Università
della
Svizzera
italiana

**Faculty
of Informatics**

How to Measure Software Redundancy

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In collaboration with:
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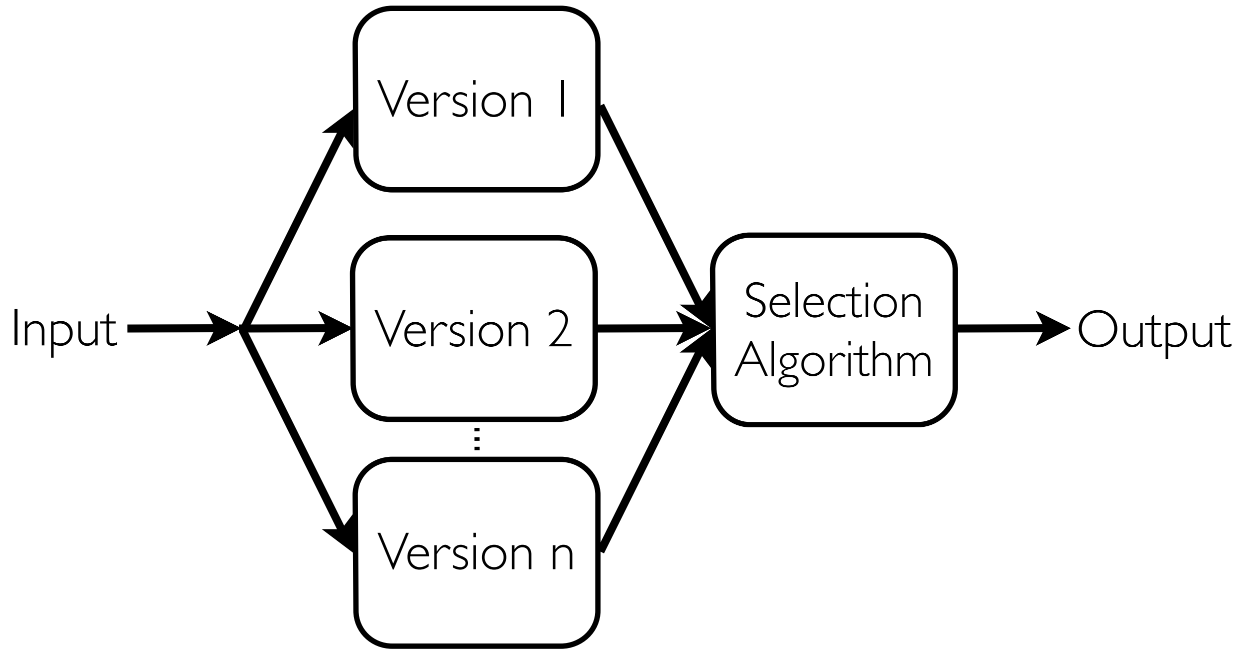
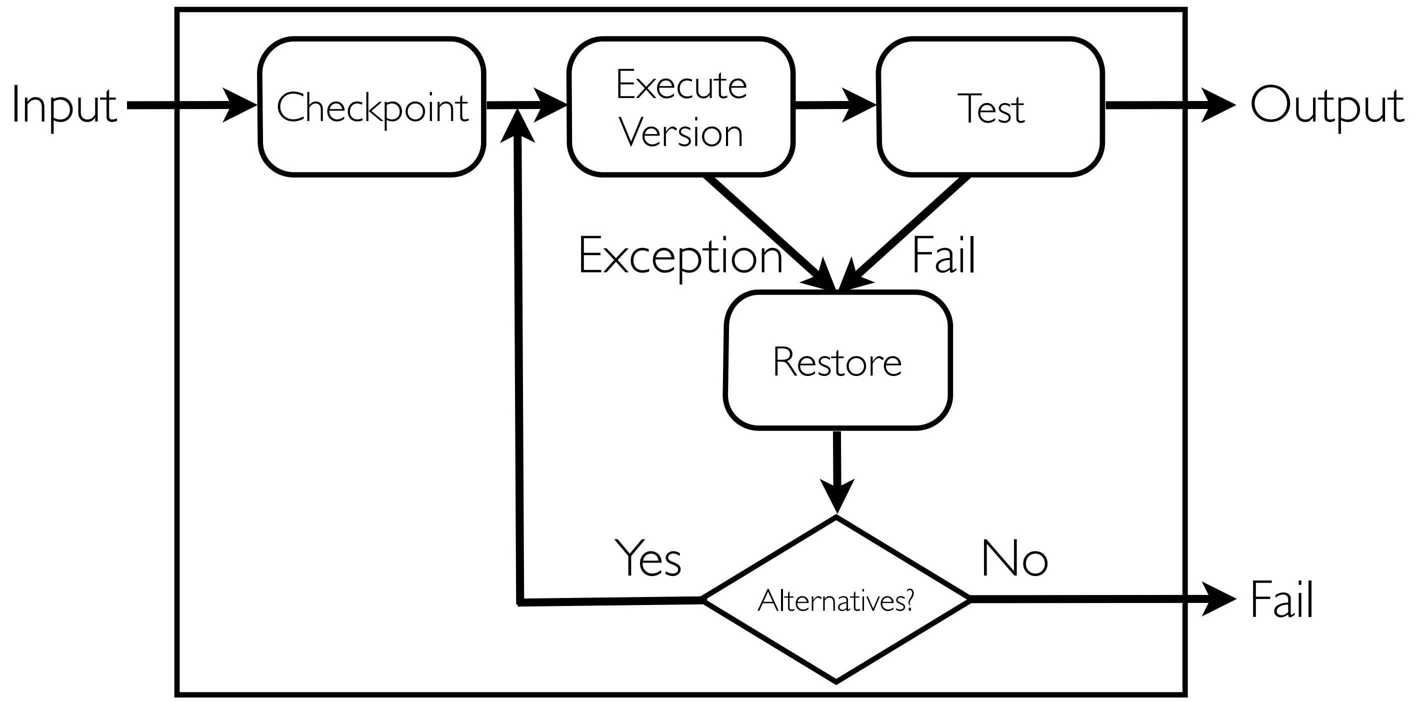
(. . .and A. Gorla, A. Goffi, N. Perino)

Software Redundancy

Software Redundancy

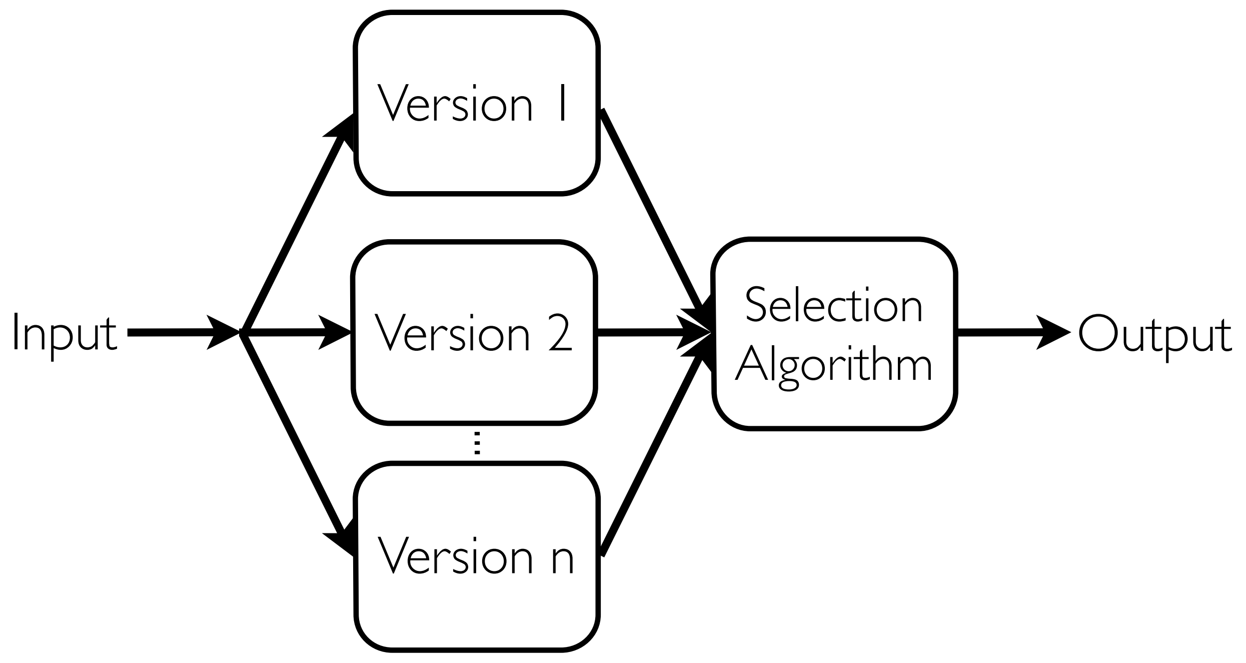


N-version

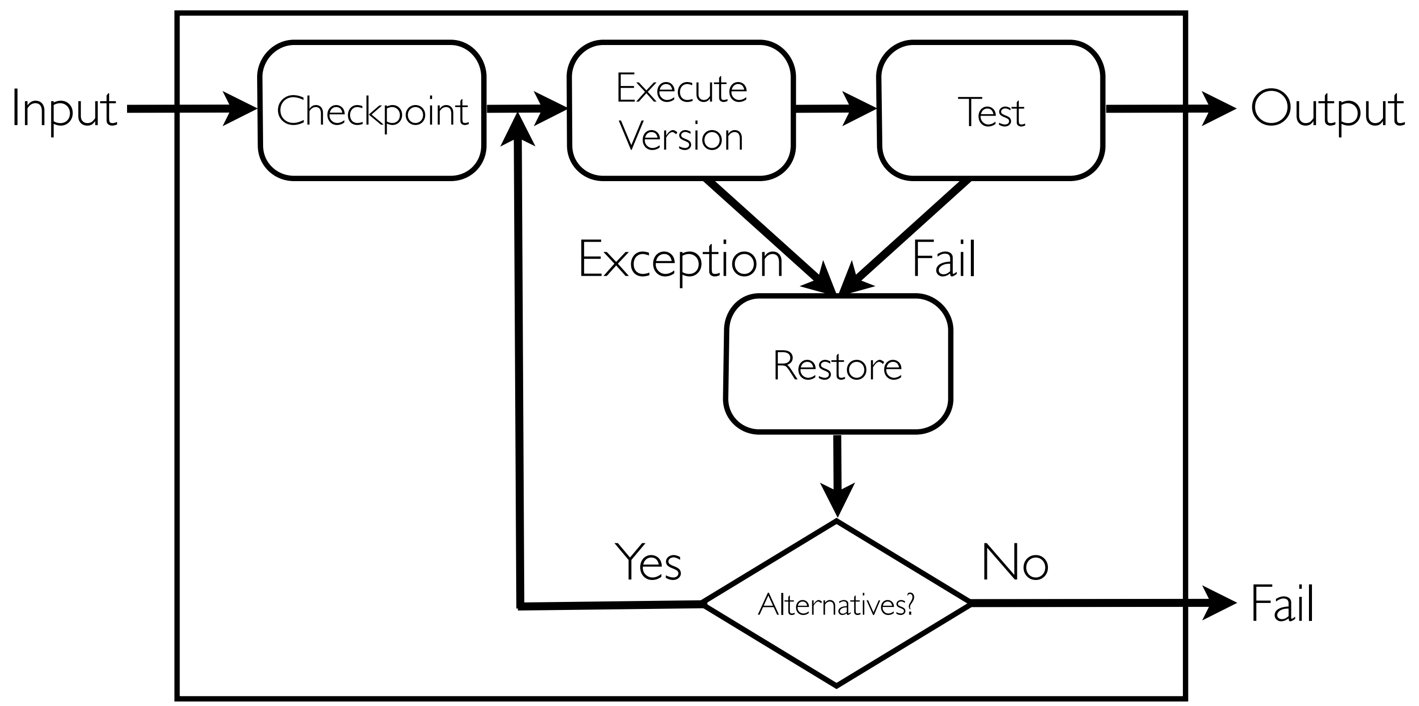


Recovery Blocks

Software Redundancy
Deliberate



N-version



Recovery Blocks

Software Redundancy
Intrinsic

Software Redundancy
Intrinsic

Google Guava

```
MultiMap m = new MultiMap();
//…
//add a key-value pair in the map
m.put(key, value);
```

Software Redundancy
Intrinsic

Google Guava

```
MultiMap m = new MultiMap();
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//add a key-value pair in the map
m.put(key, value);
 m.putAll(key, new List().add(value));
 m.entrySet().add(new Entry(key, value));
```

Software Redundancy

Intrinsic

Java

Joda-Time

eclipse

SWT

4700+ equivalences

Lucene

guava-libraries

Guava: Google Core Libraries for Java 1.6+

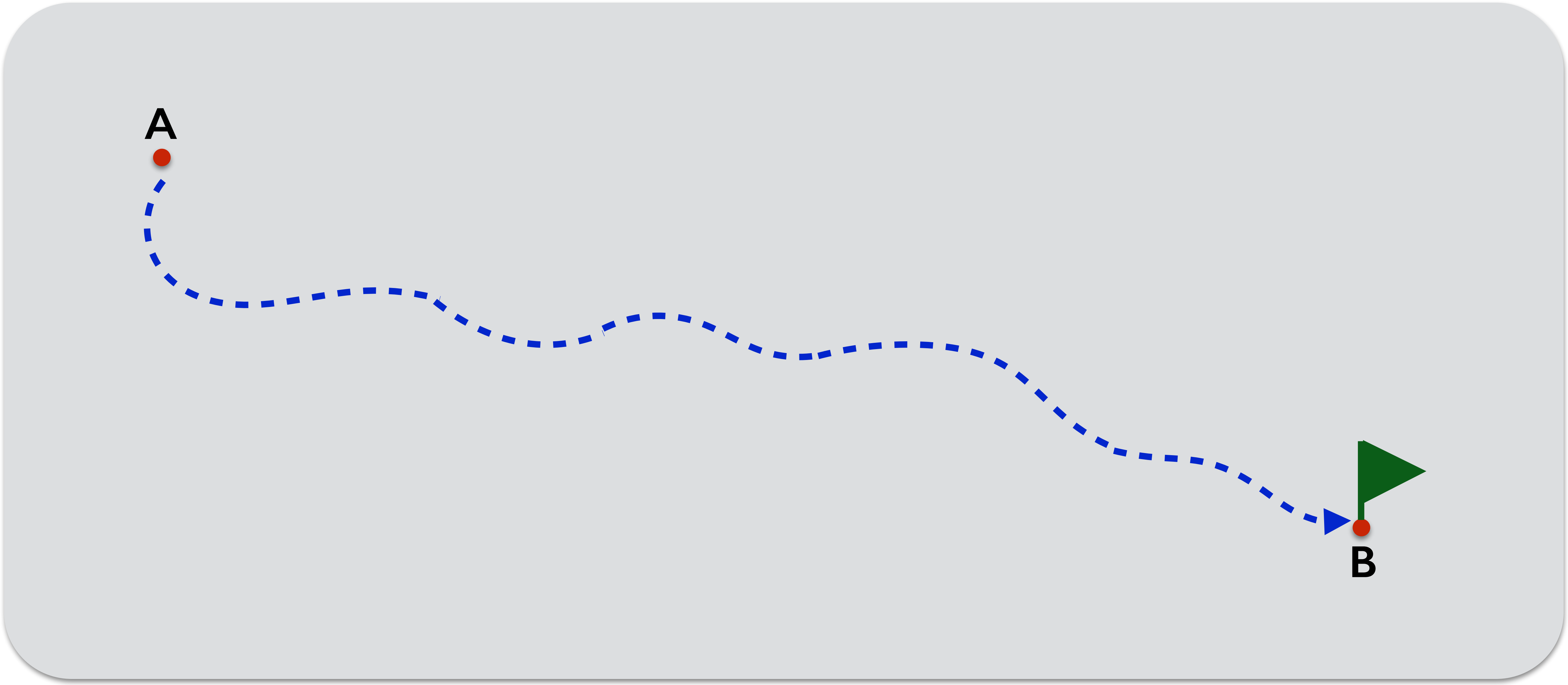
GraphStream

Exploiting Intrinsic Redundancy

Automatic Recovery From Runtime Failures
Carzaniga, Gorla, Mattavelli, Perino, Pezzè [ICSE 2013]

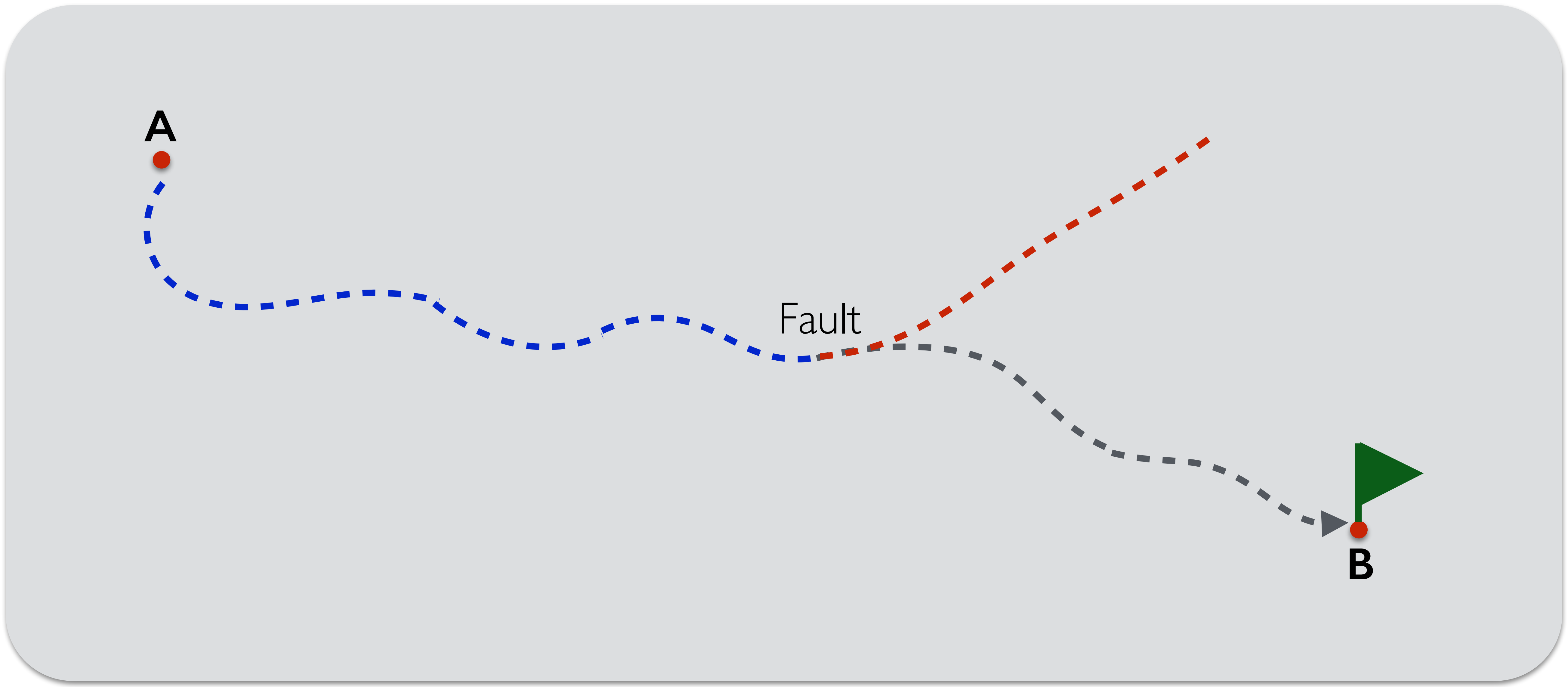
Cross-checking Oracles from Intrinsic Software Redundancy
Goffi, Carzaniga, Gorla, Mattavelli, Pezzè [ICSE 2014]

