Extends on slides by Eric Bodden
for DECA course at TU Darmstadt

Call Graph Construction

Applied Static Analysis 2016

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Software Technology Group

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DARMSTADT

Previously on APSA…


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Soot


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56
MARYLAND
FindBugs
because it's easy


CHECKER
framework

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FindBugs™
because it's easy

DOOP

CHECKMARX

coverity®
A Synopsys Company

AbsInt

FORTIFY

WALA
T. J. WATSON LIBRARIES FOR ANALYSIS

CHECKER framework

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FindBugs
because it's easy

Call Graph

DOOP

CHECKMARX

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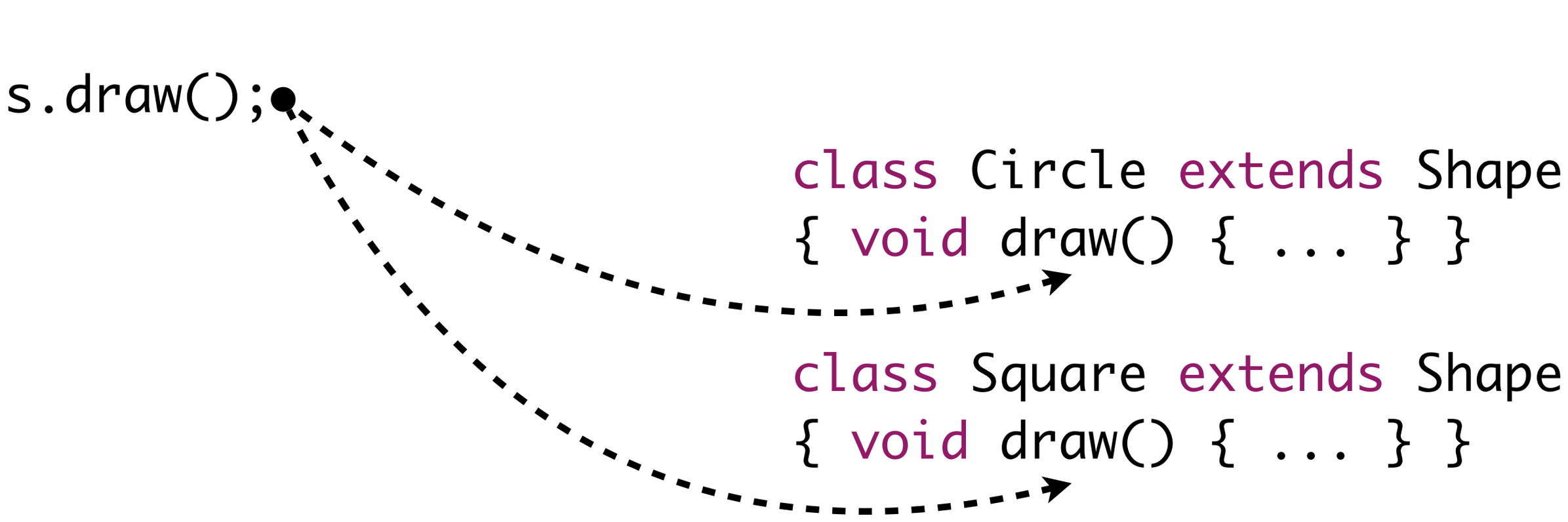
CHECKER framework

… 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 interprocedural analysis

Let’s build a CG

```
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 CG

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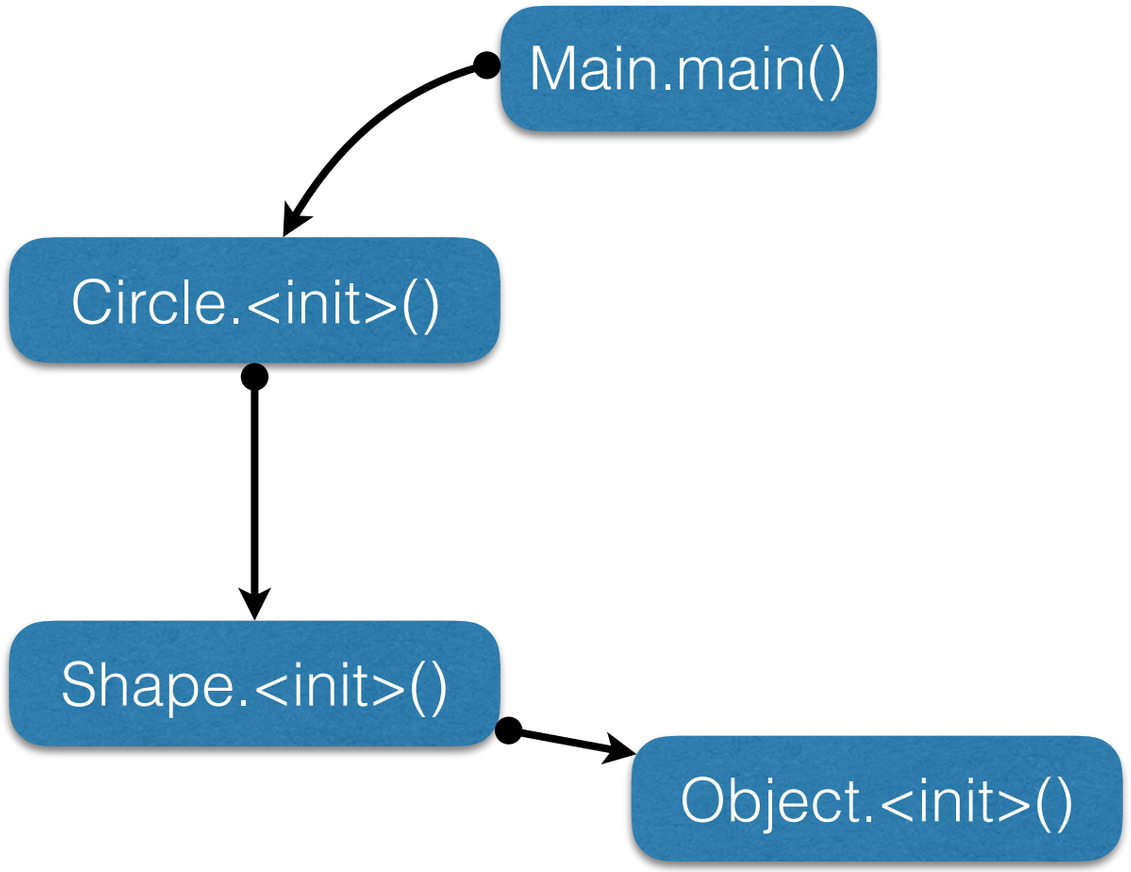
```



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}
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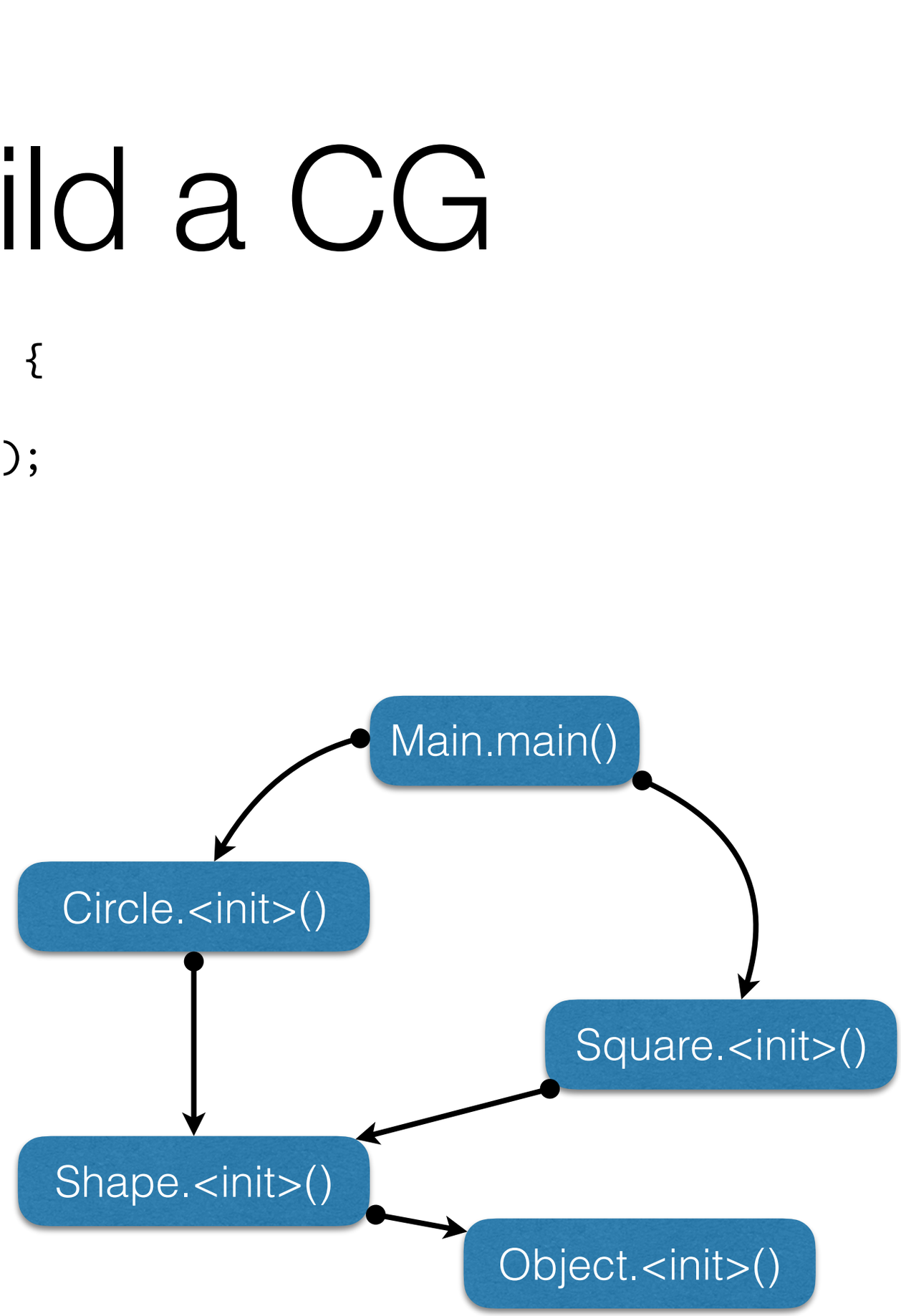

