Alias Analysis with IFDS

Applied Static Analysis 2016

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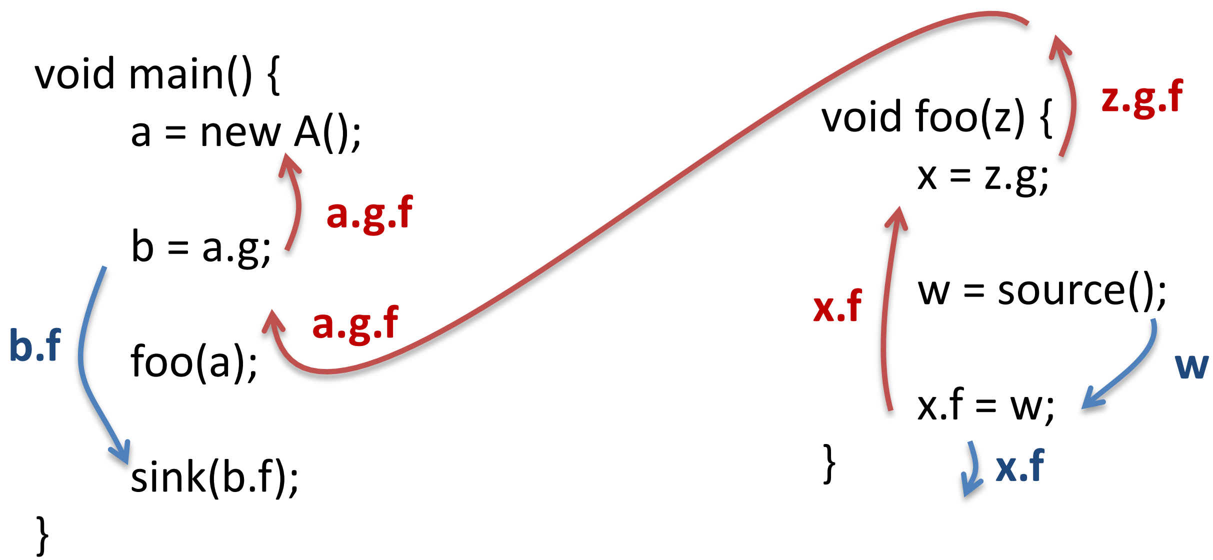
Dr. Michael Eichberg, Ben Hermann, Sebastian Proksch, Karim Ali Ph.D.

Steven Arzt, Siegfried Rasthofer, Christian Fritz, Eric Bodden, Alexandre Bartel, Jacques Klein, Yves Le Traon, Damien Oteau, and Patrick McDaniel: FlowDroid: Precise Context, Flow, Field, Object-sensitive and Lifecycle-aware Taint Analysis for Android Apps. PLDI'14

On-Demand Alias Analysis



- Spawn a backward analysis searching for aliases, when writing a field
- Spawn a forward analysis for each found alias

Activation Statement

```
void main() {
        a = new A();
        b = a.g;
        sink(b.f);
        foo(a);
}
```

a.g.f
<a.g.f, foo()>

b.f
<b.f, foo()>

a.g.f

```
void foo(z) {
        x = z.g;
        w = source();
        x.f = w;
}
```

z.g.f

x.f

w

x.f

- Spawn a backward analysis searching for aliases, when writing a field
- Spawn a forward analysis for each found alias
- Use activation statement to enable a taint only after passing that statement

Context-Free Language Reachability Problem

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Thomas Reps: Program analysis via graph reachability. ILPS'97

David Melski, and Thomas Reps: Interconvertibility of a Class of Set Constraints and Context-Free-Language Reachability. Theoretical Computer Science Journal, Volume 248, 2000