Automatic Runtime Recovery



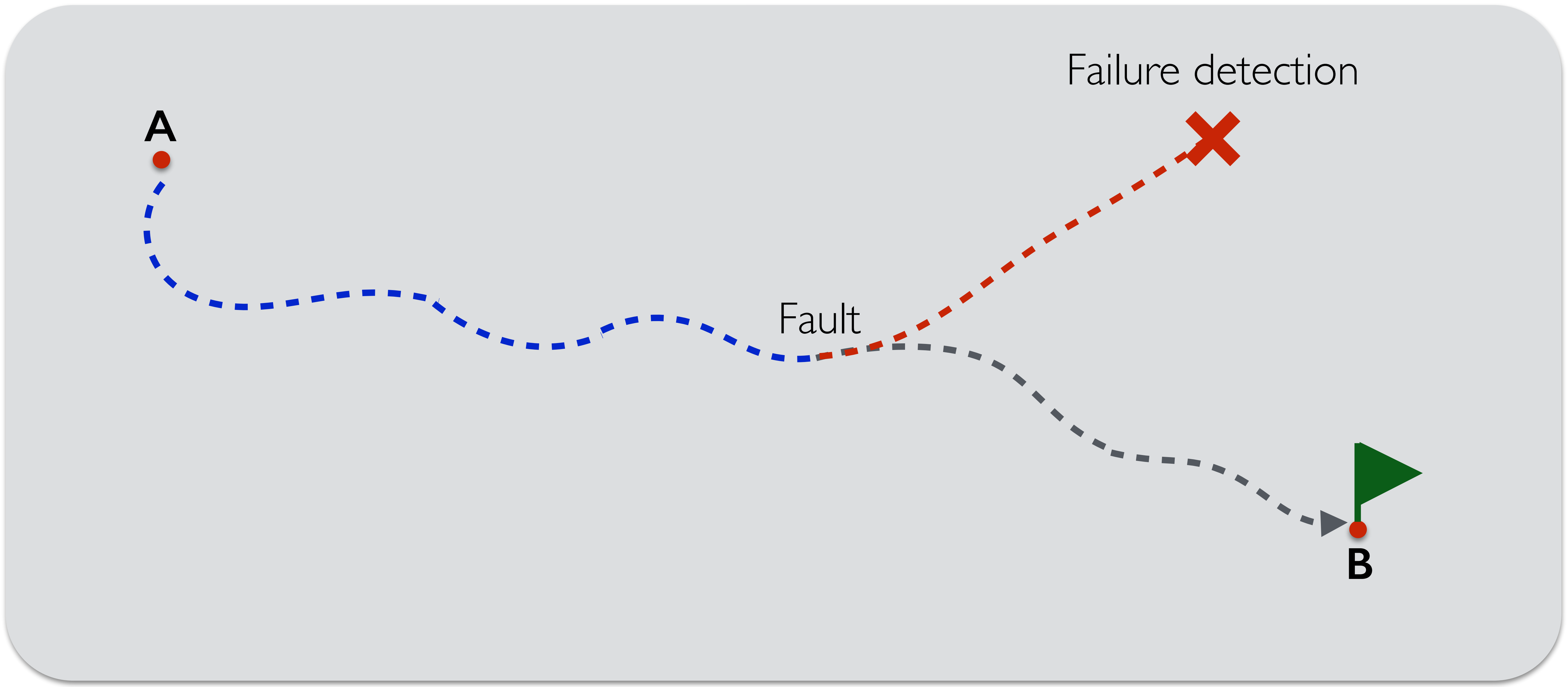
Application state space

Automatic Runtime Recovery



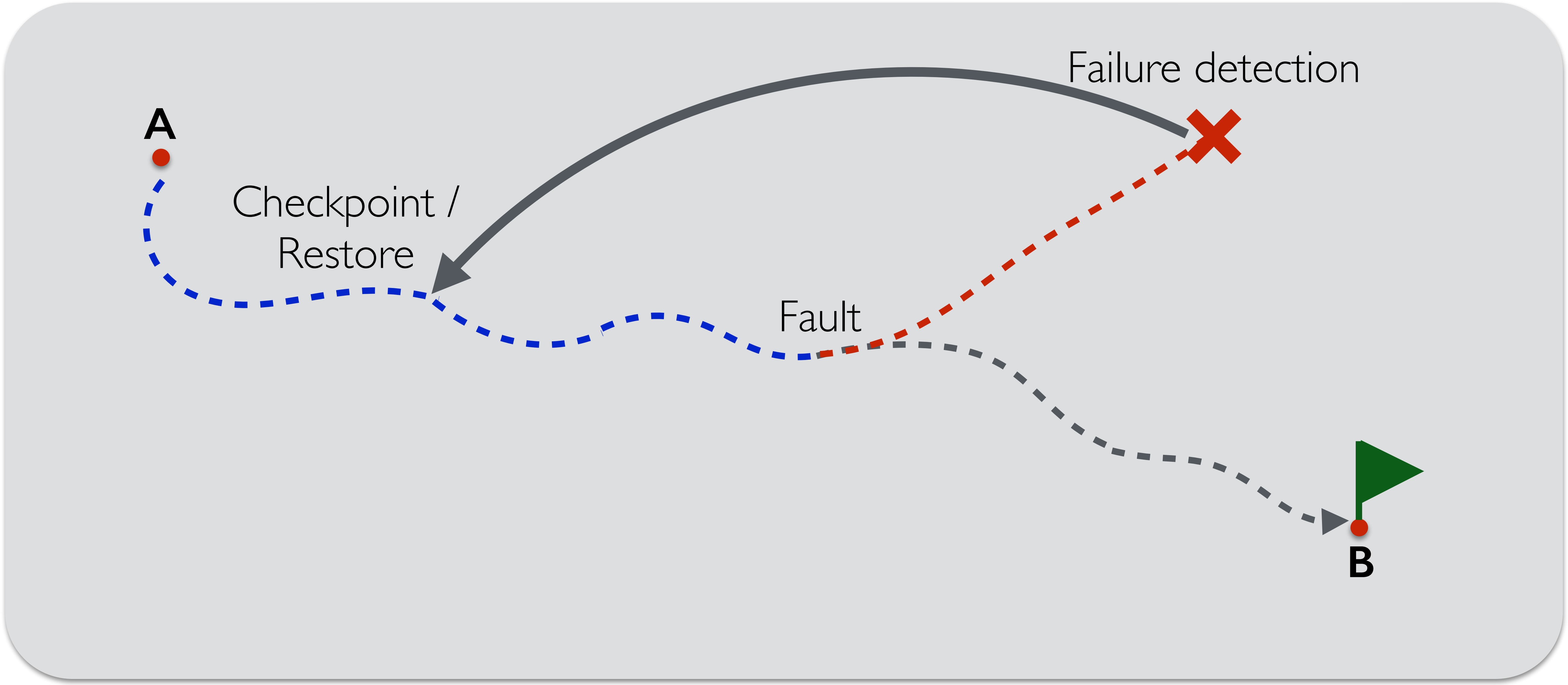
Application state space

Automatic Runtime Recovery



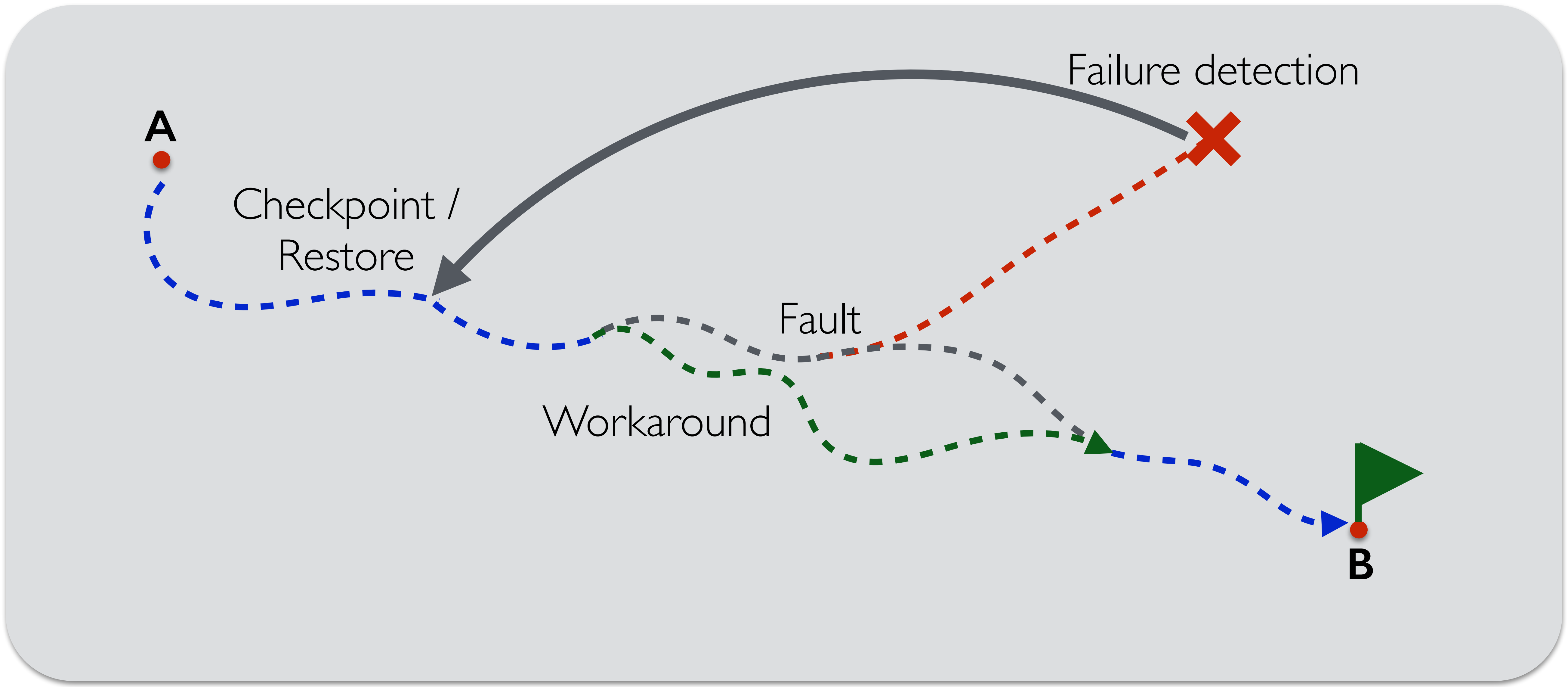
Application state space

Automatic Runtime Recovery



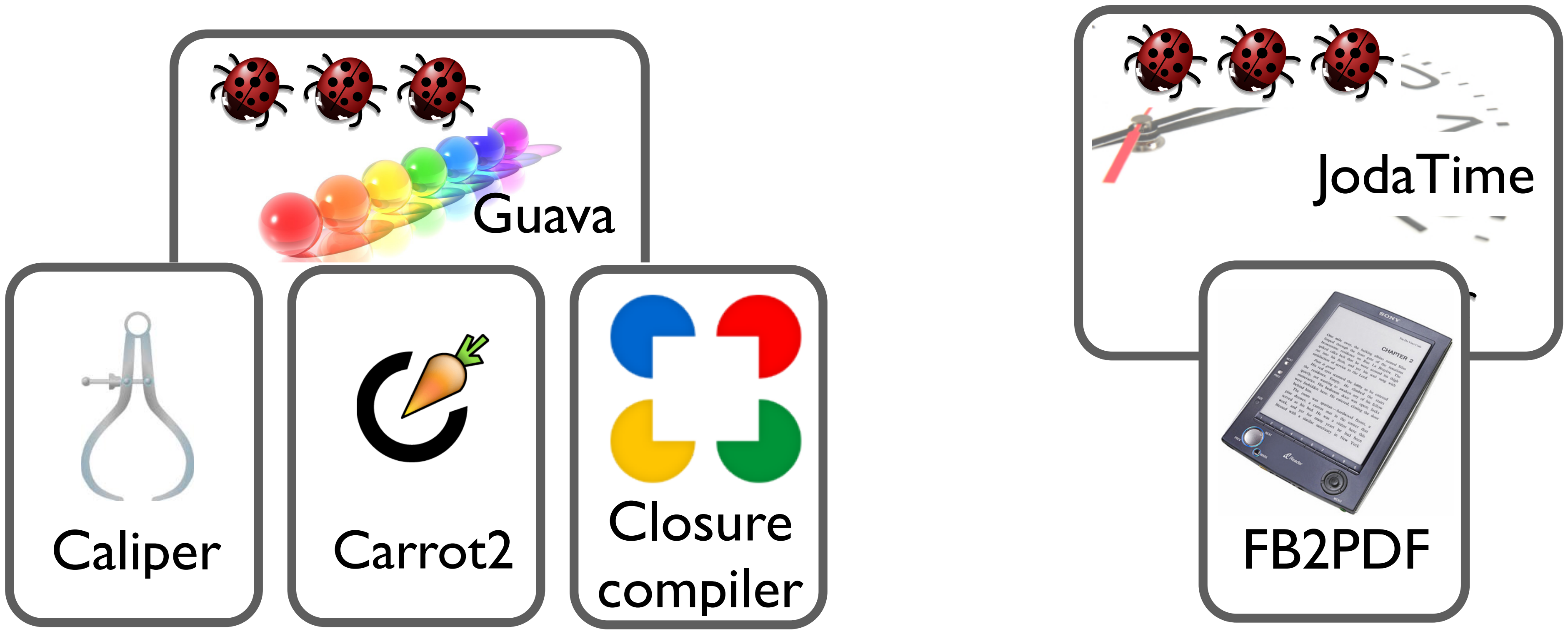
Application state space

Automatic Runtime Recovery



Application state space

Automatic Runtime Recovery



Mutants	87	50	148	347
Successfully recovered	24	24	64	67
	27%	48%	43%	19%

Software Redundancy

Software Redundancy?

Software Redundancy?

Intrinsic

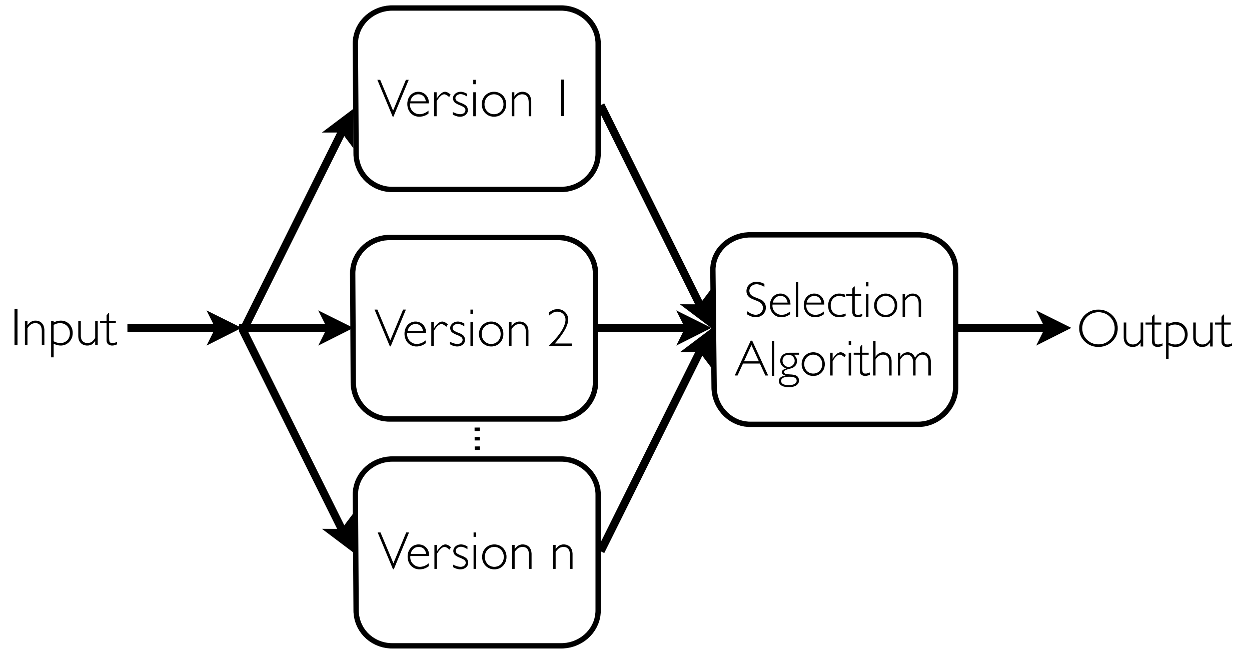
Google Guava

```
MultiMap m = new MultiMap();
//…
//add a key-value pair in the map
m.put(key, value);
 m.putAll(key, new List().add(value));
 m.entrySet().add(new Entry(key, value));
```

How much code
do they share?

Software Redundancy?

Deliberate



N-version

Failures are correlated
[Knight et al.]

Intrinsic

Google Guava

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MultiMap m = new MultiMap();
//…
//add a key-value pair in the map
m.put(key, value);
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 m.entrySet().add(new Entry(key, value));
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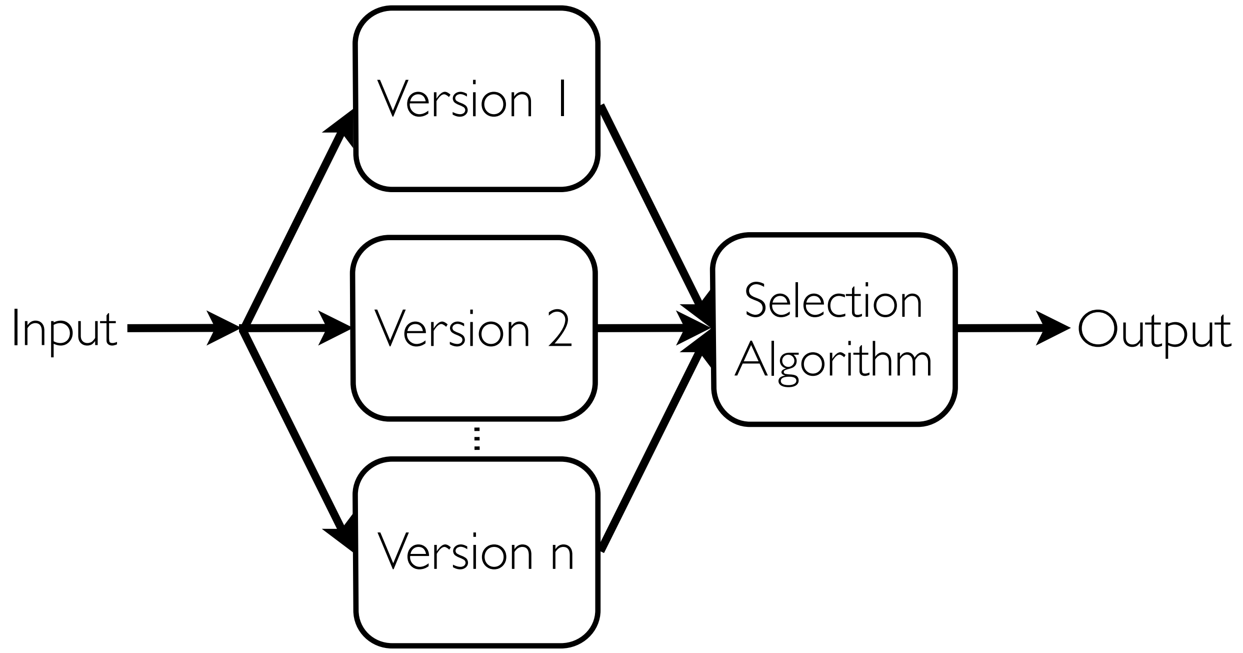
Software Redundancy?

