جامعة نيويورك أبوظبي

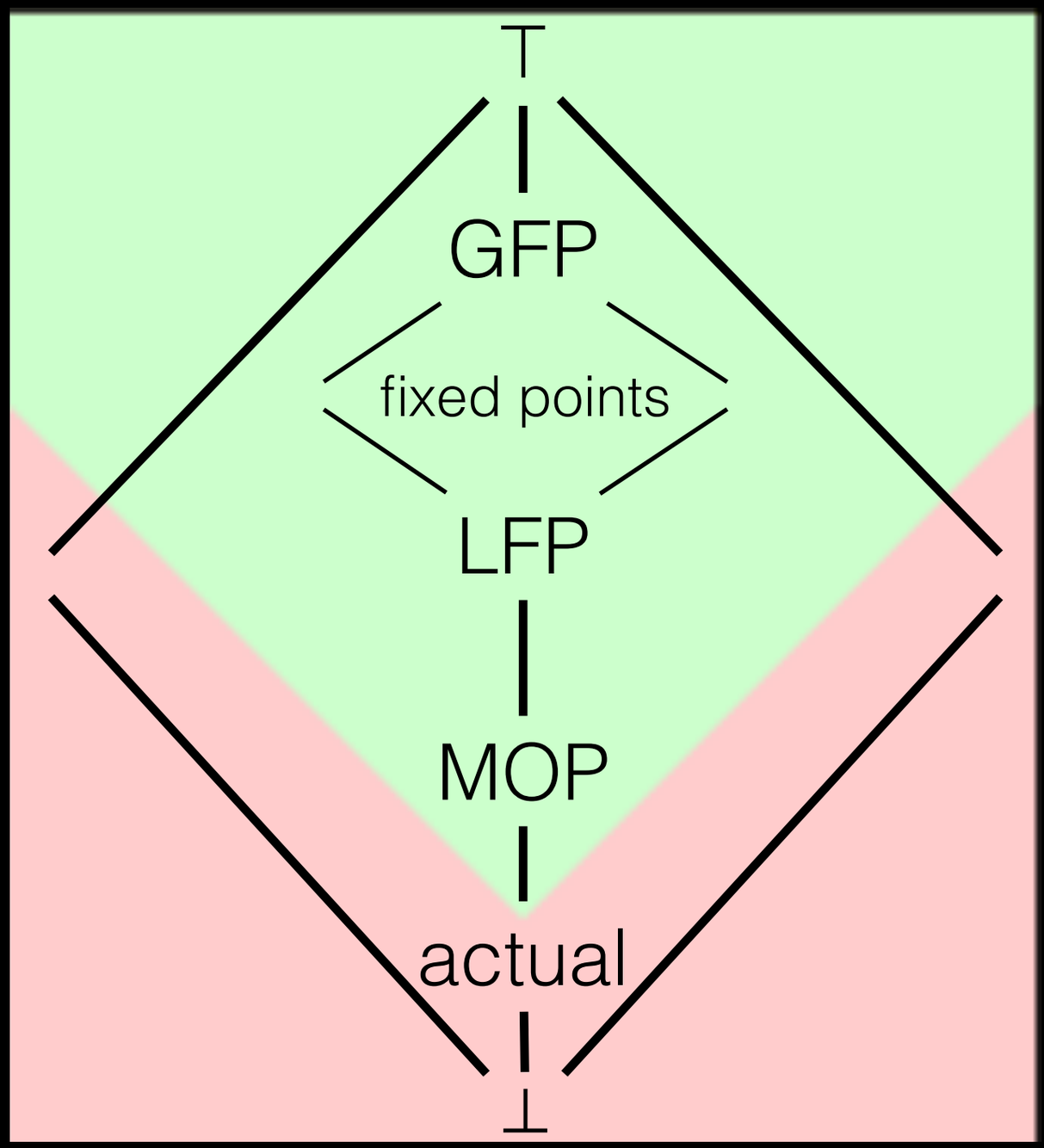
NYU ABU DHABI

Call Graph Construction

CS-UH 3260
Static Program Analysis

Karim Ali
@karimhamdanali

Previously: MOP ⊑ LFP



- Every solution S ⊒ *actual* is "safe" (i.e., sound).
- MOP ⊒ *actual*
- LFP ⊒ MOP
- A flow function `f` is distributive if `f(x) ⊔ f(y) = f(x ⊔ y)`
- If all flow functions are distributive, then LFP = MOP
- Initializing using ⊤ instead of ⊥ causes earlier termination, but yields more imprecise fixed-point

Previously: Designing a Dataflow Analysis

1. Forwards or backwards?
2. What is the domain of the analysis info (lattice elements)?
3. What's the effect a statement has on the info? (flow functions)
4. What values hold at program entry points?
5. What's the initial estimate? It's the unique element $\bot$ such that $\forall_x \bot \sqcup x = x$.
6. How to merge info? (join operator)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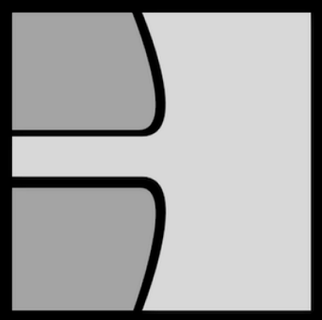


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framework

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AbsInt

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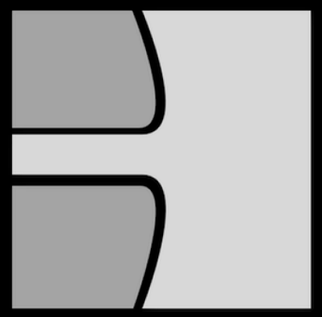

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Call Graph


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Sources
Sinks


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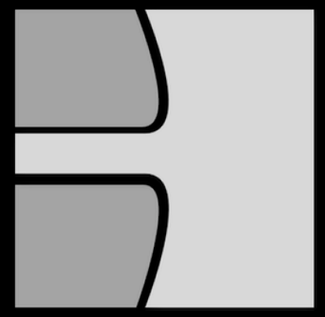



AbsInt

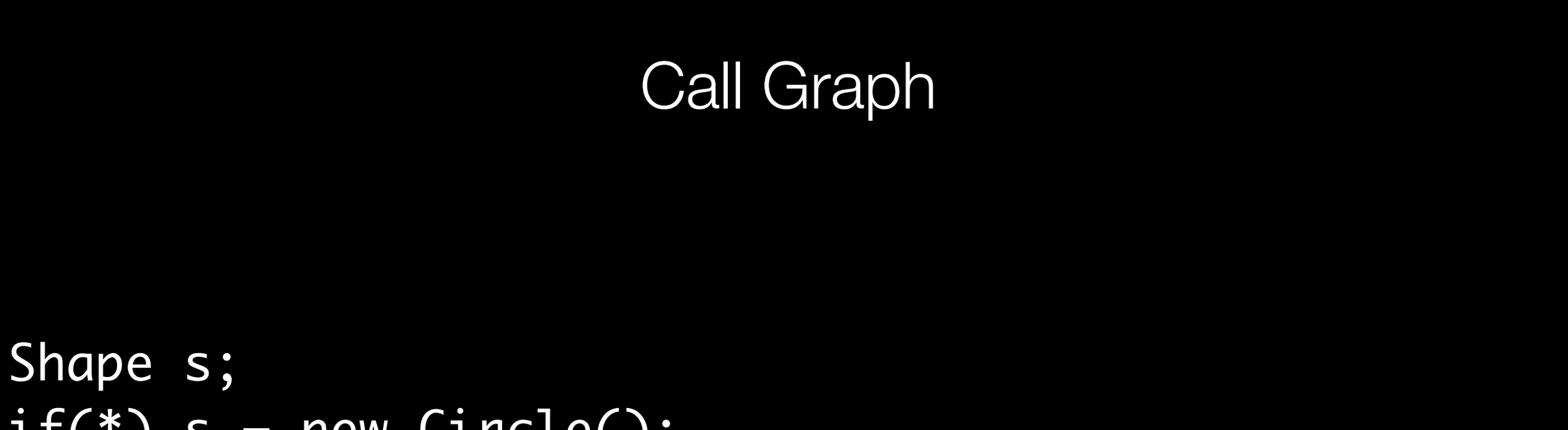

FORTIFY


CHECKER
framework

… so what is a Call Graph?

Call Graph

```
Shape s;
if(*) s = new Circle();
else s = new Square();
```



Call Graph

```
Shape s;
if(*) s = new Circle();
else s = new Square();
s.draw();
```

```
class Circle extends Shape
{ void draw() { ... } }

class Square extends Shape
{ void draw() { ... } }
```

required by every inter-procedural analysis

Let’s build a Call Graph

```
public class Main {
  public static void main(String[] args) {
    Shape s;
    if (args.length > 2) s = new Circle();
    else s = new Square();

    s.draw();
  }
}

abstract class Shape {
  abstract void draw();
}

class Circle extends Shape {
  void draw() { ... }
}

class Square extends Shape {
  void draw() { ... }
}
```

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```

Main.main()

Let’s build a Call Graph

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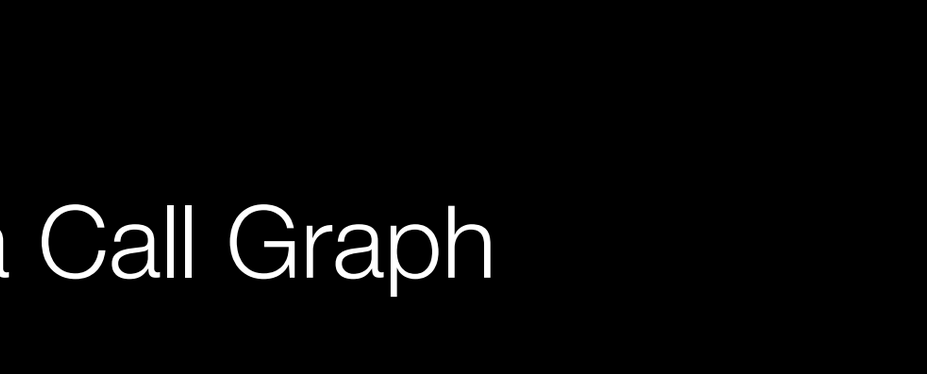

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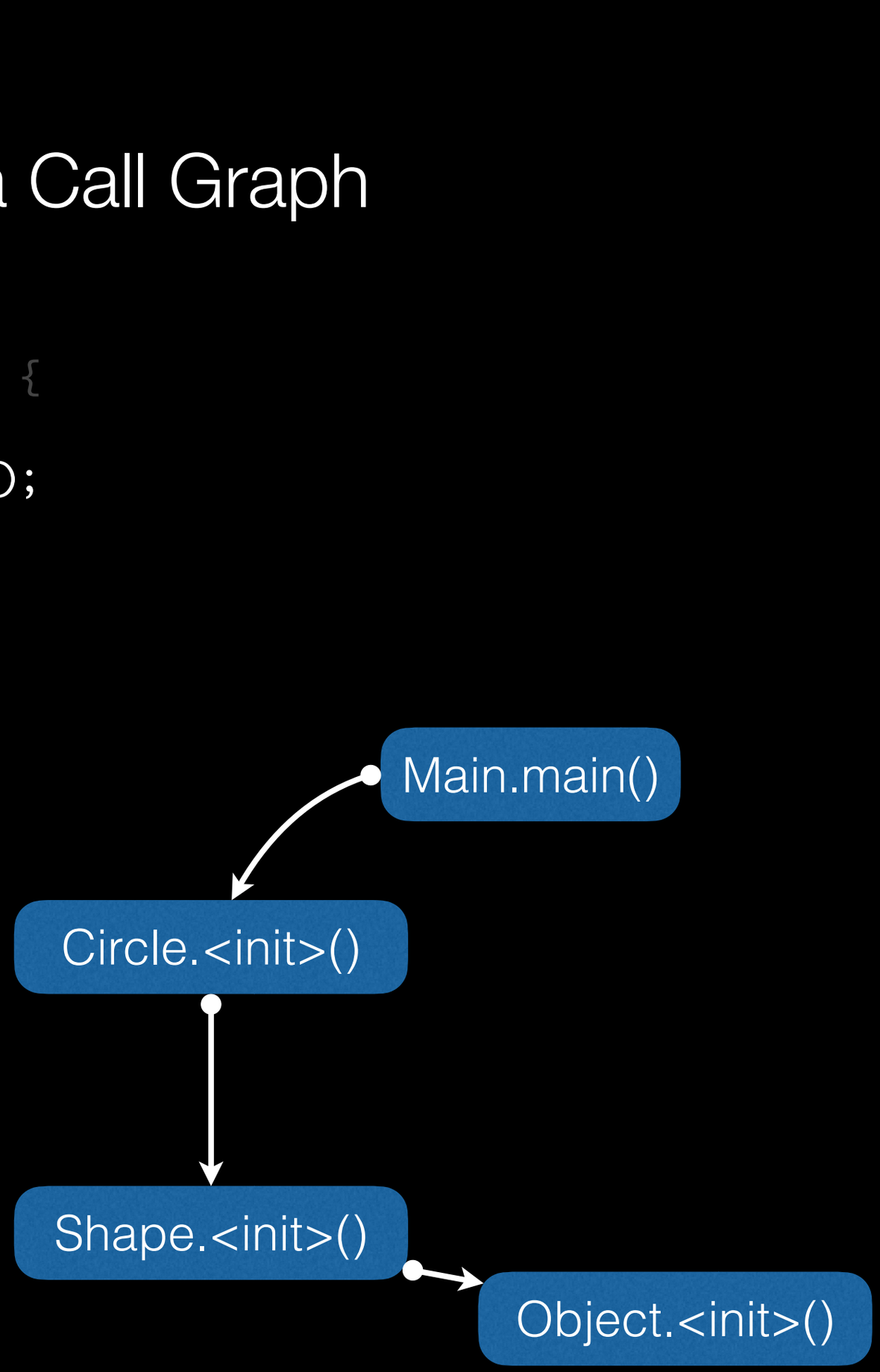

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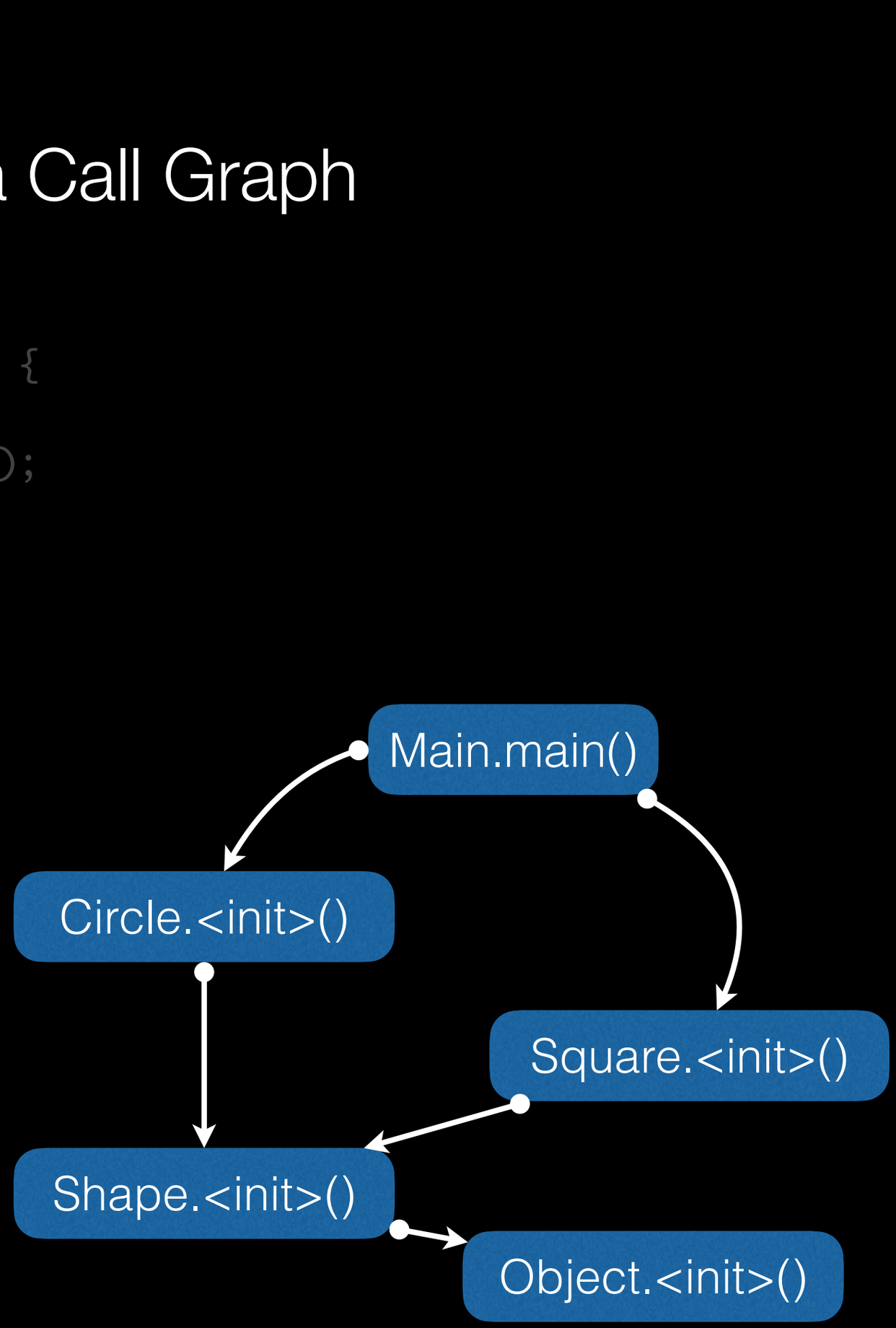

