Oracles

Martin Kellogg

Reading Quiz: oracles

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Q2: The main example in section 2 of the Daikon paper was:

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B. a trie

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- **Key question**: if we generate an input for a given path, **how do we tell** if the program behaved correctly?

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    - and, for machines, sometimes impossible!

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Implicit oracles like these are used by **many test generation tools** (e.g., most fuzzers) in the real world.

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- compare to the way that humans write tests:
  - select ***an*** input
  - select ***an*** oracle
  - compare the two
- that is, human testing usually **samples** the concrete behaviors of a program

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Today's key theme: combine test input generation (e.g., fuzzing) with **abstract, partial oracles**

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  - leads to ***property-based testing***
- Option 2: exploit **known relationships** between different inputs or programs (humans provide the relationships)
  - leads to ***metamorphic testing***
- Option 3: run the program and **automatically observe invariants** that happen to be true on human-written tests
  - leads to ***dynamic invariant detection***

Agenda: remainder of today’s lecture

- **Property-based testing**
- Metamorphic testing
- Dynamic invariant detection

Property-based testing

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- almost always paired with random input generation
  - can be viewed as "fuzzing, but using a human-written, program-specific oracle instead of an implicit oracle"
- note that PBT **requires** knowledge about the system being tested
  - if you can apply a partial oracle to *any* SUT, it's probably an implicit oracle instead

Property-based testing: benefits

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  - makes it easier for future developers to understand what is and is not being tested
- Can avoid finding and writing every case for each property
  - allows tester to focus on **the what not the how**
- Can **decrease maintenance costs** with the same (or sometimes even greater!) coverage

Property-based testing in practice

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  - Originated with QuickCheck for Haskell in 2000
  - PBT has the same kind of **mathematical vibe** as FP

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- Historically, PBT was developed first for **functional languages**
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  - PBT has the same kind of **mathematical vibe** as FP
- Now there are PBT frameworks available for mainstream programming languages
  - Hypothesis for Python and Java (https://hypothesis.works/)
  - DeepState for C/C++ (https://github.com/trailofbits/deepstate)
  - etc.

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Metamorphic testing*

Definition: ***metamorphic testing*** is a property-based testing technique in which oracles are defined by ***metamorphic relations*** (MRs) between related inputs or programs

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  - formally, a relation *R* over a set *X* can be seen as a set of ordered pairs (x,y) of members of *X*. The relation *R* holds between x and y if (x,y) is a member of *R*. [Wikipedia]

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        - today’s reading on CSmith is an example of this

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  - metamorphic testing where the outputs of **two related programs on the same input** have a metamorphic relationship
    - traditionally called ***differential testing***
    - today’s reading on CSmith is an example of this
  - metamorphic testing where the output of **the same program on two related inputs** have a metamorphic relationship
    - this is usually what’s meant by “metamorphic testing” in the literature

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Definition: ***differential testing*** is a technique for testing two related programs by comparing their output on generated test inputs. Any difference indicates non-conformance in one of the two.

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  - and sometimes neither is!
- but, differential testing provides a much stronger oracle than most other techniques (true of metamorphic testing generally!)

Metamorphic testing: differential testing MR

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- What other MRs could we use for differential testing?
    - Inversion: forall X. unzip(zip(X)) = X
    - Convergence / Idempotency: forall X. sort(sort(X)) = sort(X)

Aside: designing for testing: tests for free

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    - If possible, design your program so that this is possible

