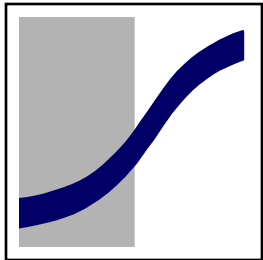


Even the Very Wise Cannot See All Ends:

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

{ ? ! " " _ ^ € - > :-) }

Formula for A Successful Keynote Speech

{ ? ! " " _ ^ € - > :-) }



Comprehensive coverage

Formula for A Successful Keynote Speech

{ ? ! " " _ ^ € - > :-) }

Bold questions

Comprehensive coverage

Formula for A Successful Keynote Speech

{ ? ! " " _ ^ € - > :-) }



Provocative assertions



Bold questions



Comprehensive coverage

Formula for A Successful Keynote Speech

{ ? ! " " _ ^ € - > :-) }

Learn from gurus

Provocative assertions

Bold questions

Comprehensive coverage

Formula for A Successful Keynote Speech

{ ? ! " " _ ^ € - > :-) }



Solid foundations

Formula for A Successful Keynote Speech

{ ? ! " " _ ^ € - > :-) }

Solid foundations

Advanced concepts

Formula for A Successful Keynote Speech

{ ? ! " " _ ^ € - > :-) }

Avoid formalism

Advanced concepts

Solid foundations

Formula for A Successful Keynote Speech

{ ? ! " " _ ^ € - > :-) }



Real-world applications

Formula for A Successful Keynote Speech

{ ? ! " " _ ^ € - > :-) }



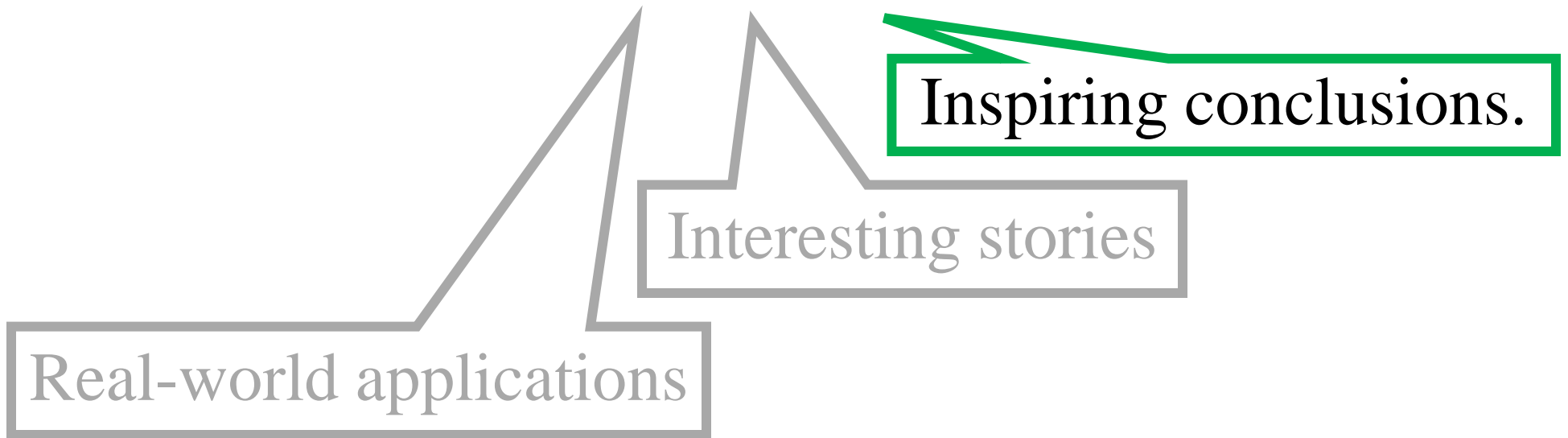
Interesting stories



Real-world applications

Formula for A Successful Keynote Speech

{ ? ! " " _ ^ € - > :-) }



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
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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
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- ◆ Background
- ◆ Many facets of the test oracle problem
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- ◆ Empirical studies?
- ◆ What do other researchers do?
- ◆ Trim the tree or tame the forest? .

