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Purity and Side Effect Analysis for Java Programs

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Introduction / Motivation

how to analyze Java programs to figure out when methods are pure, when they have side effects, and how we can reason about them safely

Why does purity matter ?

- Purity enables formal verification techniques (JML specifications)
- Simplifies reasoning about method calls → referential transparency
- Critical for:
  - **Program verification** (proofs rely on stable state)
  - **Model checking** (reduces state explosion)
  - **Compiler optimizations** (LICM, CSE, parallelization)
  - **Understanding program behavior**, summarizing effects

The Challenge ?

- Real Java methods frequently allocate and mutate temporary objects
- Traditional purity: **no writes at all**, overly restrictive
- Need a definition that captures useful practical purity, not syntactic purity

Problem: Earlier Purity Analyses Are Too Strict

Limitations of Prior Work

- Based on syntactic restrictions
- Any heap write ⇒ method considered impure
- Calling a possibly impure method ⇒ entire method impure
- Cannot distinguish:
  - Writes to pre-existing objects
  - Writes to newly allocated helper objects

Real Java Examples That Break Old Purity Analysis

- Iterators mutate internal cursor/state
- Visitor patterns allocate new objects and write internal fields
- Methods that allocate temporary data structures (builder, accumulator)

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Key Contributions

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What this paper introduces

- First implemented purity analysis for Java that:
  - * allows modifying newly allocated objects,
  - * as long as they do not escape,
  - * and still treats the method as pure
- A unified static analysis combining:
  - * context-insensitive points-to
  - * escape analysis
  - * side-effect analysis
- Interprocedural purity inference using method summaries
- Scalable implementation + empirical results

Purity Definition & Categories

Pure

- Reads from existing objects
- Writes only to new, non-escaping objects
- Does not change any part of the pre-existing reachable state

Read-only

- Reads from existing objects
- Does NOT write to any object
- All effects are observational reads

Impure

- Writes to any object reachable before the method call
- Writes to any escaping object

java

```java
int square(int x) {
    return x * x;
}
```

java

```java
int size() {
    return this.length;
}
```

java

```java
void add(int x) {
    this.size = x;          // modifies object
}
```

How purity is computed ?

Points-to Analysis — “What objects can x point to?”

↓

Escape Analysis — Which of these objects escape the method?

↓

Side-Effect Analysis — Computes ReadSet, WriteSet & EscapeSet

↓

Method Effects Summary — (R, W, E)

↓

Purity Classification

Analysis

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Points-to Analysis

Definition: Determines which heap objects each variable or field may refer to.

- Flow-insensitive, context-insensitive
- Builds the program's abstract heap graph
- Maps variables/fields → allocation sites
- Identifies objects that reads/writes may target
- Basis for constructing R(m) and W(m)

```java
x = new Node();
y = x;
```

Escape Analysis

Definition: Determines whether a newly allocated object becomes visible outside the method.

- Determines whether objects created inside a method become visible outside
- If an object does not escape, writing to it does not break purity

Escape happens if object is:

- returned
- stored into a field of a reachable object
- passed as argument to a method where it may escape

Non-escaping objects can be safely mutated

Enables the paper’s relaxed purity definition

```
Node foo() {
    Node x = new Node();   // fresh
    return x;              // escapes!
}
```

Side-Effect Analysis

Definition: Computes all heap locations a method may read or write, using points-to + escape results.

Produces:

- R(m): objects/fields read
- W(m): objects/fields written
- E(m): allocated objects that escape

```java
void inc() {
    this.x++;
}
```

Interprocedurally propagated via method summaries

Final purity classification based on (R, W, E)

Method Summary

Method Summary = (R, W, E)

The analysis computes three sets:

- **ReadSet:** R(m) — set of object abstractions that method m may read
- **WriteSet:** W(m) — set of object abstractions method m may write
- **EscapeSet:** E(m) — set of allocated objects that escape m

Purity rule:

- Pure if: $W(m) \subseteq$ fresh objects AND E(m) is disjoint from W(m)
- Read-only if: $W(m) = \varnothing$
- Impure otherwise

```
Method foo():
  ReadSet = {obj.a}
  WriteSet = {}
  EscapeSet = {}
  => Read-only
```

How Do These Analyses Come Together Into One View?

