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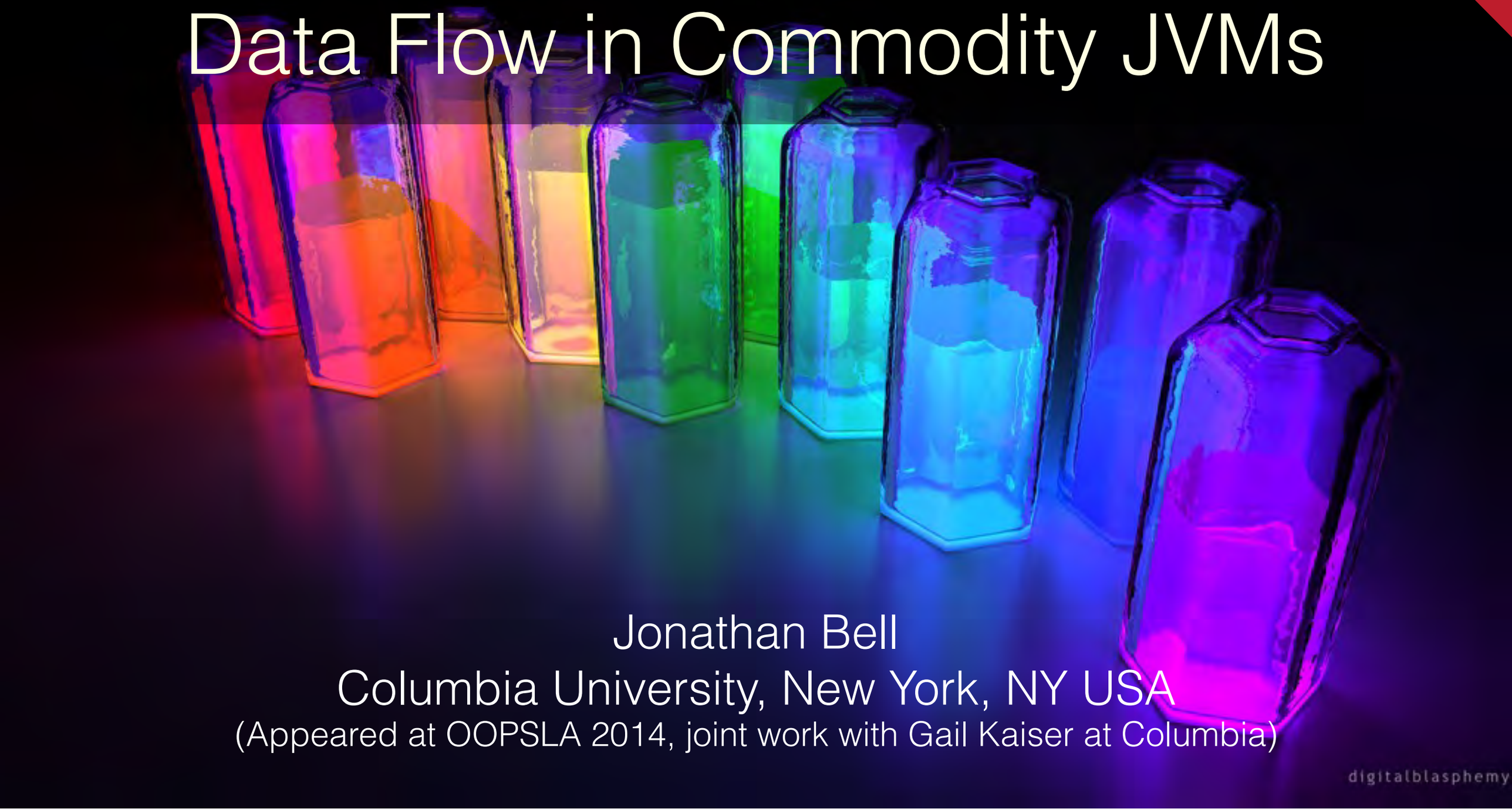
Phosphor: Illuminating Dynamic Data Flow in Commodity JVMs



