FlowMiner: Automatic Summarization of Library Data-Flow for Malware Analysis

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Need for Summarizing Libraries

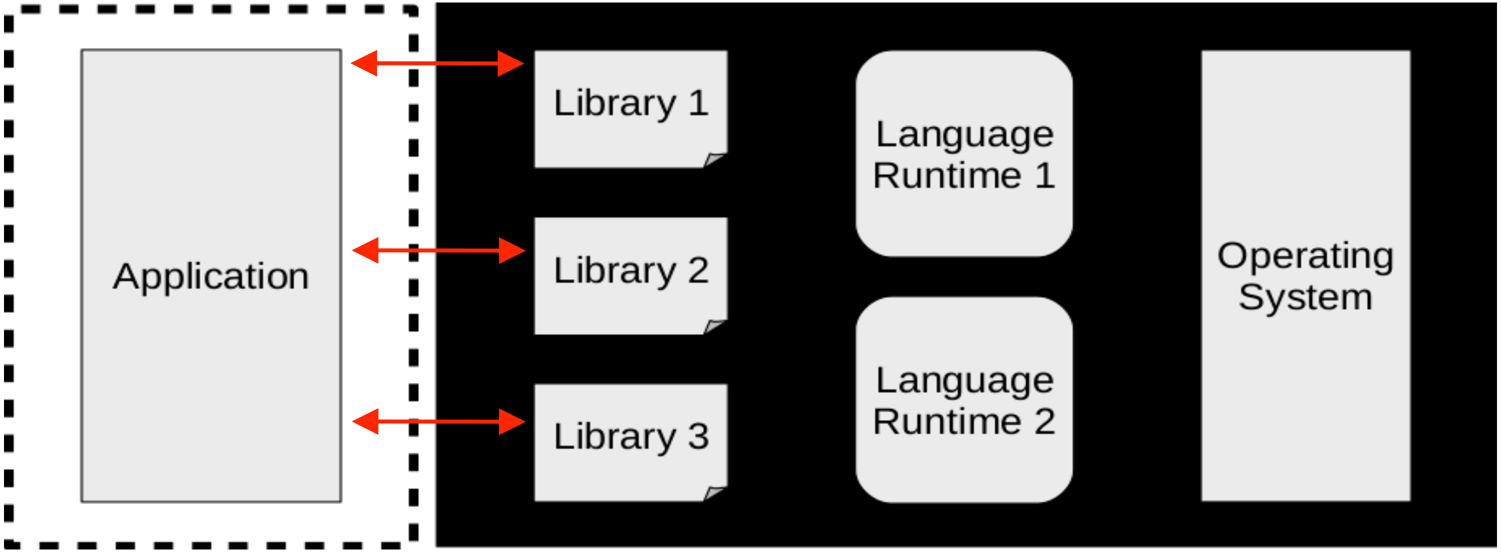
Need for Summarizing Libraries

Modern software uses large, **reusable library** components

Static Analysis **including entire library does not scale**

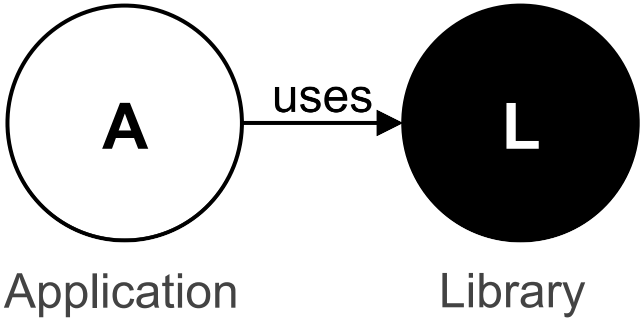
Analysis of an application **without library is inaccurate**

Summaries - Scalably include **relevant** parts of library in analysis



Need for Summarizing Libraries

Partial Program Analysis:
Analyzing a proper subset of a software



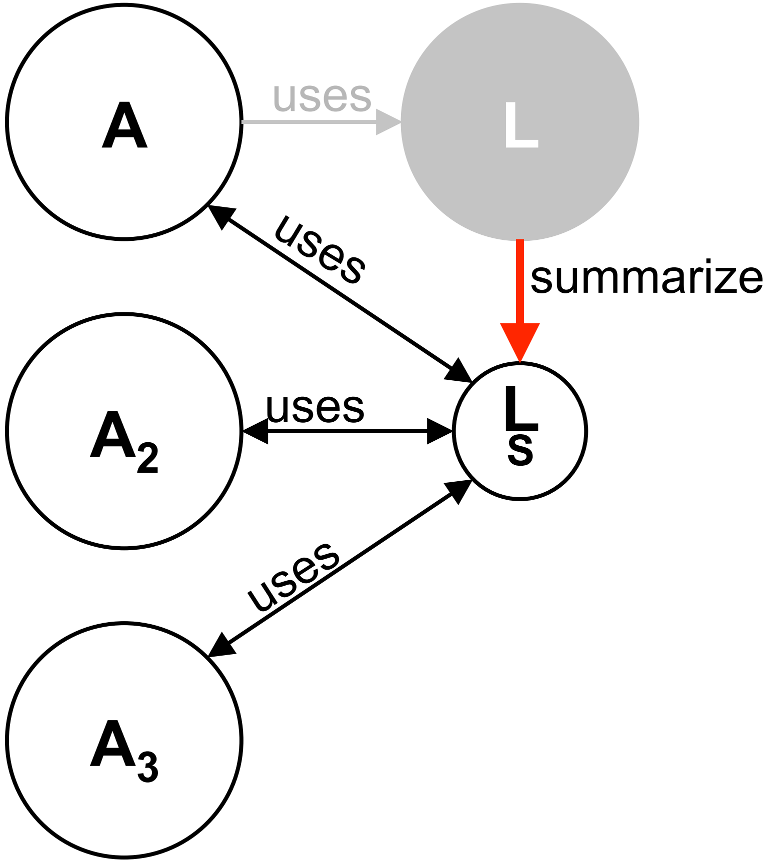
Often, A is available in source or binary, but not L

Or, L is too large to be analyzed with A

Need for Summarizing Libraries

Solution: Analyze A+L^S instead of A+L

- **L^S:** Summary of L must be
  - Expressive (fine-grained) for accurate subsequent analysis
  - More compact than library for scalability
  - Sound
  - Independent of specific analysis tools
  - Independent of app that uses L
  - Capture callbacks



Role of Summaries in Malware Detection

The Rise of Domain-Specific Malware

✓ Detecting **consumer malware** is a well-studied problem.

