Extracting Dataflow Objects and other Flow Objects

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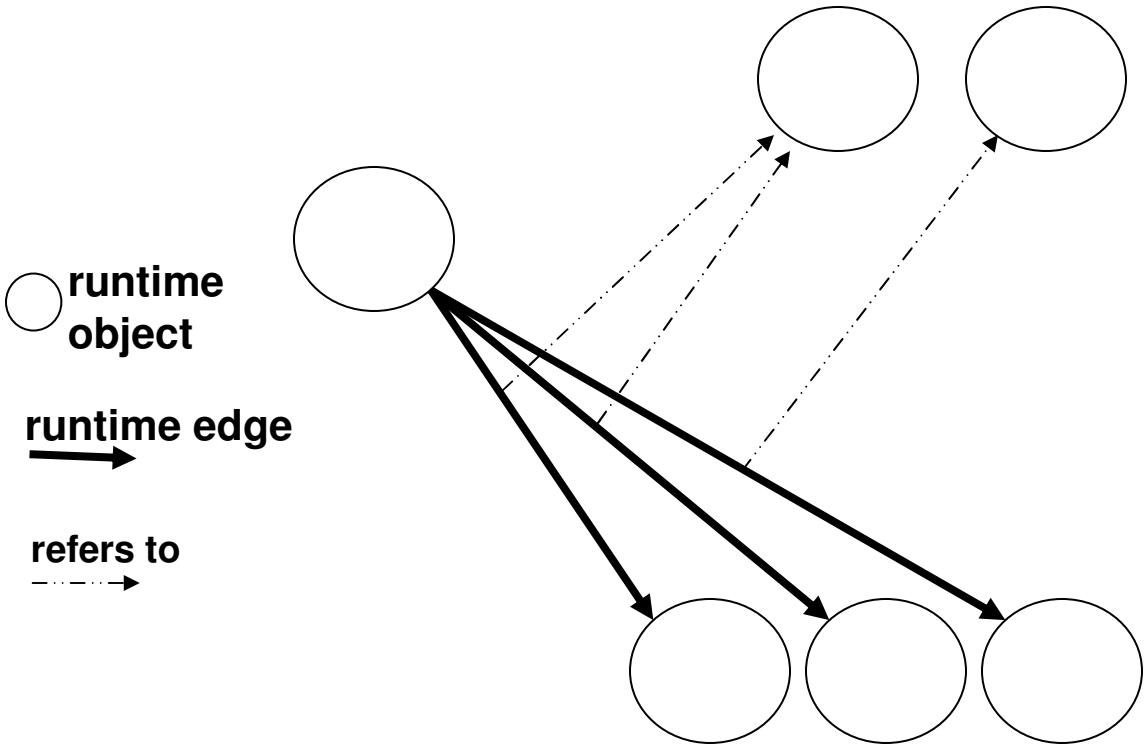
Architectural Risk Analysis (ARA) finds architectural flaws that lead security vulnerabilities [Howard and Lipner'06]

- Architects use forest-level view (not reading code)
  - Runtime architecture – not code architecture
  - Architects assign security properties to component instances and write constraints
- Limitations of ARA approaches
  - Limited support for reverse engineering forest-level view from code
  - Runtime architecture is missing or inconsistent with code
  - Lack of traceability to code from runtime architecture

Scoria approach to support ARA

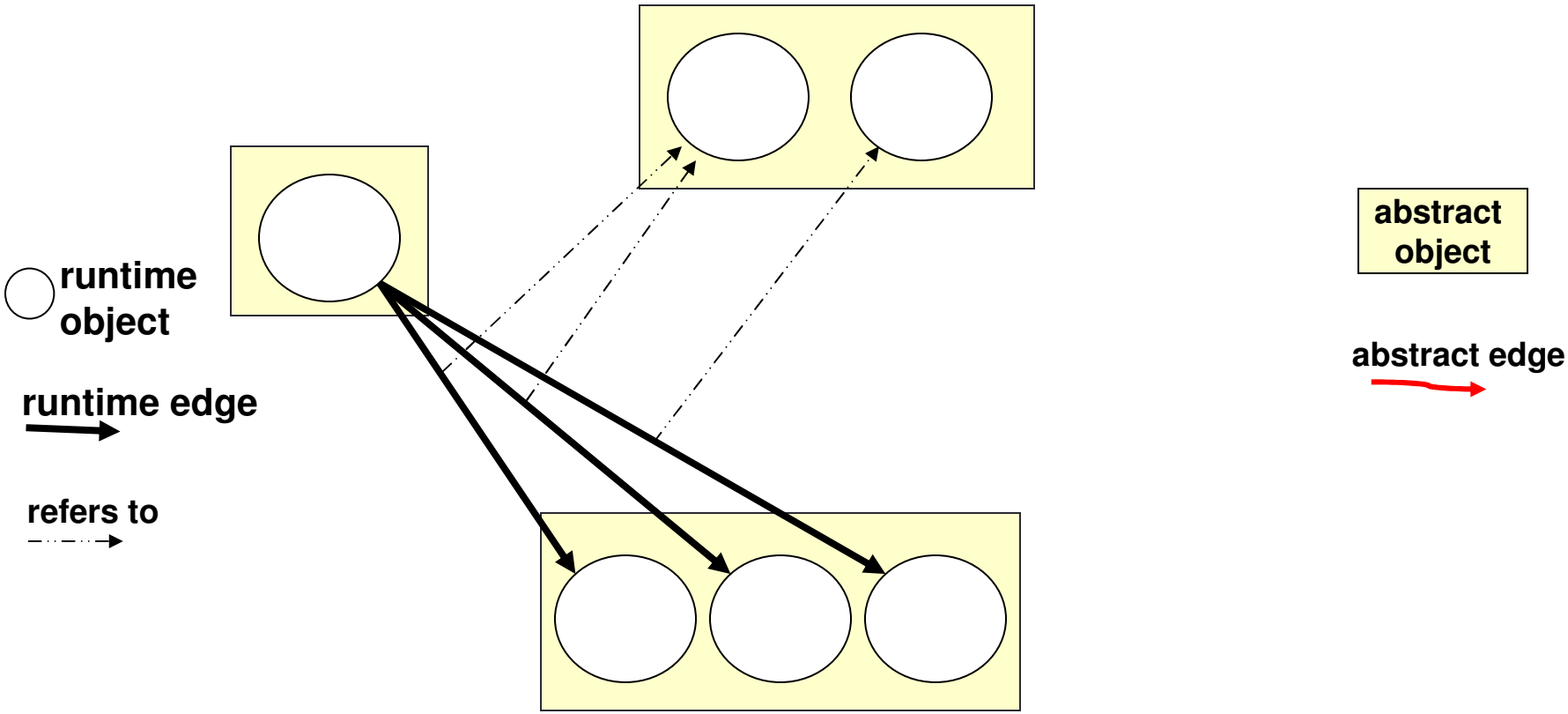
- Extract forest-level view
  - Extract object graph that shows instances – not classes
  - Object graph has traceability to code
  - Use object hierarchy to achieve architectural abstraction
- Abstraction by object hierarchy
  - Architecturally significant objects near top of hierarchy
  - Implementation details (data structures) further down
- Use static analysis to extract object graph
  - Static analysis to achieve soundness
  - Security requires worst case analysis
- Soundness: represent all objects and relations that may exist at runtime, in any possible execution

At runtime, object-oriented program appears as Runtime Object Graph



Abstract multiple runtime objects into an abstract object

- Each runtime object has **exactly one** representative in extracted object graph



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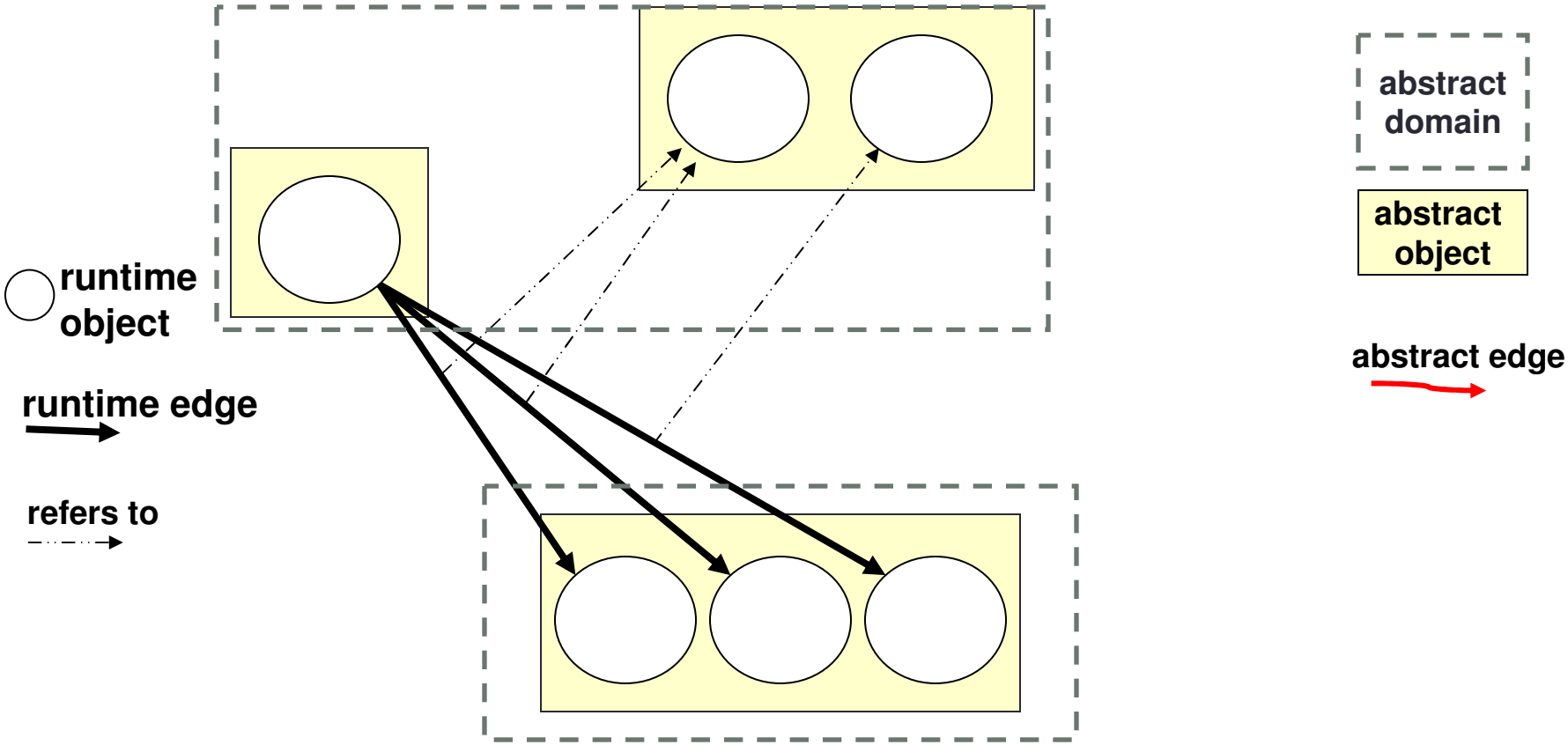
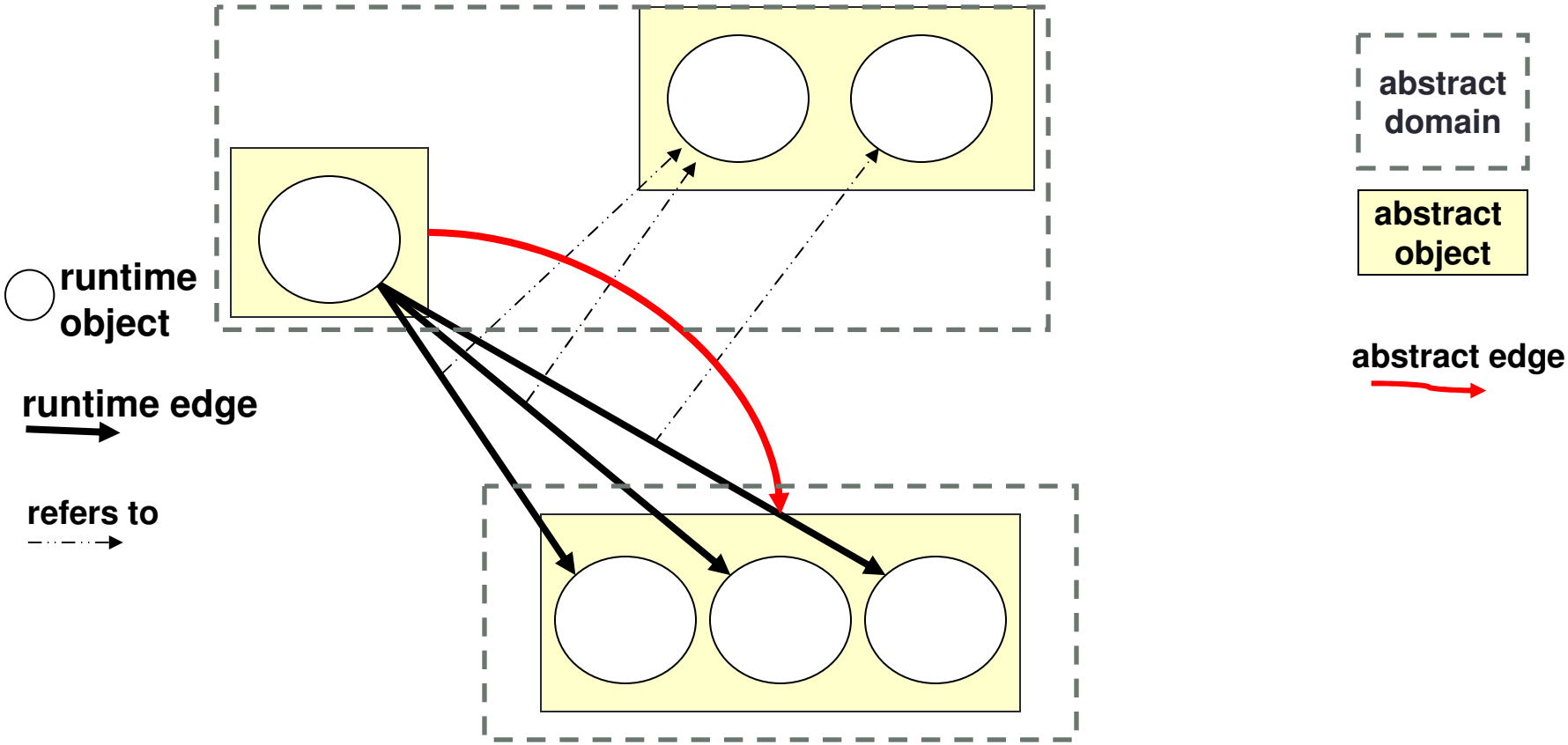
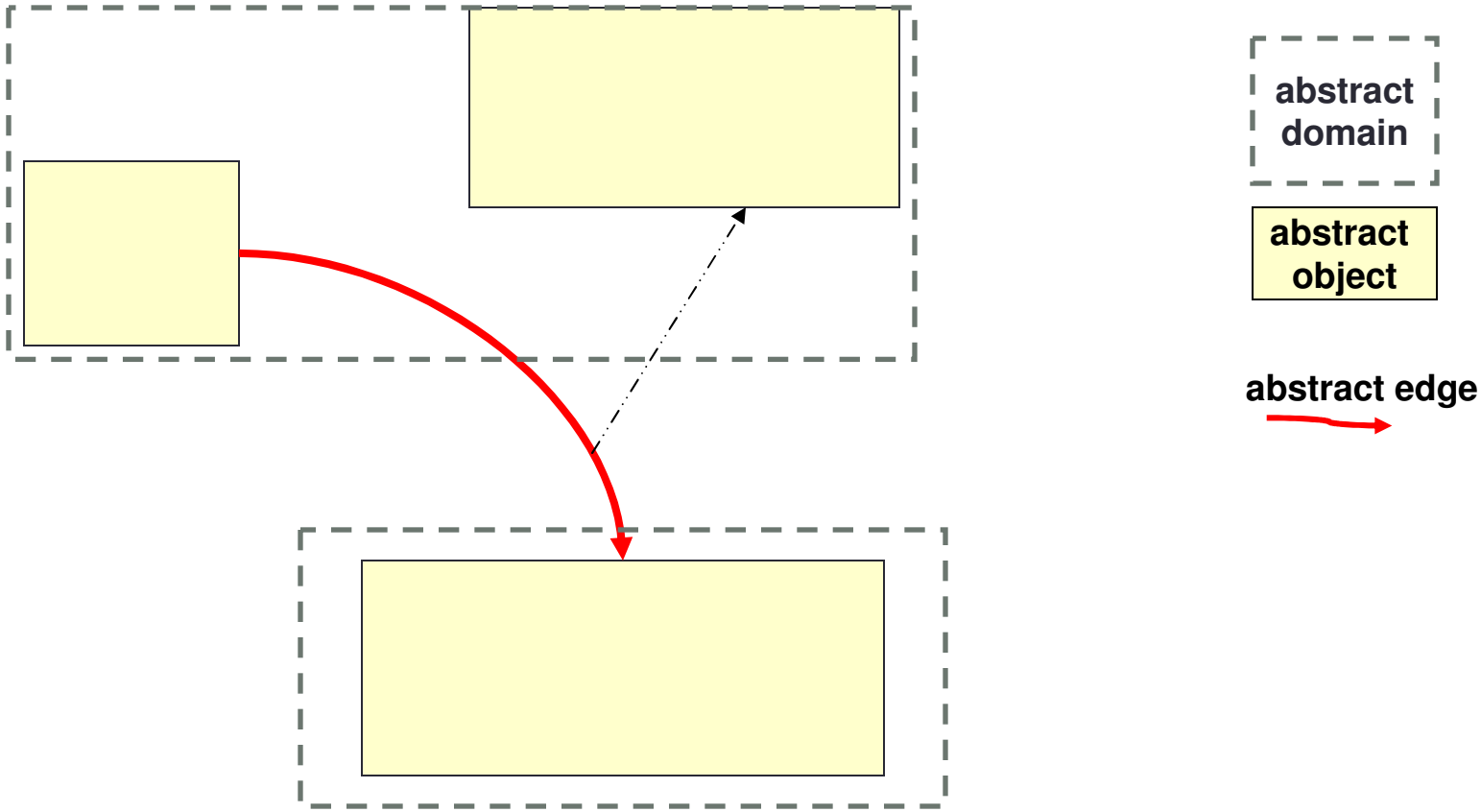