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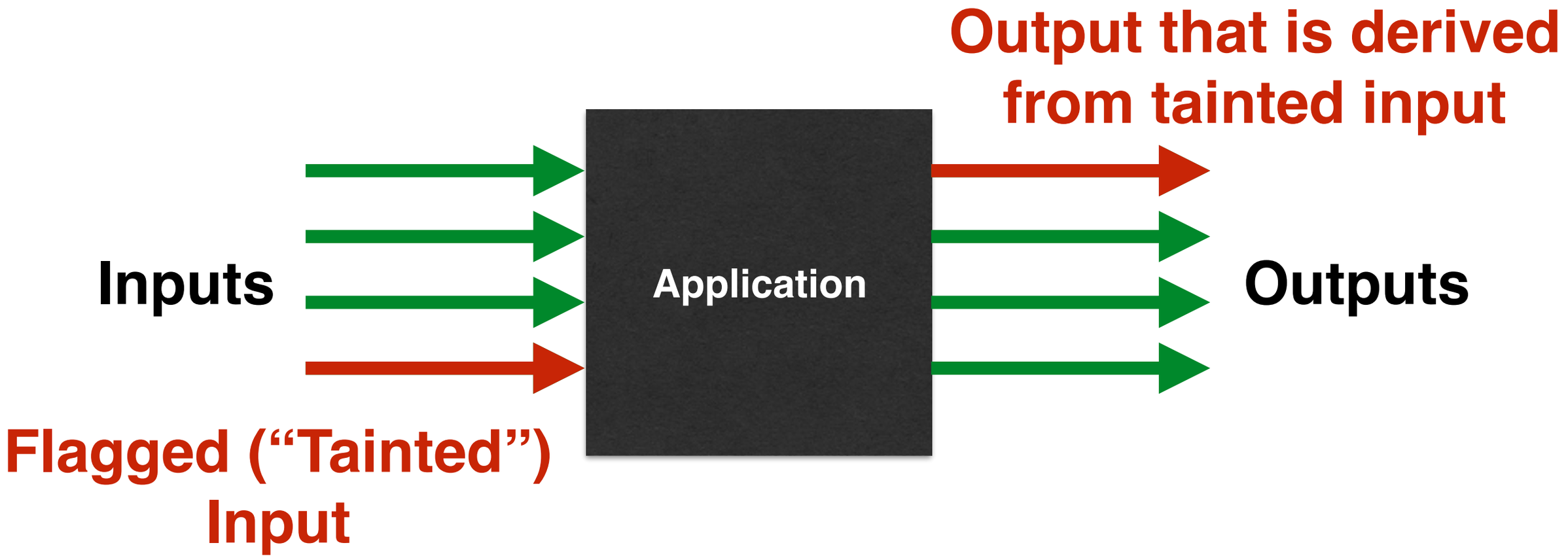
(Appeared at OOPSLA 2014, joint work with Gail Kaiser at Columbia)

Dynamic Data Flow Analysis: Taint Tracking



Taint Tracking: Applications

- End-user privacy testing: Does this application send my personal data to remote servers?
- SQL injection attack avoidance: Do SQL queries contain raw user input
- Debugging: Which inputs are relevant to the current (crashed) application state?
- Testing: Are my test cases overly specified?

Qualities of a Successful Analysis

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Soundness

No data leakage!


