Automated Generation and Evaluation of Dataflow-based Test Data for Object-Oriented Software

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Agenda

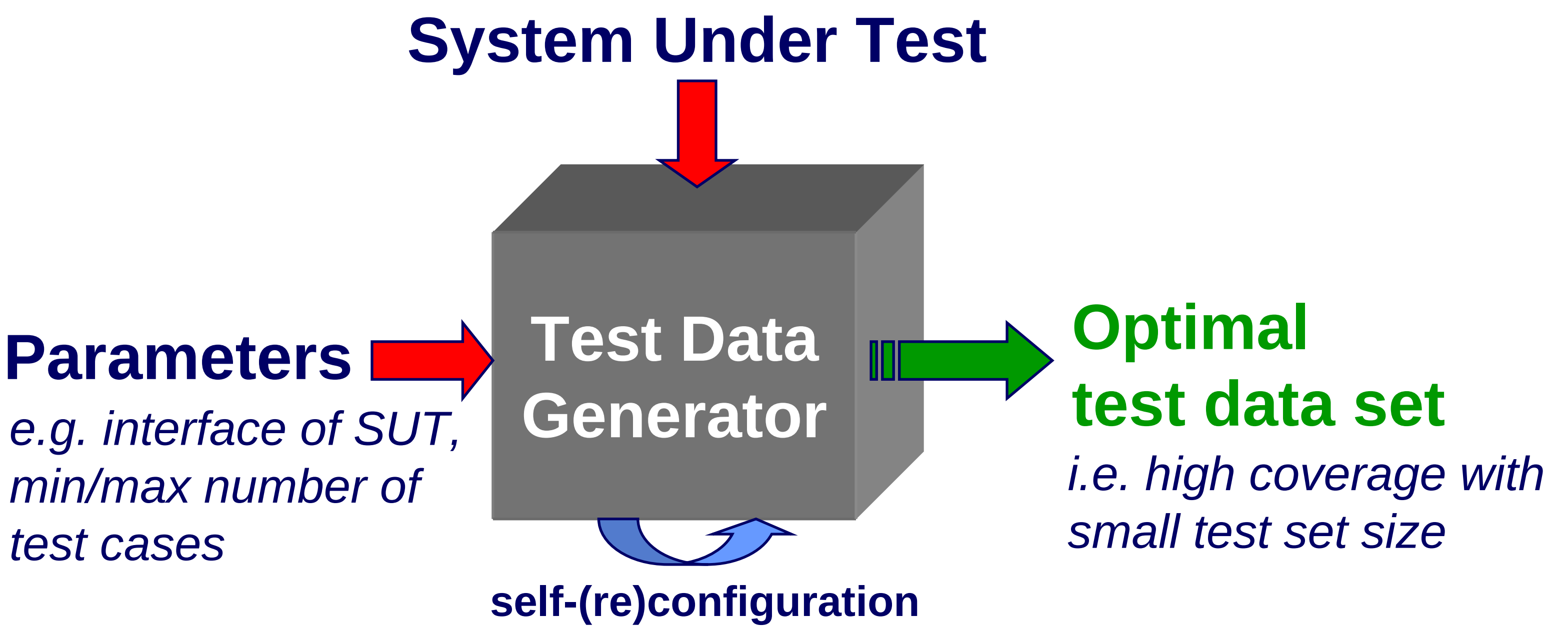
- Motivation and goal
- Introduction to dataflow based testing
- The .gEAr-Project
  - test data generation with evolutionary algorithms (global optimisation)
  - source code instrumentation
  - static analysis of byte code
  - analysis of fault-revealing capability by means of mutation analysis
- Experimental results
- Summary

Functional vs. structural testing

- **Functional testing**
  - test cases derived from specification (code seen as black-box)
  - focuses on expected/specified behaviour only
- **Structural testing**
  - considers unexpected functionality as a result of combinations of possible intended operations
    (based on code structure: code seen as white-box)
- **Effort**
  - existing tools usually just measure the coverage achieved
  - very few tools support tester with hints on how to increase coverage
  - fully automated test case generation based on deterministic static analysis is in general impossible
  - the result of each test run must be checked against specification

Vision

- **Tester's desire:**



Class structure of testing techniques

- **dynamic techniques**
  - **functional**
    - equivalence partitioning
    - cause effect graphing
  - **structural**
    - **control flow**
      - statement coverage
      - branch coverage
      - condition coverage
        - simple
        - condition/decision
        - minimal multiple
        - modified cond./decision
        - multiple
      - LCSAJ test
      - boundary interior test
      - structured path test
    - **data flow**
      - DU criteria
        - all defs
        - all p-uses
        - all c-uses
        - all p-uses/some c-uses
        - all c-uses/some p-uses
        - all uses
        - all DU-paths
      - required k-tuples
      - data context coverage
  - diversified
    - mutation test
    - back to back test
    - regression test

done
ongoing
planned

according to Liggesmeyer:
class structure of dynamic test techniques

Original dataflow criteria by Rapps/Weyuker

- **Motivation**

Just as one would not feel confident about the correctness of a portion of a program which has never been executed, we believe that if the result of some computation has never been used, one has no reason to believe that the correct computation has been performed

Sandra Rapps / Elaine J. Weyuker (1982/1985)

- **Basis of Dataflow – Oriented Testing**
  - extended variant of control flow graph, annotated with data attributes
  - so-called data flow attributed control flow graph

- **Usage of Variables**
  - after memory allocation
  - until deletion

  three different types of operations can be carried out

Dataflow relevant events

- **def** *definition*
  - associated to corresponding nodes of control flow graph containing variable defining (**not** declaring!) instruction
  - e.g. `x = f();`
- **c-use** *computational use*
  - associated to corresponding nodes of control flow graph containing computing instruction
  - e.g. `f(x + y);`
- **p-use** *predicative use*
  - associated to all edges of control flow graph going out from node containing predicate expression in order for branch coverage to be subsumed by most data-flow testing criteria
  - e.g. `if(x < y);`

Dataflow based testing criteria

- **"all-defs" – criterion requires to execute**
  - **at least one** def-clear sub-path from **each** def to **at least one** reachable use

