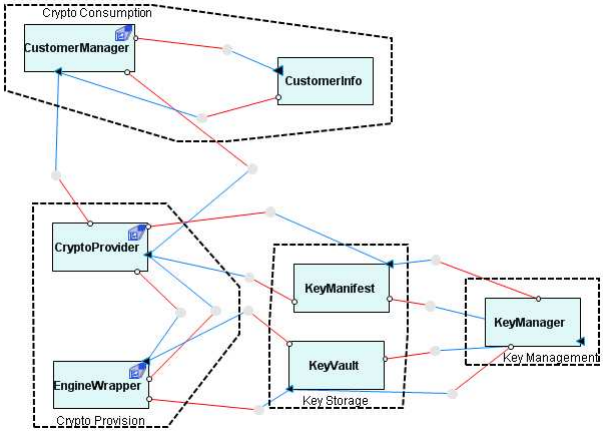
- DFD Level-2



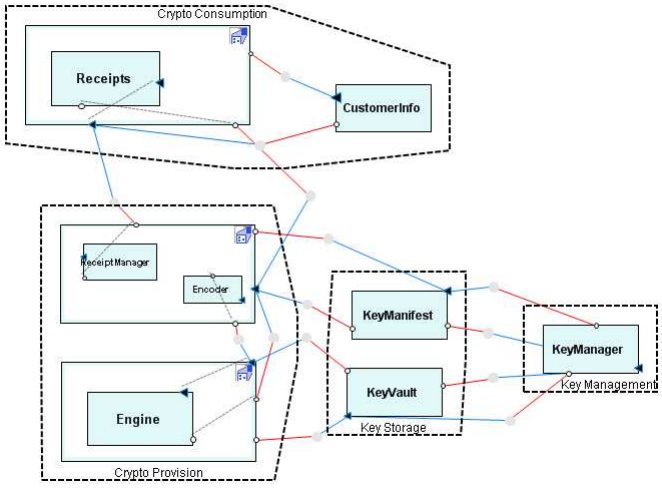
Exercise #4: CryptoDB

Solution

CryptoDB target architecture



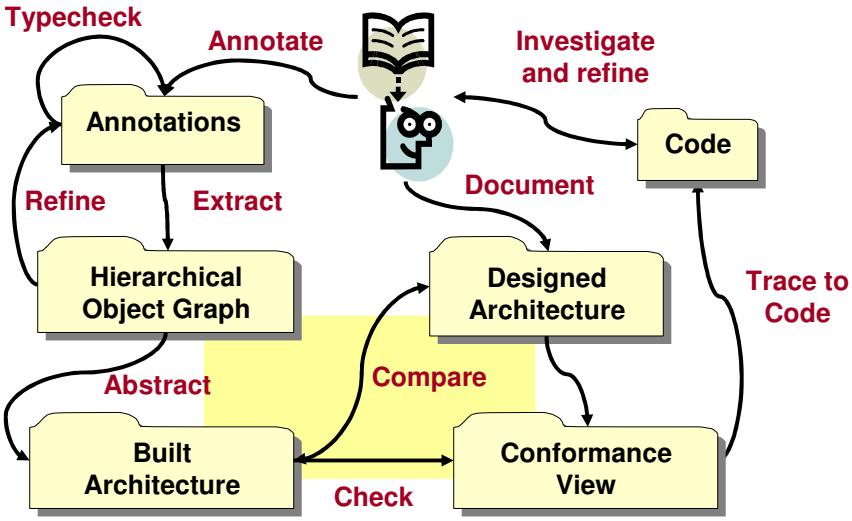
CryptoDB target architecture



Step 5

Compare built and designed architectures

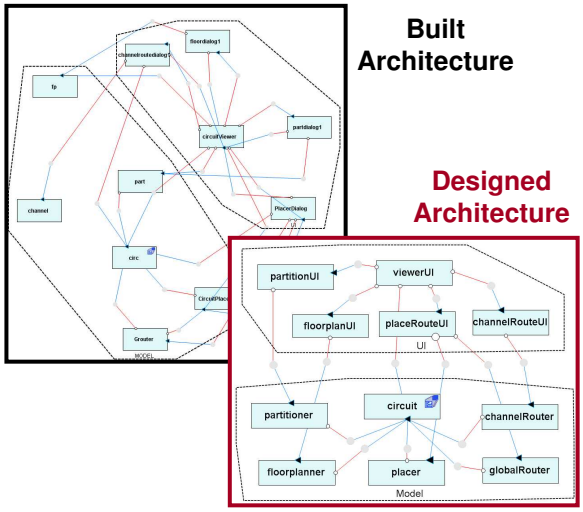
SCHOLIA conformance checking



Why is comparing built and designed architectures hard?

