Java Runtime Error Detection Through Static Data Flow Analysis

...avoiding runtime errors at development time.

Dr. Fridtjof Siebert
CTO, aicas
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Goals of this DFA

Correctness Analysis

- Proof absence of runtime errors
- Gain confidence in code
- Provide input for other tools

Not a goal are

- Compiler optimizations:
  - omit runtime checks
  - reduce application size
  - **But: very dangerous!**

Data Flow Analysis Basics

Idea

Start at main() method and follow all assignments in an iterative loop.

Result is

- Set of calls
- Set of values for each variable

Data Flow Analysis Basics

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- calls = { main } (set of calls)

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Iterate

- do {

} **until fix point is reached**;

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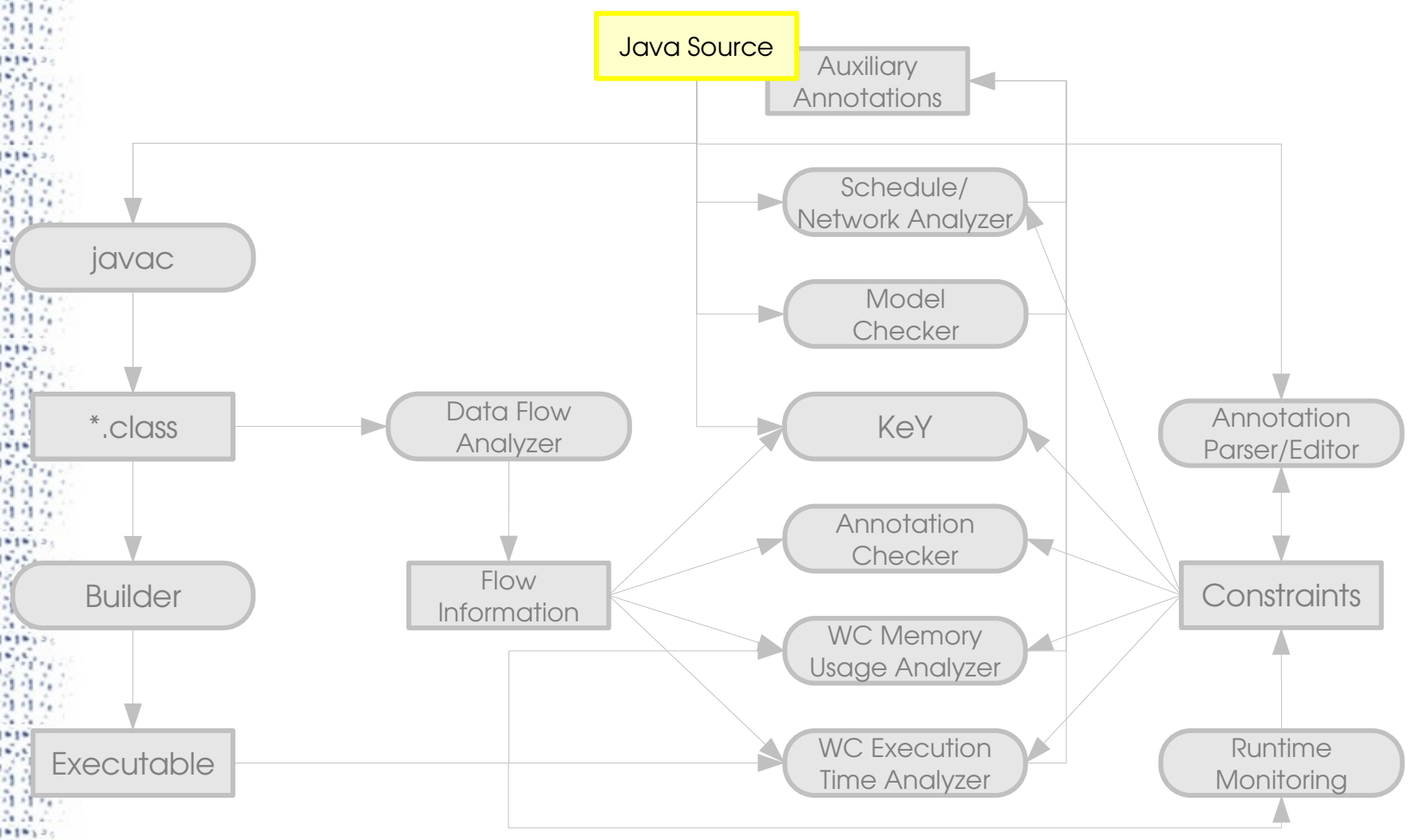
  variables = variables ∪

  { (a,X) : ∃ x: x ∈ calls ∧ "a = new X()" ∈ x) } ∪

  { (a,v) : ∃ x: x ∈ calls ∧ "**a = b**" ∈ x ∧ (b,v) ∈ values }

  } until fix point is reached;

DFA as part of larger Tool Chain



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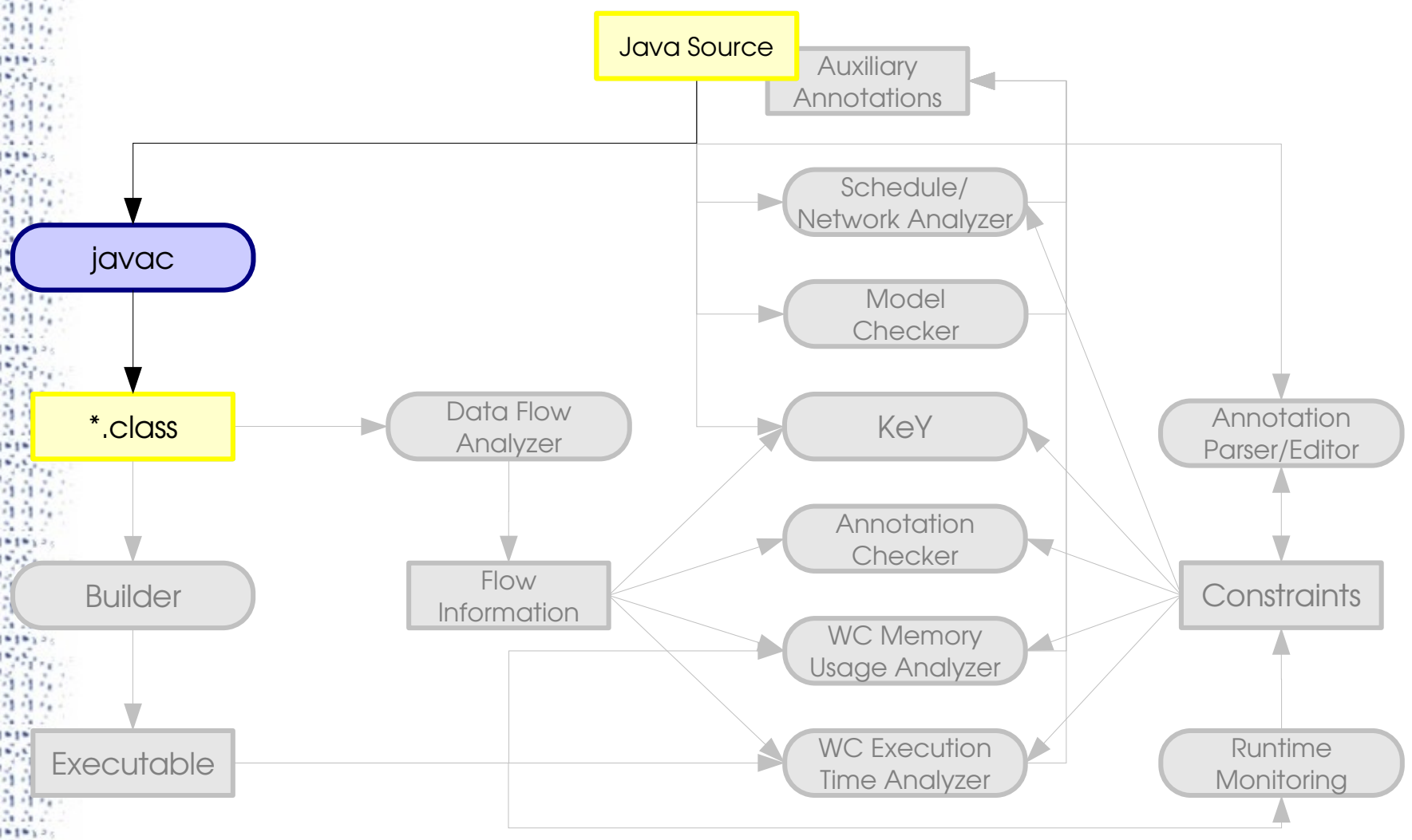