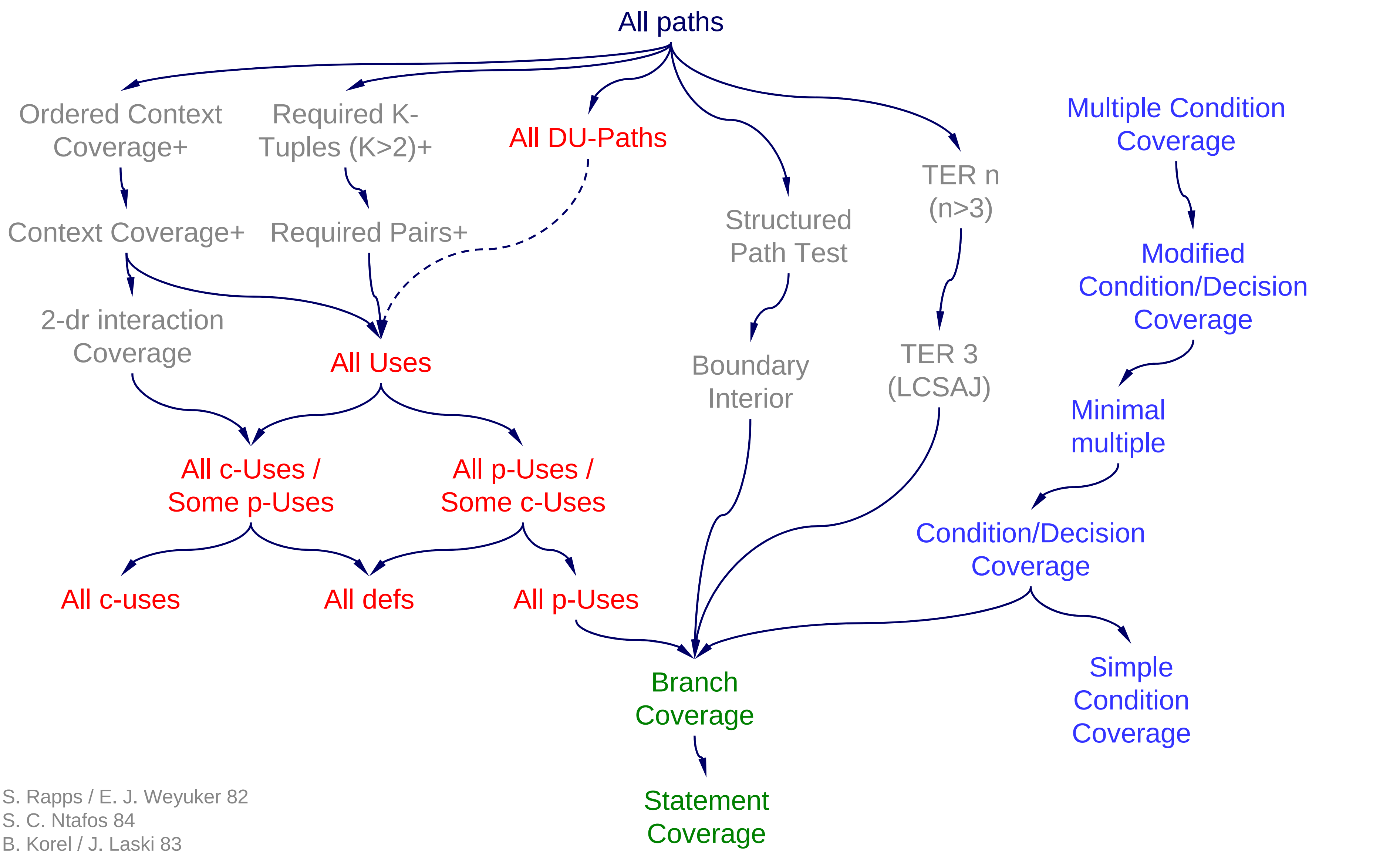
- **"all-p-uses" – criterion requires to execute**
  - **at least one** def-clear sub-path from **each** def to **each** reachable p-use
- **"all-c-uses" – criterion requires to execute**
  - **at least one** def-clear sub-path from **each** def to **each** reachable c-use

- **"all-p-uses/some-c-uses" – criterion requires to execute**
  - **at least one** def-clear sub-path from **each** def to **each** reachable p-use if a def does not reach a p-use, then to **at least one** reachable c-use
- **"all-c-uses/some-p-uses" – criterion requires to execute**
  - **at least one** def-clear sub-path from **each** def to **each** reachable c-use if a def does not reach a c-use, then to **at least one** reachable p-use

- **"all-uses" – criterion requires to execute**
  - **at least one** def-clear sub-path from **each** def to **each** reachable use

- **"all-du-paths" – criterion requires to execute**
  - **all** (feasible) **loop-free** def-clear sub-paths from **each** def to **each** reachable use

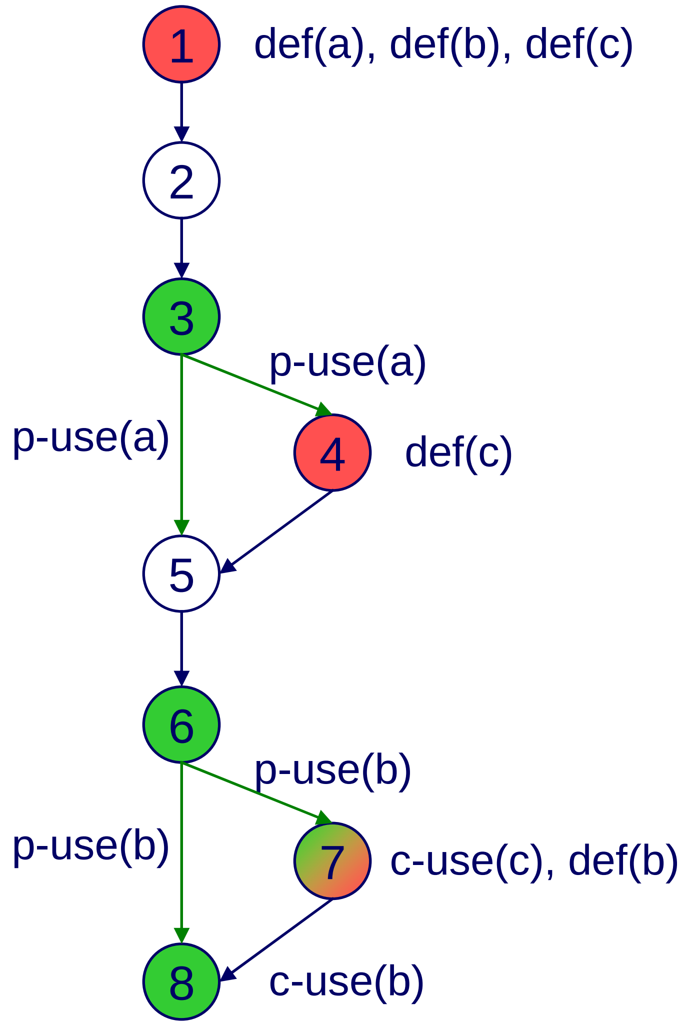
Subsumption hierarchy



S. Rapps / E. J. Weyuker 82
S. C. Ntafos 84
B. Korel / J. Laski 83

Why dataflow? – an example

```
public int f(int a, int b, String c) {
        …
        if (a > 0) {
                c = null;
        }
        …
        if (b < 0) {
                b = c.length();
        }
        return b;
}
```



statement-coverage:
1-2-3-4-5-6-8 + 1-2-3-5-6-**7**-8 ☑PASS

branch-coverage:
1-2-**3-4**-5-**6-8** + 1-2-**3-5-6-7**-8 ☑PASS

e.g. all-uses (**requires pair 4/7**):
1-2-3-**4**-5-6-**7**-8 ☒FAIL

Faults revealed by dataflow testing

- During static analysis phase:
  - dead code and syntactically endless loops
  - uses statically reachable without prior definition
  - definitions without statically reachable uses

