The Secret Sauce in Efficient and Precise Static Analysis

The Beauty of Distributive, Summary-Based Static Analyses (and how to master them)

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No. 1 goal of this talk

Refute these myths:

~~*As static analysis gets more precise, it becomes less efficient.*~~

~~*Context-sensitive and flow-sensitive analysis is impossible to scale, thus one needs to approximate.*~~

CogniCrypt

www.cognicrypt.de

[ECOOP 18]

Common mistake in static analysis

Client analysis

Highly precise: context-sensitive, field-sensitive, flow-sensitive, …

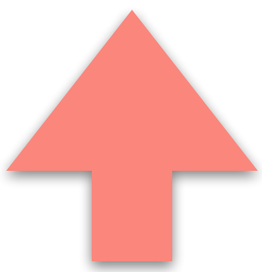
Pointer analysis

Very imprecise: Andersen-style, flow-insensitive, context-insensitive

Common mistake in static analysis

Client analysis

Highly precise: context-sensitive, field-sensitive, flow-sensitive, …



Imprecision

Pointer analysis

Very imprecise: Andersen-style, flow-insensitive, context-insensitive

Example: false positive due to flow-insensitive pointer analysis

```
A a = new A();
A b = new A();

a.x = secret();
leak(b.x);

a = b;
```

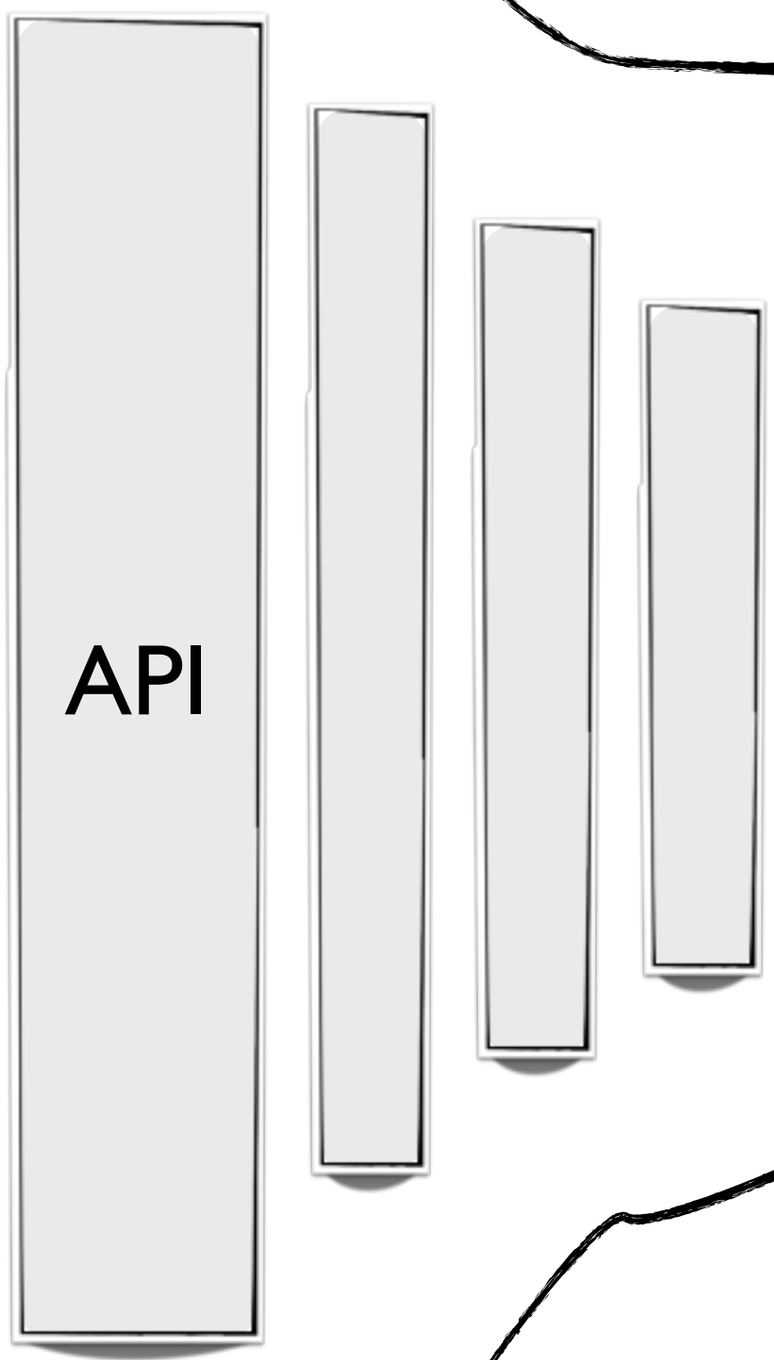
alias created afterwards, yet causes false positive

Lessons

1. **Precise pointer analyses** are key!

But precise analyses *are* hard to scale, no?

They are, as whole-program analysis, but often we can get away with a Demand-driven Analysis



Can an attacker manipulate the string?