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Points-To Graph (PTG)

A Points-To Graph (PTG) is an abstract heap model that summarizes all objects a method may interact with and how they are connected.

- Nodes represent abstract objects
- Edges represent abstract references
- Annotated with:
    - Allocation origin (inside vs. load)
    - Possible field targets
    - Escape status

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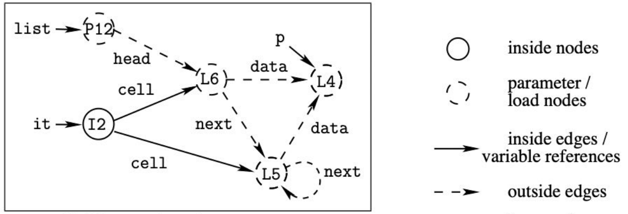
Points-To Graph (PTG)



a. Cell constructor

Node Types in Points-To Graph

- **Parameter Nodes**
  Represent object abstractions passed to the method
- **Load Nodes (L-nodes)**
  Represent objects reached via field loads from prestate objects → These are still part of the prestate
- **Inside Nodes (I-nodes)**
  Represent objects allocated by new inside the method

Edge Types

- **Outside Edges**: read from prestate (load nodes, parameter nodes)
- **Inside Edges**: created inside the method

Purity Determination via Prestate Reachability

Prestate Reachability

- Prestate = nodes reachable from parameter nodes via outside edges
- Compute reachable set Pre(m)
- Compute write set W(m)

Purity Rules

A method **m** is pure iff:

1. For all writes $w \in W(m)$:
   $target(w) \notin Pre(m)$
2. No modified inside node escapes:
   $W(m) \cap EscapingInsideNodes = \varnothing$

Example:

```
class List {
  Cell head = null;
  void add(Object e) {
    head = new Cell(e, head);
  }
  Iterator iterator() {
    return new ListItr(head);
  }
}

class Cell {
  Cell(Object d, Cell n) {
    data = d; next = n;
  }
  Object data;
  Cell   next;
}

interface Iterator {
  boolean hasNext();
  Object next();
}

class ListItr implements Iterator {
  ListItr(Cell head) {
    cell = head;
  }
  Cell cell;
  public boolean hasNext() {
    return cell != null;
  }
  public Object next() {
    Object result = cell.data;
    cell = cell.next;
    return result;
  }
}

class Point {
  Point(float x, float y) {
    this.x = x; this.y = y;
  }
  float x, y;
  void flip() {
    float t = x; x = y; y = t;
  }
}

class Main {
  static float sumX(List list) {
    float s = 0;
    Iterator it = list.iterator();
    while(it.hasNext()) {
      Point p = (Point) it.next();
      s += p.x;
    }
    return s;
  }

  static void flipAll(List list) {
    Iterator it = list.iterator();
    while(it.hasNext()) {
      Point p = (Point) it.next();
      p.flip();
    }
  }

  public static void main(String args[]) {
    List list = new List();
    list.add(new Point(1,2));
    list.add(new Point(2,3));
    sumX(list);
    flipAll(list);
  }
}
```

Example 1: sumX Is Pure

```
static float sumX(List list) {
  float s = 0;
  Iterator it = list.iterator();
  while(it.hasNext()) {
    Point p = (Point) it.next();
    s += p.x;
  }
  return s;
}
```

Purity Result:

✔ All writes target **inside node**
✔ No writes to **prestate**
→ **sumX = Pure Method**

Iterator creation:

- list.iterator() → allocates **ListItr** → **Inside Node (I-node)**
- Writes to iterator fields → **writes to I-node only**

Iterator next():

- cell = cell.next → moves internal pointer
- **Mutation stays inside I-node** (fresh object)
- No effect on list, cells, or points

Reads from list:

- Point p = (Point) it.next() → loads Point
- Point objects → **Prestate Nodes** (reachable from parameter)
- Only **read**, not written

No prestate writes:

- No modification to:
  • list (P-node)
  • Cell objects (L-nodes)
  • Point objects (prestate L-nodes)

