Even the Very Wise Cannot See All Ends: Many Facets of the Test Oracle Problem

Prof. T.H. Tse
The University of Hong Kong
Pokfulam, Hong Kong
Formula for A Successful Keynote Speech

\{ ? ! " " _ ^ \notin \rightarrow :-) \}
Formula for 
A Successful Keynote Speech

{ ? ! " " _ ^ ∉ -> :-) }

Comprehensive coverage
Formula for A Successful Keynote Speech

\{ ? ! " " _ ^ \notin -> :-) \} 

Bold questions

Comprehensive coverage
Formula for A Successful Keynote Speech

\{ ? ! " " _ ^ \notin \rightarrow :-) \}
Formula for A Successful Keynote Speech

{ ? ! " " _ ^ \notin -> :-) }

Learn from gurus
Profoundive assertions
Bold questions
Comprehensive coverage
Formula for A Successful Keynote Speech

\{ ? ! " " _ ^ \notin \to \) :-) \}
Formula for A Successful Keynote Speech

{ ? ! " " _ ^ ∈ -> :-) }

Solid foundations

Advanced concepts
Formula for A Successful Keynote Speech

\{  ?, ! " " _ ^ \notin - > ::- ) \}
Formula for A Successful Keynote Speech

\{ ? ! " " _ ^ \notin -> :-) \}

Real-world applications
Formula for A Successful Keynote Speech

{ ? ! " " _ ^ ∉ -> :-) }

Interesting stories

Real-world applications
Formula for A Successful Keynote Speech

\{ ? ! " " _ ^ \notin \rightarrow :-) \} 

Inspiring conclusions.

Interesting stories

Real-world applications
Presentation Outline

- Formula for a successful keynote speech
- A successful keynote speech.
Presentation Outline

- Background
Presentation Outline

- Background
- Many facets of the test oracle problem
Presentation Outline

- Background
- Many facets of the test oracle problem
  - **Expected outcome**
    - = actual execution result
Presentation Outline

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- Jungle of proposals
Presentation Outline

- **Background**
- **Many facets of the test oracle problem**
  - Expected outcome = actual execution result
  - Expected outcome = actual execution result
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- **Jungle of proposals**
- **Empirical studies?**
Presentation Outline

- Background
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- What do other researchers do?
Presentation Outline

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- Empirical studies?
- What do other researchers do?
- Trim the tree or tame the forest?
Background

Many facets of the test oracle problem

- Expected outcome = actual execution result
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Jungle of proposals
Empirical studies?
What do other researchers do?
Trim the tree or tame the forest?
Summary of My Work

- **Testing of object-oriented software**
  - Black and White [*ACM TOSEM* 1998]
  - TACCLE [*ACM TOSEM* 2001]
  - VITAMIN [*Communications of the ACM* 2007]
  - Equality to Equals and Unequals [*IEEE TSE* 2013].
Summary of My Work

- **Testing pervasive software**
  - [COMPSAC 2004 best paper]
  - [FSE 2006]
  - [ICSE 2008].
Summary of My Work

- **Testing services computing**
  - [ICSE 2008b]
  - [FSE 2009]
  - [WWW 2009]
  - [IEEE TSC 2015 spotlight paper]
  - [IEEE TSC 2015b].
Summary of My Work

- *Testing based on formal specifications*
  - Tabular Expressions [*IEEE TSE 2011*]
Summary of My Work

- **Testing based on formal specifications**
  - Tabular Expressions [*IEEE TSE* 2011]

- **Testing based on informal specifications**
  - CHOC’LATE [*IEEE TSE* 2003]
  - [Communications of the ACM 2010]
  - DESSERT [*IEEE TSE* 2012].
Summary of My Work

- **Spectrum-based fault localization**
  - [COMPSAC 2008 best paper]
  - [FSE 2009b]
  - [IEEE Computer 2012]
Summary of My Work

- **Spectrum-based fault localization**
  - COMPSAC 2008 best paper]
  - [FSE 2009b]
  - [IEEE Computer 2012]