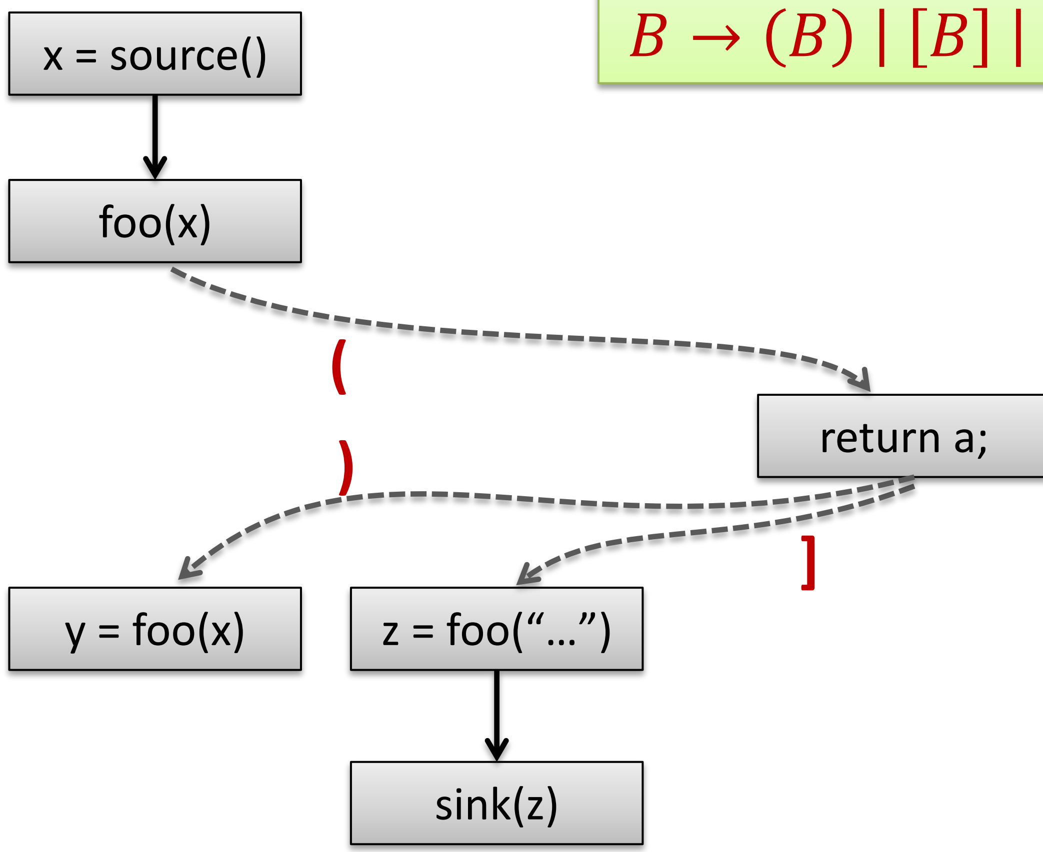
Context-Sensitive Analysis

Describe Valid Paths via Language:

$$B \rightarrow (B) \mid [B] \mid BB \mid \epsilon$$

```
main() {
    x = source();
    if(unknown()) {
        y = foo(x);
    }
    else {
        z = foo("const");
    }
    sink(z);
}

foo(a) {
    return a;
}
```



Context-Free Language Reachability Problem

- Edges in some graph are labeled
- Each path in the graph defines a word by concatenating labels of its edges
- A path is valid, if the corresponding word is in some (context-free) language

Algorithm to Solve CFL-RP

1. Normalize the grammar, such that right-hand sides only contain at most 2 symbols:

$$A \rightarrow BCD \;\Rightarrow\; A \rightarrow BA' \quad A' \rightarrow CD$$

2. Create initial worklist:

   Add to worklist W all edges of the graph

3. Add edges for ϵ-productions:

   for each rule $A \rightarrow \epsilon$ and each node i
   add $A\langle i, i\rangle$ to the graph and worklist

Edge labeled A from i to i

Algorithm to Solve CFL-RP (2)

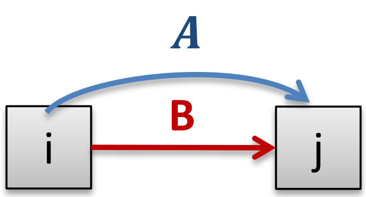
4. Add edges for other productions:

   while W is not empty

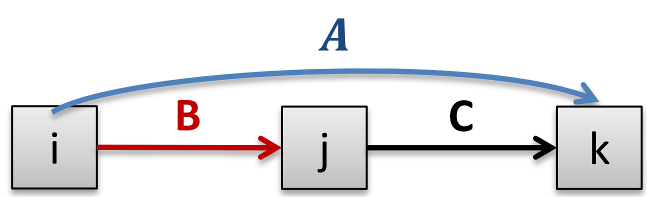
   select and remove edge $B\langle i, j\rangle$ from W

   add edges to graph and W (if not already in graph):