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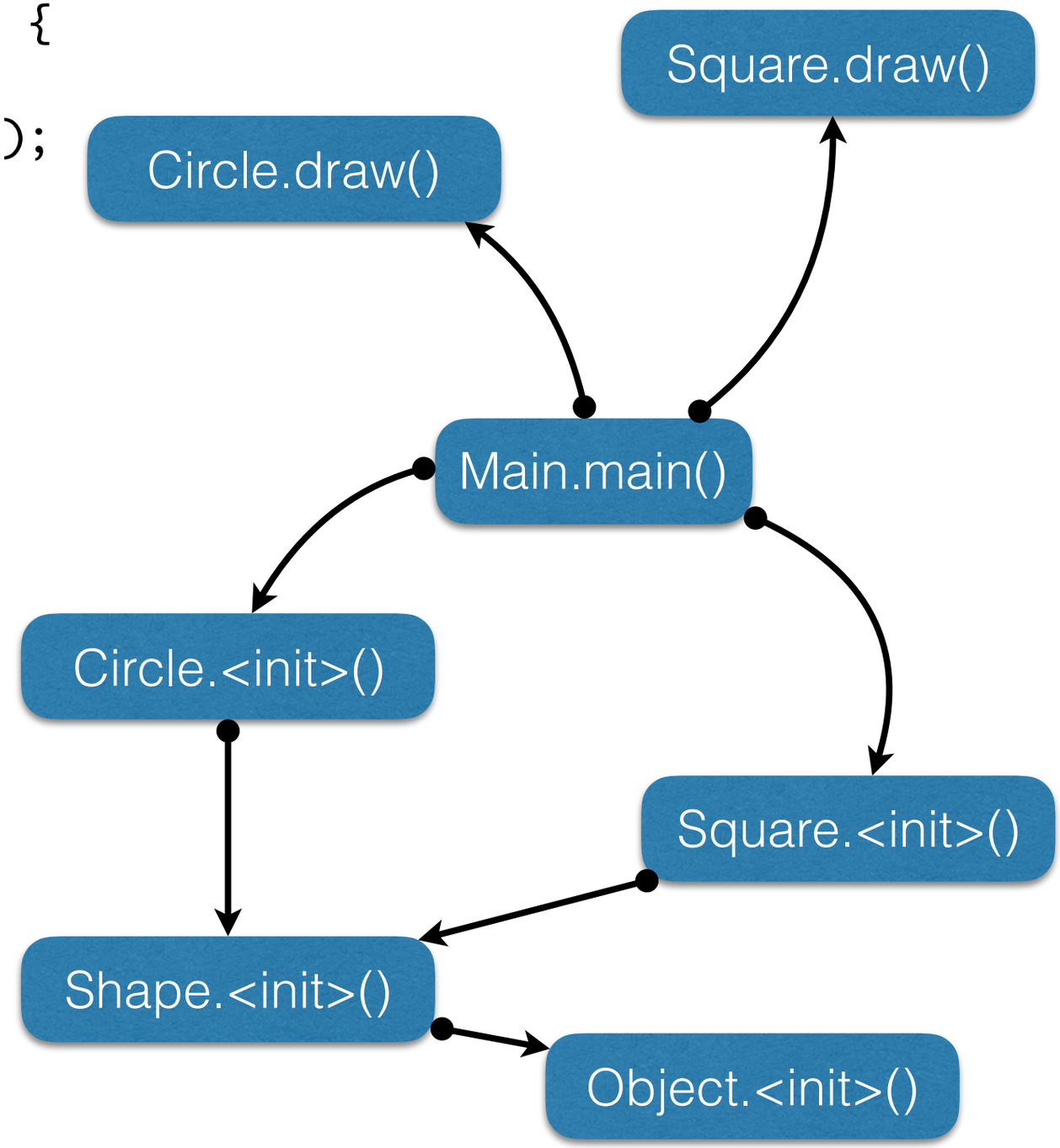
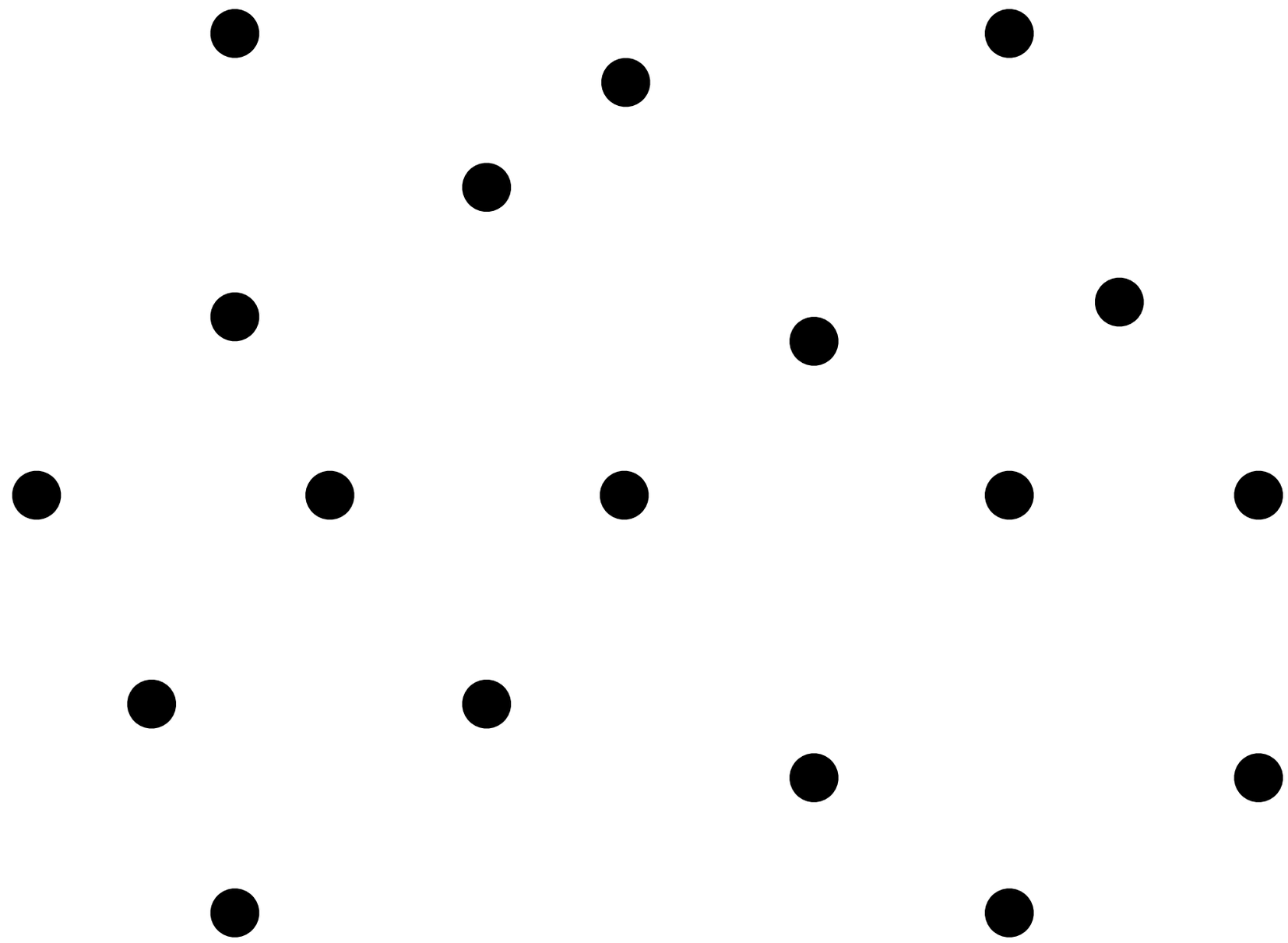
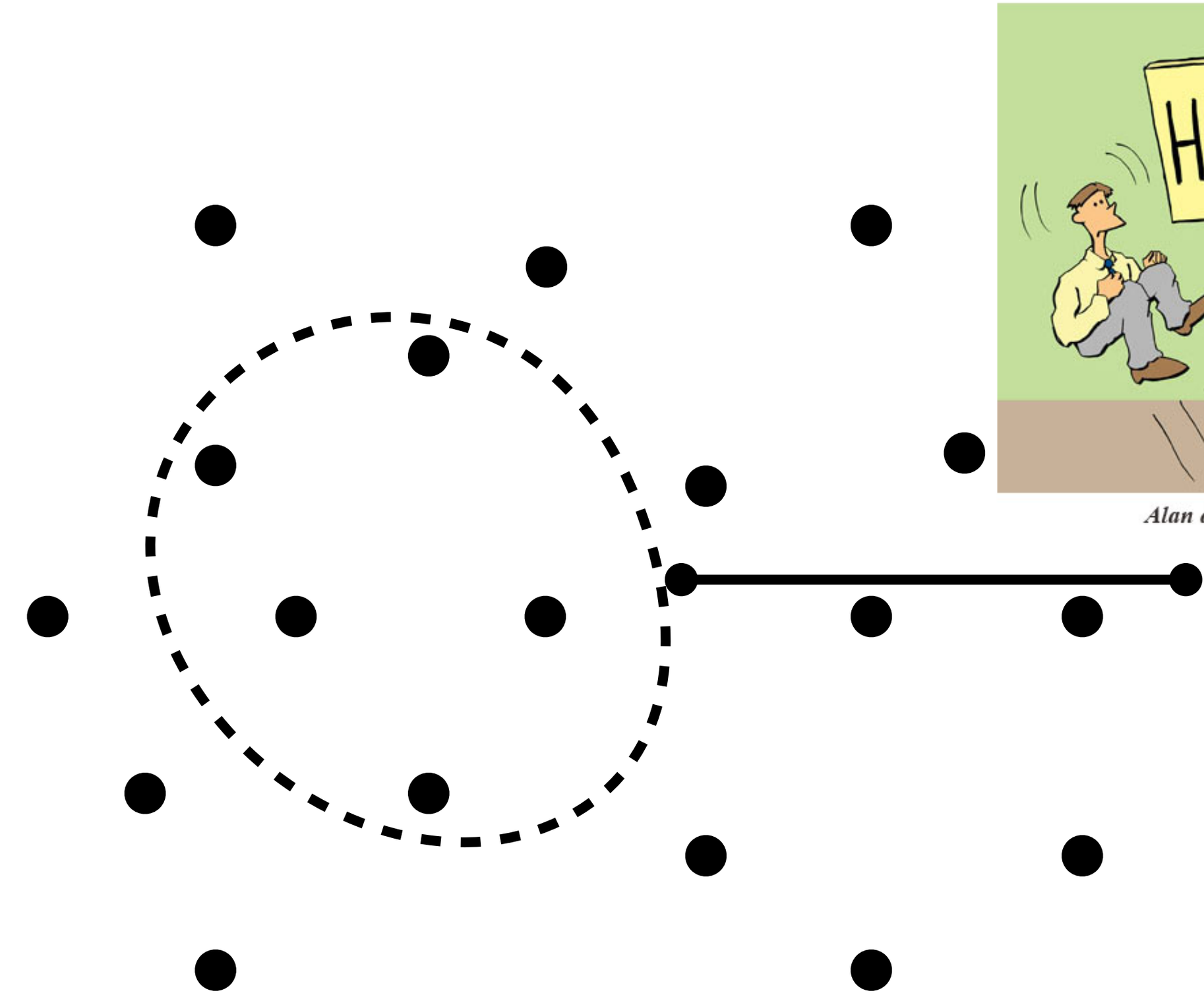
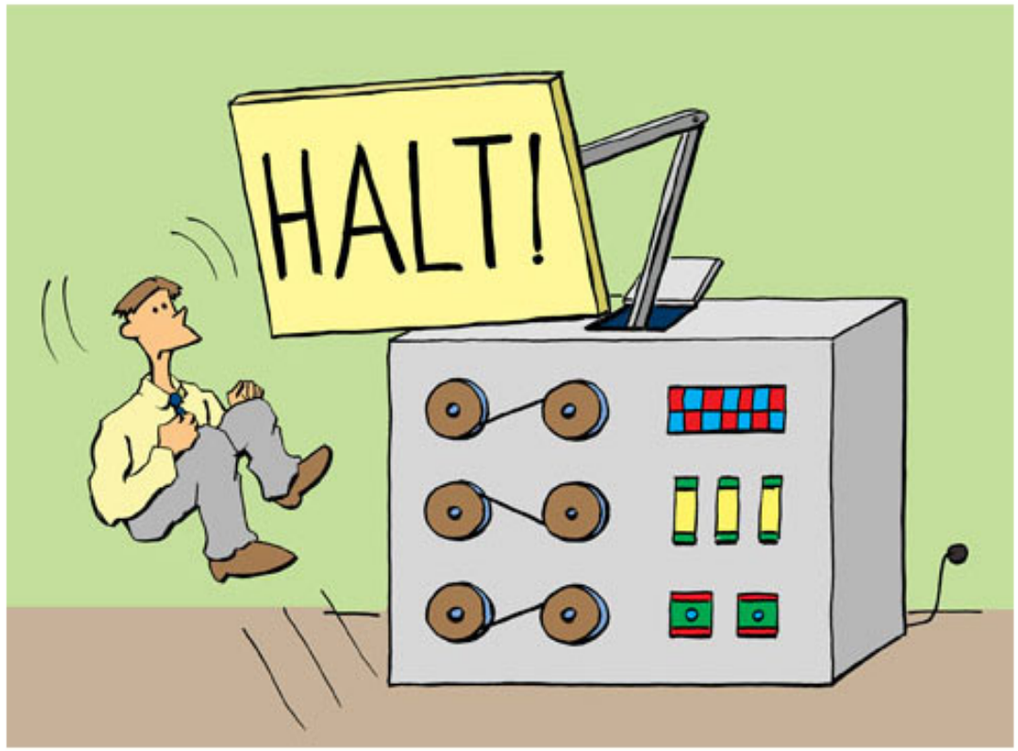


but … polymorphism!

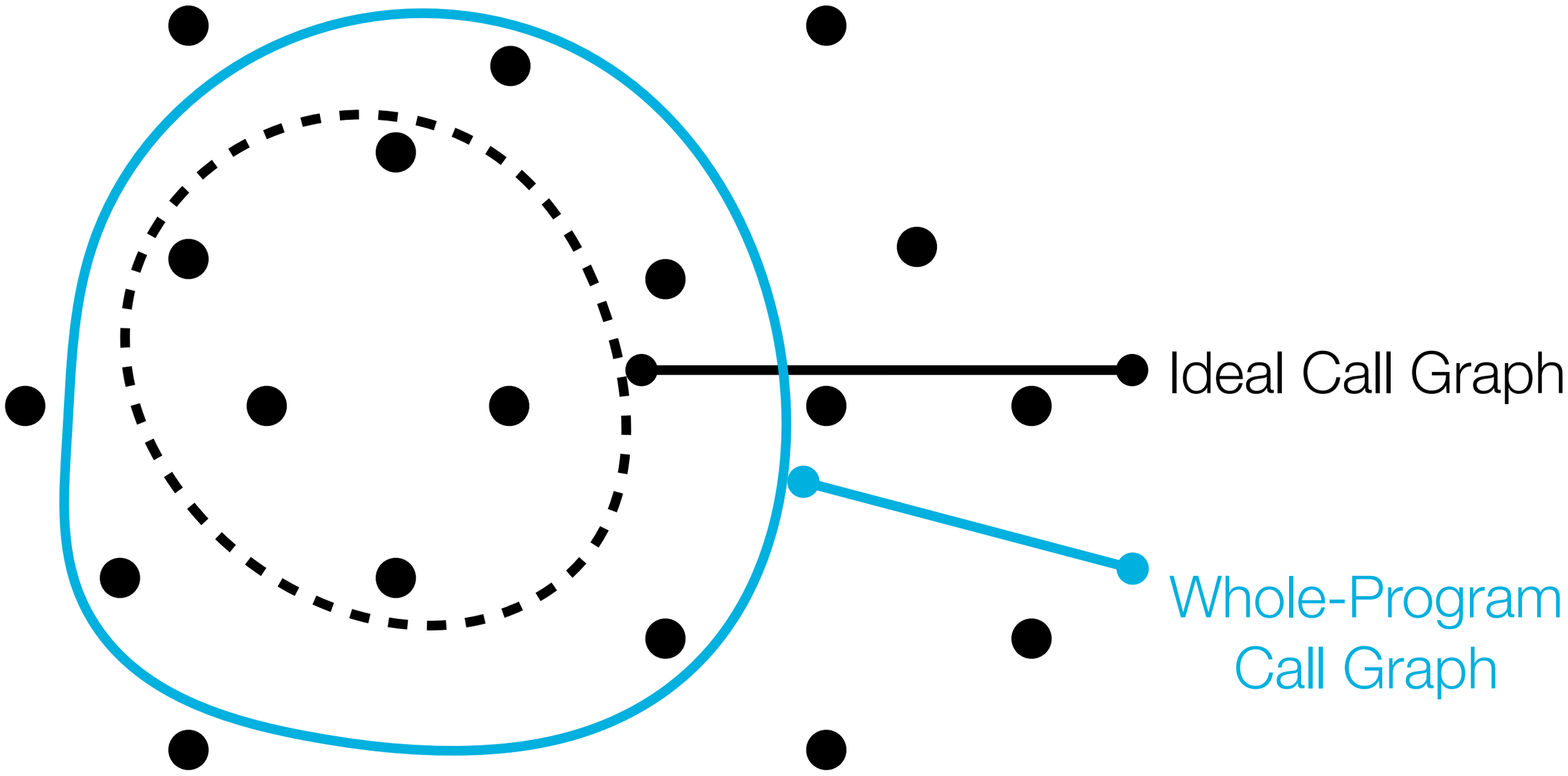


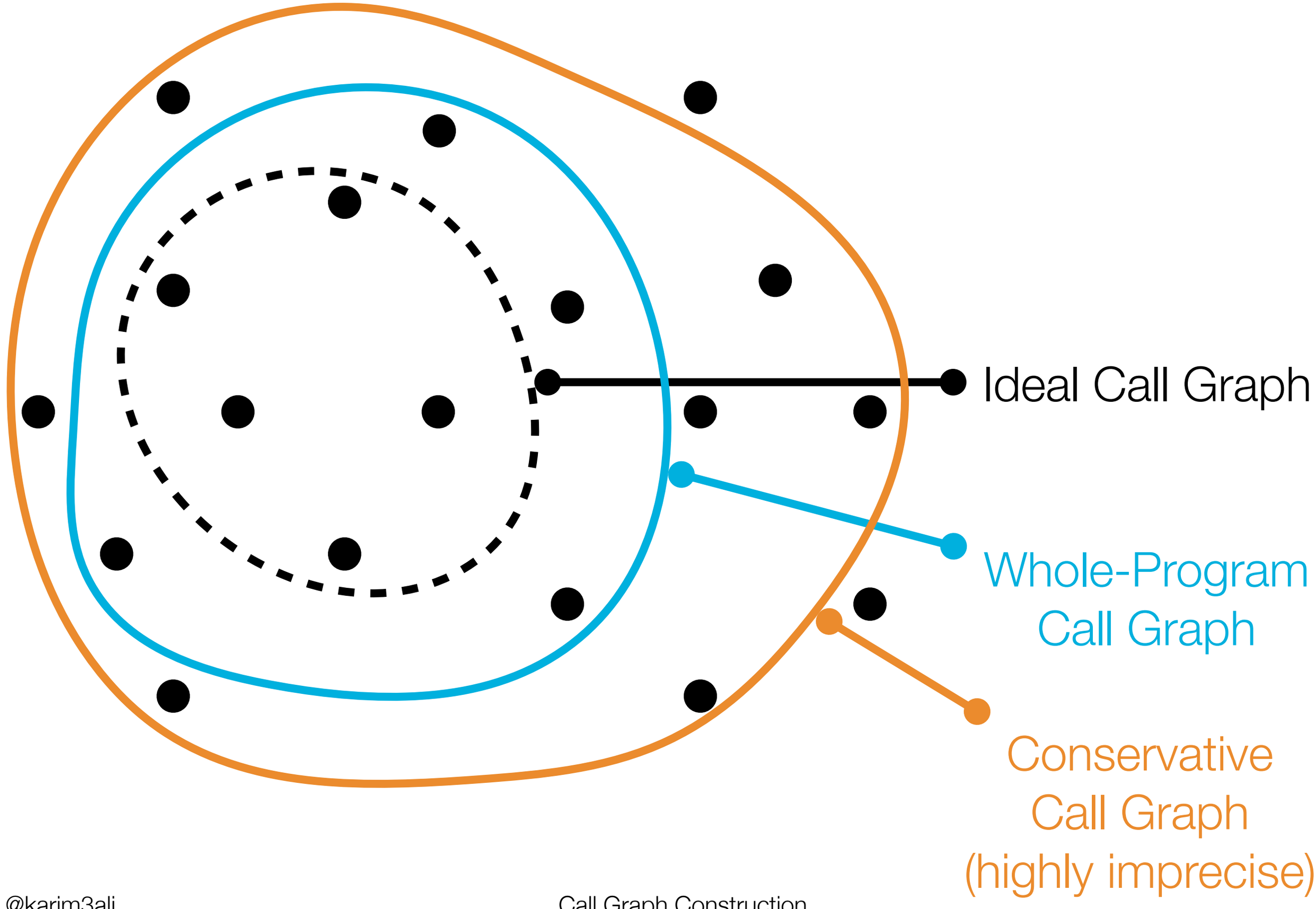


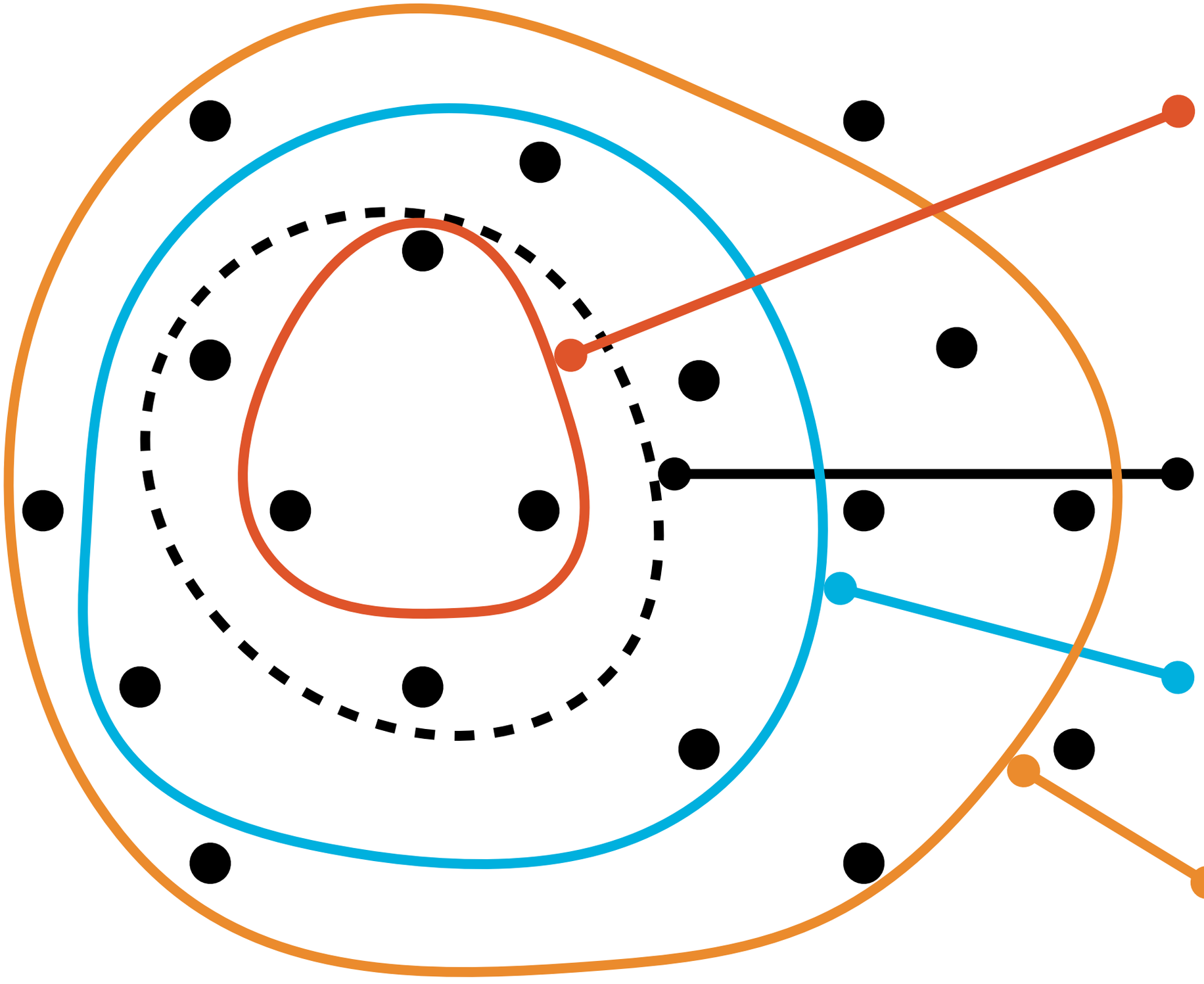


Alan designed the perfect computer

Ideal Call Graph


Ideal Call Graph
Whole-Program
Call Graph


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



Incomplete
Call Graph
(unsound)