Abstract edge is between abstract objects

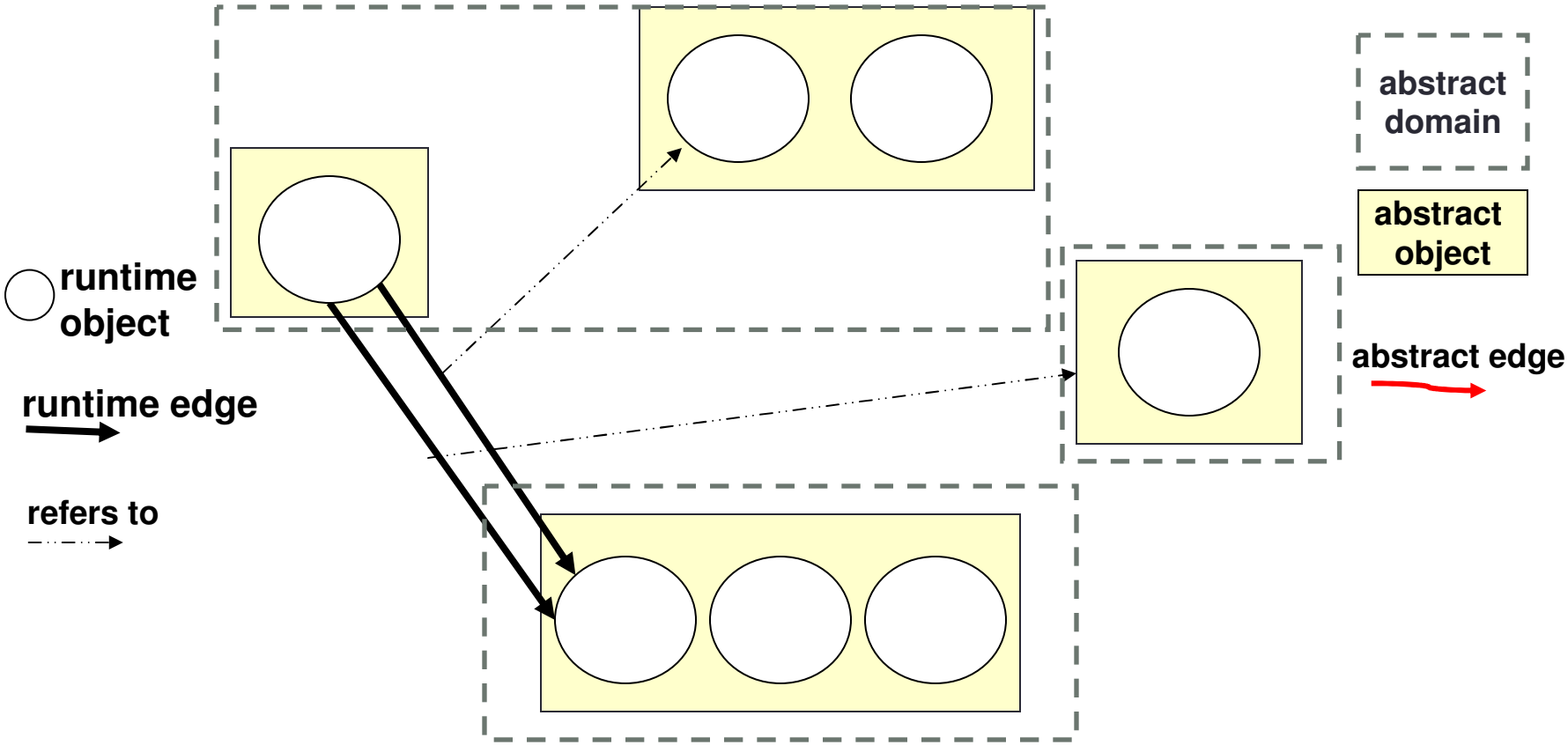
- Runtime edge between two objects maps to edge between representative of two objects



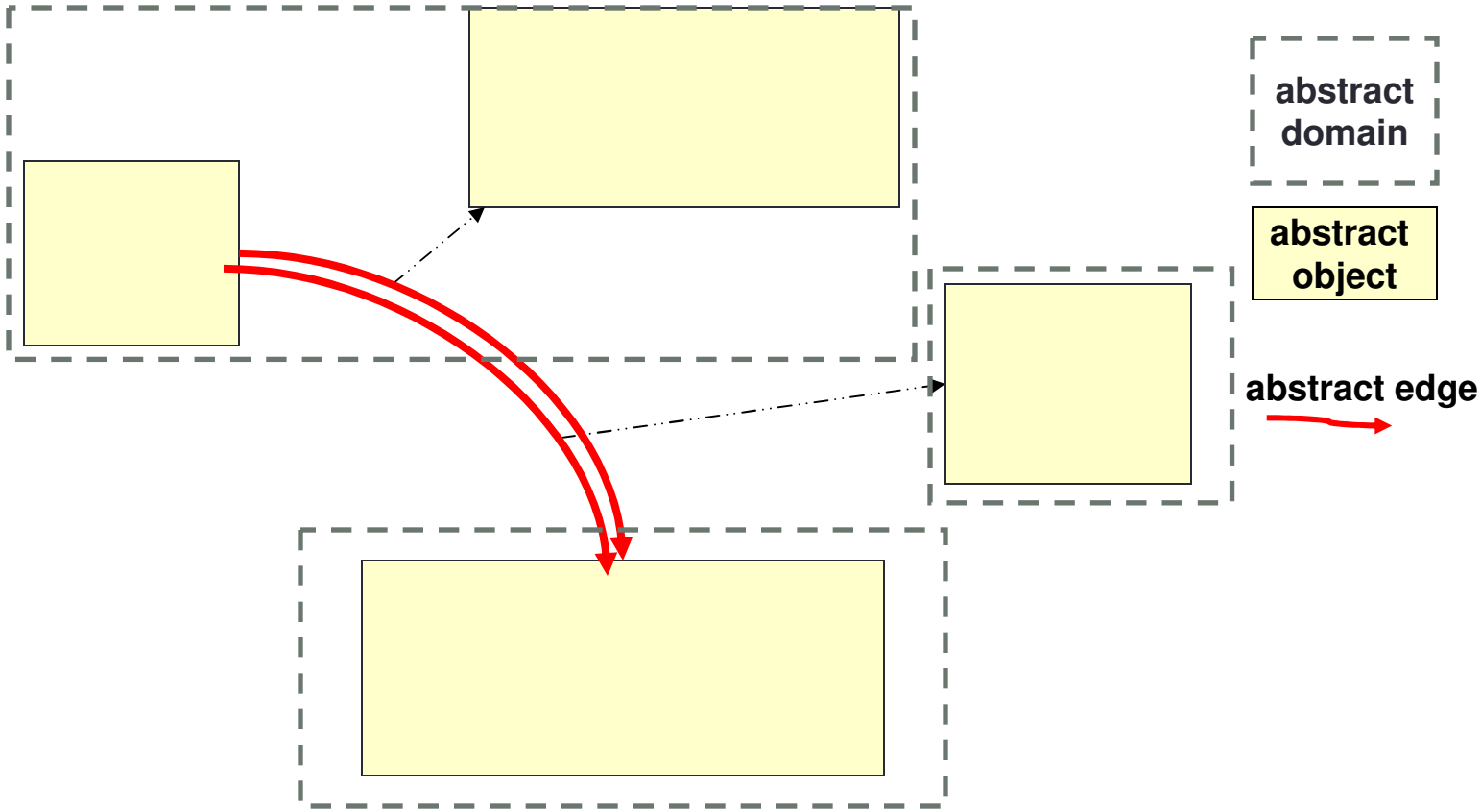
Dataflow edge between abstract objects refers to abstract object



Unique edge representative: Distinct runtime edges refer to distinct runtime object



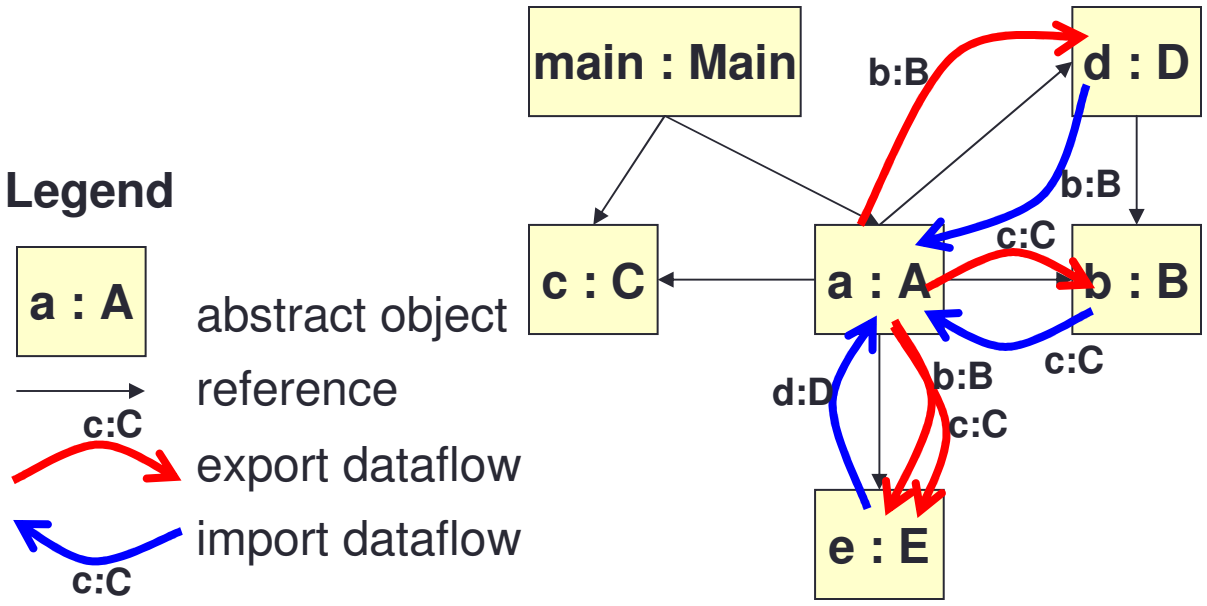
Abstract edge refers to representative of the runtime object that runtime edge refers to



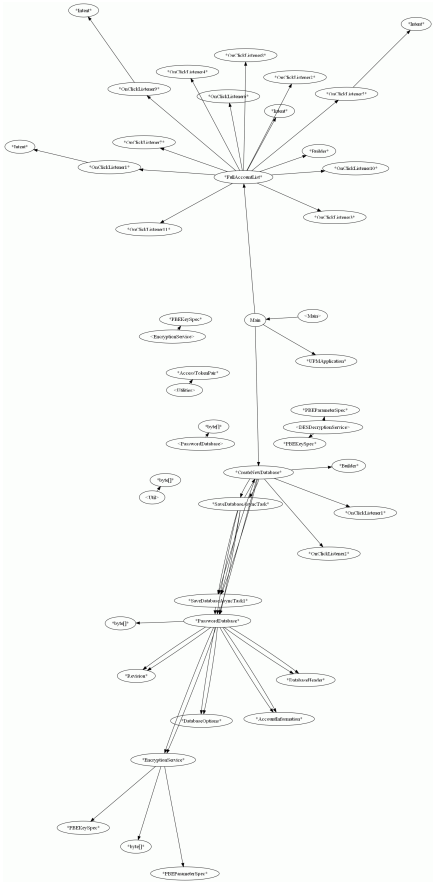
Extracting dataflow edges

- Nodes represent abstract objects
- Edges represent usage of objects:
  [Spiegel, Ph.D. Thesis'02] [Lienhard et al., COMLAN'09]
  - method invocation
  - field read
  - field write