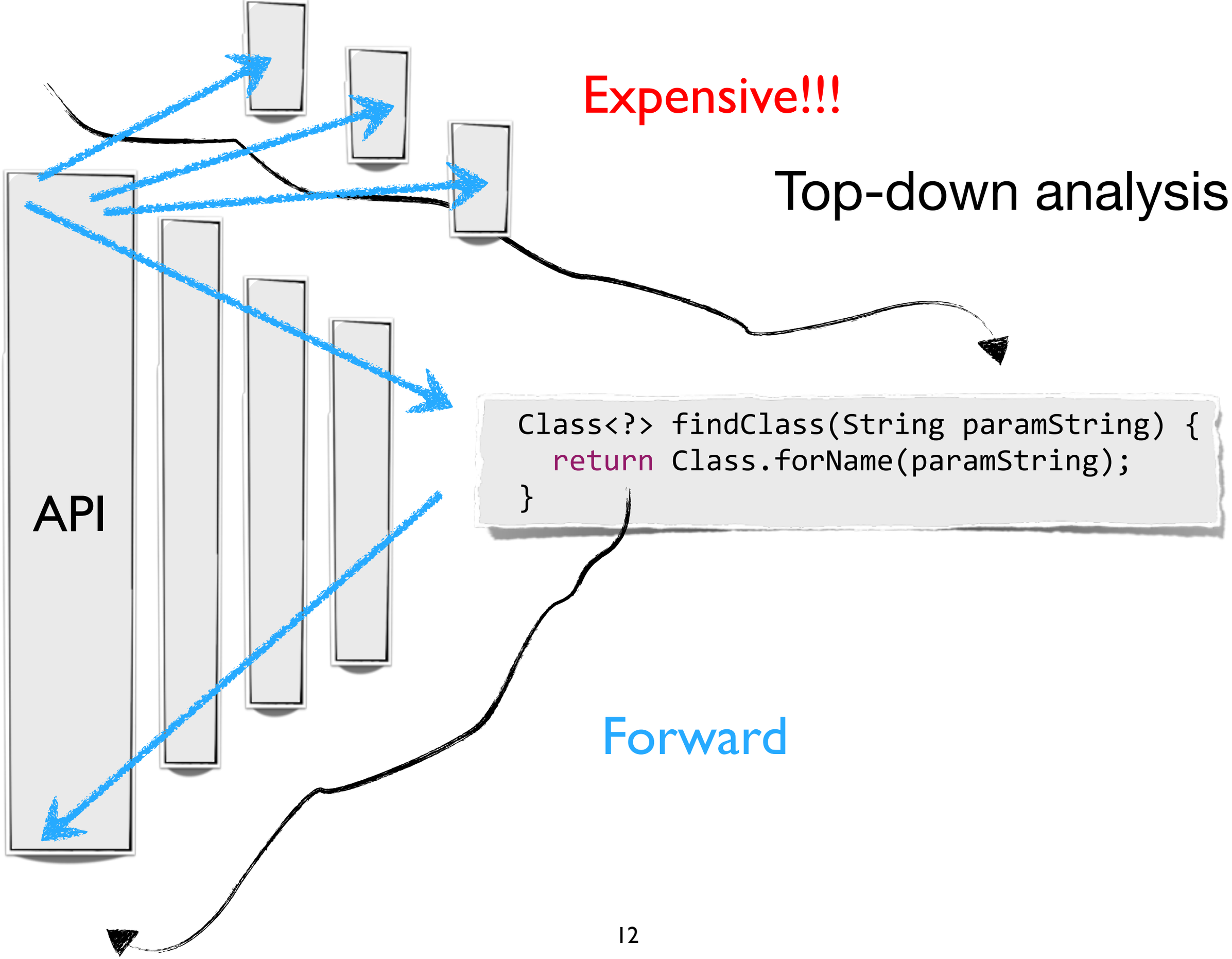
Integrity problem

```
Class<?> findClass(String paramString) {
  return Class.forName(paramString);
}
```