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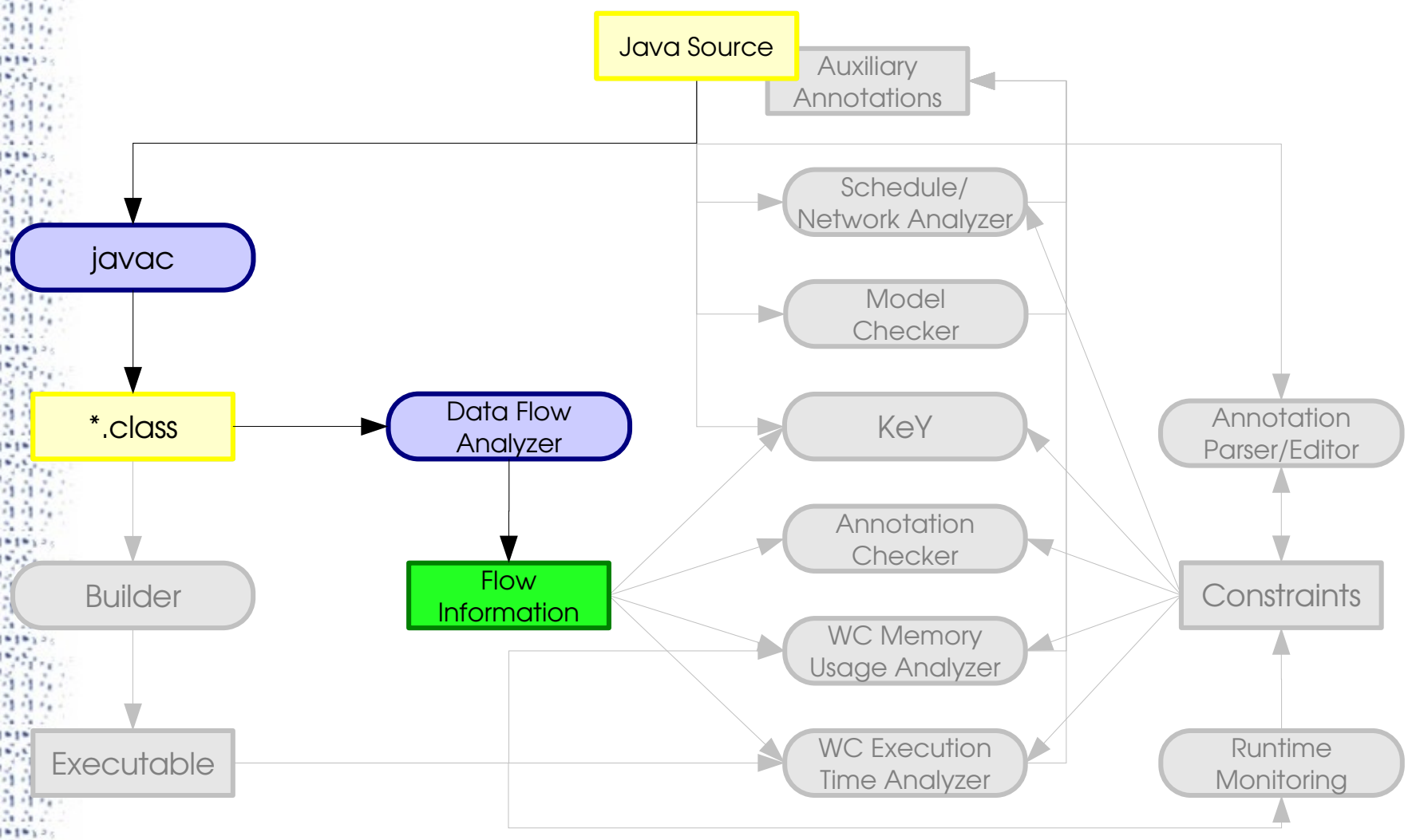

Application-wide Data-Flow Analysis

Problems

Identification of objects by type not sufficient

Granularity: Methods and Fields are not enough

```
Vector v1 = new Vector();
Vector v2 = new Vector();
v1.put(new A());
v2.put(new B());
x = v1.get();
A a = (A) x;  /* how to proof cast is ok? */
```

we need **context information!**

Main Problem

Accuracy of context information

- Only type information not sufficient
- Complete call chain causes exponential explosion

A useful solution must lie somewhere in between

- must trace types accurately enough
- must run in reasonable time and space

Object-Context

For values

- type (`new X()`)
- allocation site in source (**X.java:235**)
- object-context: type of **this**

Context information

In calls

- Java **method**
- value sets of all **arguments**
- **thread** executing method
- current set of **locks** held
- etc.

Result

Detailed information on values

v1.get() --> **A** (Test.java: line 14)

v2.get() --> **B** (Test.java: line 15)

Runtime Errors

```
...
if (device instanceof MyDevice) {

  MySensor s = (MySensor) device.sensor;


  int value = s.reading();

  ...
}
...
```

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contains only MySensor

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Deadlock detection

```
...
new Thread() {
  public void run() {
    synchronized (A) {
      synchronized (B) {
      }
    }
  }
}.start();
new Thread() {
  public void run() {
    synchronized (B) {
      synchronized (A) {
      }
    }
  }
}.start();
...
```

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}.start();
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```

Lock Order:

Thread 1: A → B

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...
```

Lock Order:

Thread 1: A → B

Thread 2: B → A

Deadlock detection

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    }
  }
}.start();
...
```