- **Debugging of concurrent systems**
  - [Information Sciences 2012]
  - [ISSTA 2012].
Summary of My Work

- Integration of testing, debugging, and proving
  - [COMPSAC 2009 best paper]
  - [QSIC 2011 best paper]
  - [IEEE TSE 2011b].
Selected PhD Graduates

- Dr W.K. Chan, Associate Professor, City University of Hong Kong
- Dr Zhenyu Zhang, Associate Professor, Institute of Software, Chinese Academy of Sciences
- Dr Bo Jiang, Associate Professor, Beihang University
- Dr Lijun Mei, IBM Research — China
- Dr Ke Zhai, Goldman Sachs.
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- **Many facets of the test oracle problem**
  - Expected outcome = actual execution result
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The Test Oracle Problem

Even the Very Wise Cannot See All Ends:
Many Facets of the Test Oracle Problem

Prof. T.H. Tse
The University of Hong Kong
Pokfulam, Hong Kong

Present 20 years of work in 45 minutes
Many Facets of the Test Oracle Problem

Even the Very Wise Cannot See All Ends

J.R.R. Tolkien
The Lord of the Rings
Many Facets of the Test Oracle Problem

Even the Very Wise Cannot See All Ends

Many Facets of the Test Oracle Problem

Prof. T.H. Tse
The University of Hong Kong
Pokfulam, Hong Kong

J.R.R. Tolkien
The Lord of the Rings

- Rawlinson and Bosworth Professor of Anglo-Saxon, University of Oxford (1925–1945)
- Merton Professor of English Language and Literature, University of Oxford (1945–1959).
Oracle

- A message supposedly from God’s inspiration, usually given by a priest
Oracle

- A message supposedly from God’s inspiration, usually given by a priest
- An utterance of deep import or wisdom; an opinion or declaration regarded as authoritative and infallible; undeniable truth.
Oracle

- A message supposedly from God’s inspiration, usually given by a priest
- An utterance of deep import or wisdom; an opinion or declaration regarded as authoritative and infallible; undeniable truth.
Test Oracle

- A *test oracle* is a mechanism to check whether
  - expected outcome according to the specification
    = actual result of executing the implementation.
Real-Life Search Engine Example
Real-Life Search Engine Example

Is 2.77M results correct?
Many Facets of the Test Oracle Problem

Challenge 1:

- **Expected outcome** = actual execution result
Metamorphic Testing

\[ \sin 0.9876 \]  

Expected ?  

Actual 0.8347
Metamorphic Testing

- Cannot be verified because we do not know what to expect

\[
\sin 0.9876
\]
Metamorphic Testing

- \( \sin 0.9876 \)
  - Expected: ?
  - Actual: 0.8347

- Cannot be verified because we do not know what to expect

- Take a follow-up test case:
  - \( \sin (\pi - 0.9876) \)
  - Expected: ?
  - Actual: 0.8347
Metamorphic Testing

\[ \sin 0.9876 \]

\[ \sin (\pi - 0.9876) \]

Expected \[ ? \]  Actual \[ 0.8347 \]
<table>
<thead>
<tr>
<th>Expression</th>
<th>Expected</th>
<th>Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin 0.9876$</td>
<td></td>
<td>0.8347</td>
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<tr>
<td>$\sin (\pi - 0.9876)$</td>
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Metamorphic Testing

\[
\sin(0.9876) = \sin(\pi - 0.9876)
\]

Expected metamorphic relation

\[
\begin{align*}
\sin(0.9876) &= \text{Expected} \, ? \quad \text{Actual} \, 0.8347 \\
\sin(\pi - 0.9876) &= \text{Expected} \, ? \quad \text{Actual} \, 0.8347
\end{align*}
\]
**Metamorphic Testing**

\[
\sin 0.9876 = \sin (\pi - 0.9876)
\]

**Expected metamorphic relation**

- Expected: 
  - Value: 0.8347
- Actual: 
  - Value: 0.8347
Metamorphic Testing

\[
\sin 0.9876
\]

\[
\sin (\pi - 0.9876)
\]

Expected metamorphic relation

\[
\sin 0.9876 = \sin (\pi - 0.9876)
\]

Expected

Actual

Actual relation

0.8347 = 0.8347
Real-Life Search Engine Example

Apply Metamorphic Testing

Real-Life Example

Is 2.77M results correct?