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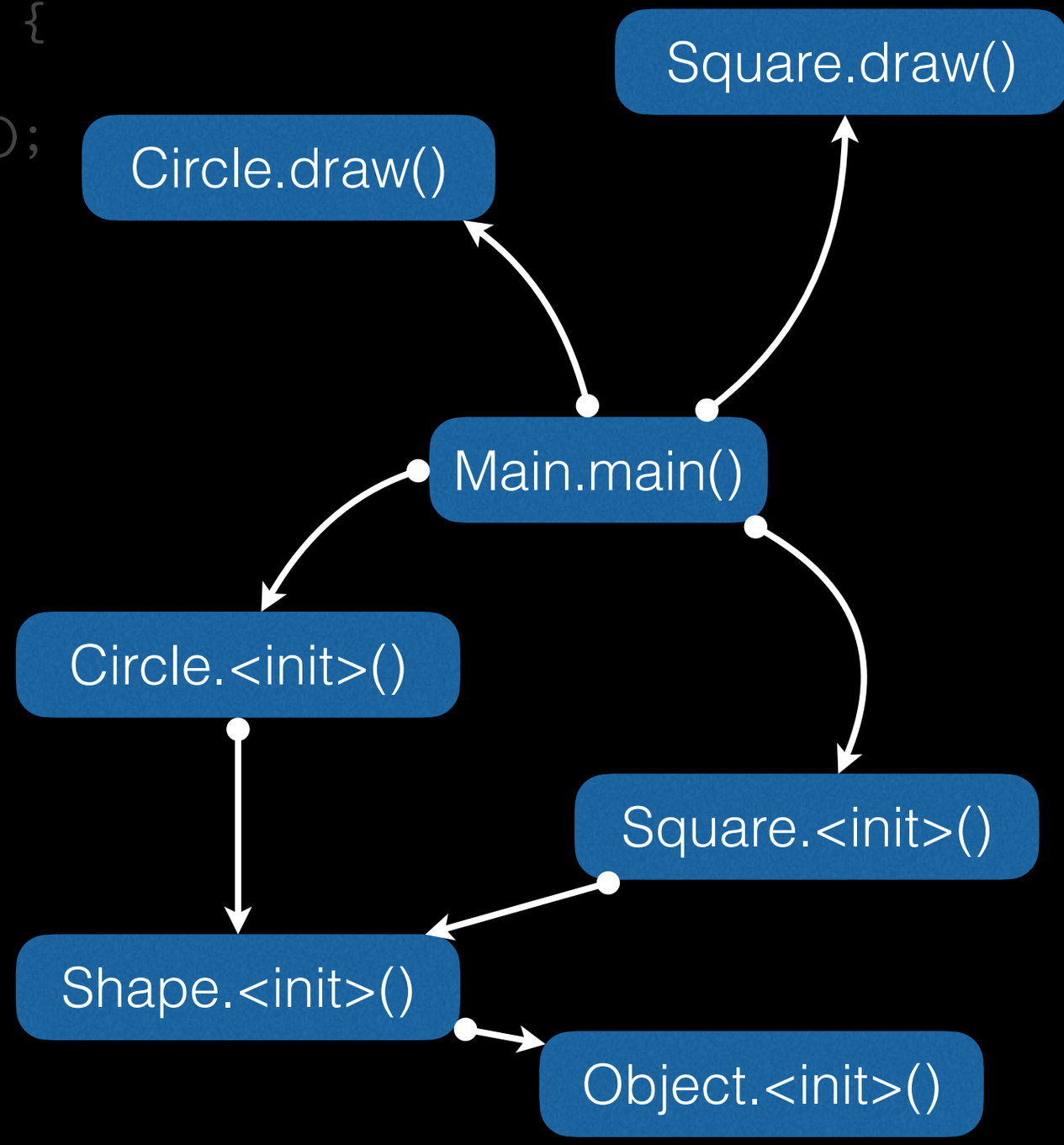
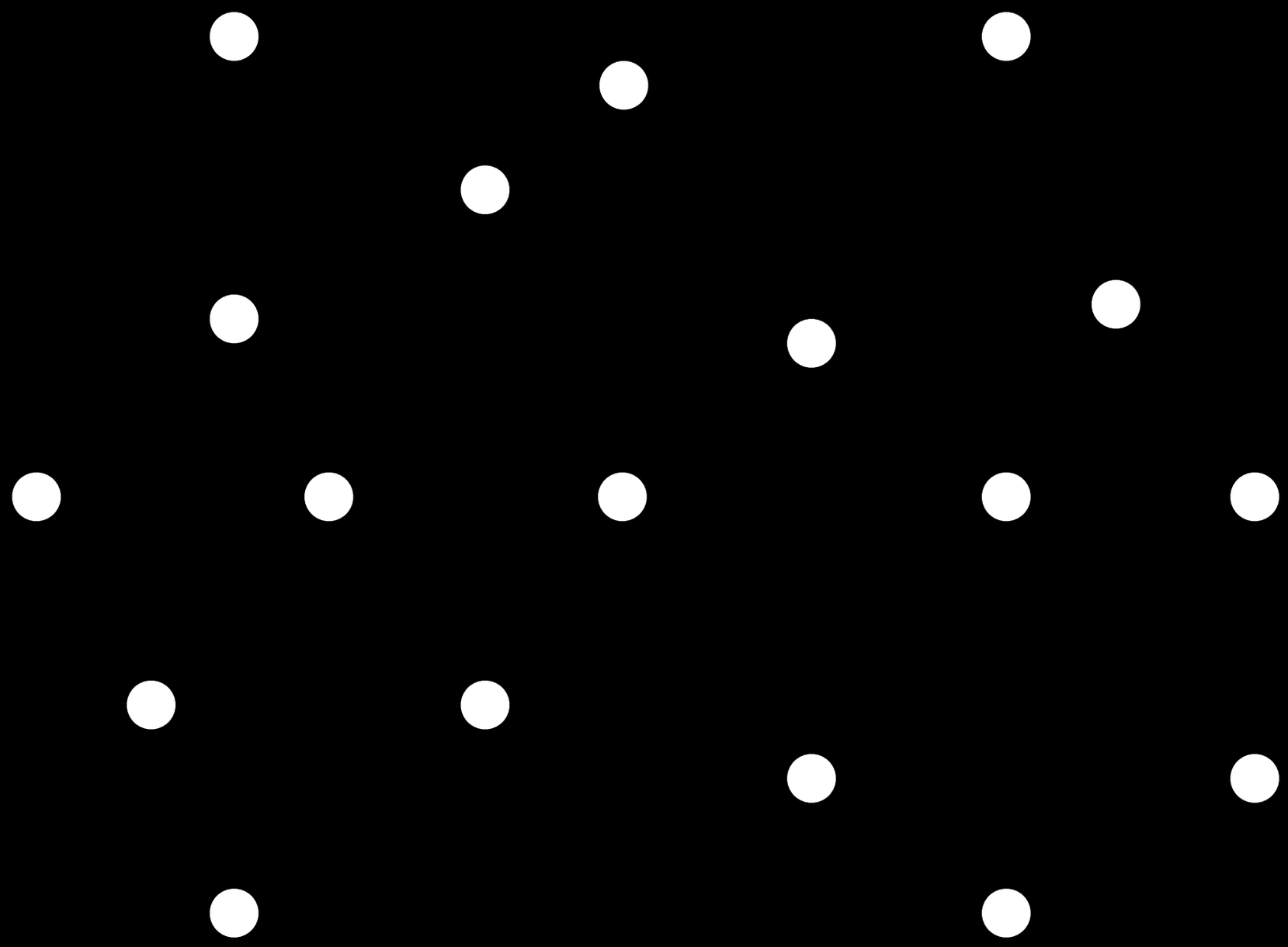
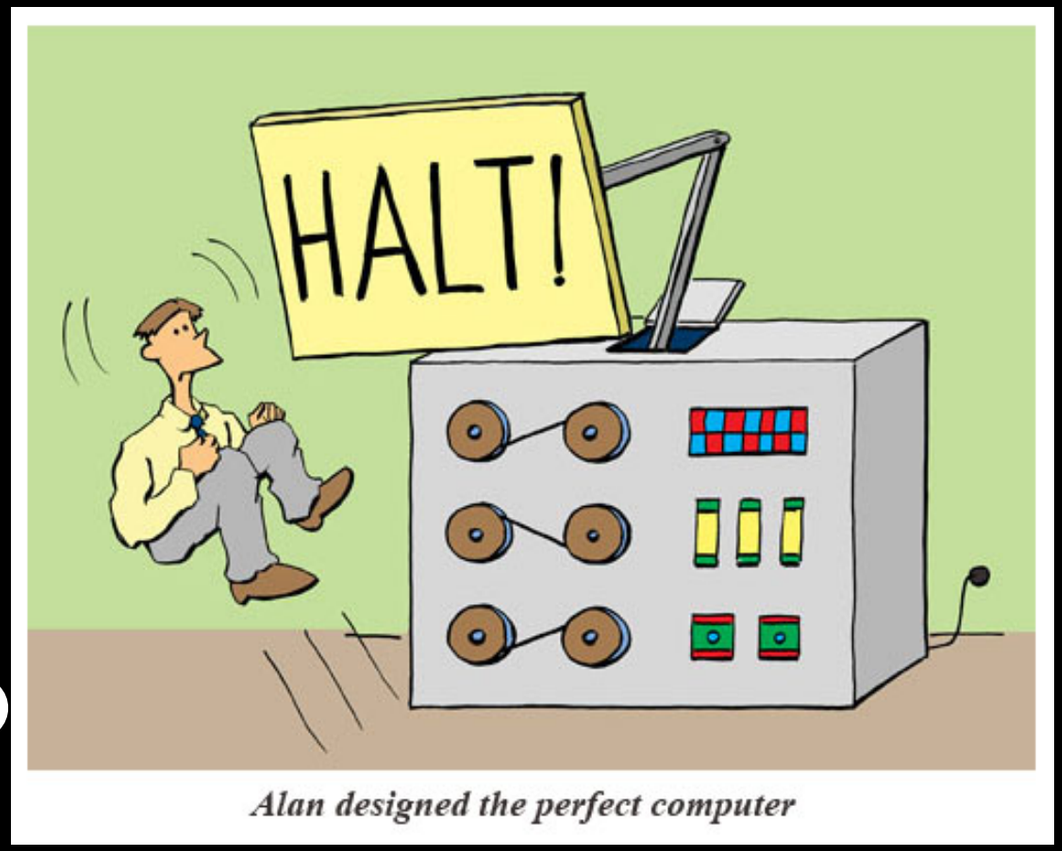


but … polymorphism!

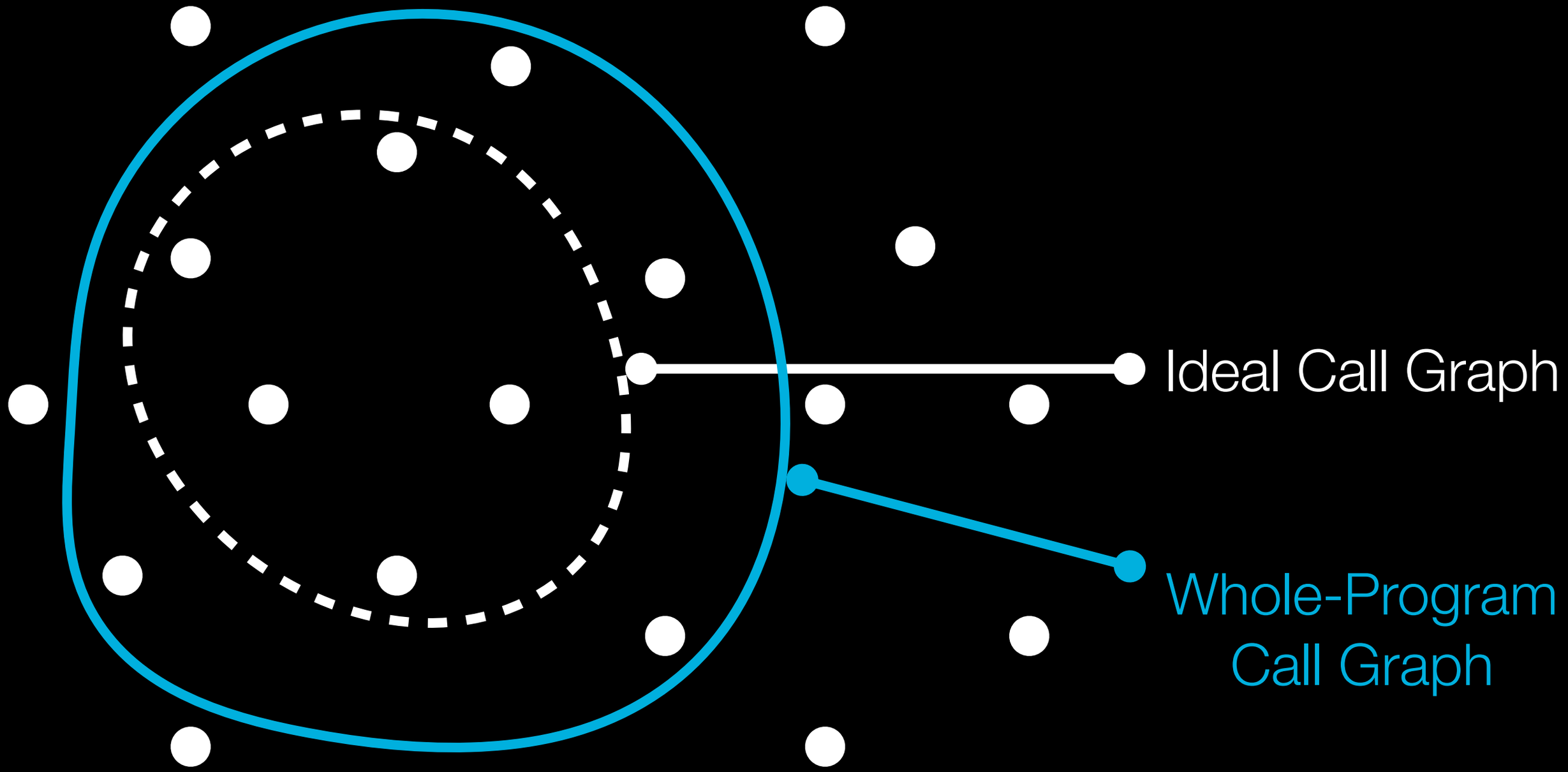


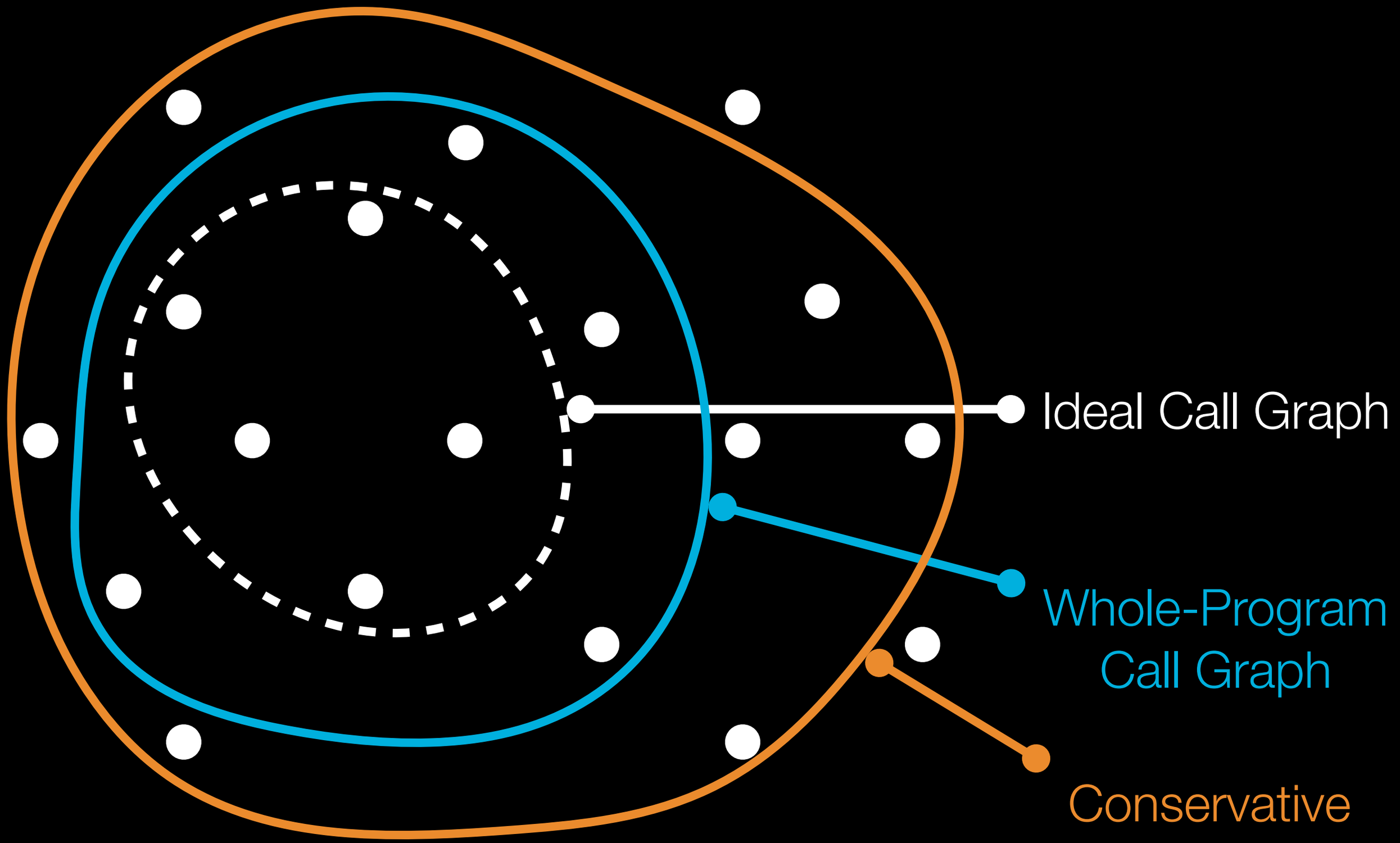


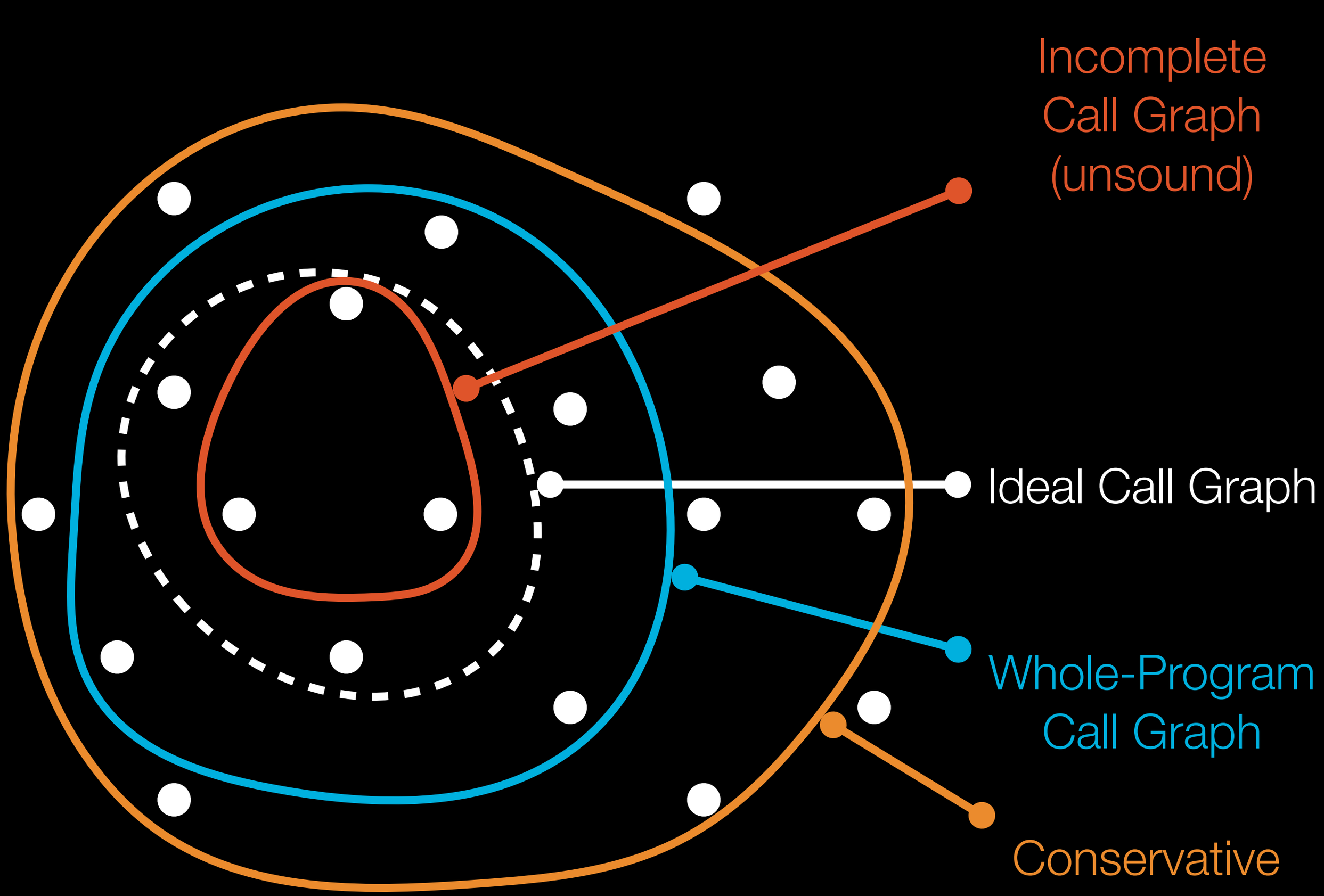
Alan designed the perfect computer

Ideal Call Graph

Image: CooperToons


Ideal Call Graph
Whole-Program
Call Graph


Ideal Call Graph
Whole-Program
Call Graph
Conservative
Call Graph
(highly imprecise)


Incomplete
Call Graph
(unsound)
Ideal Call Graph
Whole-Program
Call Graph
Conservative
Call Graph
(highly imprecise)

CG Algorithms

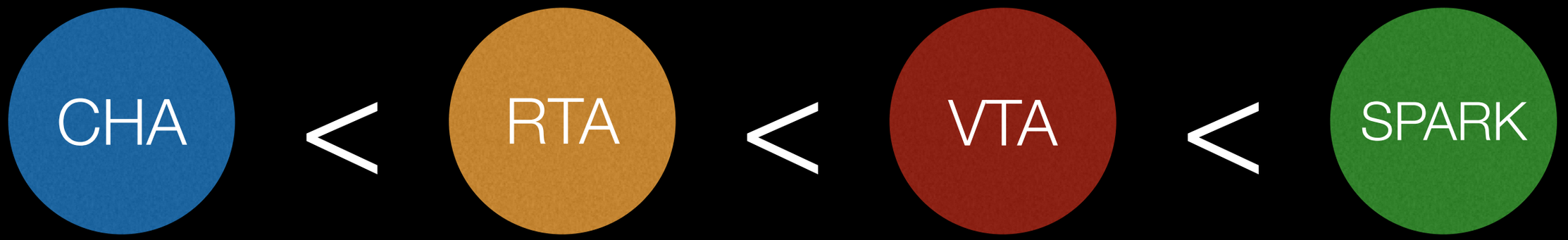
CHA

RTA

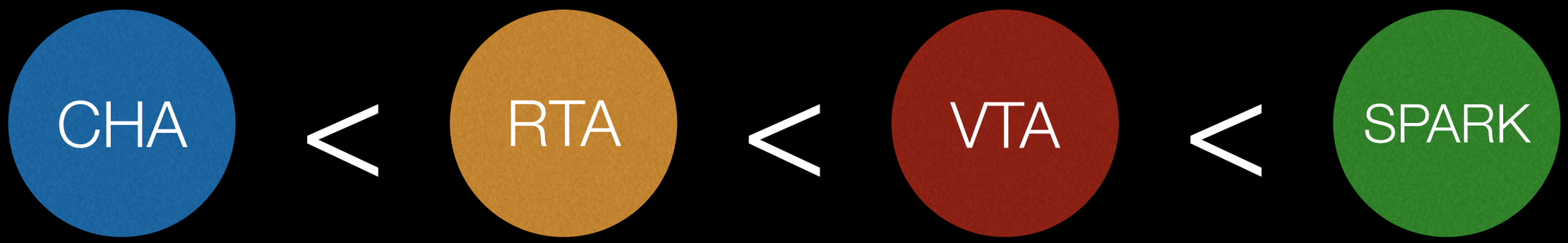
VTA

SPARK

CG Algorithms



CG Algorithms



Class Hierarchy Analysis

```
public static void main(String[] args) {
  Collection c = makeCollection(args[0]);
  c.add("elem");
}
```

```
static Collection makeCollection(String s) {
  if(s.equals("list")) {
    return new ArrayList();
  } else {
    return new HashSet();
  }
}
```

Jeffrey Dean, David Grove, and Craig Chambers. 1995. Optimization of Object-Oriented Programs Using Static Class Hierarchy Analysis. In *Proceedings of the 9th European Conference on Object-Oriented Programming* (ECOOP '95), 77-101.