Deliberate



N-version

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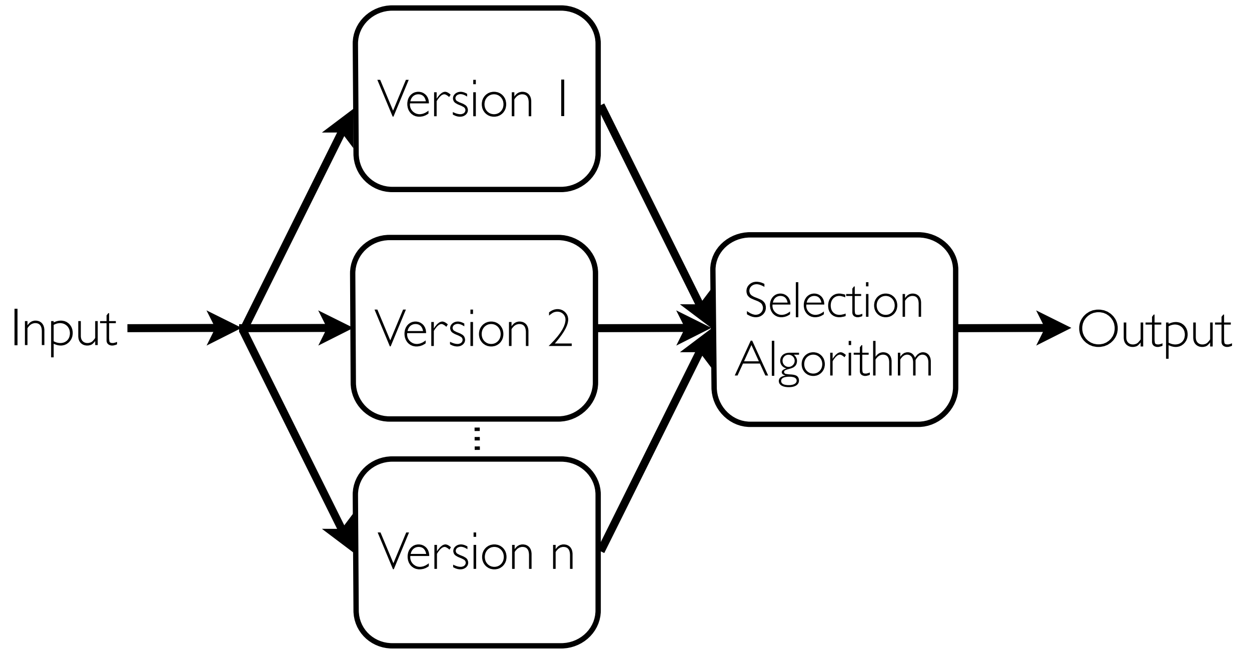
 m.entrySet().add(new Entry(key, value));
```

How much redundancy is there?

Software Redundancy?

Deliberate



N-version

Intrinsic

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 m.entrySet().add(new Entry(key, value));
```

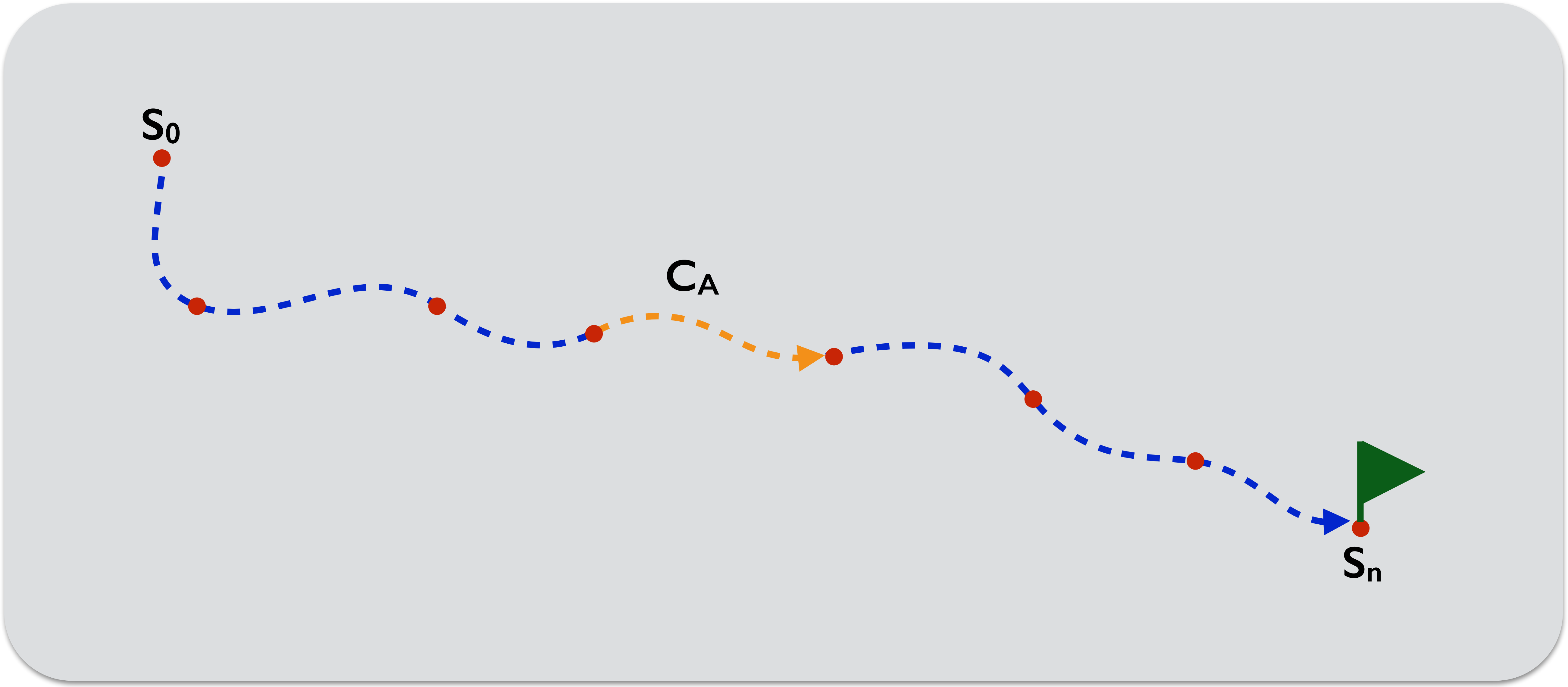
How much redundancy is there?

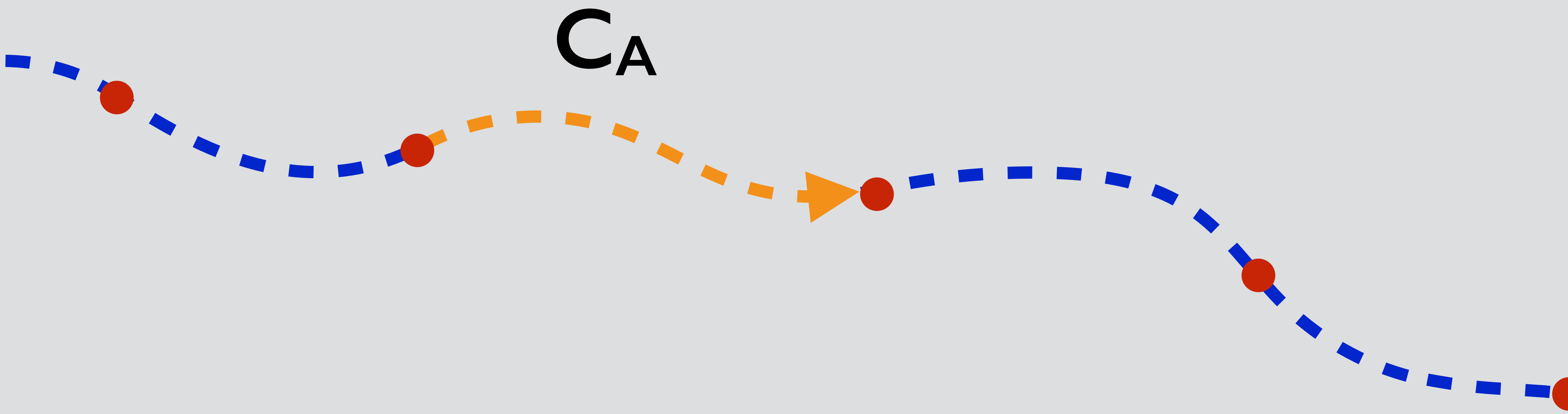
Measuring Software Redundancy
Carzaniga, Mattavelli, Pezzè [ICSE 2015]

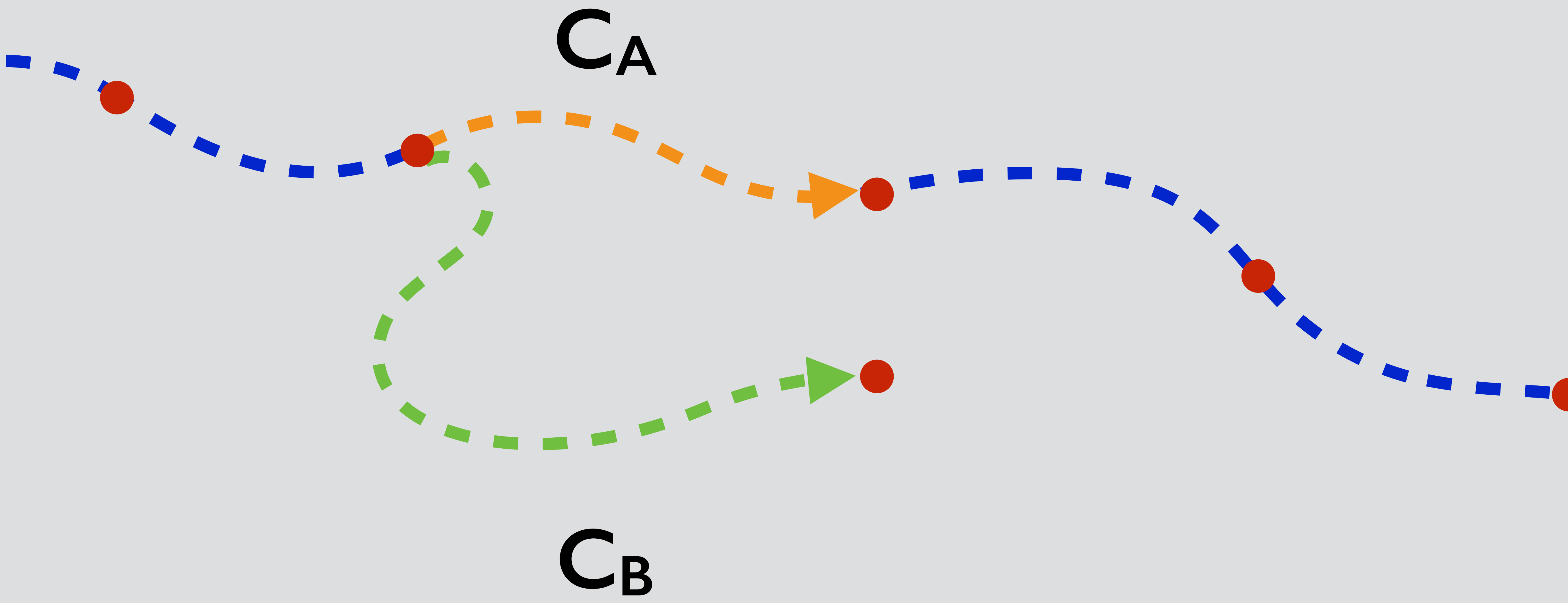
Informal Definition of Redundancy

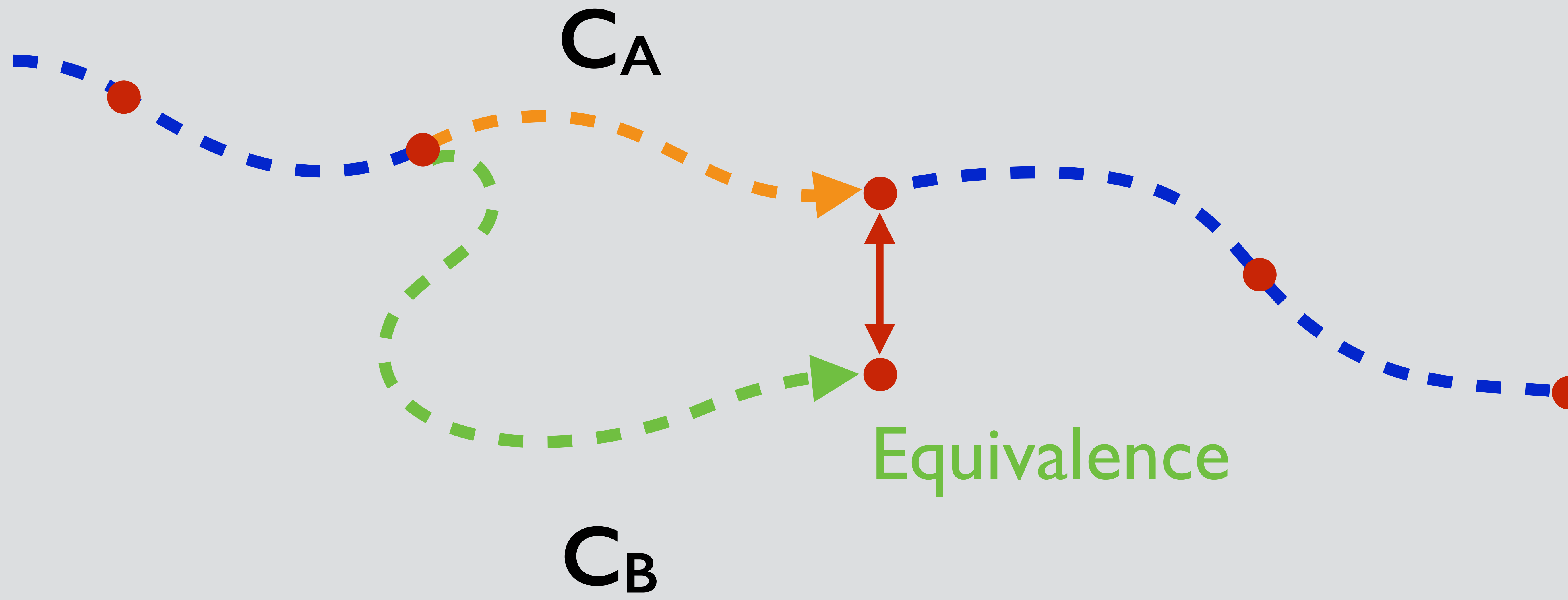
“Two fragments are redundant when they are **functionally equivalent** and at the same time their **executions are different**.