Metamorphic Relation:
More refined search should produce fewer number of entries.
Real-Life Search Engine

Refine to “children’s hospital of chicago”.

More entries indicate failure in search engine.
Real-Life Search Engine Example

Is 4.54M results correct?

hotel near "children's hospital" chicago

Ann and Robert H. Lurie Children's Hospital of Chicago in...

Lurie Children's Hospital of Chicago in Chicago, IL is ranked nationally in 10 pediatric specialties. Ann and Robert H...

health.usnews.com/best...

The University of Chicago Medicine Comer Children's Hospital

The University of Chicago Medicine Comer Children's Hospital is a state-of-the-art children's hospital. Our teams of pediatric experts use advanced ...

www.uchicagokidshospital...
Real-Life Search Engine

Refine to "children’s hospital of chicago".

More entries indicate failure in search engine.
Real-Life Search Engine Example

Human Issues

😊 Microsoft Research selected our project for a Virtual Earth award
😊 Each of my brothers has 2 doctoral degrees
😊 I have only one doctoral degree.

😢 Google asked us to submit a bug report
Metamorphic Testing

Other Real-World Applications

- Services computing
- Ubiquitous computing
- Concurrent systems
- Graphic applications
- Numerical programs.
Metamorphic Testing
Recent Track Records

Compilers

- Based on metamorphic testing, an “equivalence modulo inputs” technique identified 147 unique faults in GCC and LLVM using one metamorphic relation
Compilers

- Based on metamorphic testing, an “equivalence modulo inputs” technique identified 147 unique faults in GCC and LLVM using one metamorphic relation.

Siemens Suite

- Detected 3 new faults in Siemens suite after its long history of test case studies.
Many Facets of the Test Oracle Problem

Challenge 2:

- Expected outcome = actual execution result
Many Facets of the Test Oracle Problem

Challenge 2:

- Expected outcome $\Rightarrow$ actual execution result
- Consider the testing of real-life object-oriented software.
Testing of Object-Oriented Software
Our Real-Life Experience

- Technology-transfer project for ASM, the world’s largest supplier of assembly and packaging equipment for the semiconductor industry.
Testing of Object-Oriented Software

- Robotic arm after handling *problem* chip
- Expected Home afresh
- Actual Home afresh
- Simple concept in specification
- Complex implementation
Many Facets of the Test Oracle Problem

Challenge 2:
- Expected outcome ≠ actual execution result
- Consider the testing of real-life object-oriented software

Cannot define “=” at two different levels of abstraction.
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Testing of Object-Oriented Software

Mimic Metamorphic Testing?

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Mimic Metamorphic Testing?

Robotic arm after handling *problem* chip

Robotic arm after handling *standard* chip

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Robotic arm after handling problem chip

Robotic arm after handling standard chip
### Testing of Object-Oriented Software

**Mimic Metamorphic Testing?**

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Testing of Object-Oriented Software

Mimic Metamorphic Testing?

Robotic arm after handling *problem* chip

Robotic arm after handling *standard* chip

Expected

Home afresh

Actual

Home afresh

Home afresh

Home afresh
Testing of Object-Oriented Software

Mimic Metamorphic Testing?

Robotic arm after handling *problem* chip

Robotic arm after handling *standard* chip

Expected relation

Equivalent
Testing of Object-Oriented Software

Mimic Metamorphic Testing?

Robotic arm after handling *problem* chip

Robotic arm after handling *standard* chip

Expected relation

Equivalent
Robotic arm after handling *problem* chip

Robotic arm after handling *standard* chip

Expected relation

Equivalent

Actual relation

Equivalent
An implementation $P$ is correct with respect to the specification $Sp$ if and only if

- For any pair of equivalent sequences of operations in $Sp$, the actual objects resulting from $P$ must be equivalent.
**Challenge 3:**

- Object A = object B

What is object equivalence?
T.H. Tse is an Honorary Professor in Computer Science at The University of Hong Kong.
What is Object Equivalence?