Presentation Outline

◆ **Background**

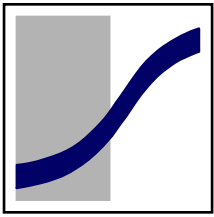
- ◆ Many facets of the test oracle problem

- Expected outcome
= actual execution result

- Expected outcome
= actual execution result

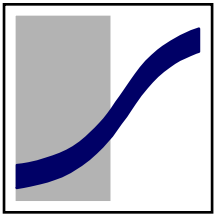
- Expected outcome
= actual execution result

- ◆ Jungle of proposals
- ◆ Empirical studies?
- ◆ What do other researchers do?
- ◆ Trim the tree or tame the forest?



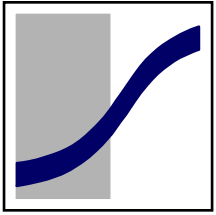
Summary of My Work

- ◆ *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

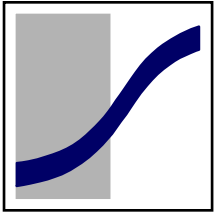
- ◆ *Testing pervasive software*
 - [*COMPSAC 2004* best paper]
 - [*FSE 2006*]
 - [*ICSE 2008*].



Summary of My Work

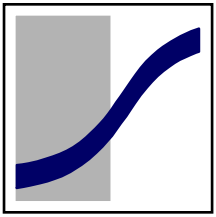
◆ *Testing services computing*

- [ICSE 2008b]
- [FSE 2009]
- [WWW 2009]
- [IEEE TSC 2015 spotlight paper]
- [IEEE TSC 2015b].



Summary of My Work

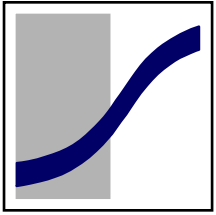
- ◆ *Testing based on formal specifications*
 - Tabular Expressions [*IEEE TSE* 2011]



Summary of My Work

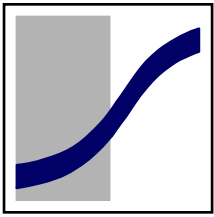
- ◆ *Testing based on formal specifications*
 - Tabular Expressions [*IEEE TSE* 2011]

- ◆ *Testing based on informal specifications*
 - CHOC'LATE [*IEEE TSE* 2003]
 - [Communications of the ACM 2010]
 - DESSERT [*IEEE TSE* 2012].



Summary of My Work

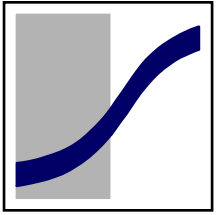
- ◆ *Spectrum-based fault localization*
 - [*COMPSAC 2008 best paper*]
 - [*FSE 2009b*]
 - [*IEEE Computer 2012*]



Summary of My Work

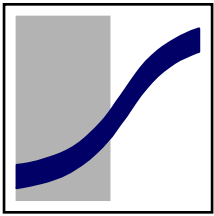
- ◆ *Spectrum-based fault localization*
 - *COMPSAC 2008 best paper]*
 - *[FSE 2009b]*
 - *[IEEE Computer 2012]*

- ◆ *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

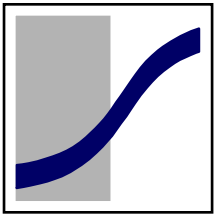
Dr W.K. Chan, Associate Professor,
City University of Hong Kong

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.



Selected PhD Graduates

Dr W.K. Chan, Associate Professor, City University of Hong Kong

Dr Yan Cai, Associate Professor, Institute of Software, Chinese Academy of Sciences.

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

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?