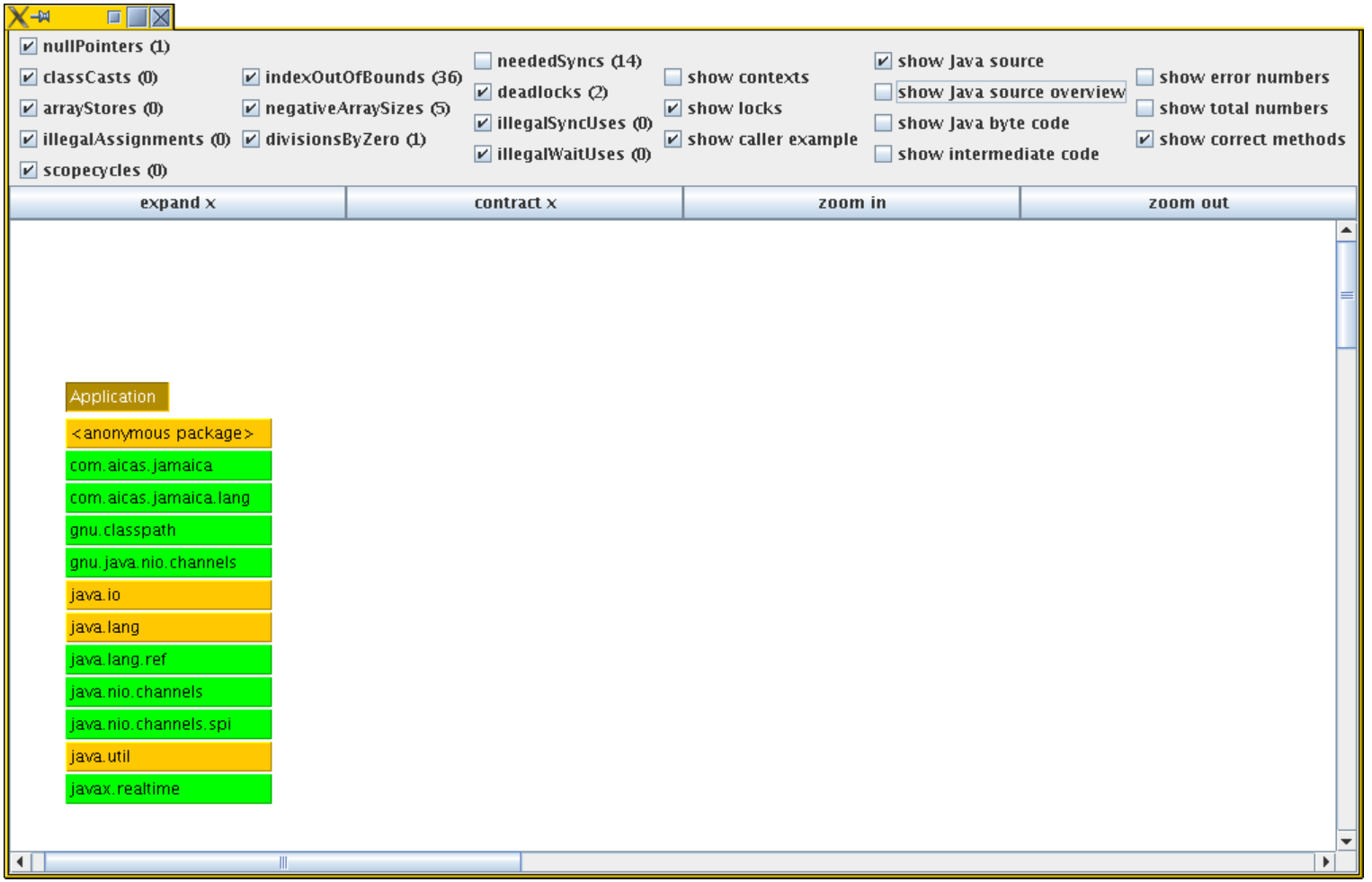
Lock Order:

Thread 1: A → B

potential deadlock!

Thread 2: B → A

Graphical Display of Results



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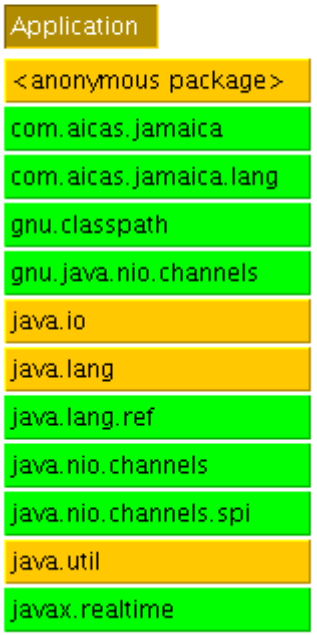

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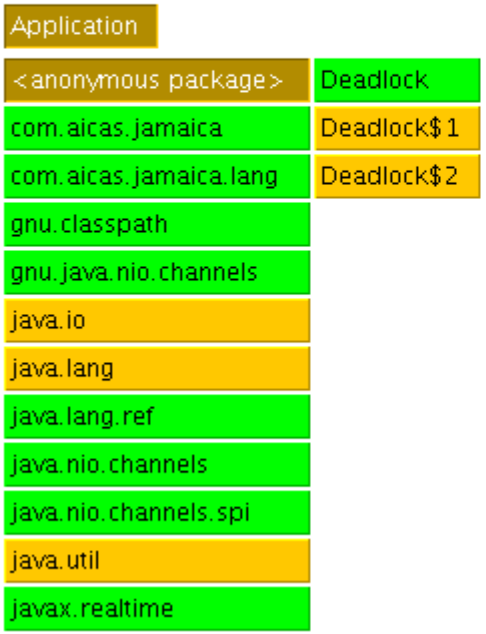

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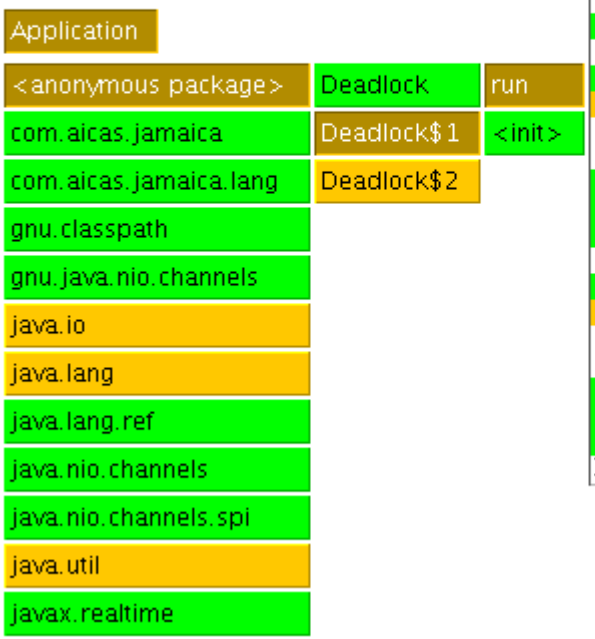


```
public class Deadlock
{
  static Object A = new Object();
  static Object B = new Object();

  public static void main(String[] args)
  {
    new Thread() {
      public void run() {
        synchronized (A) {
          synchronized (B) {
          }
        }
      }
    }.start();
    new Thread() {
      public void run() {
        synchronized (B) {
          synchronized (A) {
          }
        }
      }
    }.start();
  }
}
```

