CSE P 504

Advanced topics in Software Systems

Fall 2022

Invariants and partial test oracles

November 07, 2022

Course overview: the big picture

• **10/03:** Course introduction	HW 1
• **10/10:** Best practices and version control	In-class exercise
• **10/17:** Coverage-based testing	In-class exercise
• **10/24:** Mutation-based testing	In-class exercise
• **10/31:** Delta debugging	In-class exercise
• **11/07:** Invariants and partial oracles	In-class exercise
• **11/14:** Statistical fault localization	In-class exercise
• **11/21:** Static analysis	Happy Thanksgiving
• **11/28:** Abstract interpretation	HW 2
• **12/05:** Formal methods	In-class exercise

Reasoning about programs

Reasoning about programs

Use cases

- Testing: increase confidence in correctness
- Verification: prove facts to be true, e.g.:
  - x is never null
  - y is always greater than 0
  - a happens before b
- Debugging: understand why code is incorrect

Reasoning about programs

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Approaches

- Testing
- Abstract interpretation
- Theorem proving
- Delta debugging
- Slicing
- ...

Forward vs. backward reasoning

Forward reasoning

- Knowing a fact that is true before execution.
- Reasoning about **what must be true after execution**.
- Given a precondition, what postcondition(s) are true?

Forward vs. backward reasoning

Forward reasoning

- Knowing a fact that is true before execution.
- Reasoning about **what must be true after execution**.
- Given a precondition, what postcondition(s) are true?

Backward reasoning

- Knowing a fact that is true after execution.
- Reasoning about **what must be true before execution**.
- Given a postcondition, what precondition(s) must hold?

What are the pros and cons for each approach?

Forward vs. backward reasoning

Forward reasoning

- More intuitive for most people
- Helps understand what will happen (simulates the code)
- Introduces facts that may be irrelevant to the goal
- Set of current facts may get large
- Takes longer to realize that the task is hopeless

Backward reasoning

- Usually more helpful
- Helps understand what should happen
- Given a specific goal, indicates how to achieve it
- Given an error, gives a test case that exposes it

Pre/Post-conditions and Invariants

Terminology

Pre-condition (to a function)

- A condition that must be true when entering (the function)
- May include expectations about the arguments

Post-condition (to a function)

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- Must be true at the beginning and end of the loop body

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Pre-conditions define execution validity. Post-conditions and loop invariants define expected properties of a correct implementation, given a valid execution.

Pre-conditions and post-conditions


```java
double avgAbs(double[] nums) {
  int n = nums.length;
  double sum = 0;

  int i = 0;
  while (i != n) {
    if(nums[i]>0) {
      sum = sum + nums[i];
    else {
      sum = sum - nums[i];
    }
    i = i + 1;
  }

  return sum / n;
}
```

Entry point

Exit point

What are pre-conditions and post-conditions of this method (at the entry and exit points)?

Pre-conditions and post-conditions

```
double avgAbs(double[] nums) {
 int n = nums.length;
 double sum = 0;

 int i = 0;
 while (i != n) {
   if(nums[i]>0) {
    sum = sum + nums[i];
   else {
    sum = sum - nums[i];
   }
   i = i + 1;
 }

 return sum / n;
}
```

Pre-conditions

- nums is not null
- `nums.length > 0`

Post-conditions

- nums has not changed
- `n > 0`
- `sum >= 0`
- `return value >= 0`
- ...

(Loop) invariants

```
double avgAbs(double[] nums) {
  int n = nums.length;
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    }
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  }

  return sum / n;
}
```

Does this loop terminate?
What are pre-conditions,
post-conditions,
and loop invariants?

(Loop) invariants

```
double avgAbs(double[] nums) {
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  int i = 0;
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    }
    i = i + 1;
  }

  return sum / n;
}
```
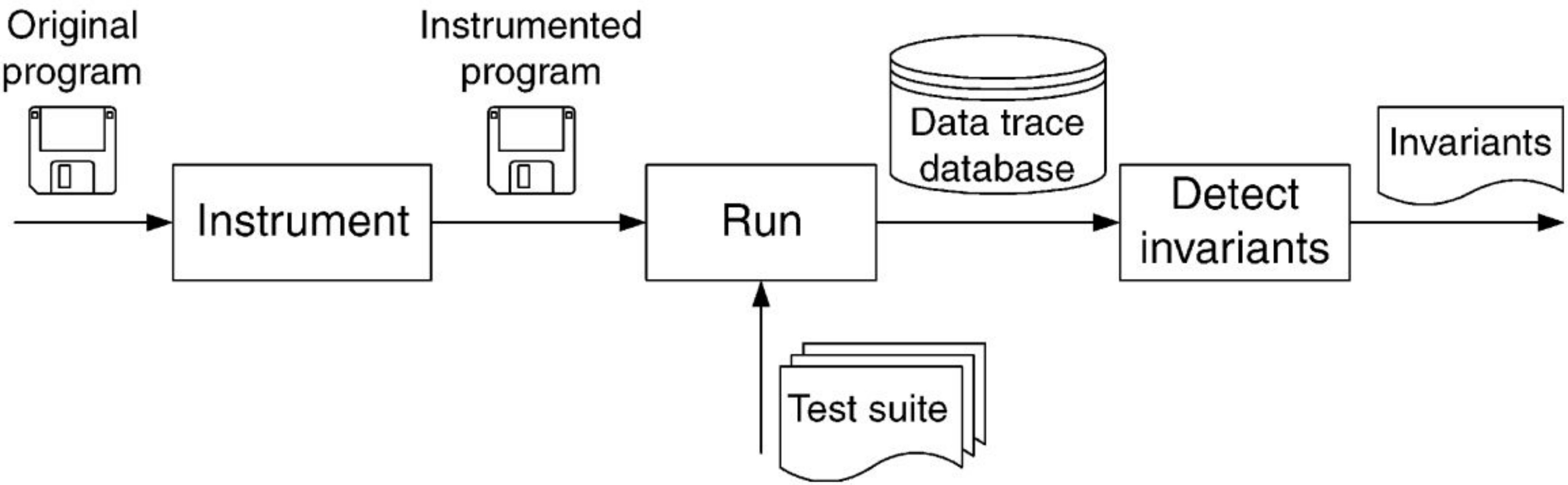

Explicitly stating invariants is hard -- reasoning about inferred variants might be easier.