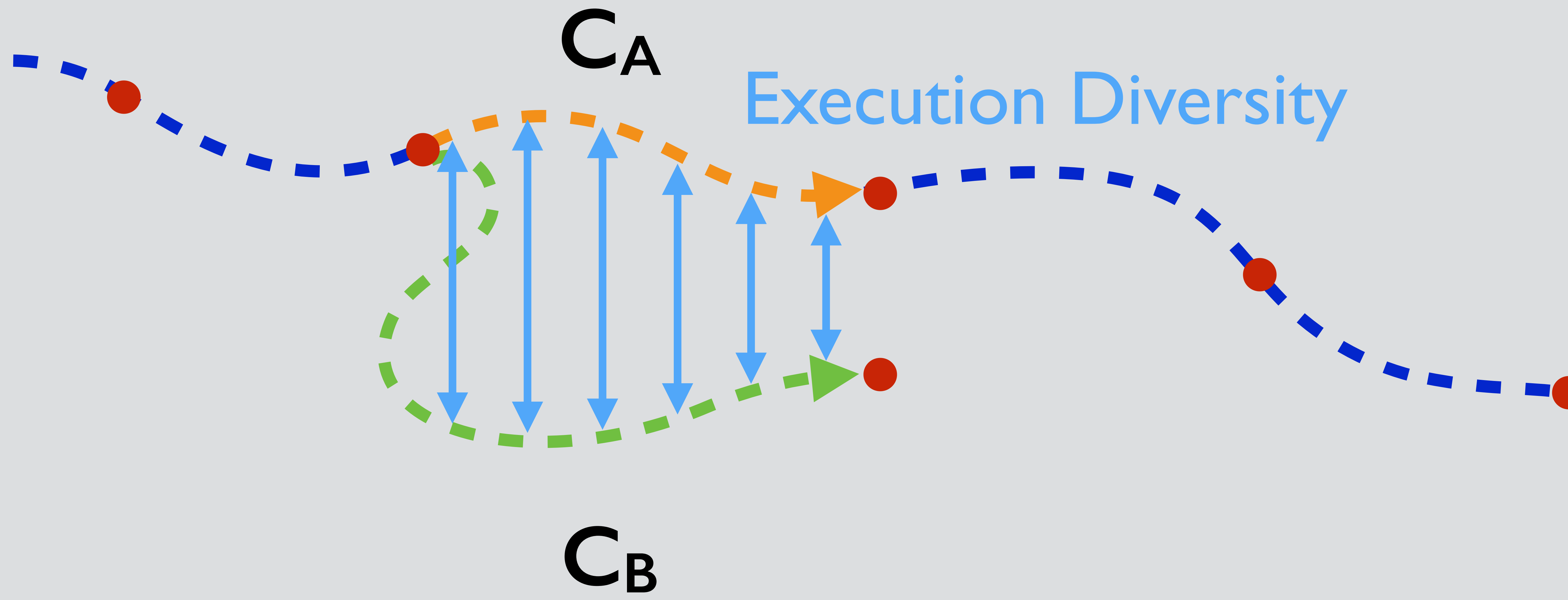
Informal Definition of Redundancy



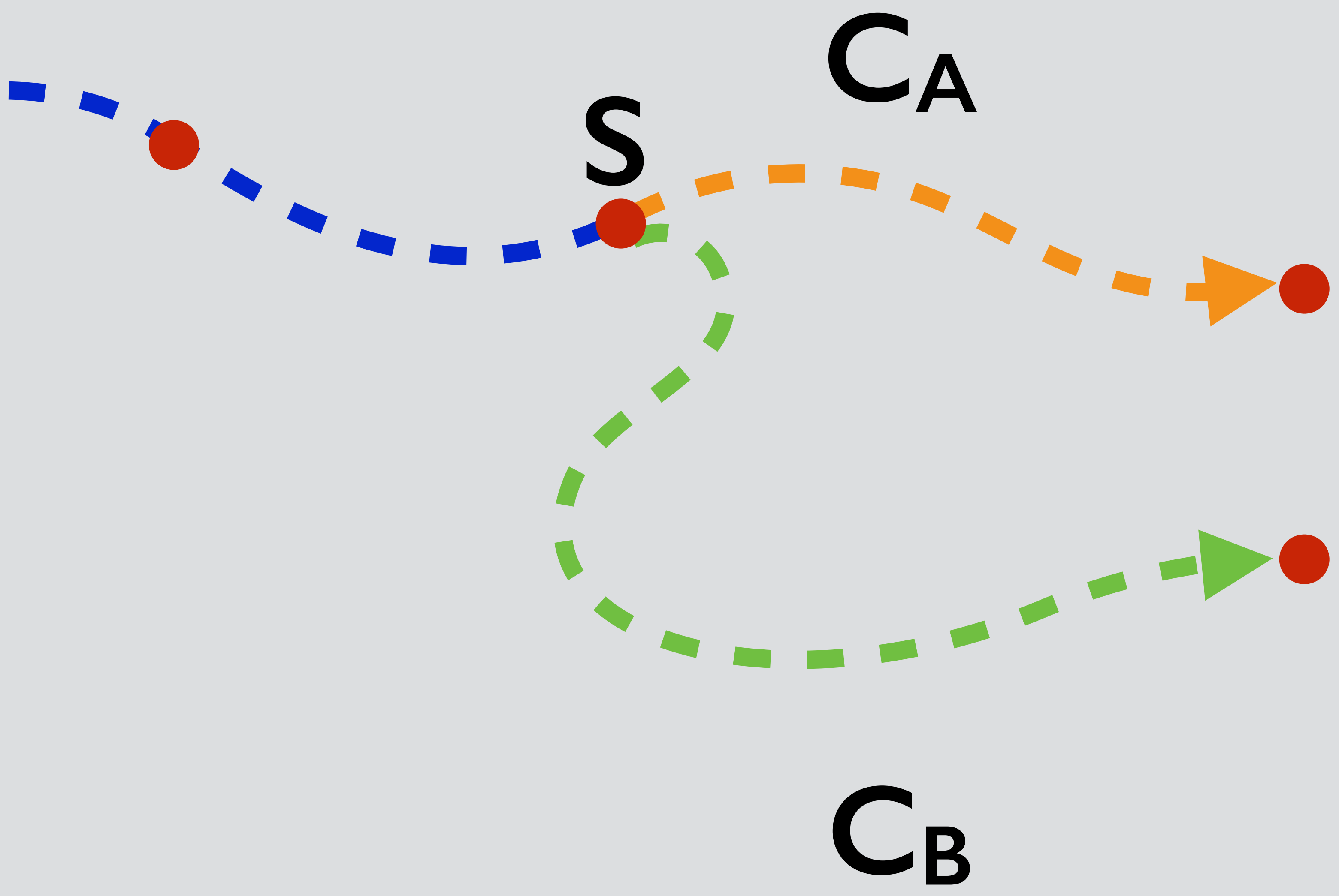

C_A


C_A
C_B

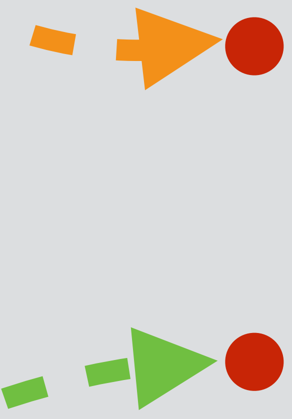

C_A
Equivalence
C_B


C_A
Execution Diversity
C_B

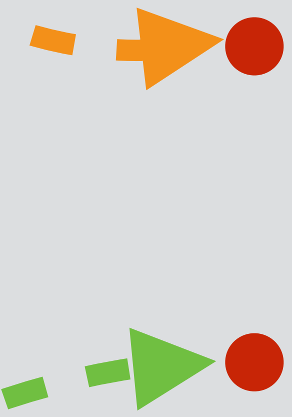
Functional Equivalence



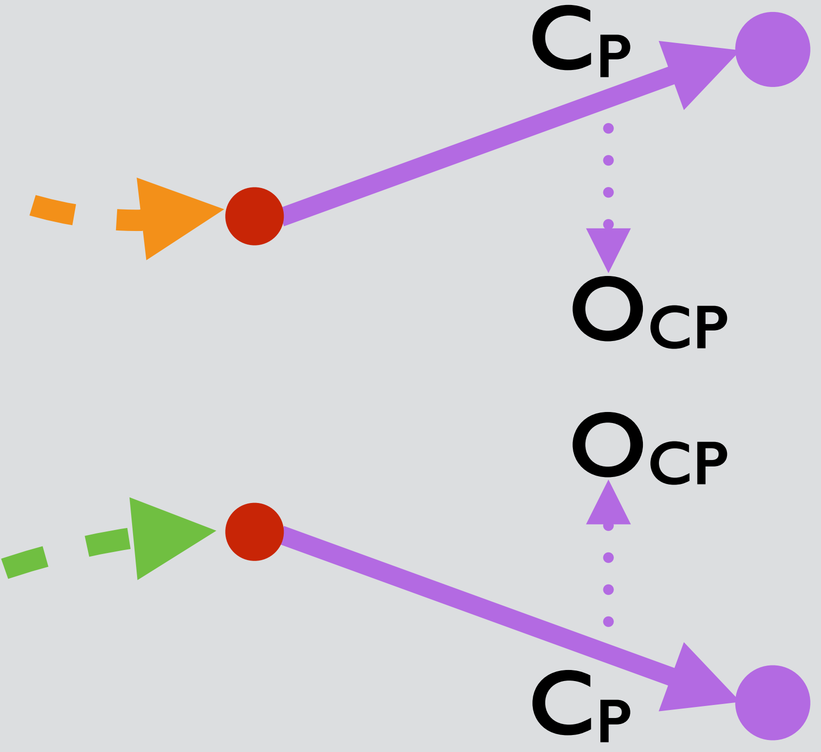
Functional Equivalence



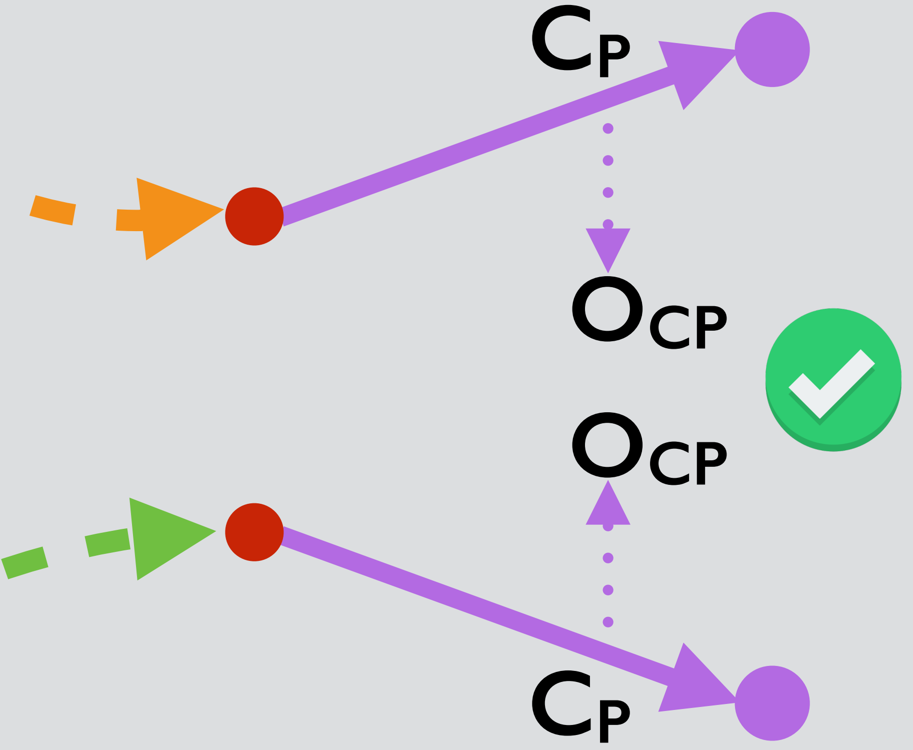
Observational Equivalence



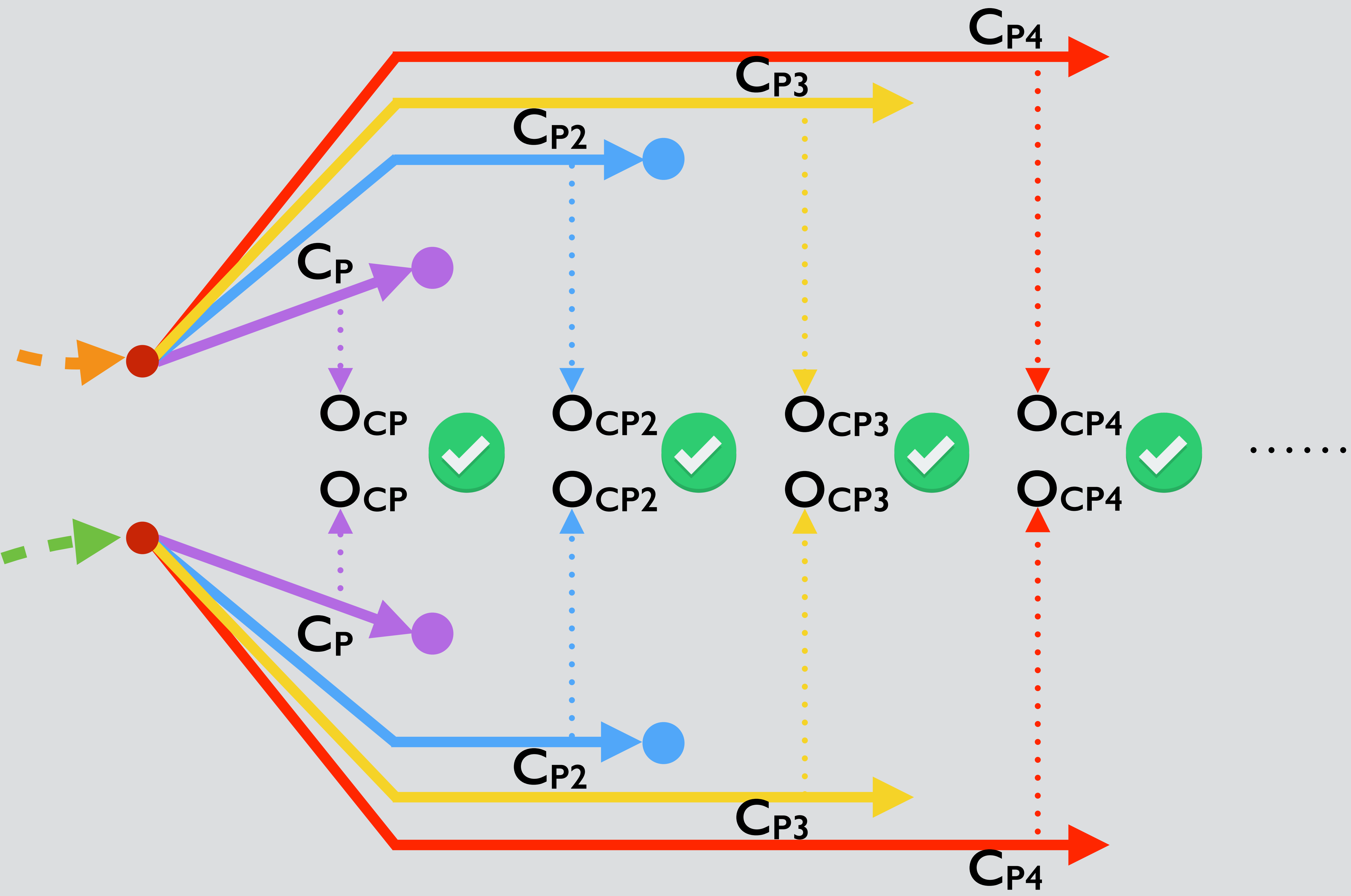
Observational Equivalence



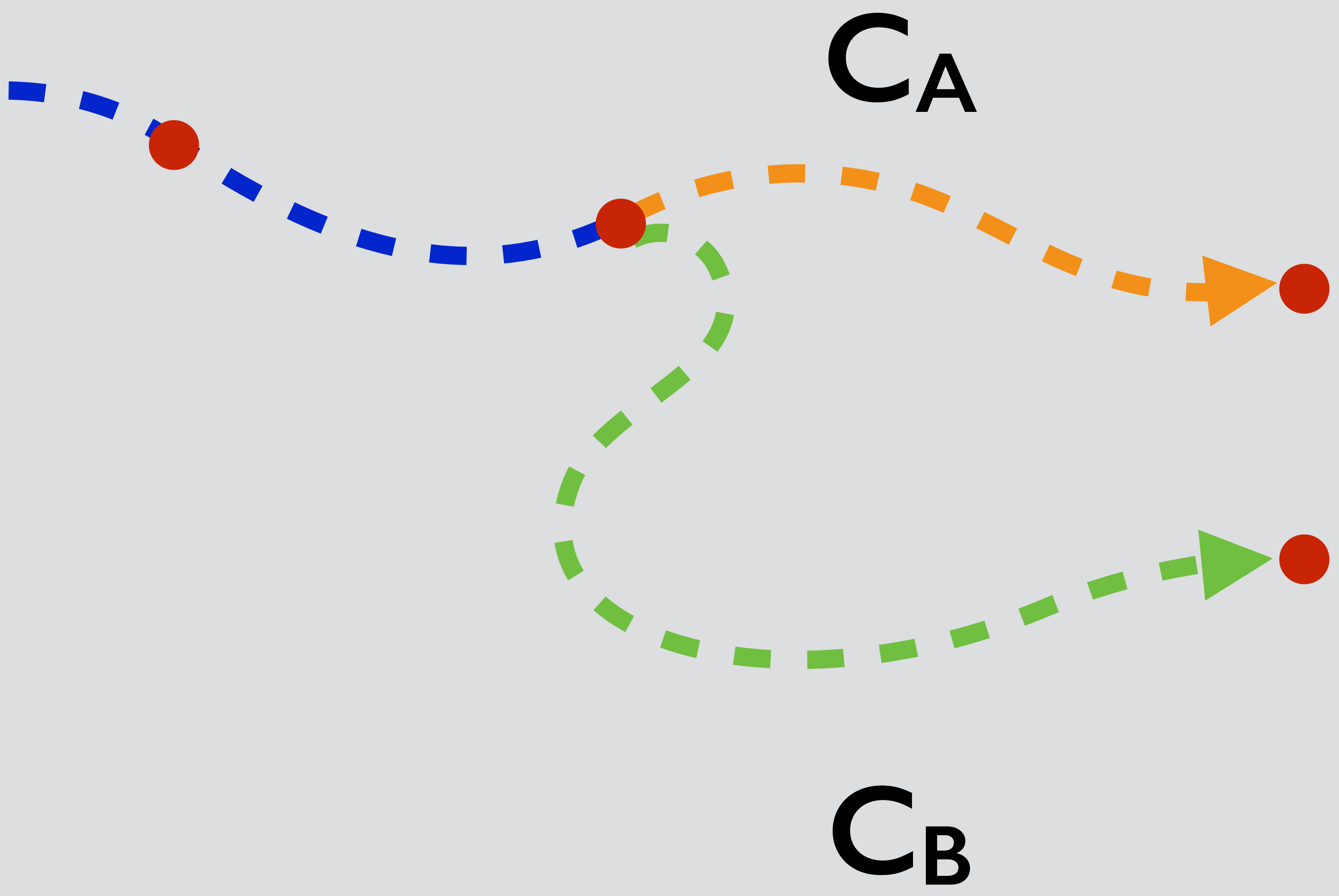
Observational Equivalence



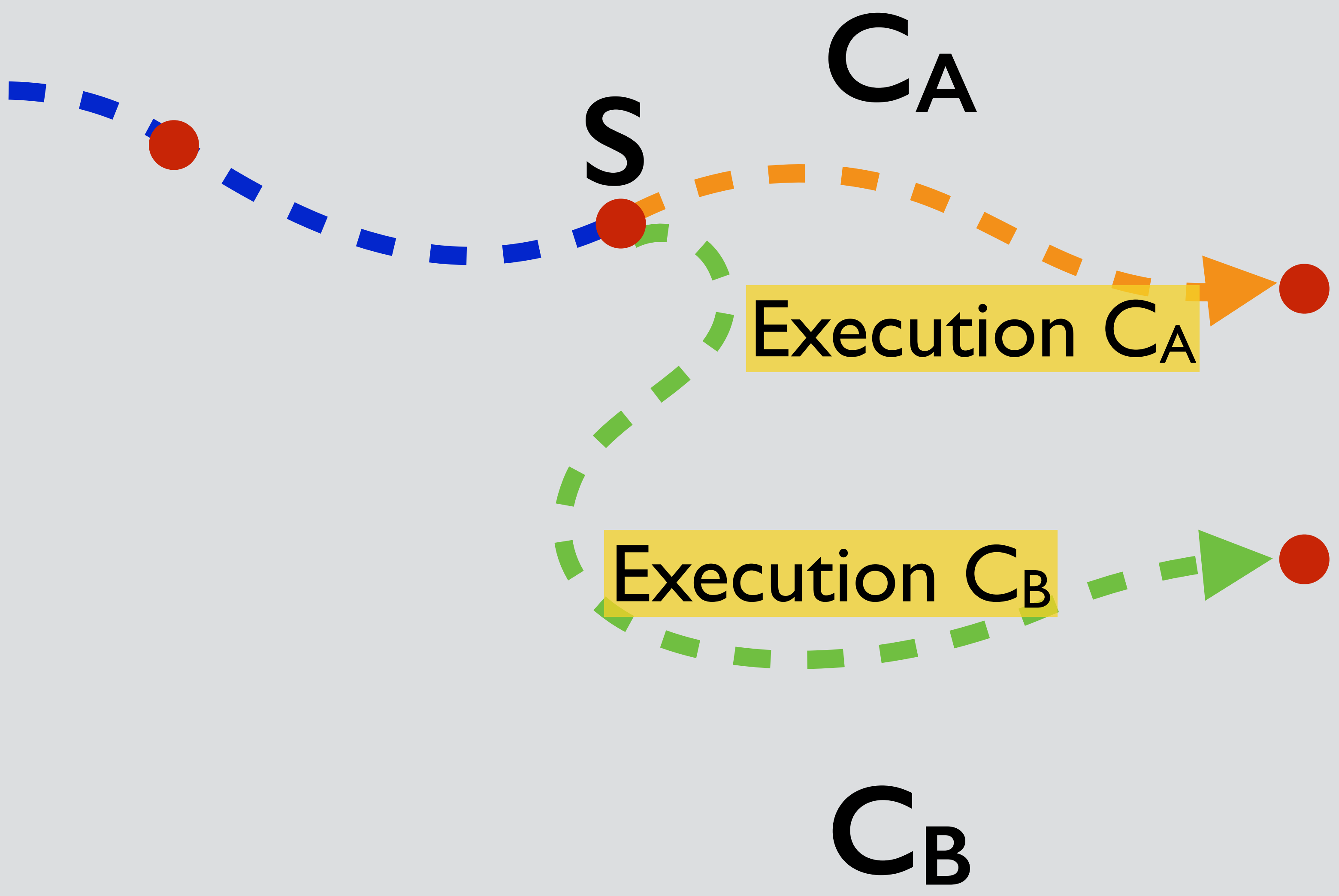
Observational Equivalence



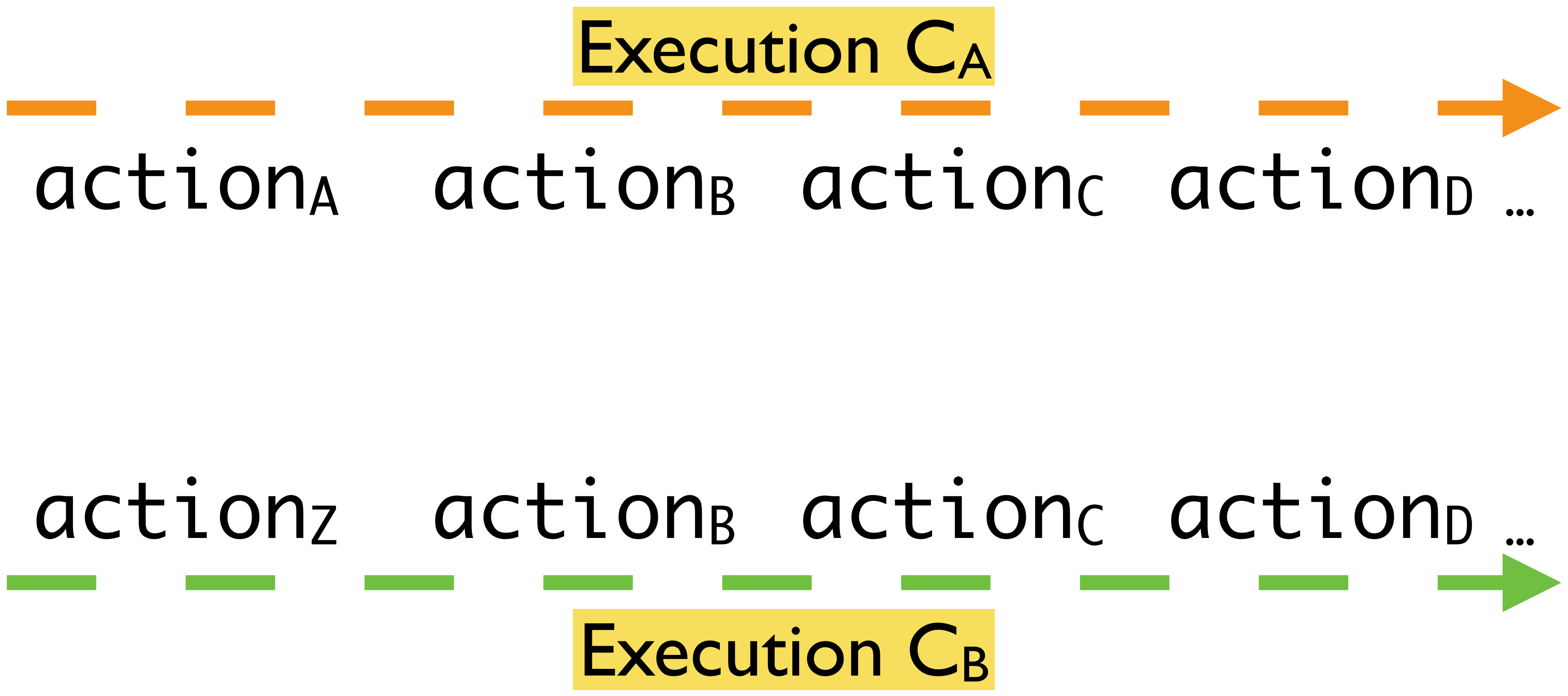
Execution Diversity



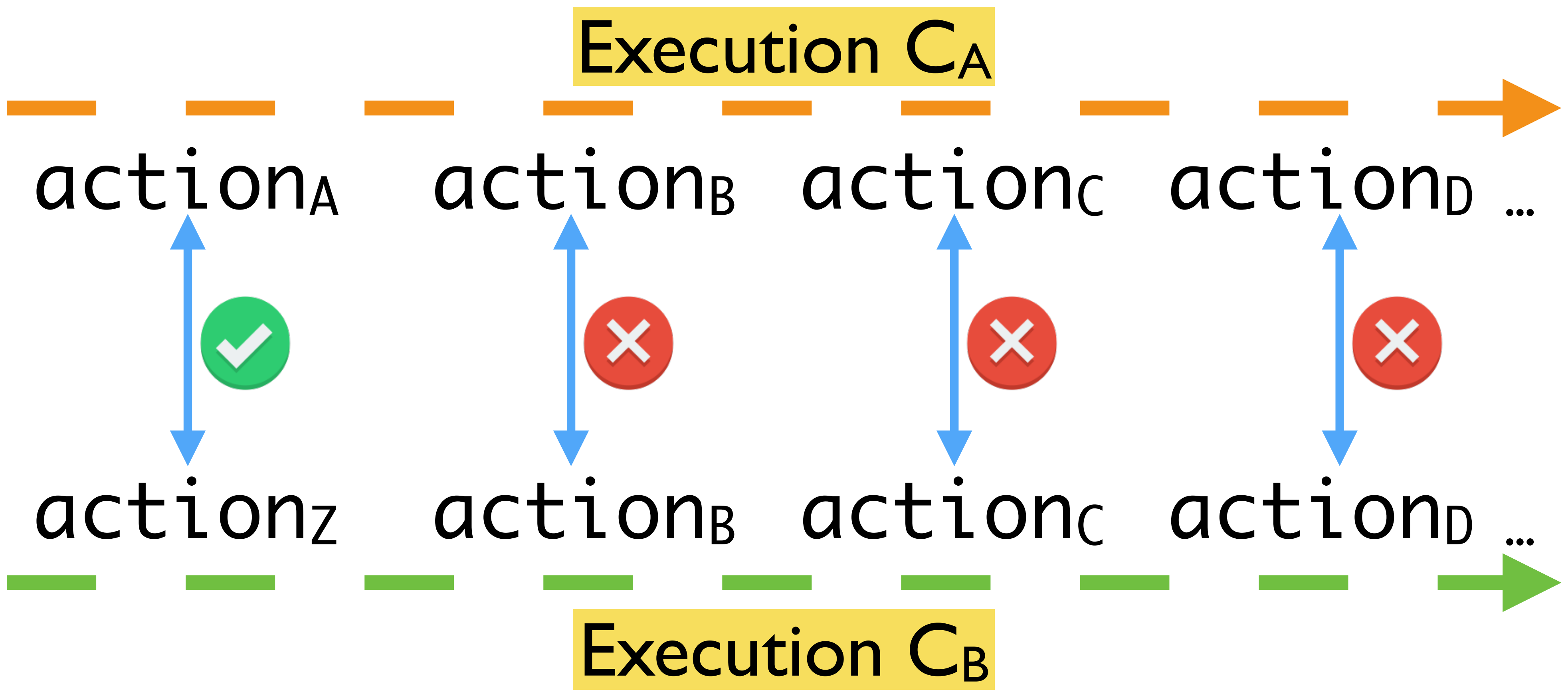
Execution Diversity



Execution Diversity


Execution C_A
$action_A$ $action_B$ $action_C$ $action_D$ …
$action_Z$ $action_B$ $action_C$ $action_D$ …
Execution C_B

Execution Diversity


Execution C_A
action$_A$ action$_B$ action$_C$ action$_D$ …
✓ ✗ ✗ ✗
action$_Z$ action$_B$ action$_C$ action$_D$ …
Execution C_B

Software Redundancy

Observational Equivalence $\wedge$ **Execution Diversity**

Software Redundancy

Observational Equivalence

Undecidable

$\wedge$

Execution Diversity

Software Redundancy

Observational Equivalence

Undecidable

$\wedge$

Execution Diversity

Binary measure ⟶ Richer measure

A Practical Measure of Redundancy

A Practical Measure of Redundancy

$$R = f\left(\text{Degree of Equivalence}, \text{Degree of Diversity}\right)$$

A Practical Measure of Redundancy

$$R_S = e_S(C_A, C_B) \times d_S(C_A, C_B)$$

$$e_S, d_S \in [0, 1]$$

A Practical Measure of Redundancy

$$R_S = 0 \times d_S(C_A, C_B)$$

$$e_S, d_S \in [0, 1]$$

A Practical Measure of Redundancy

$$R_S = e_S(C_A, C_B) \times \qquad 0$$

$$e_S, d_S \in [0, 1]$$

A Practical Measure of Redundancy

$$R_S = 1 \times 1$$

$$e_S, d_S \in [0, 1]$$

A Practical Measure of Redundancy

$$R_S = e_S(C_A,C_B) \times d_S(C_A,C_B)$$

$$e_S, d_S \in [0,1]$$

A Practical Measure of Redundancy

$$R_S = e_S(C_A, C_B) \times d_S(C_A, C_B)$$

$$e_S, d_S \in [0, 1]$$

$$\boxed{R_{C_A,C_B} = \text{AGGREGATE}(R_S)}$$

A Practical Measure of Redundancy

Sample the state space

$$R_{\boxed{S}} = e_S(C_A, C_B) \times d_S(C_A, C_B)$$

$$e_S, d_S \in [0,1]$$

$$R_{C_A,C_B} = \text{AGGREGATE}(R_S)$$

A Practical Measure of Redundancy

Observational equivalence measure

$$R_S = \boxed{e}_S(C_A, C_B) \times d_S(C_A, C_B)$$

$$e_S, d_S \in [0, 1]$$

$$R_{C_A, C_B} = \text{AGGREGATE}(R_S)$$

A Practical Measure of Redundancy

Difference between executions

$$R_S = e_S(C_A, C_B) \times d_S(C_A, C_B)$$

$$e_S, d_S \in [0, 1]$$

$$R_{C_A, C_B} = \text{AGGREGATE}(R_S)$$

A Practical Measure of Redundancy

$$R_S = e_S(C_A, C_B) \times d_S(C_A, C_B)$$

$$e_S, d_S \in [0, 1]$$

$$R_{C_A, C_B} = \underbrace{\boxed{\text{AGGREGATE}}}_{\text{Aggregate the redundancy measure}}(R_S)$$

Sampling the State Space

Sampling the State Space

```java
ArrayListMultimap var0 = ArrayListMultimap.create();
var0.clear();
ArrayListMultimap var3 = ArrayListMultimap.create();
var3.clear();
boolean var5 = var3.isEmpty();
ArrayListMultimap var6 = ArrayListMultimap.create();
var6.clear();
boolean var8 = var6.isEmpty();
boolean var9 = var3.putAll((Multimap) var6);
java.util.List var11 = var3.removeAll("hi!");
boolean var12 = var0.putAll((short) (-1), (java.lang.Iterable) var11);
var0.clear();
ArrayListMultimap var14 = ArrayListMultimap.create((Multimap) var0);
ArrayListMultimap var17 = ArrayListMultimap.create(1, 10);
var17.clear();
ArrayListMultimap var19 = ArrayListMultimap.create();
var19.clear();
ArrayListMultimap var21 = ArrayListMultimap.create((Multimap) var19);
boolean var22 = var14.put(var17, var19);
```

Sampling the State Space

```
ArrayListMultimap var0 = ArrayListMultimap.create();
var0.clear();
ArrayListMultimap var3 = ArrayListMultimap.create();
var3.clear();
boolean var5 = var3.isEmpty();
ArrayListMultimap var6 = ArrayListMultimap.create();
var6.clear();
boolean var8 = var6.isEmpty();
boolean var9 = var3.putAll((Multimap) var6);
java.util.List var11 = var3.removeAll("hi!");
boolean var12 = var0.putAll((short) (-1), (java.lang.Iterable) var11);
var0.clear();
ArrayListMultimap var14 = ArrayListMultimap.create((Multimap) var0);
ArrayListMultimap var17 = ArrayListMultimap.create(1, 10);
var17.clear();
ArrayListMultimap var19 = ArrayListMultimap.create();
var19.clear();
ArrayListMultimap var21 = ArrayListMultimap.create((Multimap) var19);
boolean var22 = var14.put(var17, var19); // Code fragment A
```

Observational Equivalence Measure

```
ArrayListMultimap var0 = ArrayListMultimap.create();
var0.clear();
ArrayListMultimap var3 = ArrayListMultimap.create();
var3.clear();
boolean var5 = var3.isEmpty();
ArrayListMultimap var6 = ArrayListMultimap.create();
var6.clear();
boolean var8 = var6.isEmpty();
boolean var9 = var3.putAll((Multimap) var6);
java.util.List var11 = var3.removeAll("hi!");
boolean var12 = var0.putAll((short) (-1), (java.lang.Iterable) var11);
var0.clear();
ArrayListMultimap var14 = ArrayListMultimap.create((Multimap) var0);
ArrayListMultimap var17 = ArrayListMultimap.create(1, 10);
var17.clear();
ArrayListMultimap var19 = ArrayListMultimap.create();
var19.clear();
ArrayListMultimap var21 = ArrayListMultimap.create((Multimap) var19);
boolean var22 = var14.put(var17, var19); // Code fragment A
```

Observational Equivalence Measure

```
boolean var22 = var14.put(var17, var19); // Code fragment A
```

Observational Equivalence Measure

```
          // Code fragment A
boolean var22 = var14.put(var17, var19);

                    // linkage: boolean var22, ArrayListMultimap var14
```

Observational Equivalence Measure

```
// Code fragment A
boolean var22 = var14.put(var17, var19);
```

```
// Code fragment B
List list = new List(); list.add(var19);
boolean var22 = var14.putAll(var17, list);
```

```
// linkage: boolean var22, ArrayListMultimap var14
```

Observational Equivalence Measure

```
// Code fragment A
boolean var22 = var14.put(var17, var19);
```

```
// Code fragment B
List list = new List(); list.add(var19);
boolean var22 = var14.putAll(var17, list);
```

```
// linkage: boolean var22, ArrayListMultimap var14

// generated probing code:
System.out.println(var22);
boolean x0 = var14.isEmpty();
System.out.println(x0);
var14.clear();
java.util.Map x1 = var14.asMap();
int x2 = var14.size();
System.out.println(x2);
int x3 = x1.size();
System.out.println(x3);
java.util.Set x4 = x1.entrySet();
java.util.Iterator x5 = x4.iterator();
boolean x6 = x4.isEmpty();
System.out.println(x6);
try {
  x5.remove();
} catch (java.lang.IllegalStateException e) {
  System.out.println(e);
}
// ... probing code continues
```