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

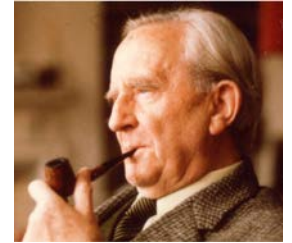
Even the Very Wise Cannot See All Ends

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



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

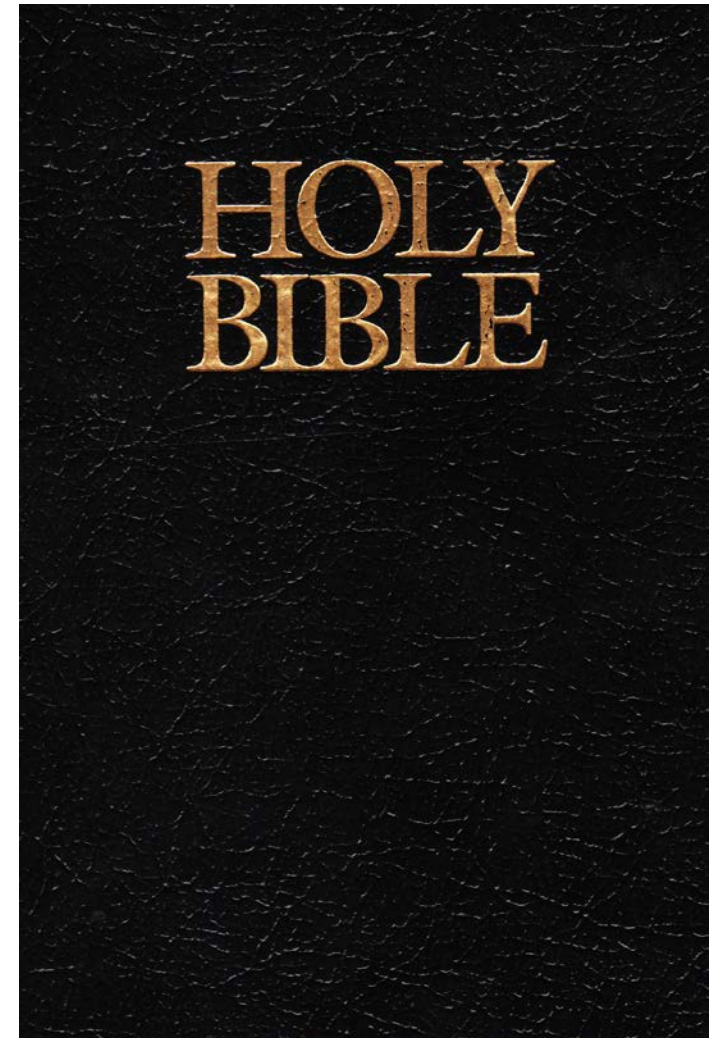
The Lord of the Rings



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

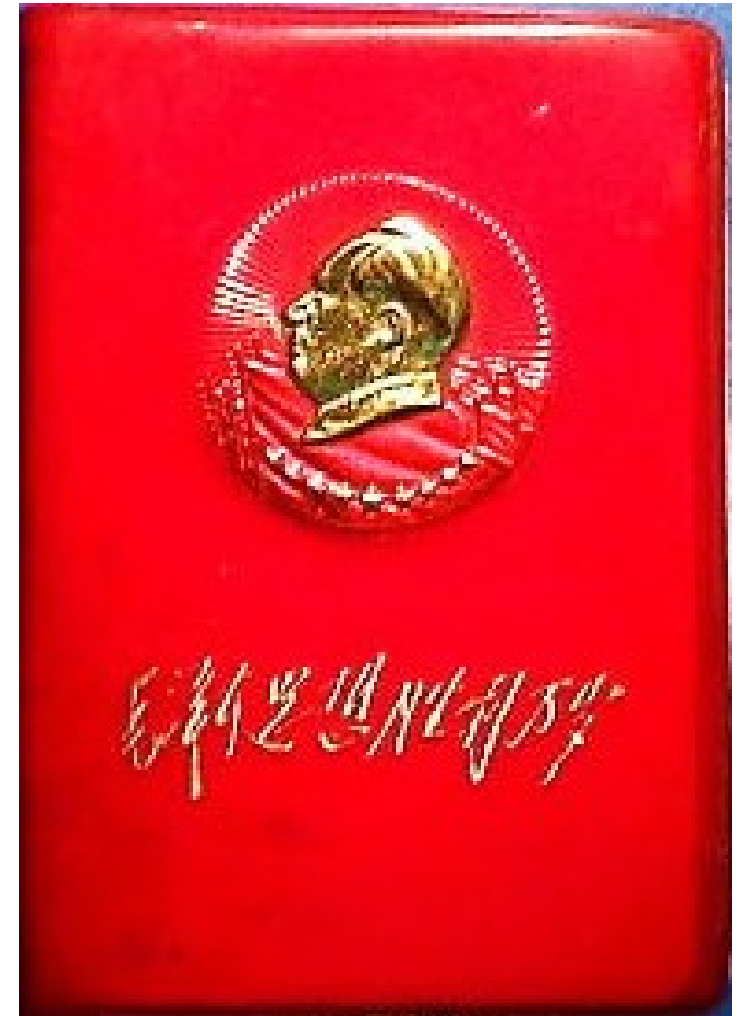
Oracle

- ◆ 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

Ann & Robert H. Lurie Children's Hospital of Chicago
Formerly Children's Memorial Hospital