Daikon live example

[(https://plse.cs.washington.edu/daikon/download/doc/daikon/Example-usage.html#Detecting-invariants-in-Java-programs)](https://plse.cs.washington.edu/daikon/download/doc/daikon/Example-usage.html#Detecting-invariants-in-Java-programs)

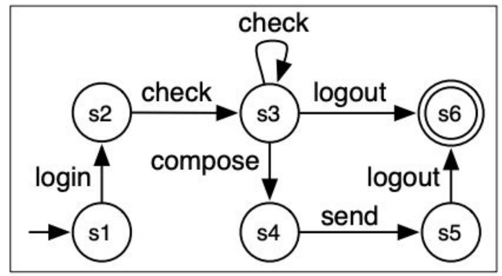
Daikon: general workflow



Log-based model inference

trace 1:	trace 2:
login	login
check	check
check	compose
logout	send
	logout

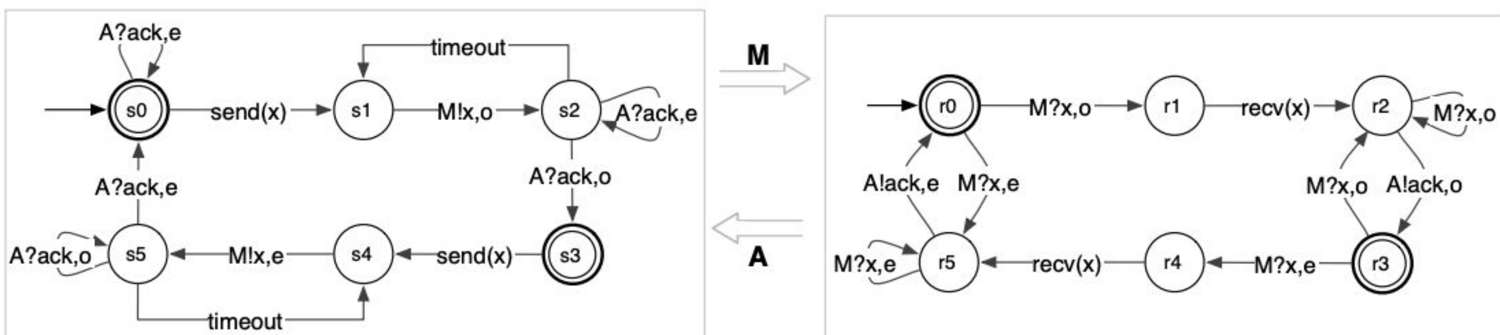
(a) Input log



(b) Output model

Sender		Receiver	
1,0	send(x)	2,1	M?x,o
2,0	M!x,o	2,2	recv(x)
3,3	A?ack,o	2,3	A!ack,o
4,3	send(x)	5,4	M?x,e
5,3	M!x,e	5,5	recv(x)
6,6	A?ack,e	5,6	A!ack,e
7,6	send(x)	8,7	M?x,o
8,6	M!x,o	8,8	recv(x)
9,9	A?ack,o	8,9	A!ack,o
10,9	send(x)	11,10	M?x,e
11,9	M!x,e	11,11	recv(x)
12,12	A?ack,e	11,12	A!ack,e

(a) Input log



(b.1) Output model (Sender) **(b.2) Output model (Receiver)**

Beschastnikh et al., Synoptic: Studying Logged Behavior with Inferred Models; Inferring Models of Concurrent Systems from Logs of their Behavior with CSight

Partial test oracles, Property-based testing Metamorphic testing*

**Chen et al. coined the term metamorphic testing in 1998, but the key idea was first described by Ammann and Knight as data diversity in 1988.*

Partial test oracles

Partial test oracle

- Necessary (but not sufficient) conditions
- Example: abs(x) >= 0

Property-based testing

Partial test oracle

- Necessary (but not sufficient) conditions
- Example: abs(x) >= 0

Property-based testing

- Check property (necessary condition) that must hold for any input, which requires knowledge about the system
- Commonly used with random input generation

How is property-based testing different from testing with input-output pairs and how is it different from fuzzing?

Property-based testing

Partial test oracle

- Necessary (but not sufficient) conditions
- Example: abs(x) >= 0

Property-based testing

- Check property (necessary condition) that must hold for any input, which requires knowledge about the system
- Commonly used with random input generation

- Contrast: testing with input-output pairs usually checks for sufficient conditions for a (small) subset of all possible inputs
- Contrast: fuzzing is usually a black-box approach that checks for a simple property (“should not crash”)

Data diversity and metamorphic testing

Simple case: related inputs with identical outcomes

- Expected output for a given input is unknown
- Two related inputs must result in the same output
- Example: abs(x) == abs(-x)