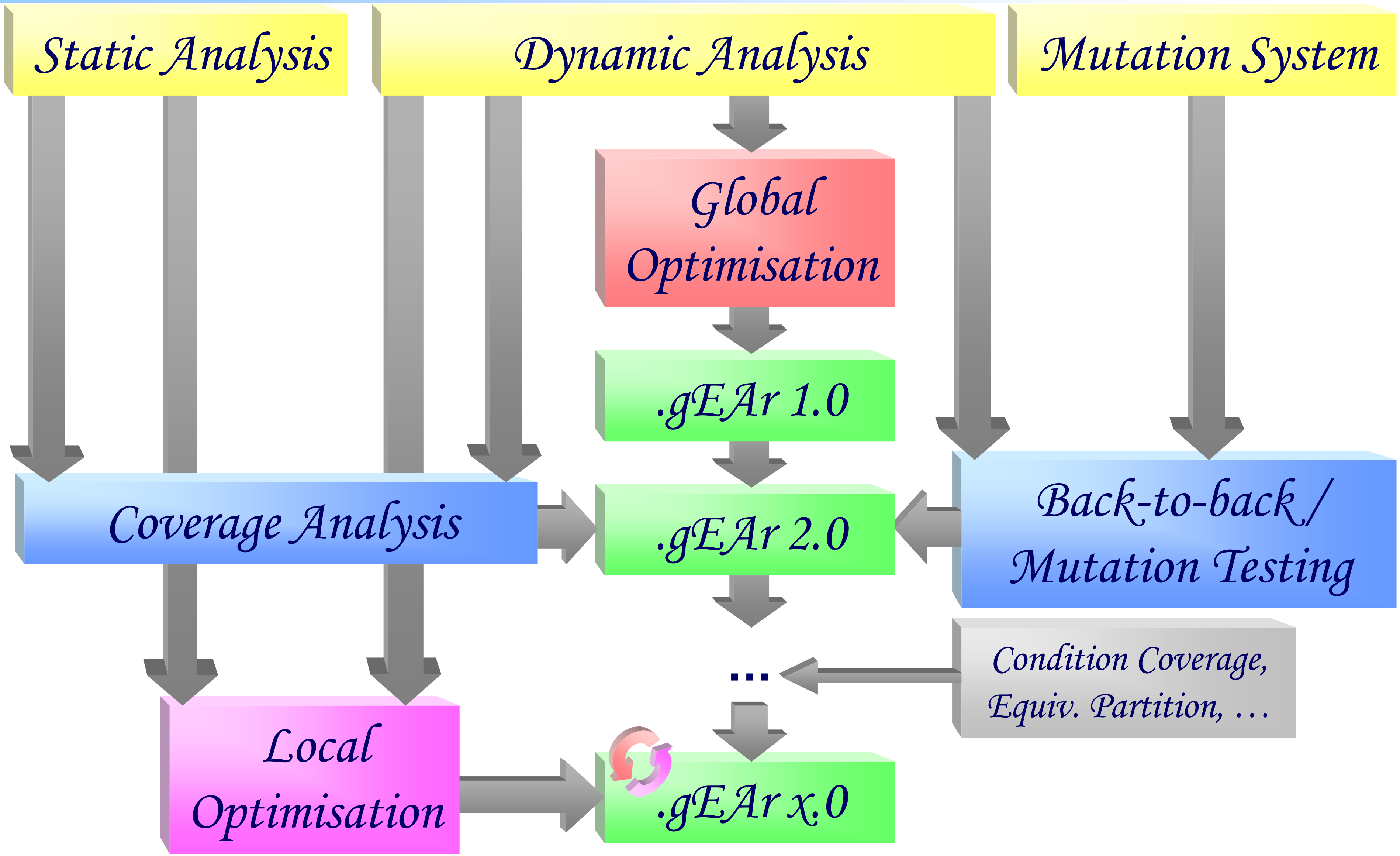
- During dynamic execution phase:
  - all-p-uses beyond branch coverage: additionally all possible data flows the decision might rely upon, not just each decision once
  - definitions with unreachable uses (even if syntactically reachable): possible hint on logical program fault
  - different kinds of data-processing faults (e.g. anomalous conversion or type-inconsistent use) since all def/use-combinations must be exercised
  - in object-oriented software: state of an object and its change in terms of definitions and uses of variables representing the state

Specifics of object-oriented Java software

- “variables” must be distinguished:
  - static fields
  - local variables
  - (object) fields: same name in each instance
  - arrays: special “objects”
- multi-threading
- “pointer-aliasing” - equivalent
  - different variables might denote the same instance
- multiple hidden def/use-associations
  - due to field access through methods
- p-uses and c-uses hardly distinguishable
  - because predicates may contain method calls

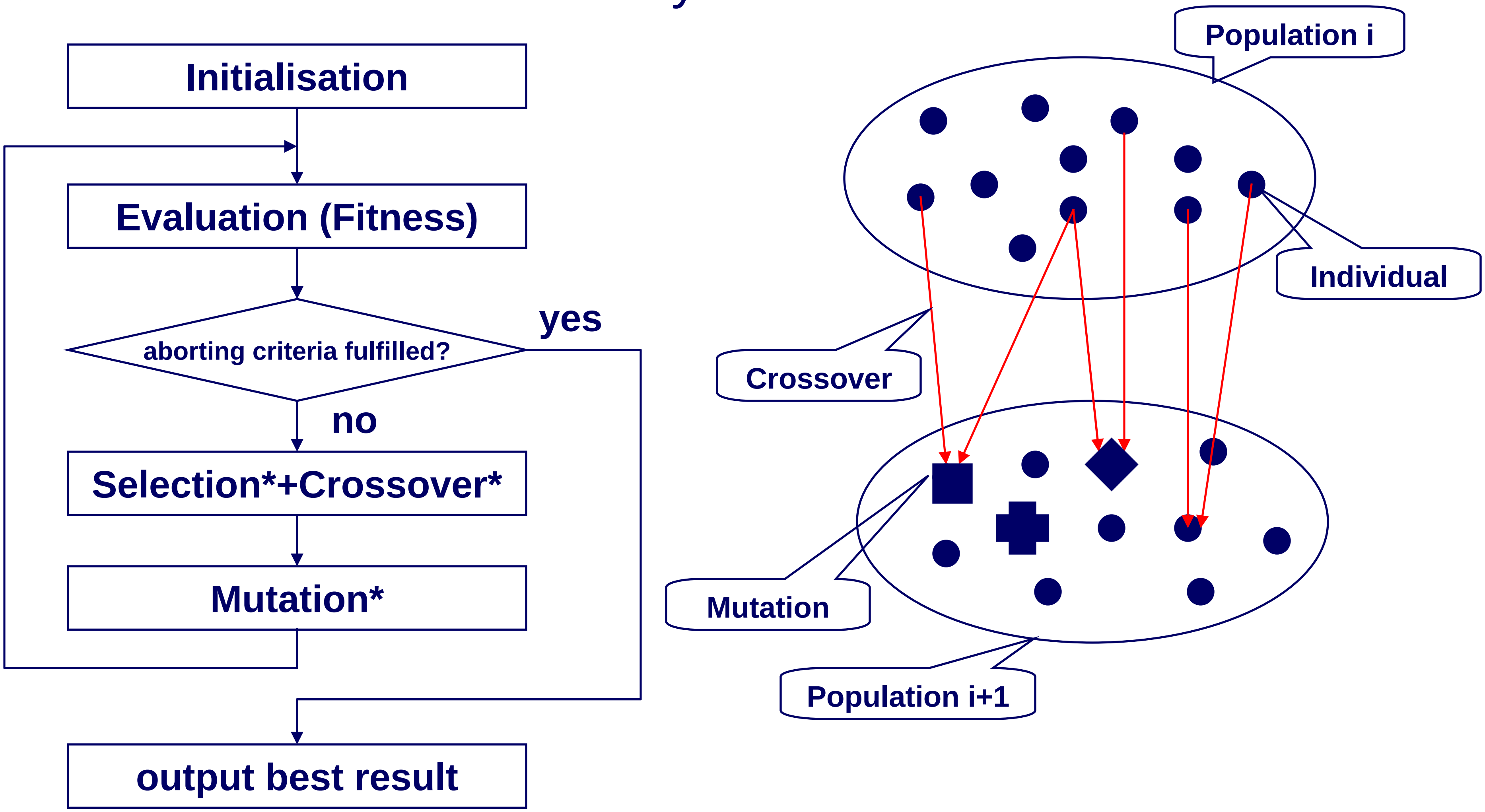
.gEAr - Project

Dataflow **o**riented **t**est-case **g**eneration with **E**volutionary **A**lgo**r**ithms