✗ Detecting **novel, sophisticated, domain-specific** malware is not.

- Crafted specifically to disrupt one aspect of one organization
- Payload is customized for target
- Domain knowledge is used to camouflage malicious behavior within benign mechanisms
- Responds to a specific trigger from adversary or environment

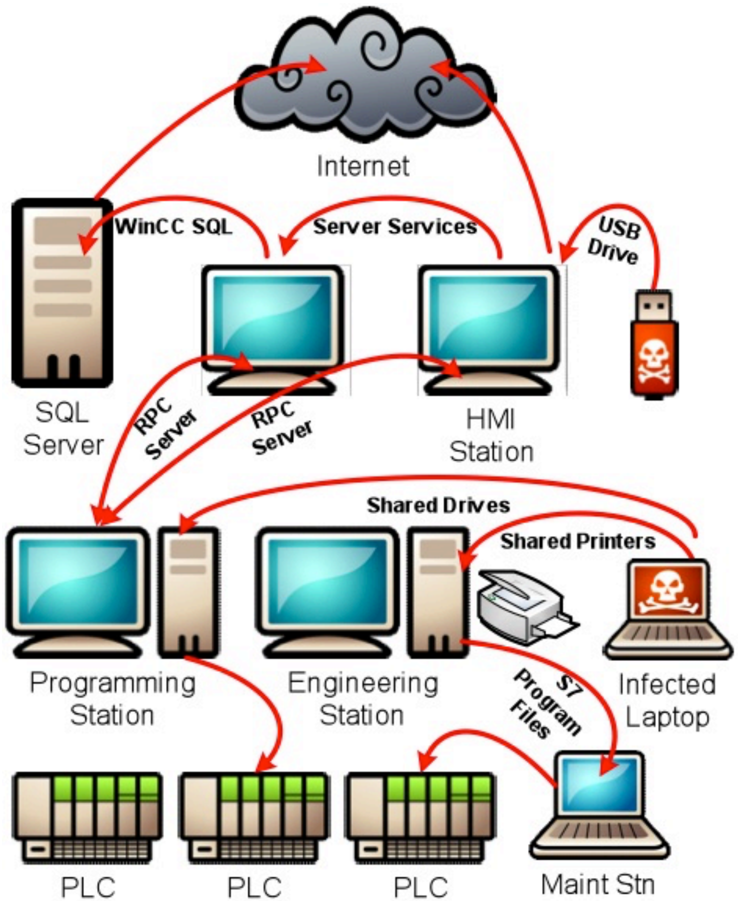
All very different characteristics from consumer malware!

STUXNET: Example of Real-World Targeted Malware

Targets Seimens uranium centrifuge PLCs in Iran

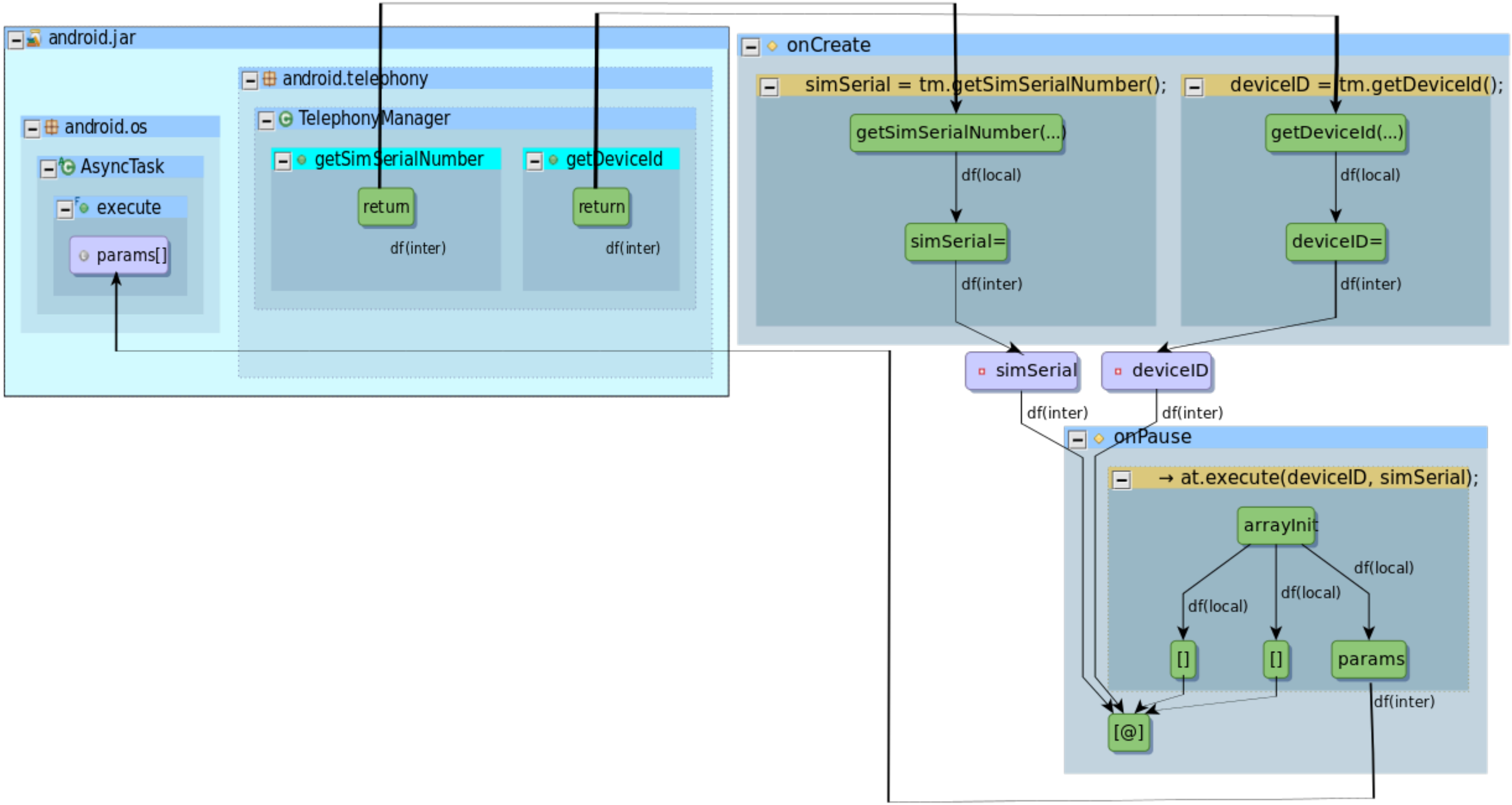
Undiscovered for ***years***

- Centrifuges began breaking in 2008
- Authors gradually made it more conventional (wanting to get caught)
- Discovered in 2010 by conventional means