Class Hierarchy Analysis

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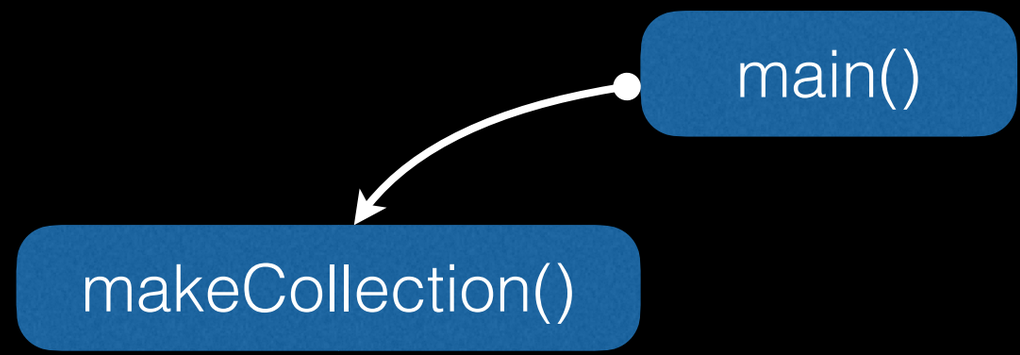


```
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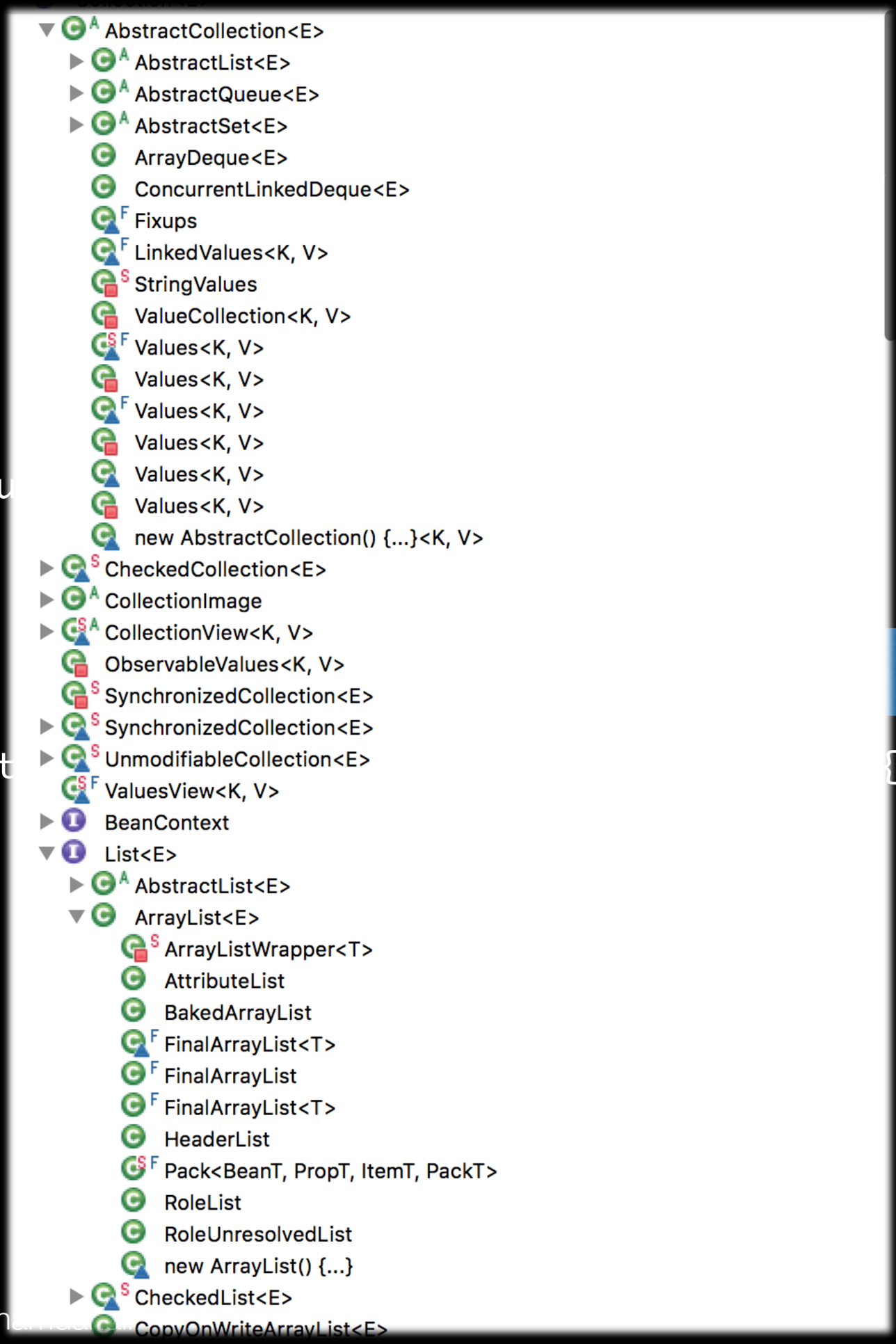
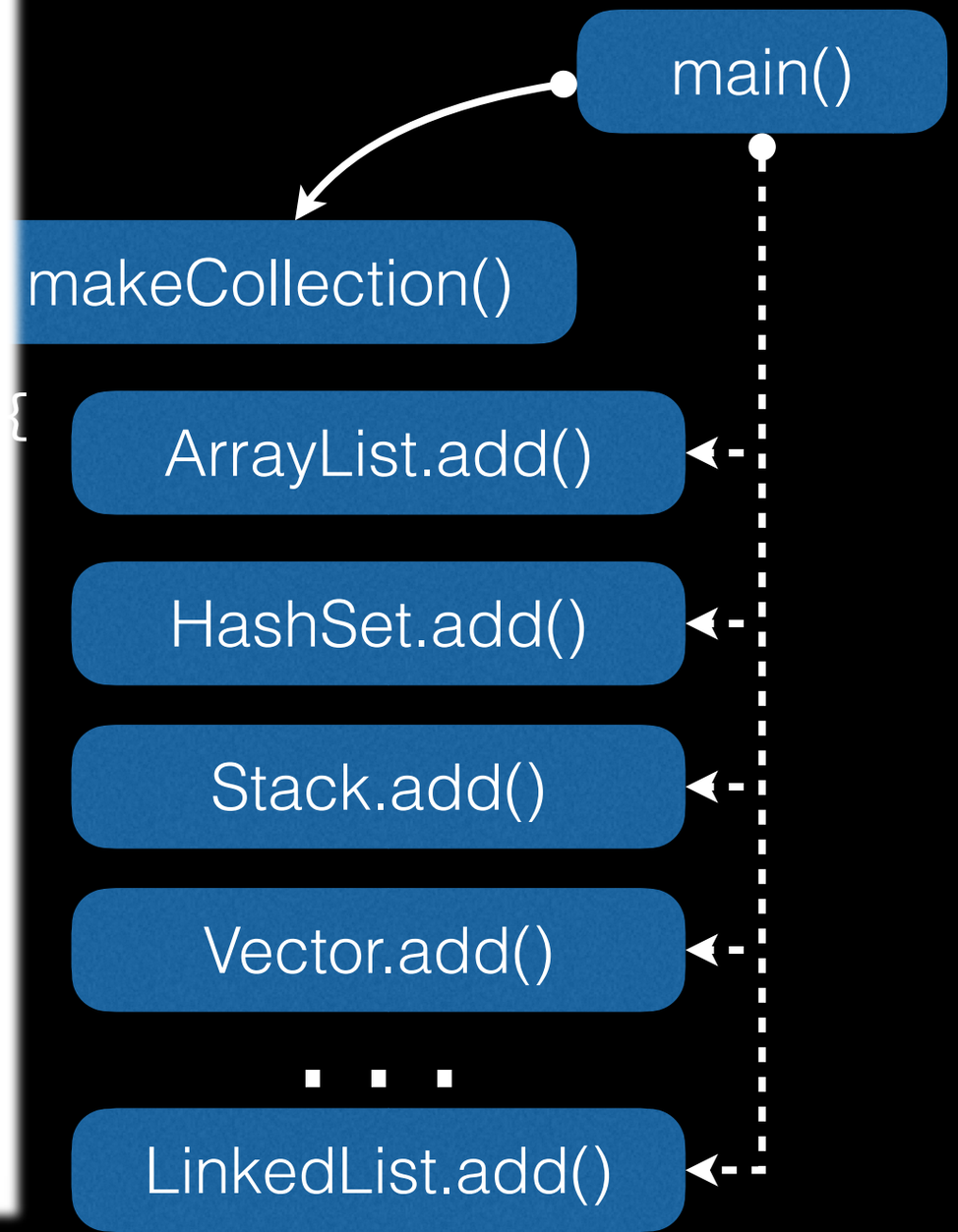
  }
}
```

Analysis


AbstractCollection<E>
AbstractList<E>
AbstractQueue<E>
AbstractSet<E>
ArrayDeque<E>
ConcurrentLinkedDeque<E>
Fixups
LinkedValues<K, V>
StringValues
ValueCollection<K, V>
Values<K, V>
Values<K, V>
Values<K, V>
Values<K, V>
Values<K, V>
Values<K, V>
new AbstractCollection() {...}<K, V>
CheckedCollection<E>
CollectionImage
CollectionView<K, V>
ObservableValues<K, V>
SynchronizedCollection<E>
SynchronizedCollection<E>
UnmodifiableCollection<E>
ValuesView<K, V>
BeanContext
List<E>
AbstractList<E>
ArrayList<E>
ArrayListWrapper<T>
AttributeList
BakedArrayList
FinalArrayList<T>
FinalArrayList
FinalArrayList<T>
HeaderList
Pack<BeanT, PropT, ItemT, PackT>
RoleList
RoleUnresolvedList
new ArrayList() {...}
CheckedList<E>
CopyOnWriteArrayList<E>


main()
makeCollection()
ArrayList.add()
HashSet.add()
Stack.add()
Vector.add()
. . .
LinkedList.add()

Class Hierarchy Analysis

- ✅ Very simple
- ✅ Sound/correct call graph
- ✅ Pretty fast to compute
- ✅ Only input is class hierarchy

- ❌ Very imprecise (a lot of edges will never occur at runtime)

Rapid Type Analysis

nalysis

- AbstractCollection<E>
  - AbstractList<E>
  - AbstractQueue<E>
  - AbstractSet<E>
  - ArrayDeque<E>
  - ConcurrentLinkedDeque<E>
  - Fixups
  - LinkedValues<K, V>
  - StringValues
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  - Values<K, V>
  - Values<K, V>
  - Values<K, V>
  - Values<K, V>
  - Values<K, V>
  - Values<K, V>
  - new AbstractCollection() {...}<K, V>
- CheckedCollection<E>
- CollectionImage
- CollectionView<K, V>
- ObservableValues<K, V>
- SynchronizedCollection<E>
- SynchronizedCollection<E>
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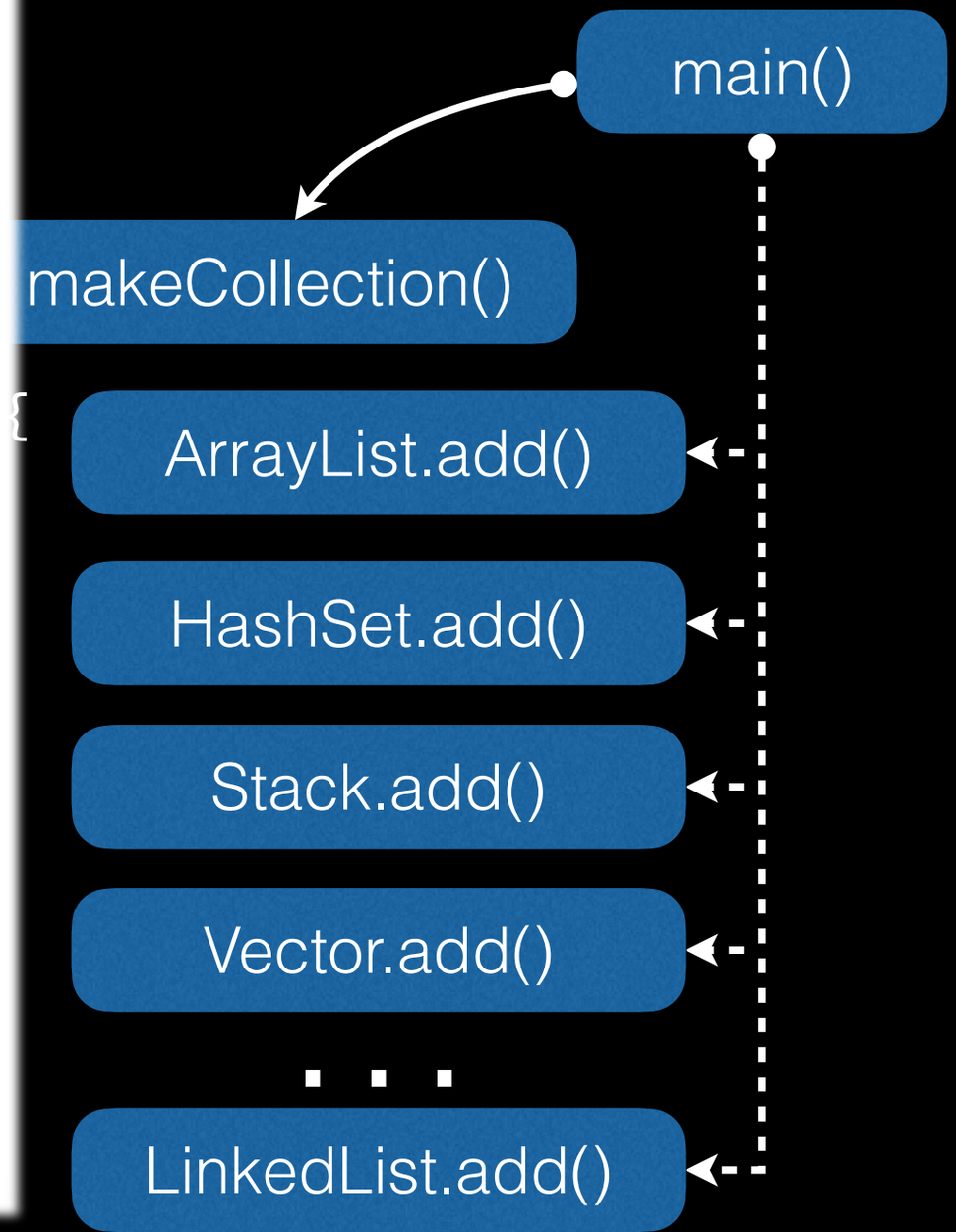

Rapid Type Analysis

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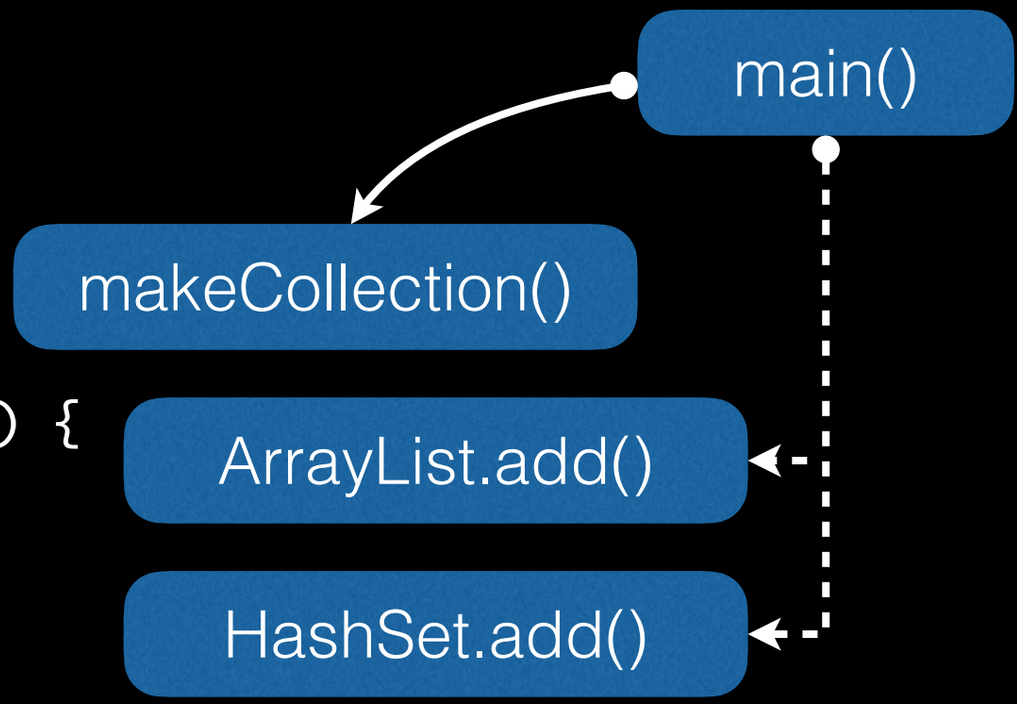


David F. Bacon and Peter F. Sweeney. 1996. Fast static analysis of C++ virtual function calls. In Proceedings of the 11th ACM SIGPLAN conference on Object-Oriented Programming, Systems, Languages, and Applications (OOPSLA '96), 324-341.

Rapid Type Analysis

- “Rapid”
- Still sound/correct call graph
- Call graph is much smaller than CHA
- Doesn't handle variable assignments

Variable Type Analysis

Variable Type Analysis

Main Idea: propagate **types** from allocation sites to potential **variable references**

Vijay Sundaresan, Laurie Hendren, Chrislain Razafimahefa, Raja Vallée-Rai, Patrick Lam, Etienne Gagnon, and Charles Godin. 2000. Practical virtual method call resolution for Java. In Proceedings of the 15th ACM SIGPLAN conference on Object-Oriented Programming, Systems, Languages, and Applications (OOPSLA '00), USA, 264-280.

Variable Type Analysis

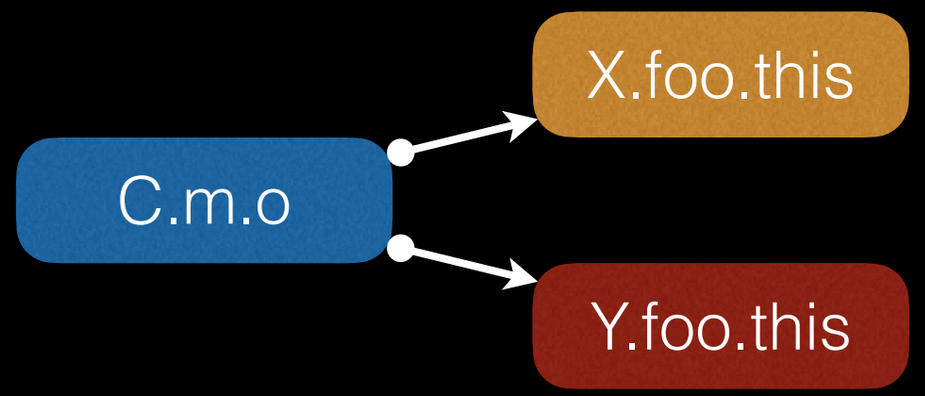
1. Start with a pre-computed call graph (e.g., CHA)
2. Build type propagation graph
3. Collapse strongly-connected components (SCCs)
4. Propagate types along the final Directed Acyclic Graph (DAG)

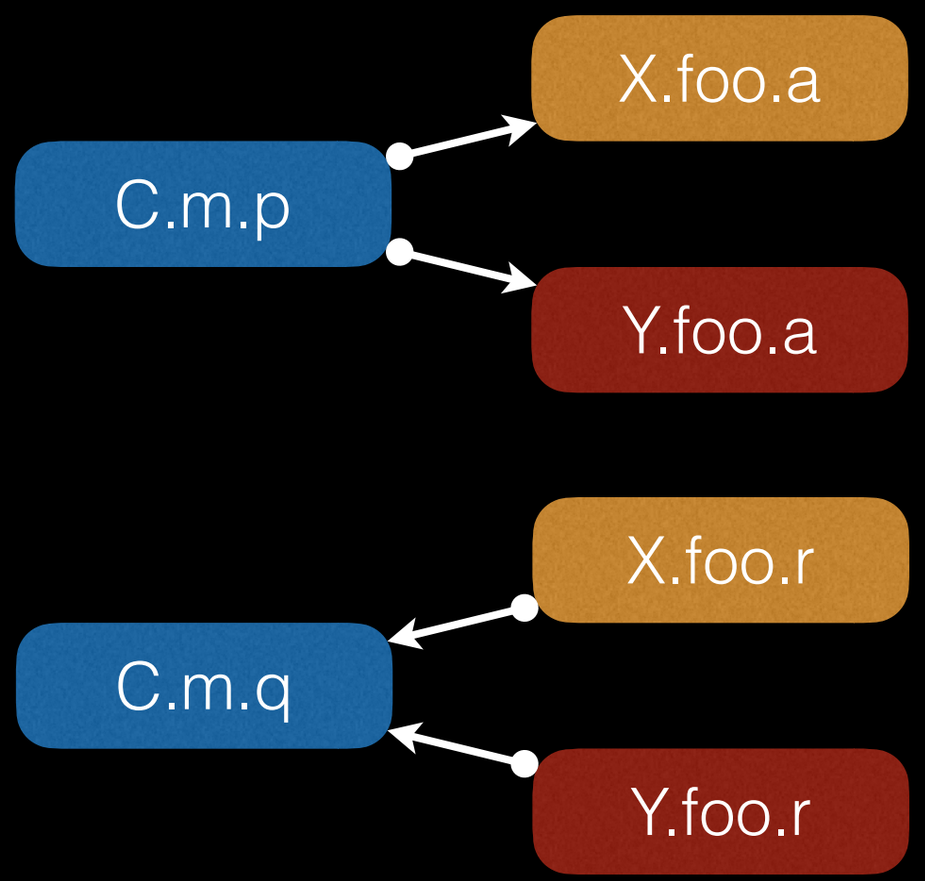
VTA - Step #1 … but why?

```
class X {
  D foo (A a){
    ...
    return(r);
  }
}

class Y {
  D foo (A a){
    ...
    return(r);
  }
}
```

```
class C {
  E m() {
    ...
    q = o.foo(p);
  }
}
```



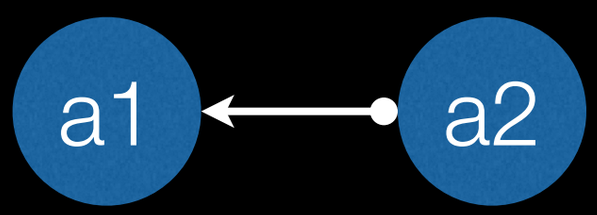


VTA - Step #2

```
A a1, a2, a3;
B b1, b3;
C c;


a1 = new A();
a2 = new A();
b1 = new B();
b3 = new B();
c = new C();

a1 = a2;
a3 = a1;
a3 = b3;
b3 = (B) a3;
b1 = c;
```



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a1 = new A();
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```