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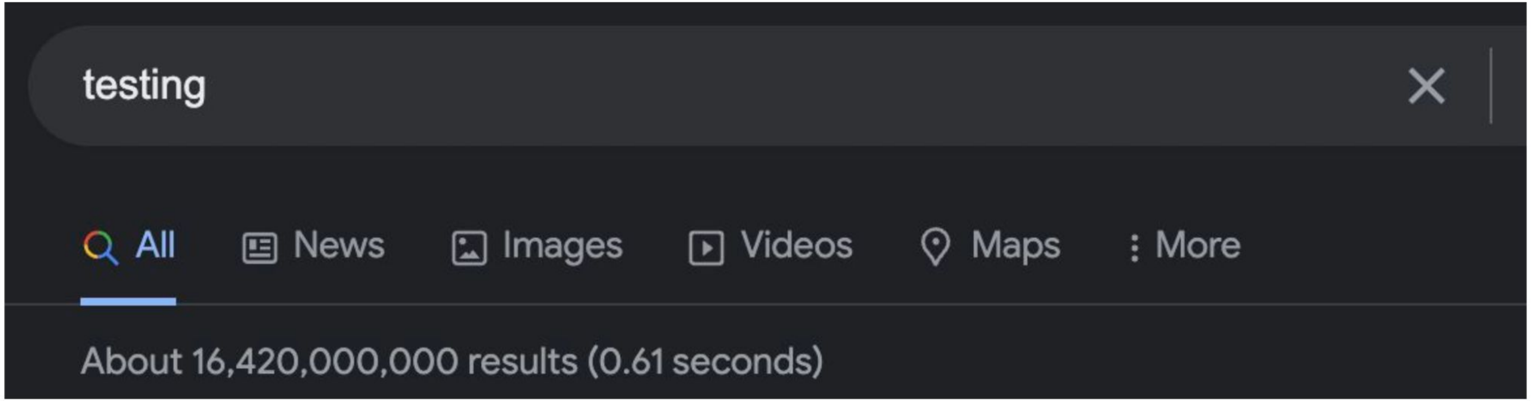
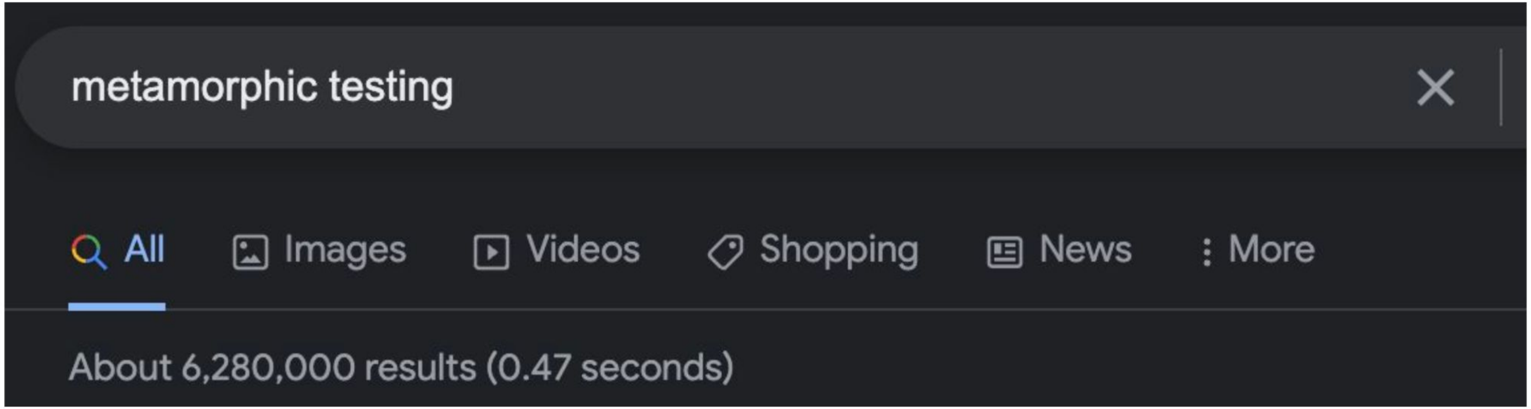
  - $R_o : o_1 \text{ -> } o_2$ (***necessary condition***)

Metamorphic testing: online service example



testing

About 16,420,000,000 results (0.61 seconds)



metamorphic testing

About 6,280,000 results (0.47 seconds)

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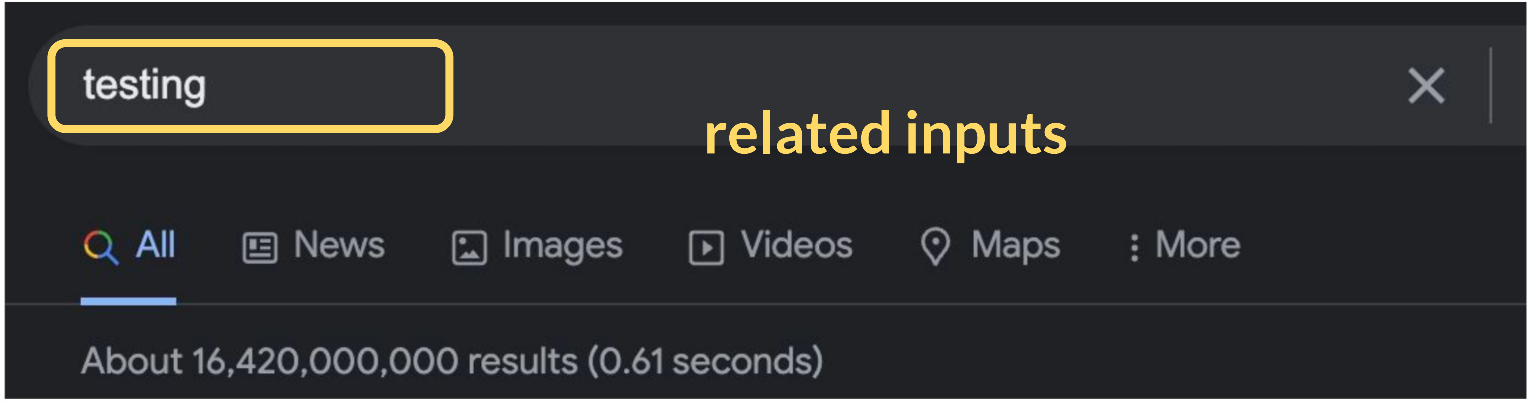