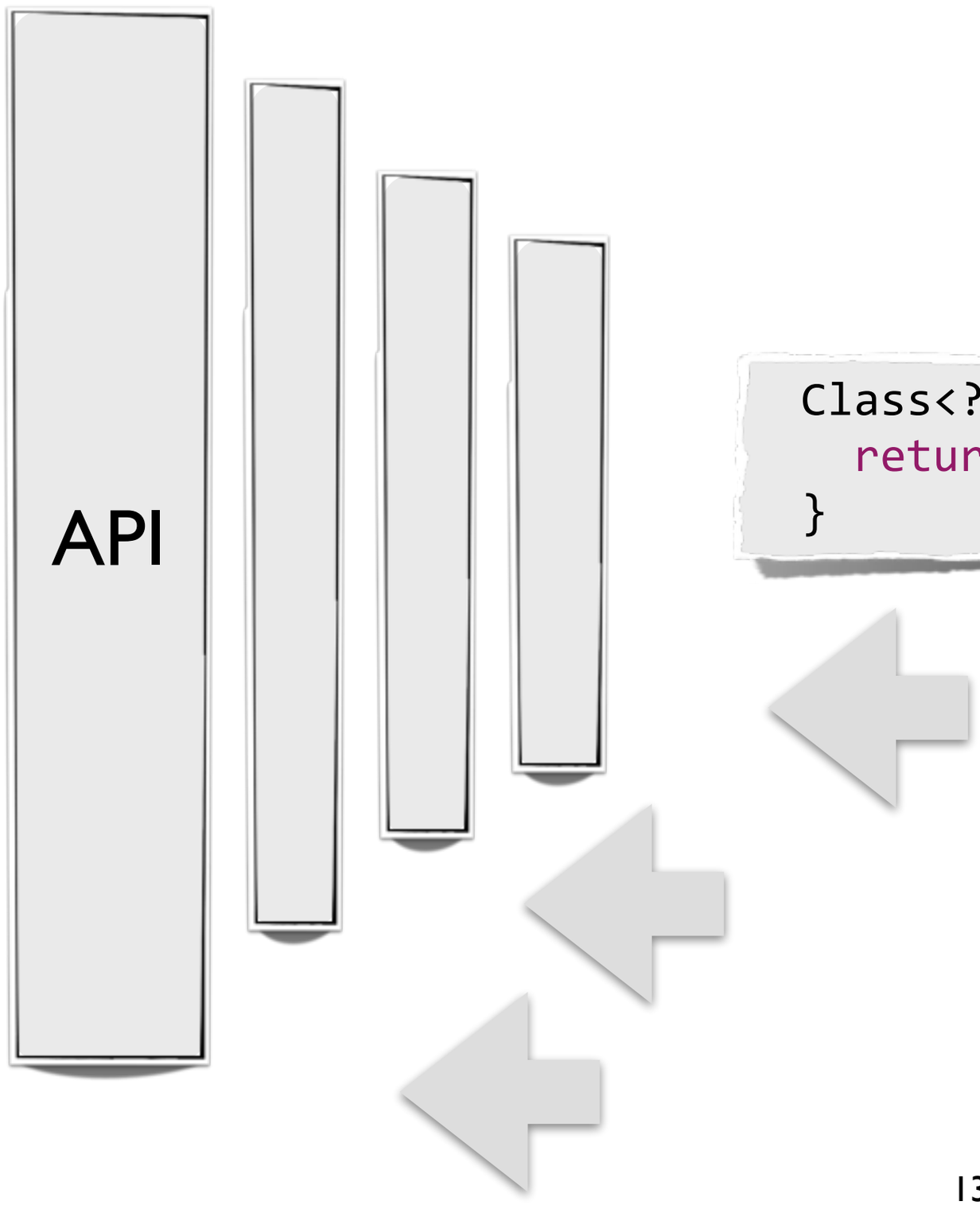
Can the attacker get hold of the returned class?

Confidentiality problem

Taint Analysis!