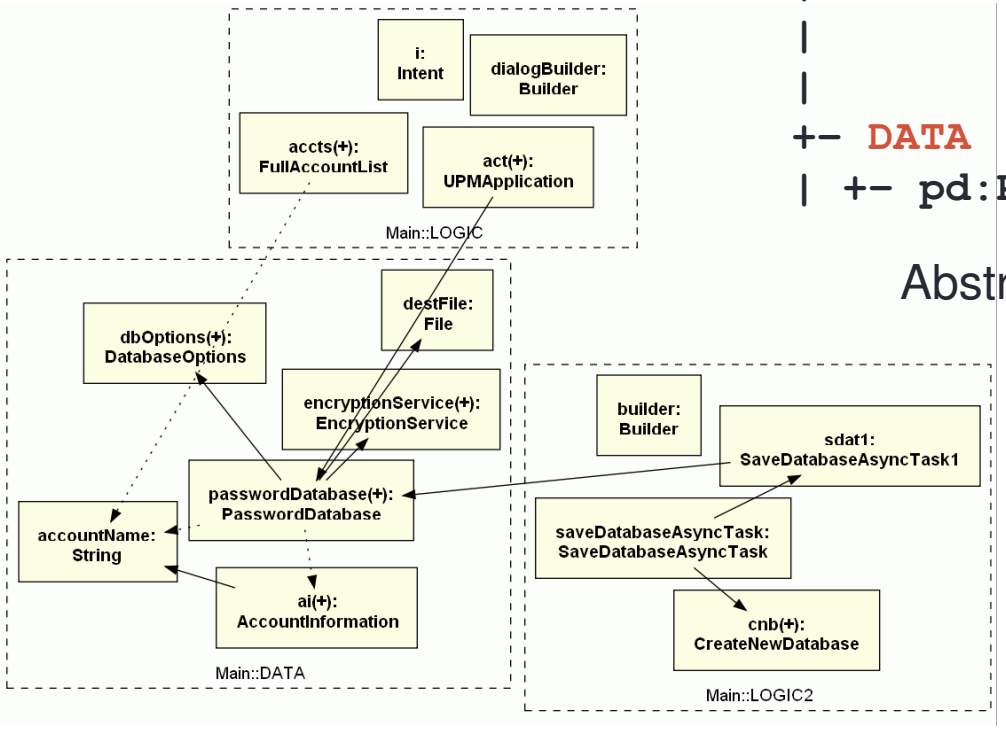
```
class A{
  B b; C c; D d; E e;
  void m1(){
    d.setB(b);
  }
  B m2(){
   return d.getB();
  }
  C m3(){
    return b.c;
  }
  void m4(){
    b.c = c;
  }
  D m5(){
     return e.m(b,c);
   }
}
```



Hierarchy: organize object hierarchically



Flat object graph
[Spiegel, Thesis '02]




```
+-m:Main
  +- LOGIC
  | +- a:UPMApplication
  |   +- MSG
  |     +- i:Intent
  |       +- OWNED
  |         +- map:HashMap
  +- DATA
  | +- pd:PasswordDatabase
```

Abstract object hierarchy

Ownership Object Graph with points-to edges
[Abi-Antoun and Aldrich, OOPSLA'09]

Use ownership types to guide extraction of object hierarchy [Aldrich and Chambers, ECOOP'04]

- Hierarchical organization of objects
  - Not available in plain Java code
  - Use annotations
  - Annotations implement type system

```
+-m:Main
   +- LOGIC
   | +- a:UPMApplication
   |    +- MSG
   |       +- i:Intent
   |          +- OWNED
   |             +- map:HashMap
   +- DATA
   | +- pd:PasswordDatabase
```

- Assign each object to one **ownership domain**
  - **Domain:** *defn. a* ***named, conceptual group of objects***
  - Domain is similar to architectural runtime tier
- Typechecker ensures annotations and code **are consistent**
- Annotations are local/modular (checked one class at a time)
- Use language support for annotations to handle legacy code

Static analysis abstractly interprets program with annotations

- Static analysis: ScoriaX
  - Whole program analysis
  - Construct a global, hierarchical Ownership Object Graph
  - Object/domain hierarchy
  - Dataflow edges

ScoriaX extracts dataflow edges and flow objects

- Extracting dataflow edges require interpreting method invocations, field reads and field writes
- Local variables, method parameters could be **`lent`**
  - In Ownership Domains, **`lent`** = borrowed object
- Method parameters, return value could be **`unique`**
  - In Ownership Domains, **`unique`** = objects passed linearly

- ScoriaX attempts to resolve **`lent`** and **`unique`**
  - It may resolve to domain declared in code
  - If not, create special domain (child of creator object) *with an automatically generated name and without a domain declaration*
  - **Flow Object:** *defn.* ***an object that resides in a special domain***

ScoriaX is a kind of points-to analysis

- Approximates a set of runtime objects which a reference in the program may alias
- Object-sensitive parameterized by constant *k* [Milanova et al. TSE'05]
- *new C1() -> . . . -> new Ck() class Ck{ new^h C(); }*
- For *k=1* : merges all objects created at object allocation site into same equivalence class

- ScoriaX distinguishes between allocations in different domains and that have different domain parameters

*new C<**p**$_{owner}$ **p**$_{params}$...>()*

- **p**$_{owner}$: owner domain
  - locally declared domain **d**
  - formal domain parameter
  - **shared**
  - **unique**
- **p**$_{params}$: additional domain parameters
  - locally declared domain **d**
  - formal domain parameter
  - **shared**

Analysis does multiple passes over code

Pass1: Extracts objects and domains

Pass2: Extracts dataflow edges

- Also extracts value flow graph (FG)

Pass3: Summarizes value flow graph and compute transitive flow

- FG* = *summarize*(FG)
- FG_P = *propagateAll*(FG)
- Only for references declared as lent or unique (improves scalability)

Pass4: Attempts to resolve lent and unique using propagated flow graph

- extracts more dataflow edges
- extracts flow objects

At every pass:

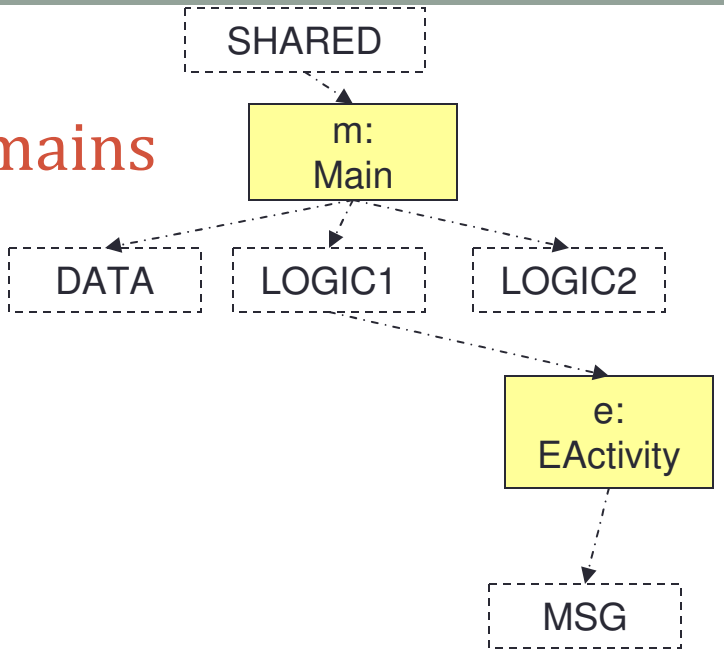
- start from the root class
- stop at a fixed-point

Pass1:Extract objects and domains

- Track `this` → abstract object **Othis**
- Track binding of formal domain parameter → actual domain

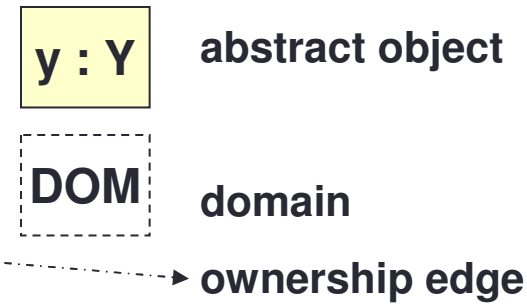
```
[this → Othis]
y = new C<DOM>();
x = y.m(a);

[this → Oy]
[C::owner → DOM]
class C<owner>{
 X<Bx> m(A<Bf> fa) { …
  return ret;
 }
}
```

Pass1:Extract objects and domains

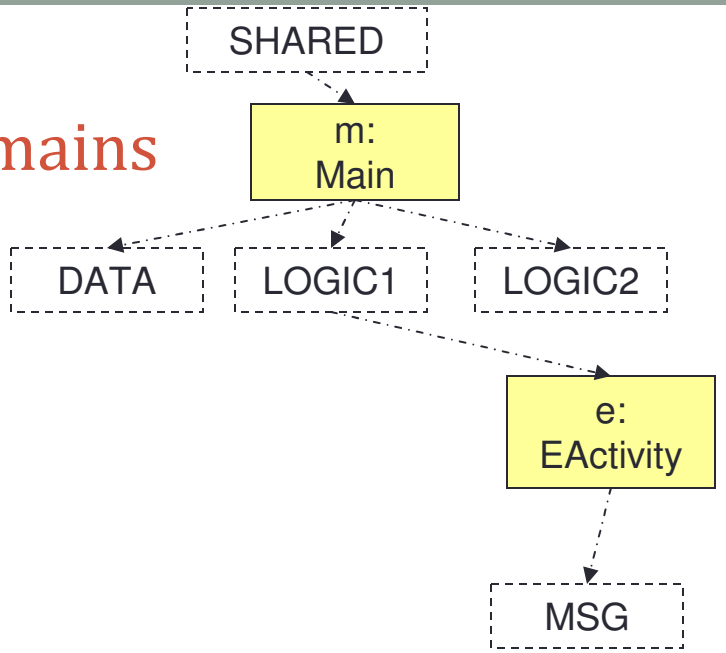



```
[this → O_root]
[::shared→SHARED]
m = new Main<shared>();
[this → O_m]
[Main::owner→SHARED]
class Main<owner>{
  domain DATA, LOGIC1, LOGIC2;
  EActivity<LOGIC1,LOGIC2,DATA> e;
  e = new EActivity<LOGIC1,LOGIC2,DATA>();
}
class EActivity<owner,L,D>
  extends Activity{}
[this → O_e]
[Activity::MSG→e.MSG]
class Activity<owner,L,D>{
   domain MSG;
}
```

Legend

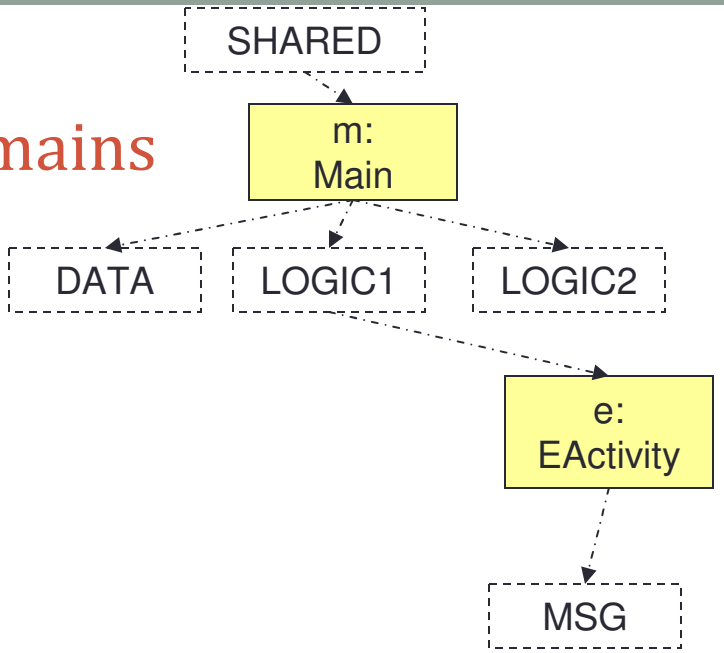


Pass1:Extract objects and domains



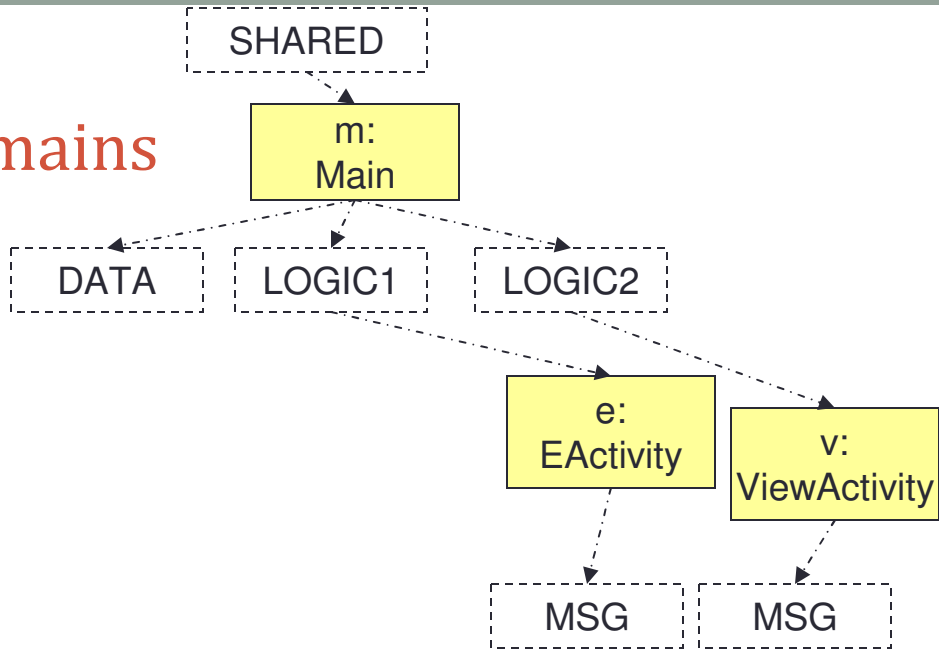

```
class EActivity<owner,L,D>
  extends Activity<owner,L,D> {

}
```

Pass1:Extract objects and domains




```
[this → Oe]
[EActivity::owner→LOGIC1,
 EActivity::L→LOGIC2,
 EActivity::D→DATA ]
class EActivity<owner,L,D>
  extends Activity<owner,L,D> {
  Activity<L,L,D> v;
  v = new ViewActivity<L,L,D>();
}
[this → Oe]
[Activity::owner→LOGIC1,
 Activity::L→LOGIC2,
 Activity::D→DATA ]
class Activity<owner,L,D>{
   domain MSG;
}
```

Pass1:Extract objects and domains



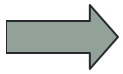

```
[this → Oe]
[EActivity::owner→LOGIC1,
 EActivity::L→LOGIC2,
 EActivity::D→DATA ]
class EActivity<owner,L,D>
  extends Activity<owner,L,D> {
  Activity<L,L,D> v;
  v = new ViewActivity<L,L,D>();
}
[this → Ov]
[Activity::owner→LOGIC2,
 Activity::L→LOGIC2,
 Activity::D→DATA ]
class Activity<owner,L,D>{
   domain MSG;
}
```