testing

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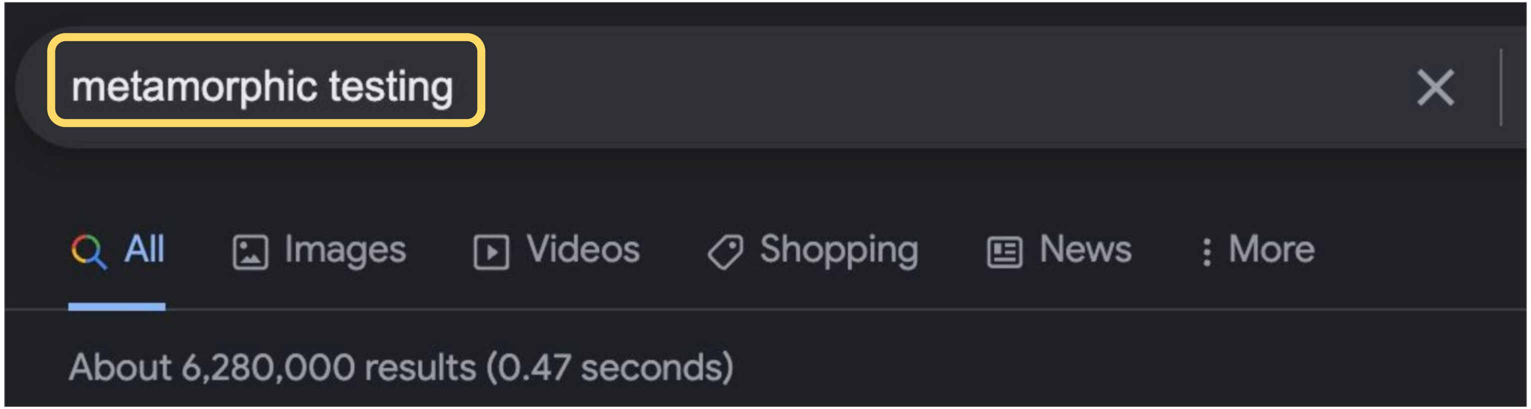

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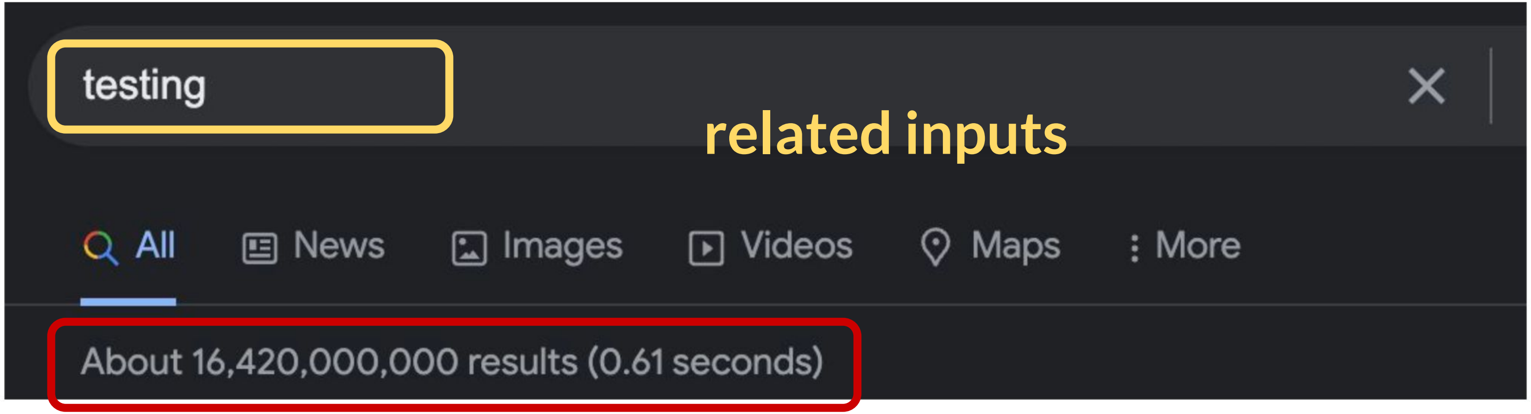

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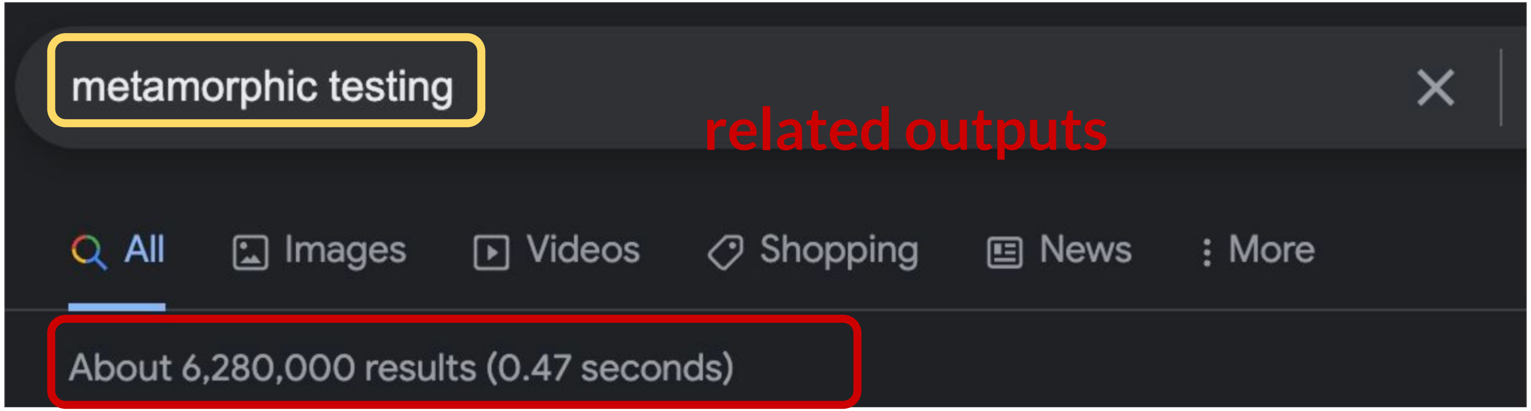