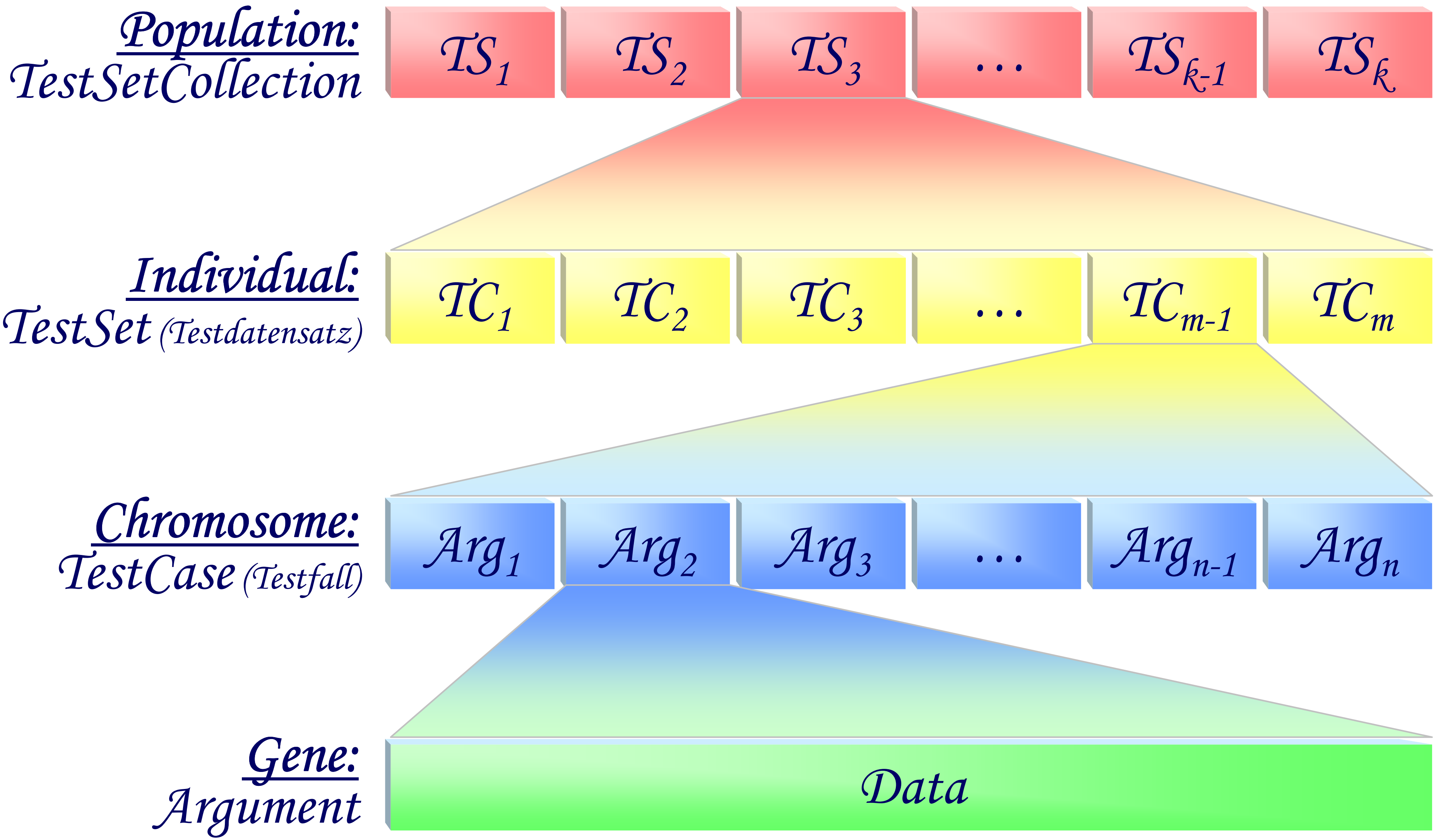


Evolutionary Algorithms

- basic idea: Darwinian theory of evolution

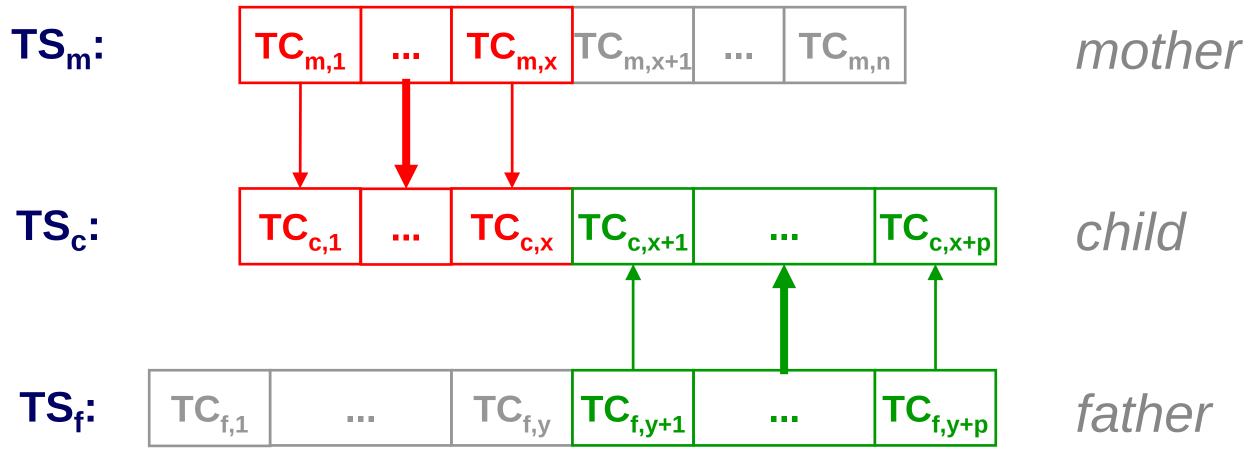


Data structure (global optimisation)