Precision
Data is tracked with the right tag

Performance

Minimal slowdowns

Portability

No special hardware, OS, or JVM

“Normal” Taint Tracking

- Associate tags with data, then propagate the tags
- Approaches:
  - Operating System modifications [Vandebogart ’07], [Zeldovich ’06]
  - Language interpreter modifications [Chandra ’07], [Enck ’10], [Nair ’07], [Son ’13]
  - Source code modifications [Lam ‘06], [Xu ’06]
  - Binary instrumentation of applications [Clause ’07], [Cheng ’06], [Kemerlis ’12]

Not portable

Hard to be sound, precise, and performant

Phosphor

- Leverages benefits of interpreter-based approaches (information about variables) but *fully portably*

- Instruments *all* byte code that runs in the JVM (including the JRE API) to track taint tags

  - Add a variable for each variable

  - Adds propagation logic

Key contribution:

How do we efficiently store meta-data for **every** variable **without** modifying the JVM itself?

JVM Type Organization

- Primitive Types
  - int, long, char, byte, etc.
- Reference Types
  - Arrays, instances of classes
  - All reference types are assignable to java.lang.Object

Phosphor's taint tag storage

	Local variable	Method argument	Return value	Operand stack	Field
Object	Stored as a field of the object				
Object array	Stored as a field of each object				
Primitive	Shadow variable	Shadow argument	"Boxed"	Below the value on stack	Shadow field
Primitive array	Shadow array variable	Shadow array argument	"Boxed"	Array below value on stack	Shadow array field

Taint Propagation

- Modify all byte code instructions to be taint-aware by adding extra instructions

- Examples:
  - Arithmetic -> combine tags of inputs
  - Load variable to stack -> Also load taint tag to stack
  - Modify method calls to pass taint tags


HERE BE DRAGONS
MARE GLACIALE
PARS
MIDDELFORD
TROMS
HASEVIK
LOKHELLE
GILLEFIORD
GIGASVND
SKARTASVND
VANDVAD
QVEDEFIORD
ROLLEN
SCONGEN
GAMBACVIK
HIC FORVM PISCIVM FREQVENTISSIMVM
OSTRAFIORD
Two big problems