Real-Life Word Processing Example

T.H. Tse is an Honorary Professor in Computer Science at The University of Hong Kong. He is a Steering Committee Chair of the IEEE International Conference on Software Quality, Reliability & Security.
What is Object Equivalence?

Real-Life Word Processing Example

Call this object $O$.

T.H. Tse is an Honorary Professor in Computer Science at The University of Hong Kong. He is a Steering Committee Chair of the IEEE International Conference on Software Quality, Reliability & Security. He was on the search committee for the editor-in-chief of *IEEE Transactions on Software Engineering* in 2013.
What is Object Equivalence?

Real-Life Word Processing Example

Click “Hidden”.

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What is Object Equivalence?

Real-Life Word Processing Example

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Call this object $H$. 
What is Object Equivalence?

Output from Object $H$

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What is Object Equivalence?

Real-Life Word Processing Example

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Take object $O$ again.
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What is Object Equivalence?

Real-Life Word Processing Example

Call this object $D$. 

T.H. Tse is an Honorary Professor in Computer Science at The University of Hong Kong. He is a Steering Committee Chair of the IEEE International Conference on Software Quality, Reliability & Security.
What is Object Equivalence?

Output from Object $D$

T.H. Tse is an Honorary Professor in Computer Science at The University of Hong Kong. He is a Steering Committee Chair of the IEEE International Conference on Software Quality, Reliability & Security.
**What is Object Equivalence?**

**Attributive Equivalence**

- Two objects will be *attributively equivalent* if they have the exactly the same *visible attributes.*
What is Object Equivalence?

Attributive Equivalence

- Simple to test
- *But* the definition is too weak to be useful ...
- Why?
T.H. Tse is an Honorary Professor in Computer Science at The University of Hong Kong, a Steering Committee Chair of the IEEE International Conference on Software Quality, Reliability & Security.
What is Object Equivalence?

Real-Life Word Processing Example

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What is Object Equivalence?

Real-Life Word Processing Example

We get an object that behaves like the original object $O$.

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What is Object Equivalence?

Real-Life Word Processing Example

T.H. Tse is an Honorary Professor in Computer Science at The University of Hong Kong, and a Steering Committee Chair of the IEEE International Conference on Software Quality, Reliability & Security.

Take object $D$ again (with deleted text).
What is Object Equivalence?

Real-Life Word Processing Example

T.H. Tse is an Honorary Professor in Computer Science at The University of Hong Kong. He is a Steering Committee Chair of the IEEE International Conference on Software Quality, Reliability & Security.
What is Object Equivalence?

Real-Life Word Processing Example

We do not get an object that behaves like the original $O$. 

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What is Object Equivalence?

Observational Equivalence

- Two objects will be observationally equivalent if they have the exactly the same visible attributes and behavior.
What is *Object Equivalence*?

**Observational Equivalence**

- Ideal criterion in object-oriented software testing

- *But* very very very very very very very very very very very very very very very very very very very very very very very very very very very very very very very very very very very very very very very very very very very very very very very very very very very very very very very very very very very very very difficult to verify:
  - Need to check an infinite combination of possible behavior for every test case.
UML State Machine Not Truly Suitable for OO Specification

- Cannot distinguish between visible and hidden attributes and behavior
- Cannot distinguish between attributive and observational equivalence
Algebraic Specification

- A **ground term** is a sequence of operations
  - $\text{show}($HKU QRS hide(TSE)$)$

- An **axiom** is a rule that specifies the refinement of a term
  - $\text{hide}($D D'$) = \text{hide}($D$) \text{hide}($D'$)$
  - $\text{show}($D D'$) = \text{show}($D$) \text{show}($D'$)$
  - $\text{show}($\text{hide}($D$)$) = \text{show}($D$)$
  - $\text{show}($W$) = W$
Algebraic Specification