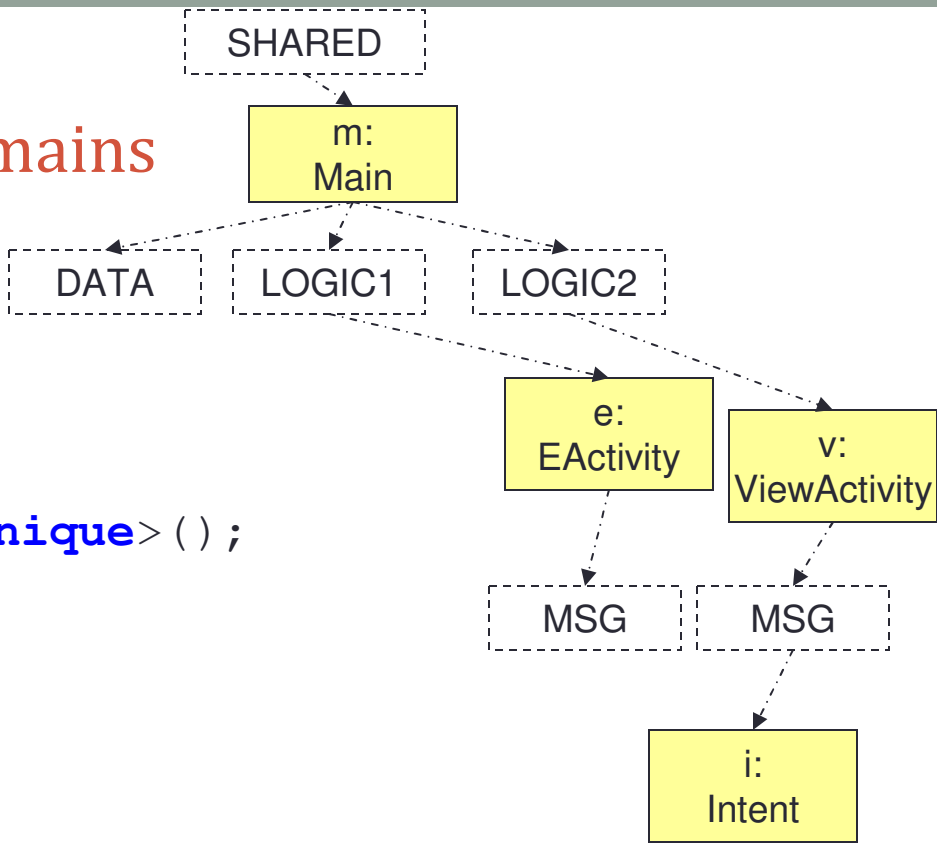
Pass2:extract value Flow Graph (FG)

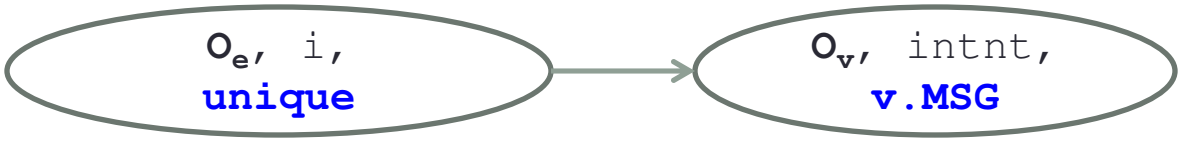
- Nodes (**O**, x, ***B***) where
  - Object O for domain-sensitivity
  - Reference x of type C<***B***…>
  - ***B*** can be:
    - locally declared domain **d**
    - formal domain parameter
    - **`shared`**
    - **`unique`**
    - **`lent`**
- Edges (**O1**, x, ***B1***) ⇝ (**O2**, y, ***B2***)
- Track assignments → value flow edge
  - `x = y` (**Othis**, y, ***By***) ⇝ (**Othis**, x, ***Bx***)
  - `x = y.m(a)`
    (**Othis**, y, ***By***) ⇝ (**Oy**, this, **owner**)
    (**Othis**, a, ***Ba***) ⇝ (**Oy**, fa, ***Bf***)
    (**Oy**, ret, ***Br***) ⇝ (**Othis**, x, ***Bx***)
  - `x = y.f` (**Oy**, f, ***By***) ⇝ (**Othis**, x, ***Bf***)
  - `x.f = y` (**Othis**, y, ***By***) ⇝ (**Ox**, f, ***Bf***)
- Attempt to resolve **`lent`** and **`unique`**
  - Resolve **`unique`**: forward in value flow
  - Resolve **`lent`** : backward in value flow

Pass2:Extract objects and domains

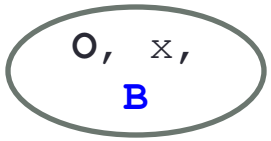
```
[this → Oe]
class EActivity<owner,L,D>
 extends Activity<owner,L,D> {
 Activity<L,L,D> v = ...;
 Intent<unique> i=new Intent<unique>();
 v.start(i);
}
[this → Ov]
class Activity<owner,L,D>{
   domain MSG;
   void start(Intent<MSG> intnt);
}
[this → Oi]
[Intent::owner→v.MSG]
class Intent<owner>{
}
```







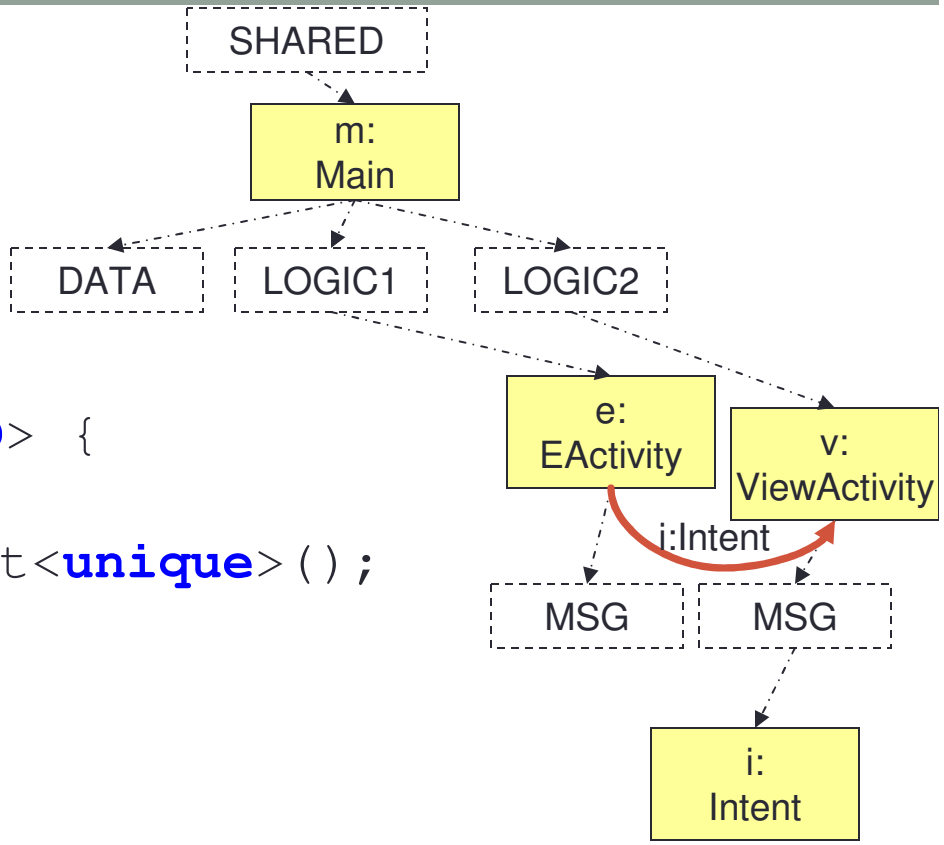
Legend



value flow node

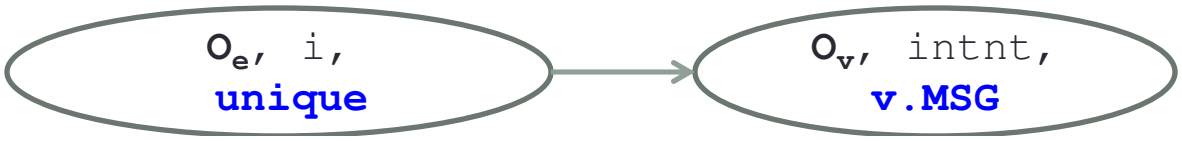
value flow edge

Pass2:Extract dataflow edges

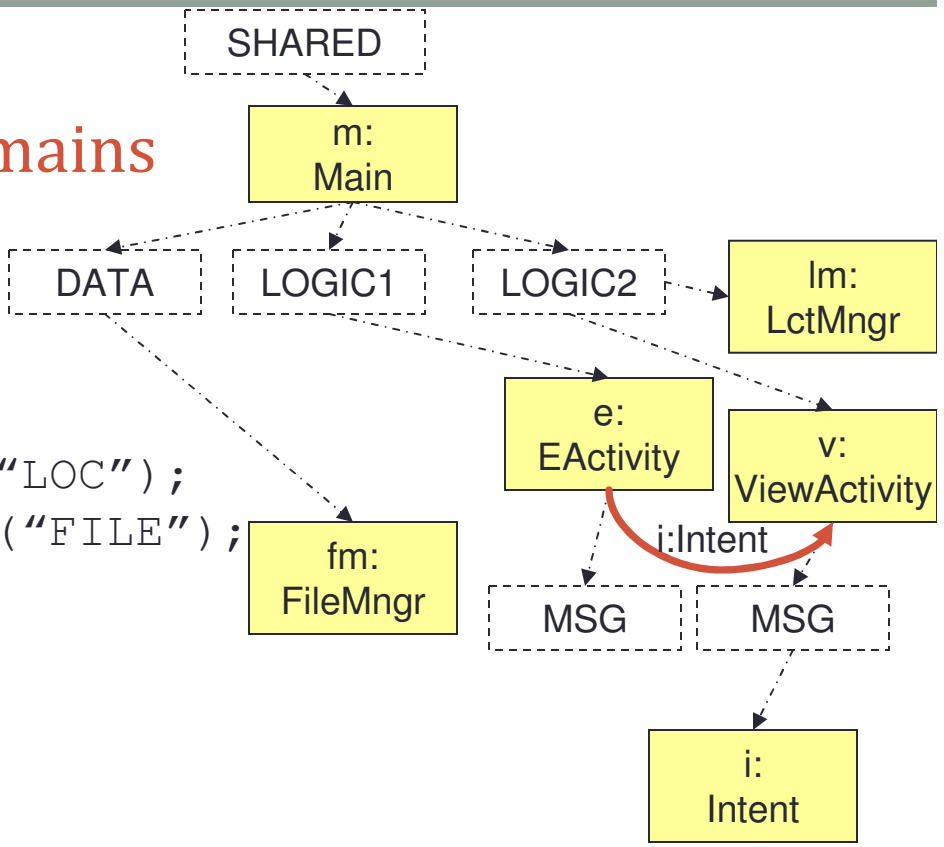



```
[this → Oe]
class EActivity<owner,L,D>
  extends Activity<owner,L,D> {
  Activity<L,L,D> v = ...;
  Intent<unique> i=new Intent<unique>();
  v.start(i);
}
```

```
[this → Oe]
[EActivity::owner→LOGIC1,
 EActivity::L→LOGIC2,
 EActivity::D→DATA ]
lookup(Activity<L,L,D>) = {Ov}
solveUnique(Oe,Intent) = {v.MSG}
lookup(Intent<unique>) = {Oi}
```

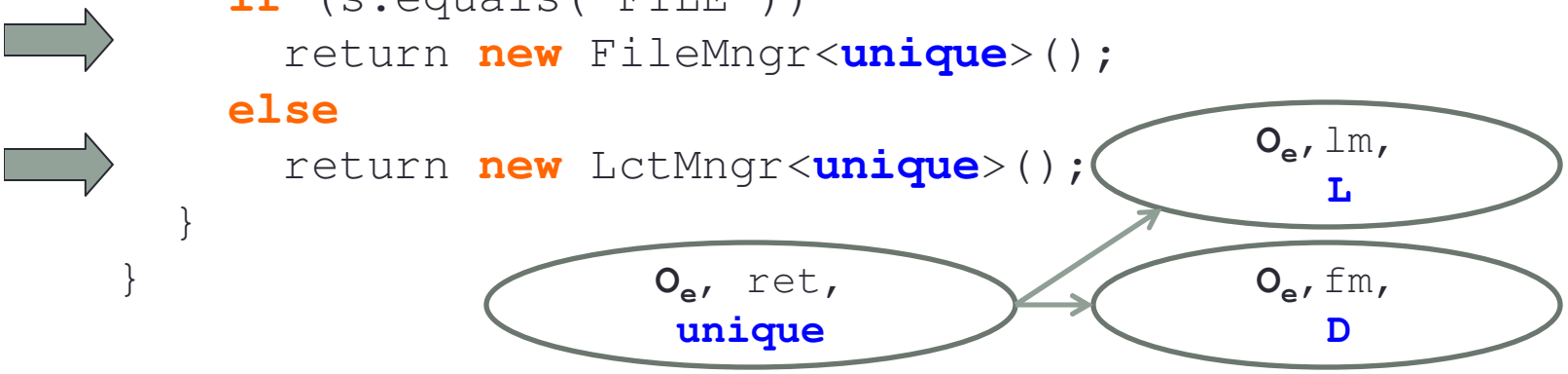


Pass2:Extract objects and domains

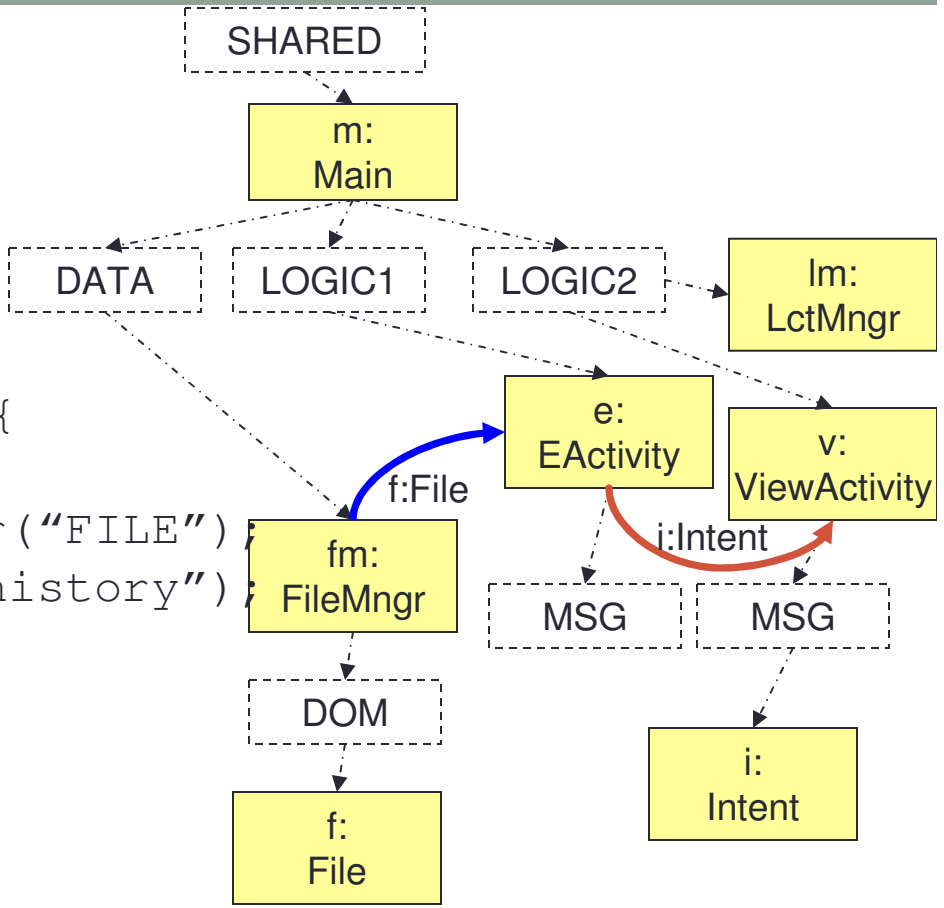



```
[this → Oe]
class EActivity<owner,L,D>
 extends Activity<owner,L,D> {
 LctMngr<L> lm = this.getMngr("LOC");
 FileMngr<D> fm = this.getMngr("FILE");
}
```