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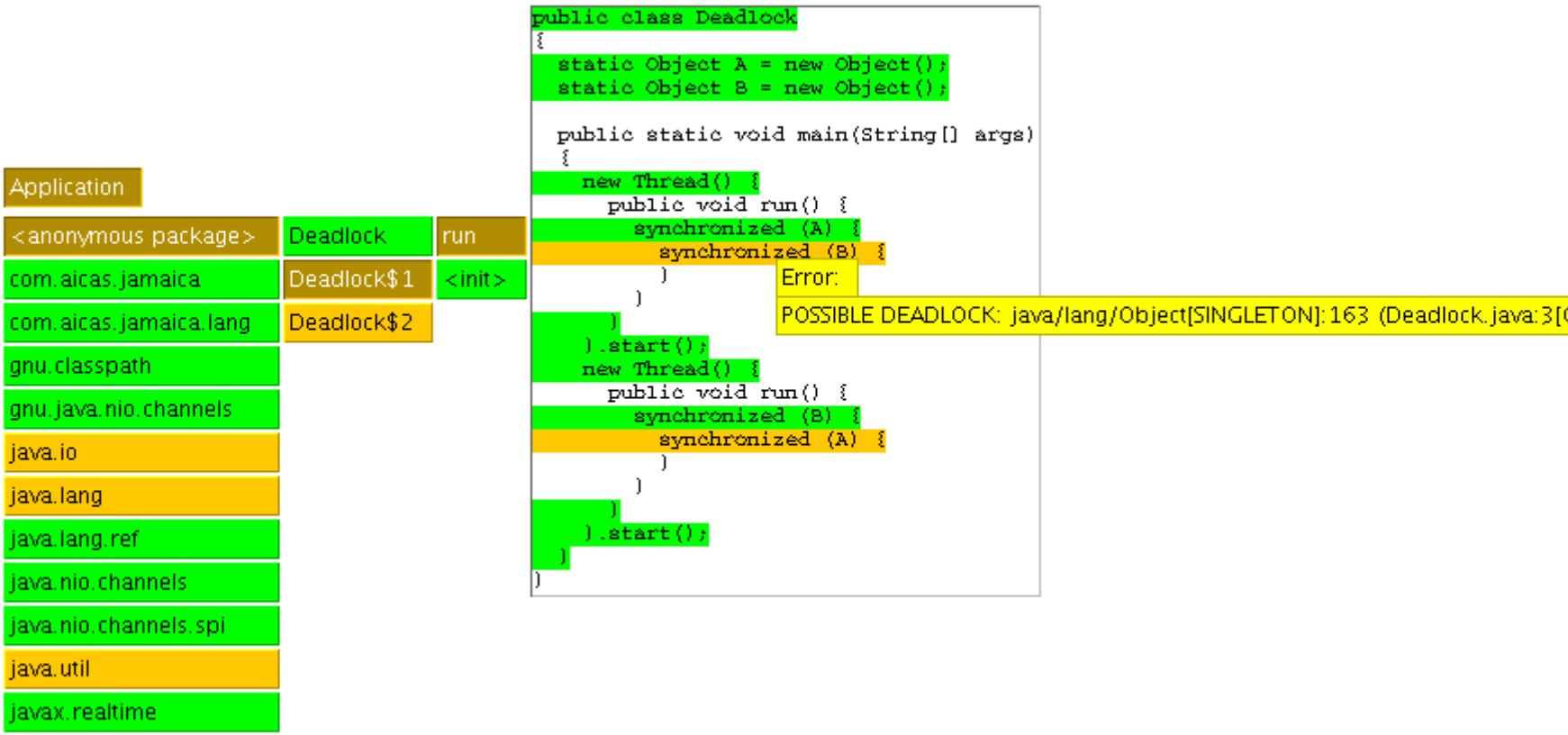
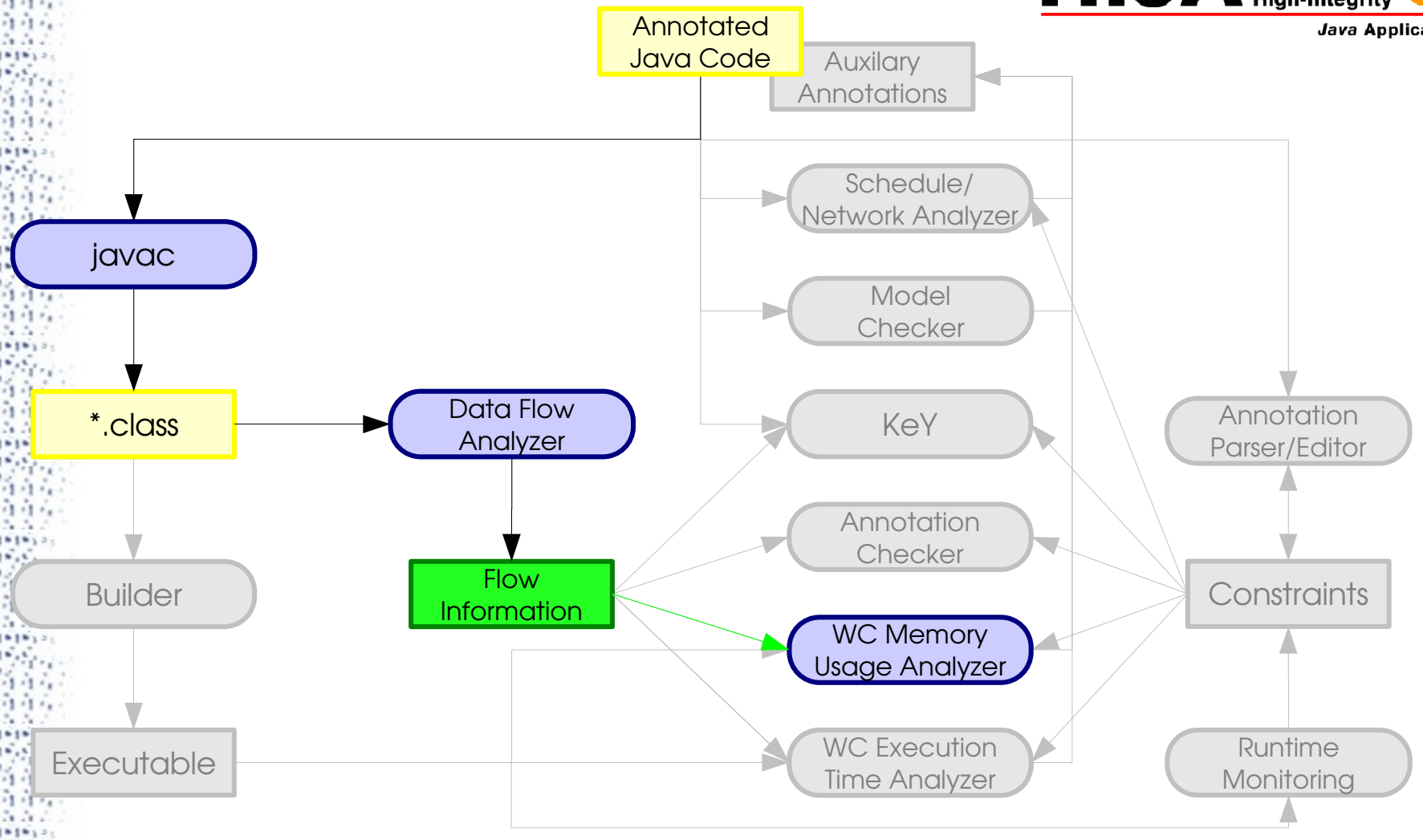