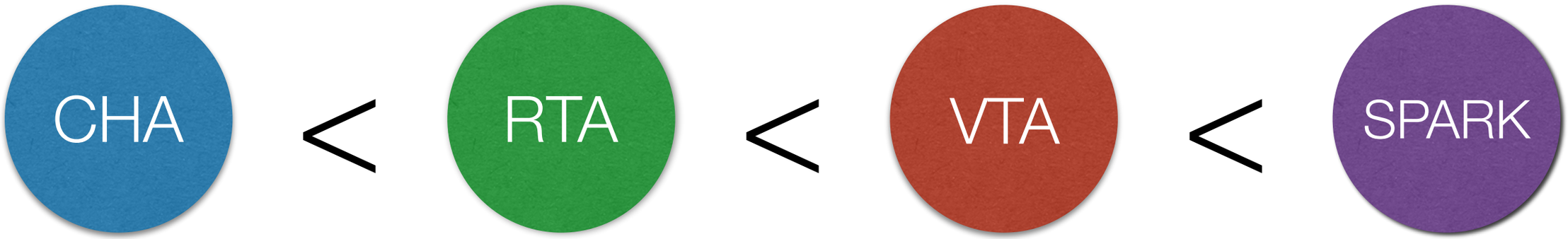
Ideal Call Graph

Whole-Program
Call Graph

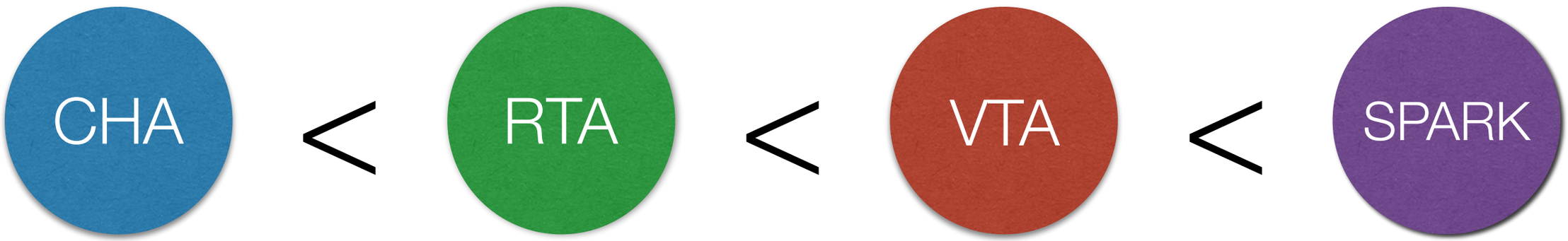
Conservative
Call Graph
(highly imprecise)

CG Algorithms

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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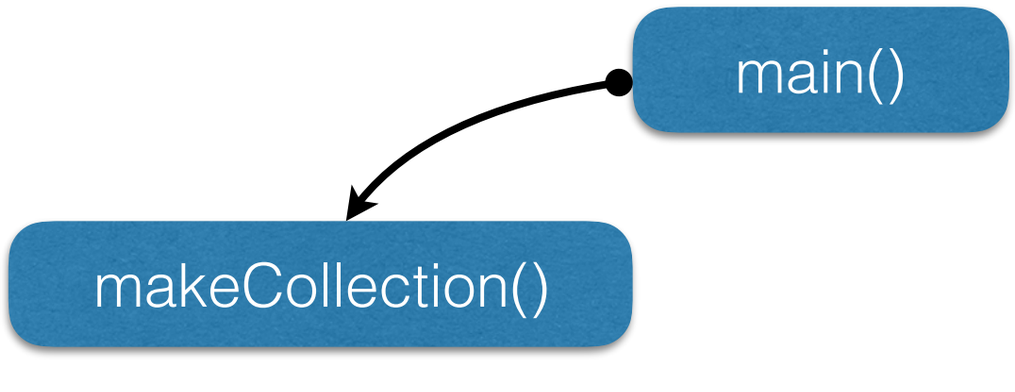
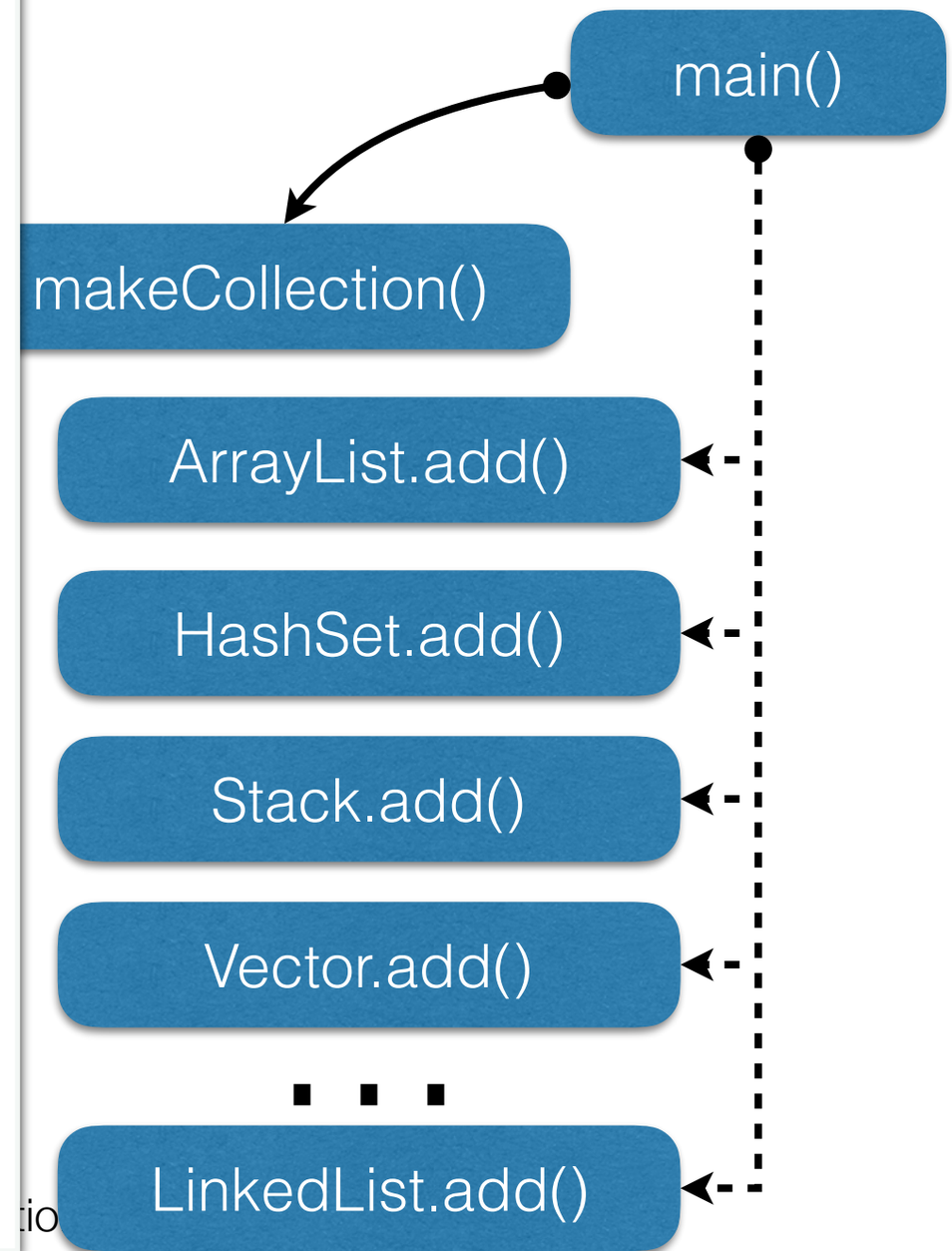



```
static Collection makeCollection(String s) {
  if(s.equals("list")) {
    return new ArrayList();
  } else {
    return new HashSet();
  }
}
```

ny 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>



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

- AbstractCollection<E>
  - AbstractList<E>
  - AbstractQueue<E>
  - AbstractSet<E>
  - ArrayDeque<E>
  - ConcurrentLinkedDeque<E>
  - Fixups
  - LinkedValues<K, V>
  - StringValues
  - ValueCollection<K, V>
  - Values<K, V>
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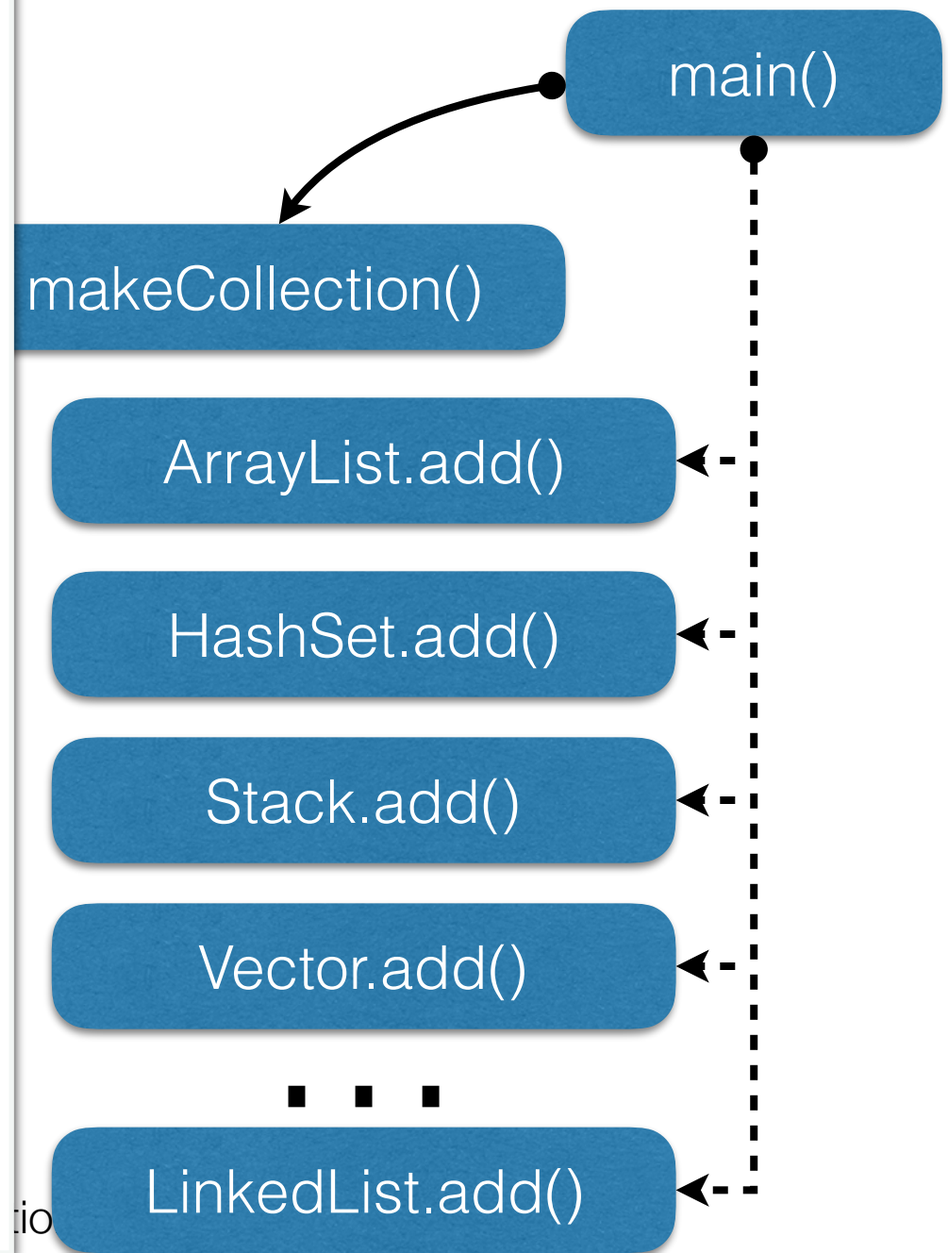
Analysis



Rapid Type Analysis

```
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    return new ArrayList();
  } else {
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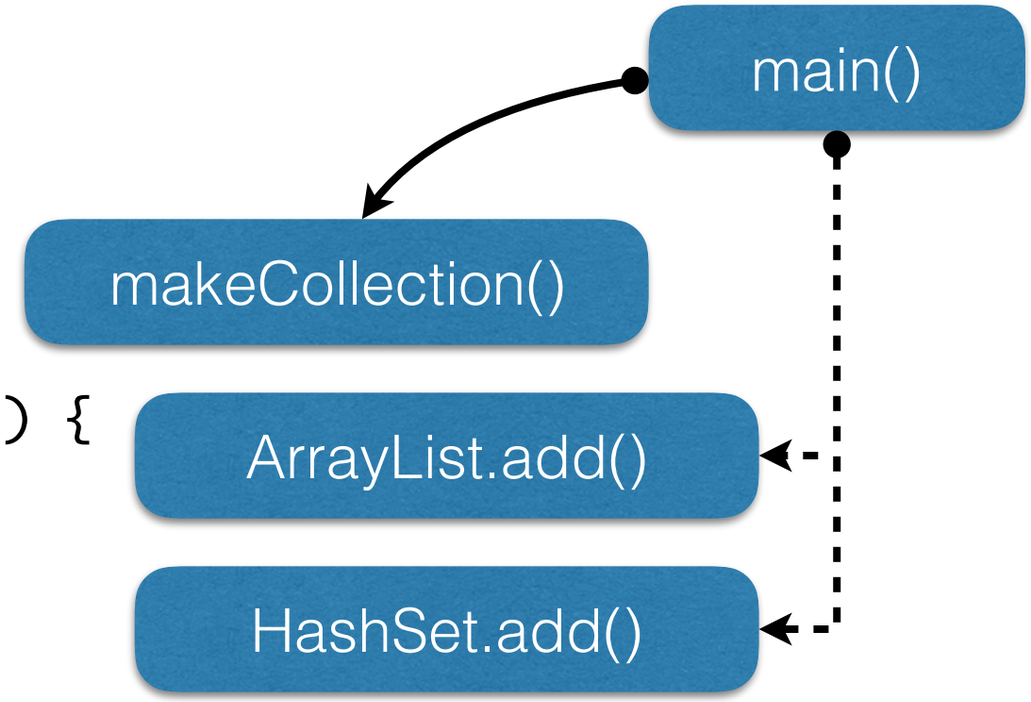
  }
}
```



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

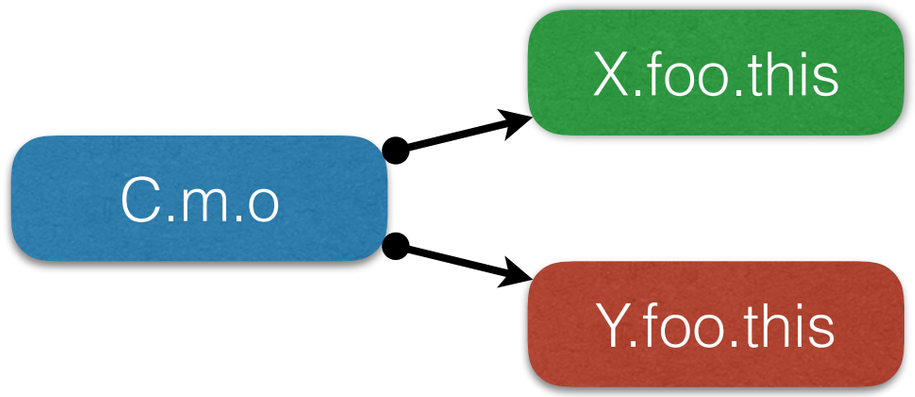
1. Start with a pre-computed call graph (e.g., CHA)
2. Build type propagation graph
3. Collapse strongly-connected components (SCCs)
4. Propagate types along the final Directed Acyclic Graph (DAG)