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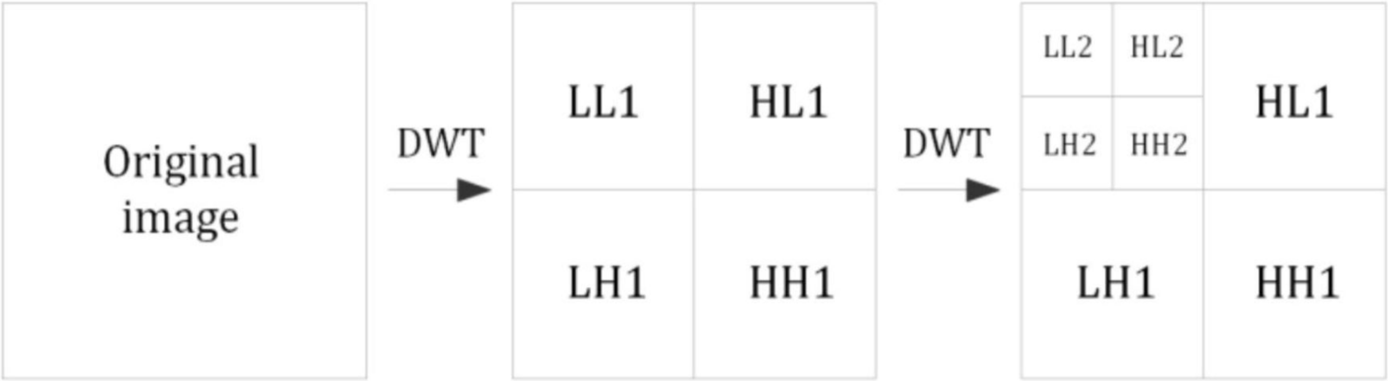
MT: discrete wavelet transform example



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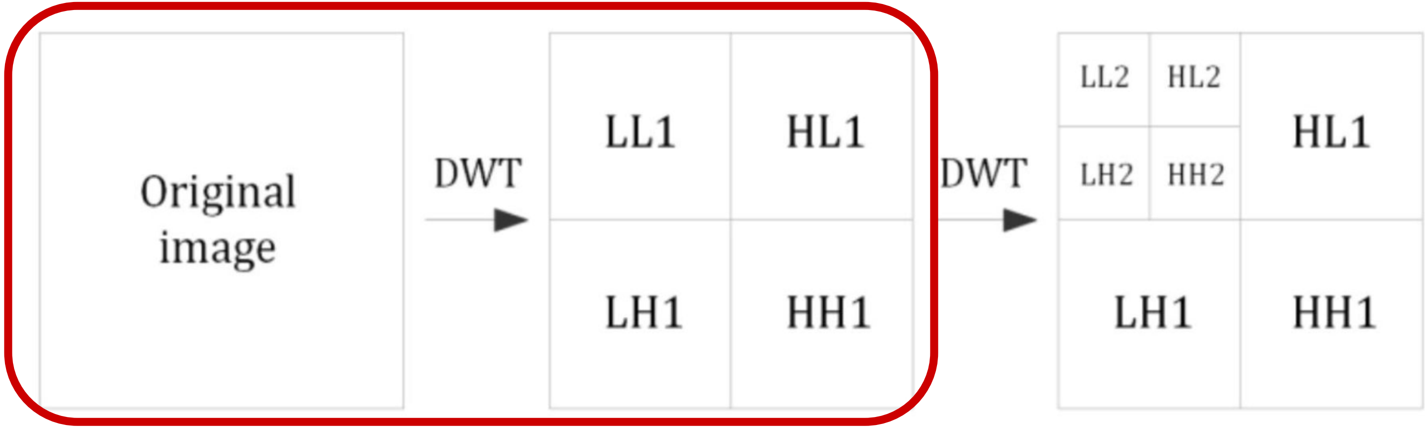