WC Memory Usage

HIJA High-Integrity Java Application



Memory Analysis

HIJA High-Integrity Java Application

Heap Use Analysis

- Traverse call graph for each thread
- Sum up all allocations

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```
> jamaica test -dfa
...
HEAP USE:  39680 FOR THREAD: java/lang/FinalizerThread
HEAP USE:      0 FOR THREAD: test$1: (test.java:6)
HEAP USE:      0 FOR THREAD: test$2: (test.java:14)
HEAP USE: 851200 FOR THREAD: INITIAL THREAD
...
DFA DONE: 6431ms.
```

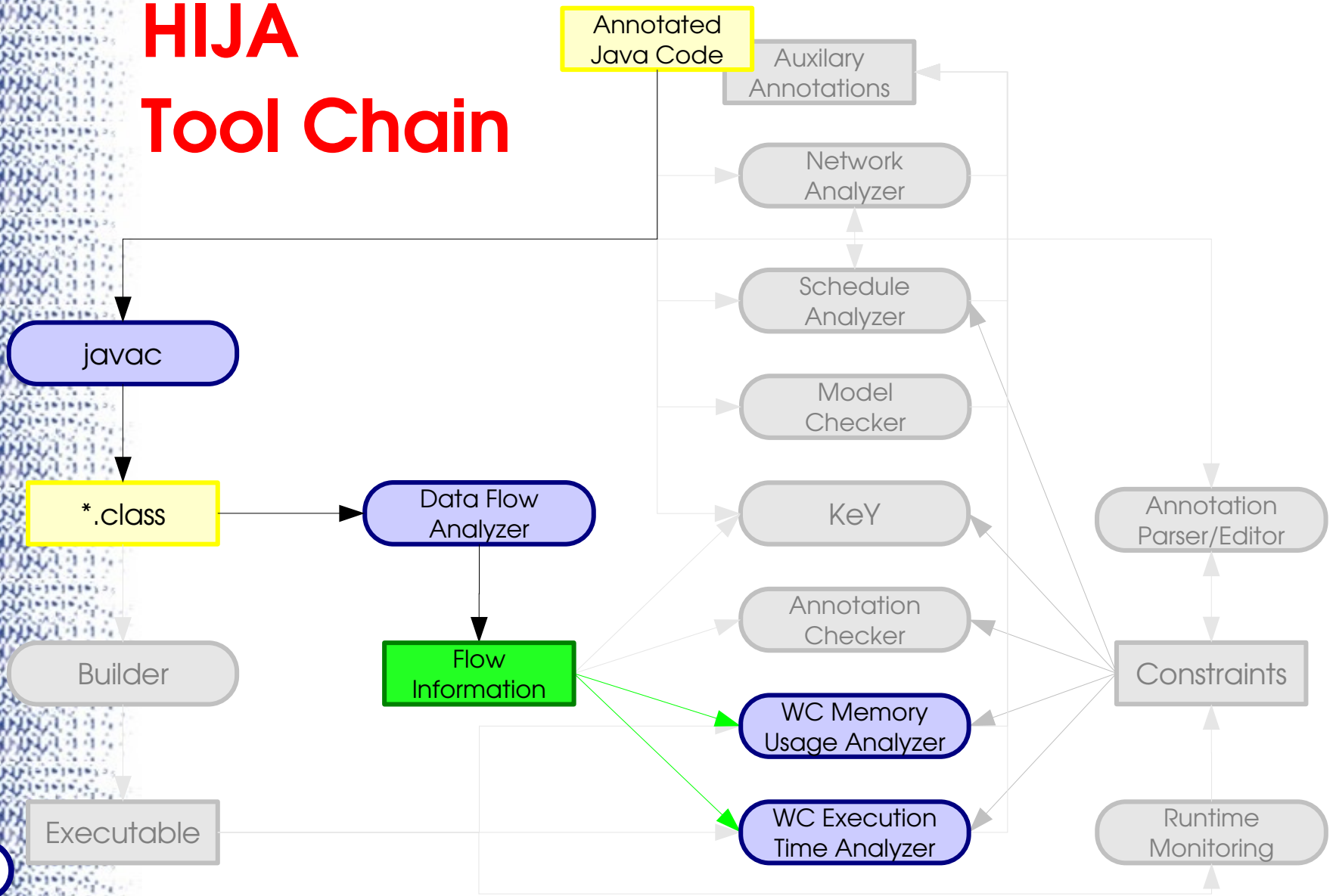
Analysis Limitations:

No information on

- loop counts
- recursion depths
- array lengths

We need annotations to provide this information!

HIJA Tool Chain



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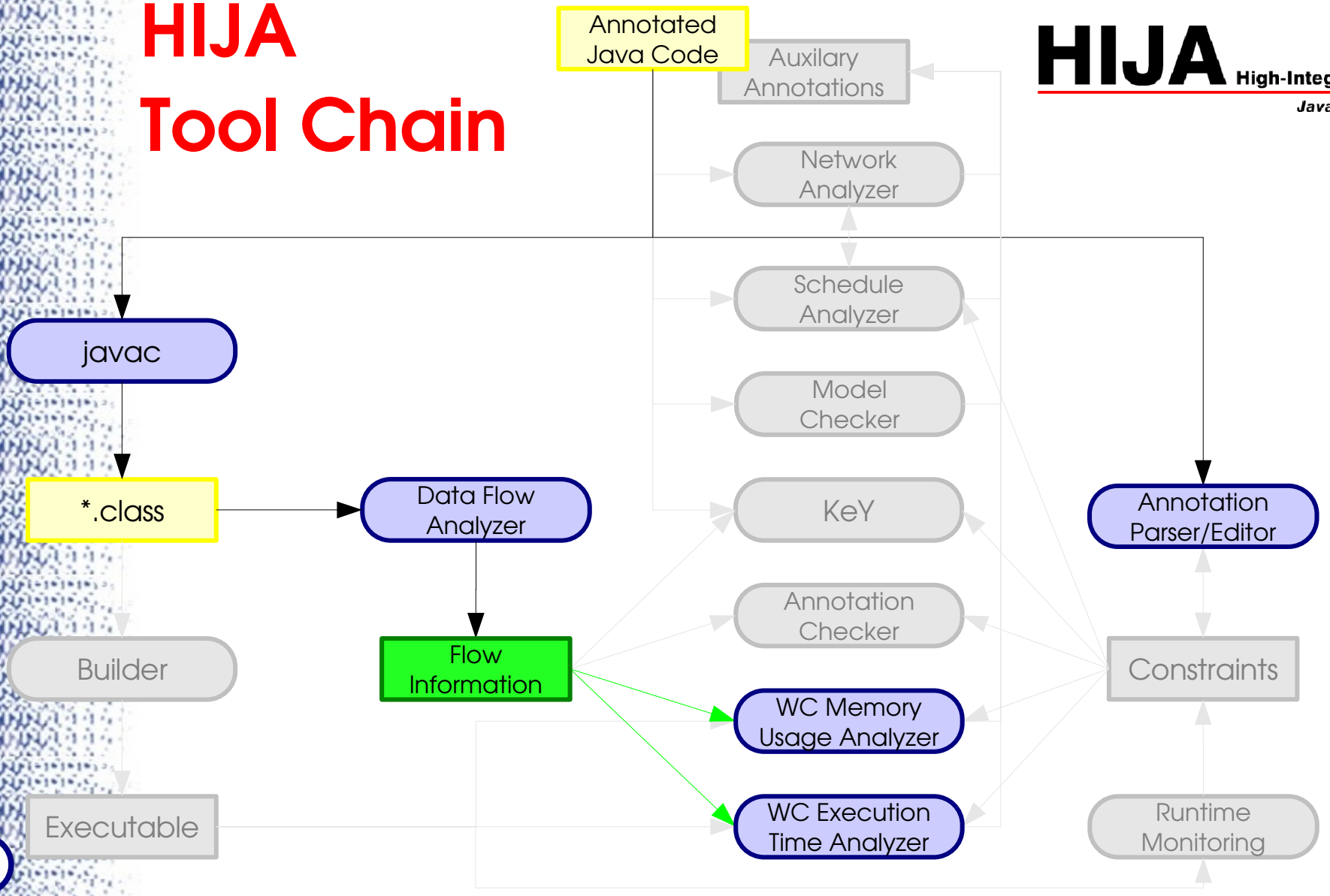

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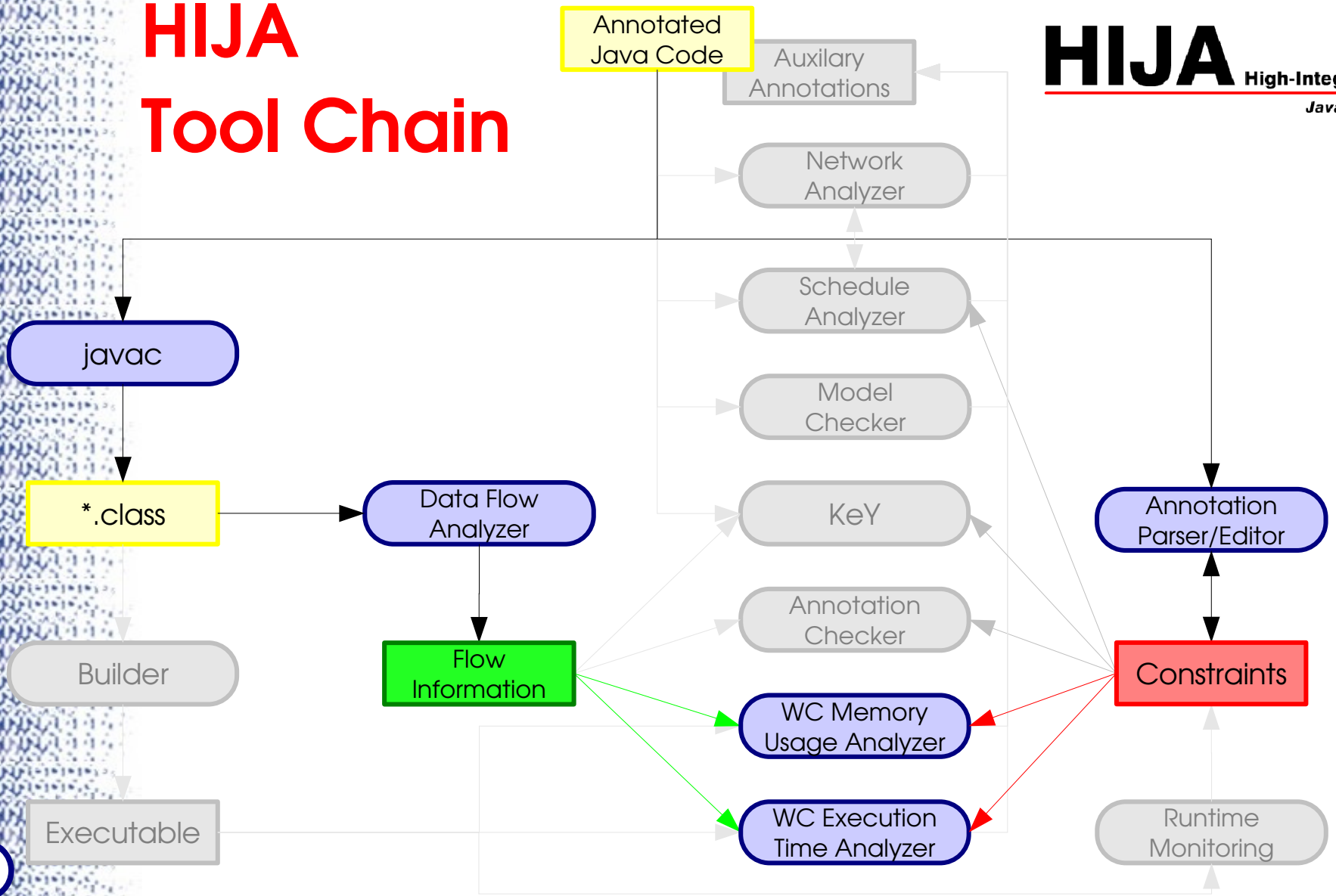

Current Status:

HIJA High-Integrity Java Application

Industrialisation Phase:

- Non-graphical Prototype tested extensively by users (Thales Avionics, Fiat, Telecom Italia)
- Very positive feedback, but also long list of requests for improvements
- Graphical version available
- Suggested improvements are being implemented

Conclusions

DFA provides a means to prove the absence of important runtime errors and to detect program errors.

The use of this analysis is fully automatic. A very fast learning curve ensures early successes.

However, analysis for large applications using dynamic class loading, reflection, native code, etc. is limited.

DFA Performance

HIJA High-Integrity Java Application

Analysis times for SPECjvm98 benchmark tests

Test	time/sec	Types with reduced acc.
check	4,9	0
compress	12	0
jess	**62,7**	**3**
raytrace	50	1
db	11,2	0
javac	710,5	58
mpegaudio	15	0
mtrt	49,1	1
jack	25,1	1
checkit	14,8	0

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HIJA High-Integrity Java Application

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Test	NullPointer			Illegal Casts			ArrayStore			Deadlocks		
	pot. error	analysed	ratio	p.e.	an.	ratio	p.e.	an.	ratio	p.e.	an.	ratio
check	10	1953	1%	3	49	6%	0	45	0%	0	48	0%
compress	33	1813	2%	4	54	7%	1	43	2%	5	43	12%
jess	552	5265	10%	16	120	13%	1	105	1%	5	60	8%
raytrace	452	3398	13%	5	58	9%	2	57	4%	20	60	33%
db	102	2370	4%	5	73	7%	1	39	3%	5	56	9%
javac	1726	9884	17%	213	360	59%	18	457	4%	17	87	20%
mpegaudio	112	9605	1%	9	60	15%	1	944	0%	5	42	12%
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jack	286	5103	6%	8	141	6%	1	99	1%	5	45	11%
hello	0	1012	0%	0	41	0%	0	21	0%	0	35	0%

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Applying DFA to RTSJ code

Detecting Scope Cycles

- MemoryArea is recorded on every call to *enter()*
- Nesting order tree of memory areas is recorded
- A potential error is flagged if nesting order not cycle-free

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Results

- all scope cycles are detected
- false positives if different nesting is used at different points in time

Applying DFA to RTSJ code

Assignment Checks