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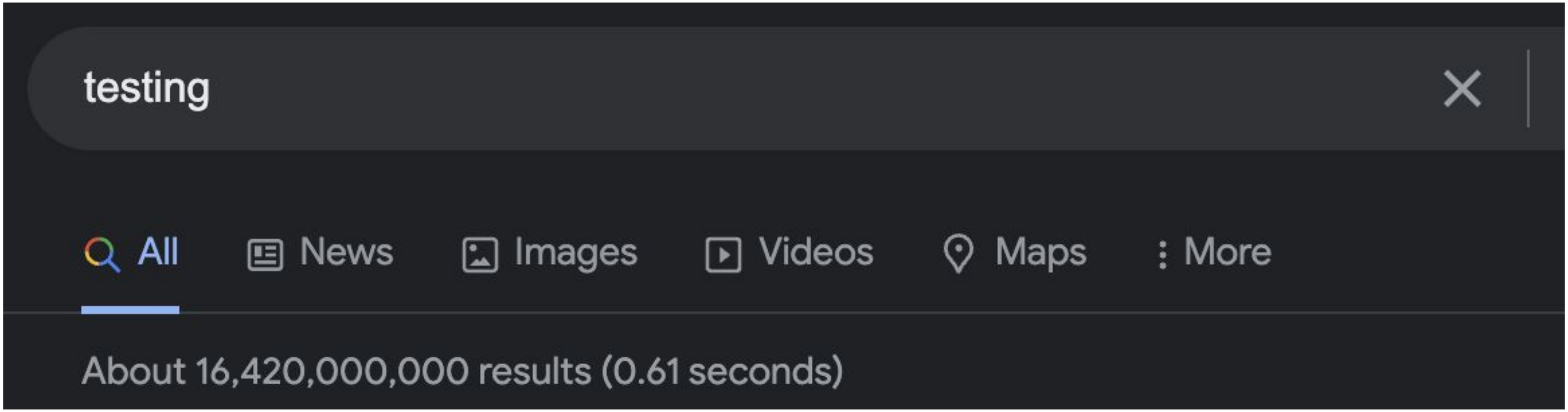
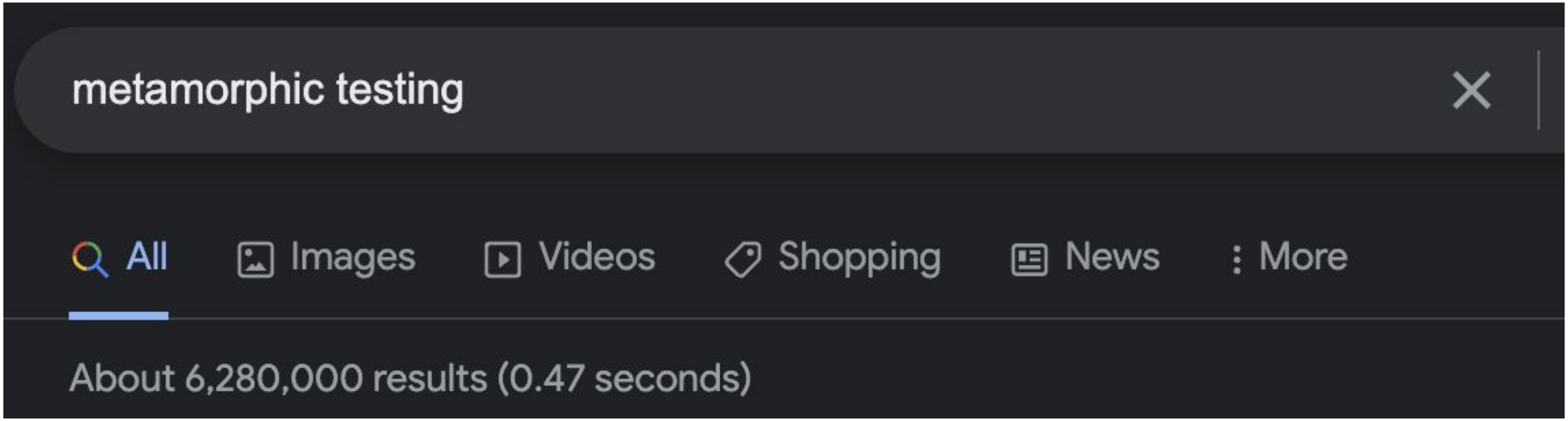
Generalization: related inputs and related outputs

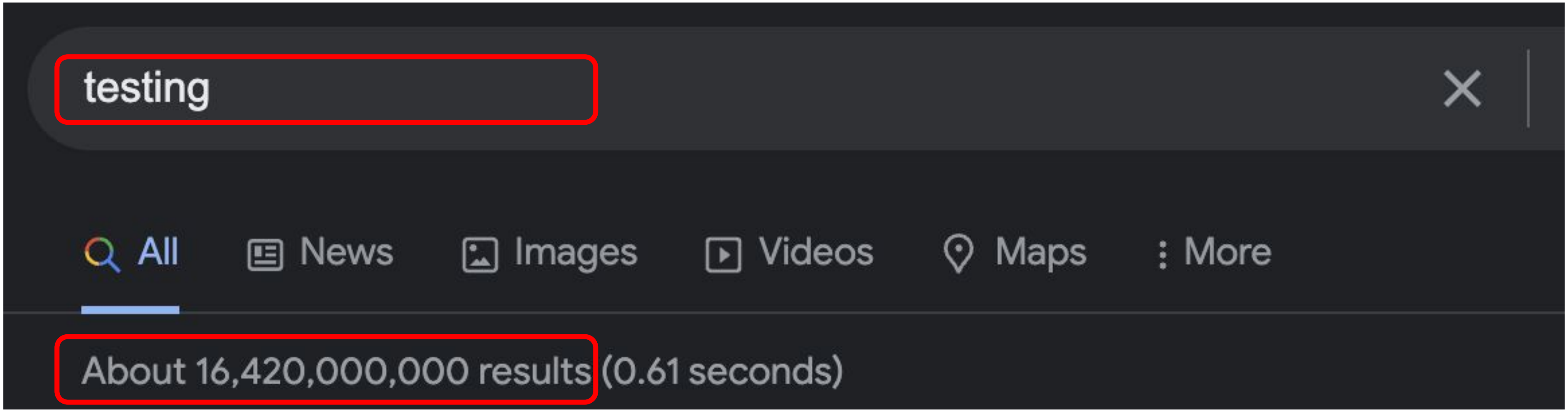
- Input i_1 yields (unknown) o_1 (initial input)
- R_i: $i_1 \Longrightarrow i_2$ (follow-up input)
- R_o: $o_1 \Longrightarrow o_2$ (necessary condition)