http://limn.it/the-morris-worm/

A Malware Example without Summaries



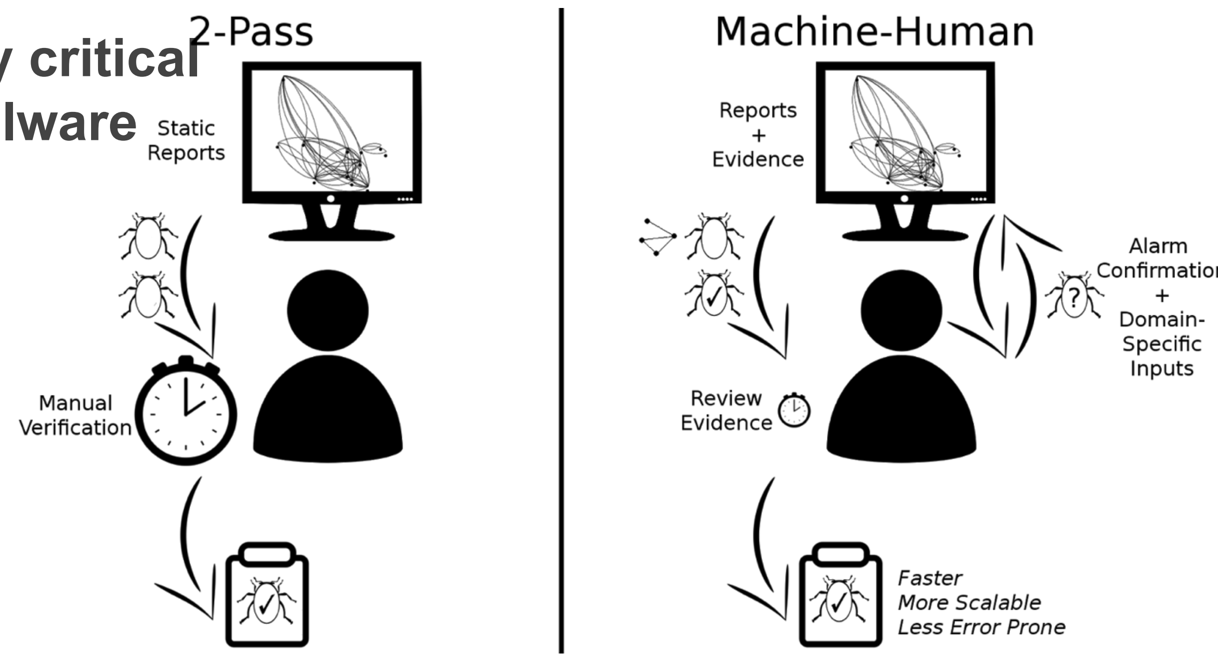
Human-in-the-loop Malware Detection

Human analyst is <u>indispensable</u> in detecting targeted malware

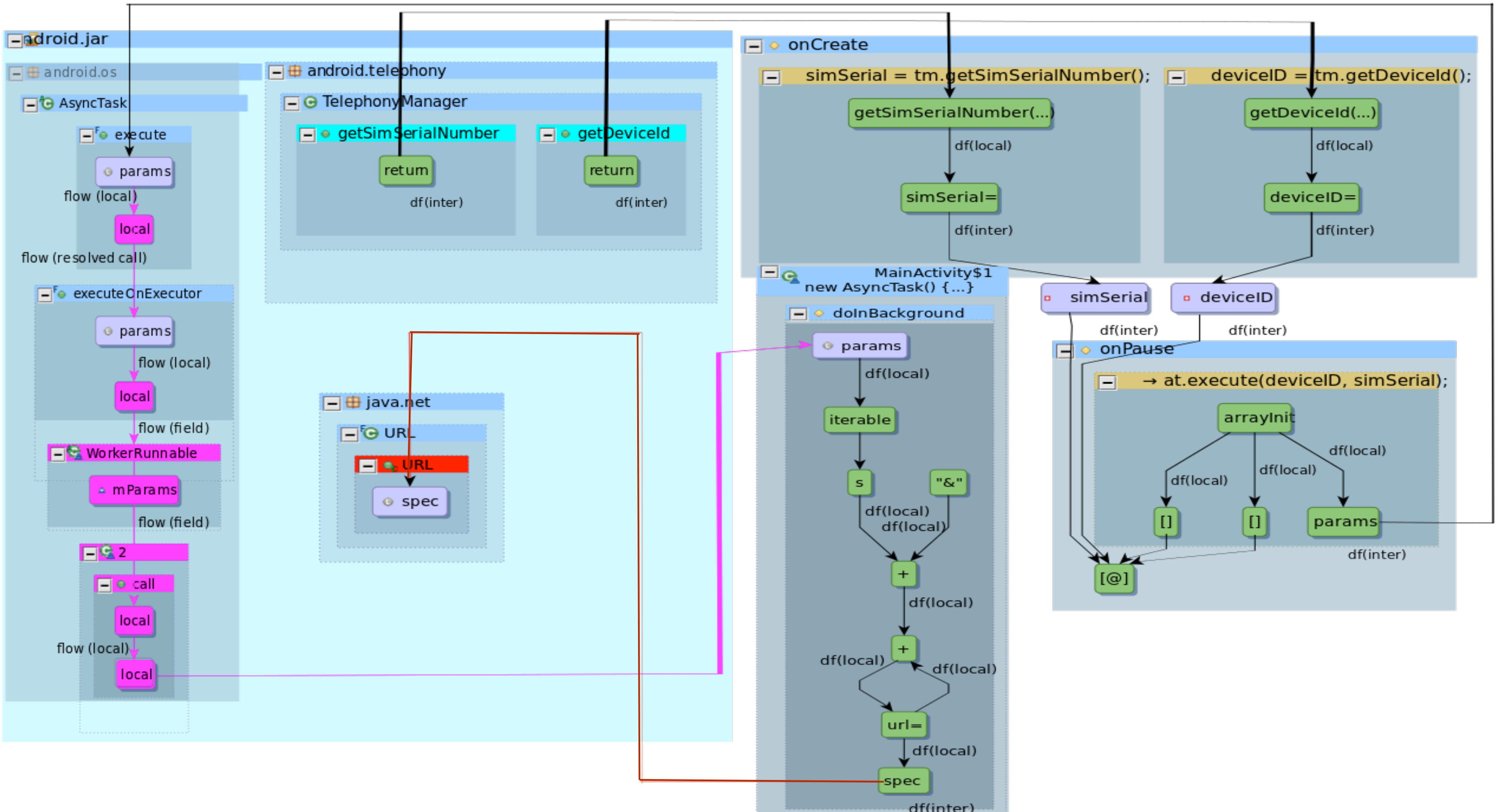
Automated tools must aid human analyst to devise, test and validate hypotheses about the existence of malware