- A ground term may be transformed into another using axioms as left-to-right rewrite rules, until it reaches a *normal form*
A ground term may be transformed into another using axioms as left-to-right rewrite rules, until it reaches a *normal form*

\[
\text{show}(\text{HKU QRS hide(TSE)})
\]
A ground term may be transformed into another using axioms as left-to-right rewrite rules, until it reaches a *normal form*

\[
\text{show}(HKU \ QRS \ \text{hide}(TSE)) \\
\rightarrow \text{show}(HKU) \ \text{show}(QRS) \ \text{show}(\text{hide}(TSE)) \\
\text{show}(D \ D') = \text{show}(D) \ \text{show}(D')
\]
A ground term may be transformed into another using axioms as left-to-right rewrite rules, until it reaches a normal form.

\[
\text{show(HKU QRS hide(TSE))} \\
\Rightarrow \text{show(HKU) show(QRS) show(hide(TSE))} \\
\Rightarrow \text{show(HKU) show(QRS) show(TSE)}
\]

\[
\text{show(hide(D)) = show(D)}
\]
Algebraic Specification

- A ground term may be transformed into another using axioms as left-to-right rewrite rules, until it reaches a normal form

\[
\text{show(HKU QRS hide(TSE))} \\
\rightarrow \text{show(HKU) show(QRS) show(hide(TSE))} \\
\rightarrow \text{show(HKU) show(QRS) show(TSE)} \\
\rightarrow \text{HKU QRS TSE}
\]

\[
\text{show(W) = W}
\]
A ground term may be transformed into another using axioms as left-to-right rewrite rules, until it reaches a **normal form**

\[
\text{show}(\text{HKU QRS hide(TSE)}) \\
\Rightarrow \text{show}(\text{HKU}) \text{ show}(\text{QRS}) \text{ show}(\text{hide(TSE)}) \\
\Rightarrow \text{show}(\text{HKU}) \text{ show}(\text{QRS}) \text{ show}(\text{TSE}) \\
\Rightarrow \text{HKU QRS TSE}
\]

*Normal form.*
Algebraic Specification

Denotational Semantics

- Mathematical meaning
- Like simultaneous equations
  \[
  \begin{align*}
  2x + 3y &= 4 \\
  5x + 6y &= 7
  \end{align*}
  \]
  - “=” means “equals”
  - The order of the equations is not important.
Algebraic Specification

Operational Semantics

- How the statements should be executed
- Like C programs
  
  ```
  j = 1;
  j = j + 2;
  ```

  - Replace the variable on the left-hand side by the value on the right-hand side.
An algebraic specification is *canonical* if every sequence of rewrites of a ground term produces a unique normal form.
An algebraic specification is *canonical* if every sequence of rewrites of a ground term produces a unique normal form.

\[
\text{show(HKU)} \quad \text{show(QRS)} \quad \text{show(hide(TSE))} \\
\rightarrow \quad \text{show(HKU)} \quad \text{show(QRS)} \quad \text{show(TSE)} \\
\rightarrow \quad \text{HKU} \quad \text{QRS} \quad \text{TSE}
\]
An algebraic specification is *canonical* if every sequence of rewrites of a ground term produces a unique normal form:

\[
\text{show(HKU) show(QRS) show(hide(TSE))} \\
\Rightarrow \text{show(HKU) show(QRS) show(TSE)} \\
\Rightarrow \text{HKU QRS TSE}
\]

\[
\text{show(HKU) show(QRS) show(hide(TSE))} \\
\Rightarrow \text{HKU QRS show(hide(TSE))} \\
\Rightarrow \text{HKU QRS TSE}
\]
For a *canonical* specification, the operational semantics agrees with the denotational semantics.
An implementation $P$ is correct with respect to the specification $S_p$ if and only if
An implementation $P$ is correct with respect to the specification $Sp$ if and only if

- $P$ satisfies the set $(AE)$ of all **attributively equivalent** pairs of ground terms in $Sp$

For example, $\text{hide(TSE)}$ and $\text{delete(TSE)}$ are attributively equivalent.
Target of OO Software Testing

According to Huo Yan Chen et al. (1998)
An implementation $P$ is correct with respect to the specification $Sp$ if and only if:

- **Equivalence Criterion**
  $P$ satisfies the set ($OE$) of all observationally equivalent pairs of ground terms in $Sp$
An implementation $P$ is correct with respect to the specification $Sp$ if and only if:

- **Equivalence Criterion**
  $P$ satisfies the set ($OE$) of all observationally equivalent pairs of ground terms in $Sp$.