Original image

DWT

LL1 HL1

LH1 HH1

DWT

LL2 HL2

LH2 HH2

HL1

LH1 HH1

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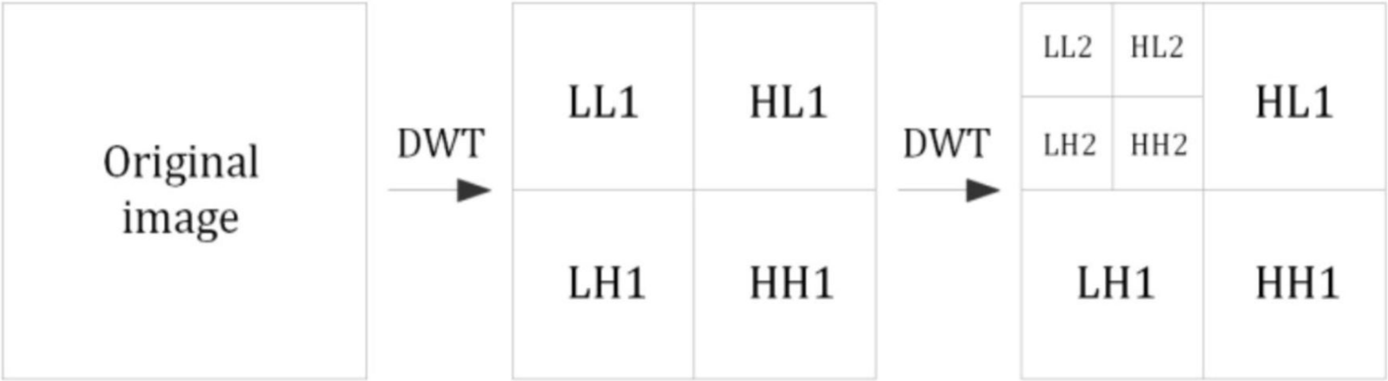
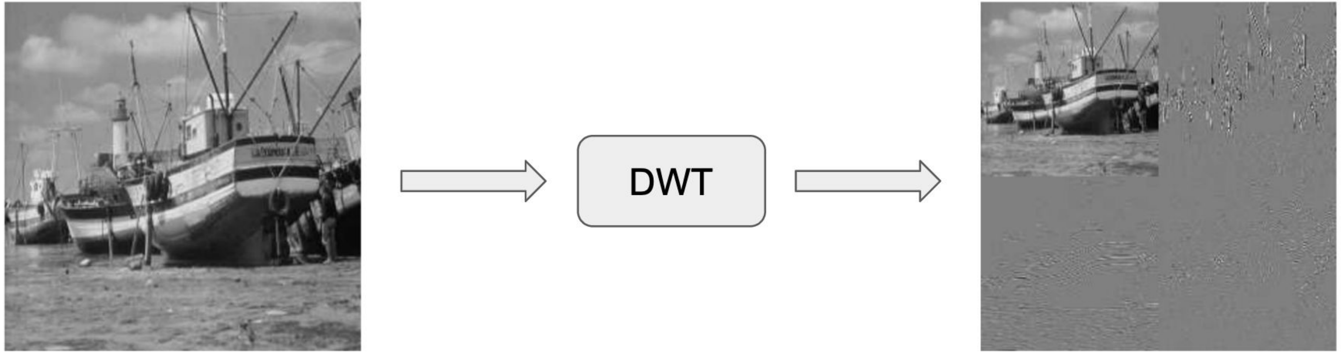
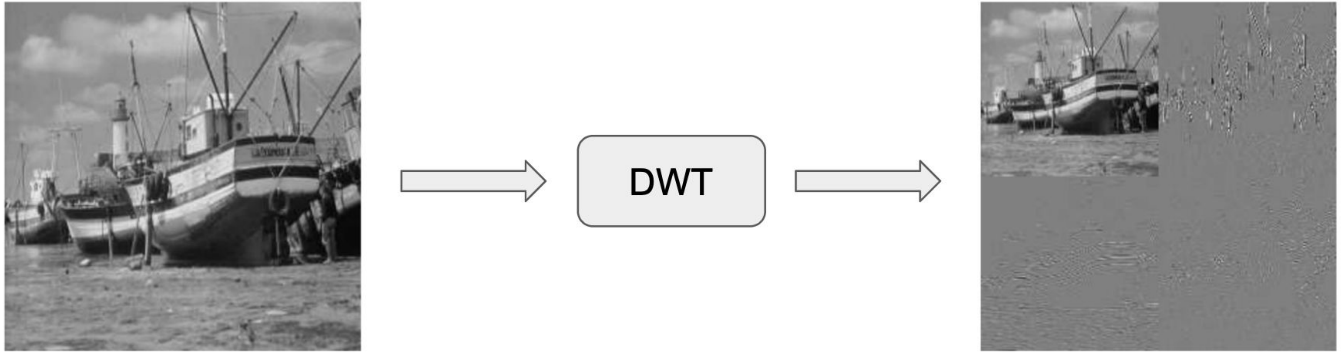




MT: DWT: concrete SUT: jpeg2000 encoder



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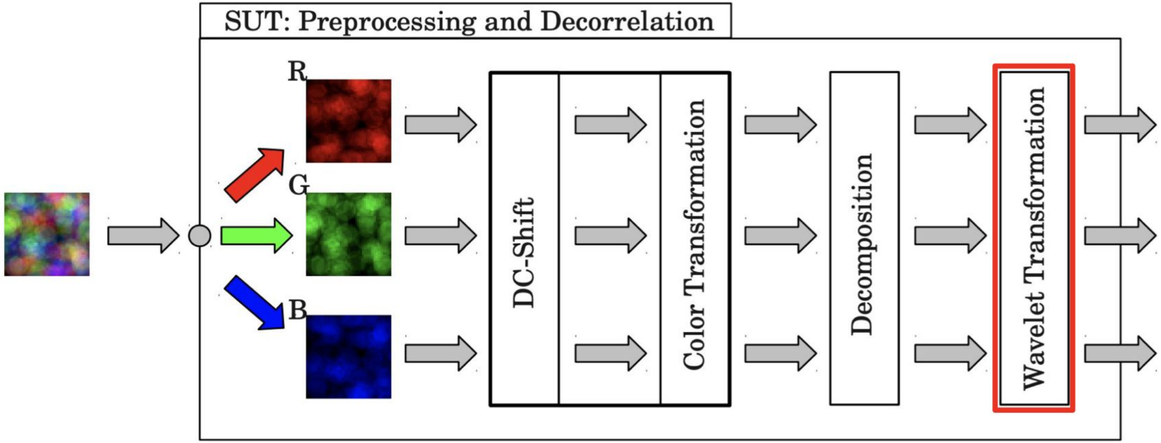