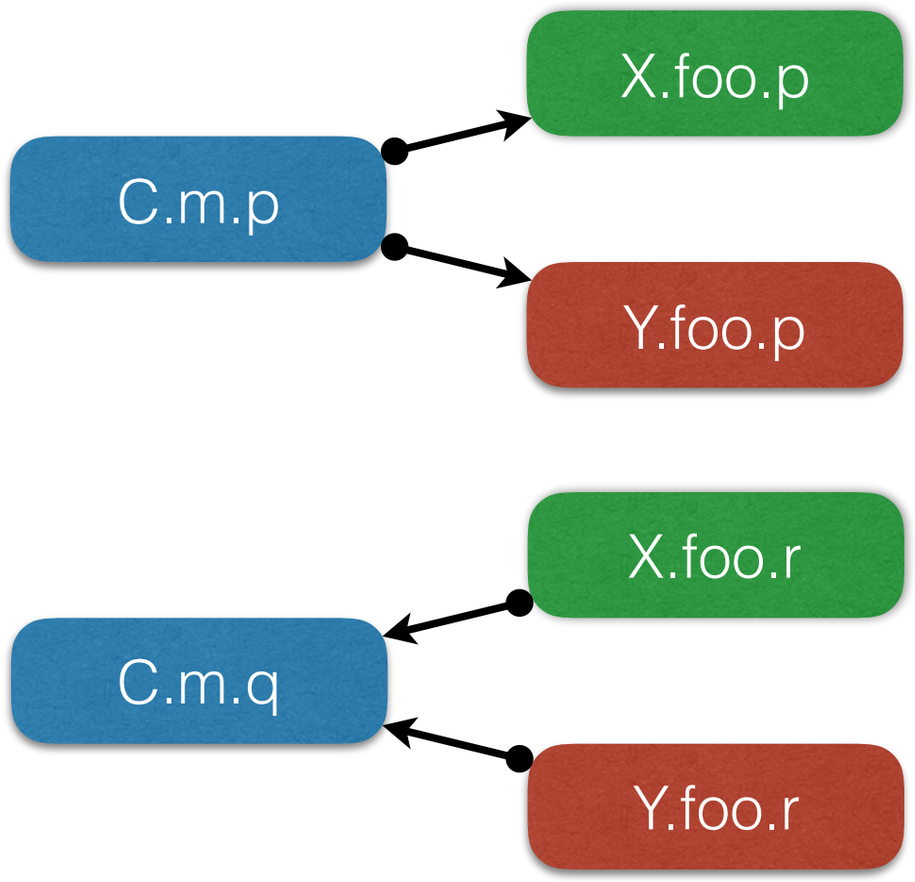
VTA - Step #1 … but why?

```
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();
c = new C();

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

VTA - Step #2

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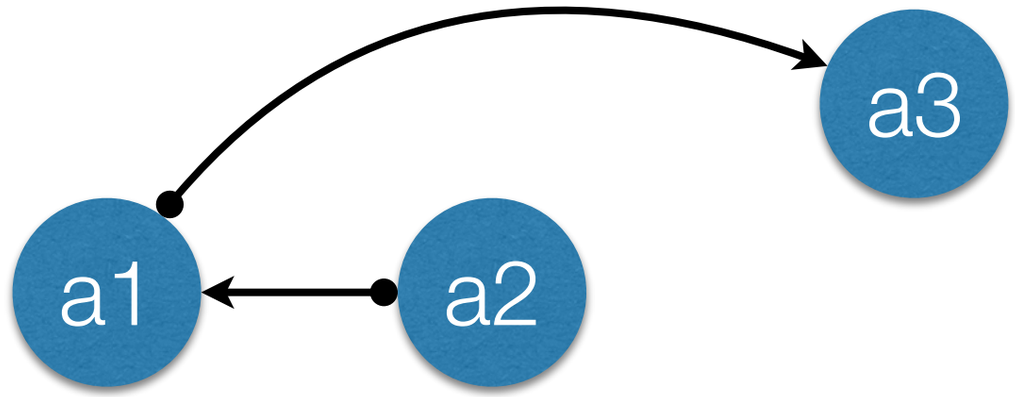

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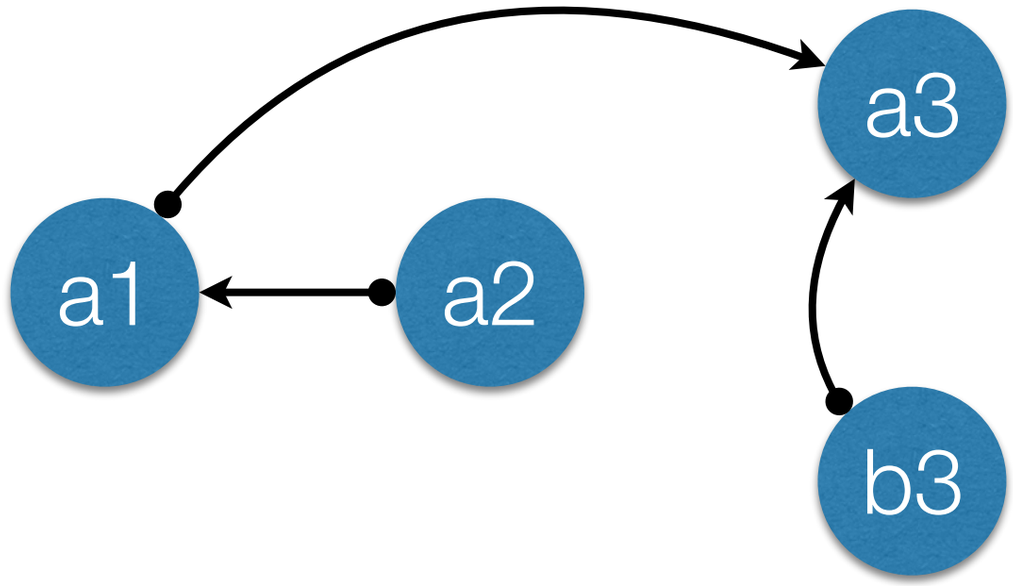

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C c;

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c = new C();

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b3 = (B) a3;
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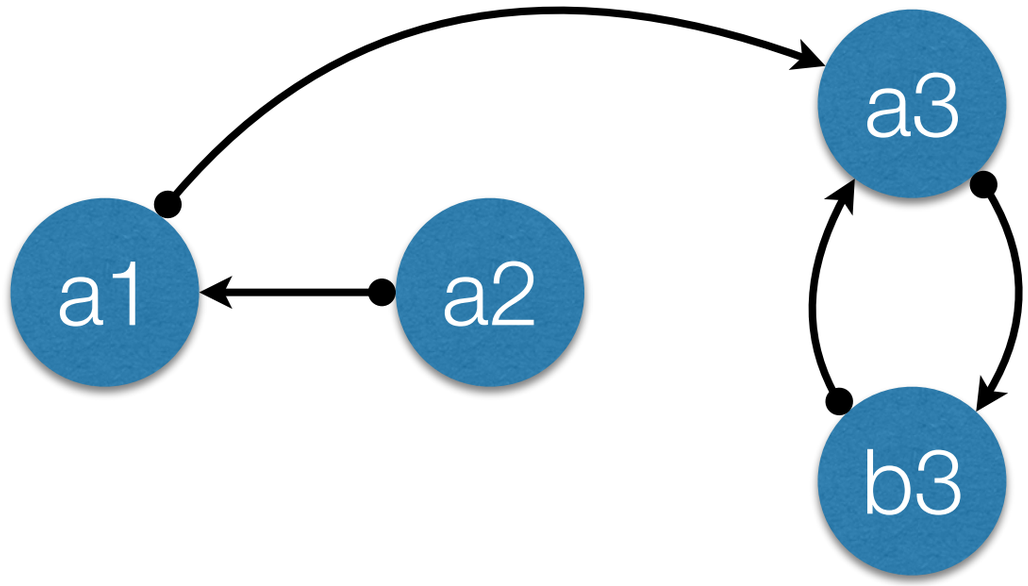
```