- **Non-Equivalence Criterion**
  $P$ satisfies the set ($OE'$) of all observationally nonequivalent pairs of ground terms in $Sp$.

For example, $\text{hide}(TSE)$ and $\text{delete}(TSE)$ are observationally nonequivalent.
Targets of OO Software Testing

\[ \text{AE} \]
Real-world short-cut, but too weak to be useful

\[ ? \]
A jungle of proposals by various researchers.

\[ \text{OE} \cup \text{OE'} \]
Real-world correctness, but very very very very very very very very very very difficult to test.
Target of OO Software Testing


- An implementation $P$ is correct with respect to the specification $Sp$ if and only if
  - $P$ satisfies the set $(GI)$ of all *ground instances* of every axiom in $Sp$
An implementation $P$ is correct with respect to the specification $Sp$ if and only if:

- **Equivalence Criterion**
  $P$ satisfies the set $(RP)$ of all “equivalent” ground pairs such that one can be rewritten to the other using axioms in $Sp$ as left-to-write rewrite rules.
An implementation $P$ is correct with respect to the specification $Sp$ if and only if:

- **Equivalence Criterion**
  $P$ satisfies the set $(RP)$ of all “equivalent” ground pairs such that one can be rewritten to the other using axioms in $Sp$ as left-to-write rewrite rules.

- **Non-Equivalence Criterion**
  $P$ satisfies the set $(RP')$ of all “nonequivalent” ground pairs.
An implementation $P$ is correct with respect to the specification $Sp$ if and only if

- $P$ satisfies the set $\{FP\}$ of all fundamental pairs in $Sp$
An implementation $P$ is correct with respect to the specification $Sp$ if and only if:

- **Equivalence Criterion**
  
  $P$ satisfies the set $(NE)$ of all normally equivalent ground pairs in $Sp$
An implementation \( P \) is correct with respect to the specification \( Sp \) if and only if:

- **Equivalence Criterion**
  \( P \) satisfies the set \( (NE) \) of all normally equivalent ground pairs in \( Sp \)

- **Non-Equivalence Criterion**
  \( P \) satisfies the set \( (NE') \) of all normally nonequivalent ground pairs in \( Sp \)
An implementation $P$ is correct with respect to the specification $Sp$ if and only if

- $P$ satisfies the set $(CI)$ of all ground instances of every axiom in $Sp$ that contains creators or constructors only.
Targets of OO Software Testing

- Comparisons through empirical studies?
What is Empirical Study?

- Research based on experimentation or observation to answer a specific question or to test a hypothesis
- Undue emphasis in software engineering, even in first-tier publication venues.
What is Empirical Study?

- Statistical significance does not mean research significance

- A hypothesis may be very probable simply because it tells us nothing, or very little

Sir Karl Popper, Professor of Logic and Scientific Method, London School of Economics (1949–1969)
What is Empirical Study?

- Statistical significance does not mean research significance
  - A hypothesis may be very probable simply because it tells us nothing, or very little
  - A high degree of probability is therefore not an indication of “goodness”

Sir Karl Popper, Professor of Logic and Scientific Method, London School of Economics (1949–1969)
What is Empirical Study?

- Statistical significance does not mean research significance
  - A hypothesis may be very probable simply because it tells us nothing, or very little
  - A high degree of probability is therefore not an indication of “goodness”
  - It may be merely a symptom of low informative content.

Sir Karl Popper, Professor of Logic and Scientific Method, London School of Economics (1949–1969)
Presentation Outline

- Background
- Many facets of the test oracle problem
  - Expected outcome = actual execution result
  - Expected outcome = actual execution result
  - Expected outcome = actual execution result
- Jungle of proposals
- Empirical studies?
- **What do other researchers do?**
- Trim the tree or tame the forest
What Do Other Researchers Do?