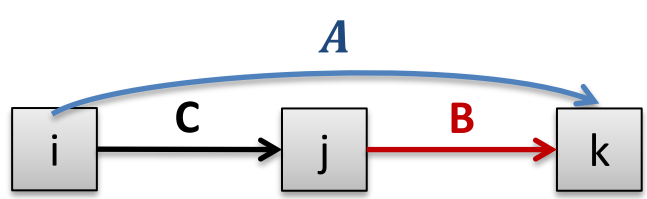
for $A \rightarrow B$:



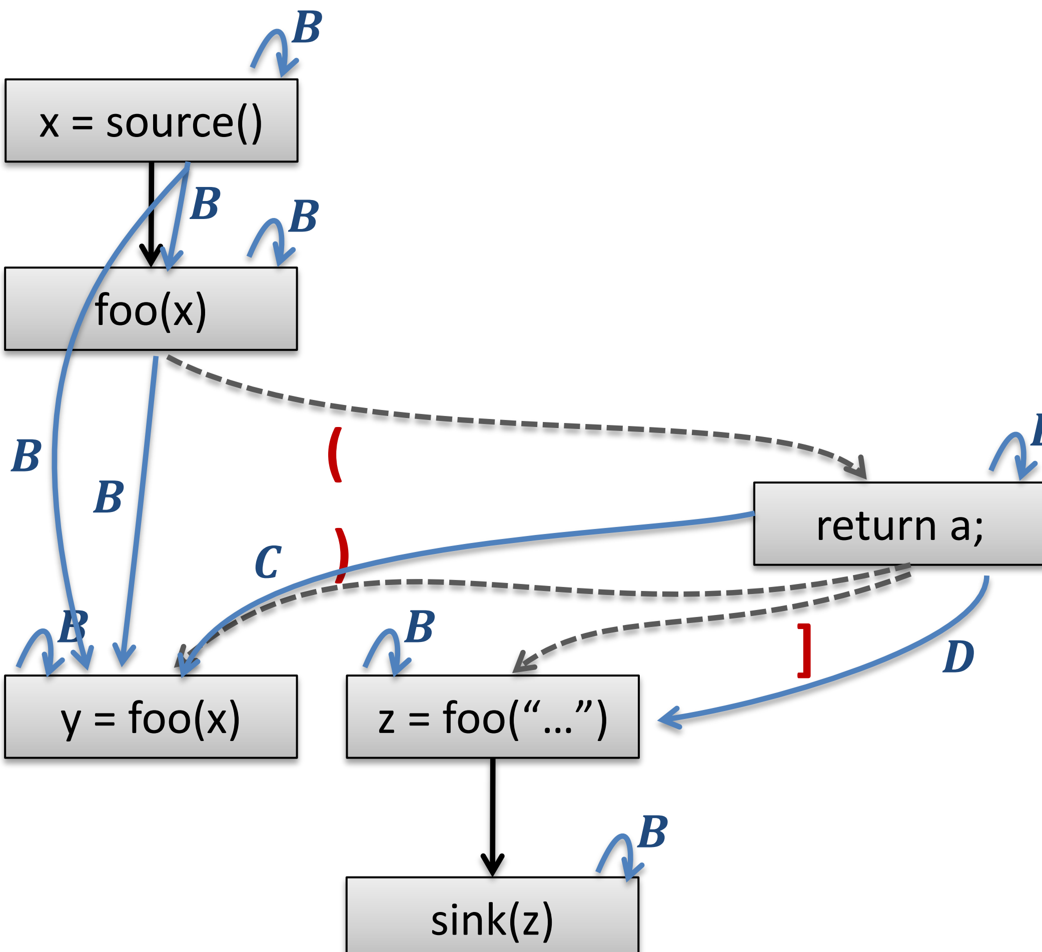
for $A \rightarrow BC$:



for $A \rightarrow CB$:



Context-Sensitive Analysis (2)