Observational Equivalence Measure

```
// Code fragment A
boolean var22 = var14.put(var17, var19);
```

```
// Code fragment B
List list = new List(); list.add(var19);
boolean var22 = var14.putAll(var17, list);
```

```
// linkage: boolean var22, ArrayListMultimap var14

// generated probing code:
System.out.println(var22);
boolean x0 = var14.isEmpty();
System.out.println(x0);
var14.clear();
java.util.Map x1 = var14.asMap();
int x2 = var14.size();
System.out.println(x2);
int x3 = x1.size();
System.out.println(x3);
java.util.Set x4 = x1.entrySet();
java.util.Iterator x5 = x4.iterator();
boolean x6 = x4.isEmpty();
System.out.println(x6);
try {
  x5.remove();
} catch (java.lang.IllegalStateException e) {
  System.out.println(e);
}
// ... probing code continues
```

```
true
false
1
1
false
…
```

```
true
false
1
1
false
…
```

✓ ✗

Observational Equivalence Measure

$$e_S(C_A,C_B) = \frac{\text{successful}}{\text{total}}$$

CP1	✓
CP2	✓
CP3	✓
CP4	✓
CP5	✓
CP6	✓
CP7	✓
CP8	✓
CP9	✓
CP10	✓

$$e_S(C_A,C_B) = 1.0$$

CP1	✓
CP2	✗
CP3	✓
CP4	✗
CP5	✓
CP6	✗
CP7	✓
CP8	✓
CP9	✓
CP10	✓

$$e_S(C_A,C_B) = 0.7$$

Difference Between Executions

```
ArrayListMultimap var0 = ArrayListMultimap.create();
var0.clear();
ArrayListMultimap var3 = ArrayListMultimap.create();
var3.clear();
boolean var5 = var3.isEmpty();
ArrayListMultimap var6 = ArrayListMultimap.create();
var6.clear();
boolean var8 = var6.isEmpty();
boolean var9 = var3.putAll((Multimap) var6);
java.util.List var11 = var3.removeAll("hi!");
boolean var12 = var0.putAll((short) (-1), (java.lang.Iterable) var11);
var0.clear();
ArrayListMultimap var14 = ArrayListMultimap.create((Multimap) var0);
ArrayListMultimap var17 = ArrayListMultimap.create(1, 10);
var17.clear();
ArrayListMultimap var19 = ArrayListMultimap.create();
var19.clear();
ArrayListMultimap var21 = ArrayListMultimap.create((Multimap) var19);
boolean var22 = var14.put(var17, var19);
```

Difference Between Executions

```
boolean var22 = var14.put(var17, var19);
```

Difference Between Executions

```
boolean var22 = var14.put(var17, var19); // Trace code fragment A
```

Projections

Difference Between Executions

```
boolean var22 = var14.put(var17, var19); // Trace code fragment A
```

Code Projections

Statement

```
ArrayListMultimap.put(LObject;LObject;)Z@66
AbstractListMultimap.put(LObject;LObject;)Z@95
AbstractMultimap.put(LObject;LObject;)Z@200
```

Statement, Depth

```
3:ArrayListMultimap.put(LObject;LObject;)Z@66
4:AbstractListMultimap.put(LObject;LObject;)Z@95
5:AbstractMultimap.put(LObject;LObject;)Z@200
```

Difference Between Executions

```
boolean var22 = var14.put(var17, var19); // Trace code fragment A
```

Data Projections

Type, Value

```
Ljava/util/Map;→{}
Ljava/util/Set;→[]
Ljava/util/HashMap;→{}
I→1
I←1
```

Class, Field, Value

```
AbstractMultimap.map→{}
HashMap.entrySet→[]
HashMap$EntrySet.this$0→{}
HashMap$HashIterator.modCount→1
HashMap$HashIterator.expectedModCount←1
```

Difference Between Executions

Code projection C_A

```
ArrayListMultimap.put(LObject;LObject;)Z@66
AbstractListMultimap.put(LObject;LObject;)Z@95
AbstractMultimap.put(LObject;LObject;)Z@200
ArrayListMultimap.hashCode()I@66
AbstractMultimap.hashCode()I@1380
AbstractMap.hashCode()I@491
AbstractMap.hashCode()I@492
HashMap.entrySet()LSet;@953
HashMap.entrySet0()LSet;@957
HashMap.entrySet0()LSet;@958
```

Code projection C_B

```
ArrayListMultimap.putAll(LObject;LIterable;)Z@66
AbstractMultimap.putAll(LObject;LIterable;)Z@248
ArrayList.iterator()LIterator;@774
ArrayList$Itr.<init>(LArrayList;LArrayList$1;)V@780
ArrayList$Itr.<init>(LArrayList;)V@780
ArrayList$Itr.<init>(LArrayList;)V@782
ArrayList$Itr.<init>(LArrayList;)V@783
ArrayList$Itr.hasNext()Z@786
ArrayList.access$100(LArrayList;)I@102
AbstractMultimap.putAll(LObject;LIterable;)Z@252
AbstractMultimap.getOrCreateCollection(LObject;)LCollection;@219
HashMap.get(LObject;)LObject;@315
HashMap.get(LObject;)LObject;@317
HashMap.hash(I)I@268
HashMap.hash(I)I@269
HashMap.get(LObject;)LObject;@318
HashMap.indexFor(II)I@276
```

Difference Between Executions

Code projection C_A

```
ArrayListMultimap.put(LObject;LObject;)Z@66
AbstractListMultimap.put(LObject;LObject;)Z@95
AbstractMultimap.put(LObject;LObject;)Z@200
ArrayListMultimap.hashCode()I@66
AbstractMultimap.hashCode()I@1380
AbstractMap.hashCode()I@491
AbstractMap.hashCode()I@492
HashMap.entrySet()LSet;@953
HashMap.entrySet0()LSet;@957
HashMap.entrySet0()LSet;@958
```

Code projection C_B

```
ArrayListMultimap.putAll(LObject;LIterable;)Z@66
AbstractMultimap.putAll(LObject;LIterable;)Z@248
ArrayList.iterator()LIterator;@774
ArrayList$Itr.<init>(LArrayList;LArrayList$1;)V@780
ArrayList$Itr.<init>(LArrayList;)V@780
ArrayList$Itr.<init>(LArrayList;)V@782
ArrayList$Itr.<init>(LArrayList;)V@783
ArrayList$Itr.hasNext()Z@786
ArrayList.access$100(LArrayList;)I@102
AbstractMultimap.putAll(LObject;LIterable;)Z@252
AbstractMultimap.getOrCreateCollection(LObject;)LCollection;@219
HashMap.get(LObject;)LObject;@315
HashMap.get(LObject;)LObject;@317
HashMap.hash(I)I@268
HashMap.hash(I)I@269
HashMap.get(LObject;)LObject;@318
HashMap.indexFor(II)I@276
```

$$d_S(C_A, C_B) = 1\text{-}\textsc{similarity}(P_{S,A}, P_{S,B})$$

A Practical Measure of Redundancy

A Practical Measure of Redundancy

S0

S1

S2

S3

S4

S5

S6

S7

S8

S9

S10

A Practical Measure of Redundancy

	e_s
S0	1.0
S1	1.0
S2	1.0
S3	1.0
S4	1.0
S5	1.0
S6	1.0
S7	1.0
S8	0.9
S9	1.0
S10	1.0

A Practical Measure of Redundancy

	e_s	d_s
S0	1.0	0.32989693
S1	1.0	0.51781228
S2	1.0	0.32989693
S3	1.0	0.51781228
S4	1.0	0.51781228
S5	1.0	0.32989693
S6	1.0	0.32989693
S7	1.0	0.51781228
S8	0.9	0.61892315
S9	1.0	0.32989693
S10	1.0	0.32989693

A Practical Measure of Redundancy

	e_s	d_s	R_s
S0	1.0	0.32989693	0.32989693
S1	1.0	0.51781228	0.51781228
S2	1.0	0.32989693	0.32989693
S3	1.0	0.51781228	0.51781228
S4	1.0	0.51781228	0.51781228
S5	1.0	0.32989693	0.32989693
S6	1.0	0.32989693	0.32989693
S7	1.0	0.51781228	0.51781228
S8	0.9	0.61892315	0.55703083
S9	1.0	0.32989693	0.32989693
S10	1.0	0.32989693	0.32989693

A Practical Measure of Redundancy

	e_s	d_s	R_s
S0	1.0	0.32989693	0.32989693
S1	1.0	0.51781228	0.51781228
S2	1.0	0.32989693	0.32989693
S3	1.0	0.51781228	0.51781228
S4	1.0	0.51781228	0.51781228
S5	1.0	0.32989693	0.32989693
S6	1.0	0.32989693	0.32989693
S7	1.0	0.51781228	0.51781228
S8	0.9	0.61892315	0.55703083
S9	1.0	0.32989693	0.32989693
S10	1.0	0.32989693	0.32989693

$$R = \mathrm{AVG}(R_s) = 0.418 \pm 0.10$$

Evaluation

“ In theory, there is no difference between theory and practice.
But, in practice, there is.

- van de Snepscheut

Evaluation

Is the proposed measure **consistent**?

Are the measurements **significant** and **useful**?

Evaluation

Is the proposed measure **consistent**?