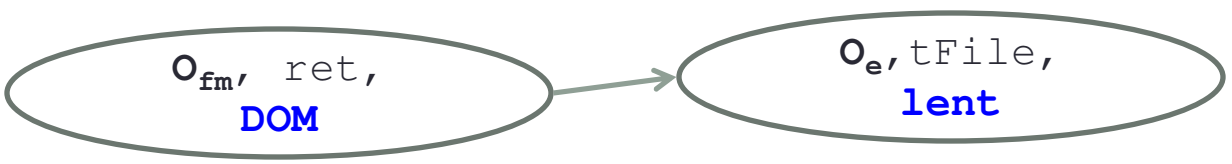
```
[this → Oe]
class Activity<owner,L,D>{
  Mngr<unique> getMngr(String<SHARED> s){
    if (s.equals("FILE"))
      return new FileMngr<unique>();
    else
      return new LctMngr<unique>();
  }
}
```



Pass2:Extract dataflow edges

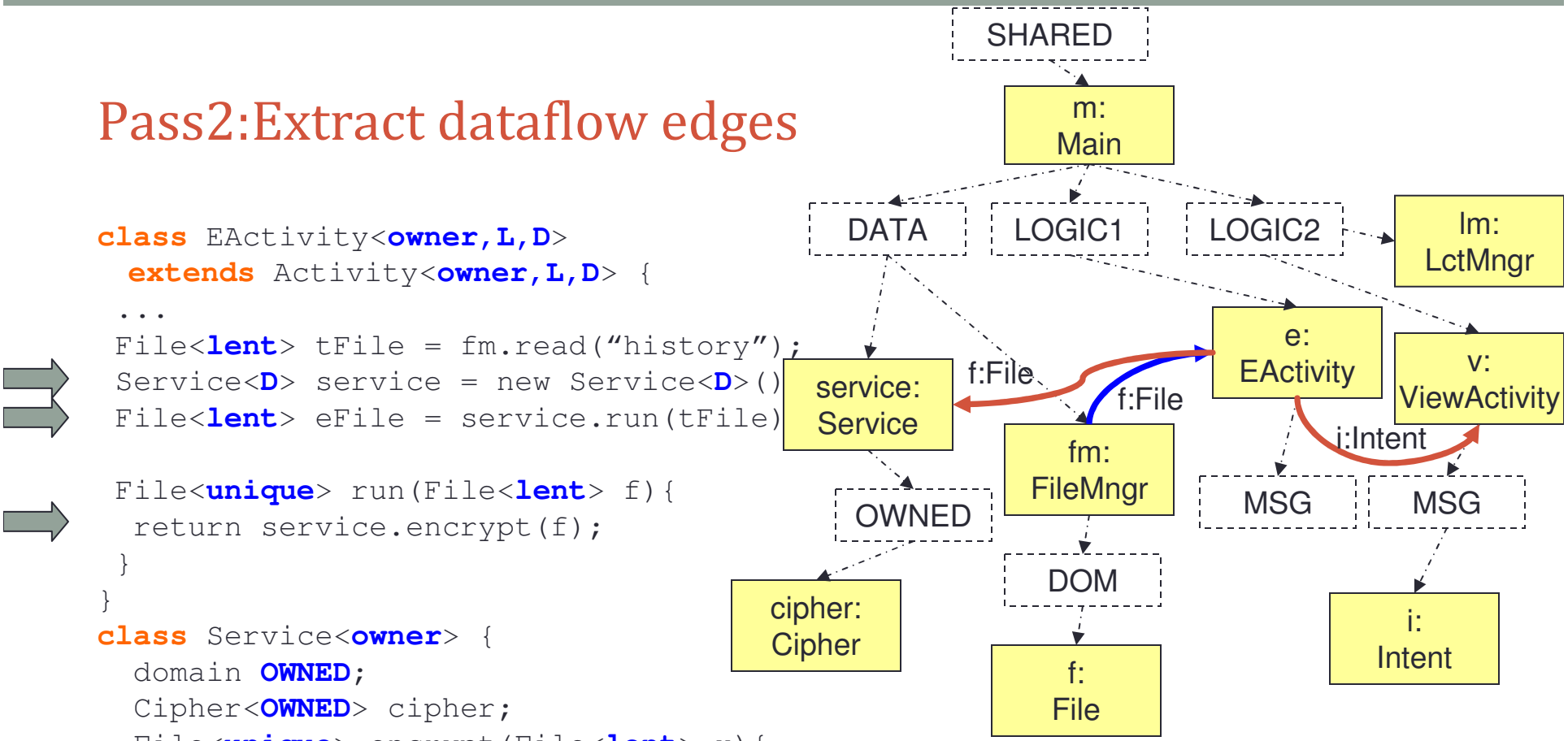



```
[this → Oe]
class EActivity<owner,L,D>
 extends Activity<owner,L,D> {
 ...
 FileMngr<D> fm = this.getMngr("FILE");
 File<lent> tFile = fm.read("history");
}

[this → Ofm]
class FileMngr<owner>
  extends Mmgr<owner> {
  domain DOM;
  File<DOM> read(String<SHARED> s){
     return new File<DOM>();
  }
}
```



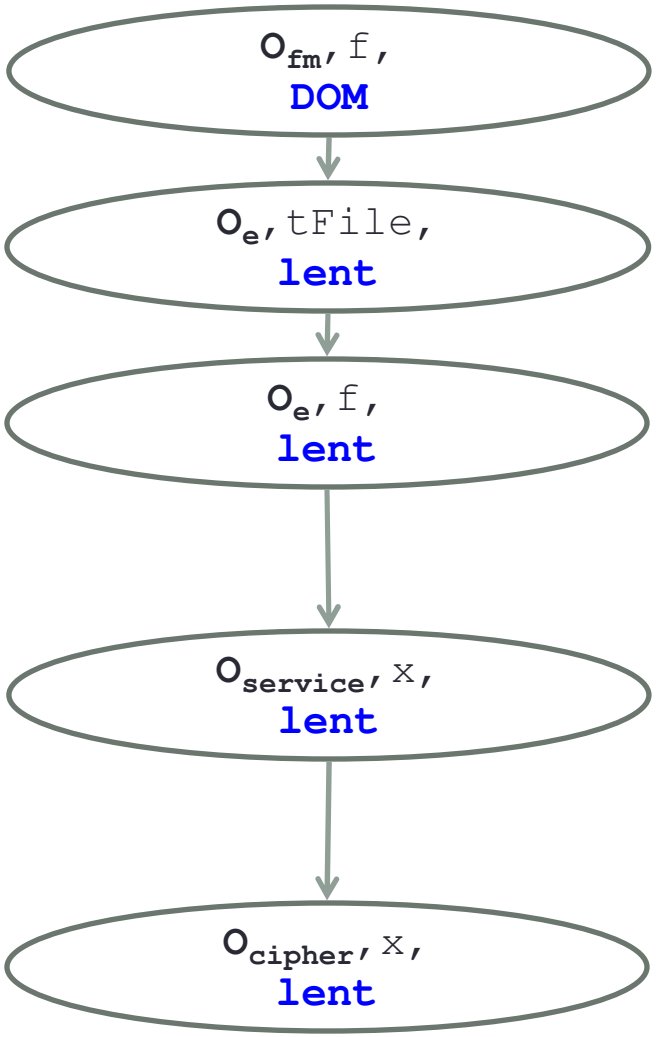
Pass2:Extract dataflow edges

```
class EActivity<owner,L,D>
  extends Activity<owner,L,D> {
 ...
 File<lent> tFile = fm.read("history");
 Service<D> service = new Service<D>()
 File<lent> eFile = service.run(tFile)

 File<unique> run(File<lent> f){
  return service.encrypt(f);
 }
}
class Service<owner> {
  domain OWNED;
  Cipher<OWNED> cipher;
  File<unique> encrypt(File<lent> x){
     return cipher.doFinal(x);
  }
}
class Cipher<owner> {
 File<unique> encrypt(File<lent> x){
     return new File<unique>();
 }
}
```



Pass2:Extract value flow graph

```
class EActivity<owner,L,D> ... {
 File<lent> tFile = fm.read("history");
 File<lent> eFile = service.run(tFile);

 File<unique> run(File<lent> f){
  return service.encrypt(f);
 }
}
class Service<owner> {
  domain OWNED;
  Cipher<OWNED> cipher;

  File<unique> encrypt(File<lent> x){
     return cipher.doFinal(x);
  }
}
class Cipher<owner> {

 File<unique> doFinal(File<lent> x){
     return new File<unique>();
 }
}
```



Pass2: Extract value flow graph

```
class EActivity<owner,L,D> ... {
 File<lent> tFile = fm.read("history");
 File<lent> eFile = service.run(tFile);
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  }
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 File<unique> encrypt(File<lent> x){

     return new File<unique>();
 }
}
```
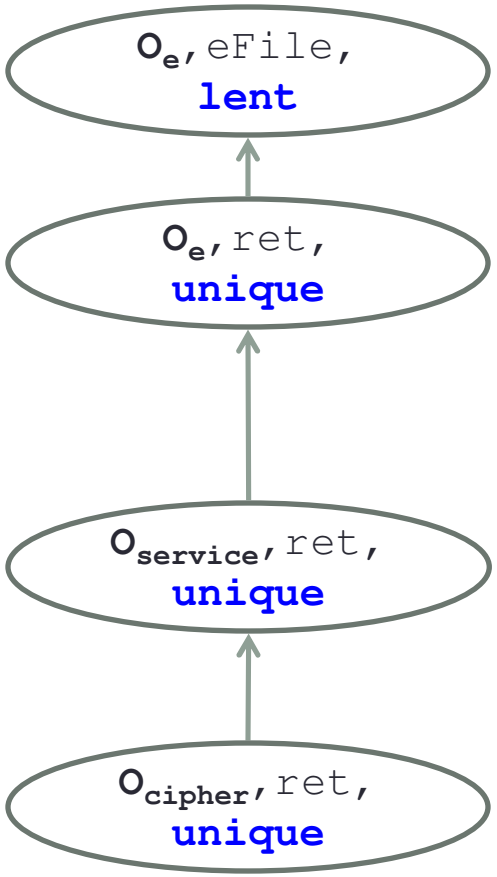
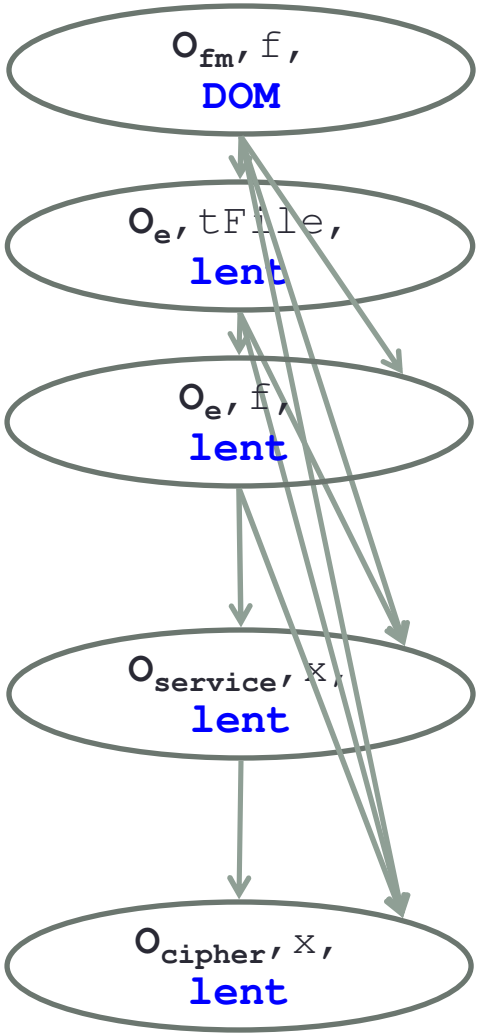



Pass3:Compute propagated flow graph

```
class EActivity<owner,L,D> ... {
 File<lent> tFile = fm.read("history");
 File<lent> eFile = service.run(tFile);
 [solveLent(Oe,File) = {fm.DOM}]
 File<unique> run(File<lent> f){
  return service.encrypt(f);
 }
}
class Service<owner> {
  domain OWNED;
  Cipher<OWNED> cipher;
  [solveLent(Oservice,File) = {fm.DOM}]
  File<unique> encrypt(File<lent> x){
     return cipher.doFinal(x);
  }
}
class Cipher<owner> {
 [solveLent(Ocipher,File) = {fm.DOM}]
 File<unique> doFinal(File<lent> x){
     return new File<unique>();
 }
}
```



Pass3:Compute propagated flow graph

```
class EActivity<owner,L,D> ... {
 File<lent> tFile = fm.read("history");
 File<lent> eFile = service.run(tFile);
 File<unique> run(File<lent> f){
  [File::unique → UNIQUE]
   return service.encrypt(f);
 }
}
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 domain OWNED;
 Cipher<OWNED> cipher;
 File<unique> encrypt(File<lent> x){
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    return cipher.doFinal(x);
 }
}
class Cipher<owner> {
 File<unique> encrypt(File<lent> x){
      [solveUnique(cipher,File) = {lent}]
      [File::unique → UNIQUE]
      return new File<unique>();
 }
}
```
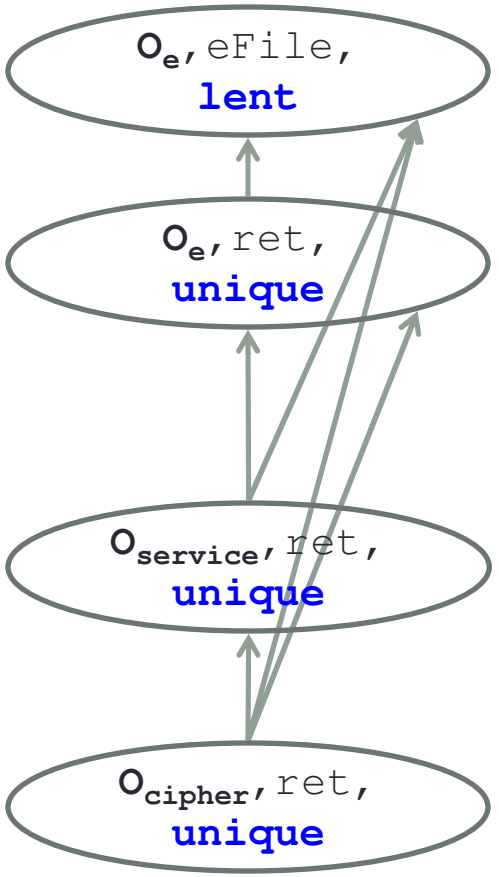
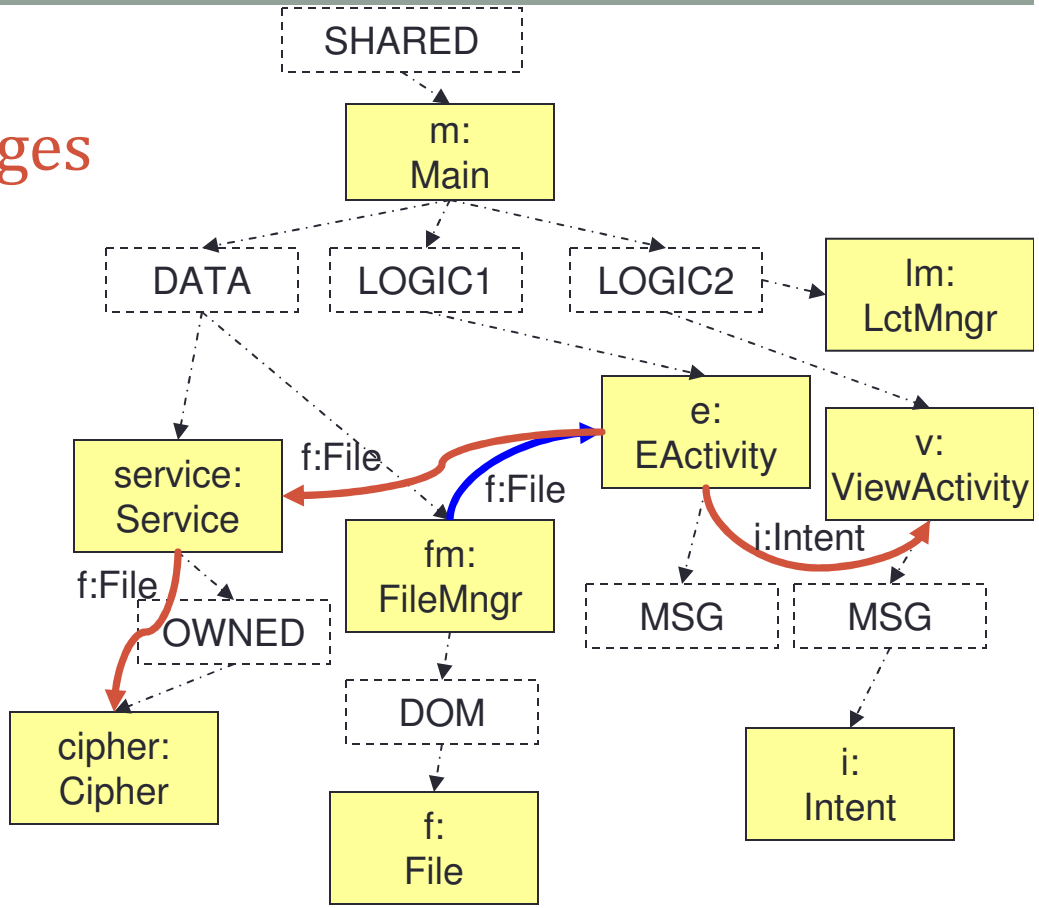