- No **unique identifiers**
- **Renames**
- Insertions
- Deletions

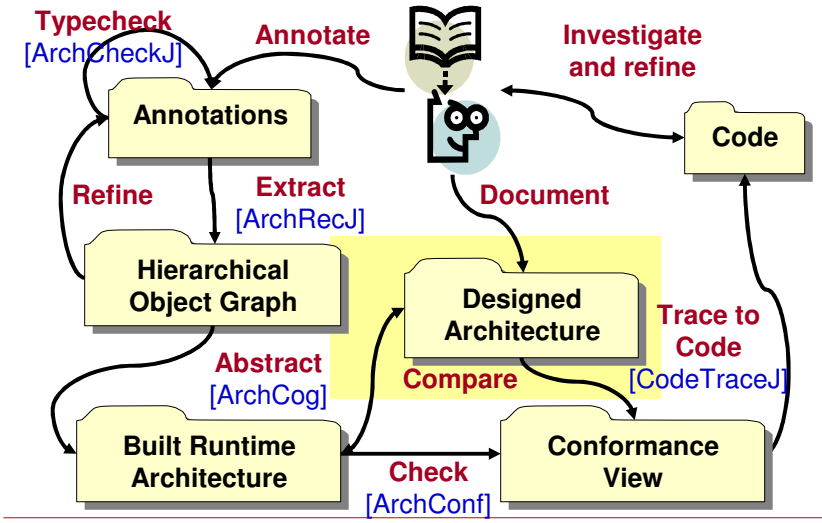
- Solution: use structural comparison



Structural comparison

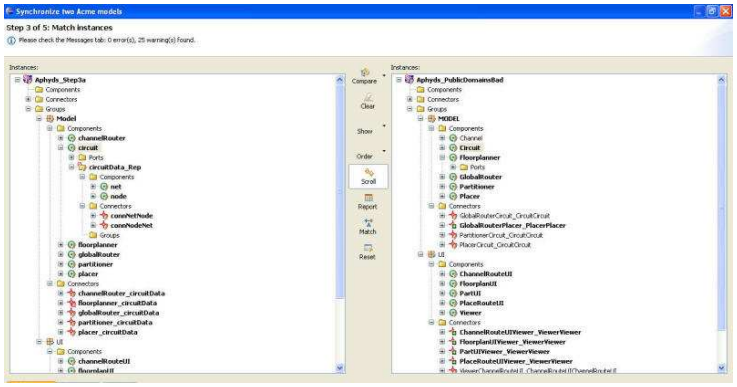
- Exploit **hierarchy** in architectural views to match the nodes
- Detect **renames**, **insertions**, **deletions** and restricted **moves**
- Previous architectural comparison detected only insertions and deletions
- Lost node **properties** needed for architectural analyses