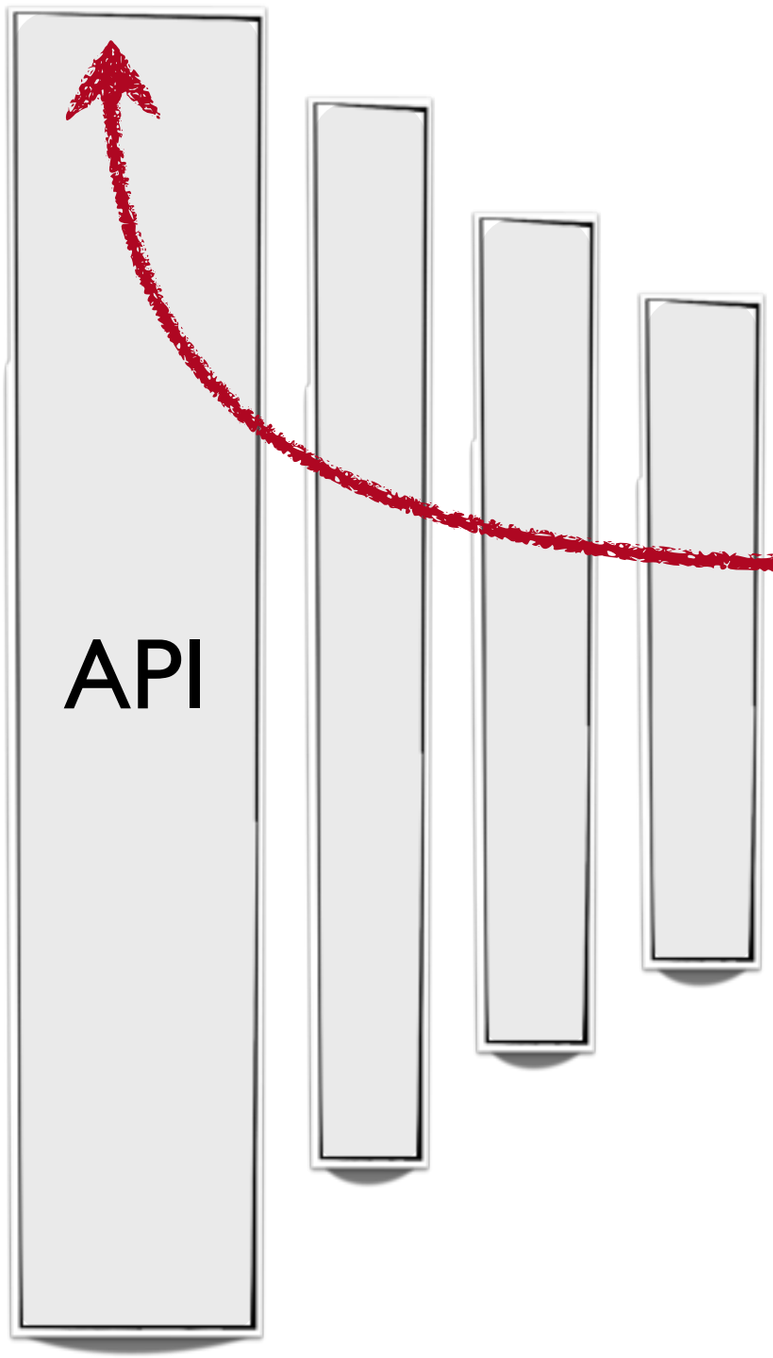

Expensive!!!
Top-down analysis
API
Class<?> findClass(String paramString) {
return Class.forName(paramString);
}
Forward

Bottom-up analysis




```
Class<?> findClass(String paramString) {
  return Class.forName(paramString);
}
```

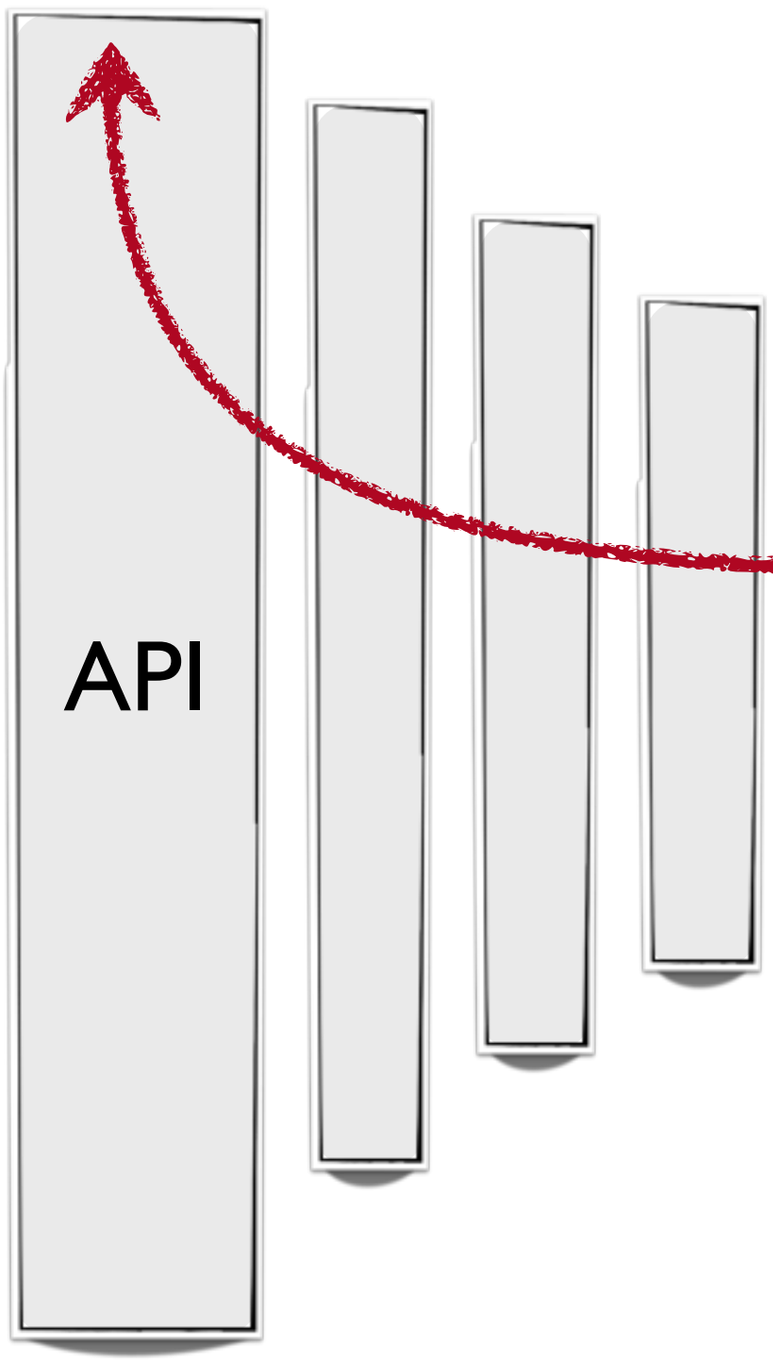
[ASE'15]



Start at stmt of interest

```
Class<?> findClass(String paramString) {
  return Class.forName(paramString);
}
```

[ASE'15]