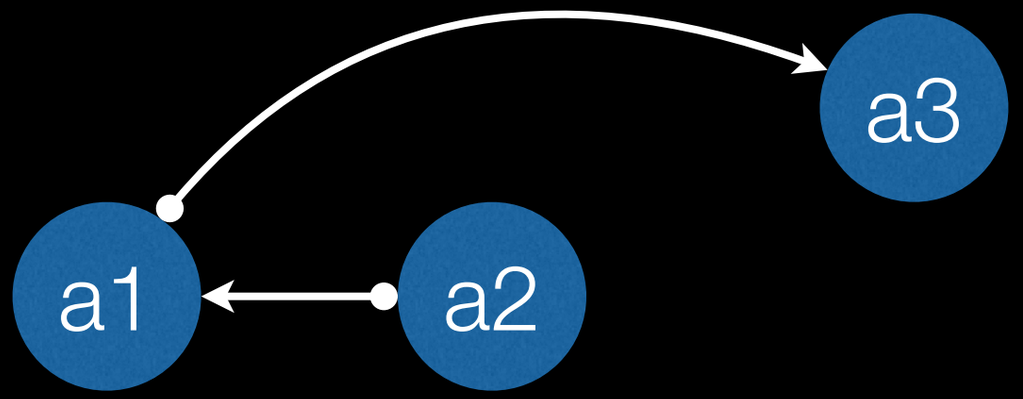

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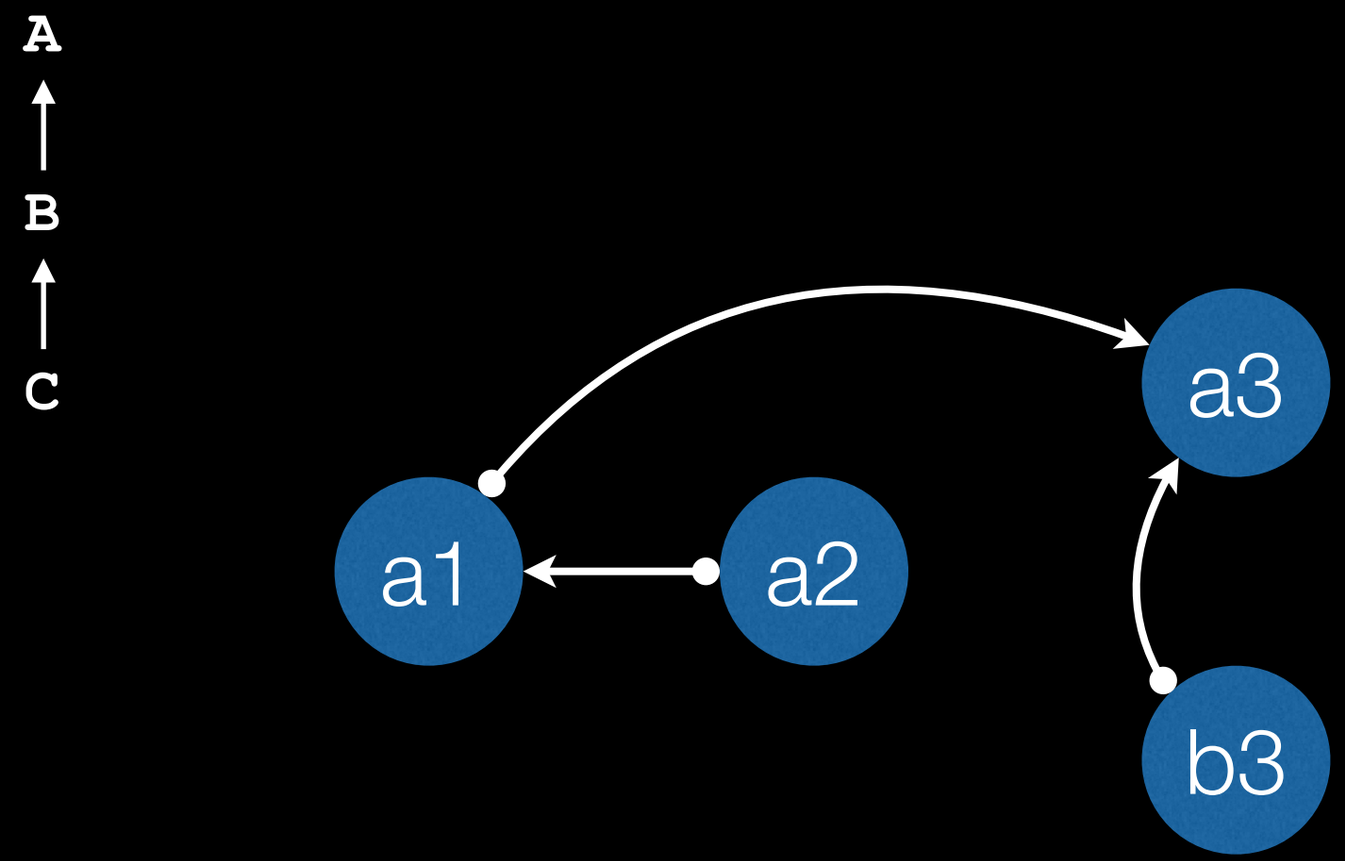

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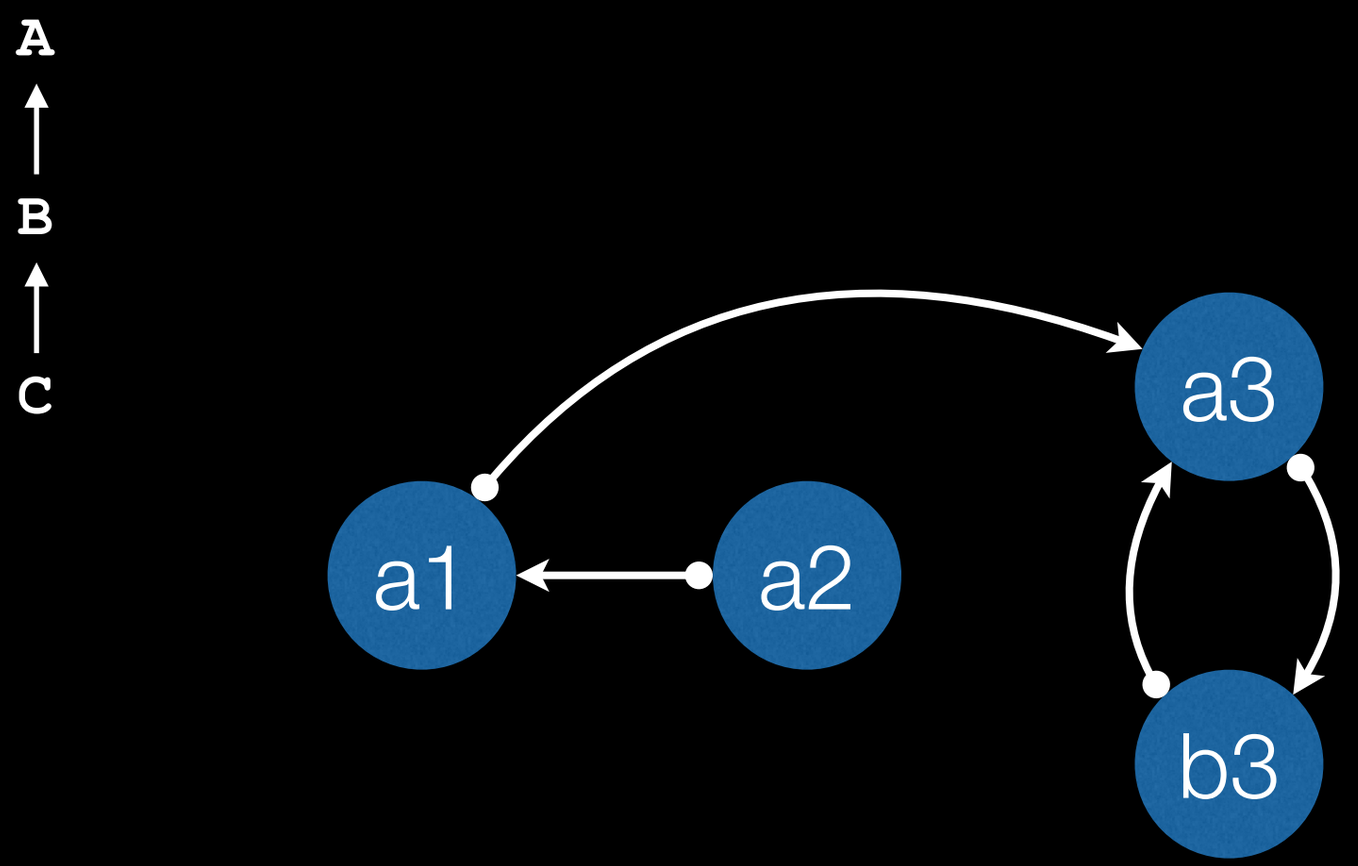
```



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a3 = b3;
b3 = (B) a3;
b1 = c;
```
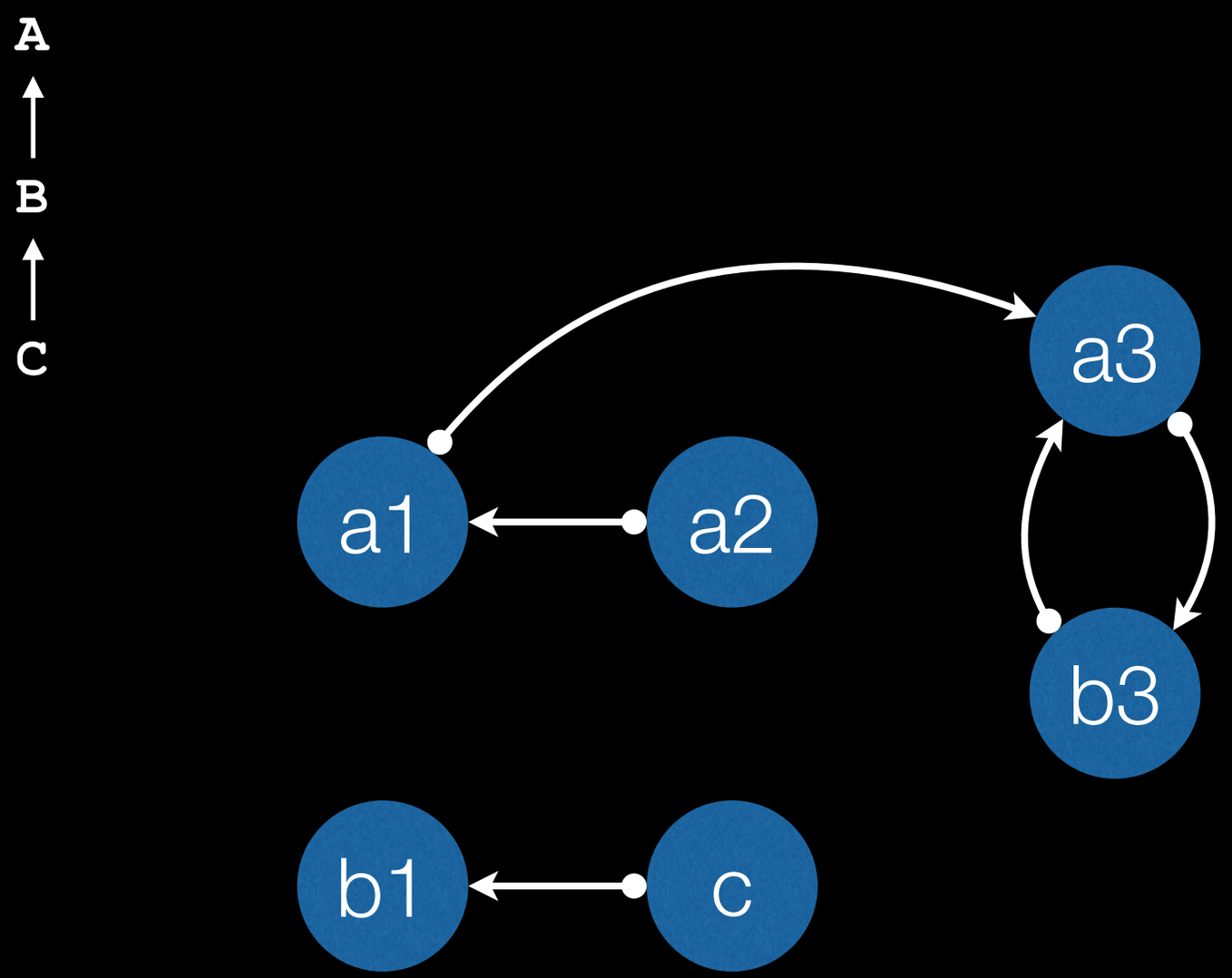
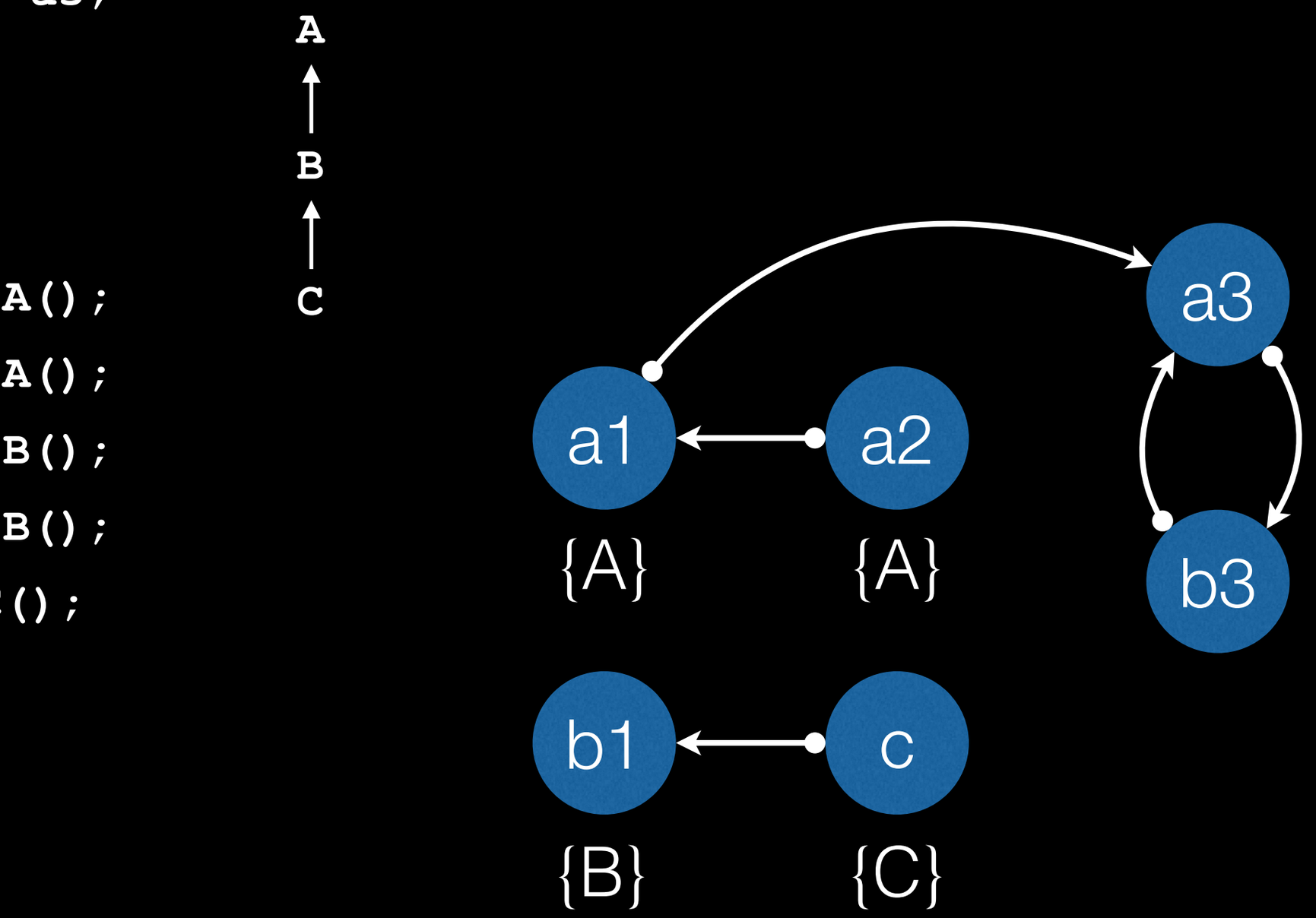



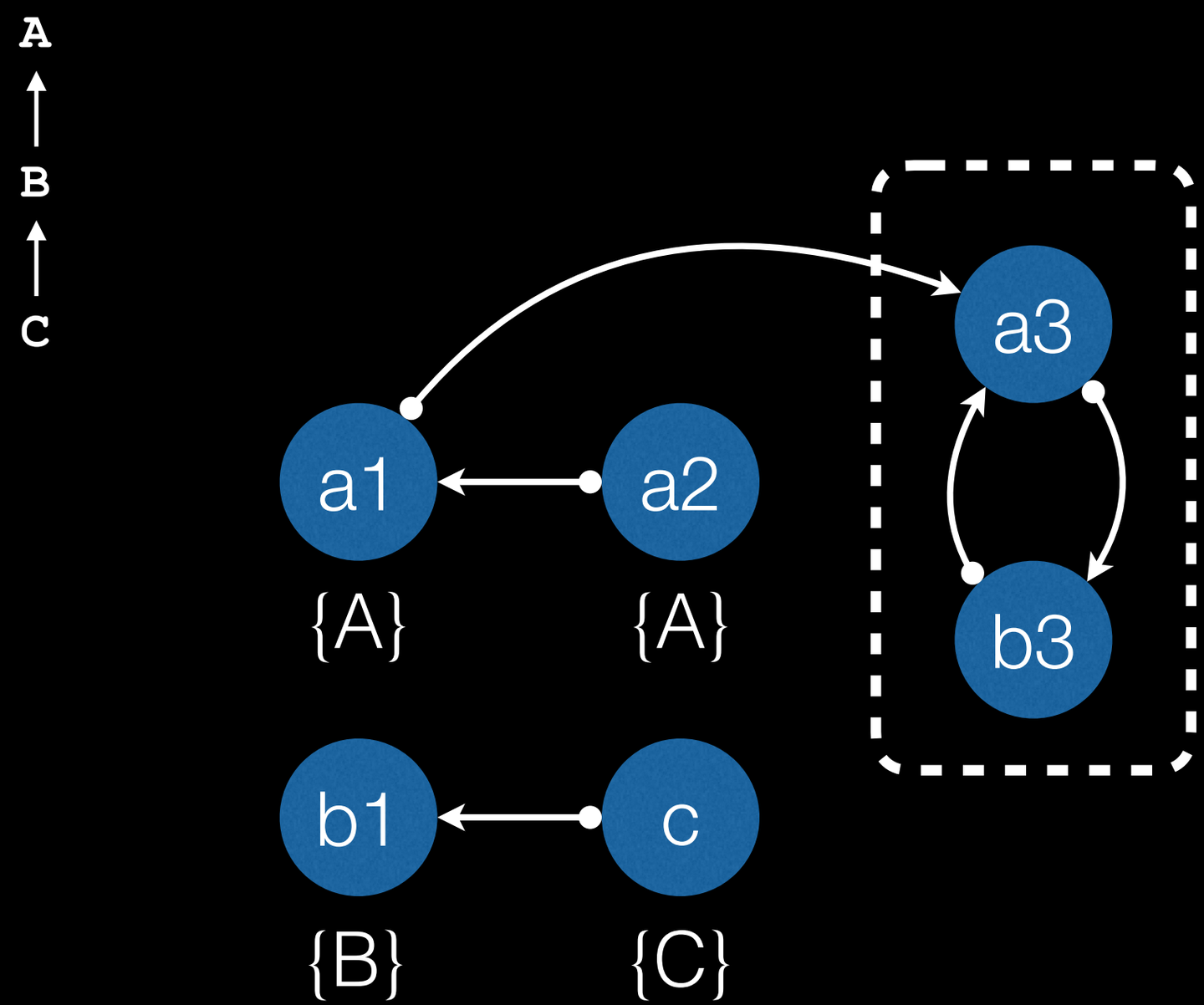
VTA - Step #2

```
A a1, a2, a3;
B b1, b3;
C c;

a1 = new A();
a2 = new A();
b1 = new B();
b3 = new B();
c = new C();

a1 = a2;
a3 = a1;
a3 = b3;
b3 = (B) a3;
b1 = c;
```



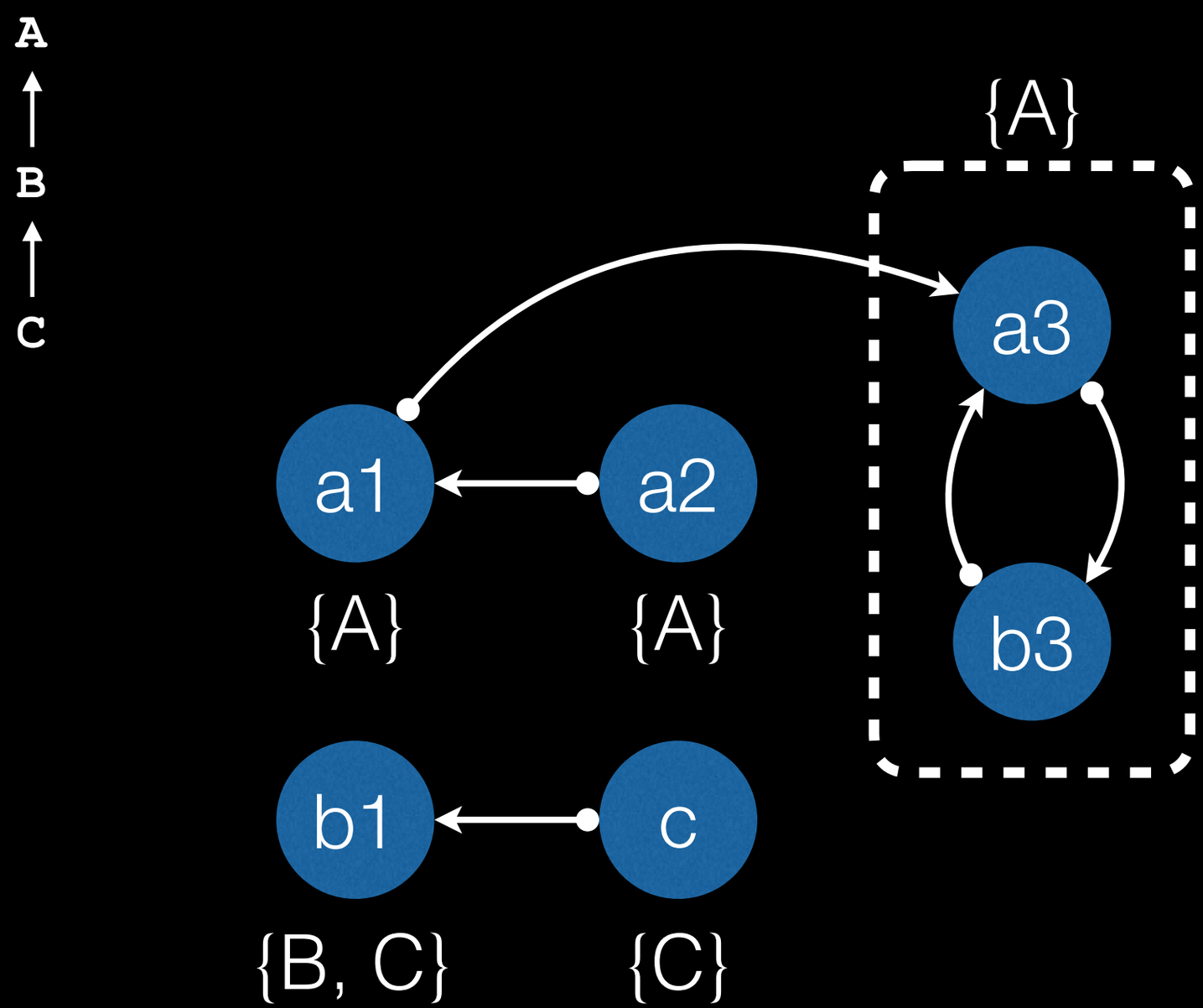
VTA - Step #3

```
A a1, a2, a3;
B b1, b3;
C c;

a1 = new A();
a2 = new A();
b1 = new B();
b3 = new B();
c = new C();

a1 = a2;
a3 = a1;
a3 = b3;
b3 = (B) a3;
b1 = c;
```



VTA - Step #4

```
A a1, a2, a3;
B b1, b3;
C c;

a1 = new A();
a2 = new A();
b1 = new B();
b3 = new B();
c = new C();

a1 = a2;
a3 = a1;
a3 = b3;
b3 = (B) a3;
b1 = c;
```



Variable Type Analysis

- ✅ More precise than RTA
- ✅ Relatively fast
- ❌ Requires an initial CG
- ❌ Field-based

SPARK

SPARK

Main Idea: propagate **information** along edges of **pointer assignment graph (PAG)**

Ondřej Lhoták and Laurie Hendren. 2003. Scaling Java points-to analysis using SPARK. In *Proceedings of the 12th international conference on Compiler Construction* (CC'03), 153-169.