Summaries are especially critical for detecting targeted malware

- **Aids quick what-if experiments**
- **Reuse of summaries**
- **Enables scalability without entire library**
- **Allows accurate detection of malware**

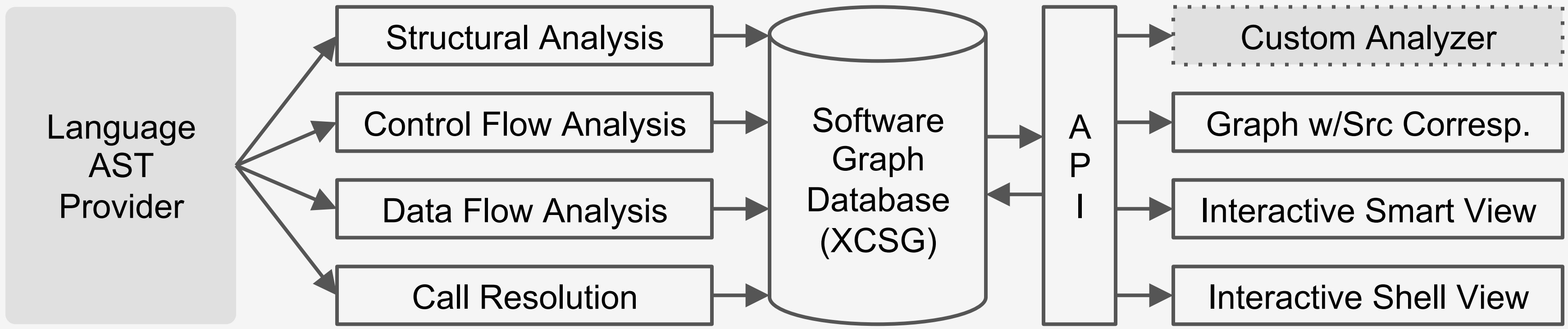


A Malware Example with Summaries



FlowMiner:
Summarization using Graph-based Program Analysis

Atlas: Graph-Based Program Analysis Platform



Polynomial-time analyzers pre-process the AST

Optimized in-memory graph database is populated

Powerful query API (select, traverse, combine)

Multiple ways to interact with graph artifacts

XCSG - Viewing Software as Directed Property Multigraph

Nodes and edges of program graph have ***properties***

- ID, Name, Kind, Keywords, etc.
- Binary properties are expressed as “tags”

The e**X**tensible **C**ommon **S**oftware **G**raph provides:

- A hierarchical structure of node and edges kinds
- Proper abstraction of common semantic meaning (even across languages)
- Well-defined semantics for each node or edge kind

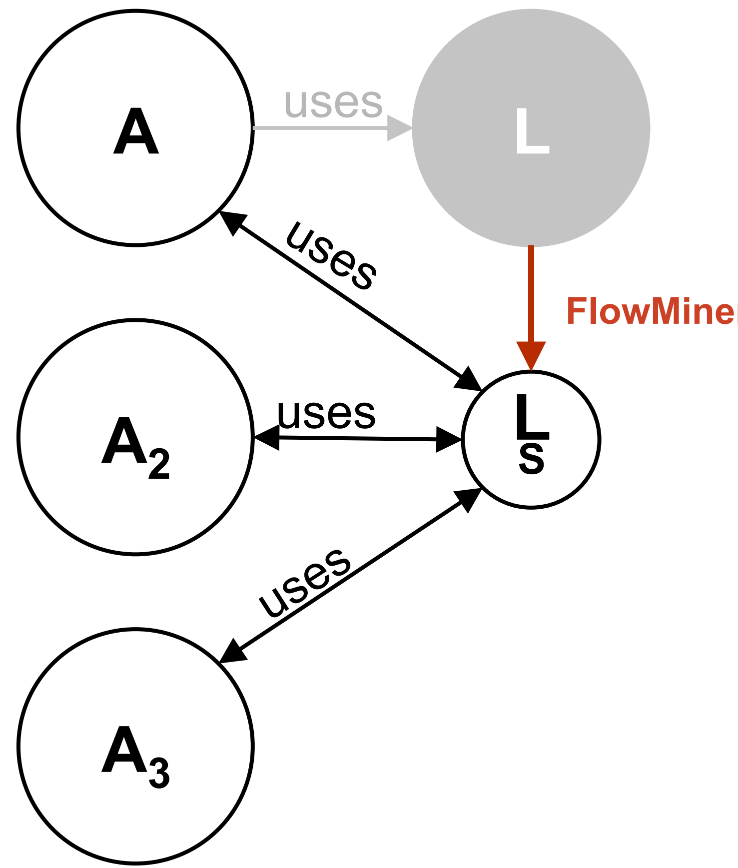
FlowMiner: Research Question

How can expressive, compact information flow summaries be mined from a library for accurate and scalable partial program analysis?