Consistency: Stability

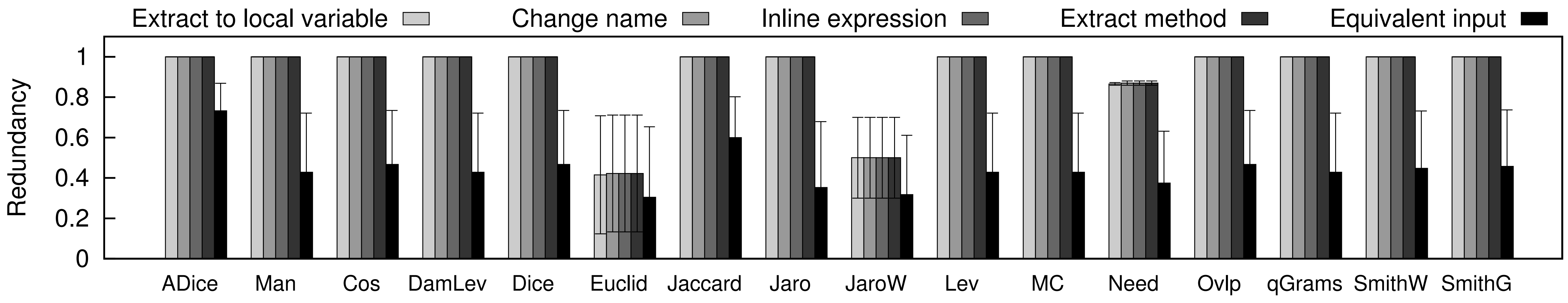
Consistency: Stability

Ground Truth

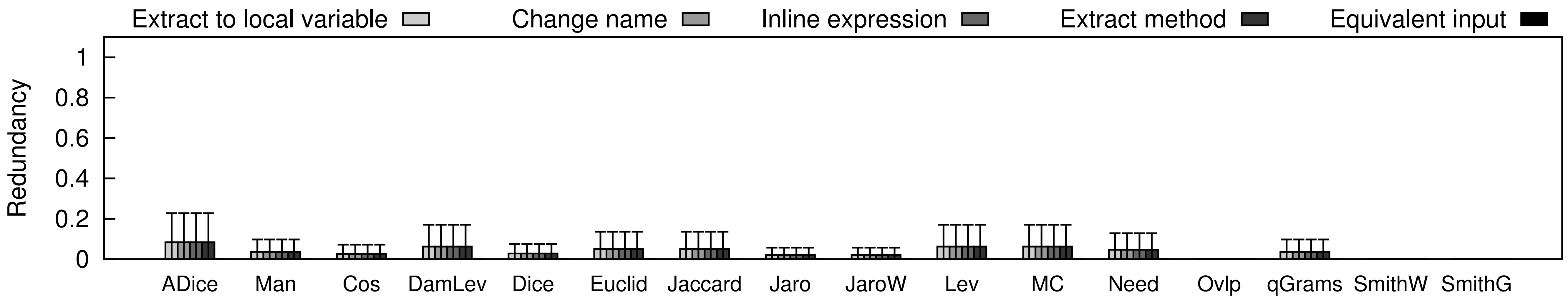
Algorithm	**# Impl.**
Binary search	4
Linear search	4
Bubble sort	7
Insertion sort	3
Merge sort	4
Quicksort	3

Consistency: Stability

Code Projections



Data Projections



Evaluation

Are the measurements **significant** and **useful**?