Pass4:Extract dataflow edges

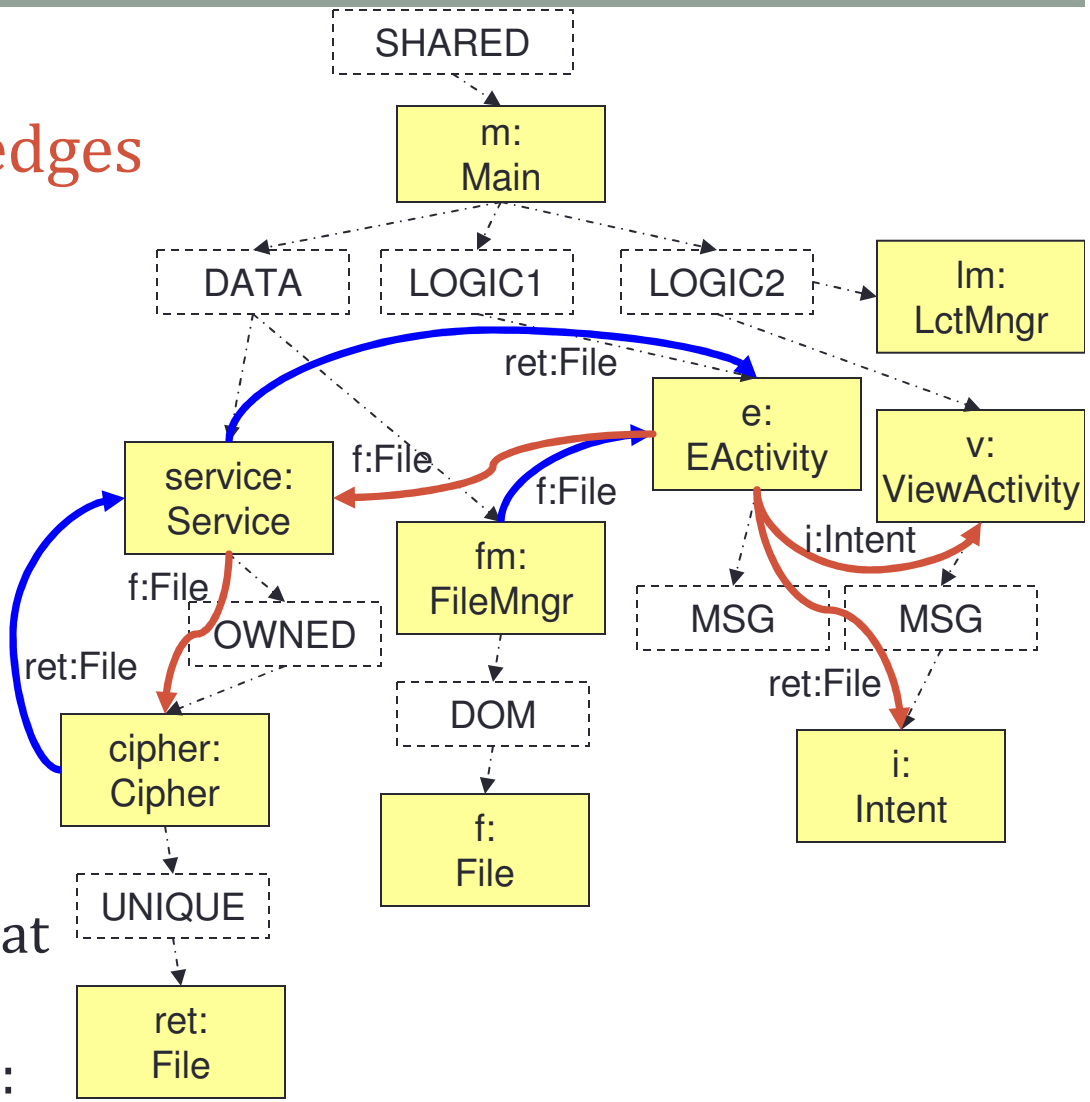
- Resolve **`lent`** to **`fm.DOM`**, the parent of **`f:File`**
- Extract another dataflow edge that refers to **`f:File`**



Pass4:Extract dataflow edges

- Analysis cannot resolve unique do a domain
- Create a fresh ODomain **`UNIQUE`** as child of **`cipher:Cipher`**
- Create flow object **`ret:File`** as child of **`UNIQUE`**

- Extract 3 dataflow edges that refer to same flow object
- Same type different objects:
  - **`ret:File`** encrypted file
  - **`f:File`** unencrypted file
  - Encrypted file flows to **`i:Intent`**



Challenges of static analysis that extract object graph with dataflow edges for security

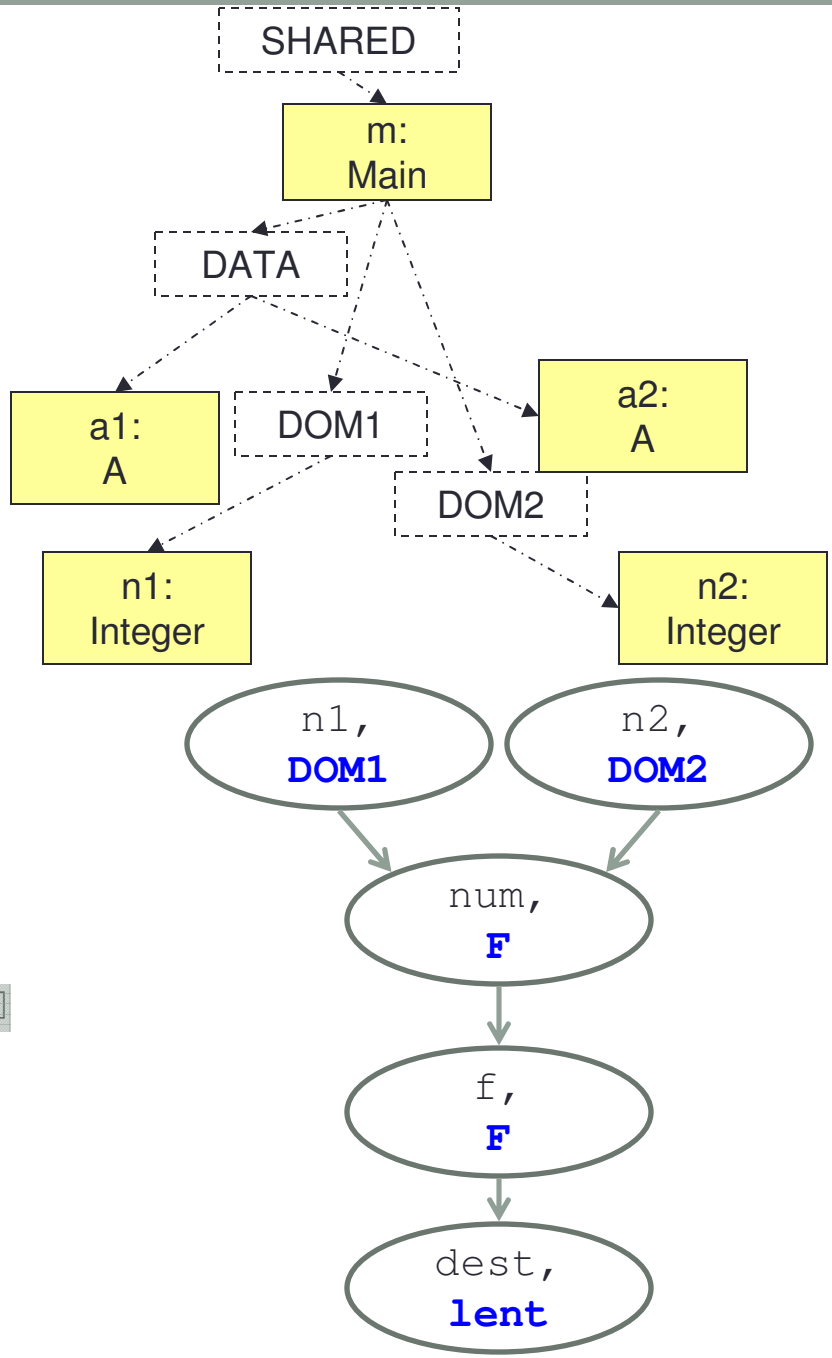
- Soundness
- Hierarchy
- Summarization
- Support for legacy code
- **Precision**
- **Aliasing**

Precision: extract multiple abstract objects for same object allocation expression

- Using a simple transitive closure of value flow graph can be imprecise
- Imprecision occurs when client code invokes same method multiple times or in different contexts
- Make the value flow domain-sensitive, call-site context sensitive, and flow insensitive
- Distinguish between receivers of method using domains
- Consider same invocation different contexts

Domain-insensitive value flow graph

```
class A<owner,F> {
  Integer<F> f;
  void set(Integer<F> num){
   f = num;
  }
  Integer<F> get() { return f; }
}
class Main<owner>{
 void main() {
  domain DATA,DOM1,DOM2;
  Integer<DOM1> n1= new Integer(-1);
  A<DATA,DOM1> a1 = new A();
  a1.set(n1);
  Integer<DOM2> n2 = new Integer(2);
  A<DATA,DOM2> a2 = new A();
  a2.set(n2);
  [resolveLent(m,Integer)={DOM1,DOM2}]
  Integer<lent> dest = a2.get();
  dest.compareTo(n1);
}
```



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  a2.set(n2);
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}
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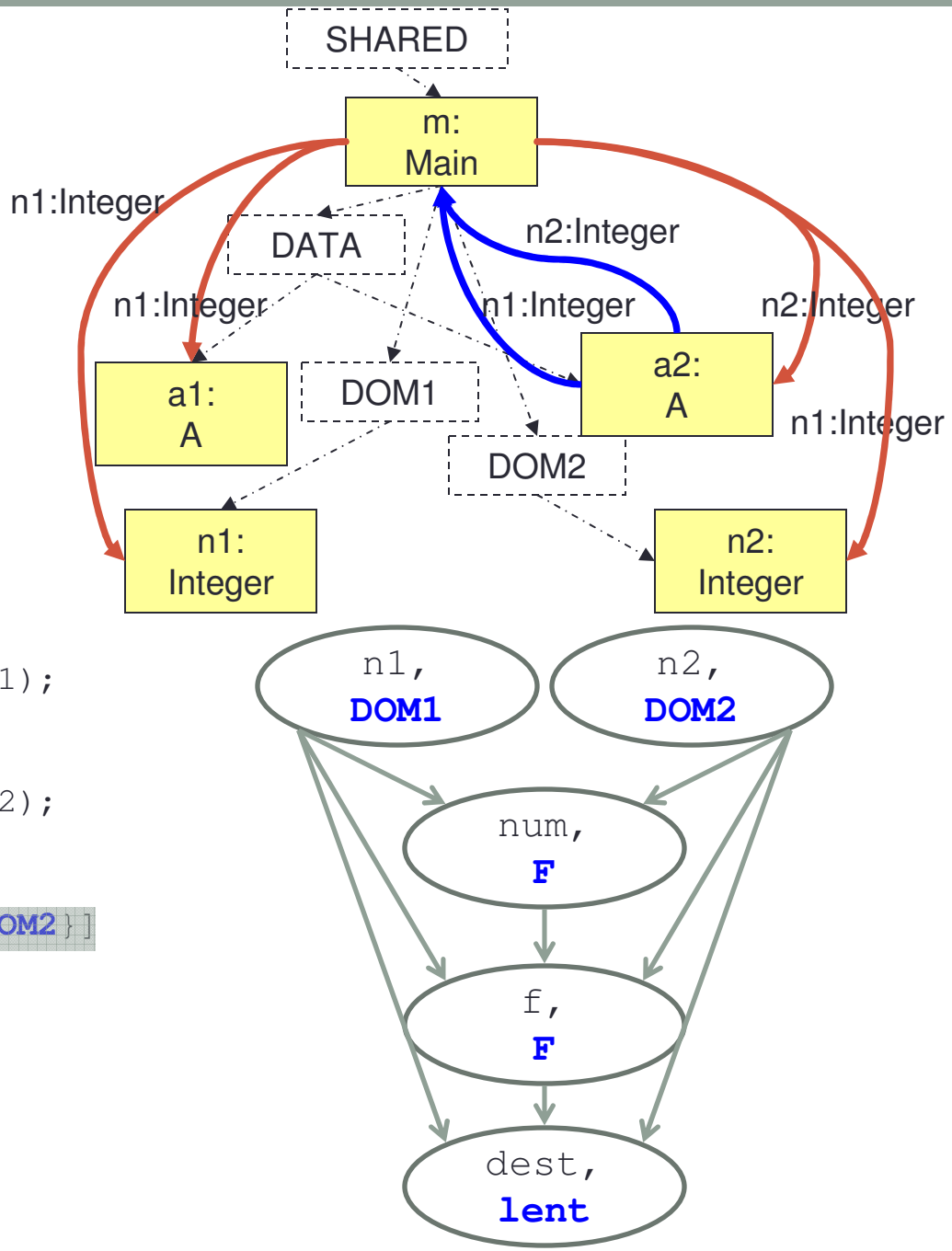