Care & Services > Research > Get Involved > Community >

Enter Keyword(s) Search

William T. Tse, MD, PhD

LurieChildrens.org > Care & Services > Find a Doctor > William T. Tse, MD, PhD

Share Email Print

William T. Tse, MD, PhD
Attending Physician, Hematology, Oncology & Stem Cell Transplant; Assistant Professor of Pediatrics, Northwestern University Feinberg School of Medicine

Specialties
Hematology/Oncology
Transplantation - stem cell

Special Interests
Hematopoietic stem cell transplantation, research

Health Care Plans Accepted
[Show Plans](#)

Languages Spoken
Chinese

Financial Assistance

For Healthcare Professionals

Sees Patients At

The map shows the Chicago area with several neighborhoods labeled: Gurnee, Waukegan, Daley, Libertyville, Arlington Heights, Schaumburg, Lincoln Park, Oak Park, Cicero, South Side, and Chicago. A red pin is placed on the Lincoln Park area, indicating the hospital's location.

Real-Life Search Engine Example

Google

hotel near "children's hospital" chicago

Web

Images

Maps

Books

More ▾

About 2,770,000 results (0.74 seconds)

[Hotels near Lurie Children's Hospital of Chicago Chicago](#)

[www.hotels-rates.com](#) > ... > [Illinois Hotels](#) > [Chicago Illinois Hotels](#) ▾

Hotels 1 - 25 of 75 - Browse and book **hotels near Hotels in Lurie Children's Hospital of Chicago Chicago**. An online **hotel** reservation directory with instant email ...

[Hotel Discounts - University of Chicago Comer Children's Hospital](#)

[www.uchicagokidshospital.org](#) > [Visiting Us](#) ▾

Chicago area **hotels** that offer discounts to Comer Children's Hospital patients and ...
House **near** the University of **Chicago** Medicine Comer Children's Hospital

*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

sin 0.9876

Expected

?

Actual

0.8347

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

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

$\sin 0.9876$

Expected

?

Actual

0.8347

$\sin (\pi - 0.9876)$

Expected

?

Actual

0.8347

Metamorphic Testing

$\sin 0.9876$

$\sin (\pi - 0.9876)$

Expected

?

Actual

0.8347

Expected

?

Actual

0.8347

Metamorphic Testing

$\sin 0.9876$

Expected

Actual

0.8347

$\sin (\pi - 0.9876)$

Expected

Actual

0.8347

Expected *metamorphic relation*

$\sin 0.9876 = \sin (\pi - 0.9876)$

Metamorphic Testing

$\sin 0.9876$

$\sin (\pi - 0.9876)$

Expected

?

Expected

?

Actual

0.8347

Actual

0.8347

Expected *metamorphic relation*

$\sin 0.9876 = \sin (\pi - 0.9876)$

Metamorphic Testing

$\sin 0.9876$

$\sin (\pi - 0.9876)$

Expected

?

Expected

?

Actual

0.8347

Actual

0.8347

Expected *metamorphic relation*

$\sin 0.9876 = \sin (\pi - 0.9876)$

Actual relation

$0.8347 = 0.8347$

Real-Life Search Engine Example

Apply Metamorphic Testing

Real-Life Example

Google hotel near "children's hospital" chicago

Web Images Maps Books More

About 2,770,000 results (0.74 seconds)

[Hotels near Lurie Children's Hospital of Chicago Chicago](#)
[www.hotels-rates.com](#) > ... > [Illinois Hotels](#) > [Chicago Illinois Hotels](#) ▾
Hotels 1 - 25 of 75 - Browse and book hotels near Hotels in Lurie Children's Hospital of Chicago Chicago. An online hotel reservation directory with instant email ...

[Hotel Discounts - University of Chicago Comer Children's Hospital](#)
[www.uchicagokidshospital.org](#) > [Visiting Us](#) ▾
Chicago area hotels that offer discounts to Comer Children's Hospital patients and ...
House near the University of Chicago Medicine Comer Children's Hospital

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” .*

Google

hotel near "children's hospital of chicago"

Web

Images

Maps

Videos

More ▾

About 5,000,000 results (0.80 seconds)

[Hotels near Lurie Children's Hospital of C](#)

[www.hotels-rates.com](#) > ... > [Illinois Hotels](#) > [Chicago](#)

Hotels 1 - 25 of 75 - Browse and book hotels near Hotels in Lurie Children's Hospital of Chicago Chicago. An online hotel reservation directory with instant email ...