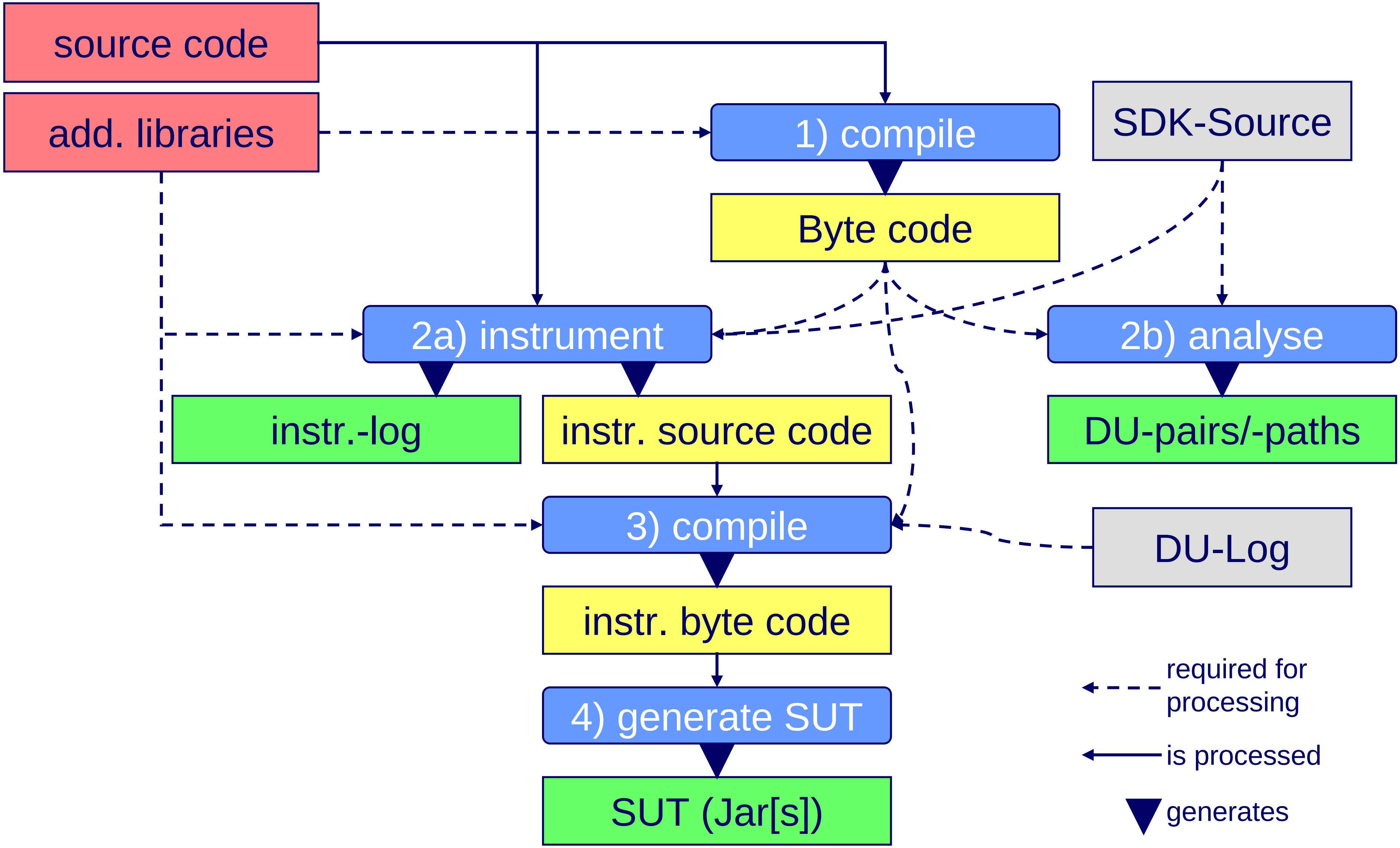
Examples: crossover, mutation

- **Crossover (example: single point)**

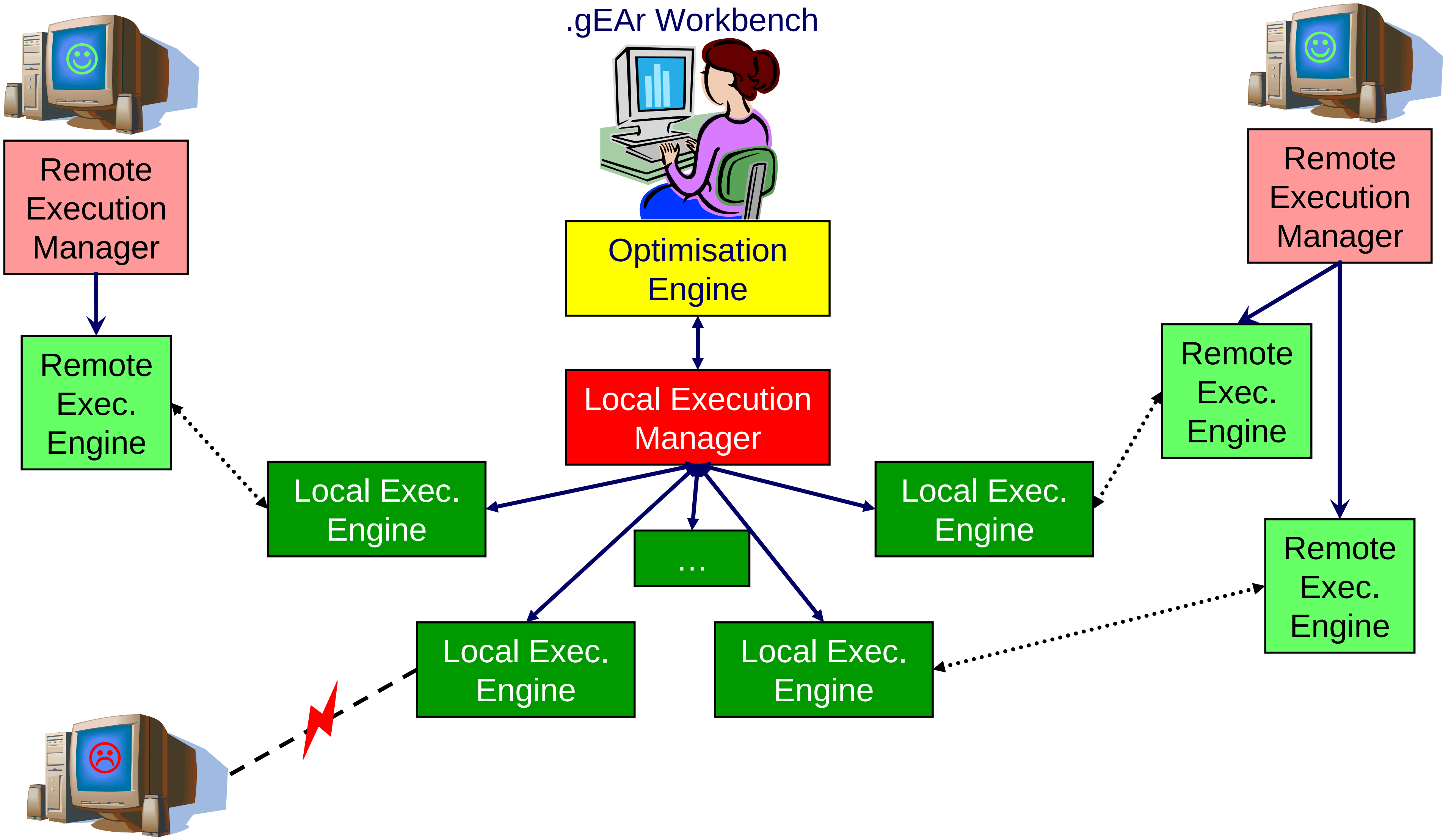


- **Mutation of a test set**
  - add a test case
  - remove a test case
  - mutate a test case:
    - add an argument
    - remove an argument
    - mutate an argument