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   f = num;
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  Integer<F> get() { return f; }
}
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 void main() {
  domain DATA,DOM1,DOM2;
  Integer<DOM1> n1= new Integer(-1);
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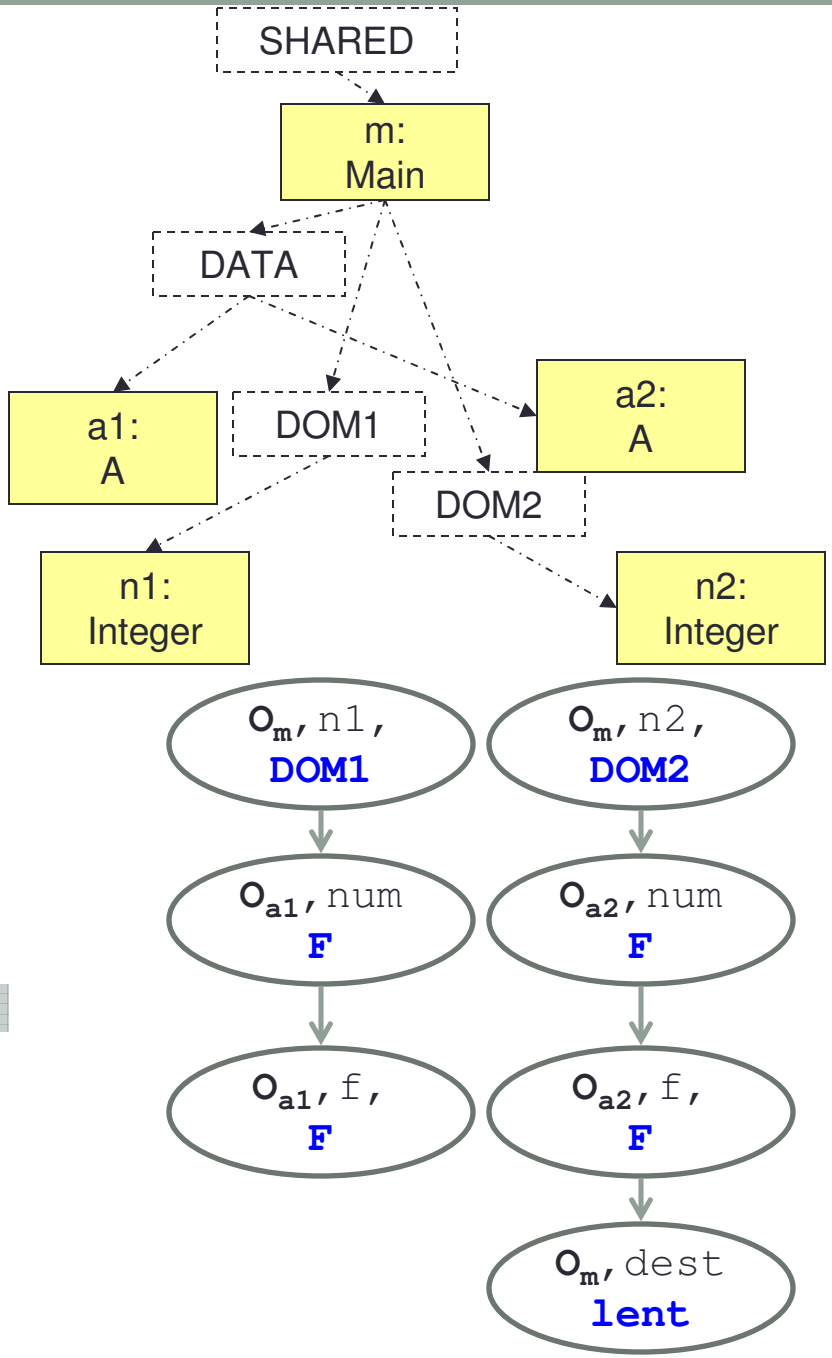
  a1.set(n1);
  Integer<DOM2> n2 = new Integer(2);
  A<DATA,DOM2> a2 = new A();
  a2.set(n2);
  [resolveLent(m,Integer)={DOM2}]
  Integer<lent> dest = a2.get();
  dest.compareTo(n1);
}
```



Domain-sensitive value flow graph

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  void set(Integer<F> num) {
   f = num;
  }
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}
class Main<owner>{
 void main() {
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  Integer<DOM1> n1= new Integer(-1);
  A<DATA,DOM1> a1 = new A();
  a1.set(n1);
  Integer<DOM2> n2 = new Integer(2);
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  a2.set(n2);
  [resolveLent(m,Integer)={DOM2}]
  Integer<lent> dest = a2.get();
  dest.compareTo(n1);
}
```
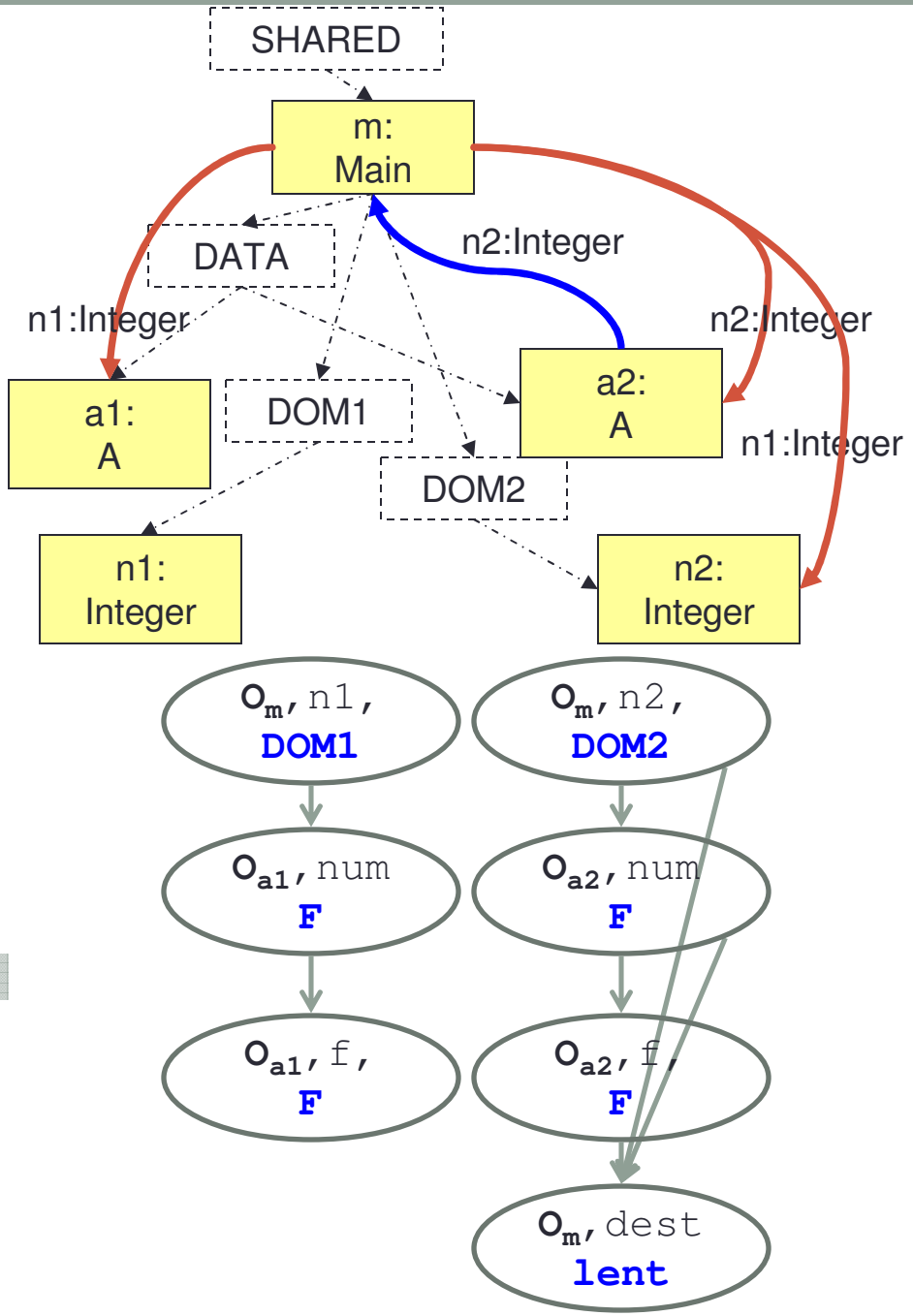
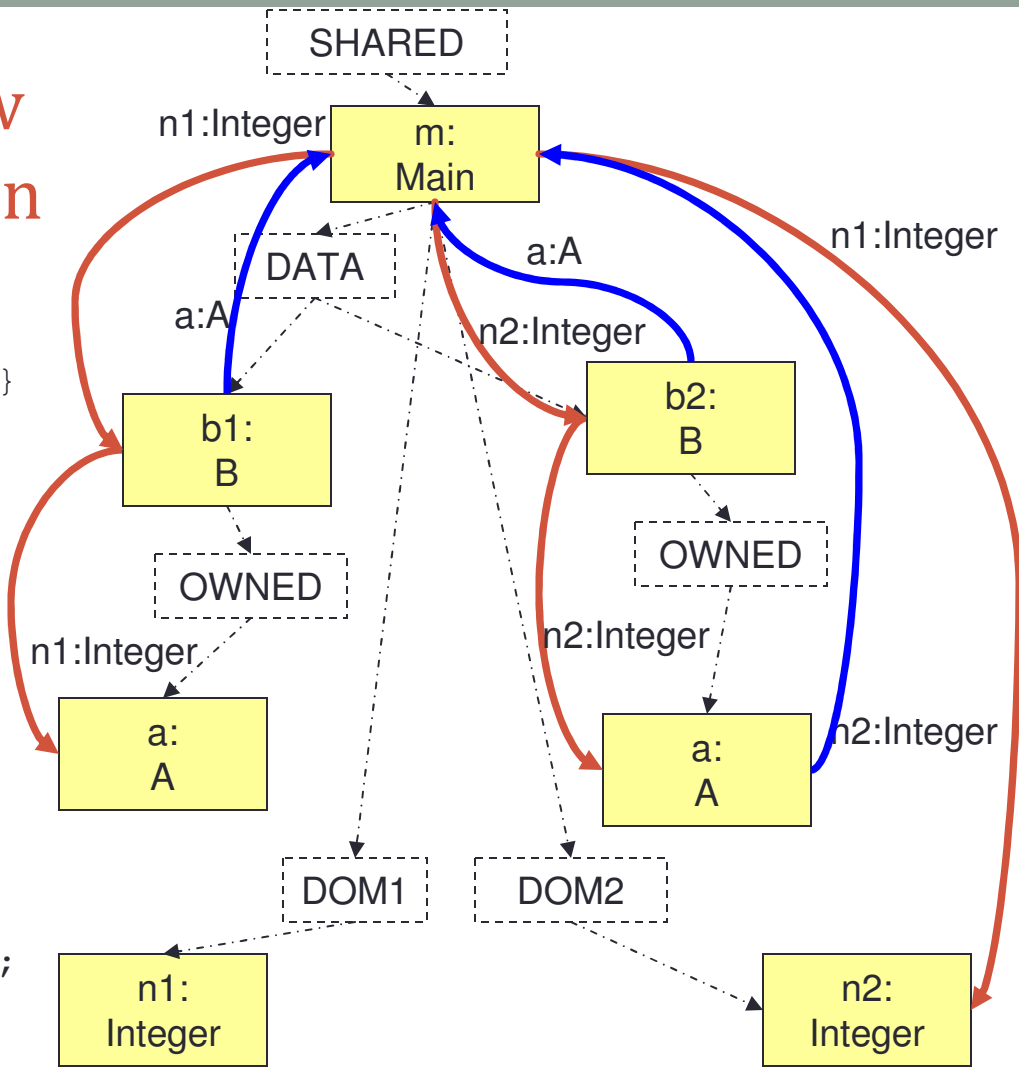



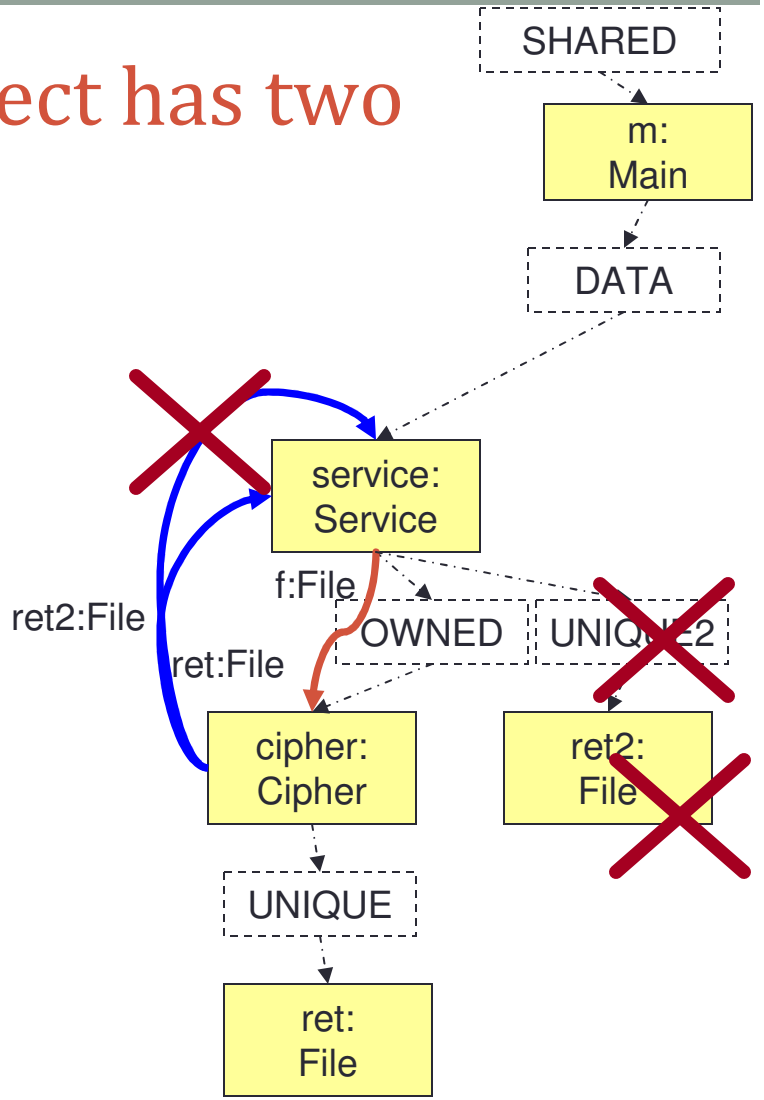
Extract multiple dataflow edges for same invocation

```
class A<owner,F> {
  Integer<F> f;
  void set(Integer<F> num){f = num;}
  Integer<F> get() { return f; }
}
class B<owner,F> {
 domain OWNED;
 A<OWNED,F> A a = new A();
 void assign(Integer<F> n) {
  a.set(n);
 }
}
class Main<owner>{
 domain DATA,DOM1,DOM2;
 void main() {
  Integer<DOM1> n1= new Integer(-1);
  B<DATA,DOM1> b1 = new B();
  b1.assign(n1);
  Integer<DOM2> n2 = new Integer(2);
  B<DATA,DOM2> b2 = new B();
  b2.assign(n2);
  Integer<lent> dest = b2.a.get();
  dest.compareTo(n1);
 }
}
```