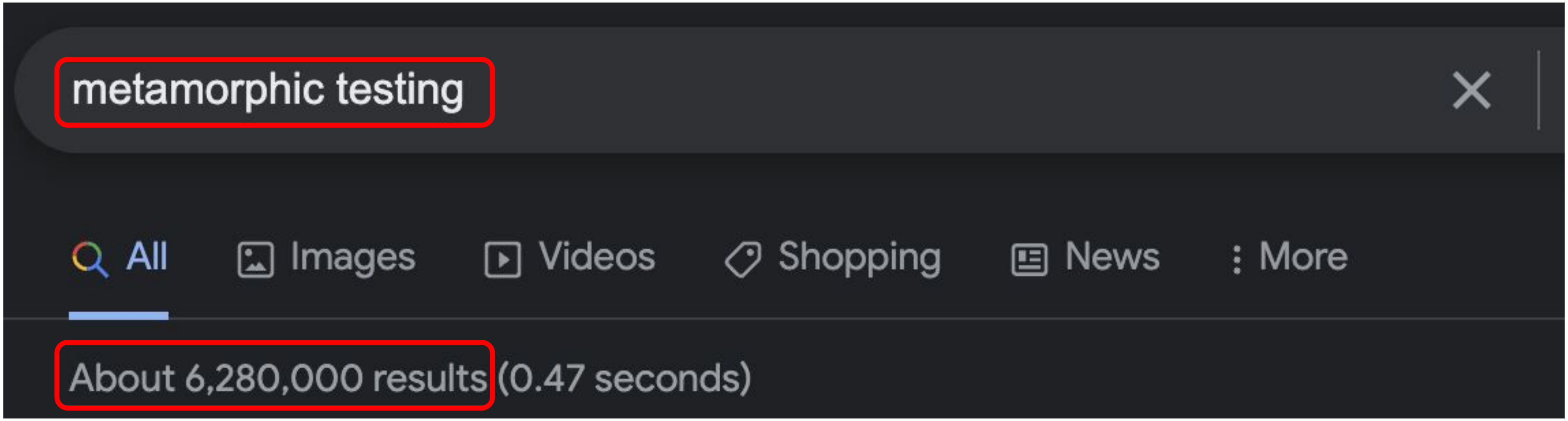
Metamorphic testing: a first example





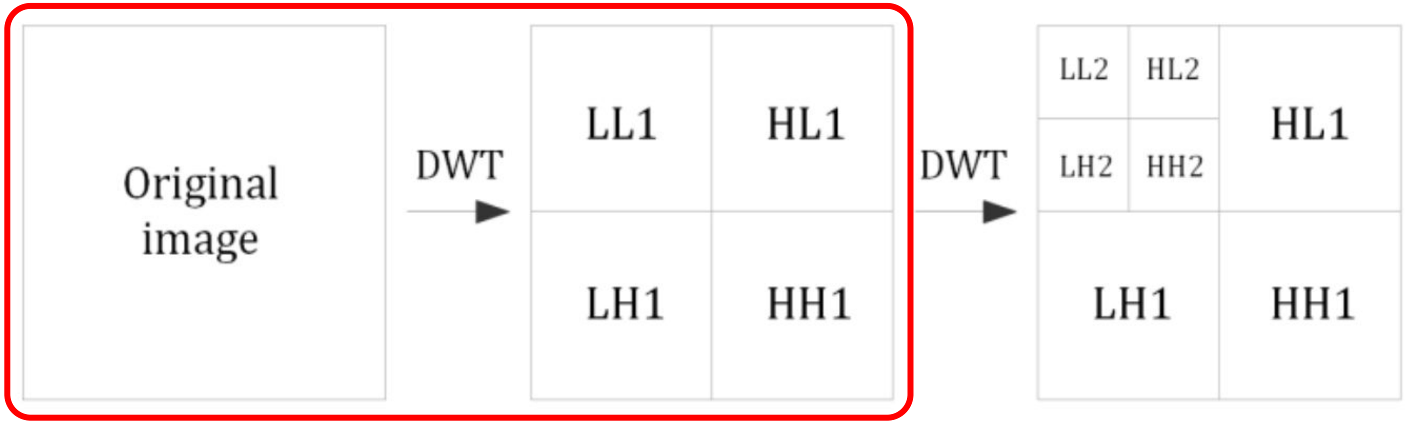
Metamorphic testing: a first example



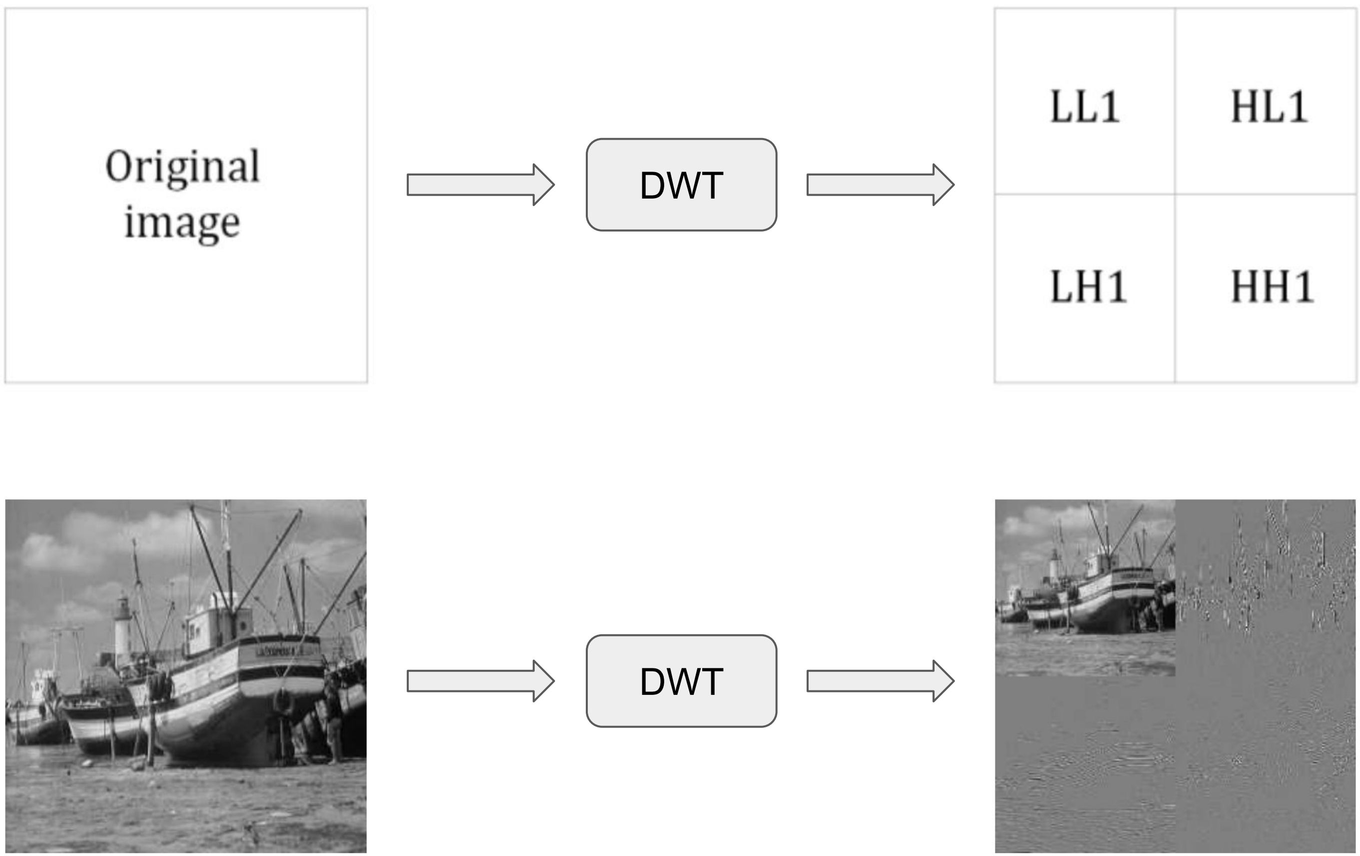


Discrete wavelet transformation