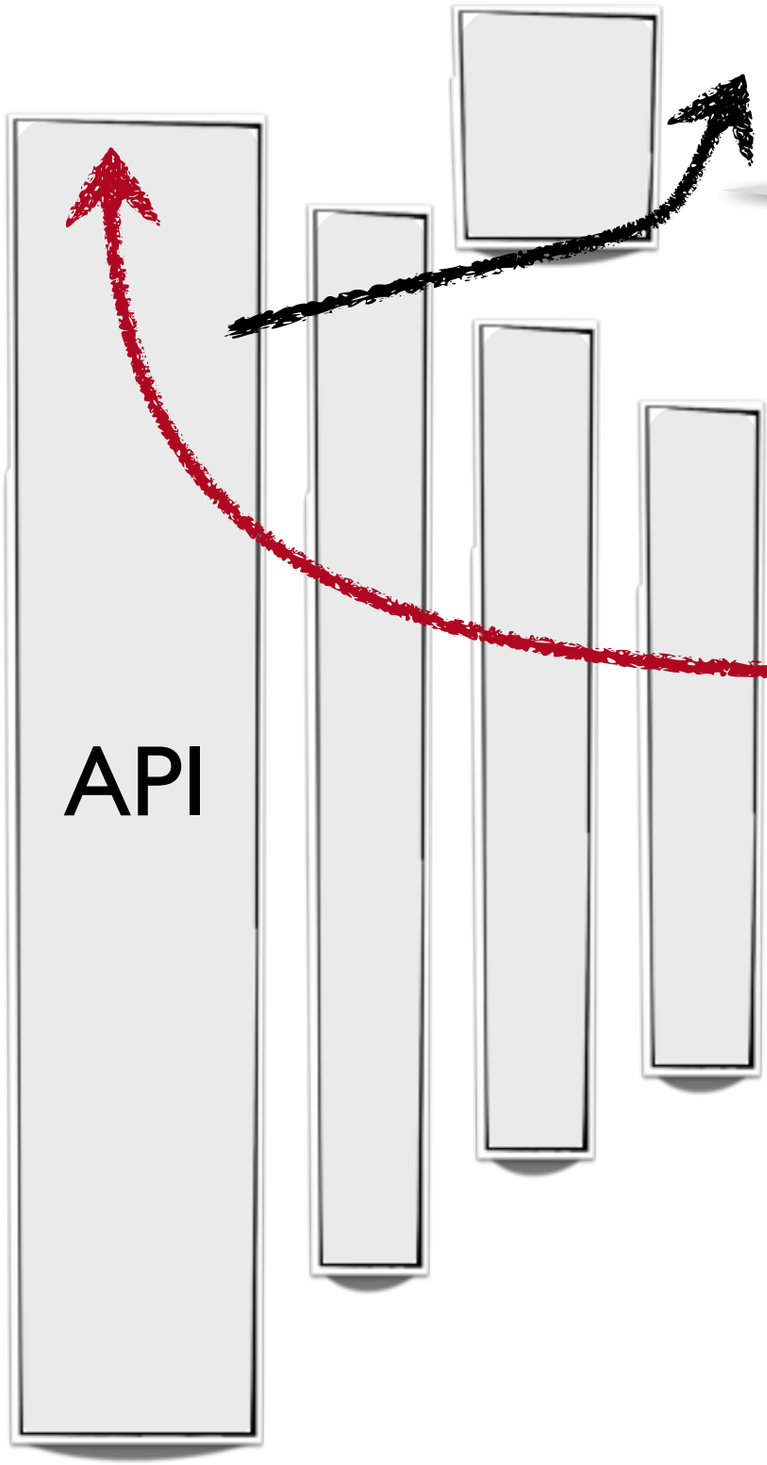
Return to
all callers

```
Class<?> findClass(String paramString) {
  return Class.forName(paramString);
}
```

aka. “unbalanced return”

no calling context!