VTA - Step #2

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

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

a1 = a2;
a3 = a1;
a3 = b3;
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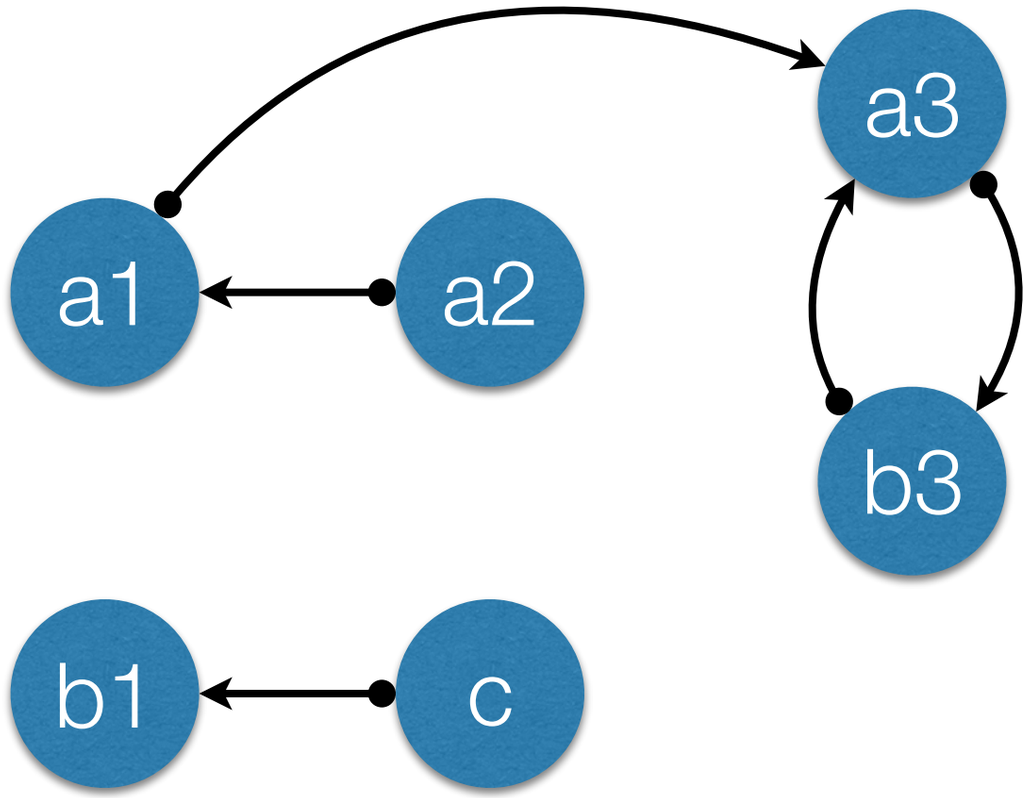
```



VTA - Step #2

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

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

a1 = a2;
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a3 = b3;
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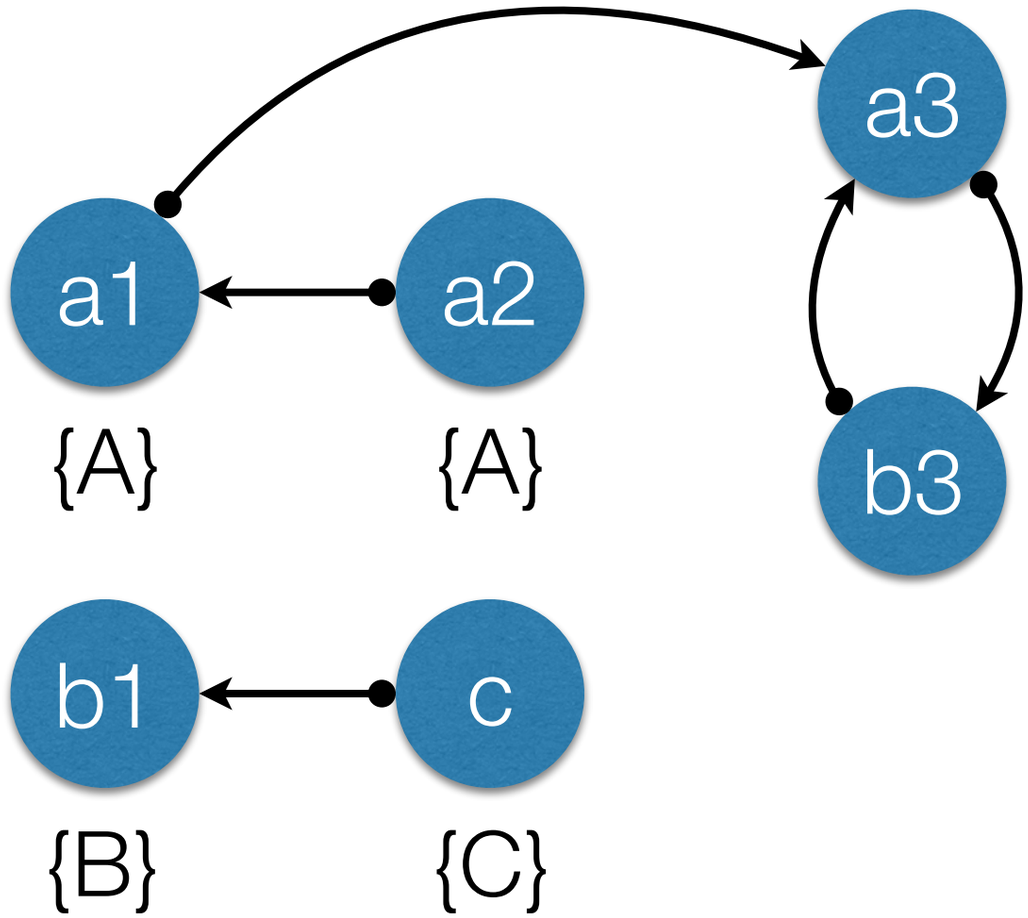
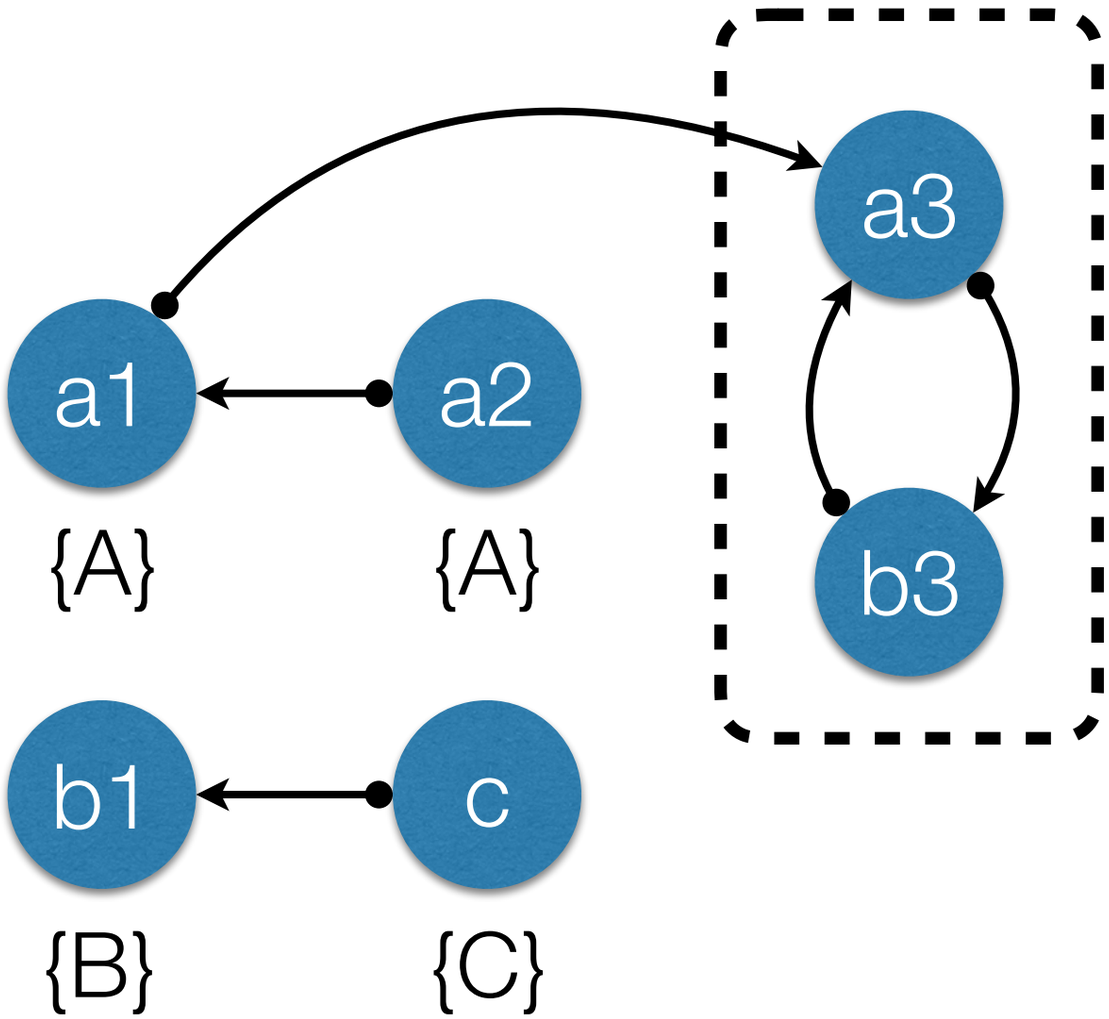


VTA - Step #3

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

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

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

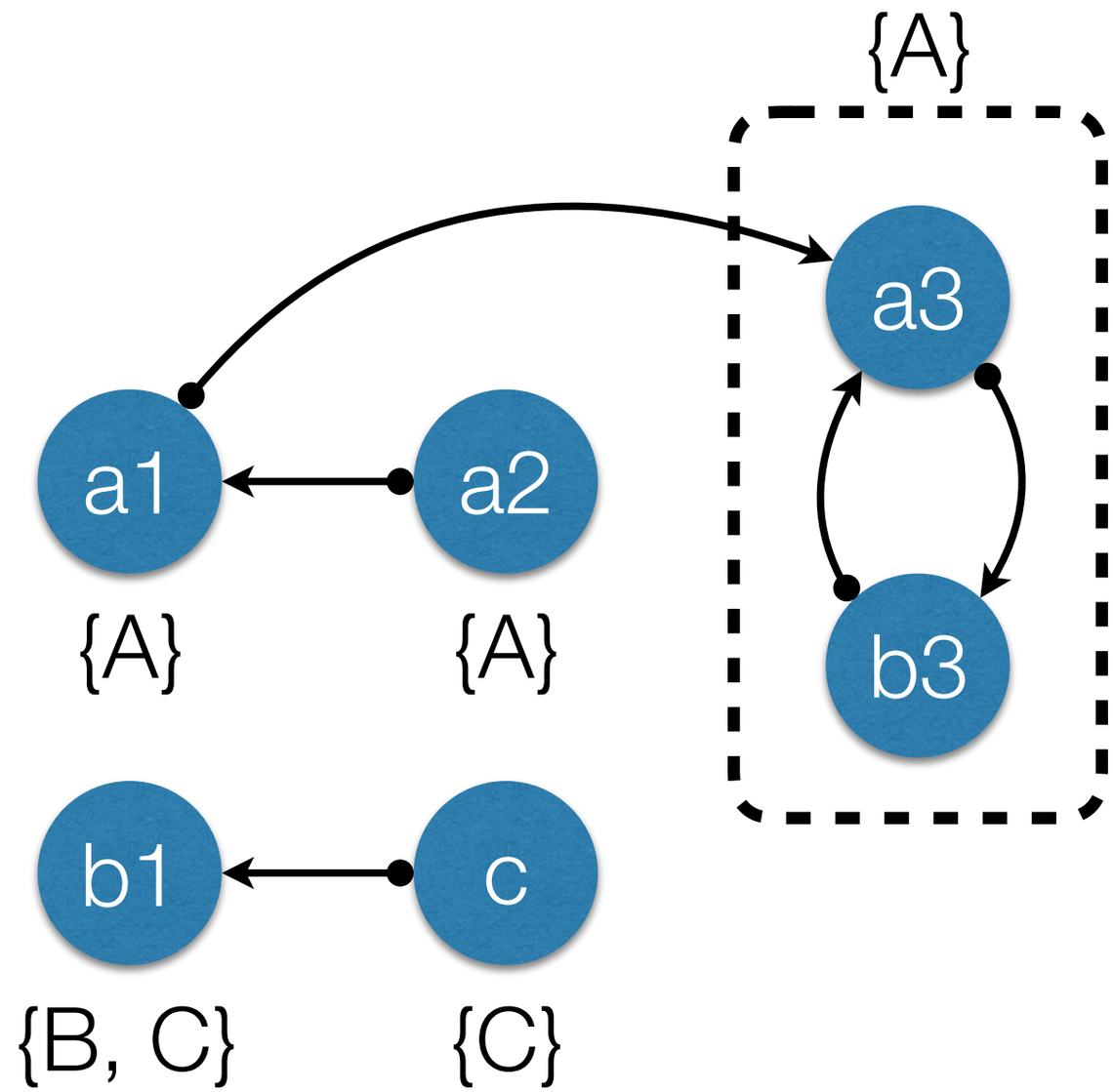


VTA - Step #4

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

a1 = new A();
a2 = new A();
b1 = new B();
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

Var

SPARK - PAG

Nodes

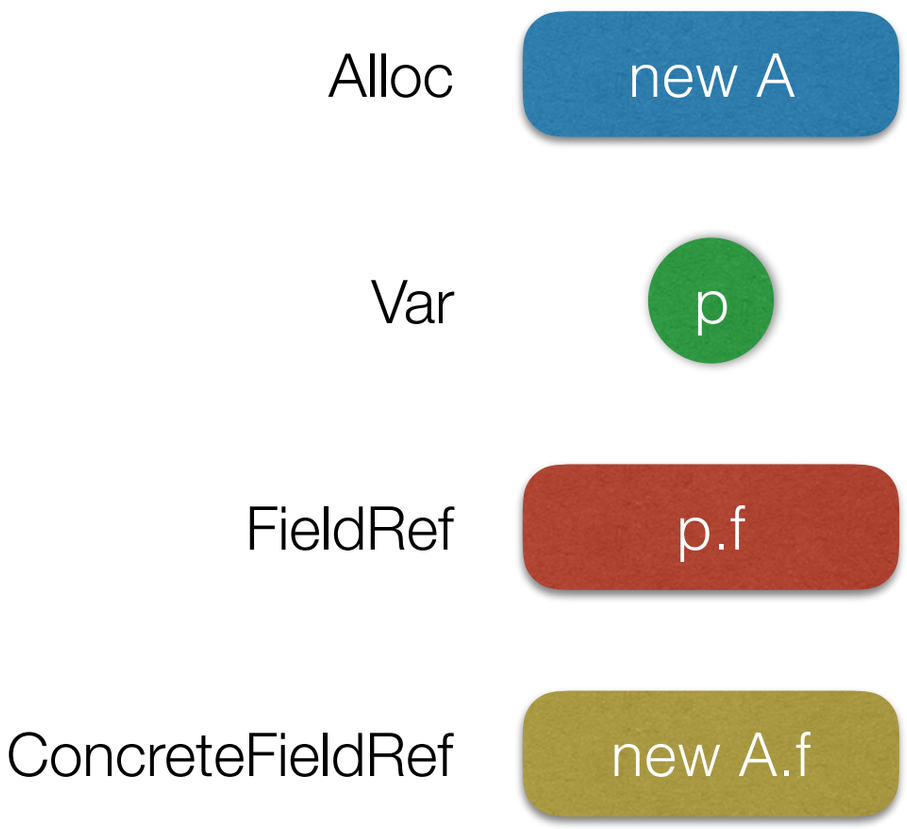
Alloc

Var

FieldRef

SPARK - PAG

Nodes



SPARK - PAG

Nodes

Alloc new A

Var p

FieldRef p.f

ConcreteFieldRef new A.f

Edges

Alloc new A → p

SPARK - PAG

Nodes

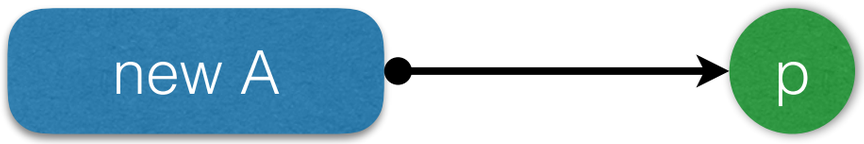
Alloc 

Var 

FieldRef 

ConcreteFieldRef 

Edges

Alloc 

Assign 

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

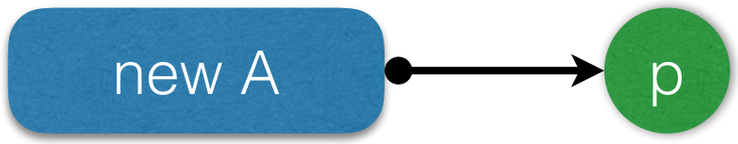
PAG - VarNode

- 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

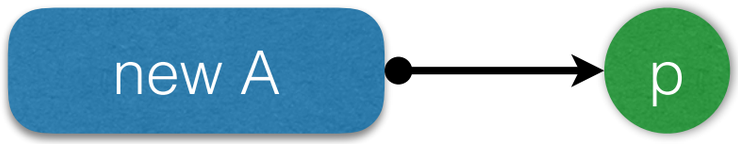
PAG - AllocEdge



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

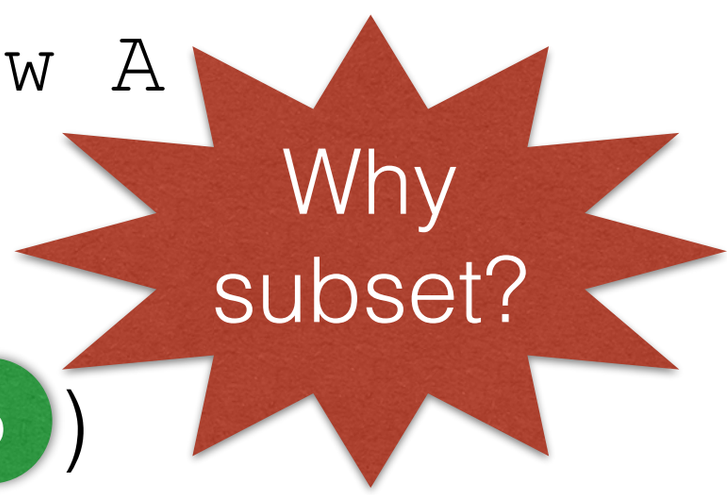
Allocation is independent of calling the constructor

PAG - AllocEdge



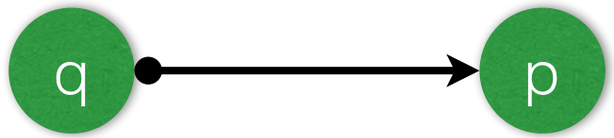
- Models the statement `p = new A`
- E.g., `hm = new HashMap`
- Induces the constraint

  pts-to(new A) ⊆ pts-to(p)



Andersen, Lars Ole. Program analysis and specialization for the C programming language. Phd Thesis. University of Copenhagen, 1994.

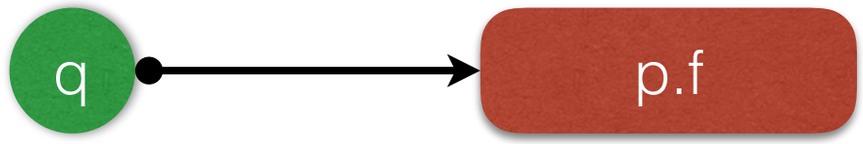
PAG - AssignEdge



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

pts-to(q) ⊆ pts-to(p)

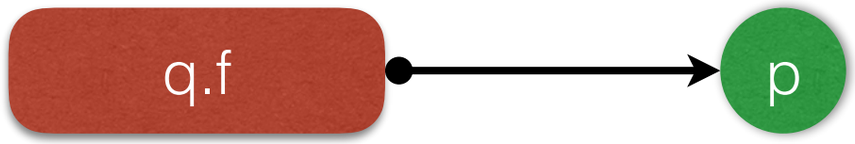
PAG - StoreEdge



- 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

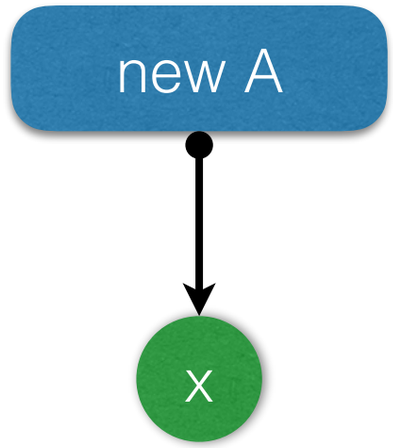
```
void foo {
  x = new A();
  y = x;
  z = new A();
  x.f = z;
  t = bar(y);
}

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);
}

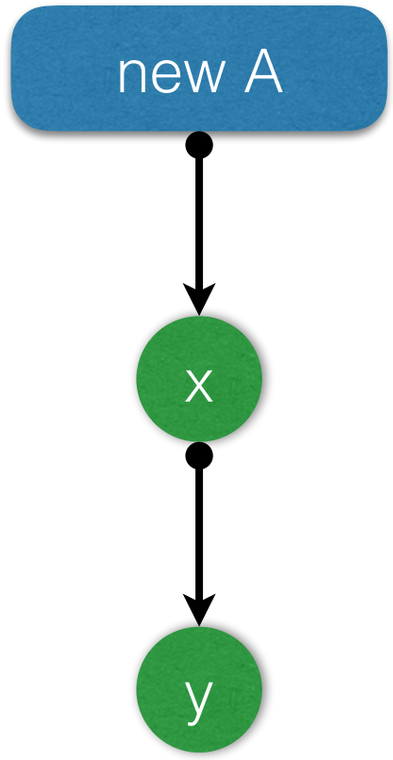
A bar(A p) {
   return p.f;
}
```



PAG - Example

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

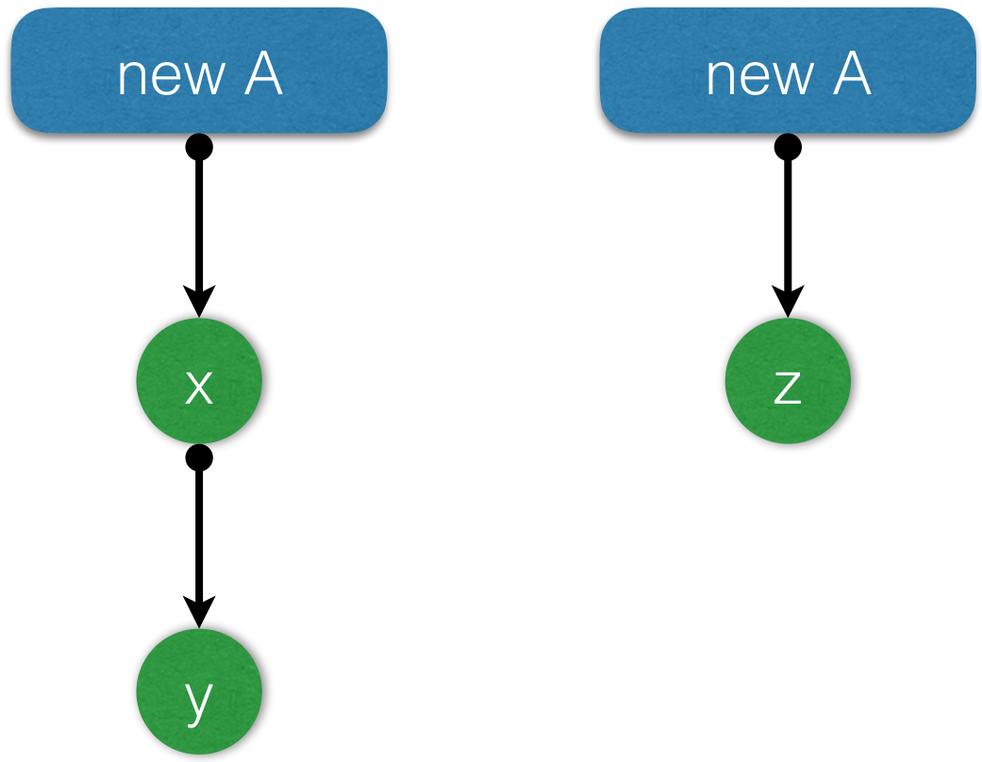
A bar(A p) {
   return p.f;
}
```