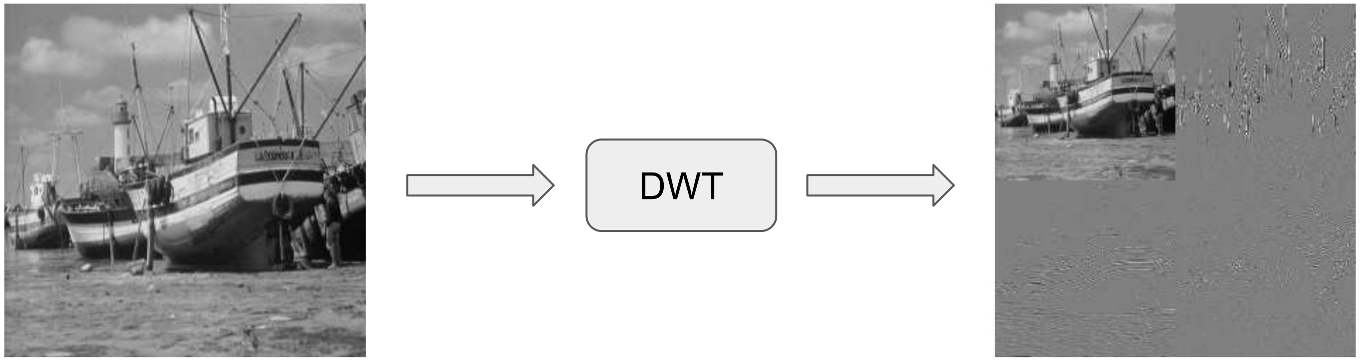
Discrete wavelet transformation

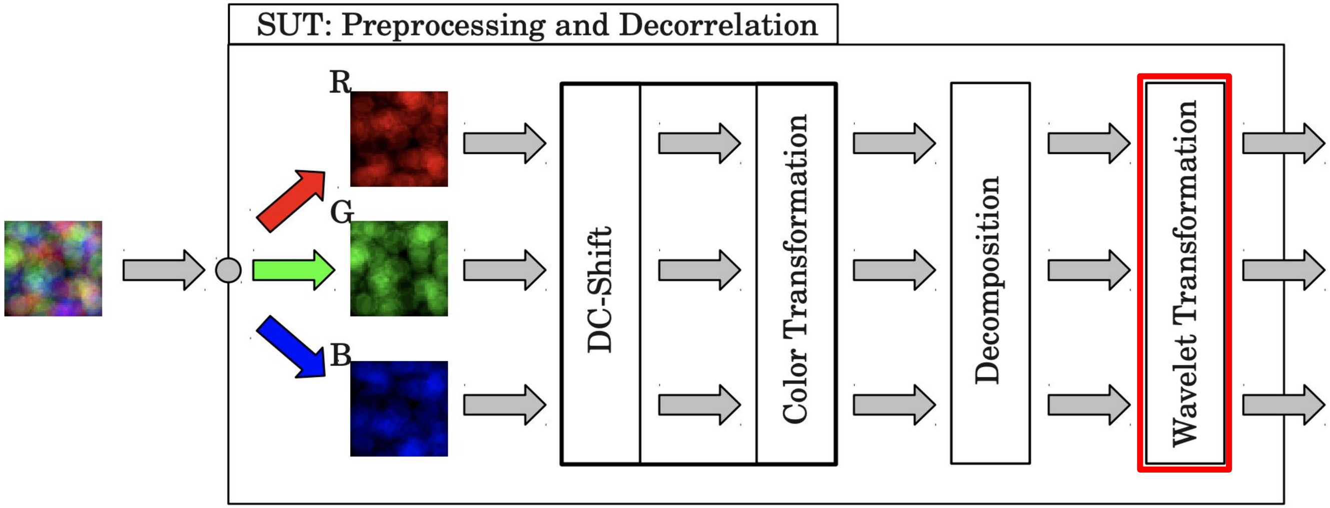


Discrete wavelet transformation

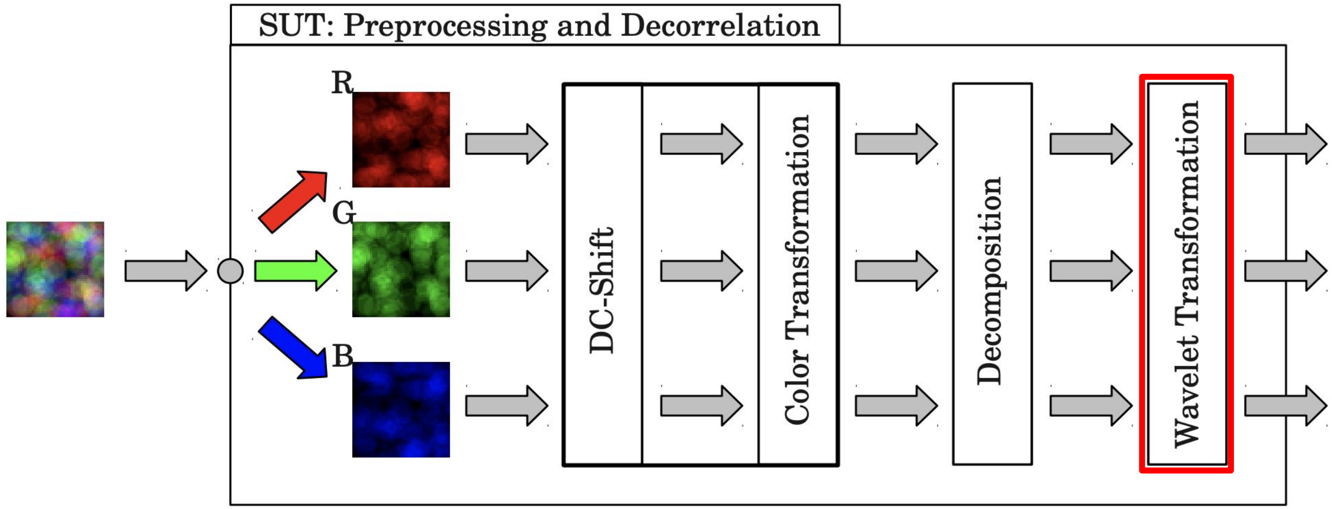


A concrete SUT: jpeg2000 encoder





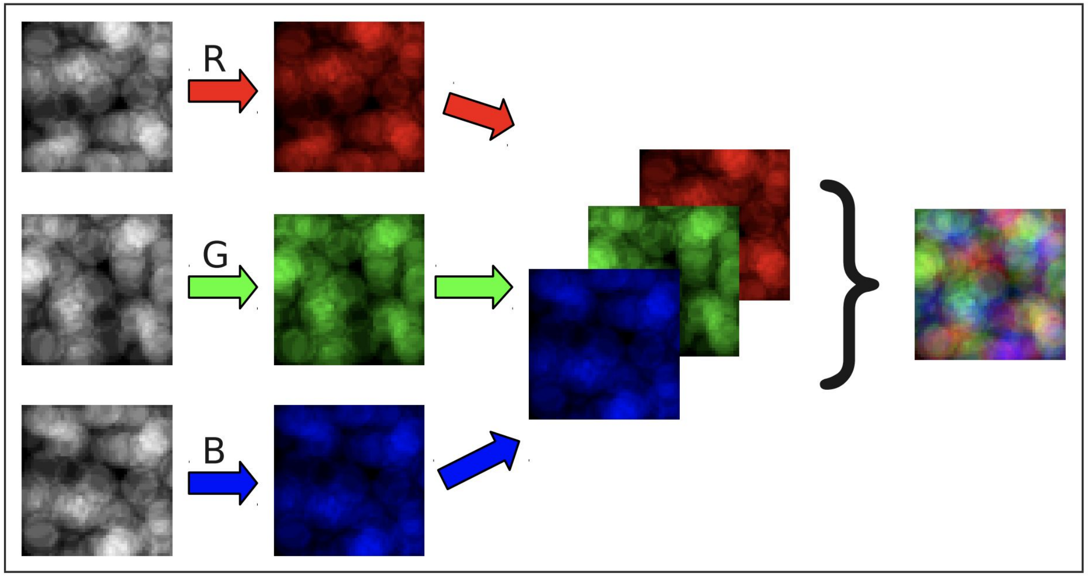