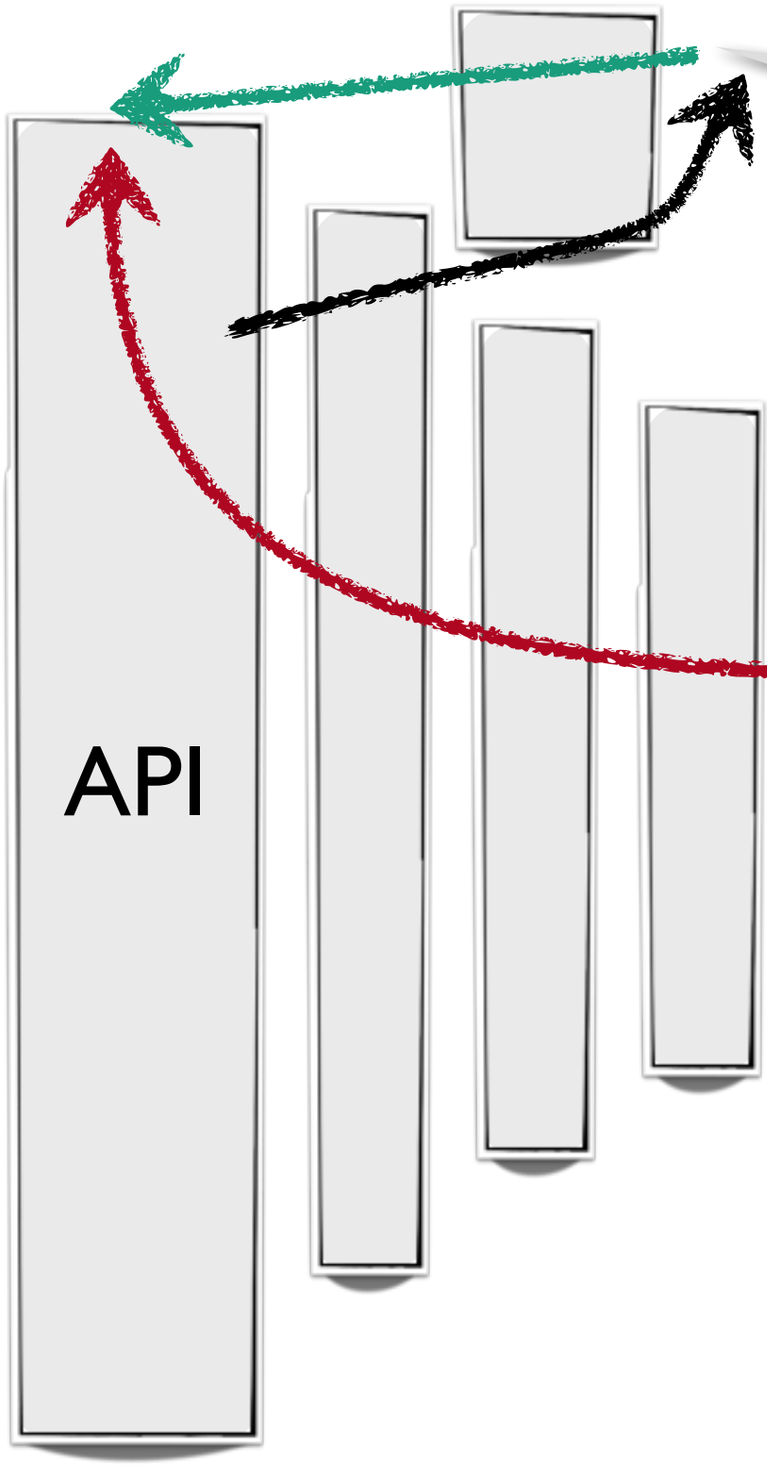
[ASE’15]



Process a call, building call stack

```
Class<?> findClass(String paramString) {
  return Class.forName(paramString);
}
```

[ASE'15]



Balanced return
only to correct call site

```
Class<?> findClass(String paramString) {
  return Class.forName(paramString);
}
```

[ASE'15]

Properties of a demand-driven analysis

- Computed responses to on-demand queries, e.g.: *pointsTo*(`a.f.g`)
- Analysis starts anywhere, “in the middle of the program”
- It typically conducts some combination of backward and forward analysis
- It necessarily has to deal with unbalanced returns

Effects of a demand-driven analysis

- The analysis becomes localised
- Precision therefore may increase
- But: it may report problems in dead code
- Can do recursive queries

On-demand analysis

- Compute **access paths** only when needed
- Compute **pointer information** only when needed
- Compute **string information** only when needed
- Compute **call edges** only when needed

[ASE 2015]

[ECOOP 2016]

[ECOOP 2018]

ongoing…

can query one another!

Lessons

1. **Precise pointer analyses** are key!
2. **Demand-driven analysis** can aid both performance and precision

Gaining further efficiency through procedure summaries

taint analysis tracks both keys

```
void main() {
    byte[] pri = privateKey();
    byte[] pub = publicKey();
    byte[] priAlias = foo(pri); //context c1
    byte[] pubAlias = foo(pub); //context c2
    ...
    log(pub);
}

byte[] foo(byte[] ba) {
    //some hard-to-analyze code omitted
    return ba;
}
```

two calling contexts

```
void main() {
    byte[] pri = privateKey();
    byte[] pub = publicKey();
    byte[] priAlias = foo(pri); //context c1
    byte[] pubAlias = foo(pub); //context c2
    ...
    log(pub);
}

byte[] foo(byte[] ba) {
    //some hard-to-analyze code omitted
    return ba;
}
```

need context-sensitivity to avoid false warning

```
void main() {
    byte[] pri = privateKey();
    byte[] pub = publicKey();
    byte[] priAlias = foo(pri); //context c1
    byte[] pubAlias = foo(pub); //context c2
    ...
    log
}

byte[] foo(byte[] ba) {
    //some hard-to-analyze code omitted
    return ba;
}
```

call-strings approach analyzes foo twice

(c1,ba)

(c2,ba)

```
void main() {
    byte[] pri = privateKey();
    byte[] pub = publicKey();
    byte[] priAlias = foo(pri); //context c1
    byte[] pubAlias = foo(pub); //context c2
    ...
    log
}

byte[] foo(byte[] ba) {
    //some hard-to-analyze code omitted
    return ba;
}
```

summary-based analysis instead only once!