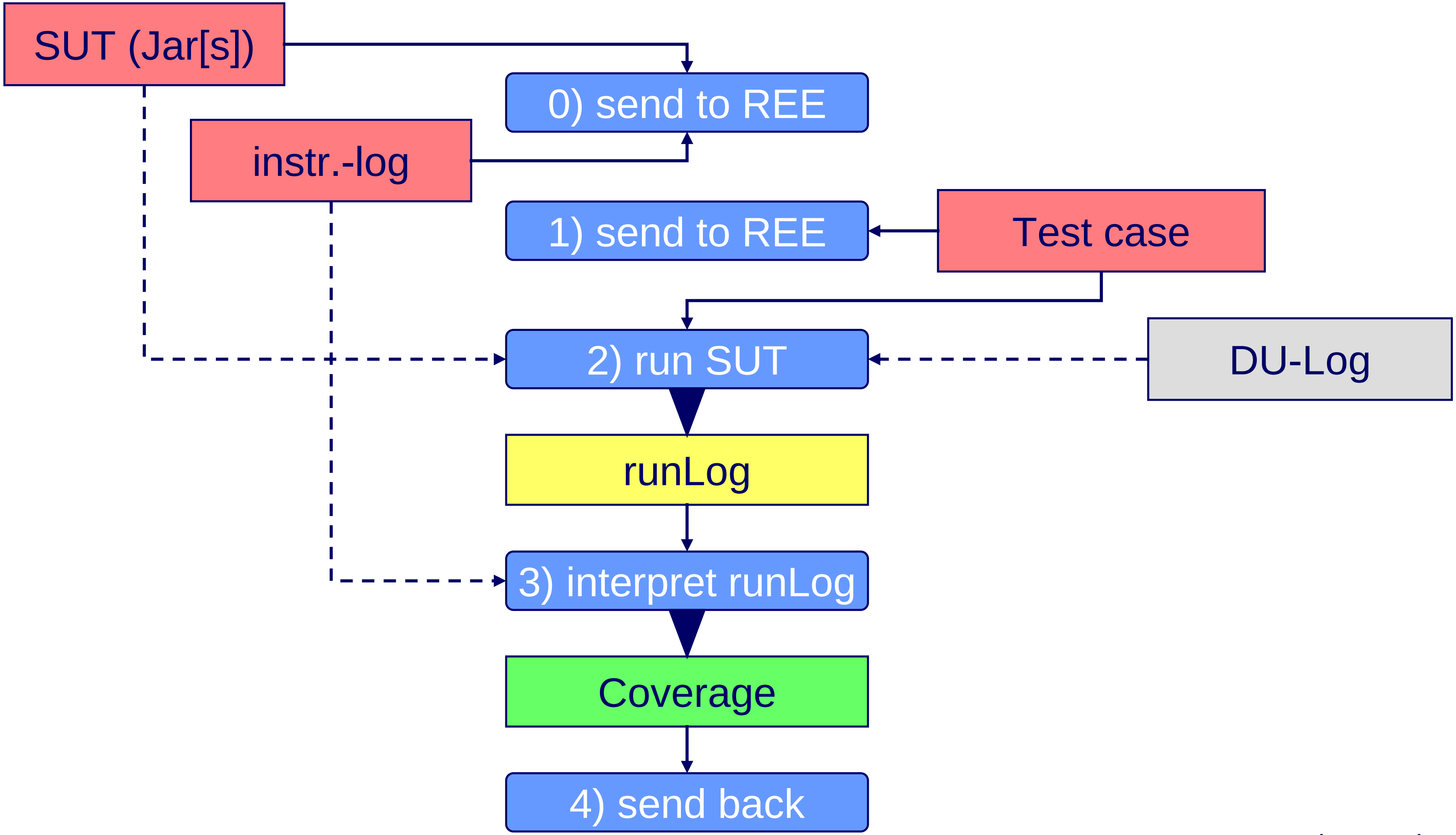
Processing of source-code



Distributed test case execution



Execution of test cases



REE: Remote Execution Engine

SUT - interface

- Test case execution corresponds to running an “application” with test parameters (a test case is therefore „String[] args“)
  - thus calling: public static void main(String[] args)

- Internal data types in .gEAr:
  - enumeration
  - string (of any character or from a given set)
  - integer (long with adjustable range; covering byte, char, int, long)
  - floating point (double with adjustable range; covering float, double)

- Tester must specify in .gEAr:
  - the arguments in terms of the types above

- Prototype: jUnit/.gEAr test driver generator

Example „OutputParameters“: source code

```
class OutputParameters {
		public static void main(String[] args) {
				try {
						System.out.println("Parameters:");
						for (int i = 0; i < args.length; i++) {
								System.out.println(" - <"+args[i]+">");
						}
						System.exit(0);
				} catch (Exception e) {
						System.exit(1);
				}
		}
}
```

Example: instrumented source code

```
class OutputParameters implements InstanceId {
    public int ___instanceId = DULog.getNewInstanceId(0);
    public final synchronized int ___getInstanceId(){return ___instanceId;}
    public static void main(String[] args){
        DULog.enter(19);
        try{
            try{
                ((java.io.PrintStream)DULog.useStatic(1,System.out)).println
                    ((java.lang.String)DULog.cp(2,"Parameters:"));
                for(int i=(int)DULog.defLocal(3,0);
                        DULog.predResult(8,DULog.newPredicate(7),
                            (int)DULog.useLocal(4,i)
                            < DULog.useArrayLength(6,(java.lang.String[])DULog.useLocal(5,args)));
                        DULog.useDefLocal(9,i++))
                {((java.io.PrintStream)DULog.useStatic(10,System.out)).println
                        ((java.lang.String)DULog.cp(14," - <"+(java.lang.String)DULog.useArray(13,
                        (java.lang.String[])DULog.useLocal(11,args),DULog.useLocal(12,i))+">"));
                }
                System.exit((int)DULog.cp(15,0));
            } catch(Exception e){DULog.exceptHandlerCall(18);DULog.defLocal(16);
                System.exit((int)DULog.cp(17,1));
            }
        } finally{DULog.leave(20);}
    }
}
```

„DULog“ short for „de.fau.cs.swe.sa.dynamicdataflowanalysis.rt.DULog“

Example: instrumentation log

1	useStatic	public static final java.io.PrintStream java.lang.System.out	4	31
2	cp	public void java.io.PrintStream.println(java.lang.String)	4	43
3	defLocal	int OutputParameters.main([Ljava.lang.String;).i	5	0
4	useLocal	int OutputParameters.main([Ljava.lang.String;).i	5	39
5	useLocal	[Ljava.lang.String; OutputParameters.main([Ljava.lang.String;).args	5	42
6	useArrayLength	[Ljava.lang.String; OutputParameters.main([Ljava.lang.String;).args	5	42
7	newPredicate	-	5	25
8	predResult	-	5	25
9	useDefLocal	int OutputParameters.main([Ljava.lang.String;).i	5	55
a	useStatic	public static final java.io.PrintStream java.lang.System.out	6	39
b	useLocal	[Ljava.lang.String; OutputParameters.main([Ljava.lang.String;).args	6	59
c	useLocal	int OutputParameters.main([Ljava.lang.String;).i	6	64
d	useArray	[Ljava.lang.String; OutputParameters.main([Ljava.lang.String;).args	6	59
e	cp	public void java.io.PrintStream.println(java.lang.String)	6	51
f	cp	public static void java.lang.System.exit(int)	8	36
10	defLocal	java.lang.Exception e	9	0
11	cp	public static void java.lang.System.exit(int)	10	36
12	exceptHandlerCall	-	9	19
13	enter	public static void OutputParameters.main(java.lang.String[])		
		PARA: [Ljava.lang.String; OutputParameters.main([Ljava.lang.String;).args	2	0
14	leave	public static void OutputParameters.main(java.lang.String[])	2	0