SPARK - PAG

Nodes

Alloc new A

SPARK - PAG

Nodes

Alloc new A

Var p

SPARK - PAG

Nodes

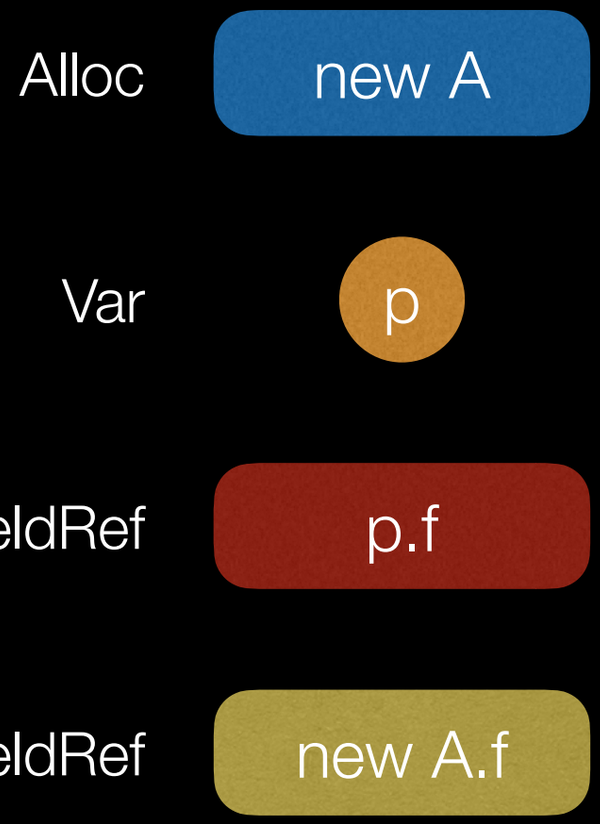
Alloc new A

Var p

FieldRef p.f

SPARK - PAG

Nodes



SPARK - PAG

Nodes

Alloc new A

Var p

FieldRef p.f

ConcreteFieldRef new A.f

Edges

SPARK - PAG

Nodes

Alloc new A

Var p

FieldRef p.f

ConcreteFieldRef new A.f

Edges

Alloc new A → p

Assign q → p

SPARK - PAG

Nodes

Alloc new A

Var p

FieldRef p.f

ConcreteFieldRef new A.f

Edges

Alloc new A → p

Assign q → p

Store q → p.f

SPARK - PAG

Nodes

Alloc new A

Var p

FieldRef p.f

ConcreteFieldRef new A.f

Edges

Alloc new A → p

Assign q → p

Store q → p.f

Load q.f → p

PAG - AllocNode

- Models allocations sites
- For each `new T` statement
- Has a type
- `AnyType` means type is unknown

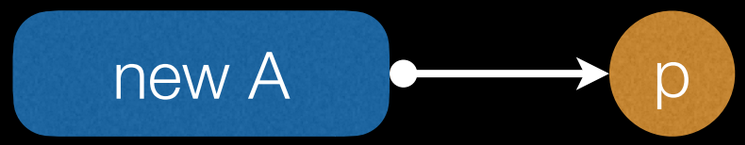
PAG - VarNode

- Represents a variable holding pointers to objects
- Local variables, method parameters, throwables
- Might have a type

PAG - FieldRefNode

- Represents a pointer dereference
- Base is a VarNode
- a.<elements> to model array contents
- Might have a type

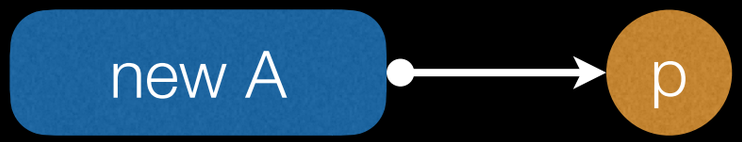
PAG - AllocEdge



- Models the statement `p = new A`
- E.g., `hm = new HashMap`

Allocation is independent of calling the constructor

PAG - AllocEdge



- Models the statement `p = new A`
- E.g., `hm = new HashMap`
- Induces the constraint

  pts-to(new A) ⊆ pts-to(p)

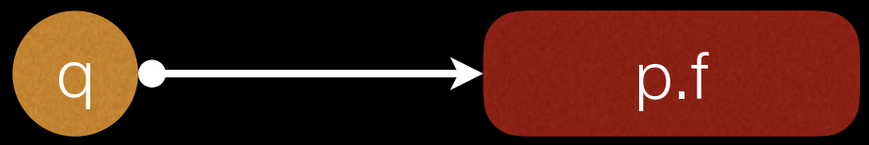
Why subset?

PAG - AssignEdge

- Models the assignment `p = q`
- Induces the constraint

pts-to(q) ⊆ pts-to(p)

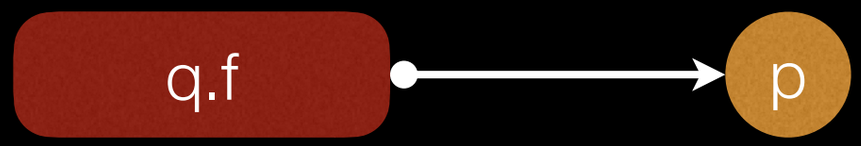
PAG - StoreEdge



- Models the assignment `p.f = q`
- Induces the constraint

  pts-to(q) ⊆ pts-to(p.f)

PAG - LoadEdge



- Models the assignment `p = q.f`
- Induces the constraint

pts-to(q.f) ⊆ pts-to(p)

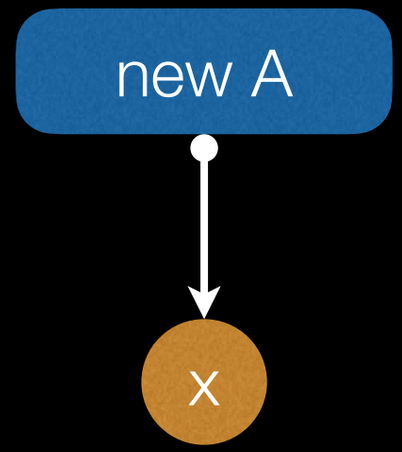
Let’s build a PAG!

PAG - Example

```
void foo {
  x = new A();
  y = x;
  z = new A();
  x.f = z;
  t = bar(y);
}

A bar(A p) {
  return p.f;
}
```

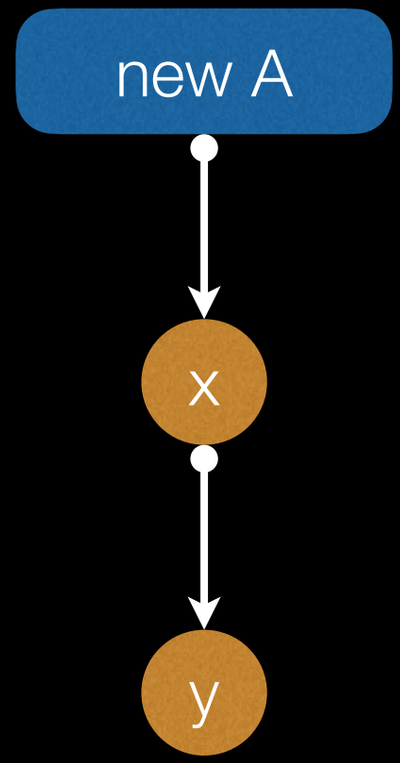
PAG - Example

```
void foo {
  x = new A();
  y = x;
  z = new A();
  x.f = z;
  t = bar(y);
}

A bar(A p) {
  return p.f;
}
```



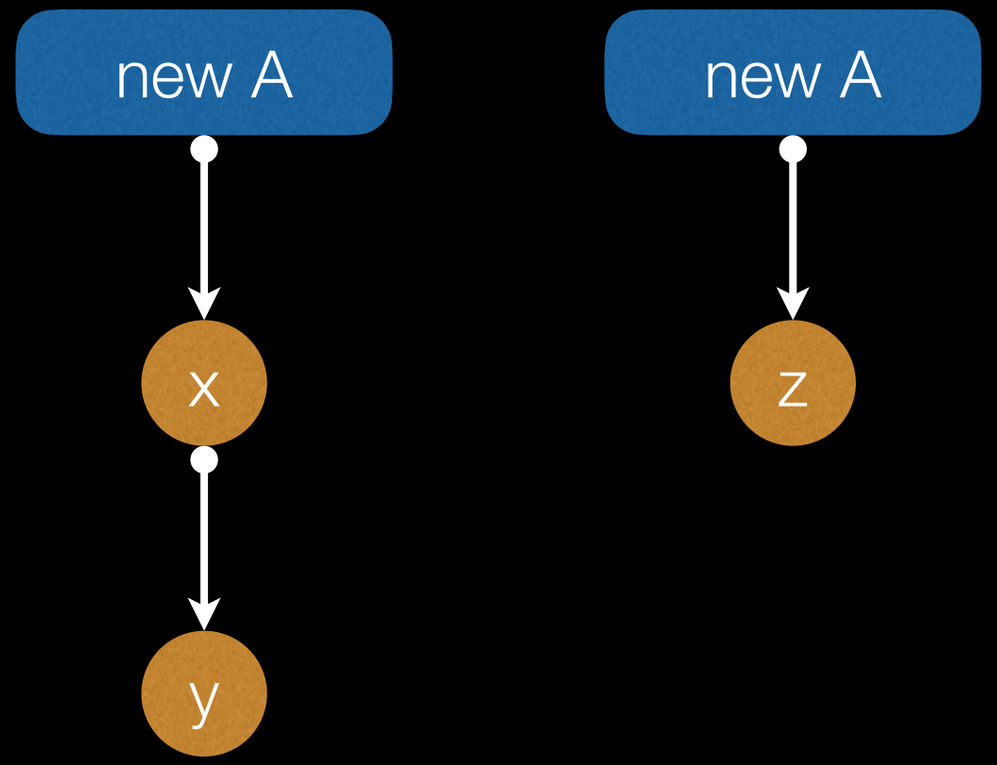
PAG - Example

```
void foo {
  x = new A();
  y = x;
  z = new A();
  x.f = z;
  t = bar(y);
}

A bar(A p) {
  return p.f;
}
```



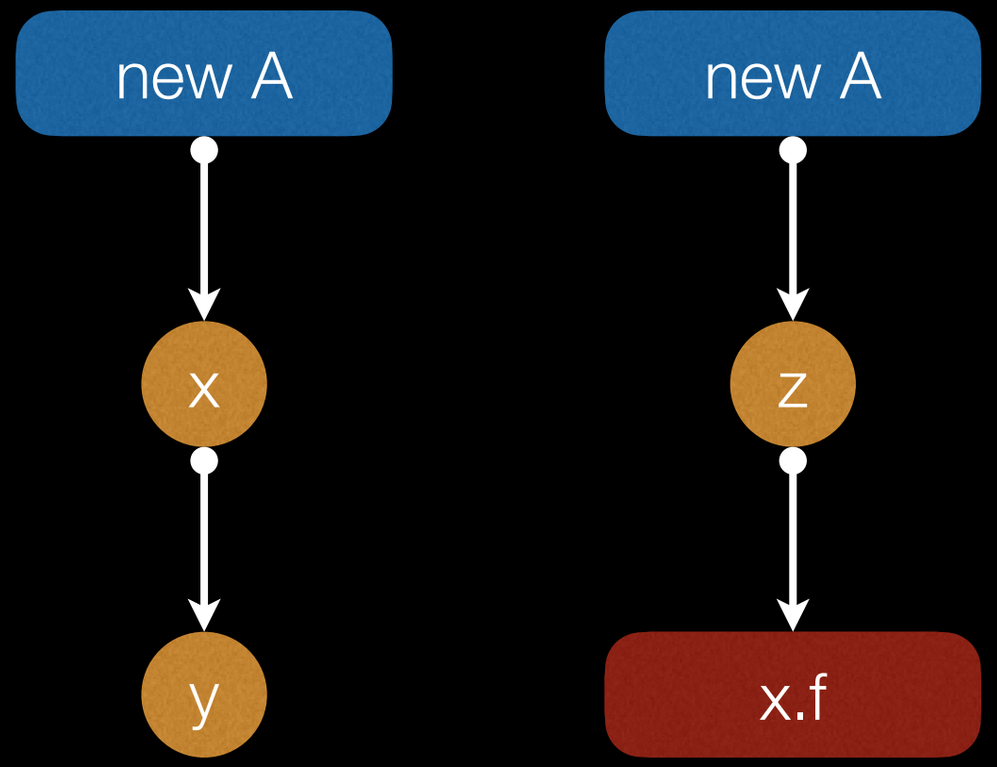
PAG - Example

```
void foo {
  x = new A();
  y = x;
  z = new A();
  x.f = z;
  t = bar(y);
}

A bar(A p) {
  return p.f;
}
```



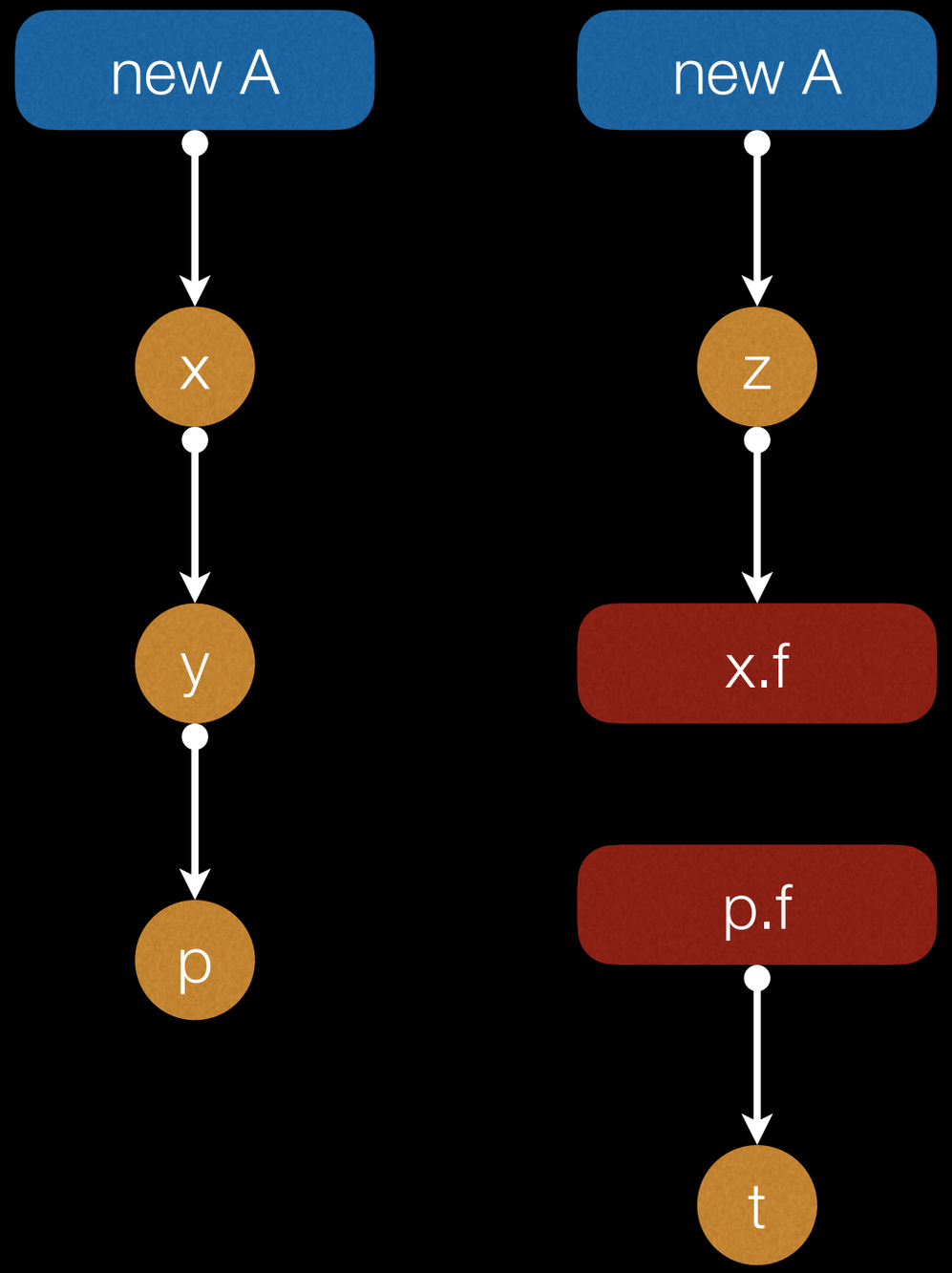
PAG - Example

```
void foo {
  x = new A();
  y = x;
  z = new A();
  x.f = z;
  t = bar(y);
}

A bar(A p) {
  return p.f;
}
```



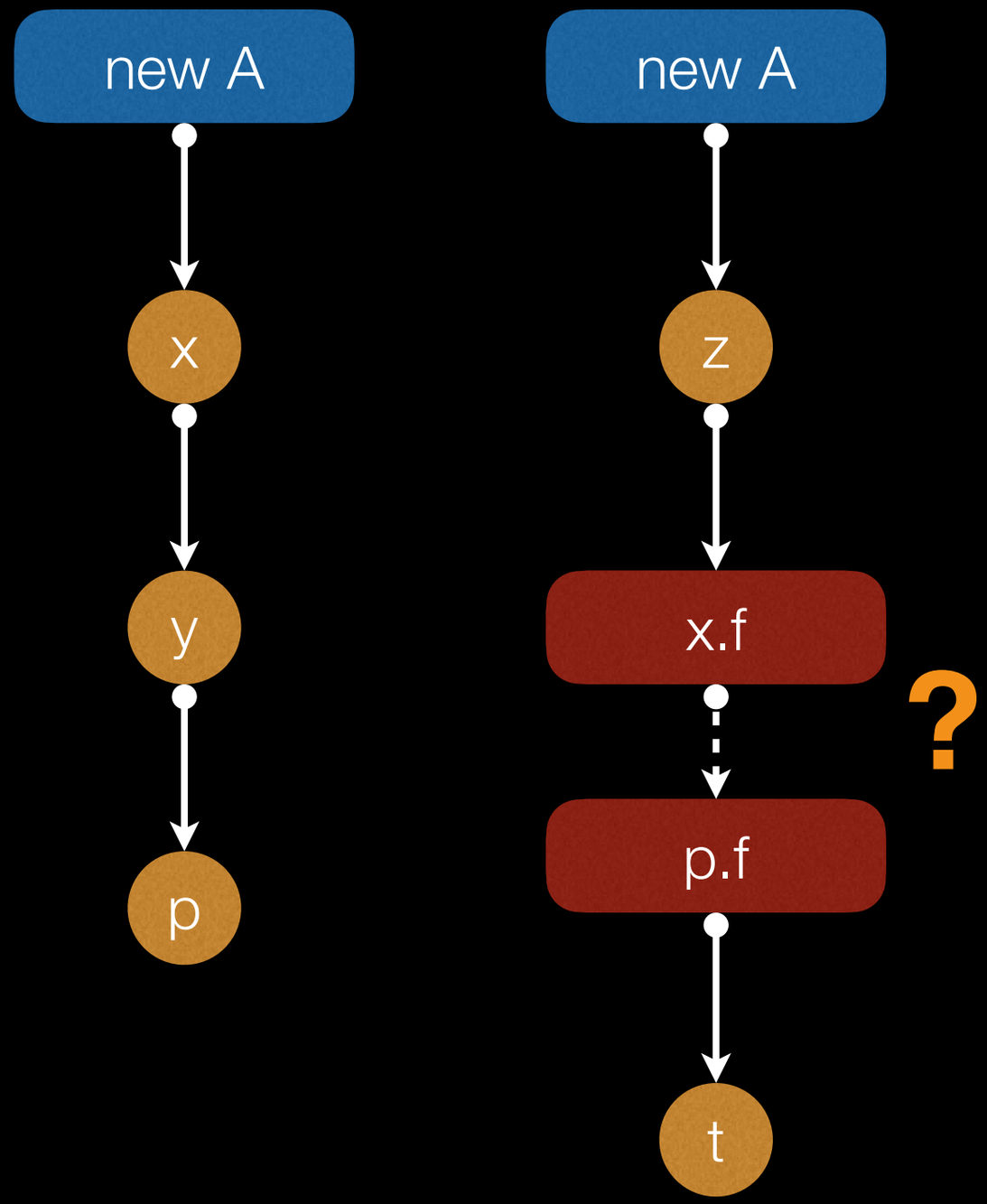
PAG - Example

```
void foo {
  x = new A();
  y = x;
  z = new A();
  x.f = z;
  t = bar(y);
}

A bar(A p) {
  return p.f;
}
```