```
MemoryArea m1 = new LTMemory(100000);
MemoryArea m2 = new LTMemory(100000);

m1.enter(new Runnable() {
   public void run() {
     final A o1 = new A();
     m2.enter(new Runnable() {
       public void run() {
         A o2 = new A();
         o2.f = o1;
         o1.g = o2; // illegal assignment!
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     });
   }
});
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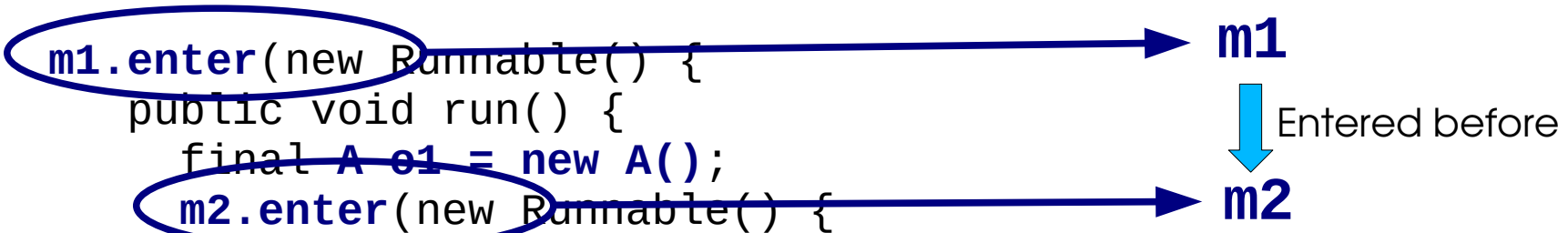

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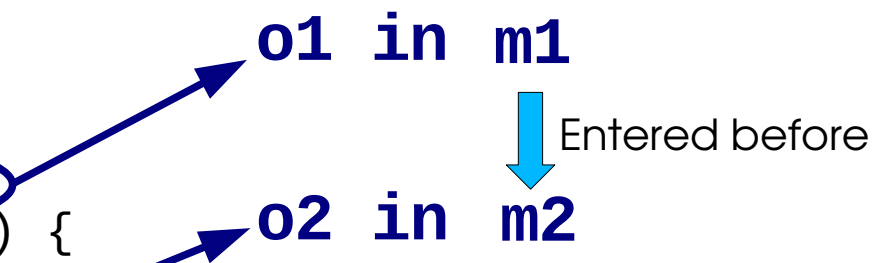