FlowMiner: Goals

One-time, automatic static analysis of L to produce summaries L^S that:

- Are **expressive** enough to be used with context, field, type, flow, and object sensitivity
- Are **compacted** to elide uninteresting details of flows
- Are **sound** (indicated flows actually occur)
- Are **portable** for use by existing tools
- Are **independent of A_i**
- Capture **callbacks** from the library back into the application



Preserve key pieces of information, discard the rest

Control-flow details are discarded

- Cannot use summaries for path-sensitivity
- Retaining control flow does not scale anyway in practice

Statically-resolvable call sites are pre-resolved

- No need to retain signature of the call site

Unimportant data-flow details *elided* with respect to *key nodes*

Preserve “Key” Nodes

Key nodes (for Java) includes

- Field Definitions
- Method Signature Elements
  - Parameters, return values
- Definitions read/written to fields
- Call Sites
  - Parameters, return, invoked signature, invoked type
- Literal Values
- Array components, accesses

Computing Summaries with Fine Granularity

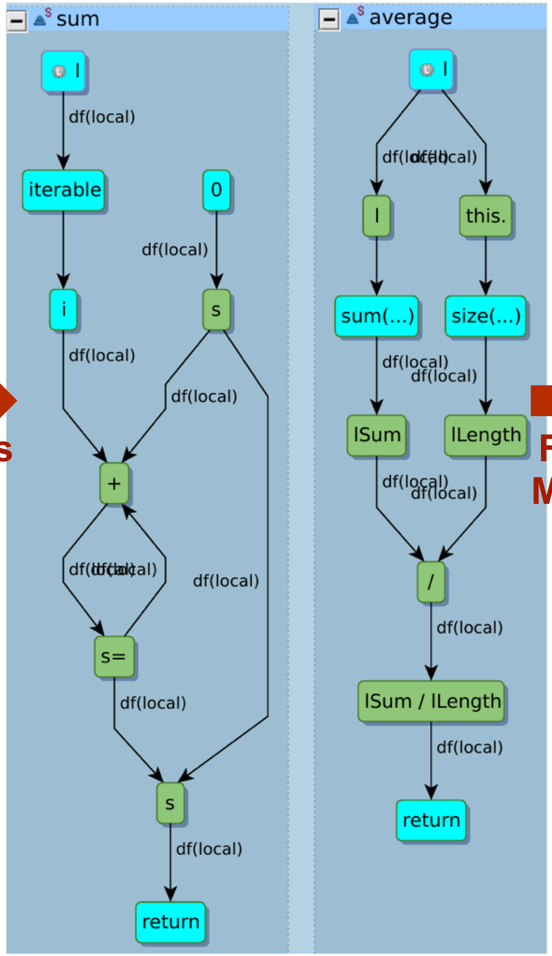
FlowMiner summaries support

- Context Sensitivity
  - Individual methods, call sites from the original library are preserved
- Flow Sensitivity
  - Preserved from Atlas data flow graph by eliding algorithm
- Field Sensitivity
  - Individual field definitions are tracked
- Object Sensitivity
  - Field access paths preserved for use in points-to analyses
- Type Sensitivity
  - Call sites that cannot be statically-resolved under open-world assumption are left to be resolved in the context of a client application
- Array / Array Index Sensitivity
  - Array components, access operands are preserved

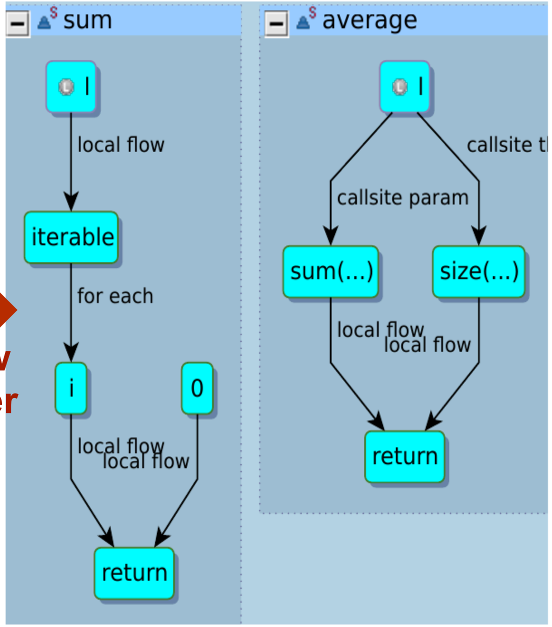
Summarizing Intra-Procedural Data Flow

```
package com.example;


class ProblemStatement{

  static int average(List<Integer> l){
          int lSum = sum(l);
          int lLength = l.size();
          return lSum / lLength;
  }

  static int sum(List<Integer> l){
          int s = 0;
          for(Integer i : l) s += i;
          return s;
  }

}
```