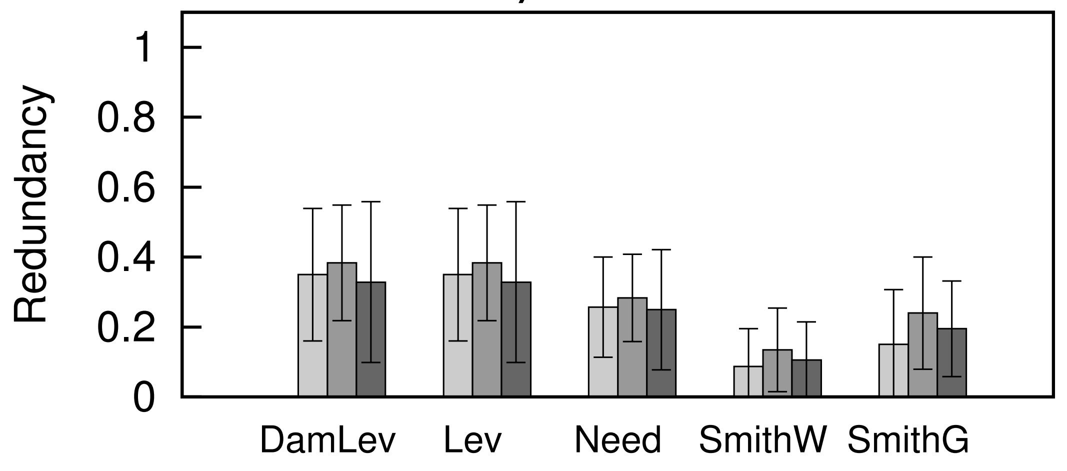
Low-level vs High-level

Code Redundancy vs Algorithmic Redundancy

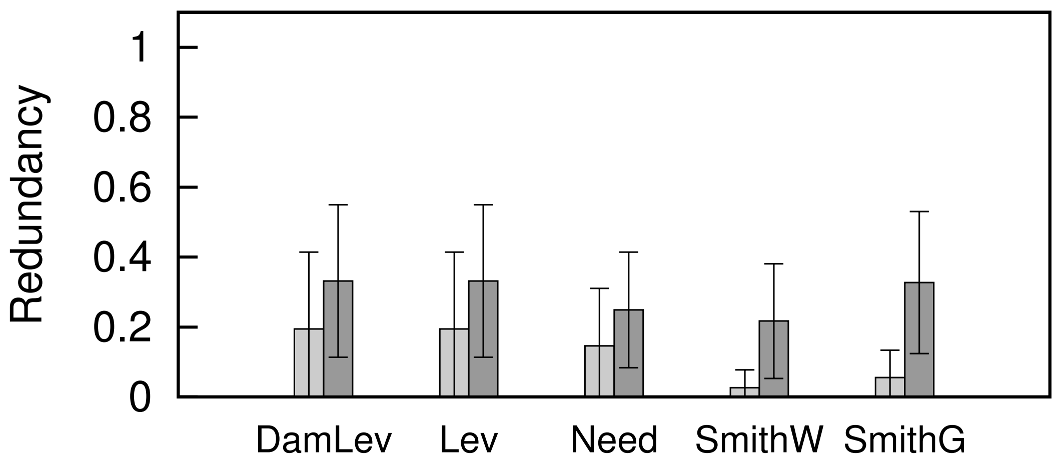
Low-level vs High-level

Code Redundancy vs Algorithmic Redundancy

Binary search

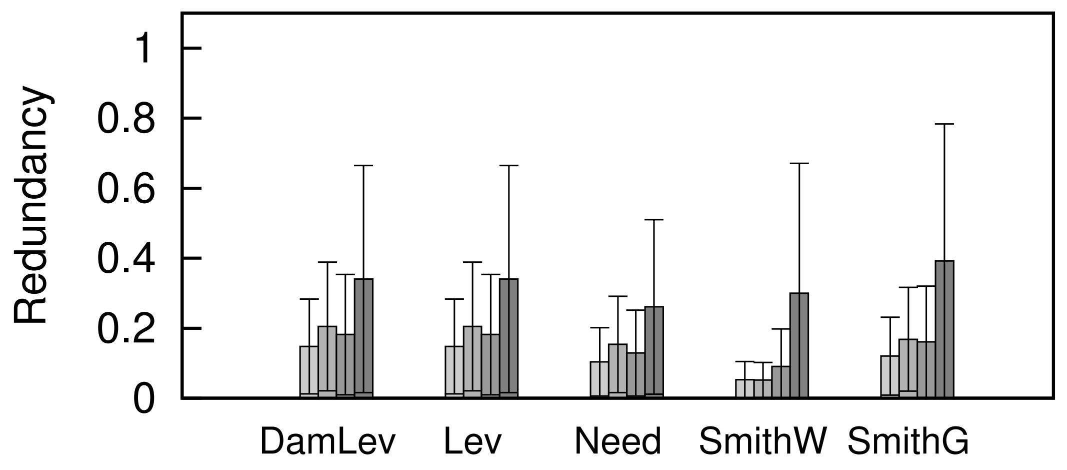


Linear search

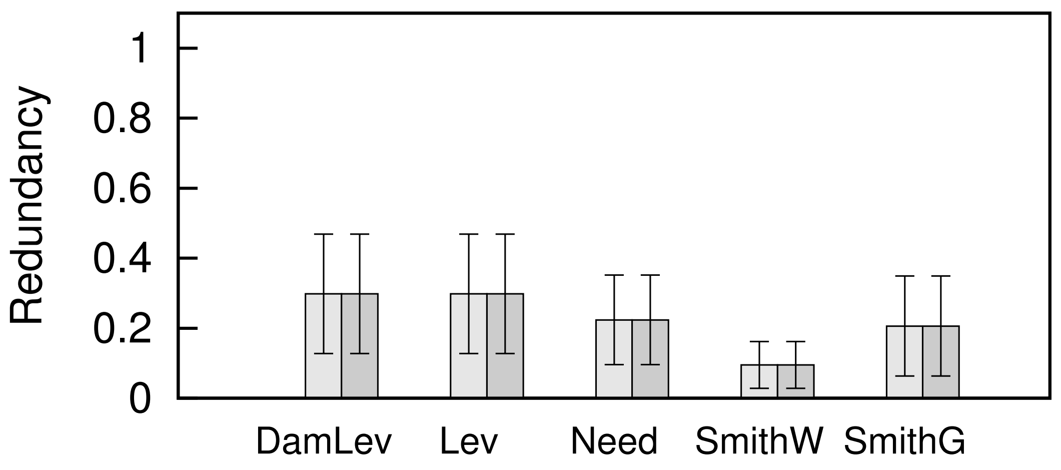


Same algorithm, different implementation

Bubble sort



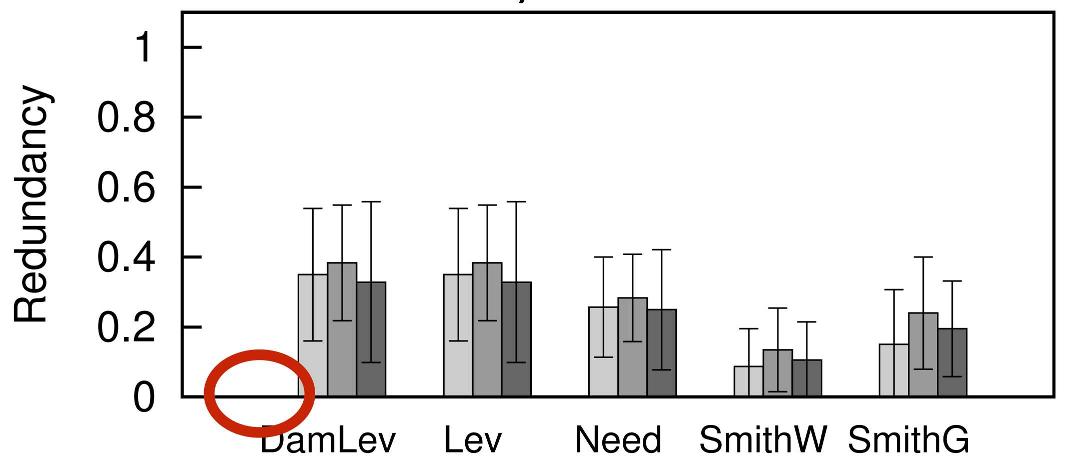
Insertion sort



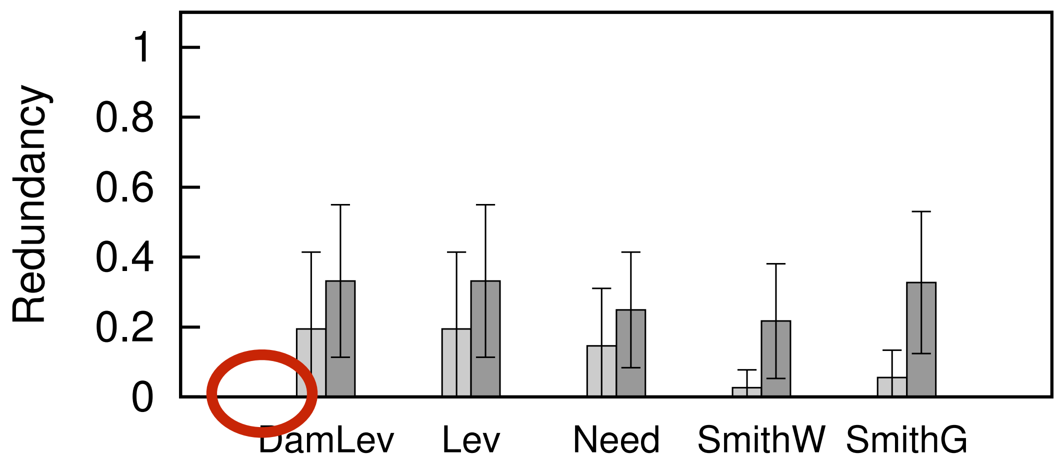
Low-level vs High-level

Code Redundancy vs Algorithmic Redundancy

Binary search

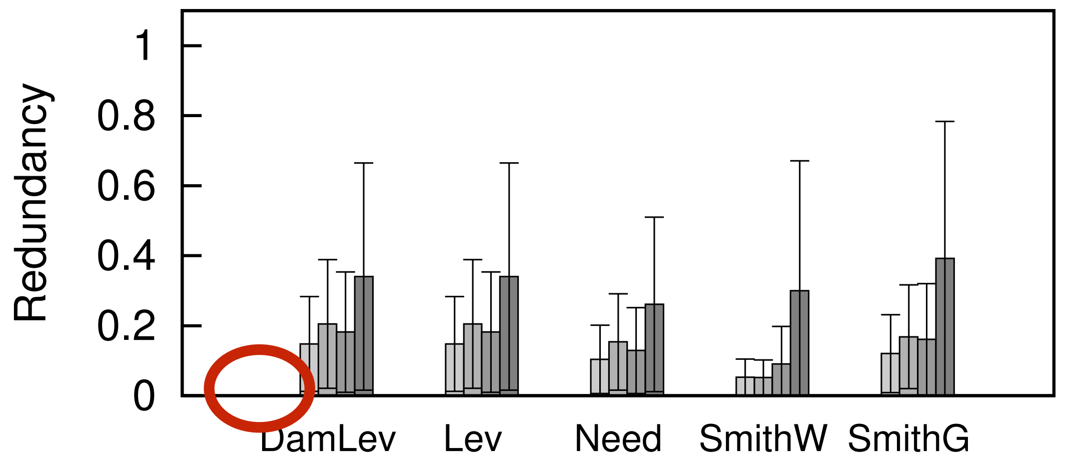


Linear search

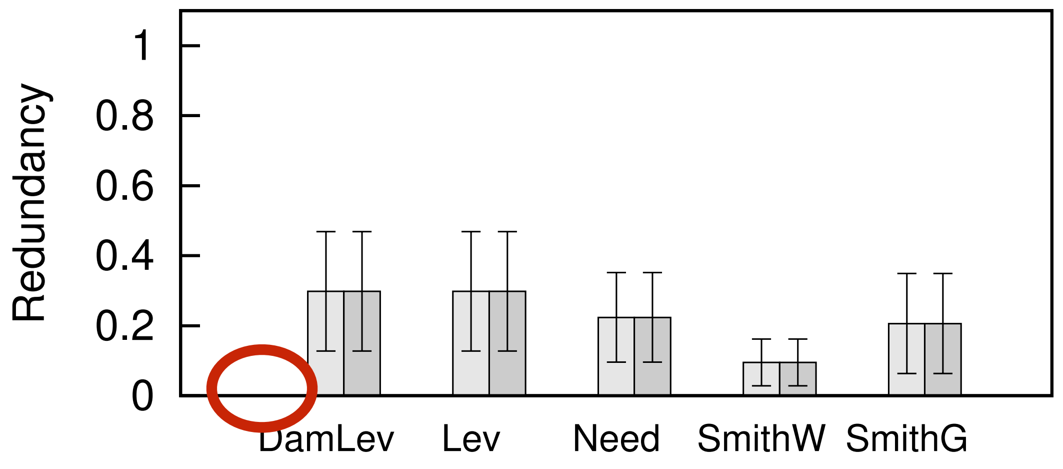


Same algorithm, different implementation

Bubble sort



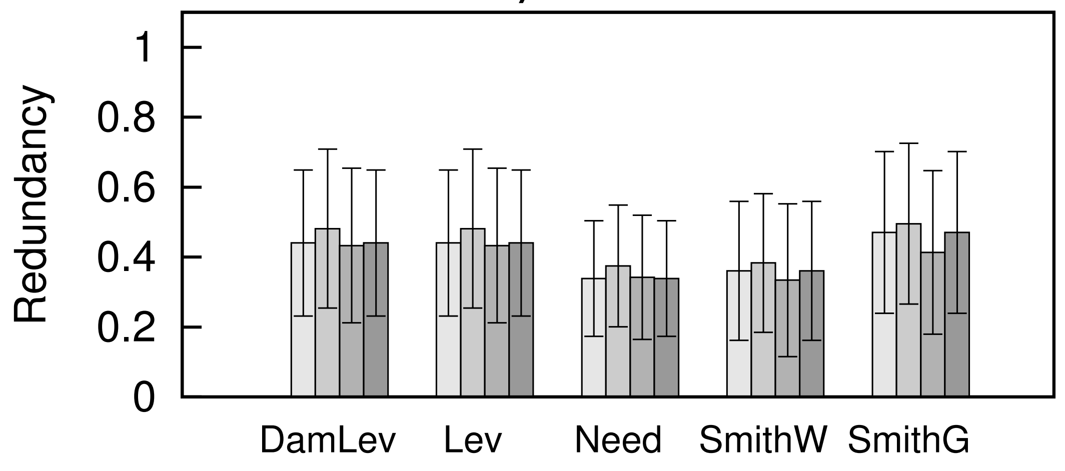
Insertion sort



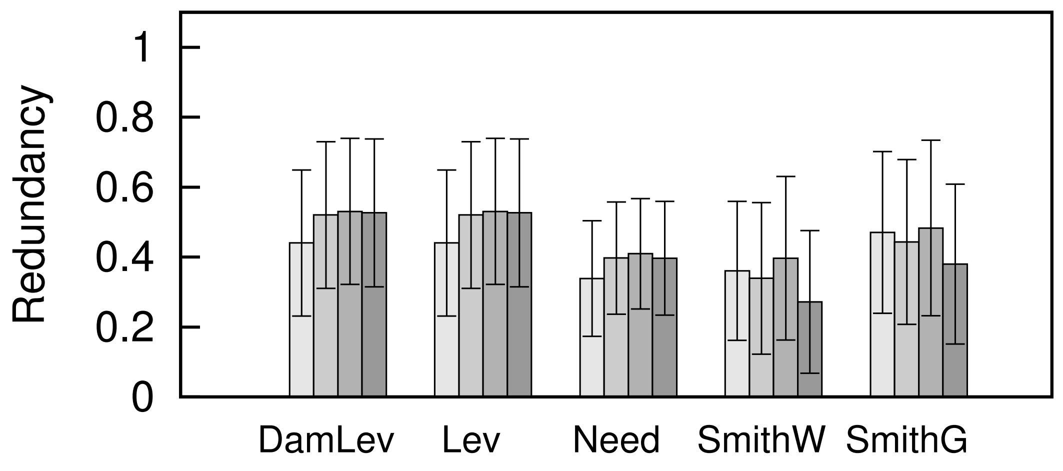
Low-level vs High-level

Code Redundancy vs Algorithmic Redundancy

Binary search

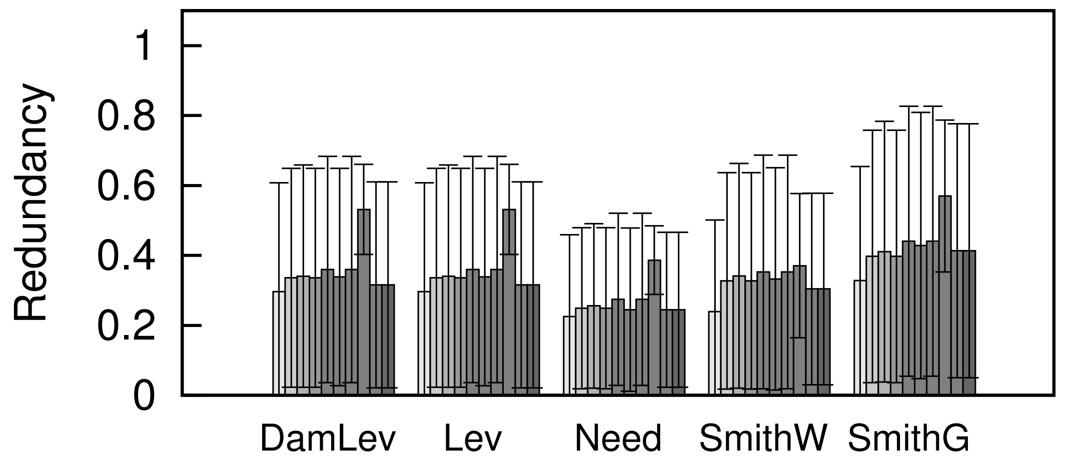


Linear search

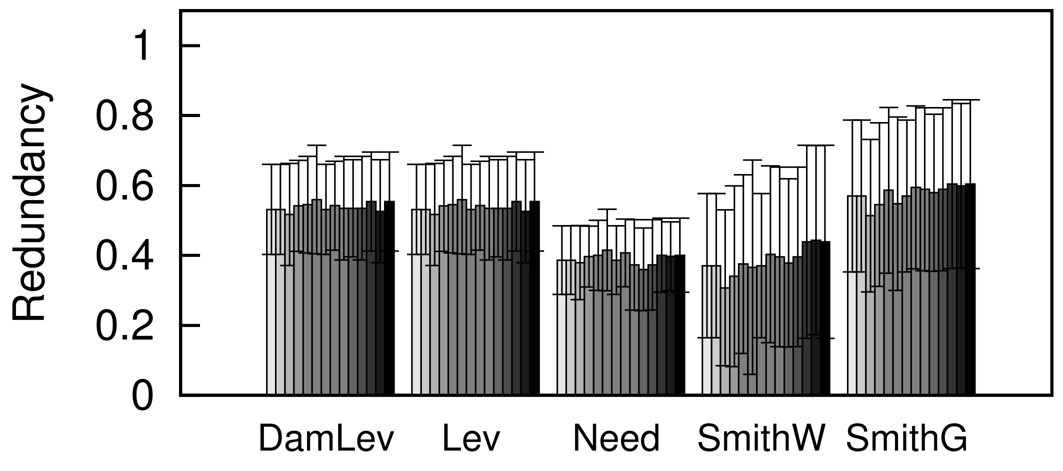


Different algorithm

Bubble sort

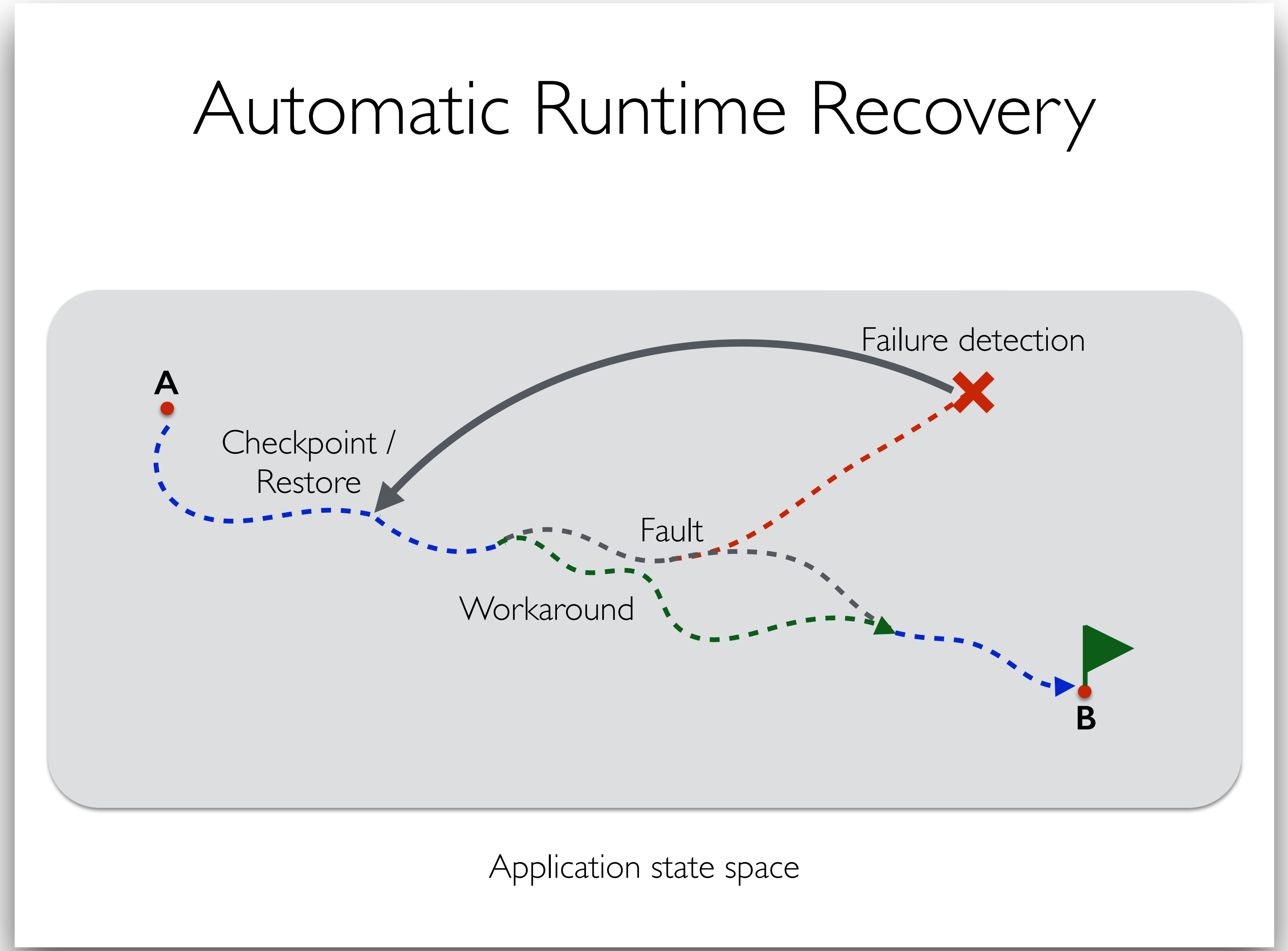


Insertion sort



Predictive Ability

Predictive Ability

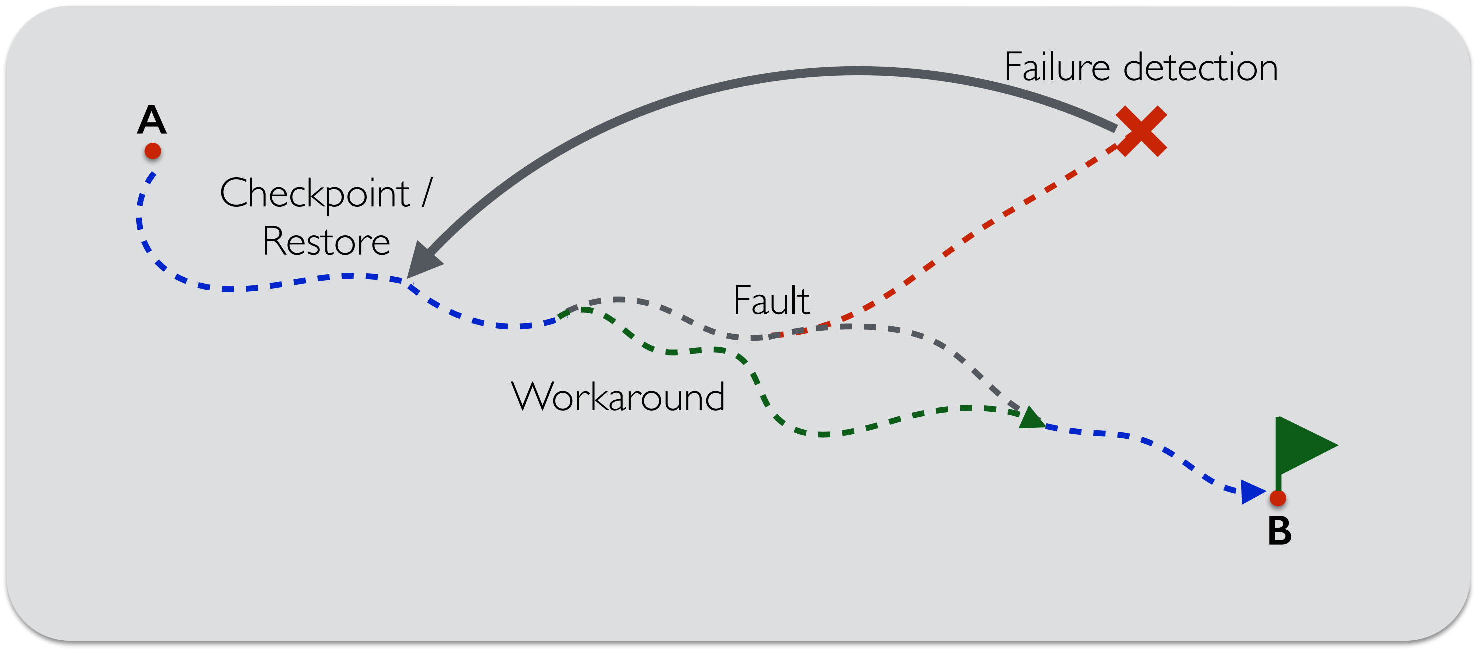


Automatic Runtime Recovery

Application state space

Predictive Ability

Automatic Runtime Recovery



Application state space

Does redundancy correlate with success?

Predictive Ability

System
Caliper
Carrot2

Predictive Ability

System	Method (C_A)
Caliper	Iterators.forArray(a)
	LinkedHashMultiset.retainAll(Collection c)
	ArrayListMultimap.putAll(Object k,Collection c)
	LinkedHashMultimap.putAll(Object k, Collection c)
	LinkedHashMultimap.create()
	LinkedHashMultimap.create(int,int)
	LinkedHashMultimap.isEmpty()
Carrot2	ImmutableMultiset.of(Object..c)
	ImmutableMultiset.of(Object..c)
	ArrayListMultimap.putAll(Object k,Collection c)
	ImmutableMultiset.of(Object o)
	Lists.newArrayList()
	Lists.newArrayList()
	Lists.newArrayListWithCapacity(int c)
	Lists.newArrayListWithCapacity(int c)
	Maps.newHashMap()
	Maps.newHashMap()
	Maps.newHashMap()

Predictive Ability

System	**Method** (C_A)	**Workaround** (C_B)
Caliper	Iterators.forArray(a)	Arrays.asList(a).iterator()
	LinkedHashMultiset.retainAll(Collection c)	foreach(o in map) if(o not in c) map.remove(o);
	ArrayListMultimap.putAll(Object k,Collection c)	foreach(o in c) put(k,o);
	LinkedHashMultimap.putAll(Object k, Collection c)	foreach(o in c) put(k,o);
	LinkedHashMultimap.create()	create(100,100)
	LinkedHashMultimap.create(int,int)	create()
	LinkedHashMultimap.isEmpty()	size() == 0 ? true : false
Carrot2	ImmutableMultiset.of(Object..c)	foreach(o in c) builder().setCount(o,count(o in c))
	ImmutableMultiset.of(Object..c)	builder().add(..c).build()
	ArrayListMultimap.putAll(Object k,Collection c)	foreach(o in c) put(k,o);
	ImmutableMultiset.of(Object o)	builder().add(o).build()
	Lists.newArrayList()	new ArrayList()
	Lists.newArrayList()	new ArrayList(10)
	Lists.newArrayListWithCapacity(int c)	new ArrayList()
	Lists.newArrayListWithCapacity(int c)	new ArrayList(c)
	Maps.newHashMap()	Maps.newHashMapWithExpectedSize(16)
	Maps.newHashMap()	new HashMap()
	Maps.newHashMap()	new HashMap(16)

Predictive Ability

System	Method (C_A)	Workaround (C_B)	Success ratio
Caliper	Iterators.forArray(a)	Arrays.asList(a).iterator()	3/3 (100%)
	LinkedHashMultiset.retainAll(Collection c)	foreach(o in map) if(o not in c) map.remove(o);	1/2 (50%)
	ArrayListMultimap.putAll(Object k,Collection c)	foreach(o in c) put(k,o);	8/41 (20%)
	LinkedHashMultimap.putAll(Object k, Collection c)	foreach(o in c) put(k,o);	0/1 (0%)
	LinkedHashMultimap.create()	create(100,100)	0/207 (0%)
	LinkedHashMultimap.create(int,int)	create()	0/202 (0%)
	LinkedHashMultimap.isEmpty()	size() == 0 ? true : false	0/34 (0%)
Carrot2	ImmutableMultiset.of(Object..c)	foreach(o in c) builder().setCount(o,count(o in c))	13/22 (59%)
	ImmutableMultiset.of(Object..c)	builder().add(..c).build()	7/19 (37%)
	ArrayListMultimap.putAll(Object k,Collection c)	foreach(o in c) put(k,o);	1/13 (8%)
	ImmutableMultiset.of(Object o)	builder().add(o).build()	0/1 (0%)
	Lists.newArrayList()	new ArrayList()	0/24 (0%)
	Lists.newArrayList()	new ArrayList(10)	0/24 (0%)
	Lists.newArrayListWithCapacity(int c)	new ArrayList()	0/20 (0%)
	Lists.newArrayListWithCapacity(int c)	new ArrayList(c)	0/20 (0%)
	Maps.newHashMap()	Maps.newHashMapWithExpectedSize(16)	0/54 (0%)
	Maps.newHashMap()	new HashMap()	0/54 (0%)
	Maps.newHashMap()	new HashMap(16)	0/54 (0%)

Predictive Ability

System	Method (C_A)	Workaround (C_B)	Success ratio	Redundancy
Caliper	Iterators.forArray(a)	Arrays.asList(a).iterator()	3/3 (100%)	1.00 ± 0.00
	LinkedHashMultiset.retainAll(Collection c)	foreach(o in map) if(o not in c) map.remove(o);	1/2 (50%)	0.61 ±0.01
	ArrayListMultimap.putAll(Object k,Collection c)	foreach(o in c) put(k,o);	8/41 (20%)	0.37 ±0.32
	LinkedHashMultimap.putAll(Object k, Collection c)	foreach(o in c) put(k,o);	0/1 (0%)	0.00 ±0.00
	LinkedHashMultimap.create()	create(100,100)	0/207 (0%)	0.12 ±0.15
	LinkedHashMultimap.create(int,int)	create()	0/202 (0%)	0.12 ±0.15
	LinkedHashMultimap.isEmpty()	size() == 0 ? true : false	0/34 (0%)	0.00 ±0.00
Carrot2	ImmutableMultiset.of(Object..c)	foreach(o in c) builder().setCount(o,count(o in c))	13/22 (59%)	0.56 ±0.07
	ImmutableMultiset.of(Object..c)	builder().add(..c).build()	7/19 (37%)	0.24 ±0.12
	ArrayListMultimap.putAll(Object k,Collection c)	foreach(o in c) put(k,o);	1/13 (8%)	0.37 ±0.32
	ImmutableMultiset.of(Object o)	builder().add(o).build()	0/1 (0%)	0.32 ±0.14
	Lists.newArrayList()	new ArrayList()	0/24 (0%)	0.00 ±0.00
	Lists.newArrayList()	new ArrayList(10)	0/24 (0%)	0.00 ±0.00
	Lists.newArrayListWithCapacity(int c)	new ArrayList()	0/20 (0%)	0.00 ±0.00
	Lists.newArrayListWithCapacity(int c)	new ArrayList(c)	0/20 (0%)	0.00 ±0.00
	Maps.newHashMap()	Maps.newHashMapWithExpectedSize(16)	0/54 (0%)	0.00 ±0.00
	Maps.newHashMap()	new HashMap()	0/54 (0%)	0.00 ±0.00
	Maps.newHashMap()	new HashMap(16)	0/54 (0%)	0.00 ±0.00

Predictive Ability

System	Method (C_A)	Workaround (C_B)	Success ratio	Redundancy
Caliper	Iterators.forArray(a)	Arrays.asList(a).iterator()	3/3 (100%)	1.00 ± 0.00
	LinkedHashMultiset.retainAll(Collection c)	foreach(o in map) if(o not in c) map.remove(o);	1/2 (50%)	0.61 ±0.01
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	LinkedHashMultimap.putAll(Object k, Collection c)	foreach(o in c) put(k,o);	0/1 (0%)	0.00 ±0.00
	LinkedHashMultimap.create()	create(100,100)	0/207 (0%)	0.12 ±0.15
	LinkedHashMultimap.create(int,int)	create()	0/202 (0%)	0.12 ±0.15
	LinkedHashMultimap.isEmpty()	size() == 0 ? true : false	0/34 (0%)	0.00 ±0.00
Carrot2	ImmutableMultiset.of(Object..c)	foreach(o in c) builder().setCount(o,count(o in c))	13/22 (59%)	0.56 ±0.07
	ImmutableMultiset.of(Object..c)	builder().add(..c).build()	7/19 (37%)	0.24 ±0.12
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	ImmutableMultiset.of(Object o)	builder().add(o).build()	0/1 (0%)	0.32 ±0.14
	Lists.newArrayList()	new ArrayList()	0/24 (0%)	0.00 ±0.00
	Lists.newArrayList()	new ArrayList(10)	0/24 (0%)	0.00 ±0.00
	Lists.newArrayListWithCapacity(int c)	new ArrayList()	0/20 (0%)	0.00 ±0.00
	Lists.newArrayListWithCapacity(int c)	new ArrayList(c)	0/20 (0%)	0.00 ±0.00
	Maps.newHashMap()	Maps.newHashMapWithExpectedSize(16)	0/54 (0%)	0.00 ±0.00
	Maps.newHashMap()	new HashMap()	0/54 (0%)	0.00 ±0.00
	Maps.newHashMap()	new HashMap(16)	0/54 (0%)	0.00 ±0.00

Predictive Ability

System	Method (C_A)	Workaround (C_B)	Success ratio	Redundancy
Caliper	Iterators.forArray(a)	Arrays.asList(a).iterator()	3/3 (100%)	1.00 ± 0.00
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	ArrayListMultimap.putAll(Object k,Collection c)	foreach(o in c) put(k,o);	8/41 (20%)	0.37 ±0.32
	LinkedHashMultimap.putAll(Object k, Collection c)	foreach(o in c) put(k,o);	0/1 (0%)	0.00 ±0.00
	LinkedHashMultimap.create()	create(100,100)	0/207 (0%)	0.12 ±0.15
	LinkedHashMultimap.create(int,int)	create()	0/202 (0%)	0.12 ±0.15
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	Lists.newArrayList()	new ArrayList()	0/24 (0%)	0.00 ±0.00
	Lists.newArrayList()	new ArrayList(10)	0/24 (0%)	0.00 ±0.00
	Lists.newArrayListWithCapacity(int c)	new ArrayList()	0/20 (0%)	0.00 ±0.00
	Lists.newArrayListWithCapacity(int c)	new ArrayList(c)	0/20 (0%)	0.00 ±0.00
	Maps.newHashMap()	Maps.newHashMapWithExpectedSize(16)	0/54 (0%)	0.00 ±0.00
	Maps.newHashMap()	new HashMap()	0/54 (0%)	0.00 ±0.00
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Predictive Ability

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	LinkedHashMultimap.putAll(Object k, Collection c)	foreach(o in c) put(k,o);	0/1 (0%)	0.00 ±0.00
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	Lists.newArrayList()	new ArrayList()	0/24 (0%)	0.00 ±0.00
	Lists.newArrayList()	new ArrayList(10)	0/24 (0%)	0.00 ±0.00
	Lists.newArrayListWithCapacity(int c)	new ArrayList()	0/20 (0%)	0.00 ±0.00
	Lists.newArrayListWithCapacity(int c)	new ArrayList(c)	0/20 (0%)	0.00 ±0.00
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	Maps.newHashMap()	new HashMap()	0/54 (0%)	0.00 ±0.00
	Maps.newHashMap()	new HashMap(16)	0/54 (0%)	0.00 ±0.00

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	LinkedHashMultimap.create()	create(100,100)	0/207 (0%)	0.12 ±0.15
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	Lists.newArrayList()	new ArrayList()	0/24 (0%)	0.00 ±0.00
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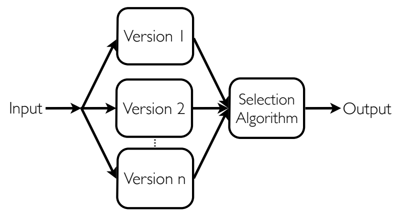
	Lists.newArrayListWithCapacity(int c)	new ArrayList()	0/20 (0%)	0.00 ±0.00
	Lists.newArrayListWithCapacity(int c)	new ArrayList(c)	0/20 (0%)	0.00 ±0.00
	Maps.newHashMap()	Maps.newHashMapWithExpectedSize(16)	0/54 (0%)	0.00 ±0.00
	Maps.newHashMap()	new HashMap()	0/54 (0%)	0.00 ±0.00
	Maps.newHashMap()	new HashMap(16)	0/54 (0%)	0.00 ±0.00

Correlation: **0.94**

Software Redundancy?