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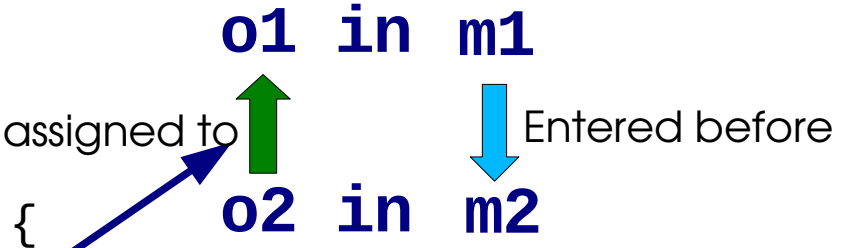

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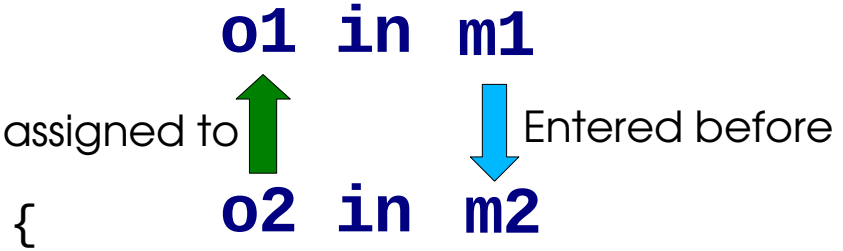

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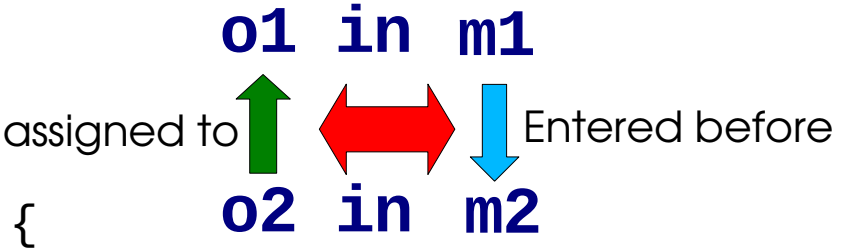

Applying DFA to RTSJ code

Assignment Checks Output

```
POTENTIALLY ILLEGAL ASSIGNEMT:
  to field A.g (test_assign.java:64)
      class: A:114:5 (test_assign.java:35)
        {IN: LTMemory:3 (test_assign.java:23)}
  <== class: A:190:5 (test_assign.java:39)
        {IN: LTMemory:4 (test_assign.java:24)}
```

Applying DFA to RTSJ code

Assignment Checks Output

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  to field A.g (test_assign.java:64)
      class: A:114:5 (test_assign.java:35)
        {IN: LTMemory:3 (test_assign.java:23)}
  <== class: A:190:5 (test_assign.java:39)
        {IN: LTMemory:4 (test_assign.java:24)}
```

Applying DFA to RTSJ code

Assignment Checks Output

```
POTENTIALLY ILLEGAL ASSIGNEMT:
  to field A.g (test_assign.java:64)
      class: A:114:5 (test_assign.java:35)
        {IN: LTMemory:3 (test_assign.java:23)}
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  <== class: A:190:5 (test_assign.java:39)
        {IN: LTMemory:4 (test_assign.java:24)}
```

Analysis Results

HIJA High-Integrity Java Application