SUT: Preprocessing and Decorrelation

R

G

B

DC-Shift

Color Transformation

Decomposition

Wavelet Transformation

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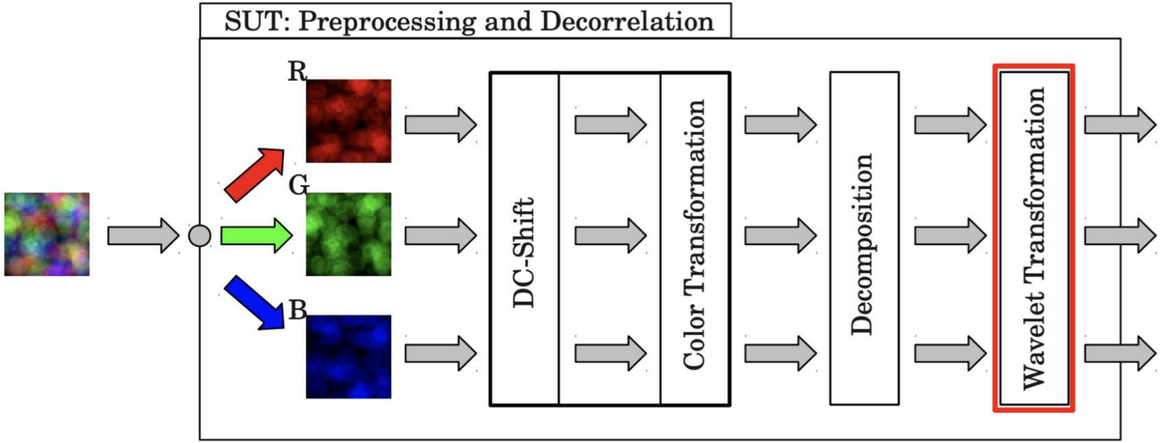

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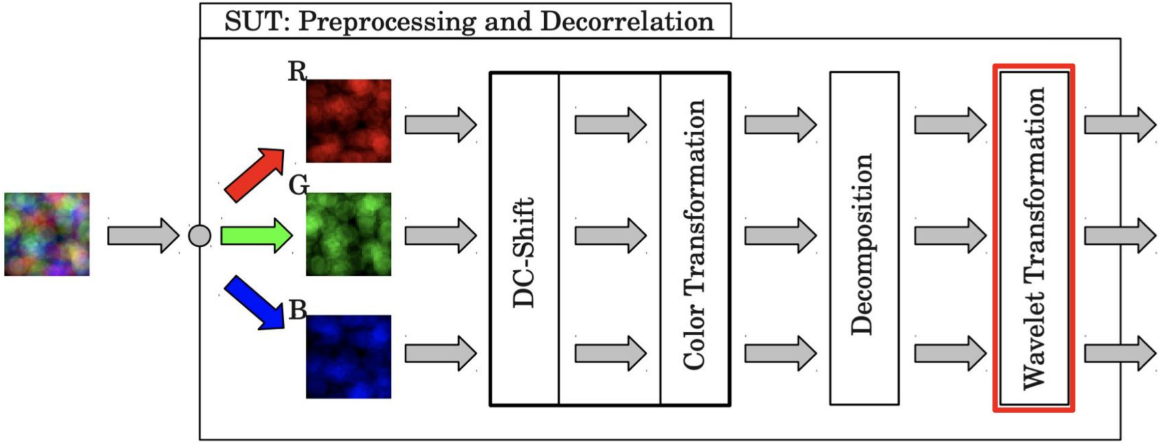