PAG - Example

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

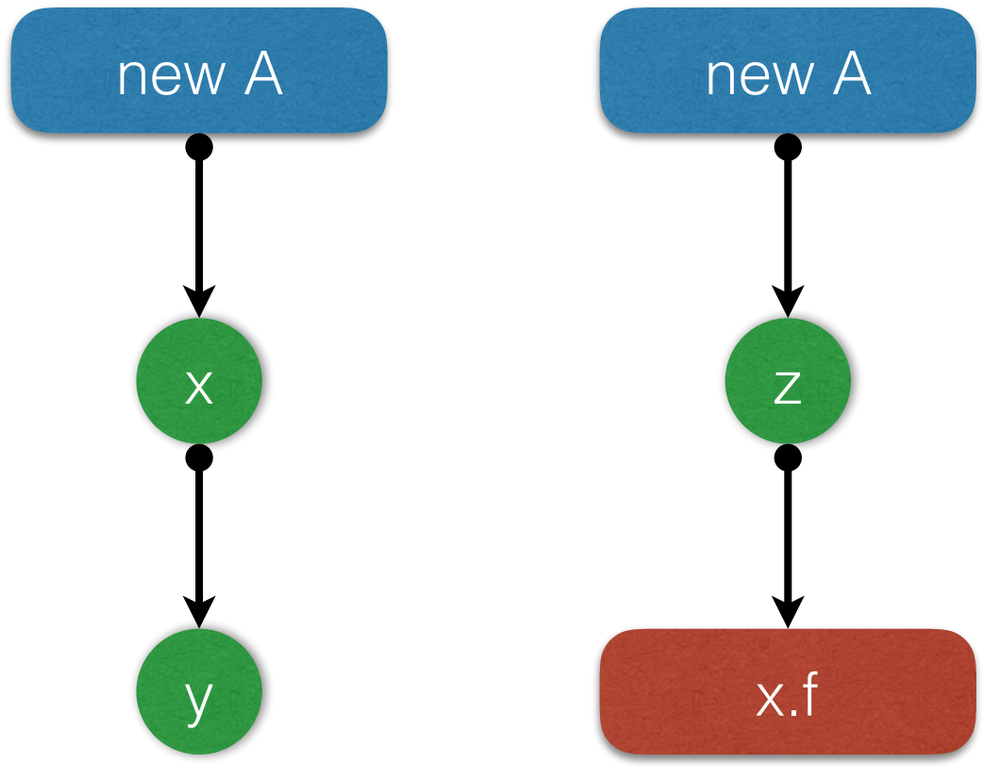
A bar(A p) {
   return p.f;
}
```



PAG - Example

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

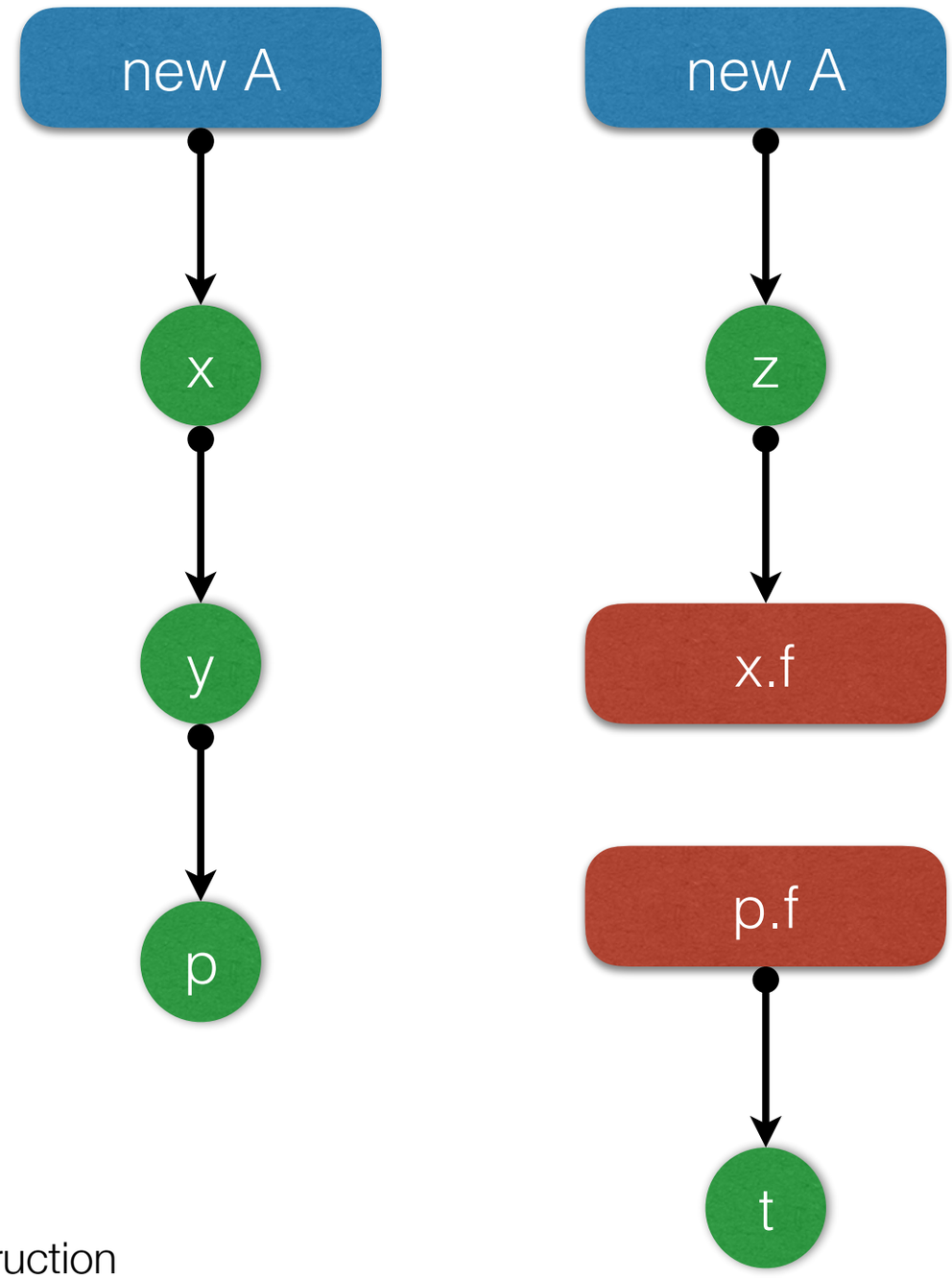
A bar(A p) {
   return p.f;
}
```



PAG - Example

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

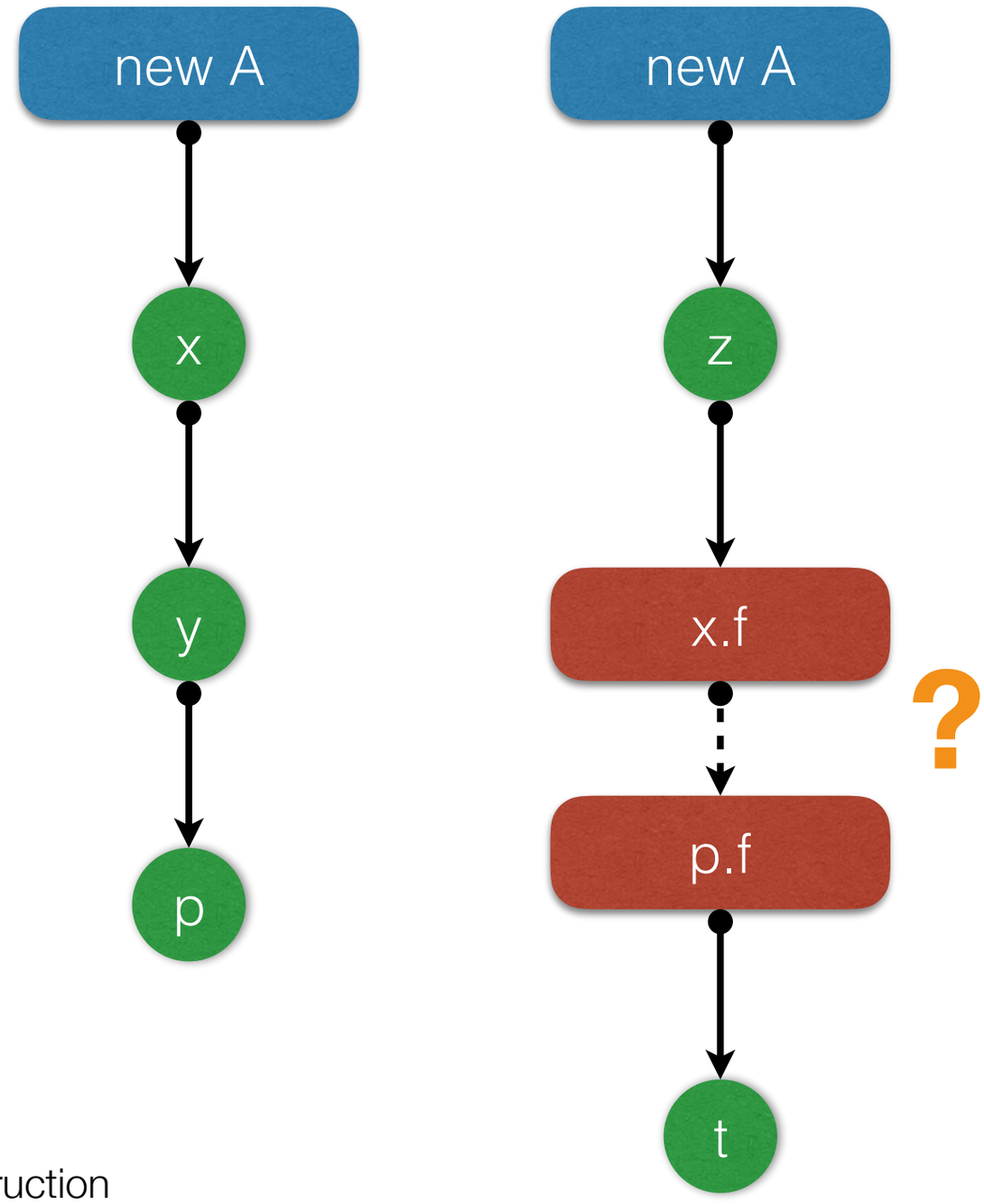
A bar(A p) {
   return p.f;
}
```



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

Field-sensitive

a.*

Field-insensitive

A.f

Field-based

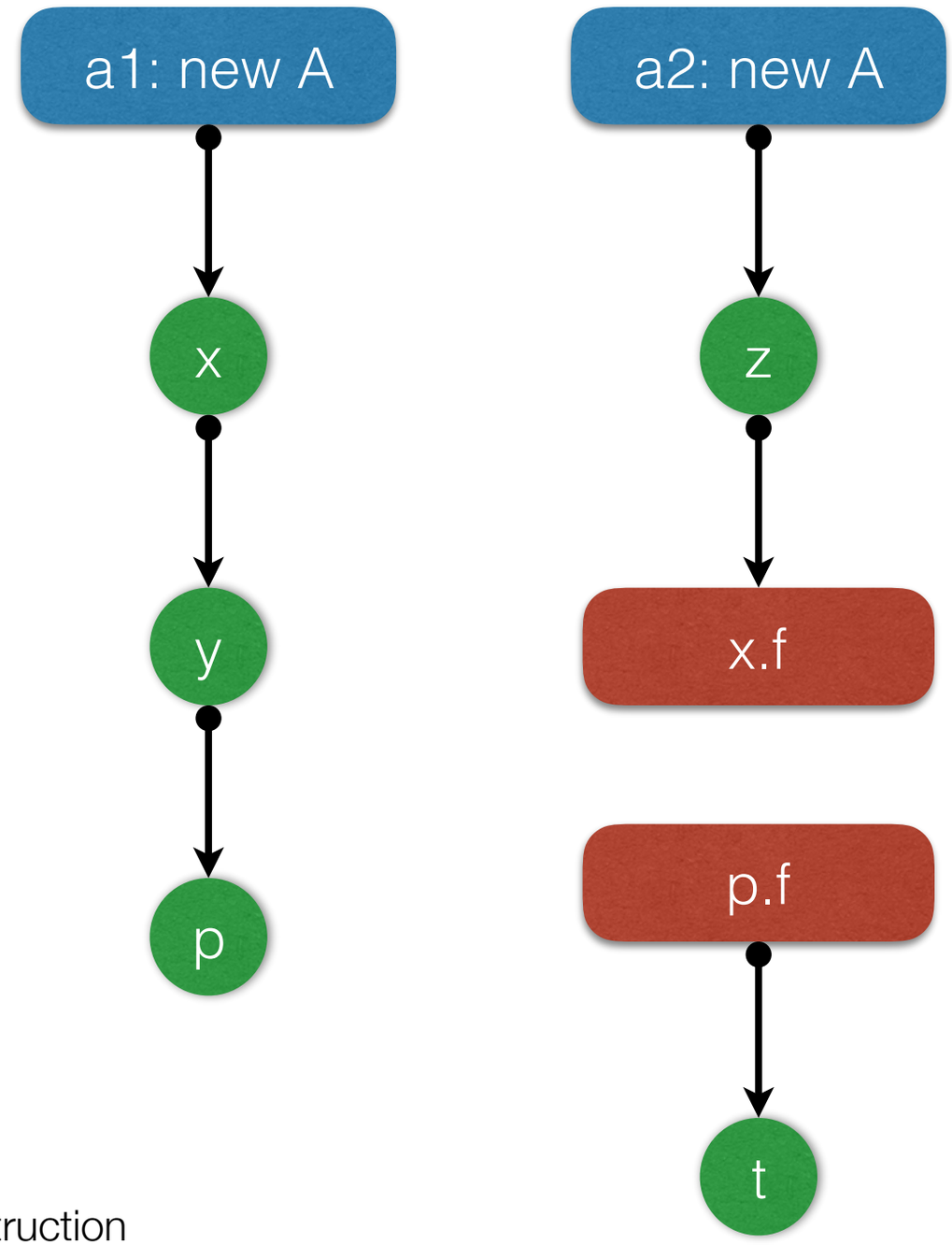
PAG - Other Considerations

- Static Initializers
- Object.finalize()
- Thread.start()
- Reflection

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;
}
```