SCHOLIA: use ArchConf



Aphyds: comparing built and designed architectures

- Accept results of structural comparison
- Optionally, force/prevent matches



Exercise #5: CryptoDB

Compare build and target architecture

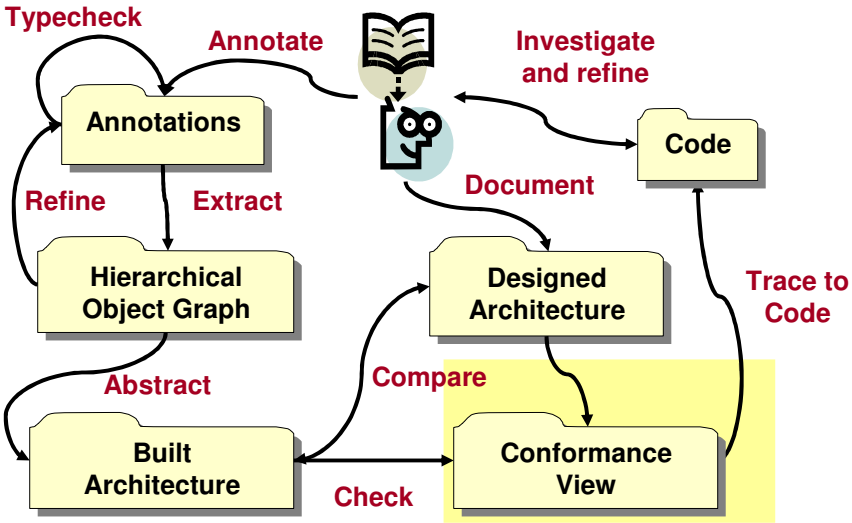
Exercise #5: CryptoDB

Solution

Step 6

Check conformance between built and designed architectures

SCHOLIA conformance checking

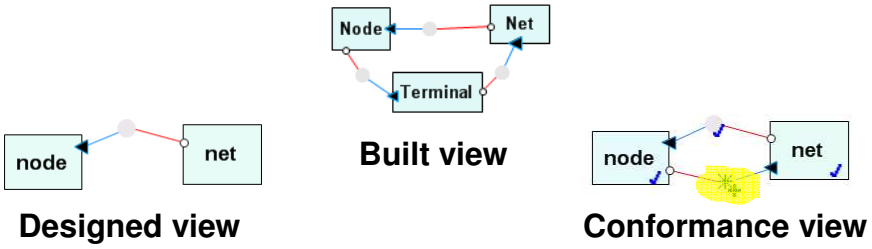


How is conformance checking different from view differencing/merging?

- Goal is not to make the built and the designed architectures **identical**
- Account for **communication in built system** that is not in designed one
  - Do not propagate all implementation objects
  - Enforce **communication integrity**
- Measure conformance as **graph edit distance** between built and designed views

Conformance checking analysis

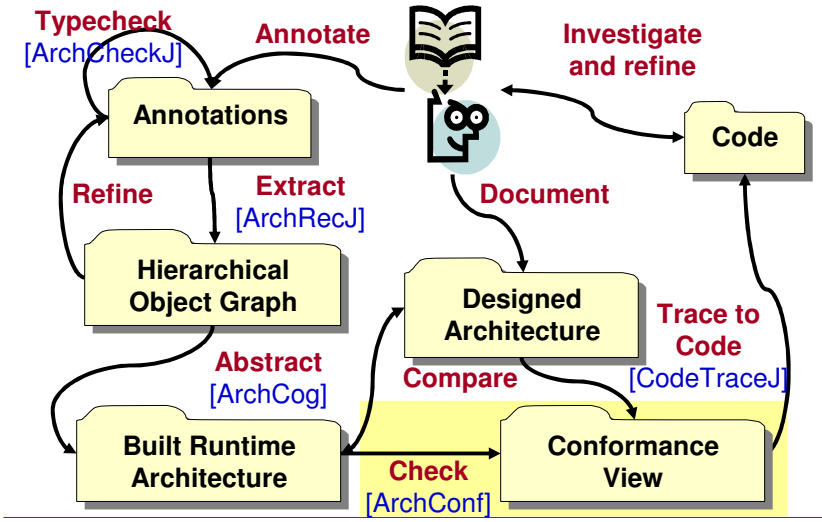
- Use built view names
- Do not directly propagate additional components
- Summarize additional components in built architecture using summary edges



Conformance check identifies key differences

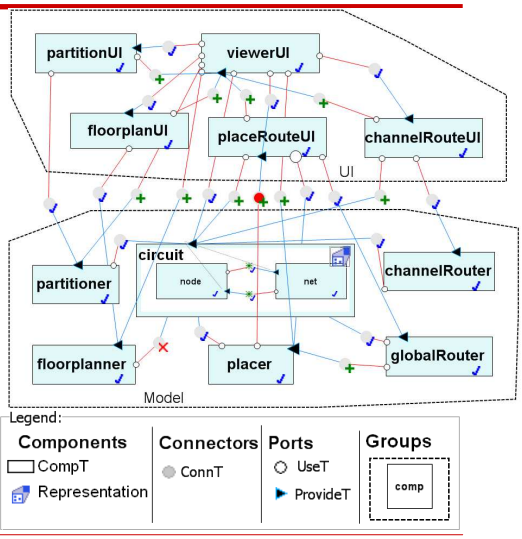
- **Convergence**: node or edge **in both** built and in designed view ✓
- **Divergence**: node or edge in built, but **not in designed** view ✚
- **Absence**: node or edge in designed view, but **not in built** view ✗