Metamorphic testing: three requirements



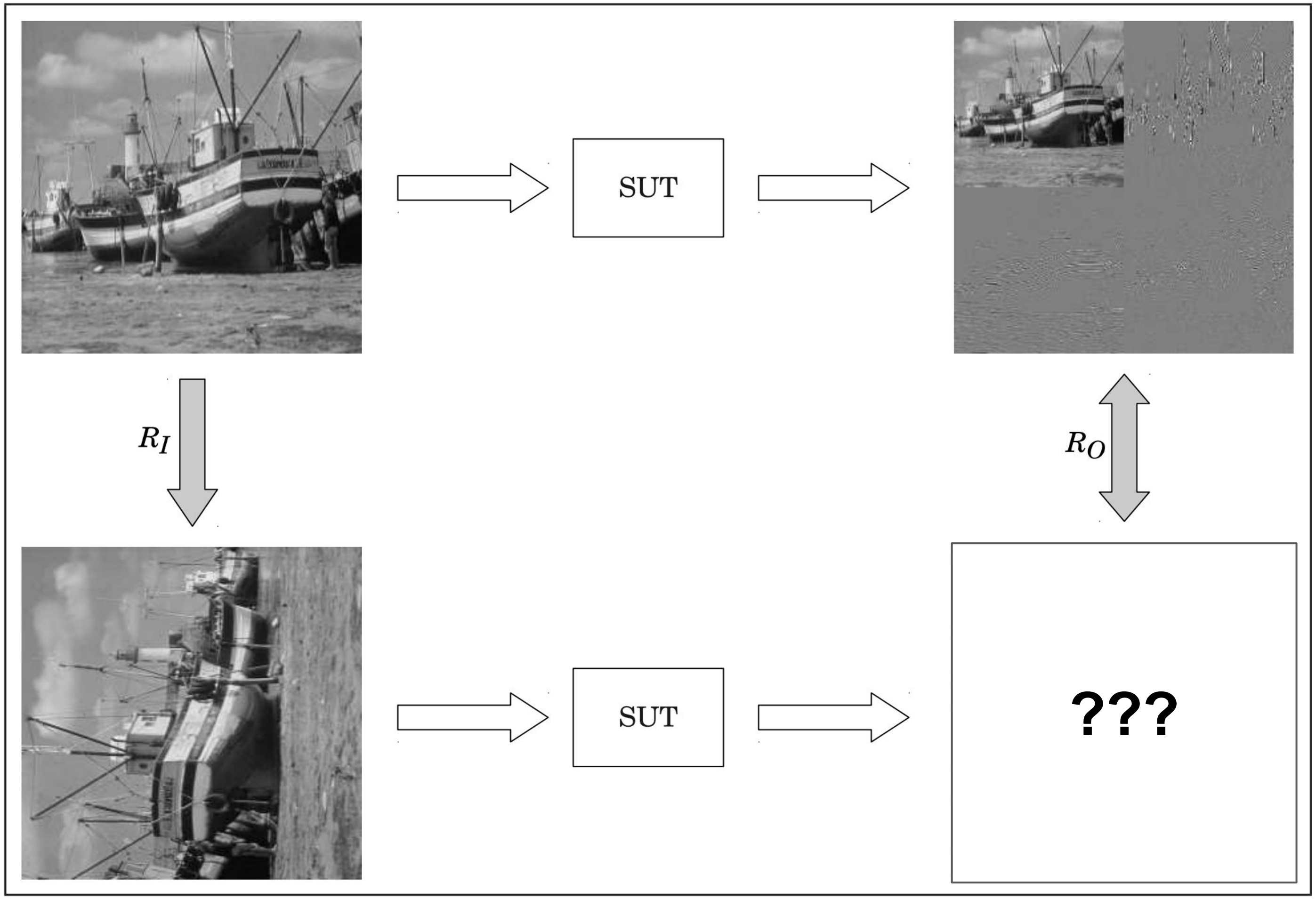
MT requires

1. A set of initial inputs (or a generator)
2. A relation R_i: generates follow-up inputs
3. A relation R_o: necessary correctness condition