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- a relation R_i that can generate follow-up inputs
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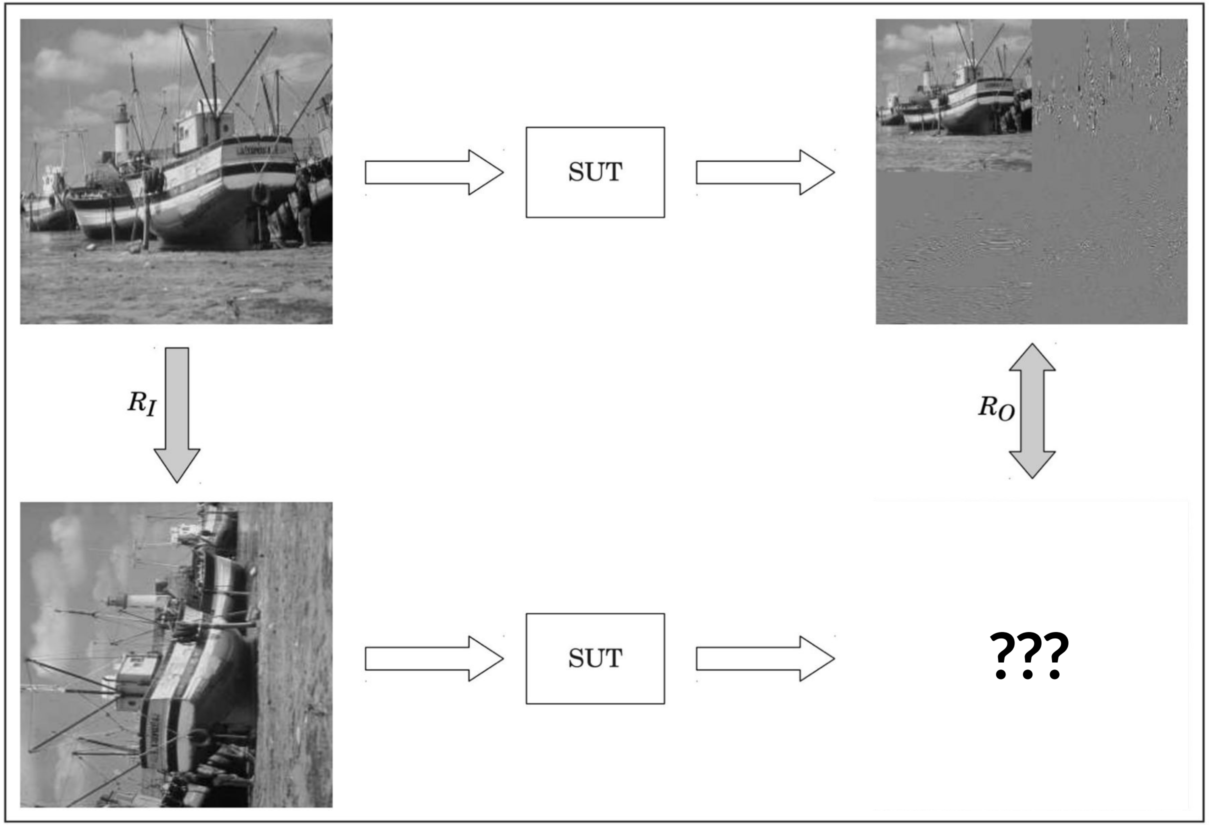

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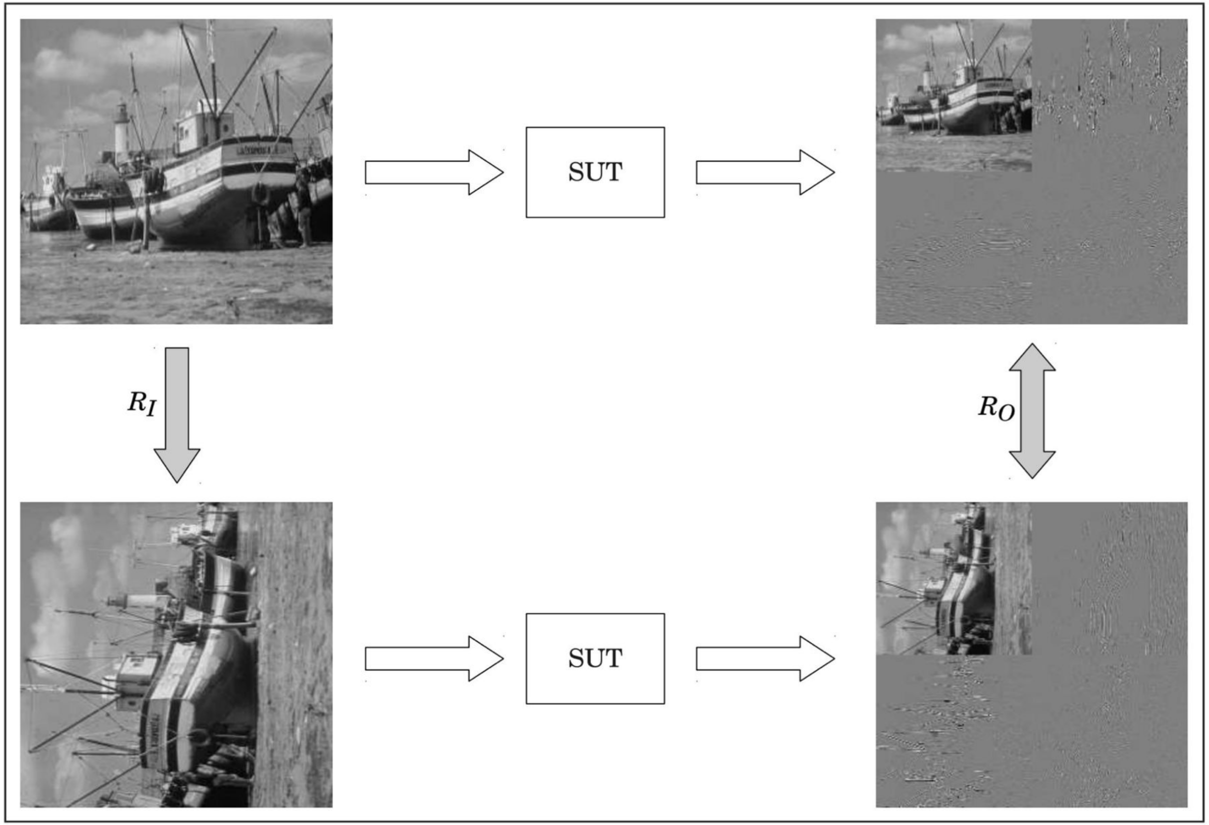

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1. R_i: Transpose the input image
   R_o: ???