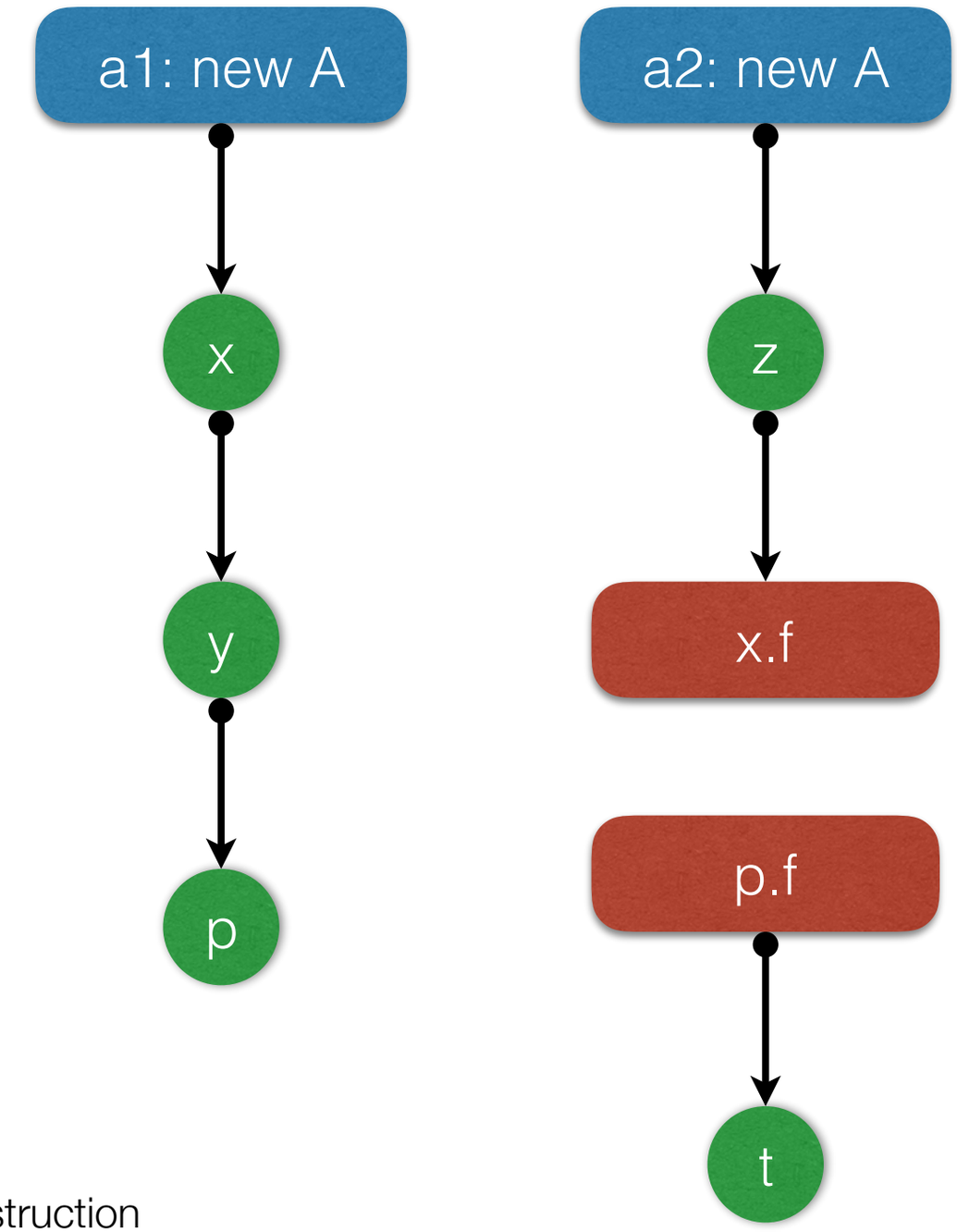


SPARK
Points-to Propagation

```
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}

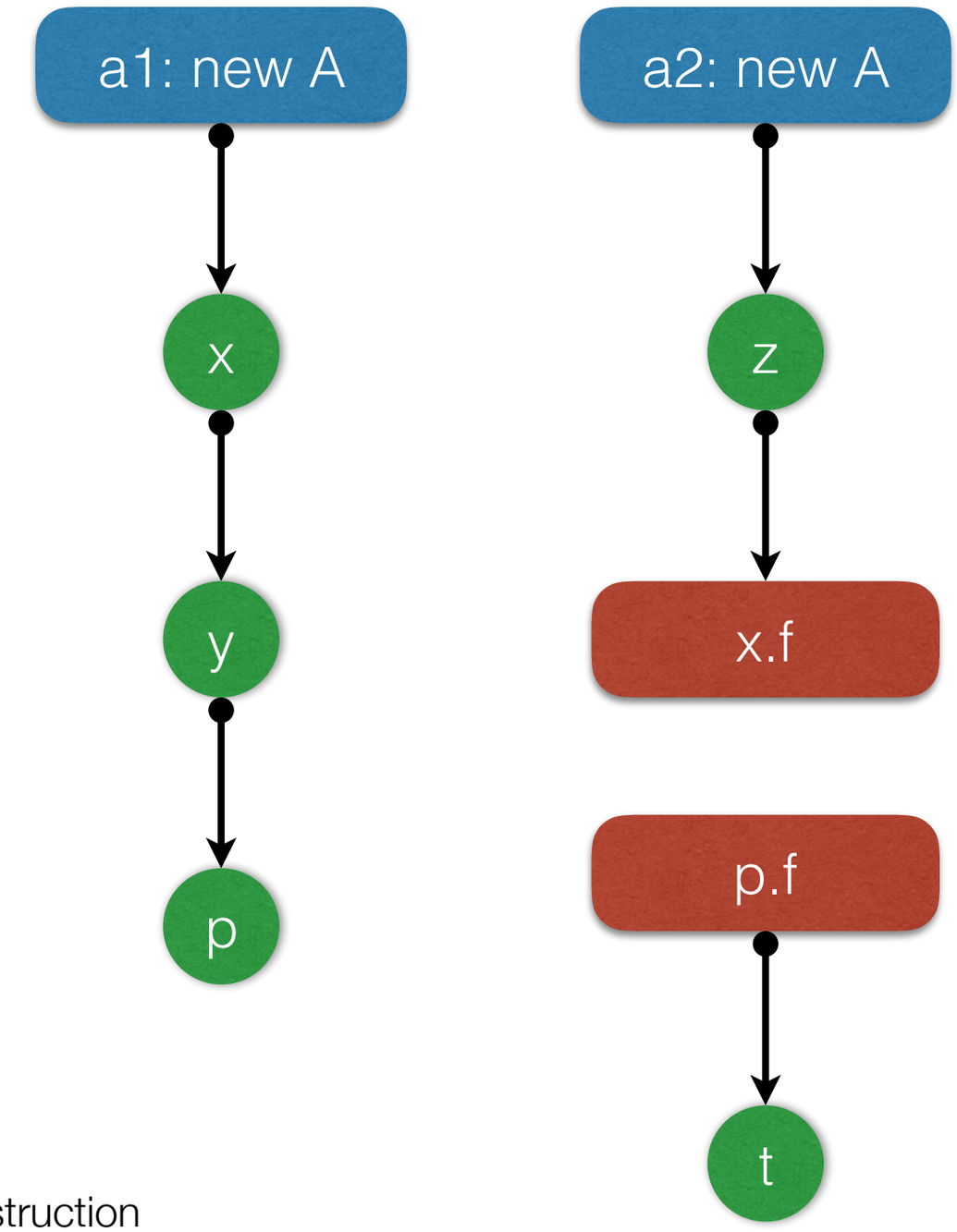


SPARK
Points-to Propagation

```
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}

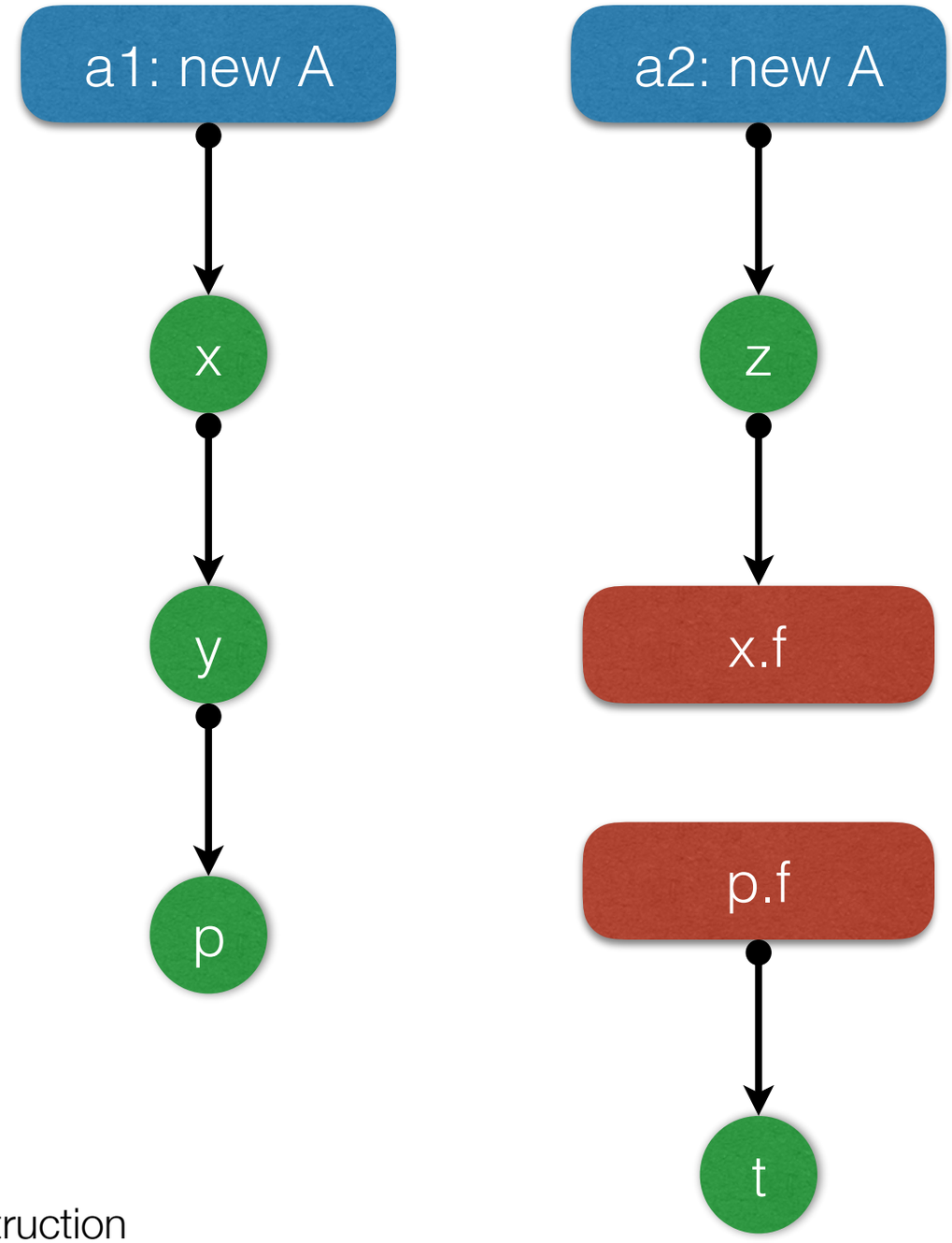


SPARK
Points-to Propagation

```
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}
```

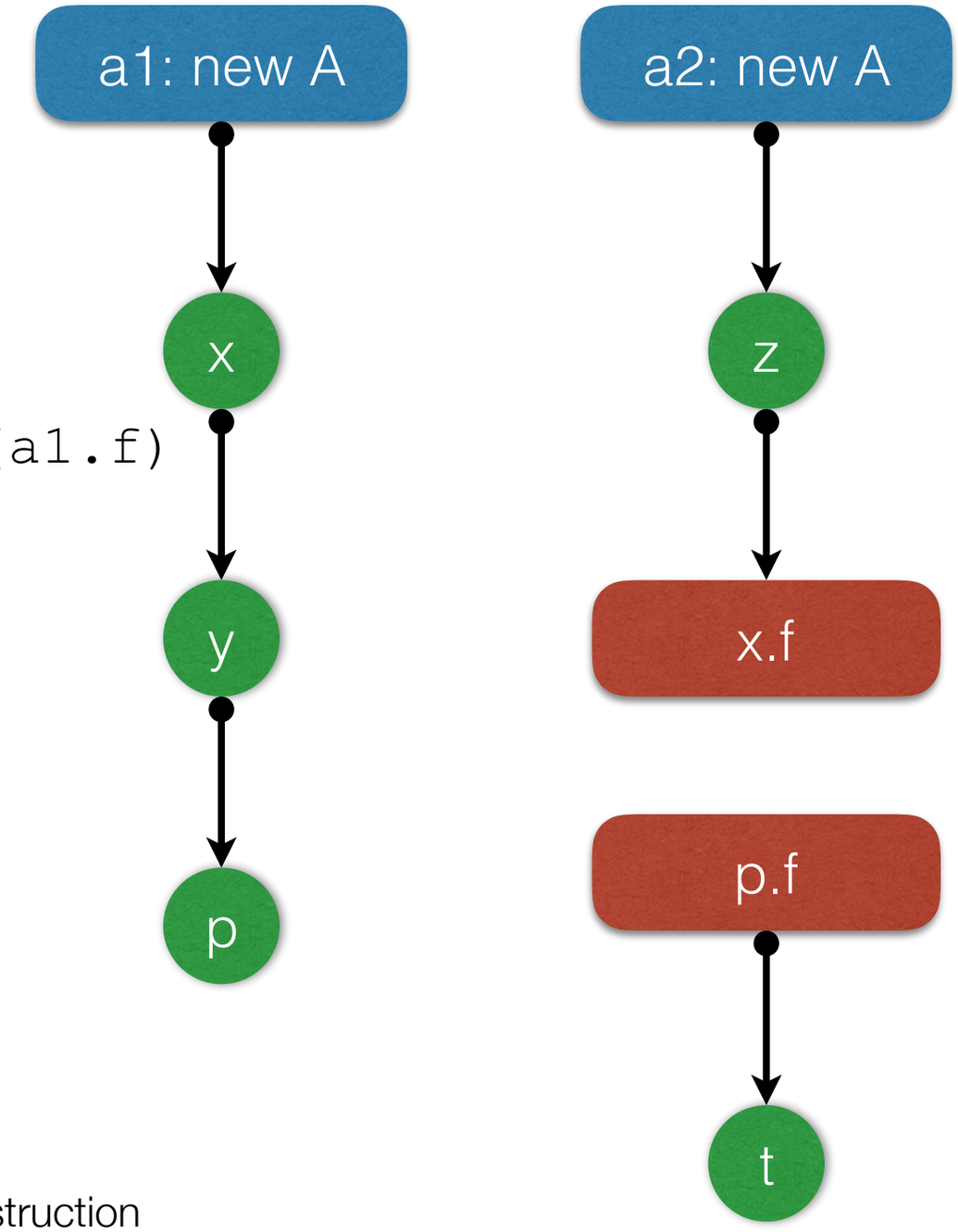


SPARK
Points-to Propagation

```
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}
```

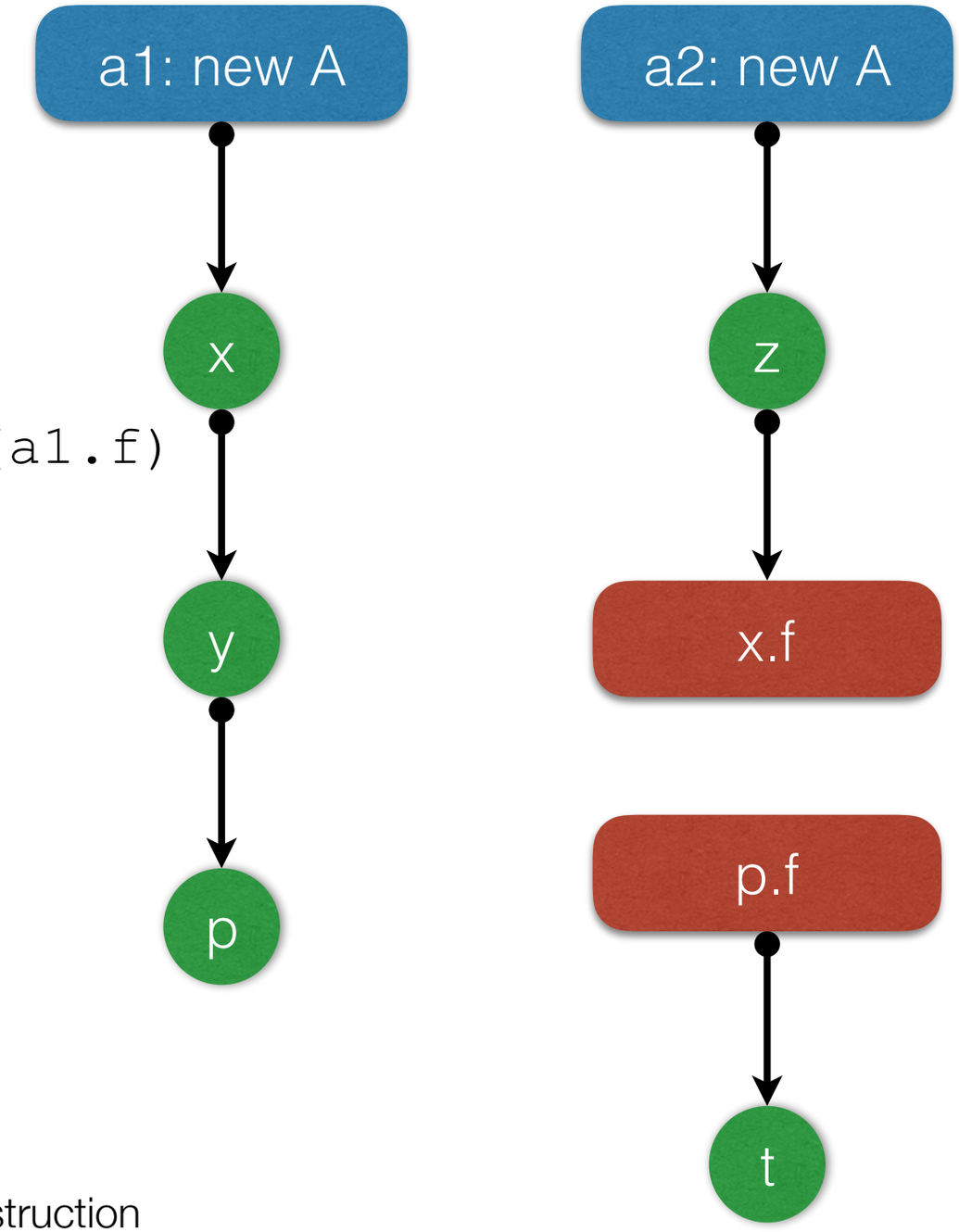


SPARK
Points-to Propagation

```
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}
```

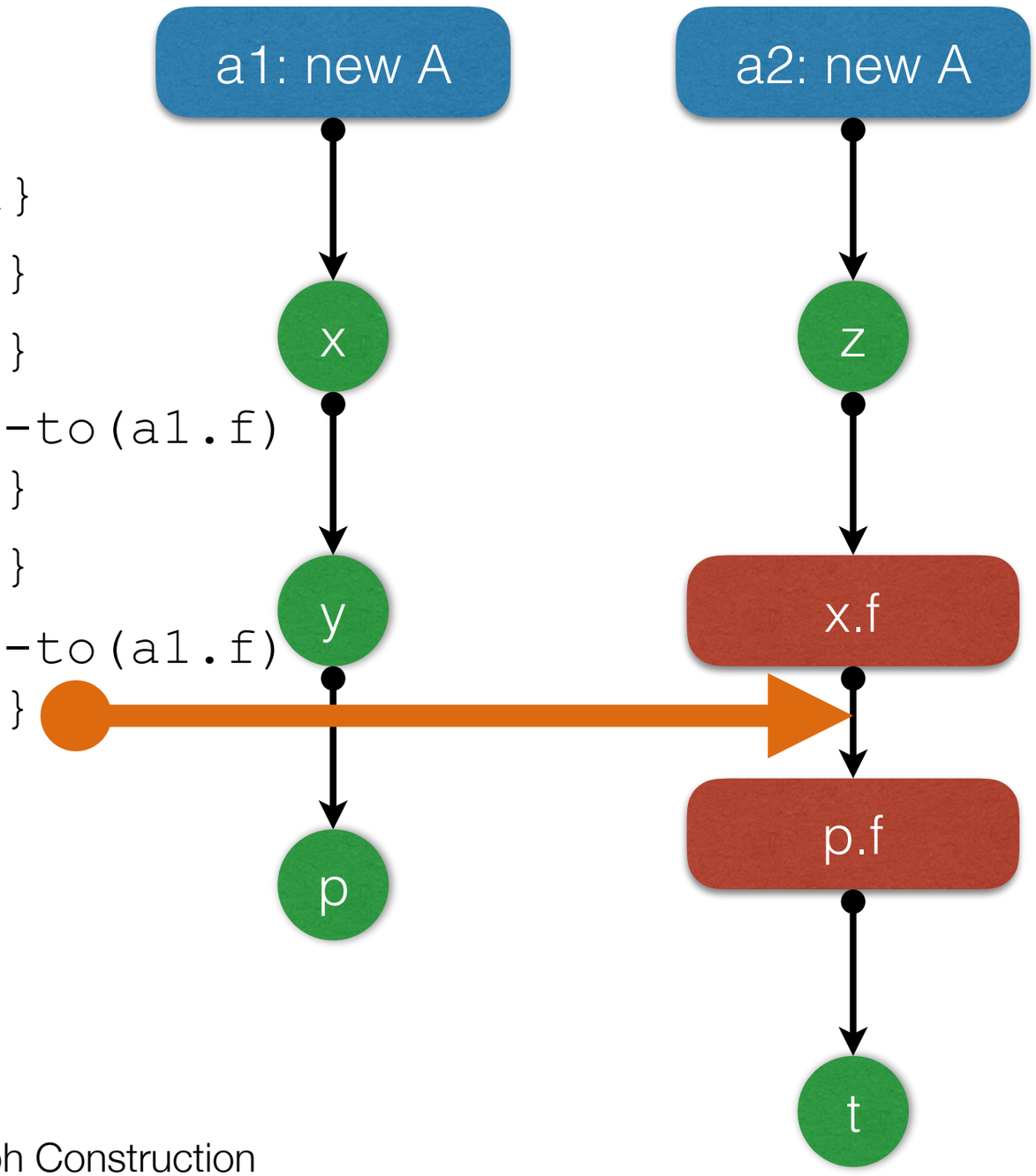


SPARK
Points-to Propagation

```
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}
```