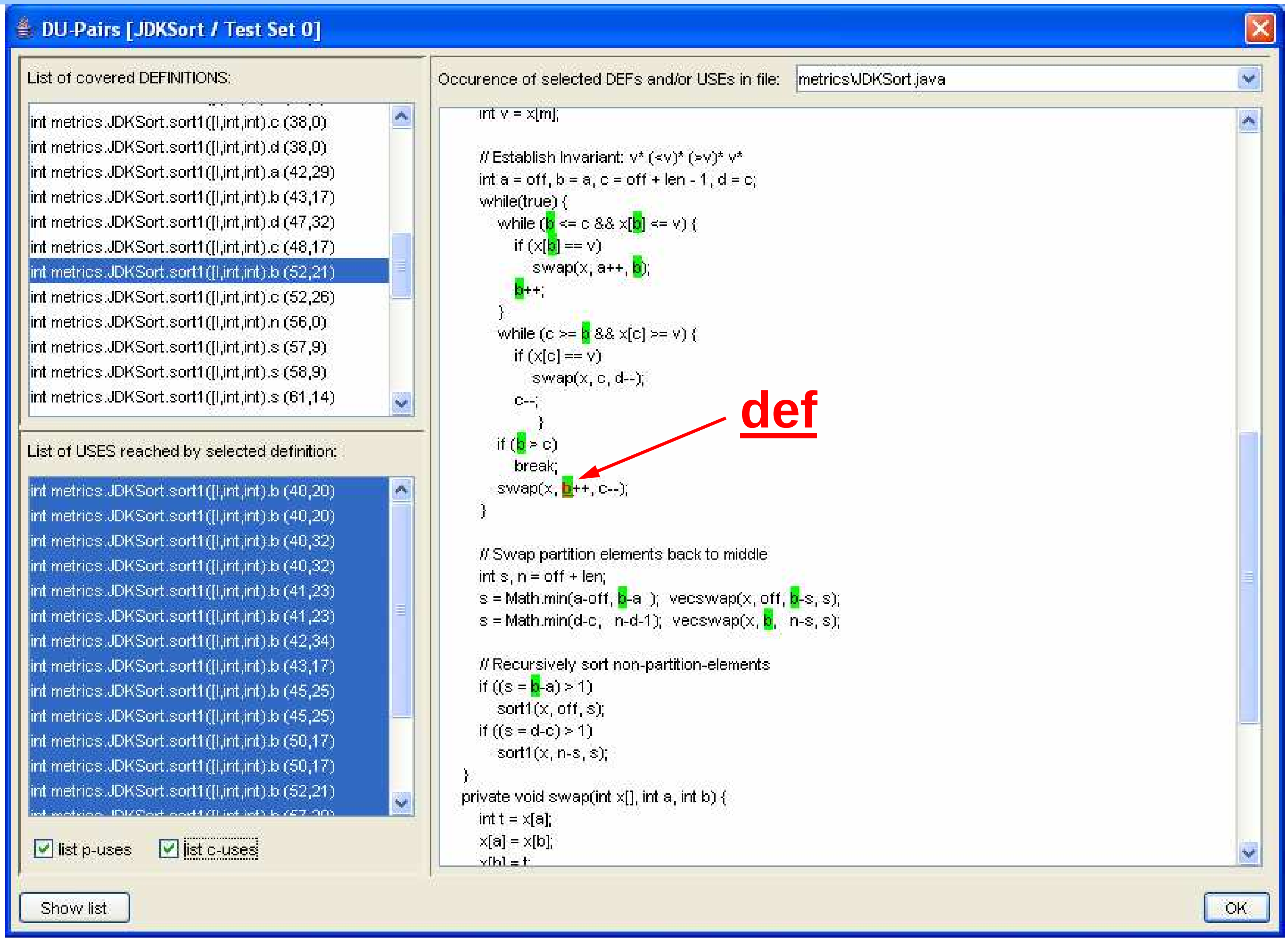
Log-Events

CallPoint
DefineArray
DefineField
DefineLocalVariable
DefineStaticVariable
EarlyConstructorEnter
EnterClassInitialisation
EnterConstructor
EnterInstanceInitialisation
EnterMethod
ExceptionHandlerCall
LeaveClassInitialisation
LeaveConstructor
LeaveInstanceInitialisation
LeaveMethod
NewArray
NewCall
NewCallCompleted
NewPredicate
NewSwitchPredicate
PredicateResult
SwitchPredicateEquivalent
SwitchPredicateResult
UseArray
UseArrayLength
UseField
UseLocalVariable
UseStaticVariable
UseDefineArray
UseDefineField
UseDefineLocalVariable
UseDefineStaticVariable

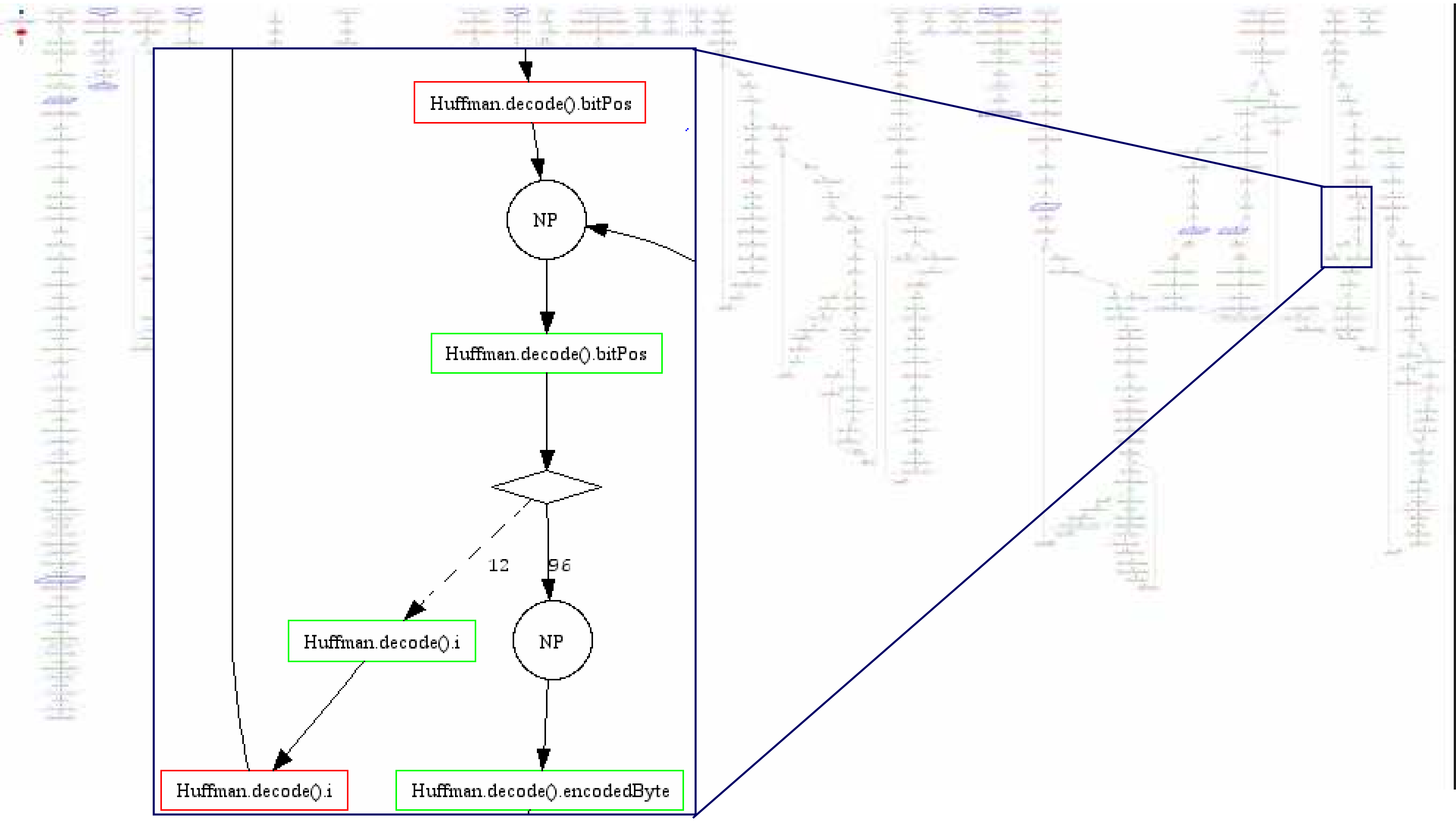
Example: Run-Log (application executed with 2 parameters)

0-NewThread
1-EnterMethod: "OutputParameters.main(java.lang.String[])"
2-DefineLocalVariable: "OutputParameters.main([Ljava.lang.String;).args"
3-UseStaticVariable: "java.lang.System.out"
4-CallPoint: "java.io.PrintStream.println(java.lang.String)" (virtual)
5-DefineLocalVariable: "OutputParameters.main([Ljava.lang.String;).i" — **def(i)**
6-NewPredicate
7-UseLocalVariable: "OutputParameters.main([Ljava.lang.String;).i" — **p-use(i)**
8-UseLocalVariable: "OutputParameters.main([Ljava.lang.String;).args"
9-NewInstance
10-UseArrayLength: "OutputParameters.main([Ljava.lang.String;).args.length"
11-PredicateResult [true]
[...]
17-UseDefineLocalVariable: "OutputParameters.main([Ljava.lang.String;).i" — **c-use(i), def(i)**
[...]
29-NewPredicate
30-UseLocalVariable: "OutputParameters.main([Ljava.lang.String;).i" — **p-use(i)**
31-UseLocalVariable: "OutputParameters.main([Ljava.lang.String;).args"
32-UseArrayLength: "OutputParameters.main([Ljava.lang.String;).args.length"
33-PredicateResult [false]
34-CallPoint: "java.lang.System.exit(int)" (virtual)
35-EndOfLog