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1. R_i: Transpose the input image
   R_o: The output components must also be transposed
2. R_i: Add a constant to all color values
   R_o: Only the DC components must change
3. R_i: Invert the color values
   R_o: The color values of the output must be inverted
4. R_i: Enlarge the input image (“zero-padding”)
   R_o: The output components must be shifted

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Some notes:

- these MRs are very **program-specific**
  - domain knowledge!
  - some MRs have interesting properties
    - e.g. MR 1 is commutative!
  - MR compositions are effective in practice

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- these MRs are very **program-specific**
  - domain knowledge!
- some MRs have interesting properties
  - e.g., MR 1 is **commutative**!
  - MR compositions are effective in practice

MT: DWT: concrete SUT: jpeg2000 encoder

1. R_i: Transpose the input image
   R_o: The output components m
2. R_i: Add a constant to all color
   R_o: Only the DC components
3. R_i: Invert the color values
   R_o: The color values of the ou
4. R_i: Enlarge the input image (“
   R_o: The output components m

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- some MRs have interesting properties
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  - especially when combined with a fuzzer for random input generation
- Often **difficult to apply**
  - designing MRs requires **domain expertise**
  - but easier for some kinds of systems than others
- My advice: **always** be on the lookout for opportunities to carry out metamorphic testing
  - **great value** in terms of increasing your confidence in a system's correctness vs effort you need to put in!

Agenda: remainder of today's lecture

- Property-based testing
- Metamorphic testing
- **Dynamic invariant detection**

Dynamic invariant detection: intuition

Observation: programs **usually** behave correctly

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- high-quality invariants can serve as test oracles

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Definition: a ***postcondition*** (to a function) is a condition that must be true when leaving (the function)

- it may (but does not have to) include expectations about the return value (of the function) or about side-effects

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Pros and cons: forward vs backward reasoning

Forward reasoning:

Backward reasoning:

Pros and cons: 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 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

Dynamic invariant detection: insight

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Dynamic invariant detection: insight

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  - Function **preco**
  - Function **postc**
  - Loop invariants (location = loop entry)

A ***loop invariant*** is an invariant that must hold at both the start and end of each iteration of the loop. We'll come back to this concept later in the semester, but for now don't worry too much about it.

Dynamic invariant detection: insight

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    - We can **detect** spurious false invariants

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  1. **generate** many candidate invariants
  2. **filter out** the false ones by running the tests!

Dynamic invariant detection: naive approach

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```
    while b do c
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  - **infinitely many :(**

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$x = c$	*constants*	$x < y$	*ordering*
$x \neq 0$	*non-zero*	$(x + y) \% b = a$	*math*
$x >= c$	*bounds*	$z = ax + by + c$	*linear*
$y = ax + b$	*linear*		

[Ernst, M. D., Cockrell, J., Griswold, W. G., & Notkin, D. (2001). *Dynamically discovering likely program invariants to support program evolution*.]

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- At most three variables => finite number of invariants to check

[Ernst, M. D., Cockrell, J., Griswold, W. G., & Notkin, D. (2001). *Dynamically discovering likely program invariants to support program evolution.*]

Dynamic invariant detection: Daikon

The Daikon invariant detection algorithm:

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The Daikon invariant detection algorithm:

- For every program location:
    - For **all triples** of in-scope variables:
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- cubic in in-scope variables
- linear in test suite size
- linear in program size

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In-class exercise: infer likely invariants

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i := 0
while i != N:
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Invariants to evaluate:

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- i<0
- i<=0
- i>0
- i>=0
- N=0
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- N>=0
- N>0
- i==N
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Evaluate invariants at program start, program end, and for the loop itself (i.e., loop invariants)

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- i>N
- i>=N

In-cla likely invariants

i is not in scope at the start of the program, so we don't need to evaluate invariants involving i

Progra

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in class we evaluated each invariant at both the start and end of the loop

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        - Example: *l + u – 1 <= 2p <= l + u* (binary search pivot)
- Nothing prevents a Daikon-like algorithm from finding these
    - but **templates are absolutely necessary** to permit Daikon to scale
        - and each additional template **bloats the complexity** (especially if it involves more variables!)

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- False positives from **linguistic coincidence**
  - e.g., `ptr % 4 == 0` or `x <= MAX_INT`
  - not false, but not related to correctness (or useful as an oracle)
    - these are true of any program!

HW5

- Two parts
  - run Daikon on a data structure of **your choice**
  - design some metamorphic relations for a real software system of **your choice**

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  - design some metamorphic relations for a real software system of **your choice**
- This homework expects you to make more decisions on your own than prior homeworks
  - that is, there are fewer guard rails
  - my advice: if you get stuck because of a difficulty with a system that you picked, remember that ***you can go back and choose a different system!*** (The course staff won't ever need to know!)