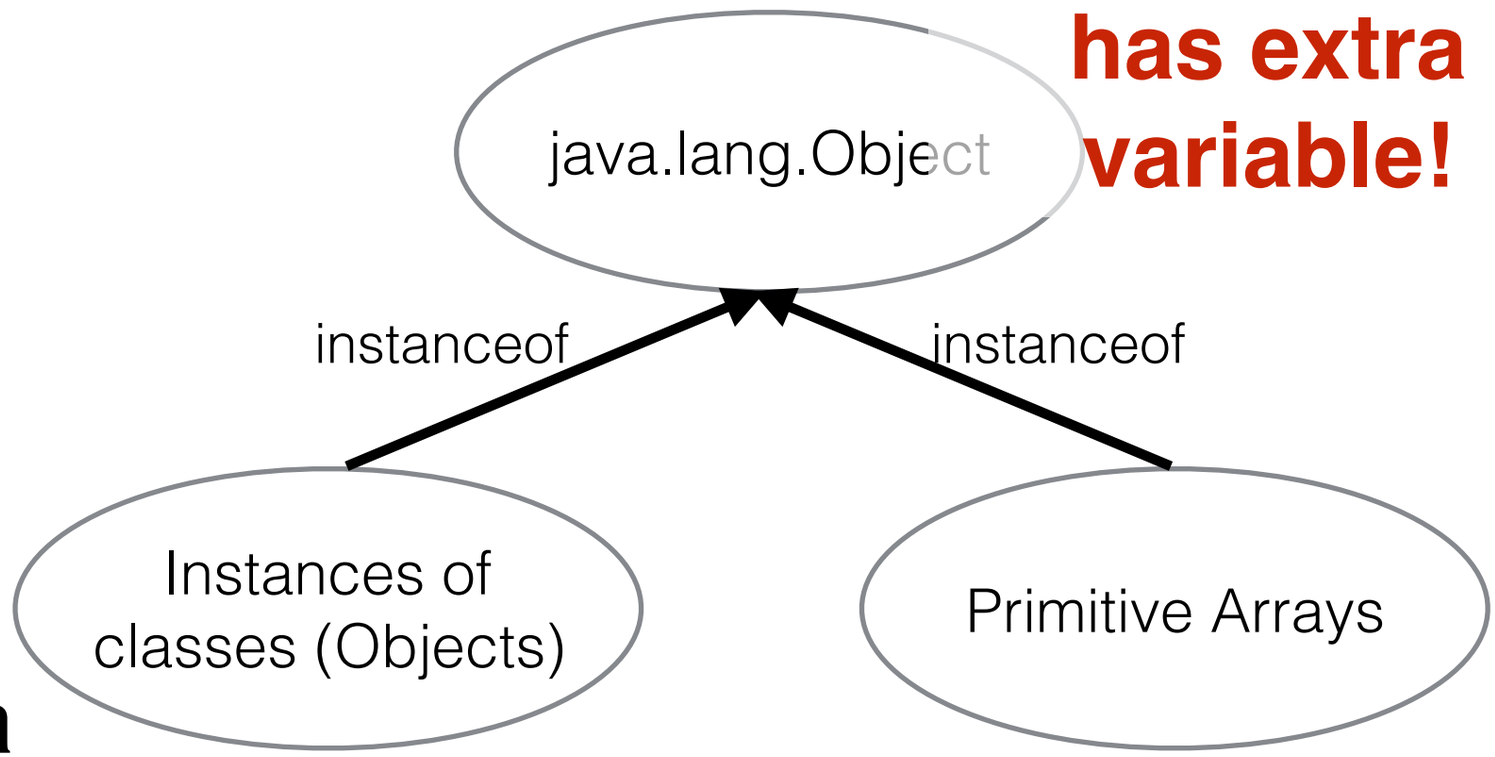
Challenge 1: Upcasting

Primitive Types

Always has extra variable!

Never has extra variable!

Sometimes has extra variable!



Always has extra variable

Challenge 1: Upcasting

```
byte[] array = new byte[5];
Object ret = array;
return ret;
```

```
int[] array_tag = new int[5];
byte[] array = new byte[5];

Object ret = new TaintedByteArray(array_tag,array);
```

Solution 1: Box taint tag with array when we lose type information

Challenge 2: Native Code

We can’t instrument everything!

Challenge 2: Native Code

```
public int hashCode() {
  return super.hashCode() * field.hashCode();
}
```

```
public native int hashCode();
```

Solution: Wrappers. Rename *every* method, and leave a wrapper behind

```
public TaintedInt hashCode$$wrapper() {
    return new TaintedInt(0, hashCode());
  }
```

Challenge 2: Native Code

Wrappers work both ways: native code can still call a method with the old signature

```
public int[] someMethod(byte in)
{
  return someMethod$$wrapper(0, in).val;
}

public TaintedIntArray someMethod$$wrapper(int in_tag, byte in)
{
  //The original method "someMethod", but with taint tracking
}
```

Design Limitations

- Tracking through native code
- Return value's tag becomes combination of all parameters (heuristic); not found to be a problem in our evaluation

Configuration Options

- Tag propagation modes:
  - Data flow
  - Control flow

```
int c = a + b;
```

```
if (a == 0) c = 0;
```

- Tag format:
  - Integer (bit vectors)
  - Object (maintain relationships sets)
- Automatic Tagging and Checking

Phosphor: API

Getting and setting tags on objects

```
Interface TaintedWithObjTag.class
public Taint getPHOSPHOR_TAG();
public void setPHOSPHOR_TAG(Object o);
```

Getting and setting tags on primitives

```
MultiTainter.class
public static Taint getTaint(<Primitive Type> c);
public static float tainted<Primitive Type>(<Primitive Type> f, Object tag);
```

Getting relationships between tags

```
Class Taint.class
public LinkedList<Taint> getDependencies();
public Object getLabel();
```