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Example 1: sumX Is Pure

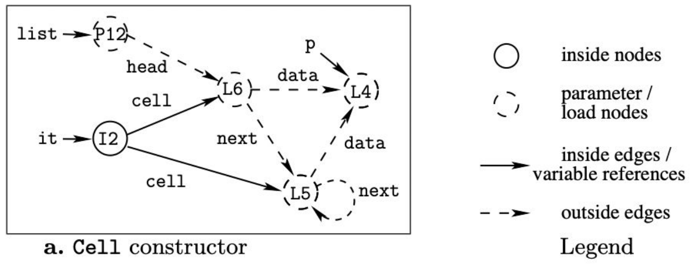

Fig. 2. Points-To Graph for the end of Main.sumX(List)

Purity Result:

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✔ No writes to **prestate**
→ **sumX = Pure Method**

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  • Point objects (prestate L-nodes)

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Example 2: `flipAll` Is Impure

```
static void flipAll(List list) {
  Iterator it = list.iterator();
  while(it.hasNext()) {
    Point p = (Point) it.next();
    p.flip();
  }
}
```

Purity Result:

✘ Writes target **prestate nodes**
✘ Mutates objects reachable from parameter

→ **flipAll = Impure Method**

Iterator creation:

- Same as sumX: new ListItr → Inside Node (I-node)

Loading points:

- Point p = (Point) it.next()
- Point objects → Prestate Nodes (from list.head)
- These existed before the call

flip():

- p.flip() writes: x = y; y = t;
- Direct write to Point.x and Point.y
- These fields belong to prestate nodes

Write path (from analysis):

- list.head.next*.data.(x | y)
- This path ends at prestate Point fields → outside/parameter nodes

Applications / Optimizations

Common Subexpression Elimination

```
a = pure_func(x, y);
b = pure_func(x, y);
```

→

```
a = pure_func(x, y);
b = a;
```

Loop-invariant Code Motion

```
for(...){
    y += pure_func(x)
}
```

→

```
temp = pure_func(x)
for(...){
    y += temp
}
```

Parallelization / Vectorization

```
int[100] arr;
for(int i = 0; i < 100; i++){
      Arr[i] = pure_func(i);
}
```

Results

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Benchmarks

Application	Description
BH	Barnes-Hut N-body solver
BiSort	Bitonic Sort
Em3d	Simulation of electromagnetic waves
Health	Health-care system simulation
MST	Bentley's algorithm for minimum spanning tree in a graph
Perimeter	Computes region perimeters in an image represented as a quad-tree
Power	Maximizes the economic efficiency of a community of power consumers
TSP	Randomized algorithm for the traveling salesman problem
TreeAdd	Recursive depth-first traversal of a tree to sum the node values
Voronoi	Voronoi diagram for random set of points

Table 1. Java Olden benchmark applications.

Results - 3.4 to 7.2 seconds

Application	All Methods		User Methods	
	count	% pure	count	% pure
BH	264	55%	59	47%
BiSort	214	57%	13	38%
Em3d	228	55%	20	40%
Health	231	57%	27	48%
MST	230	58%	31	54%
Perimeter	236	63%	37	89%
Power	224	53%	29	31%
TSP	220	56%	14	35%
TreeAdd	203	58%	5	40%
Voronoi	308	62%	70	71%

Table 2. Percentage of Pure Methods in the Java Olden benchmarks.

Strengths and weaknesses

Strengths

- The authors formalized a more relaxed version of purity and created a system to identify this definition of pure
- This relaxed definition of purity allows for more aggressive optimizations

Weaknesses

- The authors do not compare their results to other pureness analysis programs.
  - Number of functions identified as pure
  - Performance/speed of the analysis
- Their analysis requires analyzing all code paths which can be impossible for programs that utilize dynamic class loading or when the entire program is available

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Conclusion / Takeaways

Conclusion

- The authors create a more relaxed definition of what is pure
- It requires further analysis to identify this relaxed definition of a pure function, but allows more functions to be defined as pure
- This allows for more optimizations than the stricter definition of pure of no memory reads or writes.

Thank you
Q&A