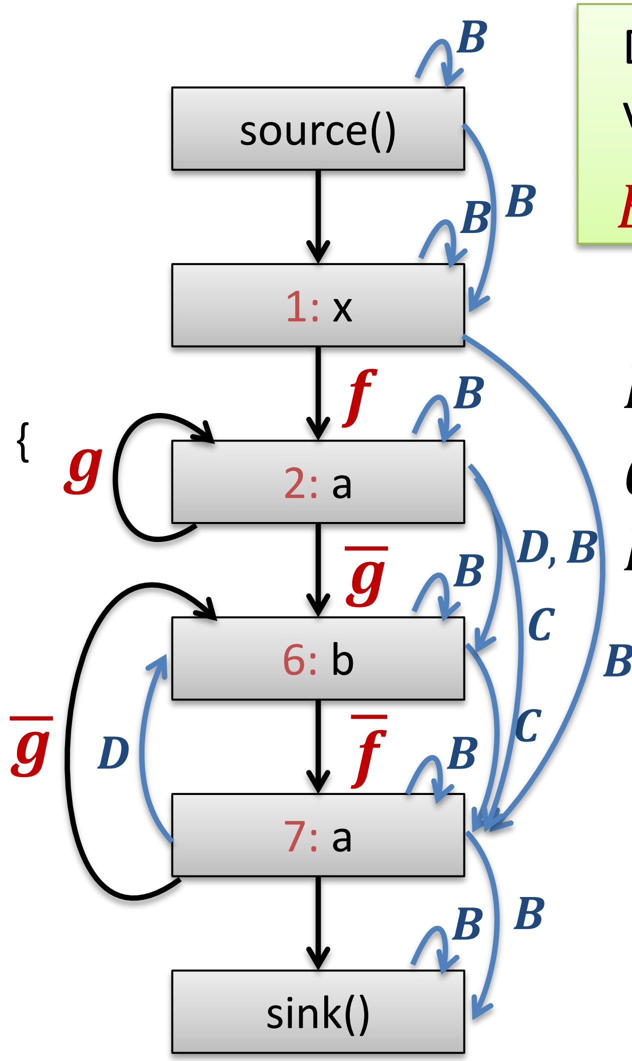
Describe Valid Paths via Language:

$B \rightarrow (B) \mid [B] \mid BB \mid \epsilon$

$$B \rightarrow (C \mid [D \mid BB \mid \epsilon$$
$$C \rightarrow B)$$
$$D \rightarrow B]$$

Field-Sensitive Analysis

```
main() {
    x = source();
    a = new A();
    a.f = x;
    a.g = a;
    while(unknown()) {
        b = a.g
        a = b.f
    }
    sink(a);
}
```



Describe Valid Paths
via Language:

$$B \to f B \overline{f} \mid g B \overline{g} \mid BB \mid \epsilon$$

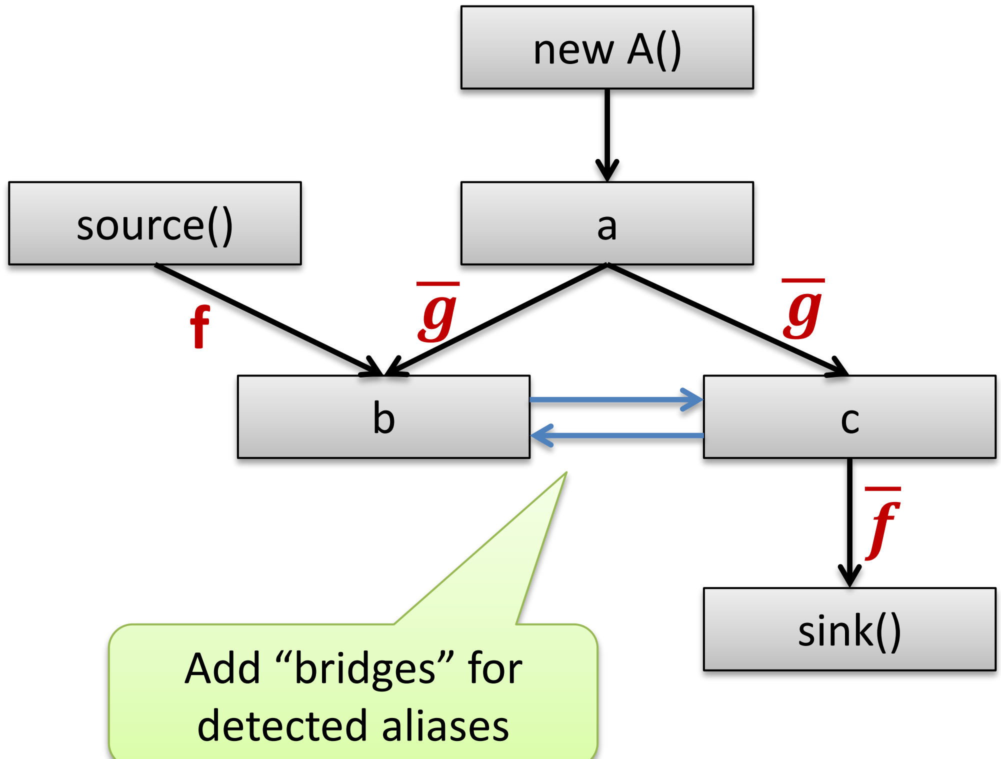
$$B \to f C \mid g D \mid BB \mid \epsilon$$

$$C \to B \overline{f}$$

$$D \to B \overline{g}$$

Aliasing

```
main() {
        a = new A();
        b = a.g;
        b.f = source();
        c = a.g;
        sink(c.f);
}
```