[Ann & Robert H Lurie Children's Hospital Of Chicago - Near North ...](#)

[www.yelp.com](#) > [Health & Medical](#) > [Hospitals](#) ▾

★★★★★ Rating: 4 - 17 reviews

17 Reviews of Ann & Robert H Lurie Children's Hospital Of Chicago "This is hands ... views of Lake Michigan and Michigan Ave, I felt like I was in a 5 star hotel!

*More entries
indicate failure
in search engine.*

Real-Life Search Engine Example



hotel near "children's hospital" chicago



百

网页

新闻

贴吧

知道

音乐

图片

视频

地图

文库

百度为您找到相关结果约4,540,000个

 您可以仅查看: [英文结果](#)

[Ann and Robert H. Lurie Children's Hospital of Chicago in ...](#)



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

health.usnews.com/best... - [百度快照](#)

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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.uchicagokidshospit... - [百度快照](#) - [评价](#)

*Is 4.54M
results
correct?*

Real-Life Search Engine



hotel near "children's hospital of chicago"

网页 新闻 贴吧 知道 音乐 图片 视频 地图 文库 更多»

百度为您找到相关结果约9,790,000个

您可以仅查看: [英文结果](#)

[Ann & Robert H. Lurie Children's Hospital of Chicago](#)

查看此网页的中文翻译, 请点击 [翻译此页](#)

Lurie Children's, formerly Children's Memorial Hospital, is one of the top pediatric providers in the Midwest, treating Chicago's kids with the highest...

www.luriechildrens.org/ - [百度快照](#) - [评价](#)

[Ann & Robert H. Lurie Children's Hospital of Chicago Jobs](#)

查看此网页的中文翻译, 请点击 [翻译此页](#)

Lurie Children's Hospital of Chicago is a unique place where children, families, physicians and staff come together to make sure our patients get the ...

luriechildrensjobs.sil... - [百度快照](#) - [评价](#)

*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
- 😞 Google asked us to submit a bug report
- 😊 Each of my brothers has 2 doctoral degrees
- 😞 I have only one doctoral degree.

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

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

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 $\boxed{=}$ actual execution result

Many Facets of the Test Oracle Problem

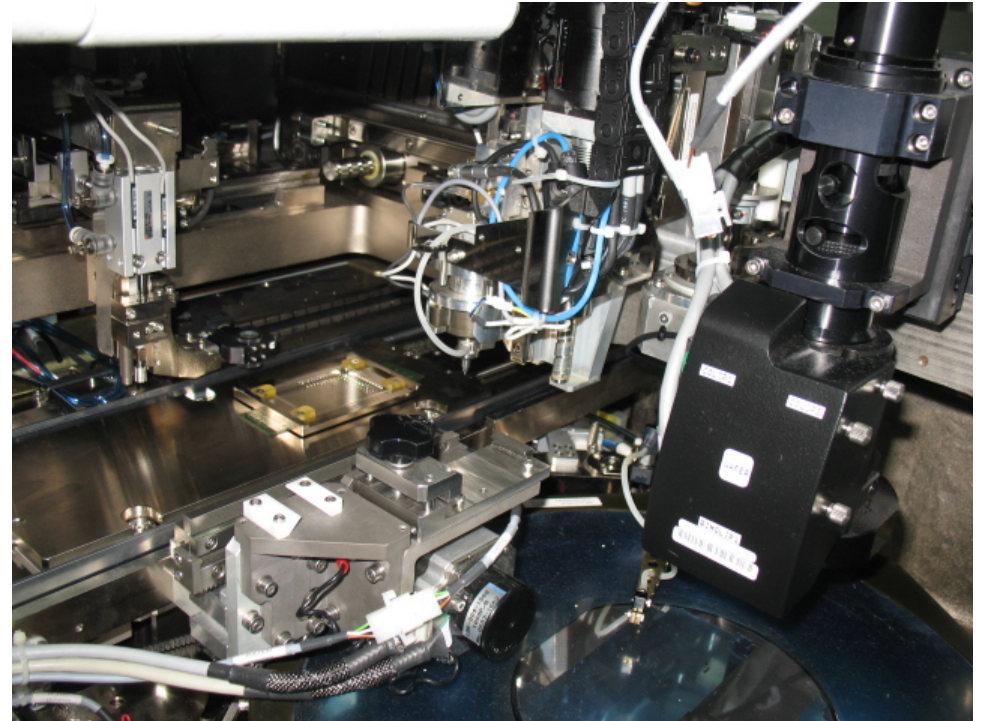
Challenge 2:

- ◆ Expected outcome $\boxed{=}$ actual execution result
- ◆ Consider the testing of real-life object-oriented software.