SCHOLIA: use ArchConf



Aphyds: developer investigates reported differences

- Study findings
- Trace to code



Convergence
Divergence
Absence

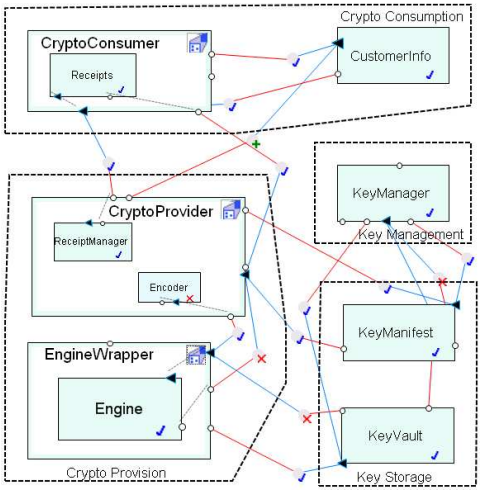
Exercise #6: CryptoDB

Check conformance between built and designed architectures

Exercise #6: CryptoDB

Solution

CryptoDB conformance analysis

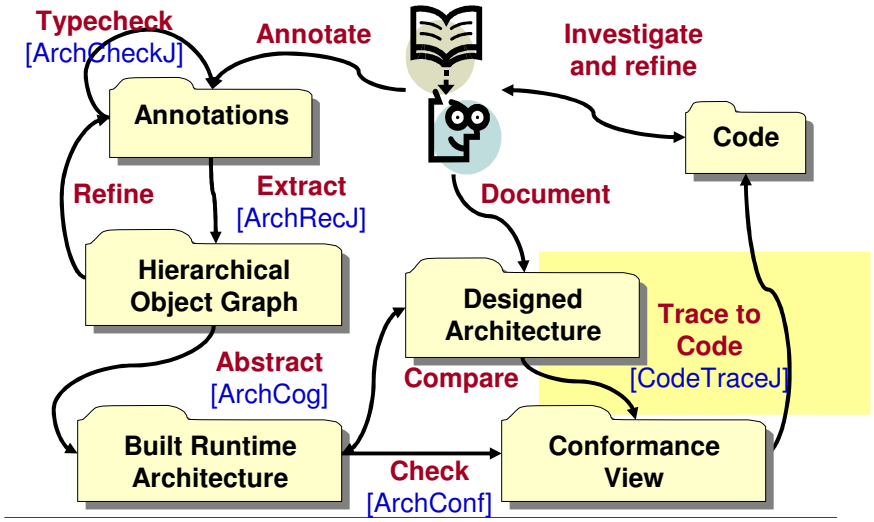


Step 7

Investigate and trace to code

• Annotate • Extract • Abstract • Document • Compare • Analyze • Investigate

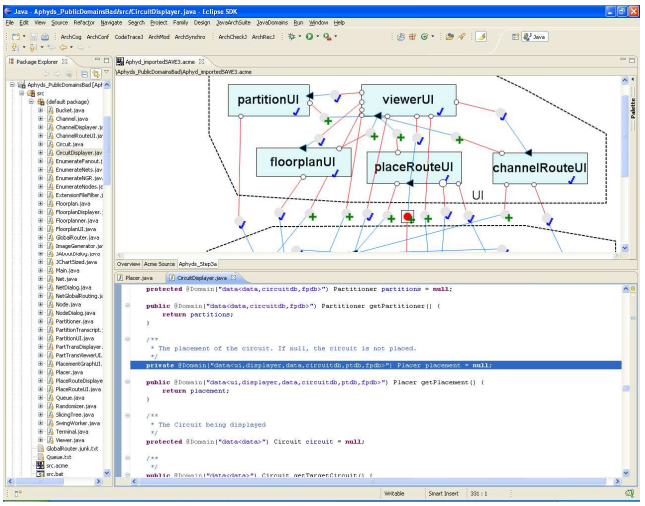
SCHOLIA: use CodeTraceJ



• Annotate • Extract • Abstract • Document • Compare • Analyze • Investigate 156

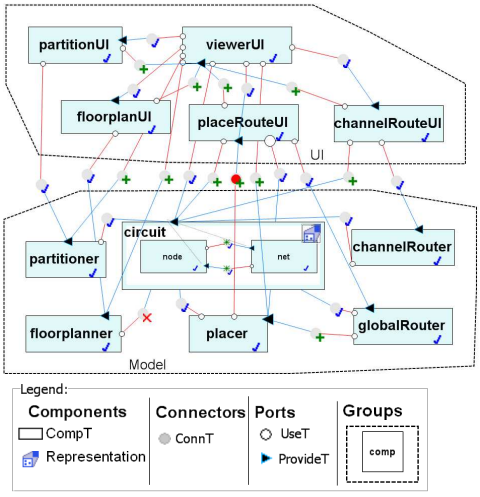
Aphyds: trace from runtime architecture, obtained statically, to lines of code

- Trace finding to code
- Previously, only UML class diagrams supported this feature

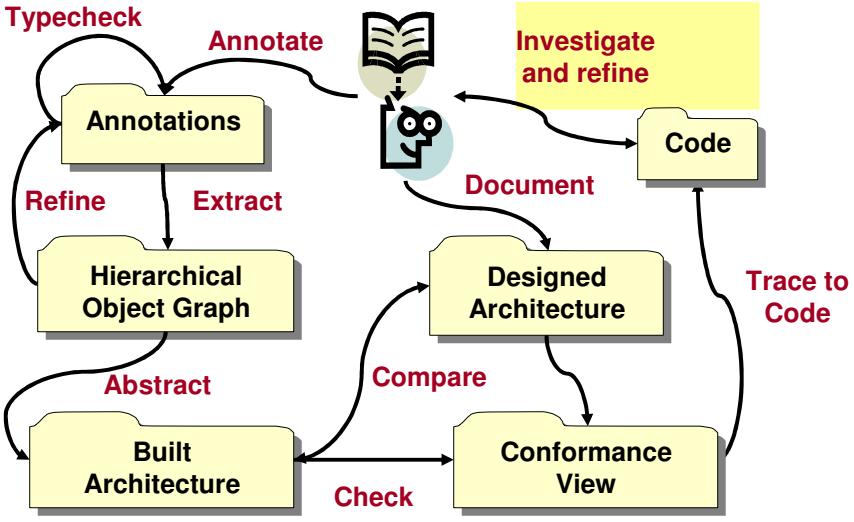


Aphyds: summary of findings

- **Missing** top-level component **partitionUI**
- **Callback** from **placer** in MODEL to **placeRouteUI** in UI
- Many connections really **bi-directional**



SCHOLIA conformance checking



Outcomes of investigating findings

a) Iteratively refine annotations based on visualizing an extracted object graph, before abstracting it;
b) Fine-tune the abstraction of an object graph into an architecture;
c) Manually guide the comparison of the built and the designed architecture, if structural comparison fails to perform the proper match;