Metamorphic testing: Input generation



Metamorphic testing: relations R_i and R_o



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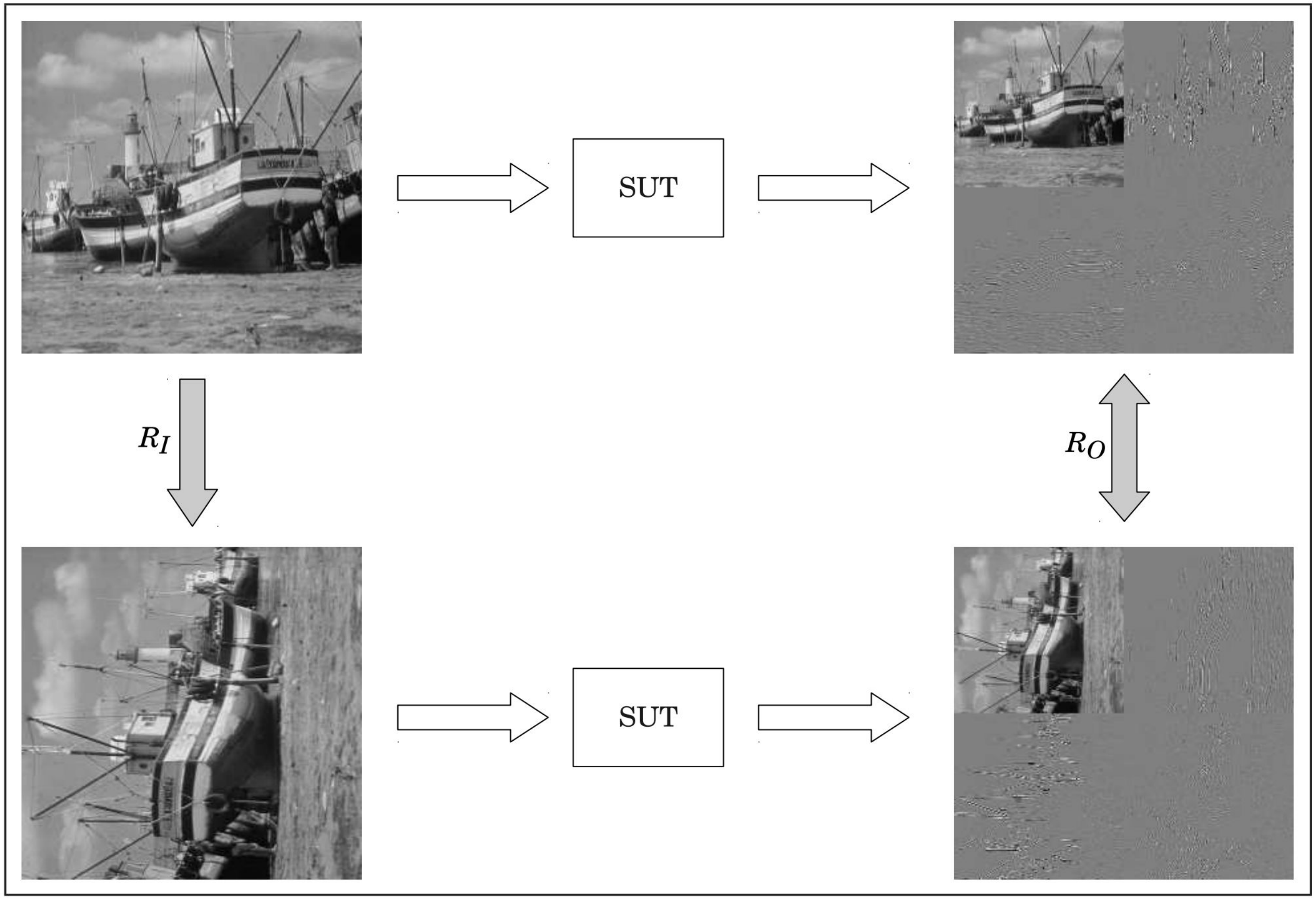
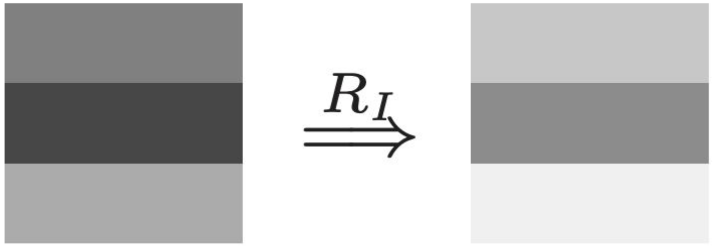


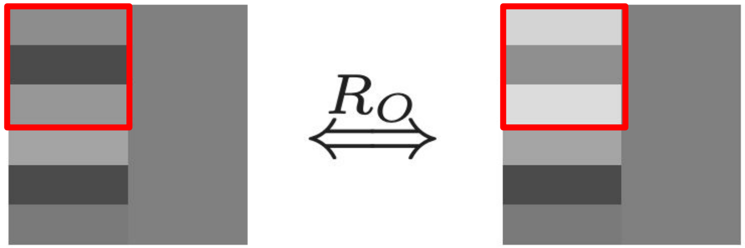
Metamorphic testing: Relations

1. R_i: Add a constant offset to all color values
   R_o: ???

Metamorphic testing: Relations

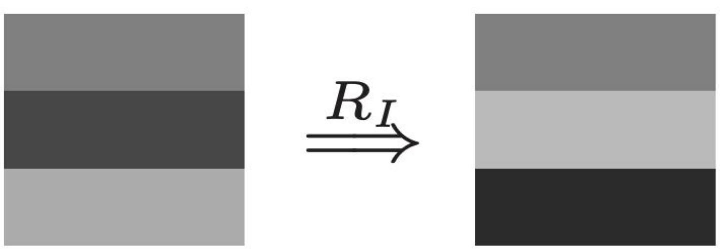
1. R_i: Add a constant offset to all color values
   $R_{o:}$ Only the DC component must change

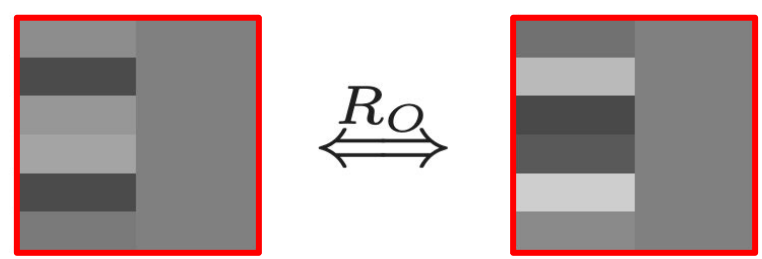




Metamorphic testing: Relations

1. R_i: Add a constant offset to all color values
   $R_{o:}$ Only the DC component must change
2. R_i: Invert the color values
   $R_{o:}$ The color values of the output must be inverted