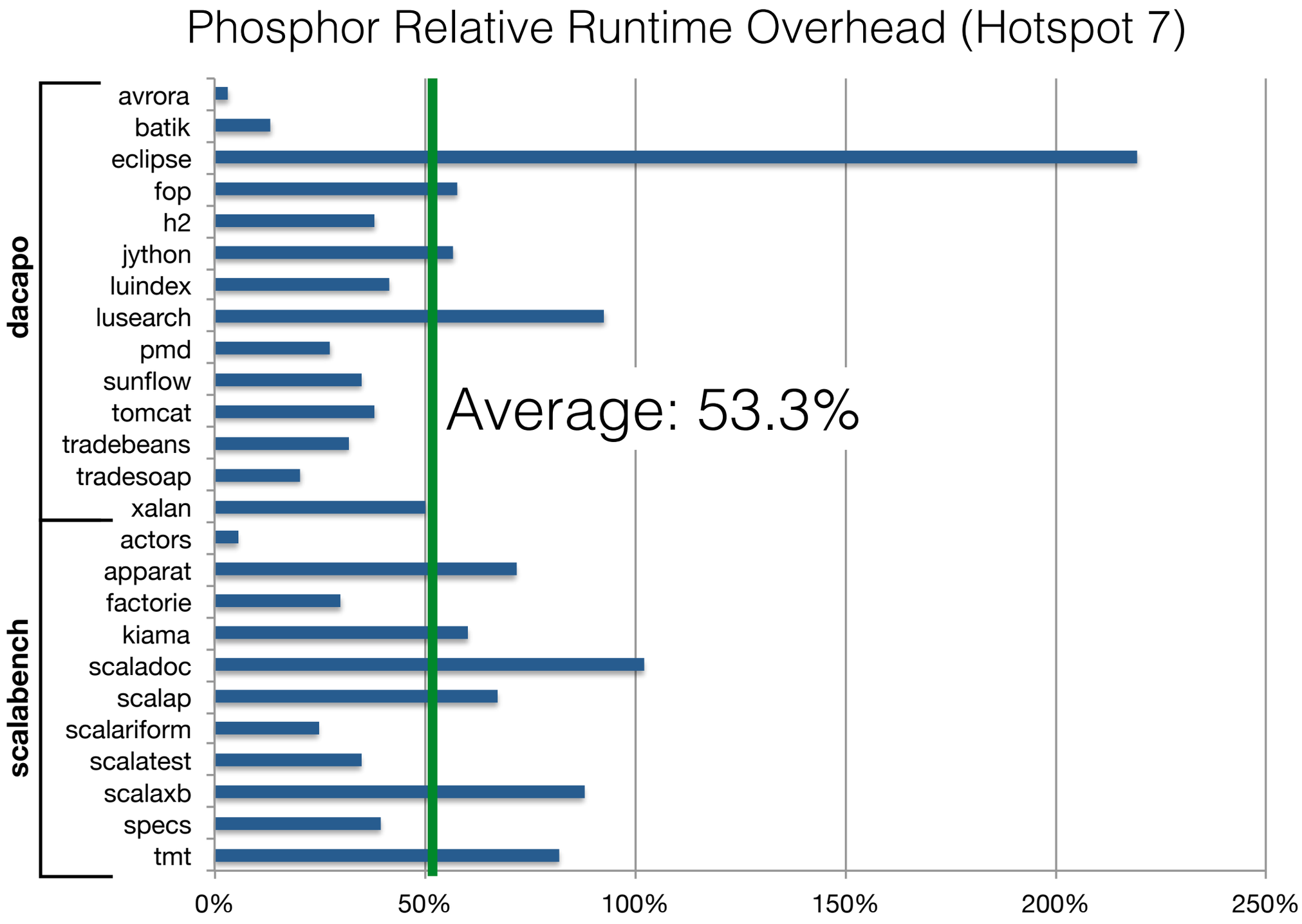
Evaluation

- Soundness & Precision
- Performance
- Portability

Soundness & Precision

- DroidBench - series of unit tests for Java taint tracking
- Passed all except for implicit flows (intended behavior)