PAG - Example

```
void foo {
  x = new A();
  y = x;
  z = new A();
  x.f = z;
  t = bar(y);
}

A bar(A p) {
  return p.f;
}
```



PAG - Fields

a.f

a.*

A.f

Field-Sensitive

Field-Insensitive

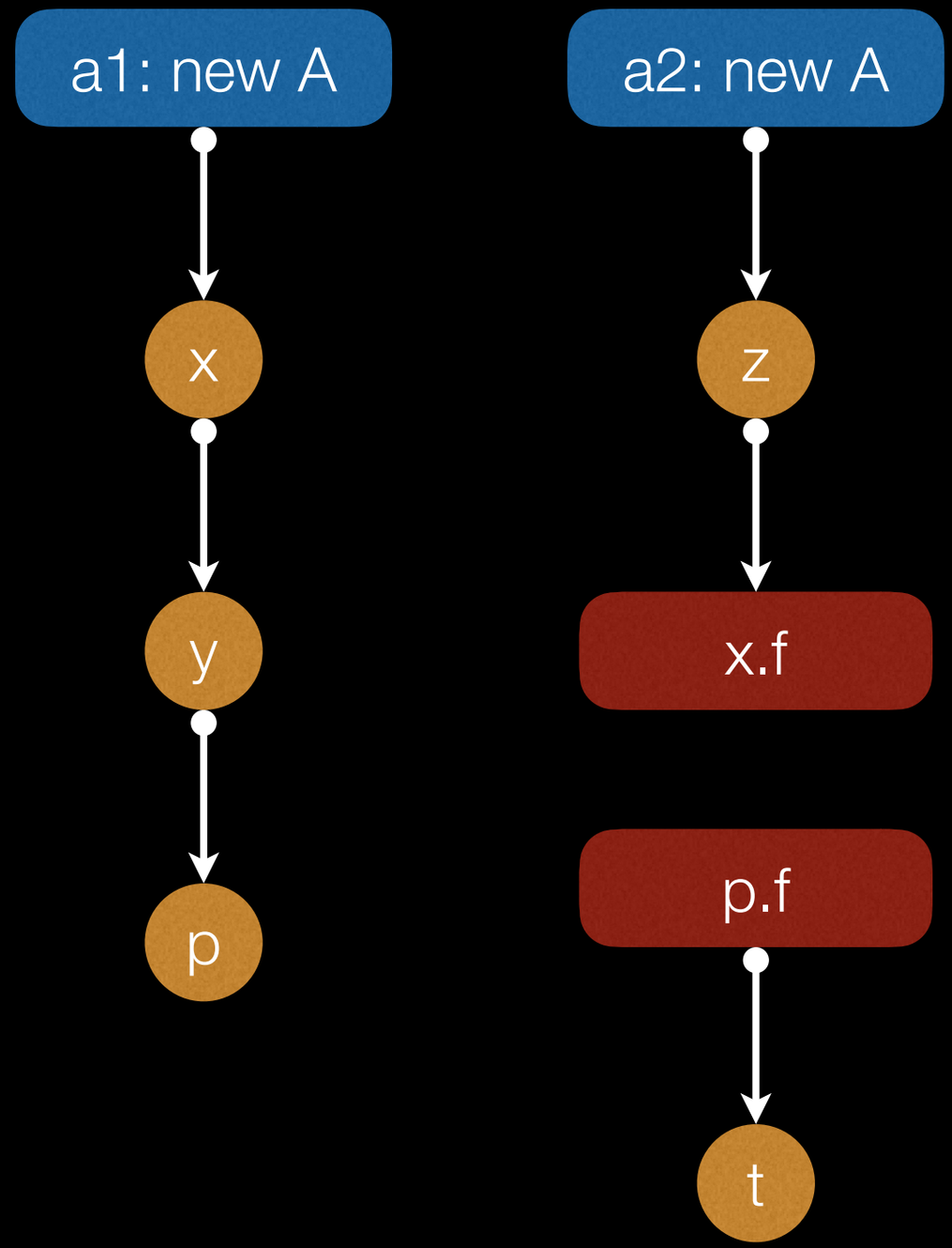
Field-Based

PAG - Other Considerations

- Static initializers
- Object.finalize()
- Thread.start()
- Reflection
- Object sensitivity

SPARK
Points-to Propagation

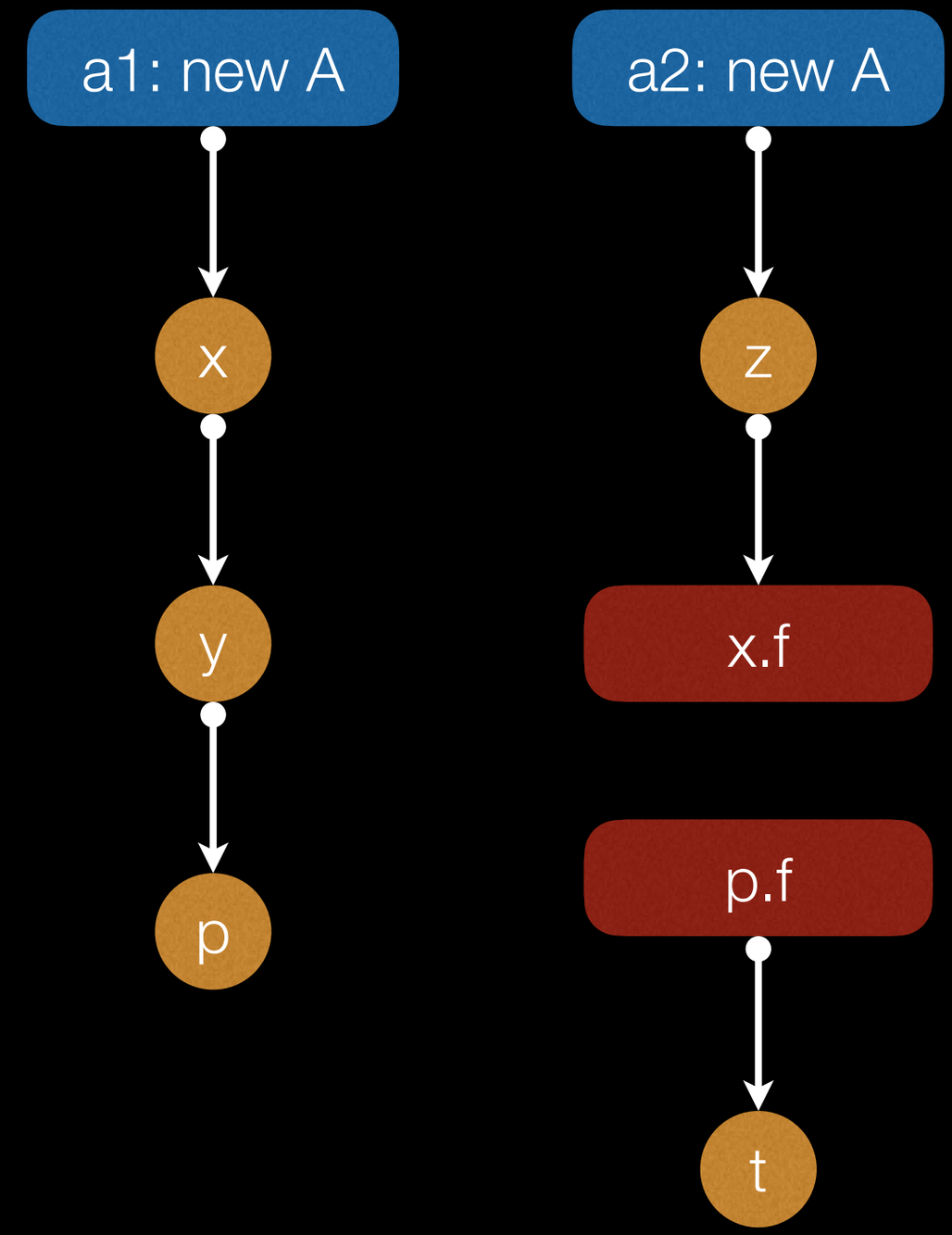
```
void foo {
  x = new A();
  y = x;
  z = new A();
  x.f = z;
  t = bar(y);
}

A bar(A p) {
  return p.f;
}
```



SPARK
Points-to Propagation

```
void foo {
  x = new A();
  y = x;
  z = new A();
  x.f = z;
  t = bar(y);
}

A bar(A p) {
  return p.f;
}
```

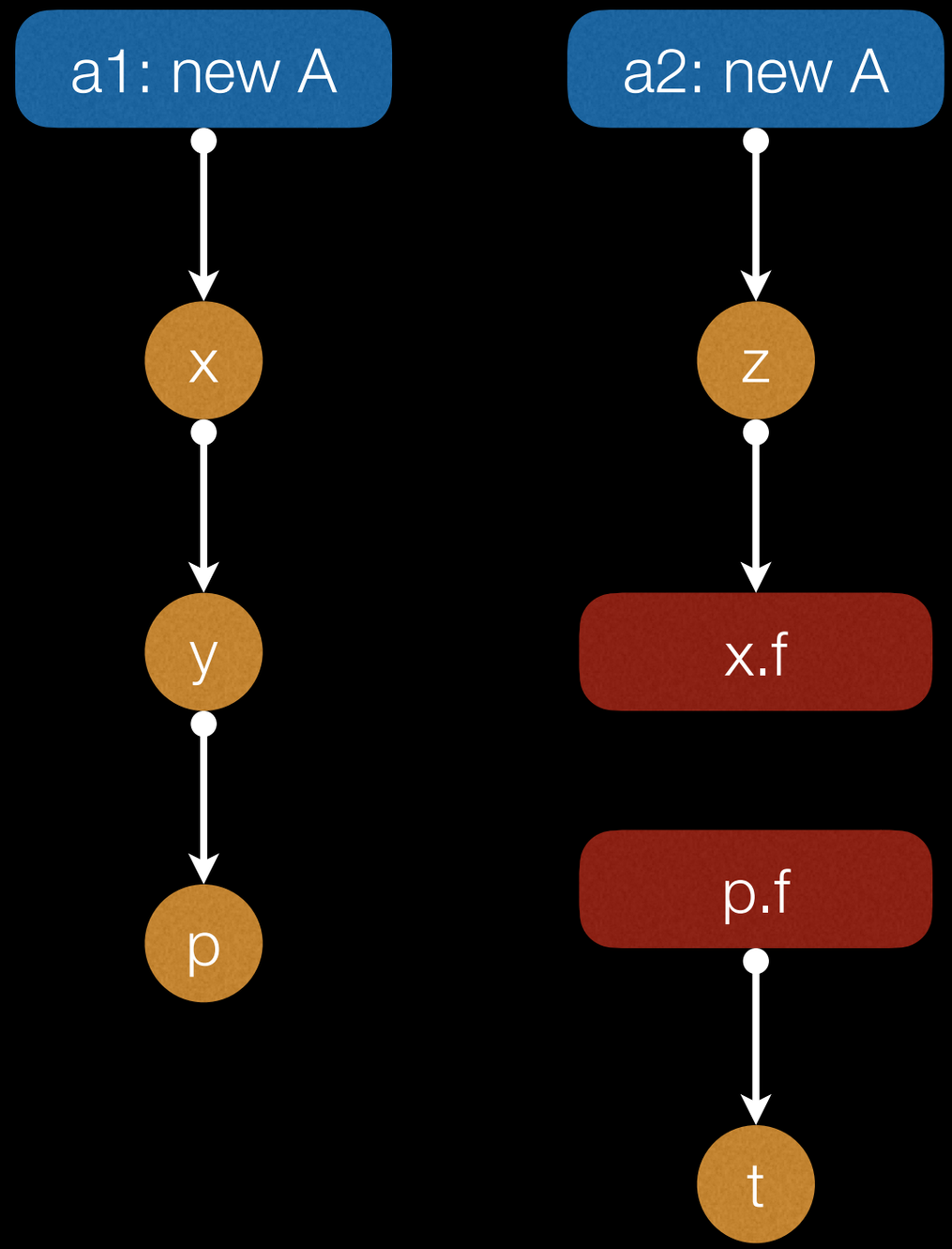
pts-to(x) = {a1}



SPARK
Points-to Propagation

```
void foo {
  x = new A();
  y = x;
  z = new A();
  x.f = z;
  t = bar(y);
}

A bar(A p) {
  return p.f;
}
```

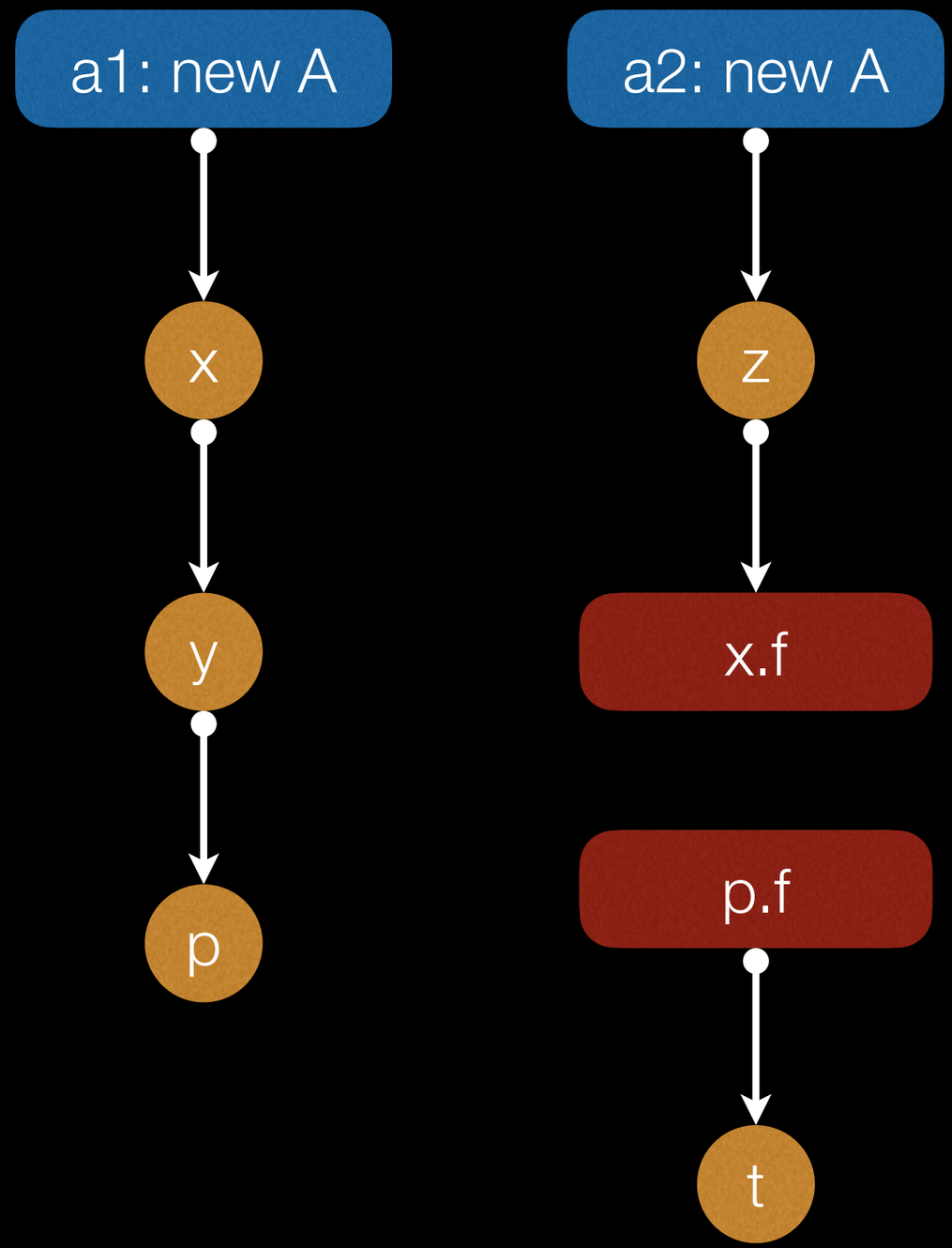
```
pts-to(x) = {a1}
pts-to(y) = {a1}
```



SPARK
Points-to Propagation

```
void foo {
  x = new A();
  y = x;
  z = new A();
  x.f = z;
  t = bar(y);
}

A bar(A p) {
  return p.f;
}
```

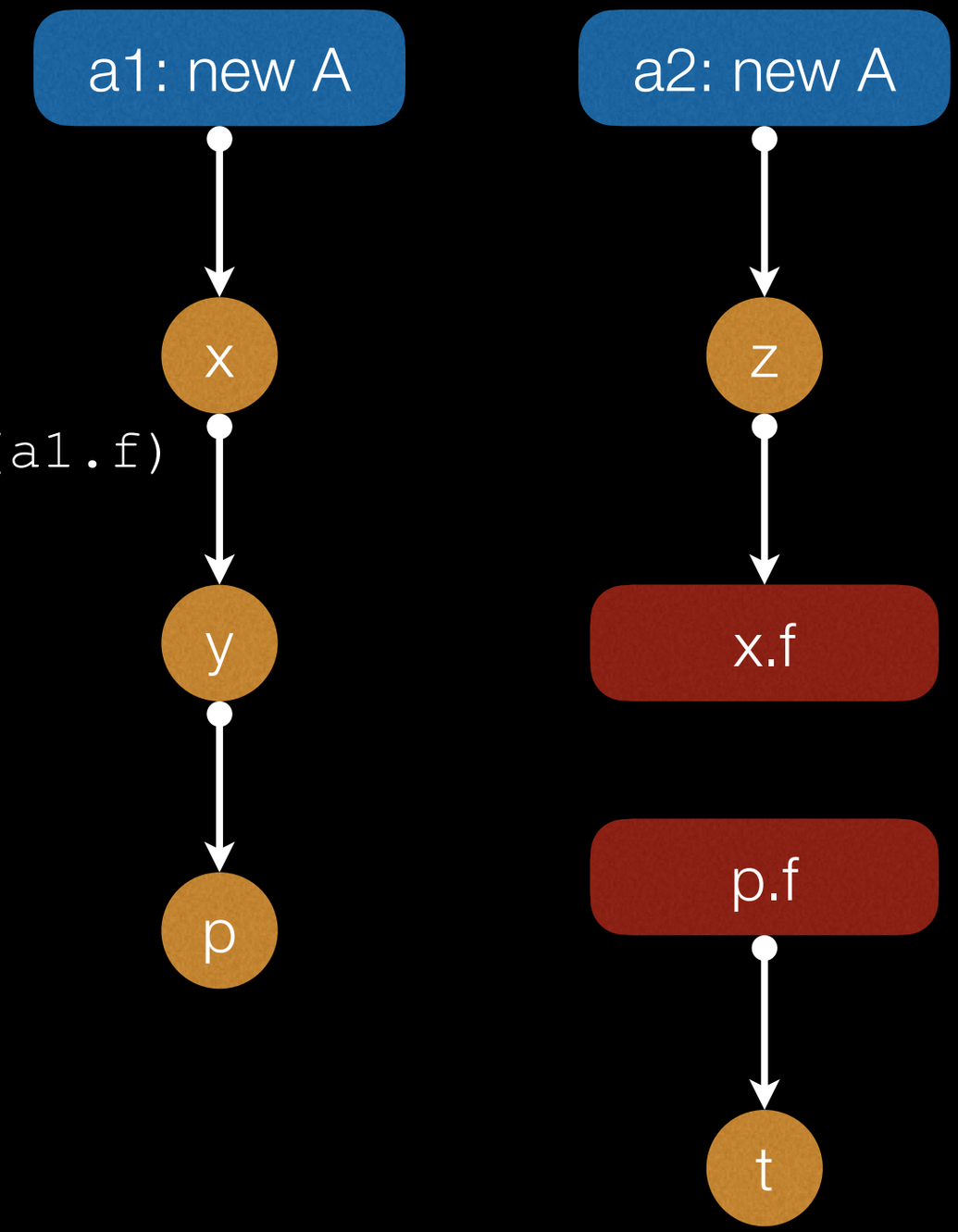
```
pts-to(x) = {a1}
pts-to(y) = {a1}
pts-to(z) = {a2}
```



SPARK
Points-to Propagation

```
void foo {
  x = new A();
  y = x;
  z = new A();
  x.f = z;
  t = bar(y);
}

A bar(A p) {
  return p.f;
}
```