Metamorphic testing: Relations

1. R_i: Add a constant offset to all color values
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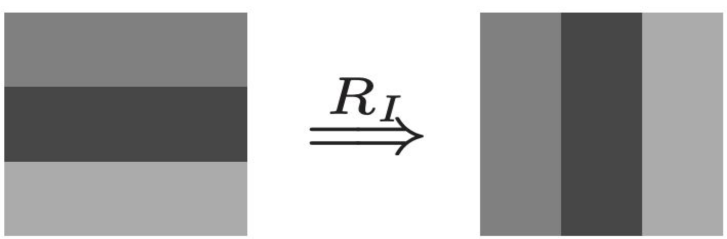
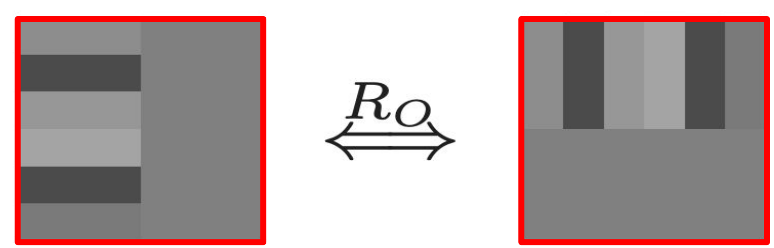
3. R_i: Transpose the input image
   R_o: The output components must be transposed





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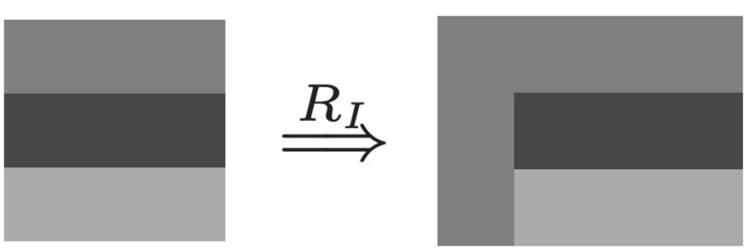
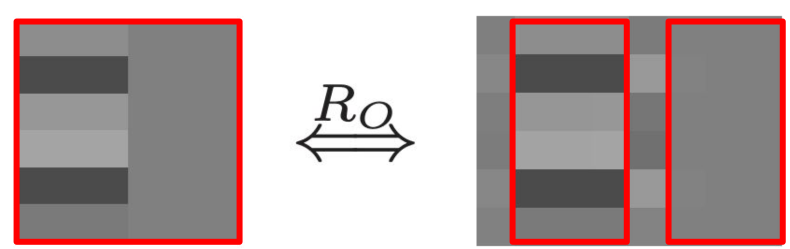
4. R_i: Enlarge the input image (“zero-padding”)
   R_o: The output components must be shifted





Metamorphic testing: Relations

1. R_i: Add a constant offset to all color values
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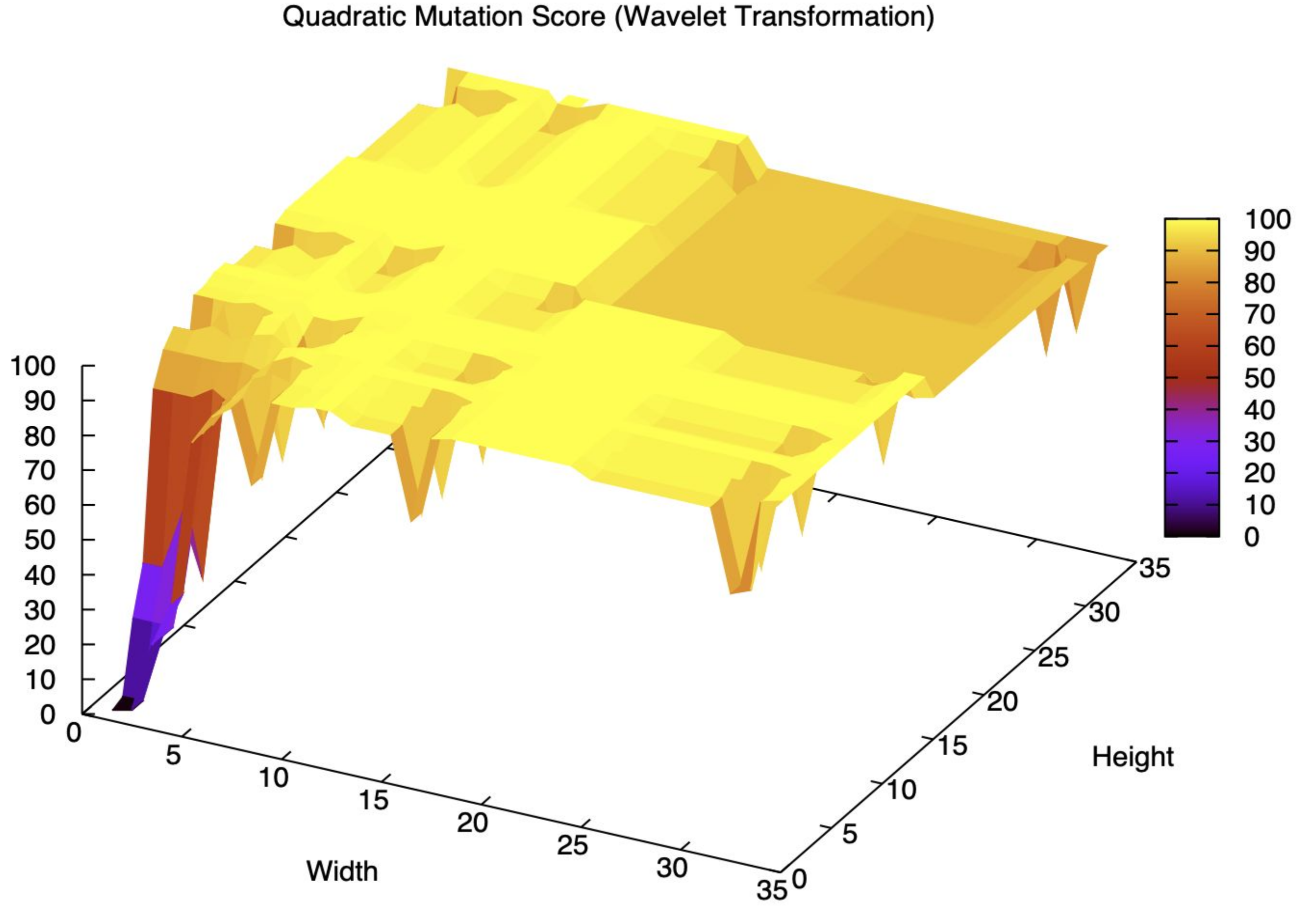
   R_o: The output components must be transposed

   Commutative
4. R_i: Enlarge the input image ("zero-padding")
   R_o: The output components must be shifted

   Time-invariant

It turns out that MR compositions are effective

Metamorphic testing: effectiveness



Putting it all together

1. (Random) input generation
2. Metamorphic testing: follow-up inputs and partial oracles
3. Delta debugging: Minimize bug-exposing inputs
4. Mutation analysis: assess the effectiveness of relations

Examples:

- GraphicsFuzz
- Testing ML-based systems