Macrobenchmarks



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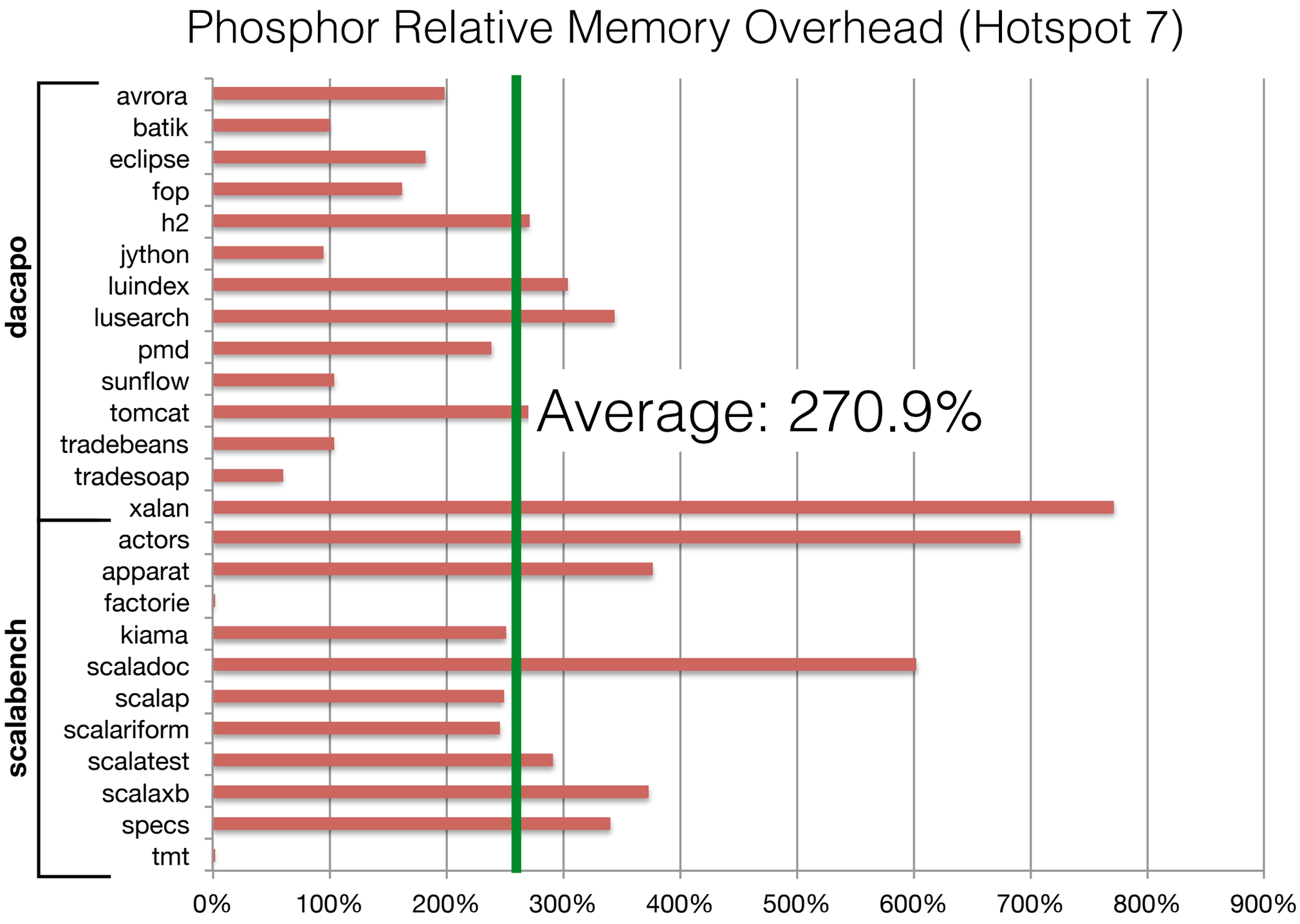
Macrobenchmarks