Deliberate



N-version

Intrinsic

Google Guava

```
MultiMap m = new MultiMap();
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//add a key-value pair in the map
m.put(key, value);
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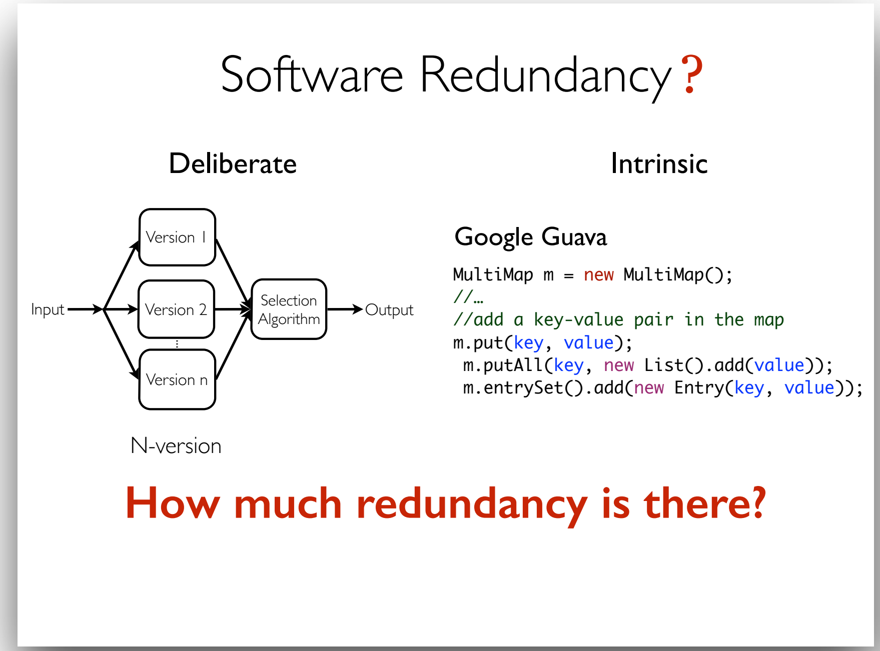
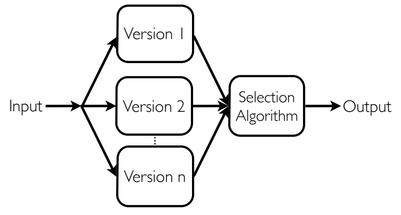
How much redundancy is there?



Software Redundancy?

Deliberate **Intrinsic**



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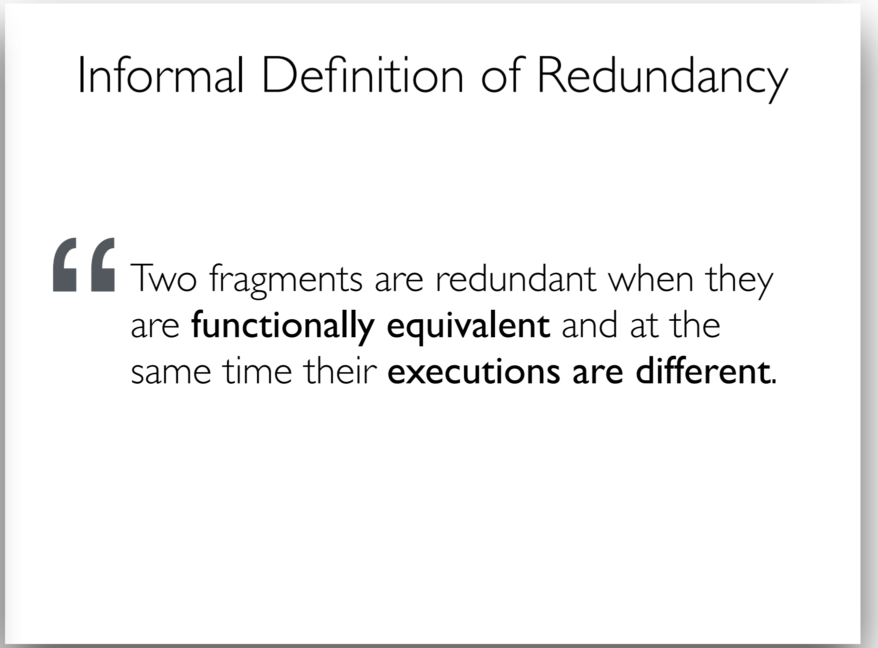
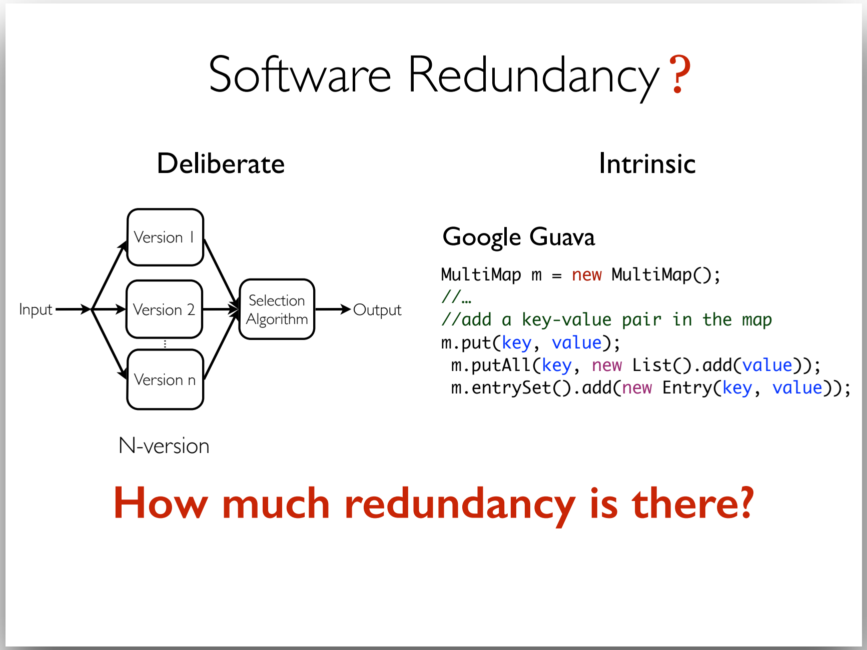


Informal Definition of Redundancy

“Two fragments are redundant when they are **functionally equivalent** and at the same time their **executions are different**.



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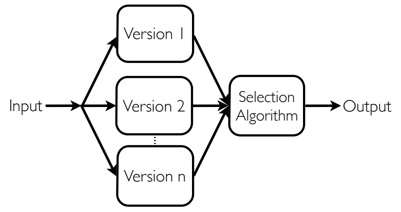

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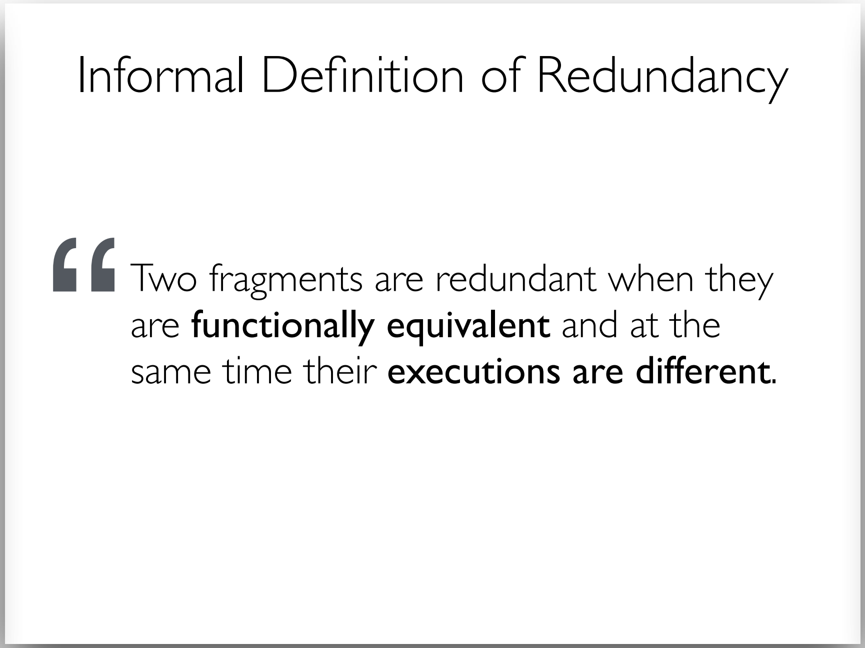

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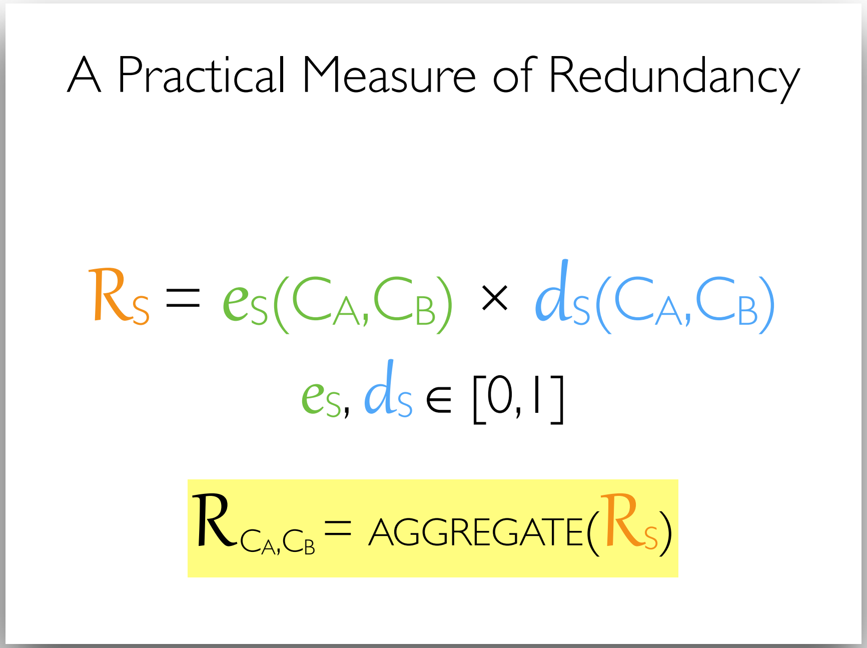

A Practical Measure of Redundancy

$$R_S = e_S(C_A, C_B) \times d_S(C_A, C_B)$$

$$e_S, d_S \in [0,1]$$

$$R_{C_A,C_B} = \text{AGGREGATE}(R_S)$$

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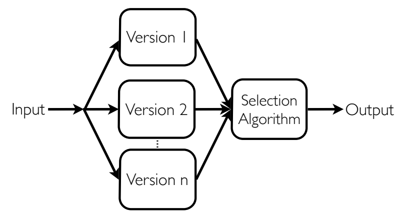

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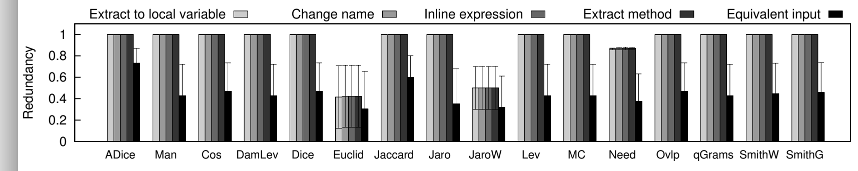
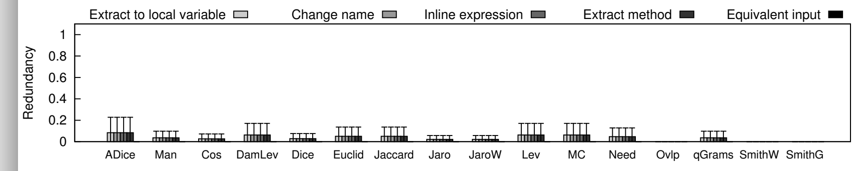
Consistency: Stability

Code Projections



Data Projections



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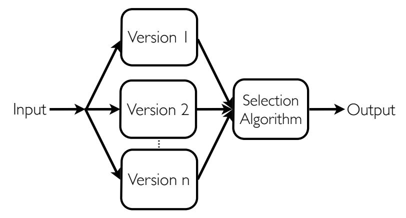

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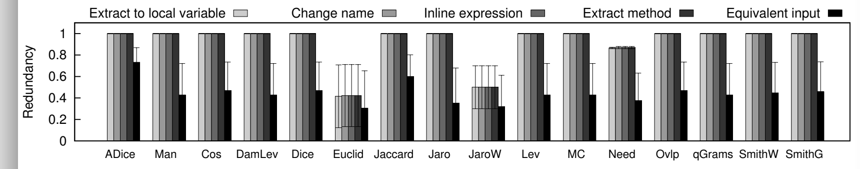

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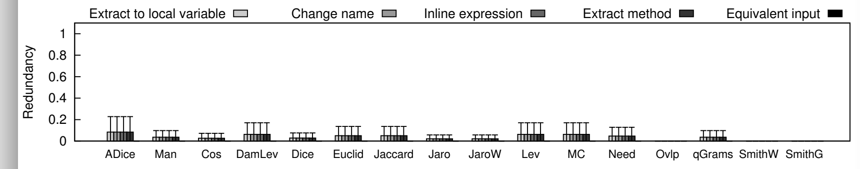
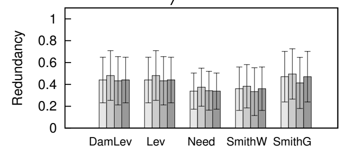


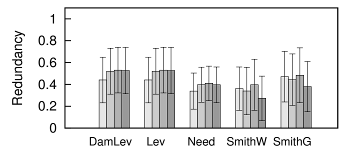
Low-level vs High-level

Code Redundancy vs Algorithmic Redundancy

Binary search

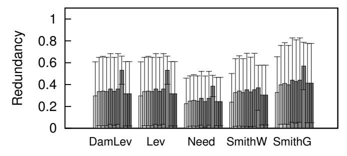


Linear search

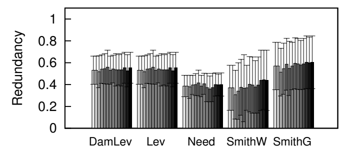


Different algorithm

Bubble sort

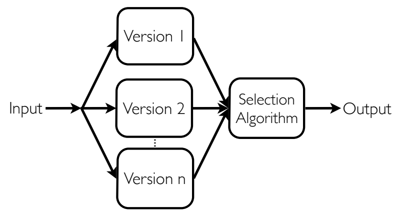


Insertion sort



Software Redundancy?

Deliberate



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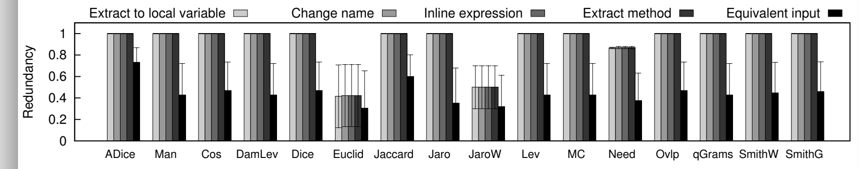

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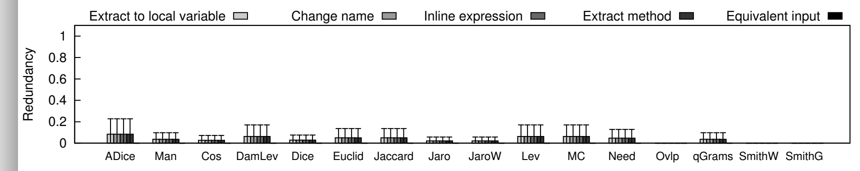

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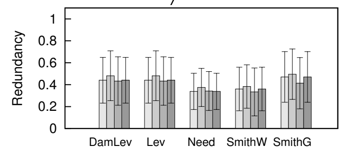

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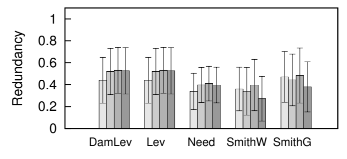

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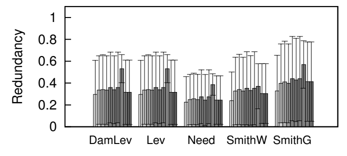
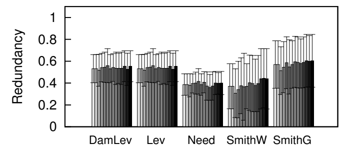


Insertion sort



Predictive Ability

System	Method (C_A)	Workaround (C_B)	Success ratio	Redundancy
Caliper	Iterators.forArray(a)	Arrays.asList(a).iterator()	3/3 (100%)	1.00 ± 0.00
	LinkedHashMultiset.retainAll(Collection c)	foreach(o in map) if(o not in c) map.remove(o);	1/2 (50%)	0.61 ±0.01
	ArrayListMultimap.putAll(Object k,Collection c)	foreach(o in c) put(k,o);	8/41 (20%)	0.37 ±0.32
	LinkedHashMultimap.putAll(Object k, Collection c)	foreach(o in c) put(k,o);	0/1 (0%)	0.00 ±0.00
	LinkedHashMultimap.create()	create(100,100)	0/207 (0%)	0.12 ±0.15
	LinkedHashMultimap.create(int,int)	create()	0/202 (0%)	0.12 ±0.15
	LinkedHashMultimap.isEmpty()	size() == 0 ? true : false	0/34 (0%)	0.00 ±0.00
Carrot2	ImmutableMultiset.of(Object..c)	foreach(o in c) builder().setCount(o,count(o in c))	13/22 (59%)	0.56 ±0.07
	ImmutableMultiset.of(Object..c)	builder().add(..c).build()	7/19 (37%)	0.24 ±0.12
	ArrayListMultimap.putAll(Object k,Collection c)	foreach(o in c) put(k,o);	1/13 (8%)	0.37 ±0.32
	ImmutableMultiset.of(Object o)	builder().add(o).build()	0/1 (0%)	0.32 ±0.14
	Lists.newArrayList()	new ArrayList()	0/24 (0%)	0.00 ±0.00
	Lists.newArrayList()	new ArrayList(10)	0/24 (0%)	0.00 ±0.00
	Lists.newArrayListWithCapacity(int c)	new ArrayList()	0/20 (0%)	0.00 ±0.00
	Lists.newArrayListWithCapacity(int c)	new ArrayList(c)	0/20 (0%)	0.00 ±0.00
	Maps.newHashMap()	Maps.newHashMapWithExpectedSize(16)	0/54 (0%)	0.00 ±0.00
	Maps.newHashMap()	new HashMap()	0/54 (0%)	0.00 ±0.00
	Maps.newHashMap()	new HashMap(16)	0/54 (0%)	0.00 ±0.00

Correlation: **0.94**