ba

<ret>

Extensional vs. intensional summaries

extensional definition of the *increment* function:

$$0 \mapsto 1, 1 \mapsto 2, 2 \mapsto 3, \ldots$$

intensional definition:

$$\lambda x.\ x \mapsto x + 1$$

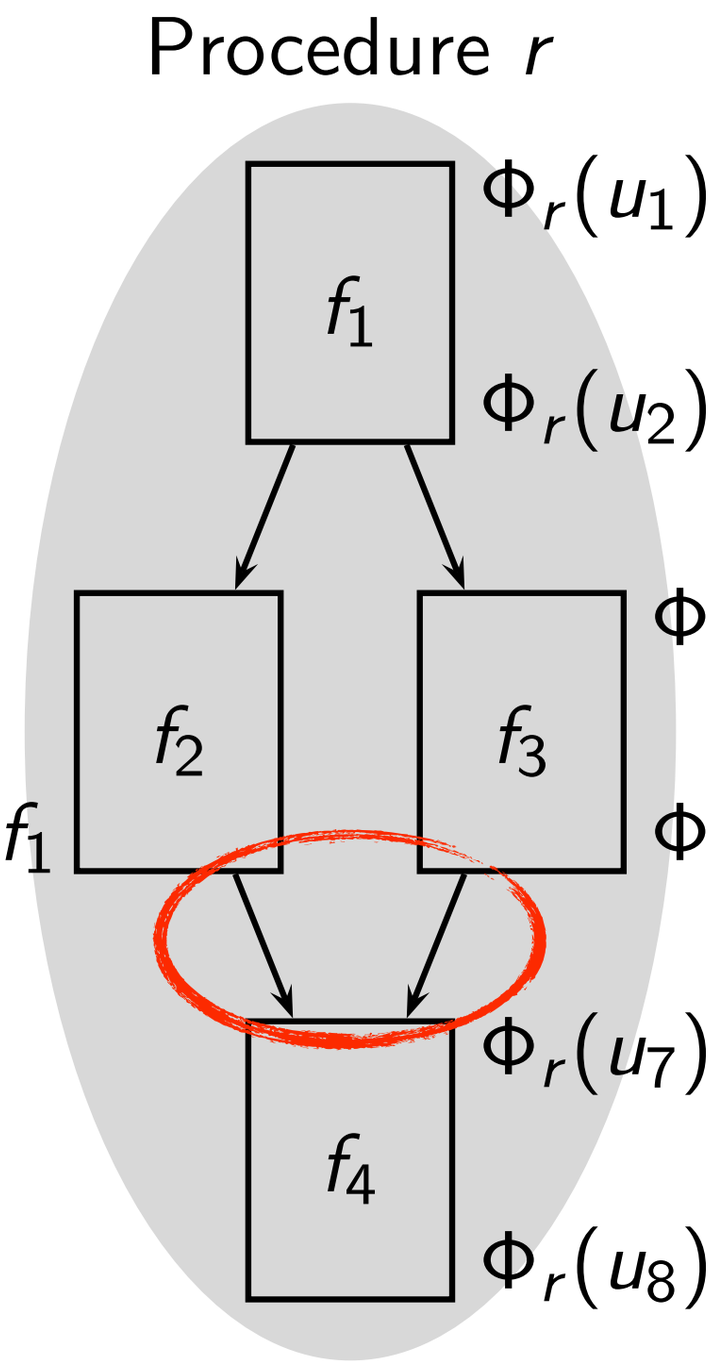
much more compact!

Lessons

1. **Precise pointer analyses** are key!
2. **Demand-driven analysis** can aid both performance and precision
3. **Summaries** avoid repeated re-analysis of callee procedures
4. One should strive for **intensional summary definitions**

How to compute summaries?

assume forward analysis…



$\Phi_r(u_1) \equiv \phi_{id}$

$\Phi_r(u_2) \equiv f_1$

$\Phi_r(u_3) \equiv f_1$

$\Phi_r(u_4) \equiv f_1$

$\Phi_r(u_5) \equiv f_2 \circ f_1$

$\Phi_r(u_6) \equiv f_3 \circ f_1$

$\Phi_r(u_7) \equiv f_2 \circ f_1 \sqcap f_3 \circ f_1$

$\Phi_r(u_8) \equiv f_4 \circ (f_2 \circ f_1 \sqcap f_3 \circ f_1)$

Slide uses illustration by Uday Khedker

Generally assume that flow functions are **monotone**:

$$f(x) \sqcap f(y) \sqsubseteq f(x \sqcap y)$$

To be able to compute intensional summaries, they **need to be distributive**:

$$f(x) \sqcap f(y) = f(x \sqcap y)$$

IFDS, IDE and WPDS compute summaries automatically, but care must be taken when choosing the appropriate heap abstraction!

two allocation sites

```
void main() {
    A a1 = new A(); //alloc1
    A a2 = new A(); //alloc2
```

allocation-site abstraction causes duplicated analysis of callee

```
//context c1
//context c2
```

```
<T> T foo(T o) {
    //some hard-to-analyze code omitted
    return o;
}
```