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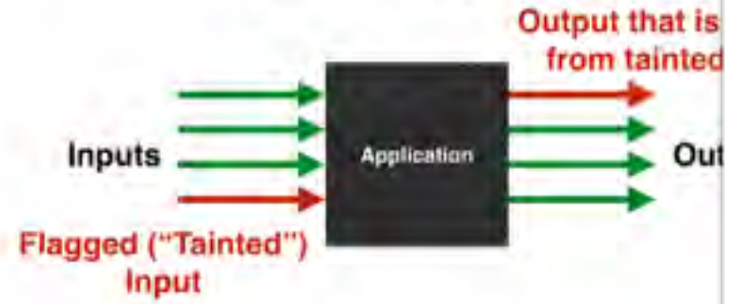
Portability

JVM	Version(s)	Success?
Oracle (Hotspot)	1.7.0_45, 1.8.0_0	**Yes**
OpenJDK	1.7.0_45, 1.8.0_0	**Yes**
Android Dalvik	4.3.1	**Yes**
Apache Harmony	6.0M3	**Yes**
Kaffe VM	1.1.9	**Yes**
Jikes RVM	3.1.3	No, but may be possible with more work

Future Work & Extension

- This is a general approach for tracking metadata with variables in unmodified JVMs
- Could track any sort of data in principle
- Static+Dynamic hybrid analysis
- Implicit flow analysis, too

Dynamic Data Flow Analys
Taint Tracking



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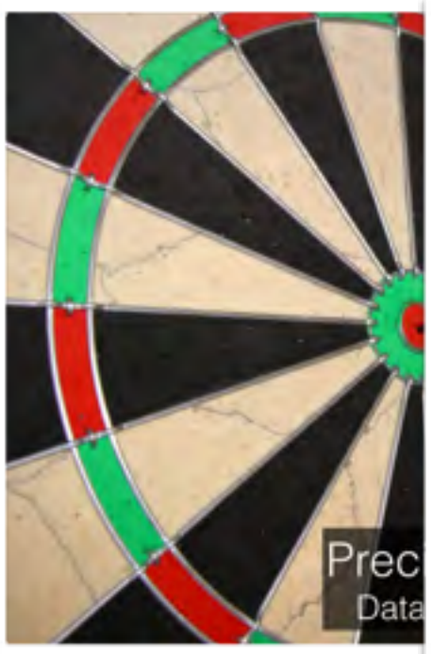

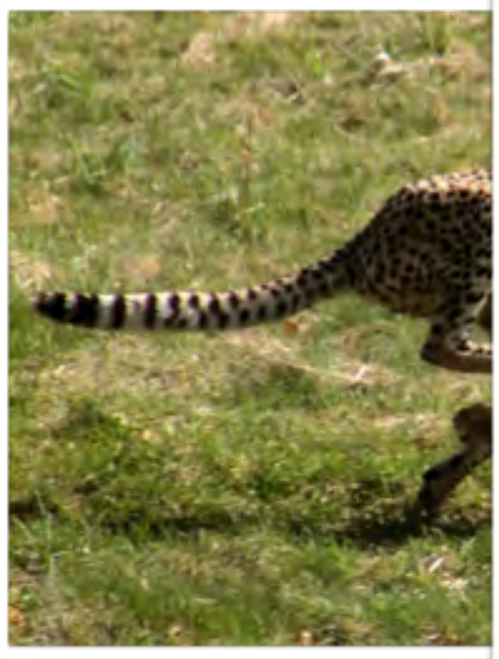

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https://github.com/Programming-Systems-Lab/Phosphor