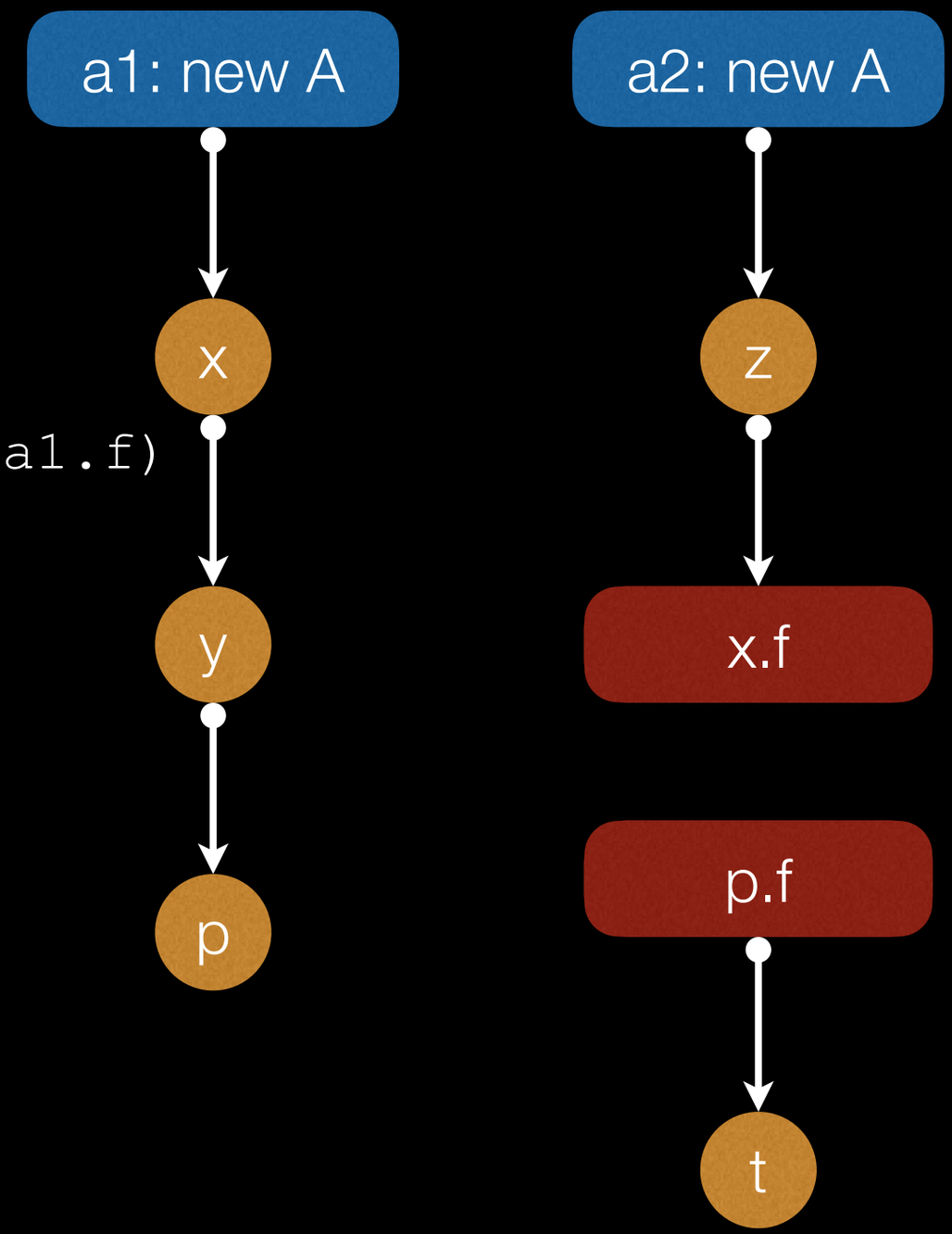
```
pts-to(x) = {a1}
pts-to(y) = {a1}
pts-to(z) = {a2}
pts-to(x.f) = pts-to(a1.f)
            = {a2}
```



SPARK
Points-to Propagation

```
void foo {
  x = new A();
  y = x;
  z = new A();
  x.f = z;
  t = bar(y);
}

A bar(A p) {
  return p.f;
}
```

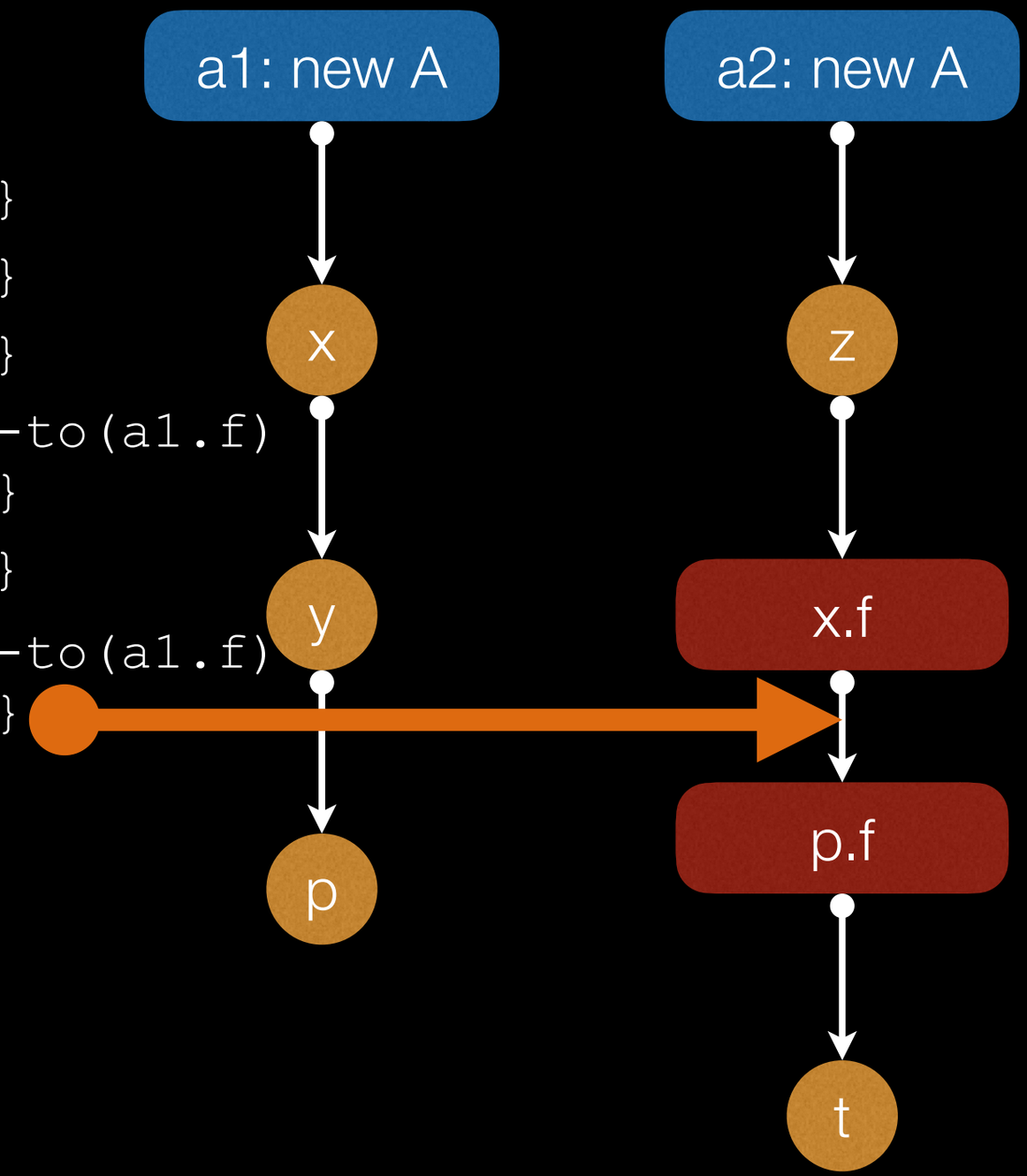
```
pts-to(x) = {a1}
pts-to(y) = {a1}
pts-to(z) = {a2}
pts-to(x.f) = pts-to(a1.f)
            = {a2}
pts-to(p) = {a1}
```



SPARK
Points-to Propagation

```
void foo {
  x = new A();
  y = x;
  z = new A();
  x.f = z;
  t = bar(y);
}

A bar(A p) {
  return p.f;
}
```

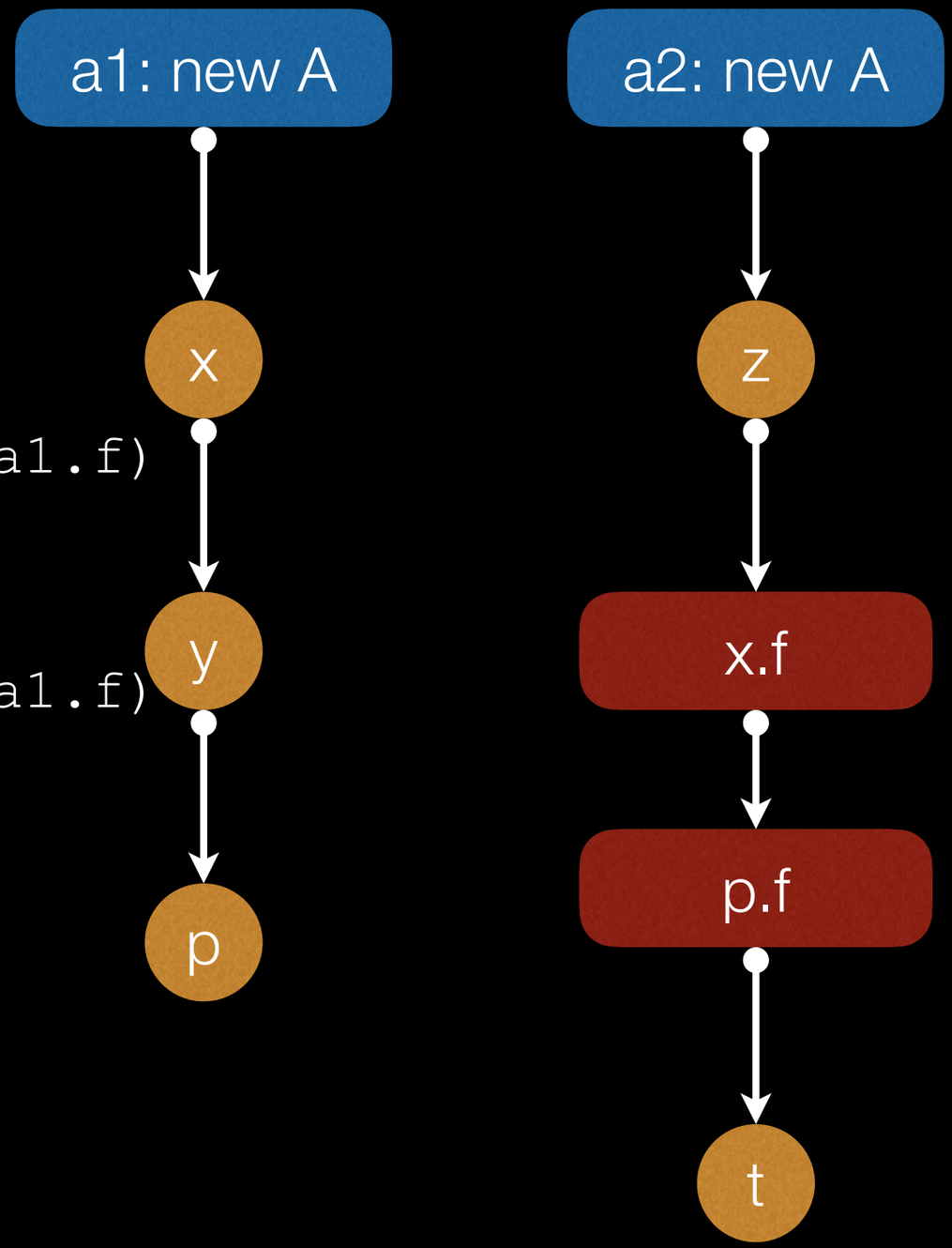
```
pts-to(x) = {a1}
pts-to(y) = {a1}
pts-to(z) = {a2}
pts-to(x.f) = pts-to(a1.f)
            = {a2}
  pts-to(p) = {a1}
pts-to(p.f) = pts-to(a1.f)
            = {a2}
```



SPARK
Points-to Propagation

```
void foo {
  x = new A();
  y = x;
  z = new A();
  x.f = z;
  t = bar(y);
}

A bar(A p) {
  return p.f;
}
```

```
pts-to(x) = {a1}
pts-to(y) = {a1}
pts-to(z) = {a2}
pts-to(x.f) = pts-to(a1.f)
            = {a2}
  pts-to(p) = {a1}
pts-to(p.f) = pts-to(a1.f)
            = {a2}

  pts-to(t) = {a2}
```



SPARK

- ✅ Very precise
- ✅ Highly customizable
- ✅ No initial call graph
- ❌ Flow-insensitive
- ❌ Quite expensive
- ❌ Large PAGs

On-the-fly CG Construction

Determining Target Calls

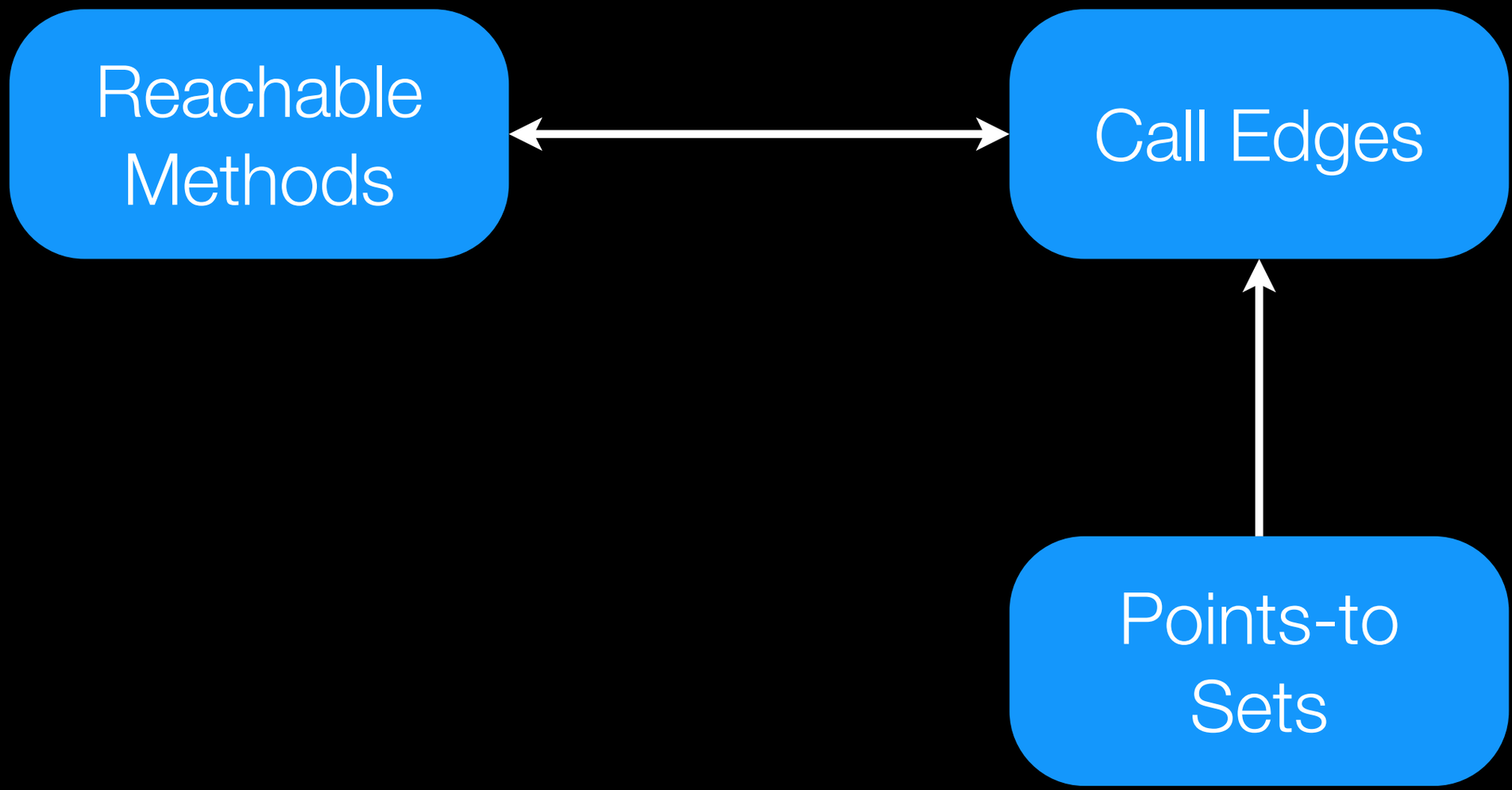
Points-to Analysis

On-the-fly CG Construction

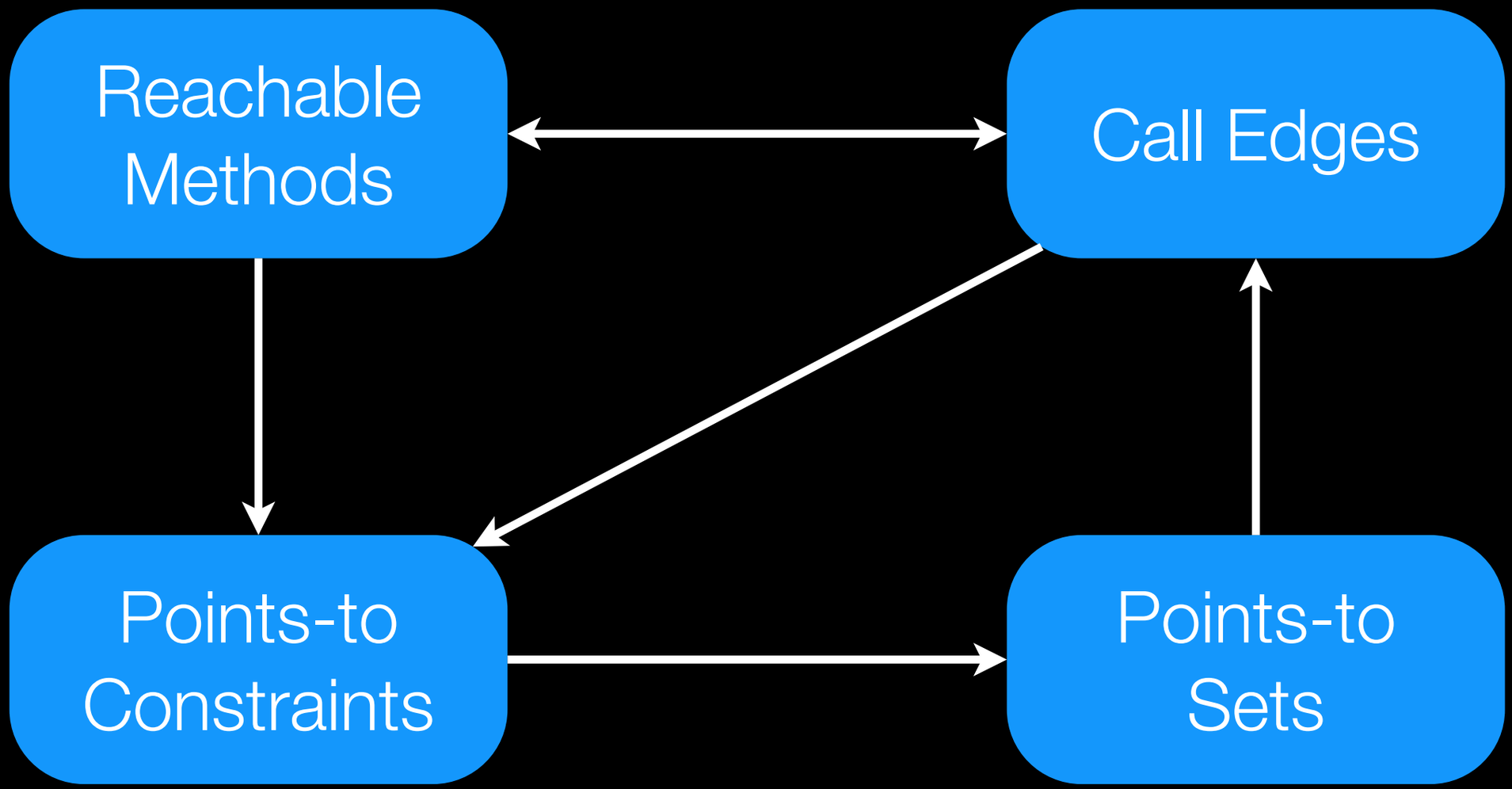
Call Edges

On-the-fly CG Construction

On-the-fly CG Construction



On-the-fly CG Construction



OTF CG Construction Algorithm

- Add entry points (e.g., main method) to the work-list and the list of reachable methods
- **Repeat until work-list is empty**
  - Pick a reachable method from the work-list
  - Find allocations sites in that method
  - Propagate those allocations along PAG edges
  - Re-resolve relevant calls in reachable methods using the updated pts-to sets
  - Add any newly-reachable methods to the work-list, and to the list of reachable methods

SPARK - OTF CG Construction

```
public class Main {
  static A a;

  public static void main(String[] args) {
    a = new A();
    a.foo();
    a.foo();
  }

  static class A {
     void foo() { a = new B(); }
  }

  static class B extends A {
     void foo() {}
  }
}
```

SPARK - OTF CG Construction

```
public class Main {
  static A a;

  public static void main(String[] args) {
    a = new A();
    a.foo();
    a.foo();
  }

  static class A {
     void foo() { a = new B(); }
  }

  static class B extends A {
     void foo() {}
  }
}
```

Main.main()

Worklist

Main.main()

Reachable

Main.main()

Points-to

SPARK - OTF CG Construction

```
public class Main {
  static A a;

  public static void main(String[] args) {
    a = new A();
    a.foo();
    a.foo();
  }

  static class A {
     void foo() { a = new B(); }
  }

  static class B extends A {
     void foo() {}
  }
}
```

Main.main()

Worklist

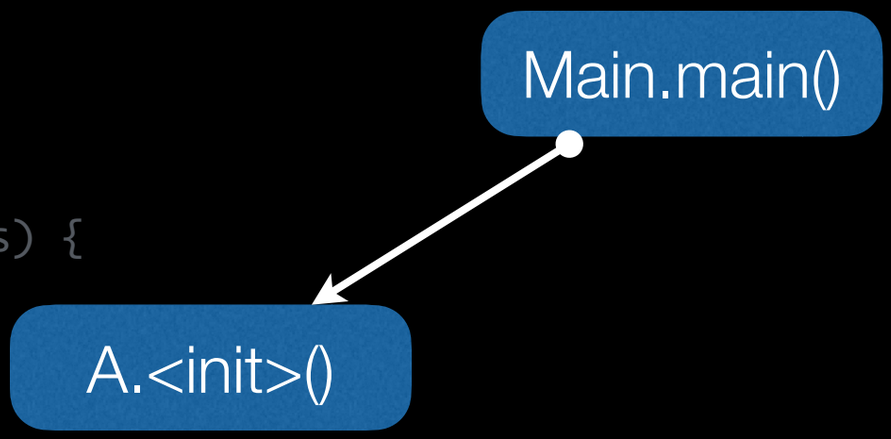
Reachable

Main.main()