Aliasing: No one runtime object has two representatives in OGraph

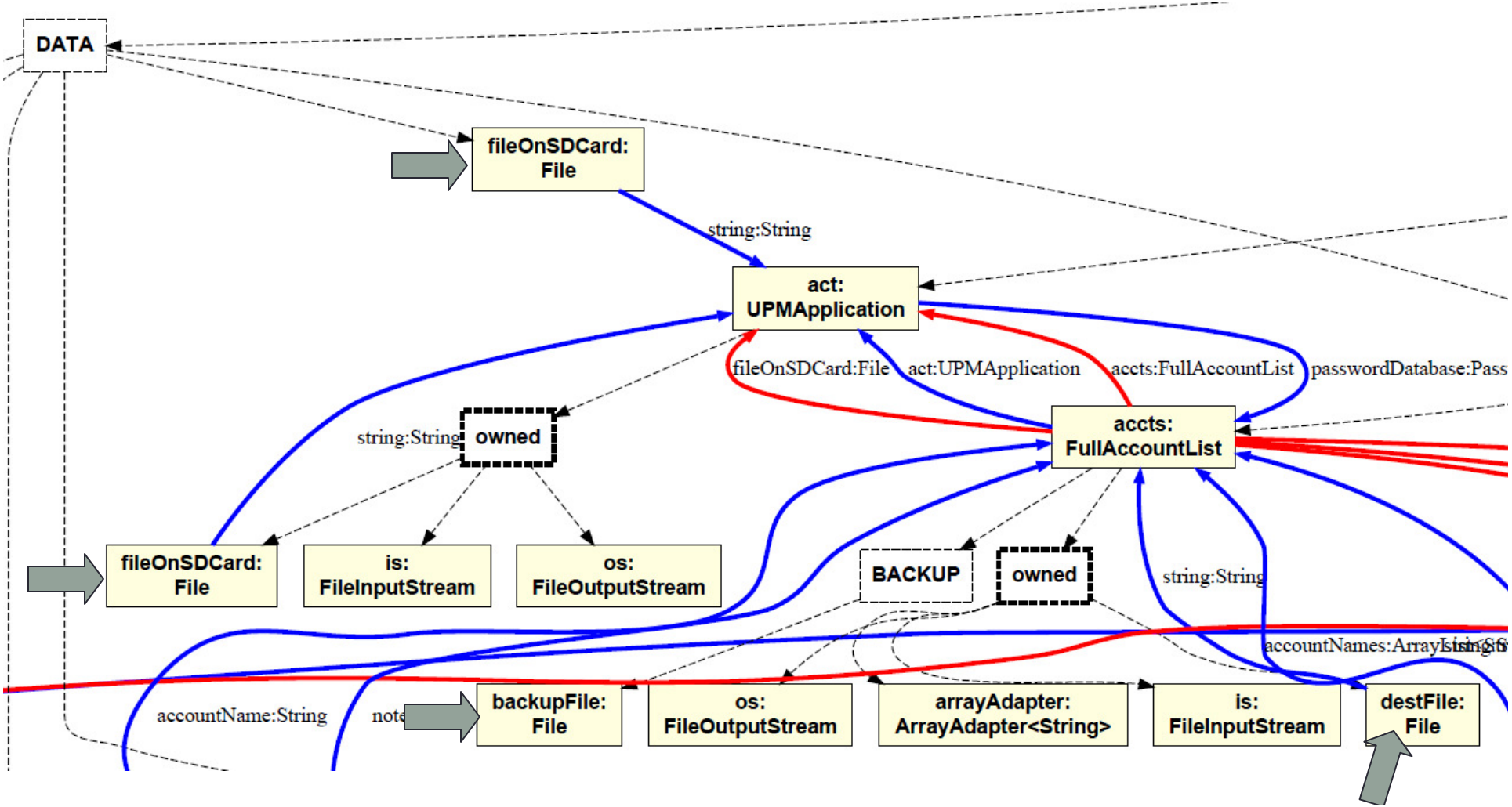
```
class EActivity<owner,L,D> ... {
 File<lent> tFile = fm.read("history");
 File<lent> eFile = service.run(tFile);
 File<unique> run(File<lent> f){
   [File::unique → UNIQUE]
   return service.encrypt(f);
 }
}
class Service<owner> {
   domain OWNED;
   Cipher<OWNED> cipher;
   File<unique> encrypt(File<lent> x){
      [File::unique → UNIQUE]
      [File::unique → UNIQUE2]
      return cipher.doFinal(x);
   }
}
class Cipher<owner> {
 File<unique> encrypt(File<lent> x){
      [solveUnique(cipher,File) = {lent}]
      [File::unique → UNIQUE]
      return new File<unique>();
 }
}
```



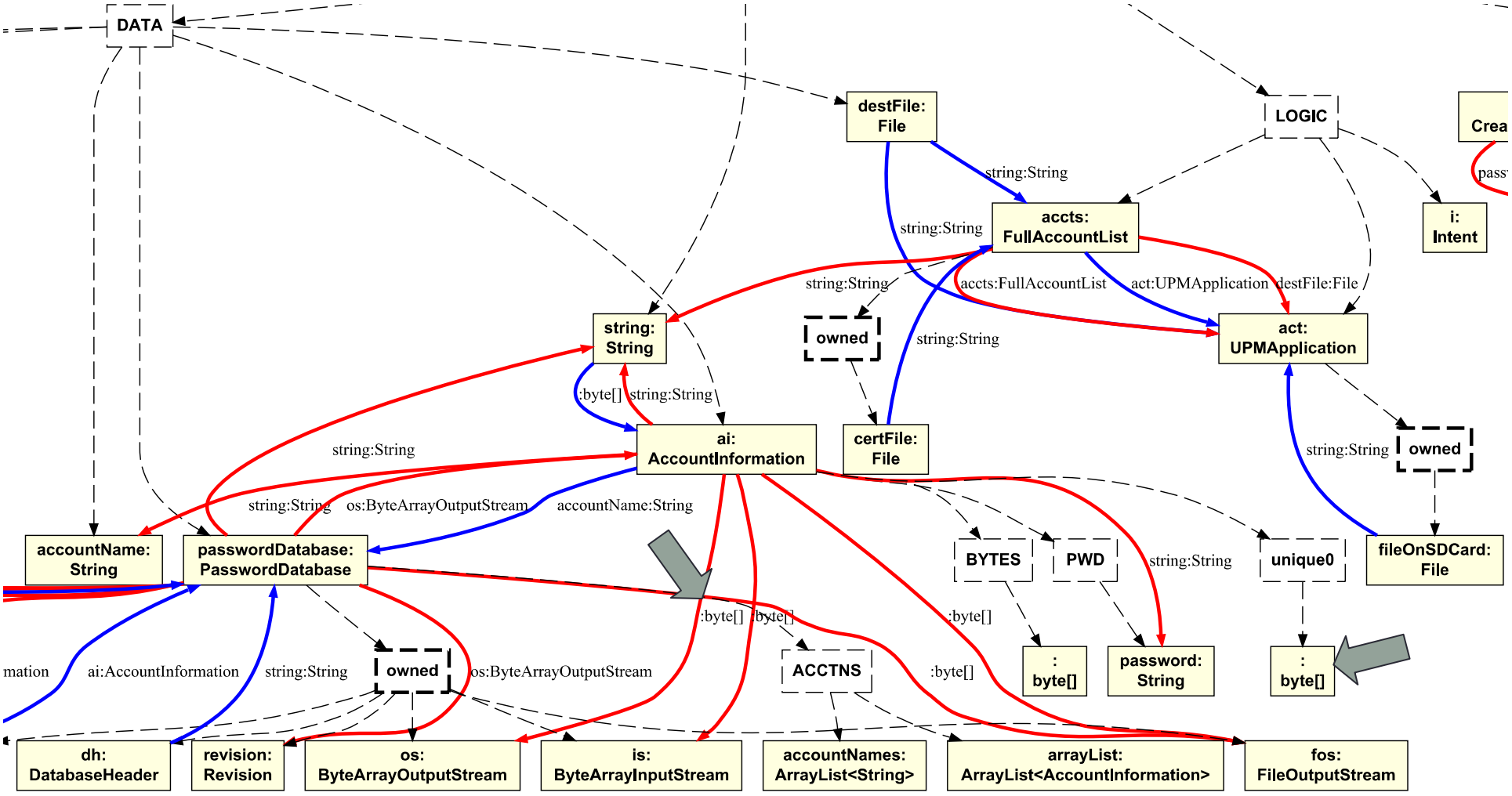
Extended example

- Universal Password Manager Application (UPMA) (4KLOC)
  - Encrypts and stores passwords in file
  - Android application
  - Annotate only code of UPMA, not Android framework
  - Follows State-Logic-Display architectural pattern

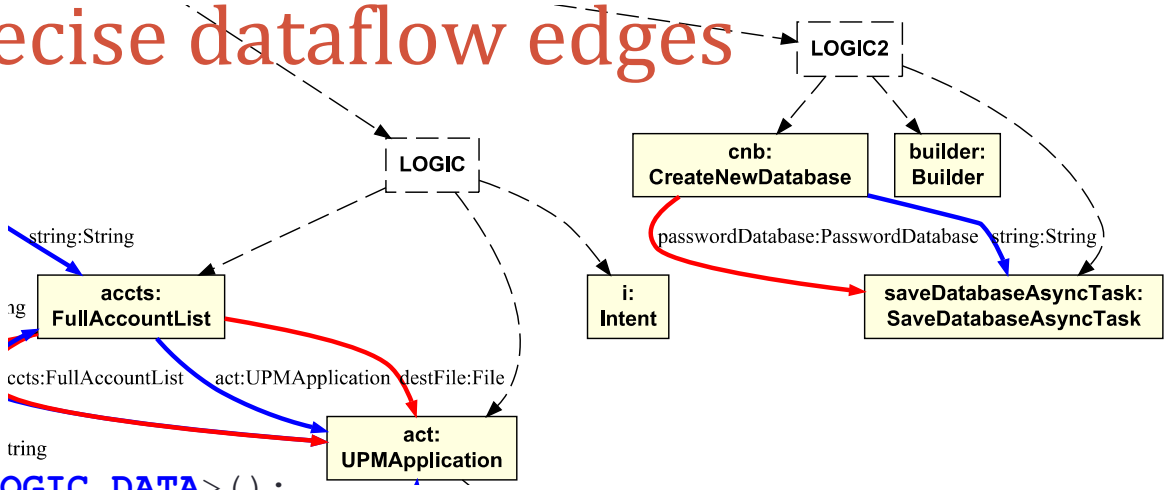
Distinguish between database file and encryption key file. Dataflow edge refers to database file



Flow object: UPMA transforms password to array of byte before encryption



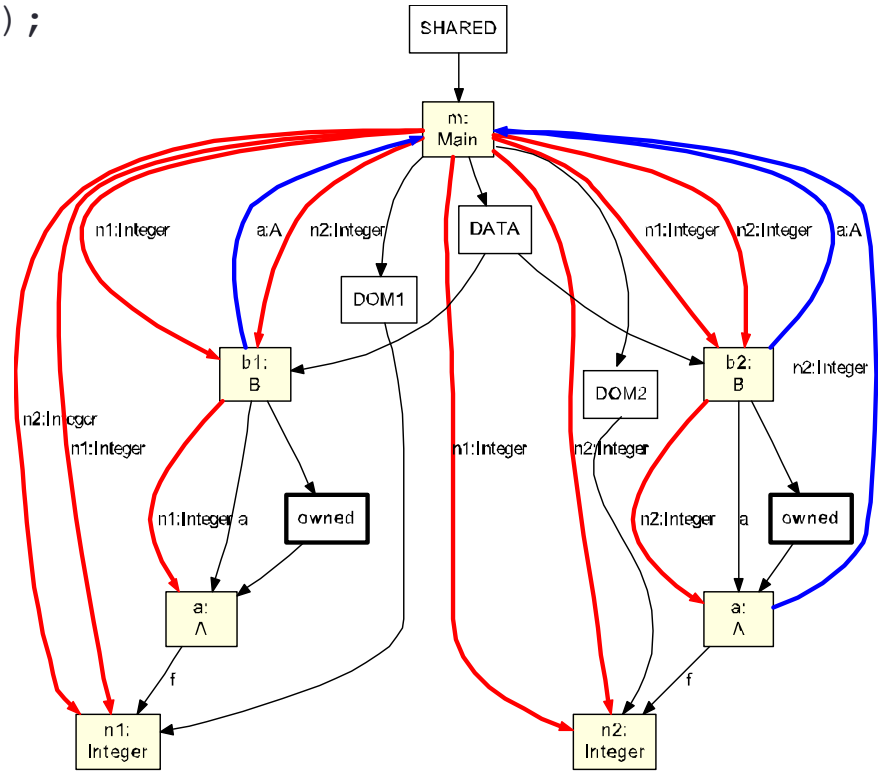
Discussion: More precise ownership types produce more precise dataflow edges




```
class Main{
 domain LOGIC2,UI,LOGIC,DATA;
 new UPMAApplication<LOGIC,UI,LOGIC,DATA>();
 new CreateNewDatabase<LOGIC2,UI,LOGIC,DATA>();
}
class UPMApplication<owner,U,L,D> extends Activity<…>{} //[owner→LOGIC]
class CreateNewDatabase<owner,U,L,D> extends Activity<…> {//[owner→LOGIC2]
 void onClick(){
  new SaveDatabaseAsynkTask<owner,U,L,D>(this);
 }
}
class SaveDatabaseAsynkTask<owner,U,L,D> … { //[owner→LOGIC2]
  Activity<owner,U,L,D> activity;
  SaveDatabaseAsynkTask (Activity<owner,U,L,D> a){
     this.activity = a; //avoid creating false positive dataflow edges
  }
}
```

Discussion: Imprecision may be due to overuse of lent and unique

```
class Main<owner>{
 domain DATA,DOM1,DOM2;
 void main() {
  Integer<unique> n1= new Integer(-1);
  B<DATA,DOM1> b1 = new B();
  b1.assign(n1);
  Integer<unique> n2 = new Integer(2);
  B<DATA,DOM2> b2 = new B();
  b2.assign(n2);
  Integer<lent> dest = b2.a.get();
  dest.compareTo(n1);
 }
}
```



Conclusion and future work

- ScoriaX extracts sound approximation of runtime architecture as abstract object graph
- Dataflow edges refer to objects
- Resolves lent and unique
- Evaluated analysis on Android application: can distinguish between database file and file that stores encryption keys

- Evaluate ScoriaX on more systems
- Find architectural flaws using object graphs [Vanciu and Abi-Antoun, ASE'13]
  - Finding Architectural Flaws in Android Apps Is Easy
  - [Vanciu and Abi-Antoun, SPLASH'13, Tool Demo] **Wed 3:30-4:15 pm**
- Use abstract object graphs for program comprehension
  - Finding the Missing Eclipse Perspective: the Runtime Perspective
  - [Giang and Abi-Antoun, SPLASH'13, Tool Demo] **Thu 10:30-11:15 am**

Extra slides

More details on Flow Graph – call-site context sensitive

- Edges (O1, x, B1) $\overset{a}{\rightsquigarrow}$ (O2, y, B2)
  - Edge label ***a*** tracks call-site context sensitivity:
    - ● direct assignment, field read
    - * field write
    - (i invocation of method *m* in the context of O
    -)i return from method *m* in the context of O
- Properties of FG
  - call-site context sensitive
  - domain-sensitive
  - flow-insensitive

Related Work

- Value flow and points-to analyses
  - Object sensitivity [Milanova et al. TSE'05] [Liu, Thesis'10]
  - Type Sensitivity [Smaragdakis et al. PLDI'11]

- Extraction of object graph
  - Flat object graph [Jackson and Waingold, TSE'01] [Spiegel, Thesis'02]
  - Dataflow edges (between classes) that refer to objects [Lienhard et al. COMLAN'09]
  - Ownership object graph with points-to edges [Abi-Antoun and Aldrich, OOPSLA'09]
  - Abstract Object Heaps [Marron et al. TSE'13]