({alloc1},o)

({alloc1},<ret>)

({alloc2},o)

({alloc2},<ret>)

```
void main() {
    A a1 = new A(); //alloc1
    A a2 = new A(); //alloc2
}
```

problem: summary for `alloc1` is not reusable for `alloc2`

```
<T> T foo(T o) {
    //some hard-to-analyze code omitted
    return o;
}
```

`//context c1`

`//context c2`

`({alloc1},o)`

`({alloc2},o)`

`({alloc1},<ret>)`

`({alloc2},<ret>)`

Instead use access paths

l..k field accesses

l . f . g . h

local variable

```
void main() {
    A a1 = new A(); //alloc1
}

<T> T foo(T o) {
    //some hard-to-analyze code omitted
    return o;
}
```

1st advantage:
much smaller abstract domain!

context c1

context c2

o

<ret>

```
void main() {
    A a1 = new A(); //alloc1
    A a2
    A a1                                    c1
    A a2                                    c2
}

<T> T foo(T o) {                o
    //some hard-to-analyze code omitted
    return o;
}                               <ret>
```

2nd advantage:
analyzing foo only once!

Lessons

1. **Precise pointer analyses** are key!
2. **Demand-driven analysis** can aid both performance and precision
3. **Summaries** avoid repeated re-analysis of callee procedures
4. One should strive for **intensional summary definitions**
5. The point of procedure summaries is not to be able to create them but to be able to **reuse** them!
6. Alloc-site-based heap abstraction **hinder summary reuse**
7. Access paths **foster reusable summaries**

Remember:

To be able to compute intensional summaries, they **need to be distributive**:

$$f(x) \sqcap f(y) = f(x \sqcap y)$$

But: distributive frameworks yield **perfect precision**!

meet over all paths

maximal fixed point

$$\forall s.\ MOP(s) \sqsubseteq MFP(s)$$

$$f(x) \sqcap f(y) \sqsubseteq f(x \sqcap y)$$

$$\forall s.\ MOP(s) = MFP(s)$$

$$f(x) \sqcap f(y) = f(x \sqcap y)$$

$$\forall s.\ MOP(s) \sqsubseteq MFP(s)$$

$$f(x) \sqcap f(y) \sqsubseteq f(x \sqcap y)$$

merging earlier gives
an over-approximation

$$f(x) \sqcap f(y) = f(x \sqcap y)$$

$$\forall s.\ MOP(s) \sqsubseteq MFP(s)$$

it does not matter
when we merge!

$$\forall s.\ MOP(s) = MFP(s)$$

$$f(x) \sqcap f(y) = f(x \sqcap y)$$

two calling contexts

```
void main()
    Pair<String> p1 =
        makePair(secretKey(),secretKey());
    Pair<String> p2 =
        makePair(secretKey(),publicKey());
}

<T> T makePair(T a, T b) {
    Pair<T> ret = new Pair<T>();
    ret.left = a;
    ret.right = b;
    return ret;
}
```

two taints

```
void main() {
    Pair<String> p1 =
        makePair(secretKey(),secretKey());
    Pair<String> p2 =
        makePair(secretKey(),publicKey());
}
```

one taint

```
<T> T
    Pair<T> ret = new Pair<T>();
    ret.left = a;
    ret.right = b;
    return ret;
}
```

at first context

```
void main()
    Pair<String> p1 =
        makePair(secretKey(),secretKey());
    Pair<String> p2 =
        makePair(secretKey(),publicKey());
}

<T> T makePair(T a, T b) {
    Pair<T> ret = new Pair<T>();
    ret.left = a;
    ret.right = b;
    return ret;
}
```

a

b

<ret>.left

<ret>.right

at second context

```
void main() {
    makePair(secretKey(),secretKey());
    Pair<String> p2 =
    makePair(secretKey(),publicKey());
}

<T> T makePair(T a, T b) {
    Pair<T> ret = new Pair<T>();
    ret.left = a;
    ret.right = b;
    return ret;
}
```

a

b

<ret>.left

<ret>.right

can reuse this partial summary!

sound only due to distributivity!

```
void main() {
    Pair<String> p1 =
        makePair(secretKey(),secretKey());
    Pair<String> p2 =
        makePair(secretKey(),publicKey());
}

<T> T makePair(T a, T b) {
    Pair<T> ret = new Pair<T>();
    ret.left = a;
    ret.right = b;
    return ret;
}
```

a → <ret>.left

b → <ret>.right

can reuse this partial summary!

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6. Alloc-site-based heap abstraction **hinder summary reuse**
7. Access paths **foster reusable summaries**
8. Intensional summaries **require distributivity**
9. Distributivity yields **perfect precision**
10. Distributive summaries can be **more effectively reused**

My 10 laws of precise and efficient analysis

1. **Precise pointer analyses** are key!
2. **Demand-driven analysis** can aid both performance and precision
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10. Distributive summaries can be **more effectively reused**

Valid until disproven ! ;-)

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