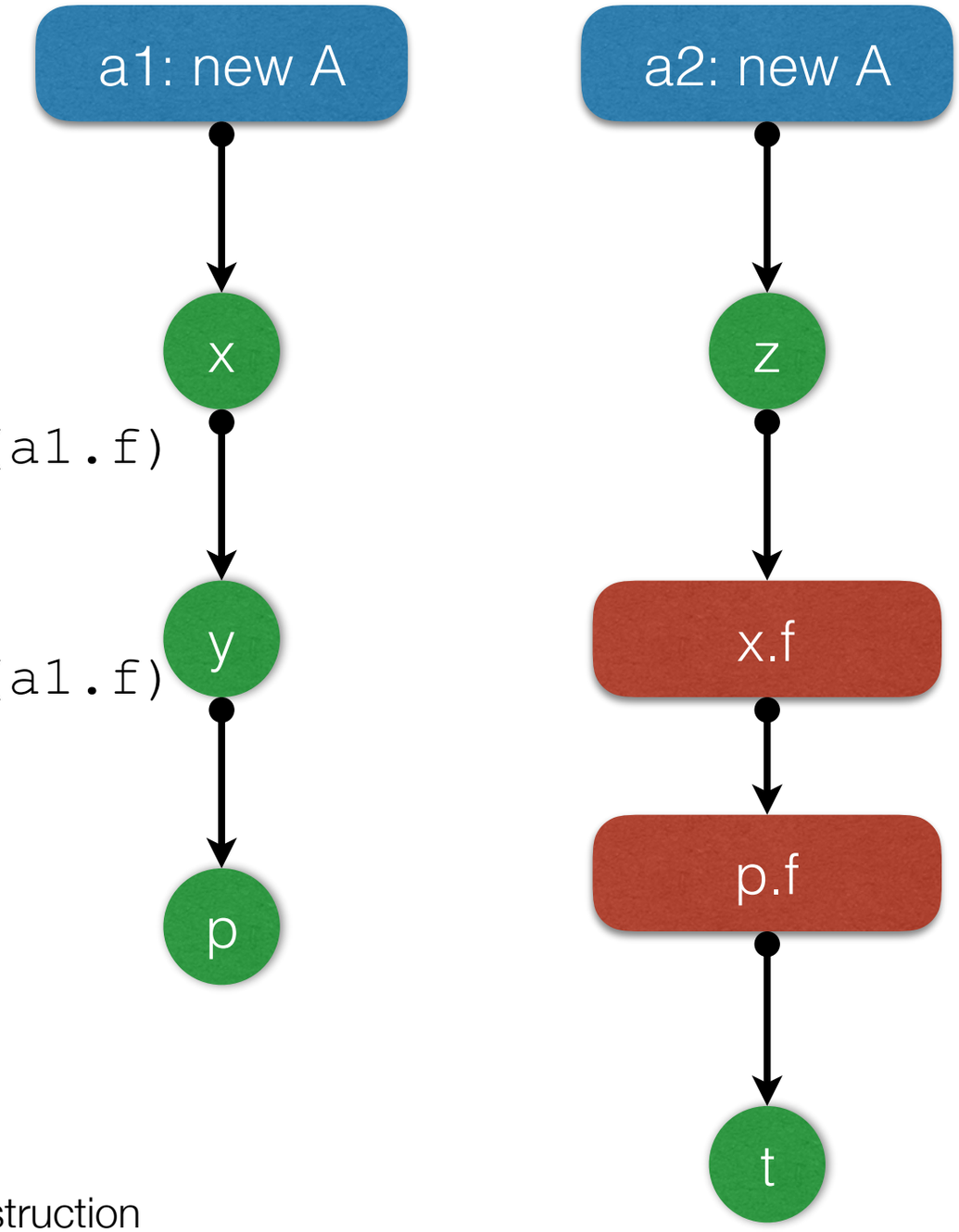


SPARK
Points-to Propagation

```
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

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

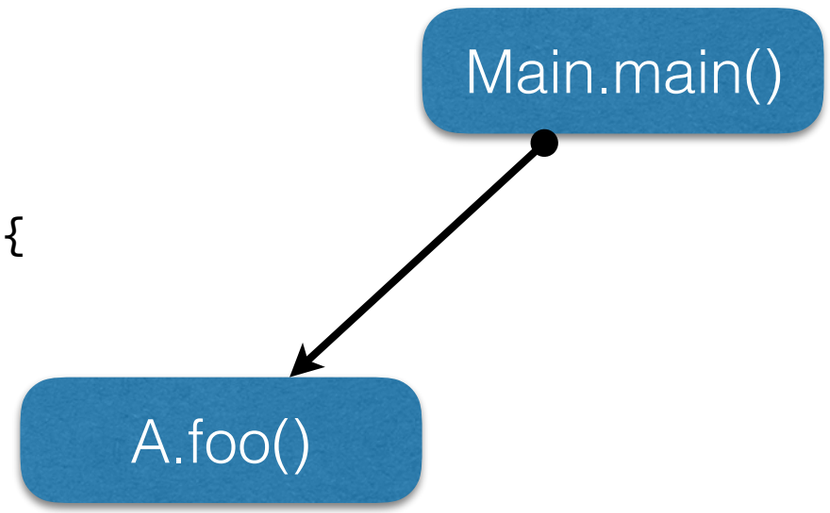
SPARK - OTF CG Construction

```
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()

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

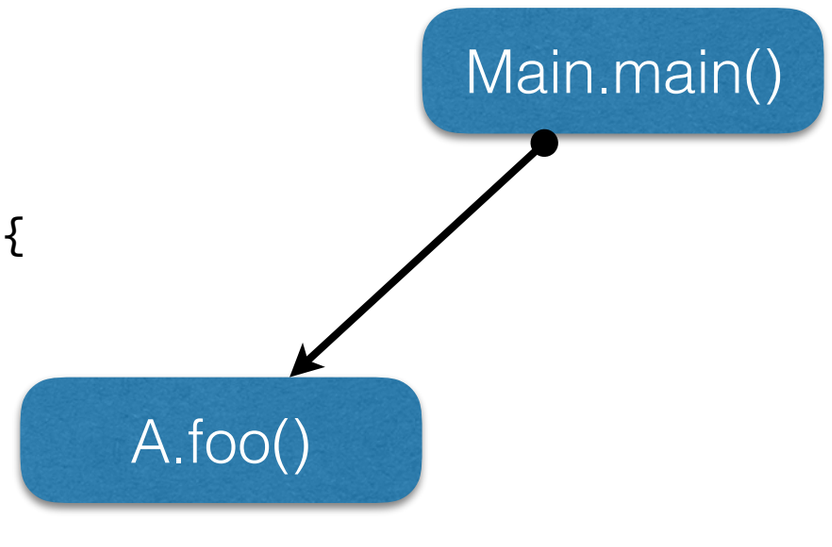
SPARK - OTF CG Construction

```
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.foo()

Reachable

Main.main()

A.foo()

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

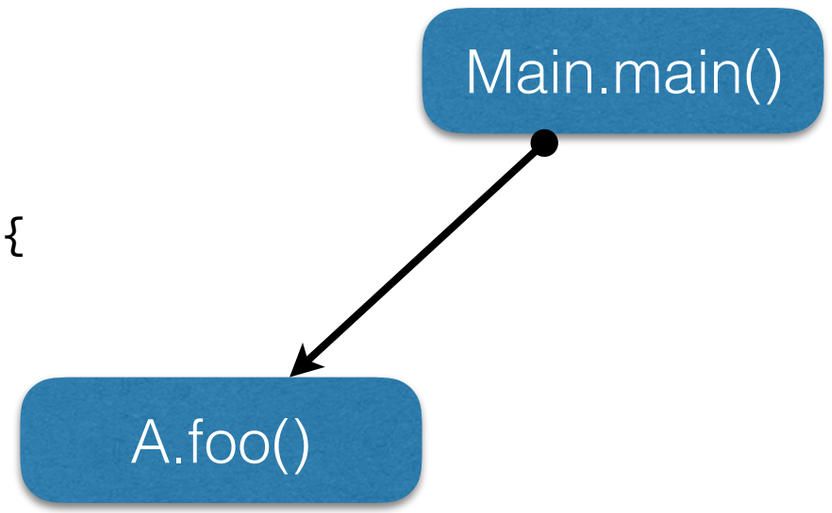
SPARK - OTF CG Construction

```
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.foo()

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

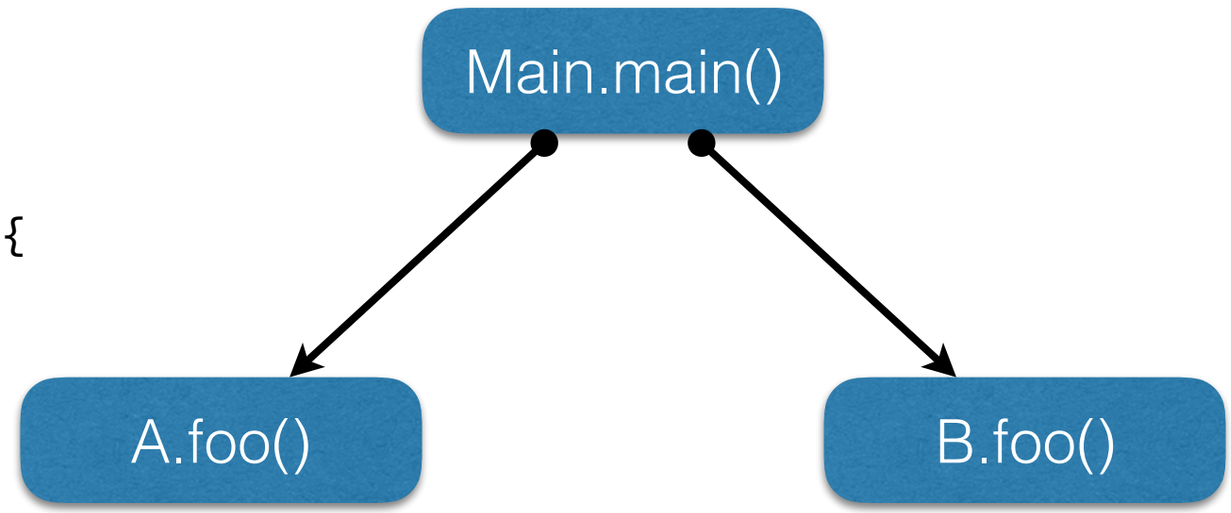
SPARK - OTF CG Construction

```
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.foo()

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

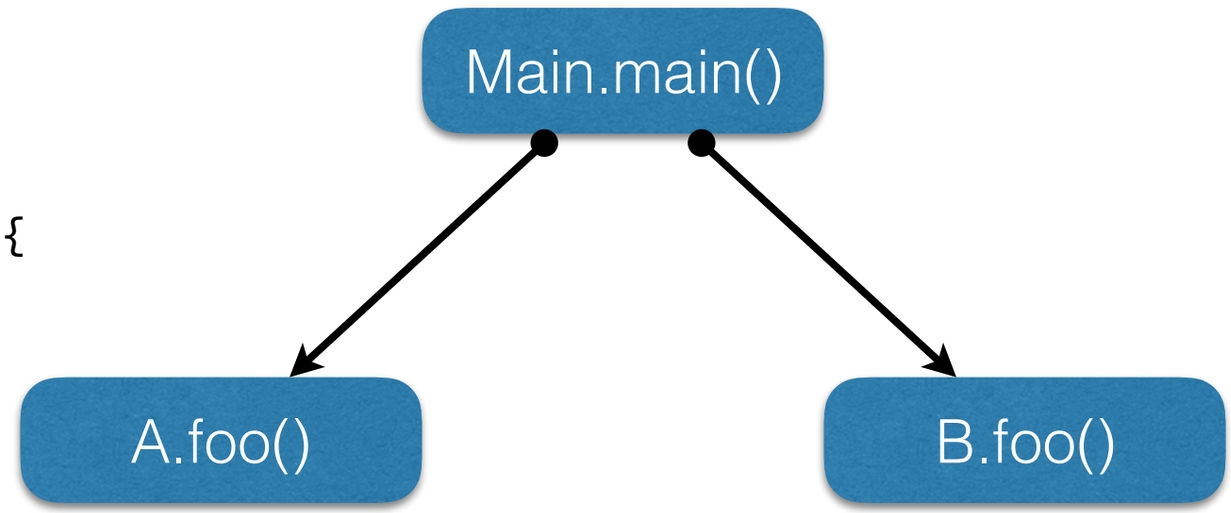
SPARK - OTF CG Construction

```
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()

A.foo()

B.foo()

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

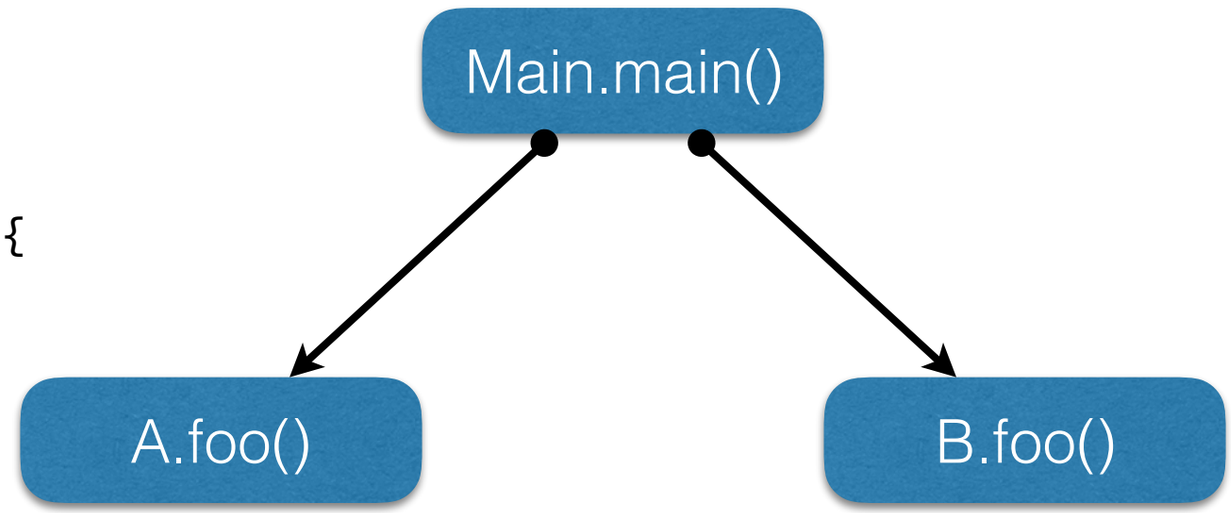
SPARK - OTF CG Construction

```
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

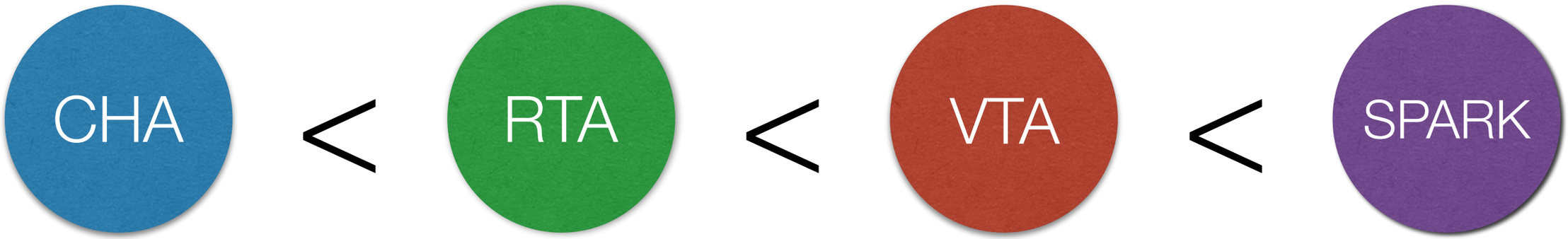
Reachable

Main.main()

A.foo()

B.foo()

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


CHA
<
RTA
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VTA
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SPARK

Practice Time!

Requirements

- Clone the following repos into your Eclipse workspace

  - `git clone` https://github.com/Sable/soot

  - `git clone` https://github.com/Sable/jasmin

  - `git clone` https://github.com/Sable/heros

  - `git clone` https://github.com/karimhamdanali/probe

- Do a `git pull` https://github.com/stg-tud/apsa and add the Eclipse project “callgraphs” to your Eclipse setup