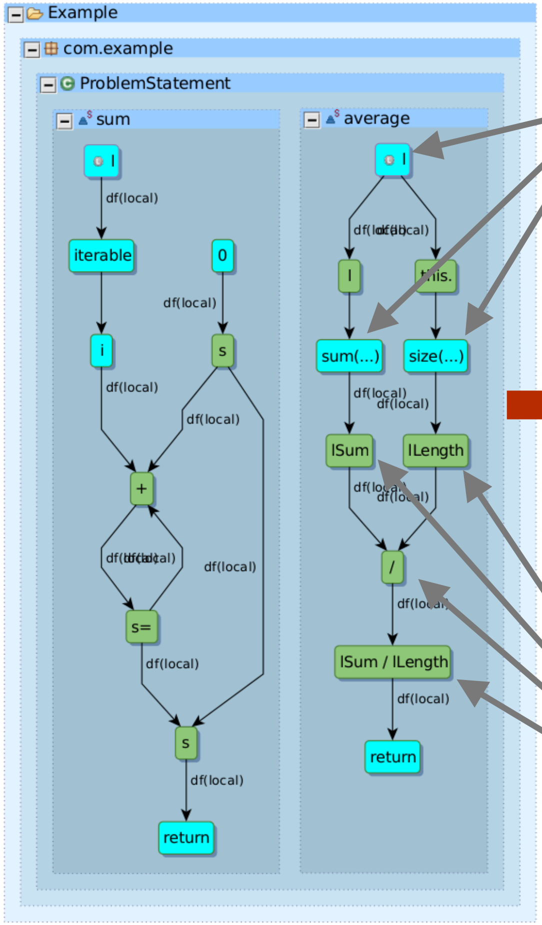
Atlas



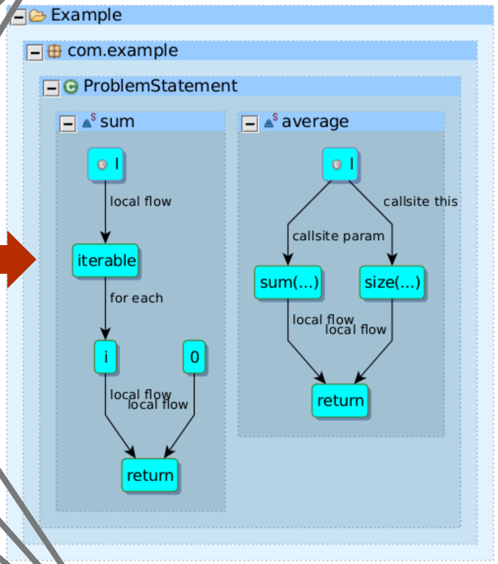
Flow Miner



Intra-procedural Flow - Elided Local Flow Algorithm



Preserved in the summary



Elided in the summary

Algorithm 1 Mining summary data flows

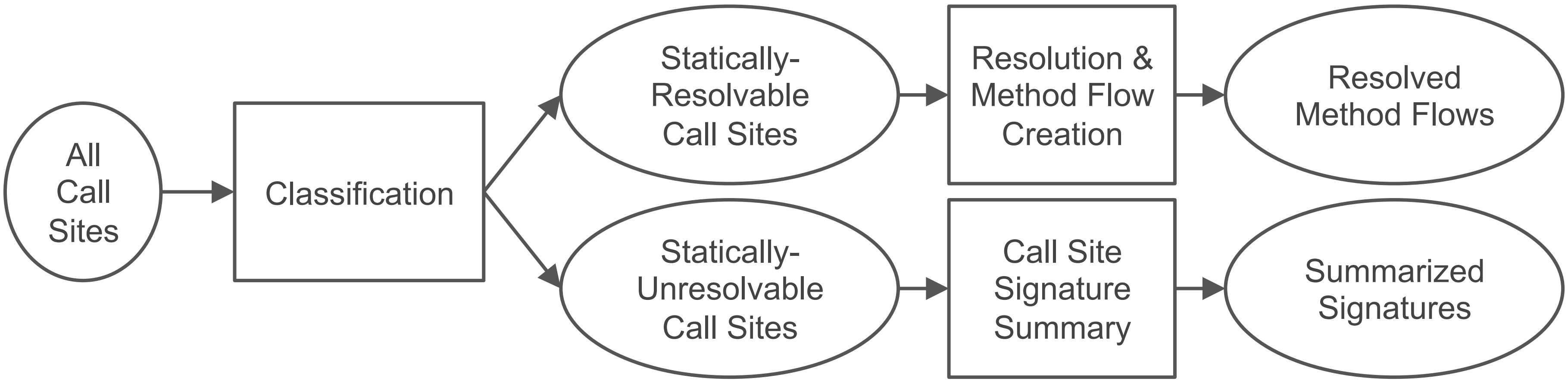
procedure MINEFLOW(K, $G(\mathfrak{P})$)
  for all $k \in K$ **do**
    reachable $= \leftarrow$ ElidedFlow(k, K, $G(\mathfrak{P})$)
    for all $k' \in$ reachable **do**
      Add summary flow edge from k to k'
    end for
  end for
end procedure

procedure ELIDEDFLOW(k, K, $G(\mathfrak{P})$)
  frontier $\leftarrow \{k\}$
  result $\leftarrow \{\emptyset\}$
  for all $f \in$ frontier **do**
    frontier $\leftarrow$ frontier - f
    for all f' s.t. (f, f') is a data flow edge in $G(\mathfrak{P})$ **do**
      if $f' \in K$ **then**
        result $\leftarrow$ result $\cup f'$
      else if $f' \notin$ frontier **then**
        frontier $\leftarrow$ frontier $\cup f'$
      end if
    end for
  end for
  return result
end procedure

Inter-procedural Flow - Summarizing Call Sites

Open World Assumption: Client applications may introduce new virtual dispatch targets when the library is used.

- Should not pre-resolve open-world virtual call sites in the summary!
  - All possibilities may not be captured
  - Must be able to capture *callbacks* into the target application



FlowMiner: Compaction

Argument: FlowMiner summaries cannot be further compacted without information loss

Removing *any* summary node removes a *key* program artifact

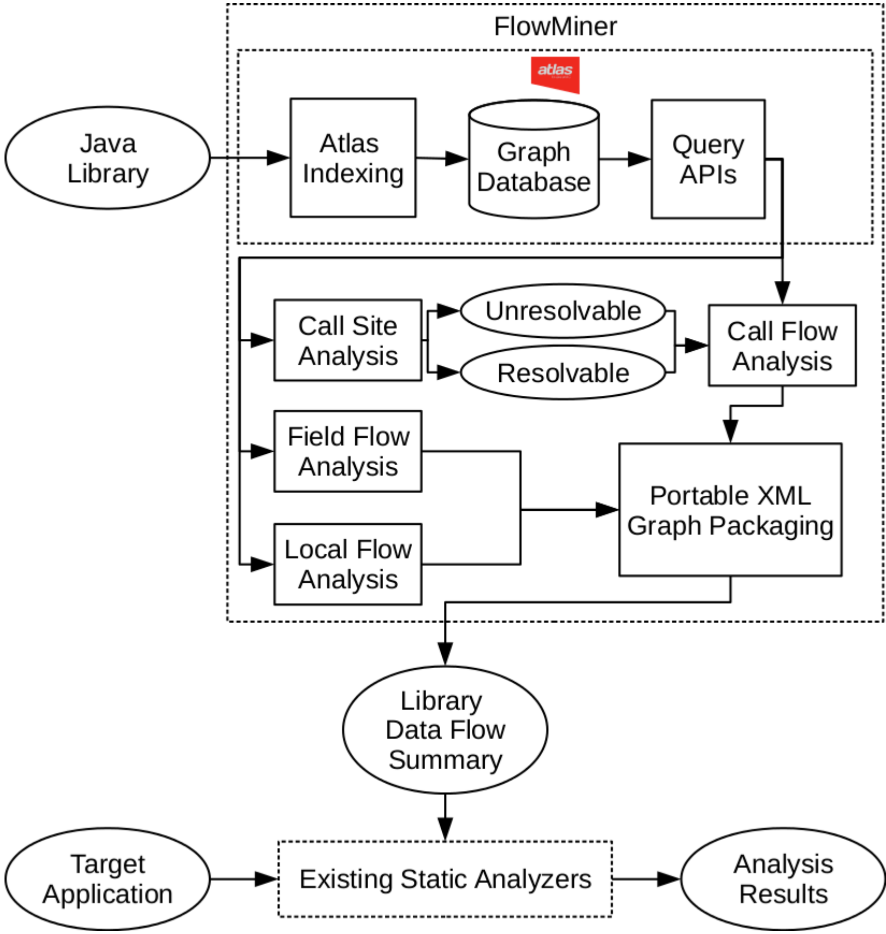
- Parameter, Identity, Return, Field, Array Component, Literal Value, Call Site