Context- and Field-Sensitive Analysis

Context-Sensitive: $A \rightarrow (A) \mid [A] \mid AA \mid \epsilon \mid fA \mid gA \mid A\overline{f} \mid A\overline{g}$

Field-Sensitive: $B \rightarrow fB\overline{f} \mid gB\overline{g} \mid BB \mid \epsilon \mid (B \mid [B \mid B) \mid B]$

Context- and Field-Sensitive: $L(A) \cap L(B)$

In general, intersection of context-free languages is an undecidable problem.

Should be a valid path: $[f(g)\overline{gf}]$

context- and field-sensitive analysis is proven to be undecidable:

Thomas Reps: Undecidability of Context-Sensitive Data-Dependence Analysis. TOPLAS 2000.

IDE Framework

Applied Static Analysis 2016

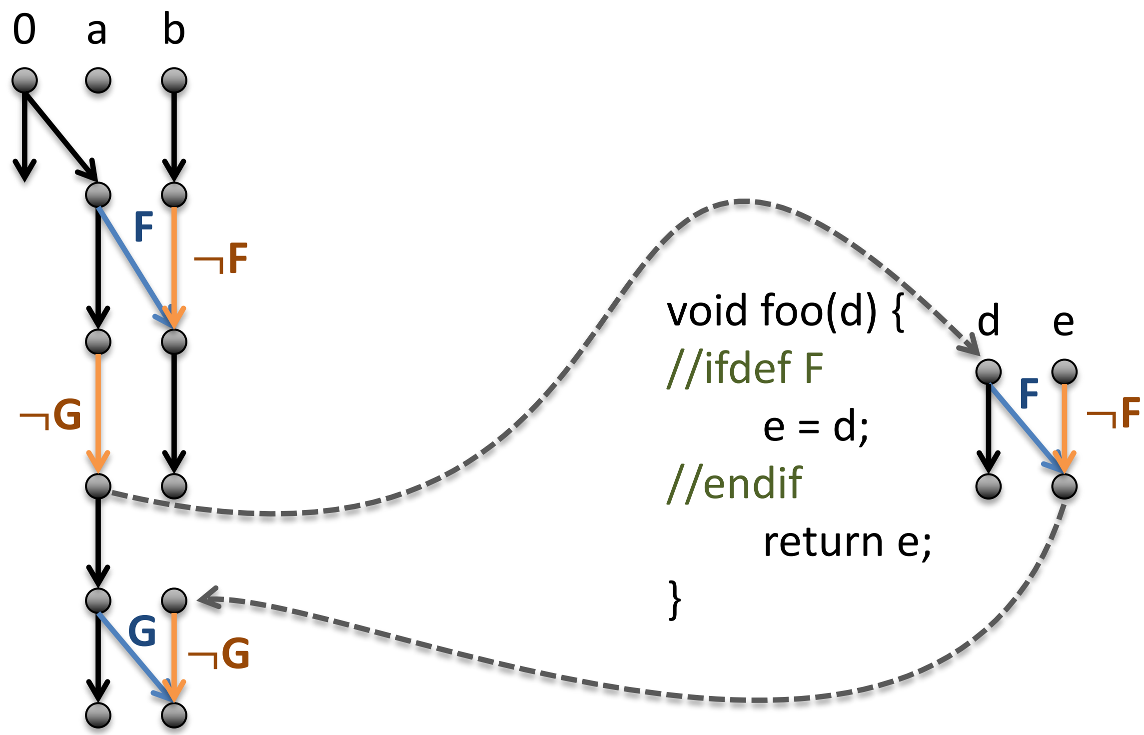
Johannes Lerch

Dr. Michael Eichberg, Ben Hermann, Sebastian Proksch, Karim Ali Ph.D.