d) Update code if she decides designed architecture is correct, but implementation violates architecture;
e) Update designed architecture if she considers implementation highlights mission in architecture

Exercise #7: CryptoDB

Investigate and trace to code

Exercise #7: CryptoDB

Solution

CryptoDB summary

- What did you learn?

Discussion

Limitations

- Manual **annotation burden**
  - Impractical without **annotation inference**
  - Active area of research
- Annotation **expressiveness limitations**
- **Extraction** does not handle
  - Distributed systems (single virtual machine)
  - Dynamic architectural reconfiguration
- **Comparison** can fail to match if views are too discrepant, quadratic in the view sizes
- **False positives possible**
  - As is the case with *any sound static analysis*
  - **Few** when developer fine-tunes annotations

Conclusion

- You learned about **SCHOLIA**, to **extract statically** a **hierarchical runtime architecture** from a program in a widely used object-oriented language, using **typecheckable annotations**
- If intended architecture exists, SCHOLIA can **analyze, at compile-time, communication integrity** between implementation and target architecture
- In practice, SCHOLIA can find structural differences between an existing system and its target architecture
- SCHOLIA can **establish traceability** between an implementation and an intended runtime architecture
- SCHOLIA complements architectural views of code structure or partial views of runtime architecture obtained using dynamic analysis