```
> jamaica -dfa test
NEEDEDSYNCS                :  29 (  29 locations out of    78)
DEADLOCKS                  : 101 (   9 locations out of    79)
SCOPE CYCLES               :   0 (   0 locations out of     0)
ILLEGAL ASSIGNMENTS        :   0 (   0 locations out of   764)
CLASSCAST EXCEPTIONS       : 128 (  17 locations out of    90)
ARRAY STORE EXCEPTIONS     :   3 (   1 locations out of   310)
NULL POINTER EXCEPTIONS: 503 (139 locations out of 11041)
 + test.dfa_results.summary
 + test.dfa_results
```

# of Source Code Positions with this problem

Conclusion

The RTSJ is the established standard for realtime Java.

The HIJA project extends the domain of Java by safety- and business-critical applications.

Automatic tools for correctness analysis reduces the manual validation & verification work significantly.

Project homepage: **www.hija.info**.

JamaicaVM

Who is aicas GmbH?

- **Founded** in March 2001 in Karlsruhe, Germany
- **Products:** Realtime Java implementations

- **Today:** 20 employees, offices in Karlsruhe (D), Berlin (D) and New Haven/CT (USA)

Business-Critical Profile

HIJA High-Integrity Java Application

Relaxations compared to safety-critical profile:

- dynamic features for non-critical tasks
- Strict Partitioning for critical tasks:
  - Memory: Local memory area for each task
  - CPU utilization
- Tools to proof correctness of critical tasks

HIJA Tools:

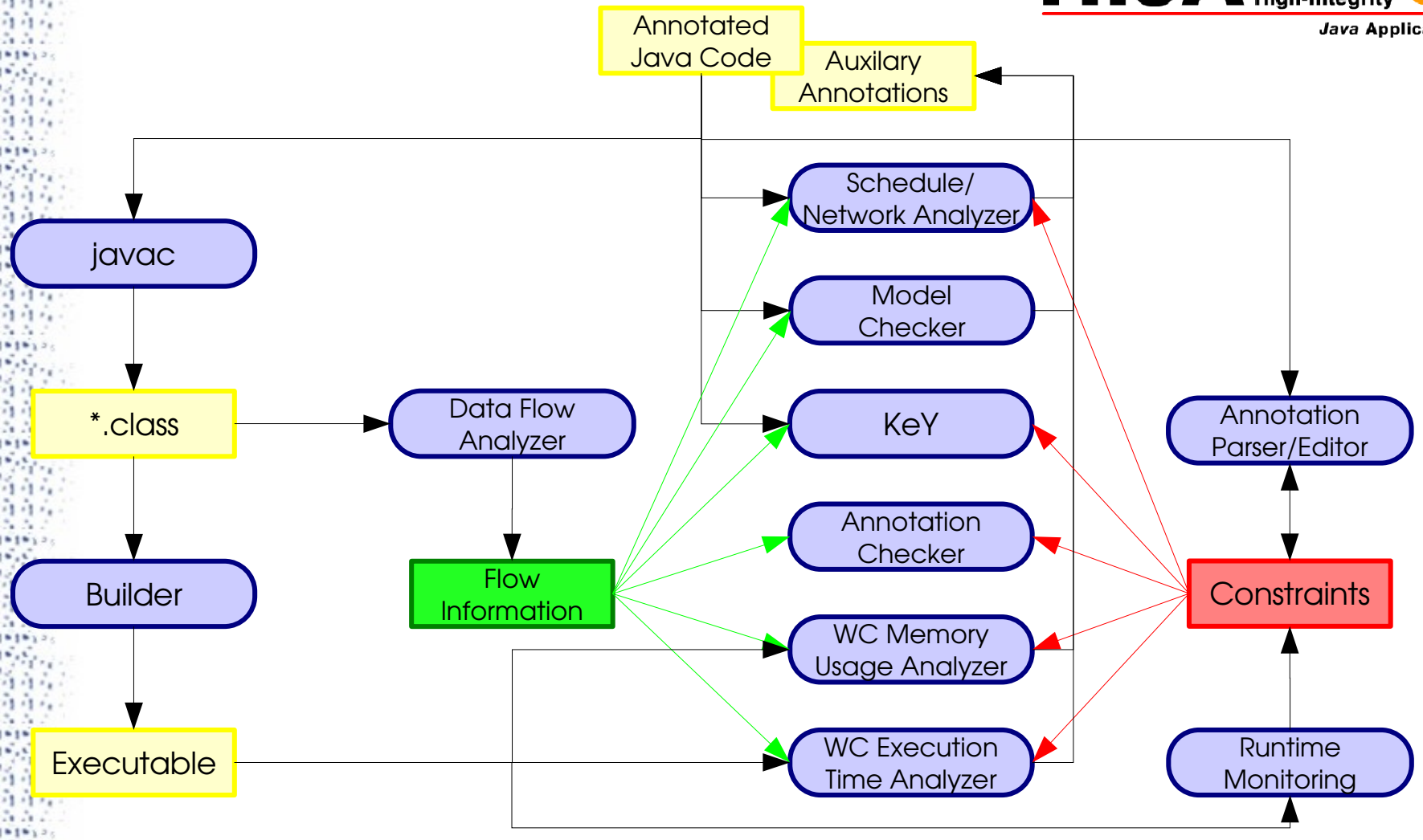
HIJA High-Integrity Java Application

Tools for correctness proof of application:

- DFA analysis to proof absence of runtime errors
- Formal verification using JML annotations (KeY)
- Model-Checker based tools to verify distributed system and multi-threading

DFA in HIJA Tool Chain

HIJA High-Integrity Java Application



Safety-Critical Profile

HIJA High-Integrity Java Application

Guiding Principles:

- Conservative approach
  - no concepts that go too far for SC community
- Do not fragment the market:
  - Base specification on standard Java and RTSJ
  - SC-Java programs should run on any RTSJ JVM
- Use of annotations for off-line checking, not for semantic changes

The HIJA Safety-Critical Java Profile

... building certifiable applications with Java technology

Dr. Fridtjof Siebert
Director of Development, aicas GmbH
Embedded World Conference
Nürnberg, 2006

HIJA-Project: High-Integrity Java

Project overview:

- 6th FP EC-funded project
- started June '04
- duration: 27 months, until Aug'06
- Project coordinator: The Open Group

HIJA-Project

HIJA High-Integrity Java Application

Project partners:

THALES

aicas realtime

Aonix

TELECOM ITALIA

UNIVERSITÄT KARLSRUHE (TH)

bellstream

TRIALOG

FZI

CENTRO RICERCHE FIAT

THE Open GROUP

THE UNIVERSITY of York

Project Overview

HIJA High-Integrity Java Application

Goals

- Identify suitable profiles
- Tools for functional and non-functional analysis
- Reference implementations of profiles

Work based on results of earlier projects:

HIDOORS, AJACS, Expresso, KeY, etc.

JamaicaVM

AERO VM

Project Overview

HIJA High-Integrity Java Application

Three main profiles are defined:

All are subsetting the Java language, standard APIs and Realtime Specification for Java (RTSJ)

- Safety-Critical profile
  - certification up to the highest criticality level (DO178B-A).
- Business-Critical profile
- Flexible Dynamic profile (OSGi, etc.)

Safety-Critical Profile

HIJA High-Integrity Java Application

Severe restrictions on Java and RTSJ:

- Clear distinction: initialization phase, mission phase
- No dynamic loading, thread creation, etc. during mission phase
- No GC
- Strict Partitioning:
  - Memory: Local memory area for each task
  - CPU utilization: RTSJ cost monitoring
- Use of annotations to document correctness of classes

HIJA SC-Java Profile

HIJA High-Integrity Java Application

Concurrency Model:

- Fixed-priority preemptive scheduling, 28 priorities
- FIFO within priority

Schedulable Objects:

- Periodic Threads
- BoundAsyncEventHandler
- all threads and handlers created in initialization phase.

Synchronization:

- Via Java synchronized methods
- Priority Ceiling Emulation Protocol

HIJA SC-Java Profile

Memory Management Phases:

- Initialization phase:
  allocation in Immortal Memory only

- Mission phase:
  allocation in Scoped Memory only
  - each scope local to one task
  - no sharing of objects in scopes between tasks
  - scope is cleared after each release

HIJA SC-Java Profile

HIJA High-Integrity Java Application

Absence of memory related runtime errors:

- Static analysis of worst-case stack
- Static analysis of worst-case heap
- Static analysis of to avoid AssignmentError (no storing of scoped references into objects with longer lifespan)

Use of annotations:

- To document scope-safety of library code

Reference Value Identification

Objects are identified by Allocation Point

- v1 is Vector(Test.java:12)
- v2 is Vector(Test.java:13)

and (recursively) by a list of allocation contexts (instance of „this“ at allocation site)

- v1.data is Object()(Vector.java:54)
  Vector(Test.java:12);
- v2.data is Object()(Vector.java:54)
  Vector(Test.java:13);

Granularity

Do not work on methods, but on Call Points

Call Points are identified by

- Set of Values of „this“ or first argument
- Vector(Test.java:13)

example: 2 call points for Vector.put

- Vector.put(Vector(Test.java:12),
  A(Test.java:14))
- Vector.put(Vector(Test.java:13),
  A(Test.java:15))

Granularity

example: 2 conditional values for data array

- Vector.data(x) is **A**(Test.java: line 14)
  if data is Object()(Vector.java:54)
  Vector(Test.java:**12**);
  Vector.data(x) is **B**(Test.java: line 15)
  if data is Object()(Vector.java:54)
  Vector(Test.java:**13**);

Memory Analysis

HIJA High-Integrity Java Application

Stack Use Analysis

- Traverse call graph for each thread
- Find maximum stack use in each branch

Memory Analysis

HIJA High-Integrity Java Application

Stack Use Analysis

- Traverse call graph for each thread
- Find maximum stack use in each branch

```
> jamaica test -dfa
...
STACK USE:  1264 FOR THREAD: java/lang/FinalizerThread
STACK USE:   104 FOR THREAD: test$1: (test.java:6)
STACK USE:   104 FOR THREAD: test$2: (test.java:14)
STACK USE:  1764 FOR THREAD: INITIAL THREAD
...
DFA DONE: 6431ms.
```

Applying DFA to RTSJ code

Assignment Checks

```
MemoryArea m1 = new LTMemory(100000);
MemoryArea m2 = new LTMemory(100000);

m1.enter(new Runnable() {
    public void run() {
      final A o1 = new A();
      m2.enter(new Runnable() {
        public void run() {
          A o2 = new A();
          o2.f = o1;
          o1.g = o2; // illegal assignment!
        }
      });
    }
});
```

Applying DFA to RTSJ code

Assignment Checks

```
MemoryArea m1 = new LTMemory(100000);
MemoryArea m2 = new LTMemory(100000);

m1.enter(new Runnable() {
   public void run() {
     final A o1 = new A();
     m2.enter(new Runnable() {
       public void run() {
         A o2 = new A();
         o2.f = o1;
         o1.g = o2; // illegal assignment!
       }
     });
   }
});
```

o1 in m1

Entered before

m2

Applying DFA to RTSJ code

Assignment Checks

```
MemoryArea m1 = new LTMemory(100000);
MemoryArea m2 = new LTMemory(100000);

m1.enter(new Runnable() {
   public void run() {
     final A o1 = new A();
     m2.enter(new Runnable() {
       public void run() {
         A o2 = new A();
         o2.f = o1;
         o1.g = o2; // illegal assignment!
       }
     });
   }
});
```