Points-to

SPARK - OTF CG Construction

```
public class Main {
  static A a;

  public static void main(String[] args) {
    a = new A();
    a.foo();
    a.foo();
  }

  static class A {
     void foo() { a = new B(); }
  }

  static class B extends A {
     void foo() {}
  }
}
```



Worklist

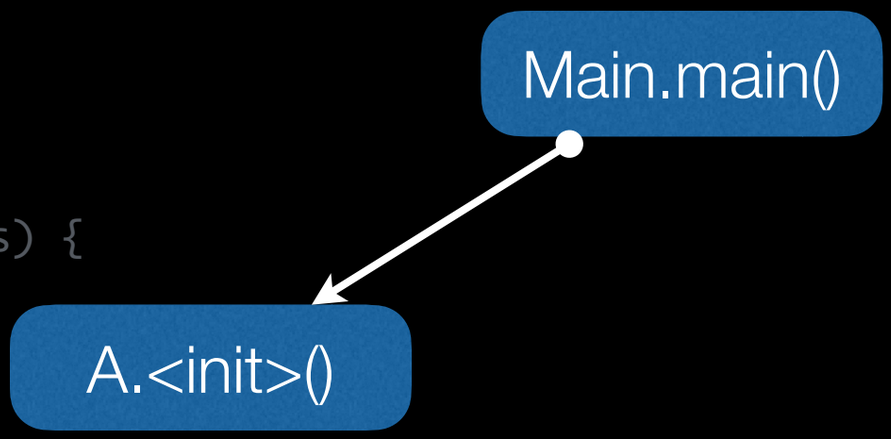
Reachable

Main.main()

Points-to `pts-to(a) = {new A}`

SPARK - OTF CG Construction

```
public class Main {
  static A a;

  public static void main(String[] args) {
    a = new A();
    a.foo();
    a.foo();
  }

  static class A {
     void foo() { a = new B(); }
  }

  static class B extends A {
     void foo() {}
  }
}
```



Worklist

A.<init>()

Reachable

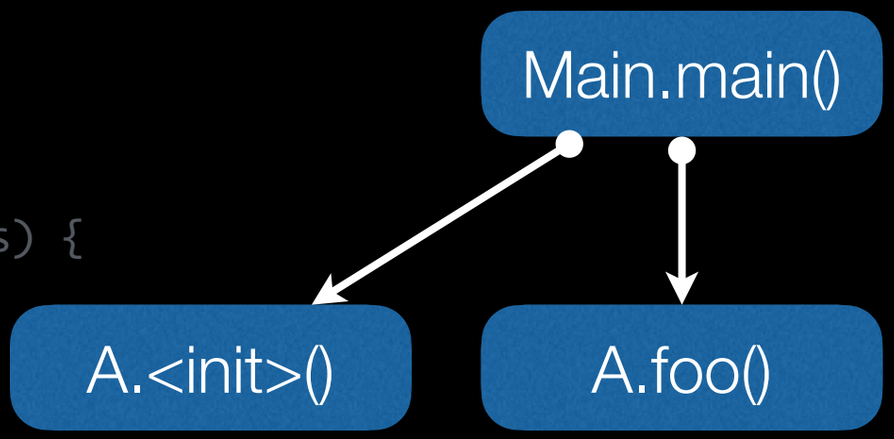
Main.main()

A.<init>()

Points-to `pts-to(a) = {new A}`

SPARK - OTF CG Construction

```
public class Main {
  static A a;

  public static void main(String[] args) {
    a = new A();
    a.foo();
    a.foo();
  }

  static class A {
     void foo() { a = new B(); }
  }

  static class B extends A {
     void foo() {}
  }
}
```



Worklist

Reachable

Main.main()

A.<init>()

Points-to `pts-to(a) = {new A}`

SPARK - OTF CG Construction

```
public class Main {
  static A a;

  public static void main(String[] args) {
    a = new A();
    a.foo();
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  }

  static class A {
     void foo() { a = new B(); }
  }

  static class B extends A {
     void foo() {}
  }
}
```
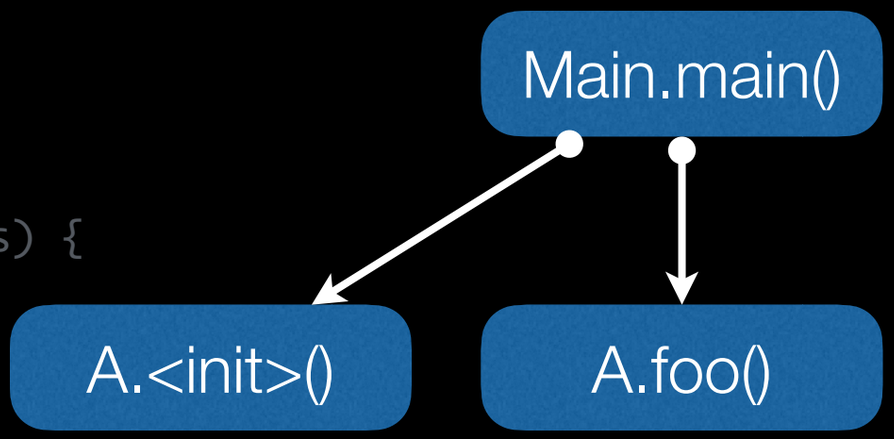



Worklist

A.foo()

Reachable

Main.main()

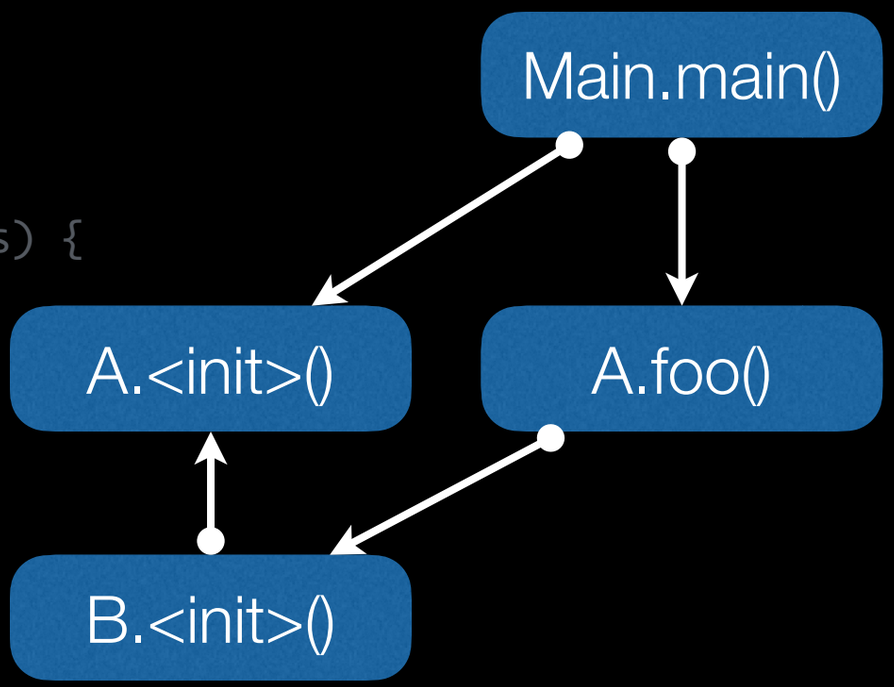
A.<init>()

A.foo()

Points-to `pts-to(a) = {new A}`

SPARK - OTF CG Construction

```
public class Main {
  static A a;

  public static void main(String[] args) {
    a = new A();
    a.foo();
    a.foo();
  }

  static class A {
     void foo() { a = new B(); }
  }

  static class B extends A {
     void foo() {}
  }
}
```



Worklist

Reachable

Main.main()

A.<init>()

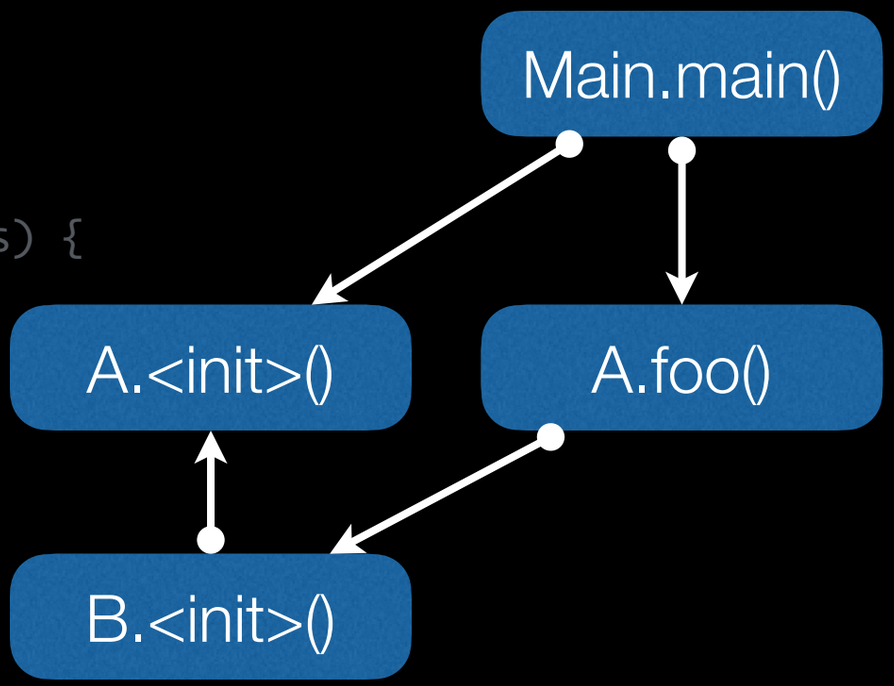
B.<init>()

A.foo()

Points-to `pts-to(a) = {new A}`

SPARK - OTF CG Construction

```
public class Main {
  static A a;

  public static void main(String[] args) {
    a = new A();
    a.foo();
    a.foo();
  }

  static class A {
     void foo() { a = new B(); }
  }

  static class B extends A {
     void foo() {}
  }
}
```



Worklist

Reachable

Main.main()

A.<init>()

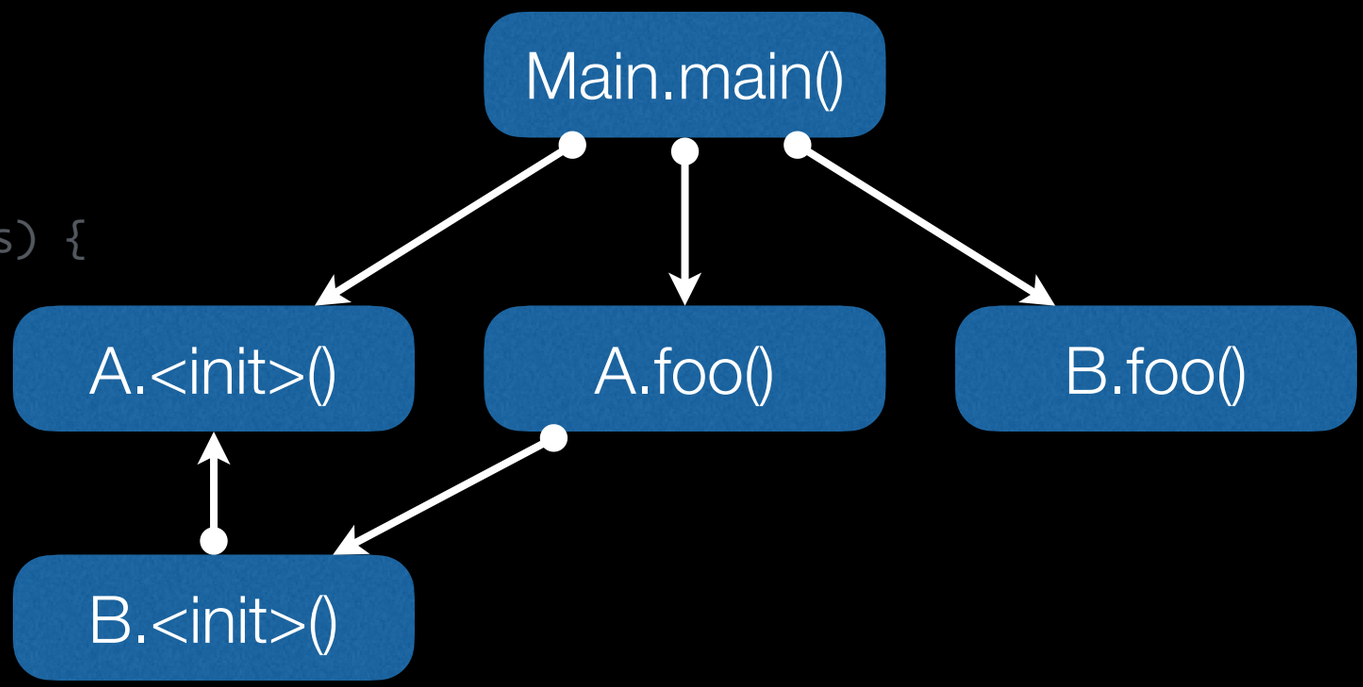
B.<init>()

A.foo()

Points-to `pts-to(a) = {new A, new B}`

SPARK - OTF CG Construction

```
public class Main {
  static A a;

  public static void main(String[] args) {
    a = new A();
    a.foo();
    a.foo();
  }

  static class A {
     void foo() { a = new B(); }
  }

  static class B extends A {
     void foo() {}
  }
}
```



Worklist

Reachable

Main.main()

A.<init>()

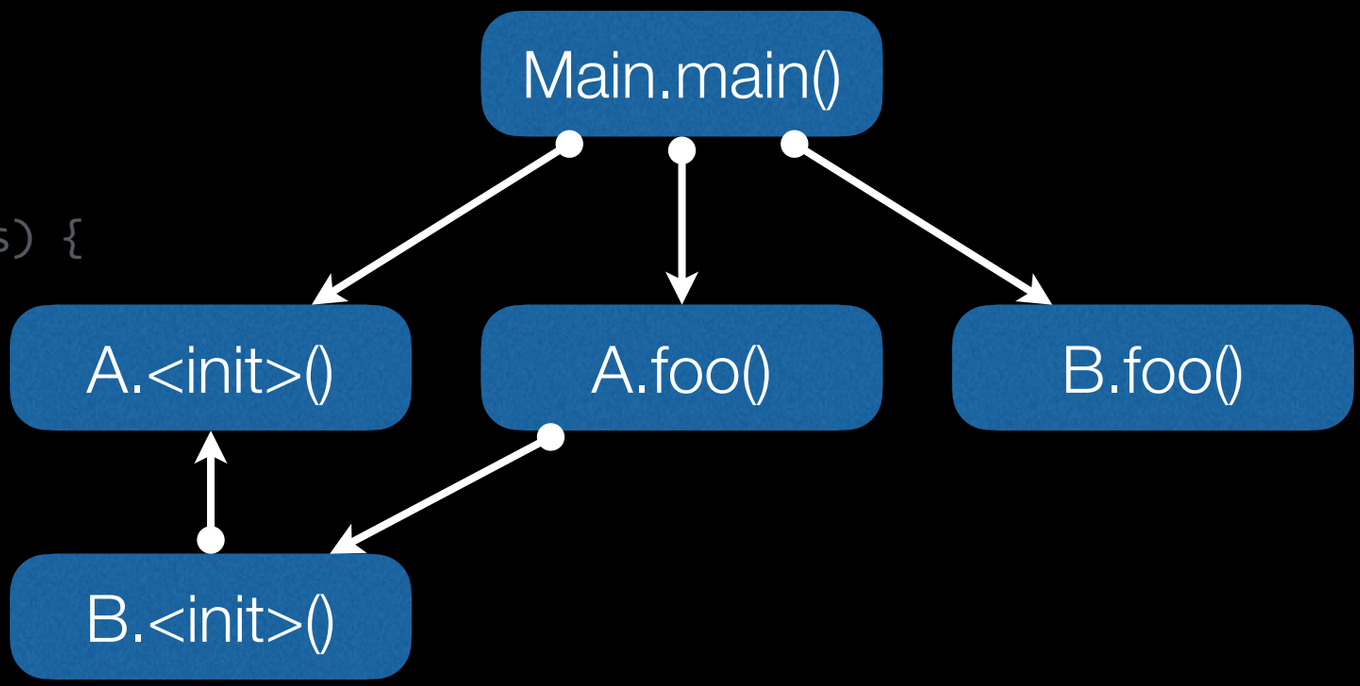
B.<init>()

A.foo()

Points-to `pts-to(a) = {new A, new B}`

SPARK - OTF CG Construction

```
public class Main {
  static A a;

  public static void main(String[] args) {
    a = new A();
    a.foo();
    a.foo();
  }

  static class A {
     void foo() { a = new B(); }
  }

  static class B extends A {
     void foo() {}
  }
}
```



Worklist

B.foo()

Reachable

Main.main()

B.foo()

A.<init>()

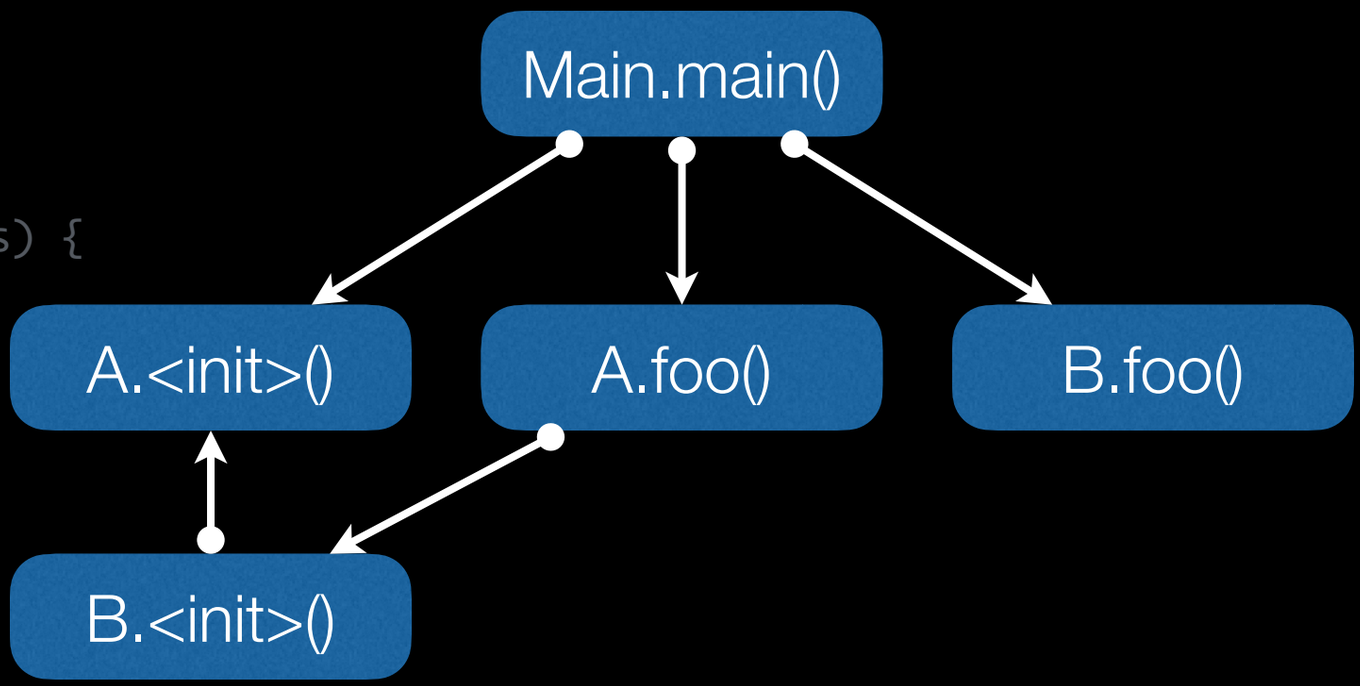
B.<init>()

A.foo()

Points-to `pts-to(a) = {new A, new B}`

SPARK - OTF CG Construction

```
public class Main {
  static A a;

  public static void main(String[] args) {
    a = new A();
    a.foo();
    a.foo();
  }

  static class A {
     void foo() { a = new B(); }
  }

  static class B extends A {
     void foo() {}
  }
}
```

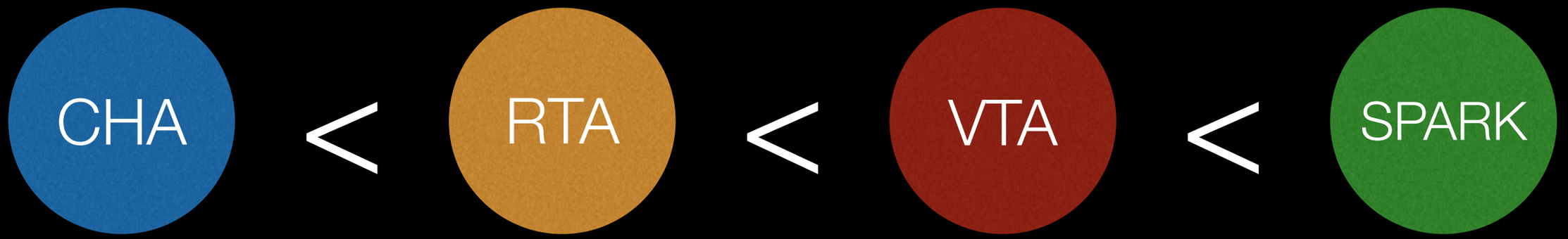


Worklist

Reachable

- Main.main()
- B.foo()
- A.<init>()
- B.<init>()
- A.foo()

Points-to `pts-to(a) = {new A, new B}`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Next

- Call graph hands-on