Mooly Sagiv , Thomas Reps, and Susan Horwitz : Precise interprocedural dataflow analysis with applications to constant propagation. TAPSOFT '95

SPL^{LIFT}

```
void main() {
        a = source();
//ifdef F
        b = a;
//endif
//ifdef G
        a = null;
//endif
        b = foo(a);
//ifdef G
        b = a;
//endif
        sink(b);
}
```




```
void foo(d) {
//ifdef F
        e = d;
//endif
        return e;
}
```

Eric Bodden, Társis Tolêdo, Márcio Ribeiro, Claus Brabrand, Paulo Borba, and Mira Mezini: SPL^{LIFT}: statically analyzing software product lines in minutes instead of years. PLDI'13

Interprocedural, Distributive, Environment Problems

Environment Transformer / Edge Function:

$$e: V \rightarrow V$$

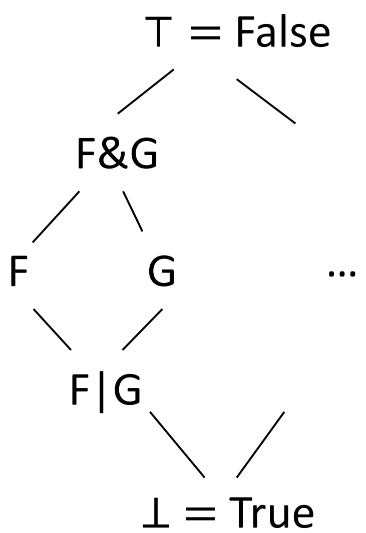
Finite height semi-lattice

distributive function

Characteristics:

- meet operator can be chosen arbitrarily
- computes composition of edge functions
  (always possible, but ideally generates early results)