Removing *any* summary edge (A, B) disconnects *at least one* possible flow between key artifacts

- Can construct a client application such that this leads to a false negative

FlowMiner Implementation Architecture

- Targets arbitrary Java library bytecode (JAR)
- One-time static analysis
- Expressed as extension to XCSG graph schema (Atlas)
- Portable XML packaging of summaries
- Existing analyzers can leverage summary file



FlowMiner:
Evaluation on Android

FlowMiner on Android: Evaluation Results

Library	$\lvert V \rvert$	$\lvert E \rvert$	$\lvert V^S \rvert / \lvert V \rvert$ (%)	$\lvert E^S \rvert / \lvert E \rvert$ (%)	Field Flows	Object Flows	% False Positives* avoided
Android 4.2.2	6651277	33964070	37.11%	22.57%	1129523	16053060	92.96%
Android 4.3.1	6867245	35165616	37.10%	22.51%	1206542	16816490	92.83%
Android 4.4.4	7707688	44150241	36.98%	20.06%	1216178	17069468	92.88%
Android 5.0.2	8684208	45649066	37.05%	21.93%	1556027	21874691	92.89%

|V|, |E| - # Nodes, # Edges in the original program graph

$|V|^S$, $|E|^S$ - # Nodes, # Edges in the summary program graph

Field Flows - Data-flow edges in FlowMiner's summary that tracks flows at field level granularity

Object Flows - Data-flow edges if object level flows are tracked

FlowMiner on Android: Correctness

Library	$\|V\|$	$\|E\|$	$\|V^S\|/\|V\|$ (%)	$\|E^S\|/\|E\|$ (%)	Field Flows	Object Flows	% False Positives* avoided
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4 Recent versions of Android

Sound: No spurious flows added (no false positives)

Complete: All flows covered (no false negatives)

FlowMiner on Android: Compactness

Library	$\|V\|$	$\|E\|$	$\|V^S\|/\|V\|$ (%)	$\|E^S\|/\|E\|$ (%)	Field Flows	Object Flows	% False Positives* avoided
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Summary Graph $G^S=(V^S,E^S)$ retained from the original graph

only ~37% Nodes

20% - 23% Edges

Considerably smaller than original program graphs

FlowMiner on Android: Expressiveness

Library	$\|V\|$	$\|E\|$	$\|V^S\|/\|V\|$ (%)	$\|E^S\|/\|E\|$ (%)	Field Flows	Object Flows	% False Positives* avoided
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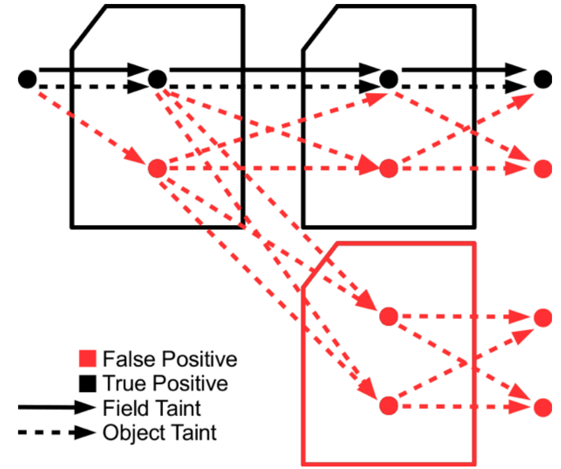
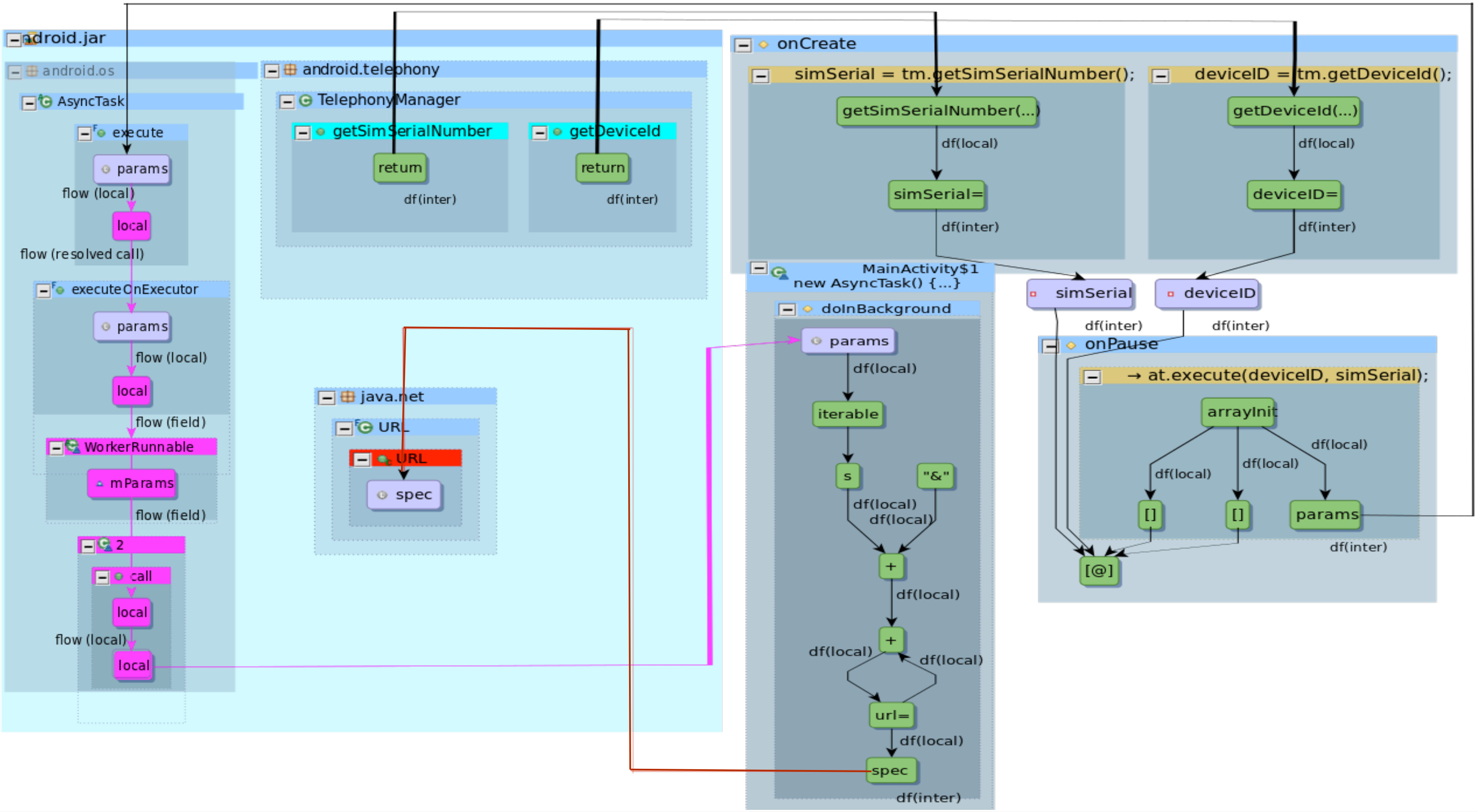
*False Positives comparison
- Field-sensitive vs Object-sensitive flow tracking
  - Comparison to Clapp et al.