General Relativity

- luminiferous aether
- corpuscular model
- Lorentz’s theory of electrons
- electromagnetic mass
- absolute space and time
- light constancy
- principle of relative motion
- gravitational time dilation
- hole argument
- general covariance
- gravitational redshift
- field equations

- A jungle of proposals
What Do Other Researchers Do?
General Relativity

So many people today — and even professional scientists — seem to me like somebody who has seen thousands of trees but has never seen a forest.

Albert Einstein
_The Collected Papers of Albert Einstein_
Princeton University Press
What Do Other Researchers Do?

General Relativity

◆ Trim the individual trees?

◆ Tame the forest!

What Do Others Do?

General Relativity

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◆ A jungle of proposals

Albert Einstein
What Do Other Researchers Do?

Spectrum-Based Fault Localization

- Risk evaluation formulas

- AMPLEx2
- Anderberg
- Arithmetic Mean
- Binary
- CBI Inc.
- Cohen
- Dice
- Euclid
- Fleiss
- Goodman
- Hamann
- Hamming, etc.
- Jaccard
- Kulczynski2
- M2
- Naish1
- Naish2
- Ochiai
- $q_e$
- Rogers & Tanimoto
- Rogot1
- Russel & Rao
- Scott
- Simple Matching
- Sokal
- Sørensen-Dice
- Tarantula
- Wong1
- Wong2
- Wong3
What Do Other Researchers Do?

Spectrum-Based Fault Localization

- Another jungle of proposals
- Comparisons through empirical studies in *IEEE TSE*, *ICSE*, and *FSE*. 
What Do Other Researchers Do?
Spectrum-Based Fault Localization

- Trim the individual trees?
- Tame the forest!

What Do Others Do?
Spectrum-Based Fault Localization

- Risk evaluation formulas
  - AMPL\textsuperscript{E2}, Anderberg, Arithmetic Mean, Binary, CBI Inc., Cohen
  - Dice, Euclid, Fleiss, Goodman, Hamann, Hamming, etc.
  - Jaccard, Kulczynski2, M2, Naish1, Naish2, Ochiai, $\phi_e$
  - Rogers & Tanimoto, Rogot1, Russel & Rao, Scott, Simple Matching
  - Sokal, Sørensen-Dice, Tarantula, Wong1, Wong2, Wong3

T.Y. Chen and Team
Spectrum-Based Fault Localization

According to T.Y. Chen and Team (2013)

- Theoretical framework to compare risk evaluation formulas for single-fault programs
- No single formula can outperform the rest
- Among the formulas under study, only five are “maximal”
- Most of best-known formulas are not among them.
Test Case Generation Techniques
According to T.Y. Chen and Team (2008)

- Prove that no test case generation technique can be better than random testing by more than 50%
  - in the absence of further information on possible locations of failure-causing inputs
- Adaptive random testing is close to this theoretic limit.
Partition Testing Techniques
According to T.Y. Chen and Team (2000)

- Prove that proposed proportional sampling strategy is the only partition testing technique that ensures probability of finding at least one failure is no lower than random testing for any program.
Targets of OO Software Testing

- Trim the individual trees?
- Tame the forest!

Comparisons through empirical studies?
Toward Ultimate Target of OO Software Testing

Tame the Forest

- $FP \subset CI \subset GI \subset RP \subset NE \subset OE \subset AE$

Subset but not equal
Toward Ultimate Target of OO Software Testing

Tame the Forest

- \( FP \subset CI \subset GI \subset RP \subset NE \subset OE \subset AE \)
- \( OE \subset OE \cup OE' \) (Subset but not equal)
- Hence, \((P\text{ satisfies } AE) \Rightarrow (P\text{ satisfies } OE)\)
  \(\Rightarrow (P\text{ satisfies } NE) \Rightarrow (P\text{ satisfies } RP)\)
  \(\Rightarrow (P\text{ satisfies } GI) \Rightarrow (P\text{ satisfies } CI)\)
  \(\Rightarrow (P\text{ satisfies } FP)\) and
- \((P\text{ satisfies } OE \cup OE') \Rightarrow (P\text{ satisfies } OE)\)

Not helpful.
Ultimate Target of OO Software Testing

Tame the Forest

- Have we made full use of algebraic specifications?
- Given a **canonical** specification $S_p$ with **proper imports** and a **complete** implementation $P$
  - $(P$ satisfies $AE)$
Have we made full use of algebraic specifications?