Lattice used in SPL^{LIFT}



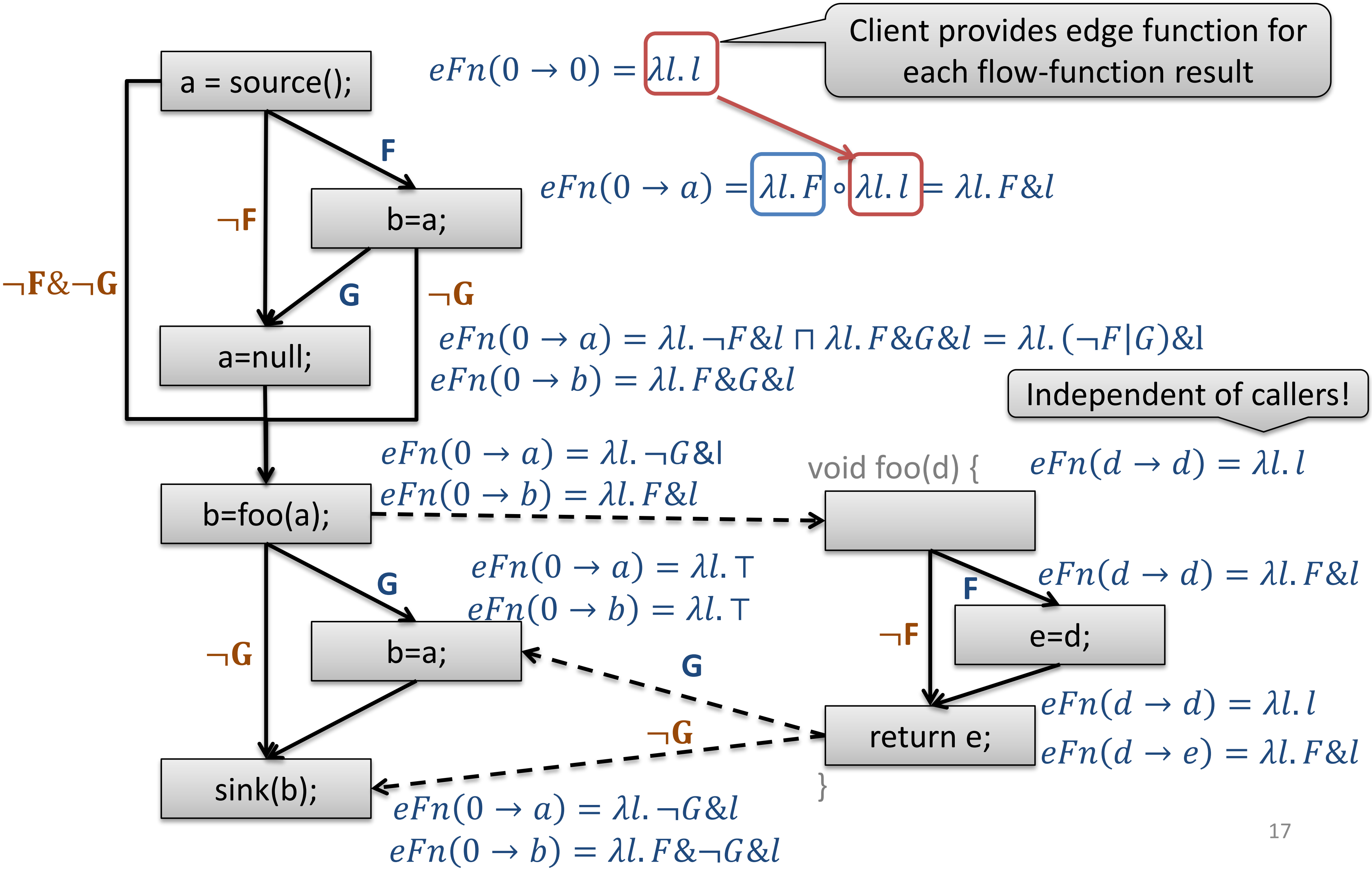
all edges initialized with ⊤

move down when joining facts

move up when composing functions

at initial seeds we use ⊥

SPL^{LIFT}



Client provides edge function for each flow-function result
$eFn(0 \rightarrow 0) = \boxed{\lambda l.\, l}$
$eFn(0 \rightarrow a) = \boxed{\lambda l.\, F} \circ \boxed{\lambda l.\, l} = \lambda l.\, F\&l$
a = source();
F
¬F
b=a;
¬F&¬G
G
¬G
a=null;
$eFn(0 \rightarrow a) = \lambda l.\, \neg F\&l \sqcap \lambda l.\, F\&G\&l = \lambda l.\, (\neg F|G)\&l$
$eFn(0 \rightarrow b) = \lambda l.\, F\&G\&l$
Independent of callers!
$eFn(0 \rightarrow a) = \lambda l.\, \neg G\&l$
$eFn(0 \rightarrow b) = \lambda l.\, F\&l$
void foo(d) {
$eFn(d \rightarrow d) = \lambda l.\, l$
b=foo(a);
$eFn(0 \rightarrow a) = \lambda l.\, \top$
$eFn(0 \rightarrow b) = \lambda l.\, \top$
G
$eFn(d \rightarrow d) = \lambda l.\, F\&l$
F
¬F
e=d;
¬G
b=a;
G
$eFn(d \rightarrow d) = \lambda l.\, l$
return e;
$eFn(d \rightarrow e) = \lambda l.\, F\&l$
¬G
sink(b);
}
$eFn(0 \rightarrow a) = \lambda l.\, \neg G\&l$
$eFn(0 \rightarrow b) = \lambda l.\, F\&\neg G\&l$

Phase 2 of the Algorithm

Computes values at each node/instruction

- Use $\perp$ at initial seeds of the analysis
- Evaluate edge functions to succeeding statements until reaching fixpoint

- Useful only if interested in concrete values at each node/instruction (e.g. Linear Constant Propagation)
- In many cases only reachability is of interest (e.g., SPL$^{\text{LIFT}}$, Correlated Calls)

From IDE to IFDS

- Use identity ($\lambda e. e$) edge functions only
  → IFDS is a subset of IDE

- Note: in Heros IFDSSolver is implemented as a subclass of IDESolver

IDE-Exercise

Extend the Analysis built in the IFDS Exercise to an IDE Analysis that Considers Correlated Calls

Correlated Method Calls

Could be type B or C at runtime

```
main() {
    A a = unknown();
    x = source();
    b = a.foo(x);
    c = a.bar(x);
    sink(c);
}
```

```
interface A {
    X foo(X);
    X bar(X);
}
```

```
class B implements A {
    X foo(X x) {
        return x;
    }

    X bar(X x) {
        return null;
    }
}
```

```
class C implements A {
    X foo(X x) {
        return null;
    }

    X bar(X x) {
        return x;
    }
}
```

Marianna Rapoport, Ondřej Lhoták, and Frank Tip: Precise Data Flow Analysis in the Presence of Correlated Method Calls. SAS'15

Task

- Use Edge Functions to track the upper type boundaries of variables used as receiver

```
main() {
    A a = unknown();
    x = source();
    b = a.foo(x);
    c = a.bar(x);
    sink(c);
}
```