~93% fewer false positive flows



Malware Example with Summaries



FlowMiner: Related Work

Component-Level Data-flow Analysis (Rountev et al.)

- Theoretical framework for summarizing an Interprocedural Control Flow Graph (ICFG)
- Captures virtual calls (callbacks), elides uninteresting details
- *Incomplete handling of fields*
- *Lacking concrete implementation*

Mining Information Flow Specifications From Concrete Executions (Clapp et al.)

- Instrument Android and create a special emulation environment
- Dynamically exercise Android APIs to produce execution traces
- Post-process traces to infer *coarse* information flow summaries.
- *Coarse object tainting is inaccurate, misses callbacks*
- *Incomplete path coverage*

Summary

FlowMiner

- **One-time, automatic** static extraction of data flow summaries
- **Expressive** & fine-grained
  - Can be used with context, field, type, flow, and object sensitivity
- **Compact**
  - Elides uninteresting details of flows
- **Sound**
  - Indicated flows actually occur
- **Portable** for use by existing tools
- **Captures callbacks** from the library back into the application
- **Practically Efficient** open source tool
  - **Validated** on recent versions of Android

Related Publications

Tom Deering, Suresh Kothari, Jeremias Sauceda, and Jon Mathews. May 2014. Atlas: a new way to explore software, build analysis tools. In *Companion Proceedings of the 36th International Conference on Software Engineering* (ICSE Companion 2014). ACM, New York, NY, USA, 588-591.

Benjamin Holland, Tom Deering, and Suresh Kothari. May 2015. Security Toolbox for Detecting Novel and Sophisticated Malware. In *Companion Proceedings of the 37th International Conference on Software Engineering* (ICSE Companion 2015). ACM, New York, NY, USA.

Thank You!

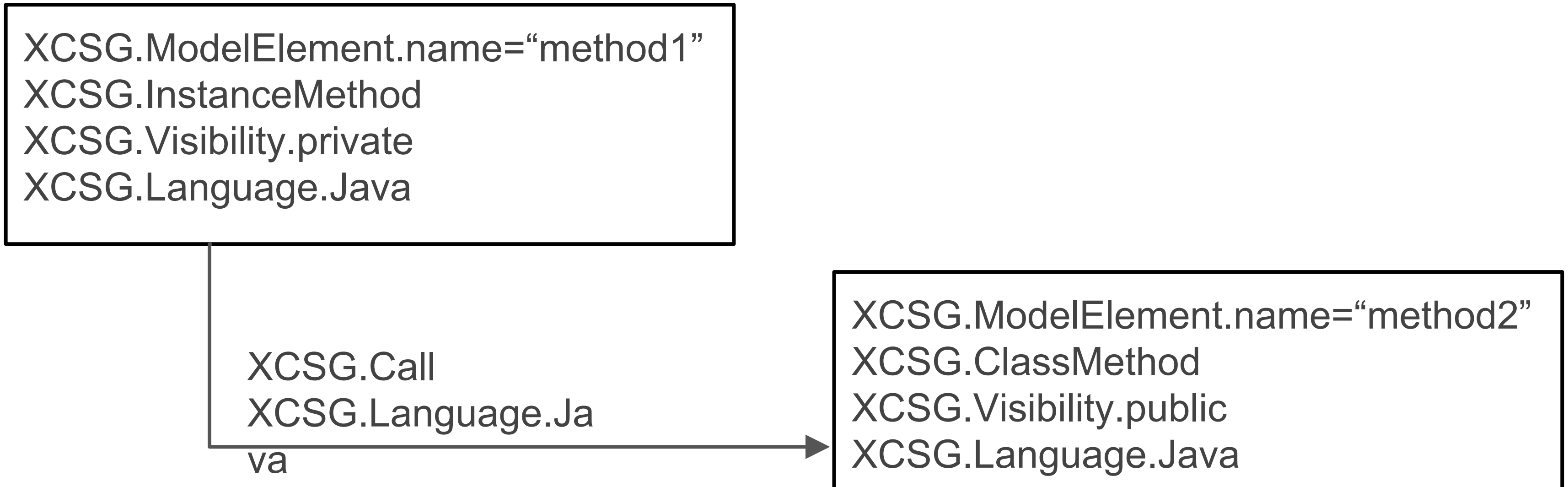
EnSoft Team Jon Mathews, Jeremias Sauceda, Nikhil Ranade, Kevin Korslund, Theodore Murdock

DARPA APAC & STAC programs

XCSG/Atlas Additional Slides

Atlas: XCSG Directed Property Multigraph

```
private void method1(){ method2(); }
public static void method2(){}
```



Atlas: XCSG Directed Property Multigraph

Edge Kind	Meaning
Contains	Destination is nested within origin.
Element Type	Origin array contains destination element kind.
Overrides	Origin method overrides the destination method.
Supertype	Destination is a supertype of the origin type.
Type Of	Destination type is static type of origin.
Control Flow	Dest block follows origin block.
Call	Origin calls destination method.
Data Flow	Origin def flows to destination use.

Atlas: API for Automated Analyzers

Analysis results can be built using low-level ***graph*** or convenience ***select***, ***traverse***, and ***combine*** operations on the XCSG-compliant graph.

```
Q someType = types(“AnInterestingType”);
Q supertypeHierarchy = edges(XCSG.Supertype).forward(someType);

Q someMethod = methods(“anInterestingMethod”);
Q reverseCallGraph = edges(XCSG.Call).reverse(someMethod);
Q combinedResult = supertypeHierarchy.union(reverseCallGraph);
```