Given a *canonical* specification $Sp$ with *proper imports* and a *complete* implementation $P$

- $(P$ satisfies $AE)$
  $\iff (P$ satisfies $OE)$
Have we made full use of algebraic specifications?

Given a *canonical* specification $\text{Sp}$ with *proper imports* and a *complete* implementation $P$

$(P \text{ satisfies } AE) \iff (P \text{ satisfies } OE) \iff (P \text{ satisfies } OE')$
Ultimate Target of OO Software Testing

Tame the Forest

- Have we made full use of algebraic specifications?
- Given a *canonical* specification $Sp$ with *proper imports* and a *complete* implementation $P$
  - $(P \text{ satisfies } AE) \iff (P \text{ satisfies } OE) \iff (P \text{ satisfies } OE') \iff (P \text{ satisfies } OE \cup OE')$
Tame the Forest

- Have we made full use of algebraic specifications?
- Given a \textit{canonical} specification $Sp$ with \textit{proper imports} and a \textit{complete} implementation $P$
  
  - ($P$ satisfies $AE$)
    \iff ($P$ satisfies $OE$) \iff ($P$ satisfies $OE'$)
    \iff ($P$ satisfies $OE \cup OE'$)
    \iff ($P$ satisfies $NE$) \iff ($P$ satisfies $RP$)
    \iff ($P$ satisfies $GI$) \iff ($P$ satisfies $CI$)
    \iff ($P$ satisfies $FP$).
**Ultimate Target of OO Software Testing**

**Tame the Forest**

**In short**

- Given a *canonical* specification $Sp$ with *proper imports* and a *complete* implementation $P$
  
  $$ (P \text{ satisfies } AE) \iff (P \text{ satisfies } OE \cup OE') $$

Real-world short-cut considered too weak to be useful

Real-world correctness considered too difficult to test.
Many Facets of the Test Oracle Problem

**Challenge 4:**

- Expected outcome = actual execution result
Ubiquitous Computing

- Computing everywhere and at any time
- Applications operate in dynamic environment
Ubiquitous Computing

- Computing everywhere and at any time
- Applications operate in dynamic environment
- Expected outcome = actual execution result
Ubiquitous Computing

- Computing everywhere and at any time
- Applications operate in dynamic environment
- Expected outcome = actual execution result
- When does a test case end?
Ubiquitous Computing

- Computing everywhere and at any time
- Applications operate in dynamic environment
- Expected outcome = actual execution result
- When does a test case end?
  - Middleware remains active and environment context keeps changing!
Ubiquitous Computing
Expected and Actual Context Trends

- Expected Result
- Actual result

Any difference?
Ubiquitous Computing

- Computing everywhere and at any time
- Applications operate in dynamic environment
- Expected outcome = actual execution result
- When does a test case end?
  - Middleware remains active and environment context keeps changing!

- Identify **checkpoints** where the system is momentarily stable.
Conclusion

- Many facets of the test oracle problem
Conclusion

Many facets of the test oracle problem

- **Expected outcome** = actual execution result

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Metamorphic testing

Many facets of metamorphic testing.
Many facets of the test oracle problem
- Expected outcome = actual execution result
- Expected outcome = actual execution result

Algebraic specifications

Many facets of algebraic specifications.
Conclusion

- Many facets of the test oracle problem
  - Expected outcome = actual execution result
  - Expected outcome = actual execution result
  - Expected outcome = actual execution result

Many facets of ubiquitous computing.
Conclusion

- Jungle of problems
- Jungle of proposals
- Empirical studies are just an exploratory first step rather than the ultimate goal
- Tame the forest rather than trimming individual trees.
Your Comments are Welcome
Thank you
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