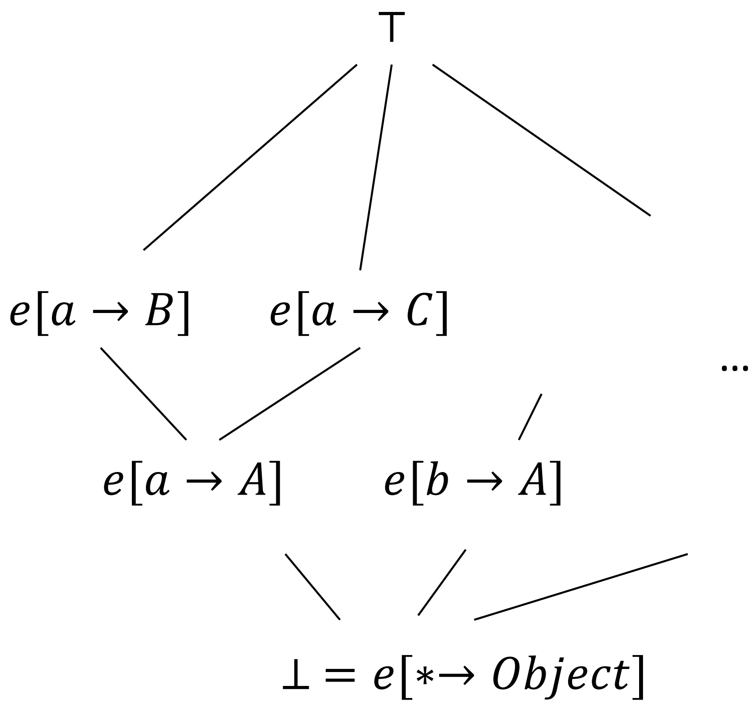
$\lambda e.\, e[a \rightarrow B]$

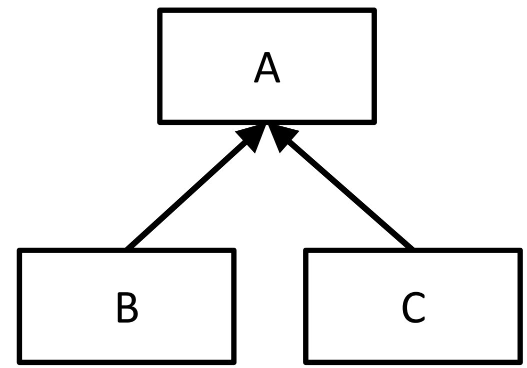
$\lambda e.\, e[a \rightarrow C] \circ \lambda e.\, e[a \rightarrow B] = \lambda e.\, T$

```
class B implements A {
    X foo(X x) {
        return x;
    }

    X bar(X x) {
        return null;
    }
}
```

Lattice





Partial-order function
is the subtype relation for
each mapped variable

$$\lambda e.\, e[a \to B] \circ \lambda e.\, e[a \to A] = \lambda e.\, e[a \to B]$$

$$\lambda e.\, e[a \to B] \circ \lambda e.\, e[a \to C] = \lambda e.\, \top$$

$$\lambda e.\, e[a \to B] \sqcap \lambda e.\, e[a \to C] = \lambda e.\, e[a \to A]$$

EdgeFunctions Interface

```
public interface EdgeFunctions<N, D, M, V> {
	public EdgeFunction<V> getNormalEdgeFunction(N curr, D currNode,
			N succ, D succNode);

	public EdgeFunction<V> getCallEdgeFunction(N callStmt, D srcNode,
			M destinationMethod, D destNode);

	public EdgeFunction<V> getReturnEdgeFunction(N callSite, M calleeMethod,
			N exitStmt, D exitNode, N returnSite, D retNode);

	public EdgeFunction<V> getCallToReturnEdgeFunction(N callSite, D callNode,
			N returnSite, D returnSideNode);
}
```

Already implemented in IDE-Exercise template project

EdgeFunction Interface

```
public interface EdgeFunction<V> {

    V computeTarget(V source);

    EdgeFunction<V> composeWith(EdgeFunction<V> secondFunction);

    EdgeFunction<V> joinWith(EdgeFunction<V> otherFunction);

    public boolean equalTo(EdgeFunction<V> other);
}
```

Needs to be implemented

Exercise Template

- apsa/2016/ifds
  - ifds-exercise
  - ifds-solution
  - ide-exercise
  - testcases

Template for last exercise

Example solution to last exercise

Template for this exercise
(extending ifds-solution)

Updated to include testcase for
correlated calls