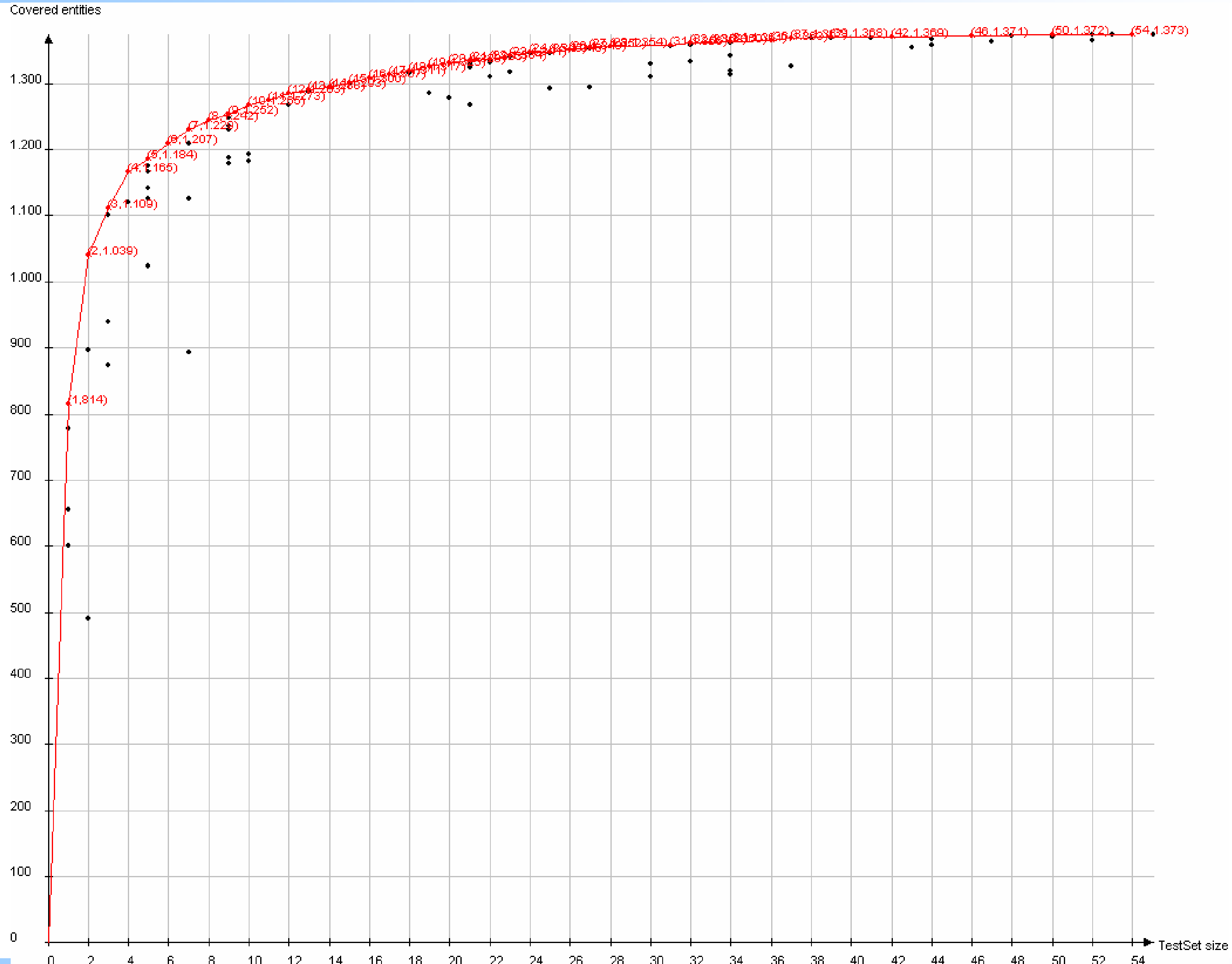
Covered DU-pair browser



Covered dataflow-annotated CFG



BigFloat: Pareto-front of all-uses



Static analysis and coverage measure

- dynamic analysis
  - can determine the number of actually executed def/use-pairs
  - achieved through introducing logging probes into source code
  - sufficient for test case generation
  - no adequate termination criterion in terms of coverage achieved
- static analysis
  - determines number of def/use-pairs and all corresponding DU-paths
  - program represented as Java Interclass Graph (JIG)
  - performed in terms of symbolic execution of byte-code by applying a fixed point iteration to each method
- determining coverage measure
  - covered basic blocks of byte code logged by byte code instrumentation
  - matching thus logged data with corresponding statically determined information

Analysis of fault-revealing capability

- problem (in general)
  - high coverage alone does not guarantee a high quality of the test set
- solution
  - back-to-back testing against “mutant” programs
- idea
  - if the original program is correct and any slightly different version of it is wrong, than a good test set should trigger differences in behaviour during execution of the correct and any wrong version
- method
  - mutate original program by introducing small changes (e.g. replacing “<=“ by “<“), thus giving a set of slightly different programs
  - execute each mutant and compare its behaviour with that of original program, saying that the mutant is killed if a difference in behaviour could be observed
  - the higher the mutation score (ratio of killed mutants), the better the test case/set is assumed to be w.r.t. its ability to detect faults

Experimental results (coverage, quality)

Project	Size in LOC (classes / bytes)	branches executed (coverage)	DU-pairs executed (coverage)	test cases required	Mutants class+tradition. (mutat. score)
BigFloat (arbitrary precision)	540 (3 / 17.526)	145	1511	17 (232)	65+1463=1528 (76,77% / ~96%)
Dijkstra (shortest path)	141 (2 / 4.080)	26	168	3 (8)	13+207=220 (71,82% / ~76%)
Hanoi (The Towers)	38 (1 / 1.279)	4 (100,0%)	42 (96,7%)	2 (11)	1+226=227 (77,53% / ~86%)
Huffman (compression codec)	298 (2 / 8.931)	61	353	3 (6)	47+576=623 (84,27% / 100%)
JDK-sort* (integer-array sort)	82 (1 / 2.639)	37 (97,4%)	315 (96,0%)	3 (108)	0+852=852 (64,79% / ~82%)
JDK-logging* (logging facility)	5.439 (27 / 113.046)	345	1643	61	454+1516=1970

** extracted from JDK*

according to byte code coverage analysis including potentially non-coverable entities

without considering test driver

Experimental results* (effort, variance)

Project CPU-time**	**Coverage** Average Min / Max	**Test set size** Average Min / Max	**Generation** Average Min / Max
The Towers of Hanoi ~ 1:20	42 42 / 42	2 2 / 2	10.4 3 / 20
Dijkstra's shortest path ~ 5:20	213 213 / 213	2 2 / 2	63.2 25 / 165
JDK integer-array sort ~ 6:58	315 315 / 315	2 2 / 2	79.6 15 / 264
Huffman encoding ~ 9:14	368 368 / 368	3 3 / 3	64.2 39 / 96

* average over 5 runs: multi-objective aggregation (mutation rate: 25%)
coverage weight: 1 vs. test set size weight: 0.05

** resources on workbench host in min:sec (for 200 generations; test case execution parallelized on 6 PCs)

considering test driver

Summary

- Motivation:
  - functional testing covers only a subset of the “true functionality” provided by a given code (neglecting Trojan horse behaviour)
  - structural (especially dataflow) testing increases the chance of finding abovementioned faults
- State-of-the-art in practice
  - expensive test data generation
  - expensive check of test results because of large test sets
- Proposed solution by means of .gEAr:
  - maximise the coverage according to a given testing strategy
  - minimise the number of test cases (=> reduced effort)
  - achieve both goals by fully automated test set generation