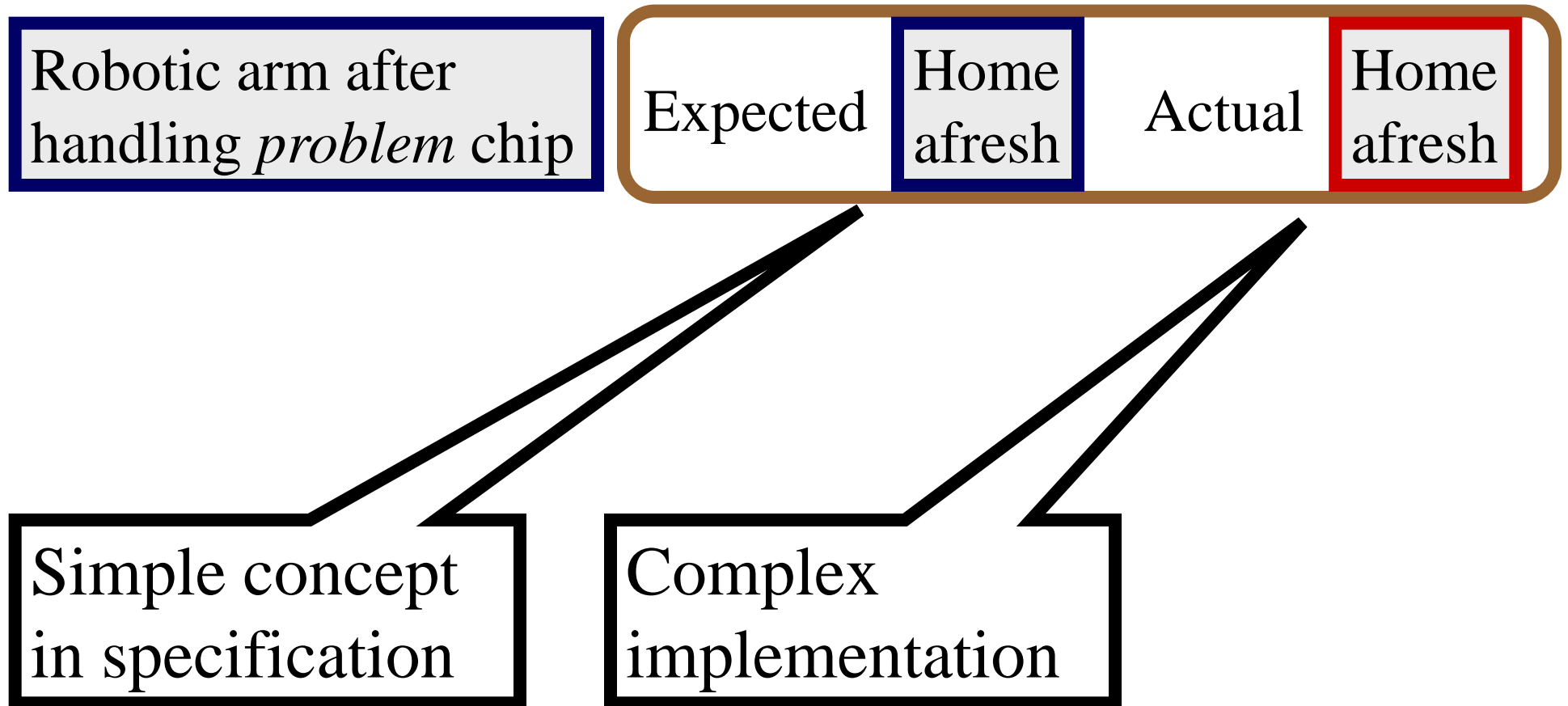
Testing of Object-Oriented Software

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



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.

Testing of Object-Oriented Software

Mimic Metamorphic Testing?

Robotic arm after
handling *problem* chip

Expected

Home
afresh

Actual

Home
afresh

Testing of Object-Oriented Software

Mimic Metamorphic Testing?

Robotic arm after
handling *problem* chip

Expected

Home
afresh

Actual

Home
afresh

Robotic arm after
handling *standard*
chip

Testing of Object-Oriented Software

Mimic Metamorphic Testing?

Robotic arm after
handling *problem* chip

Expected

Home
afresh

Actual

Home
afresh

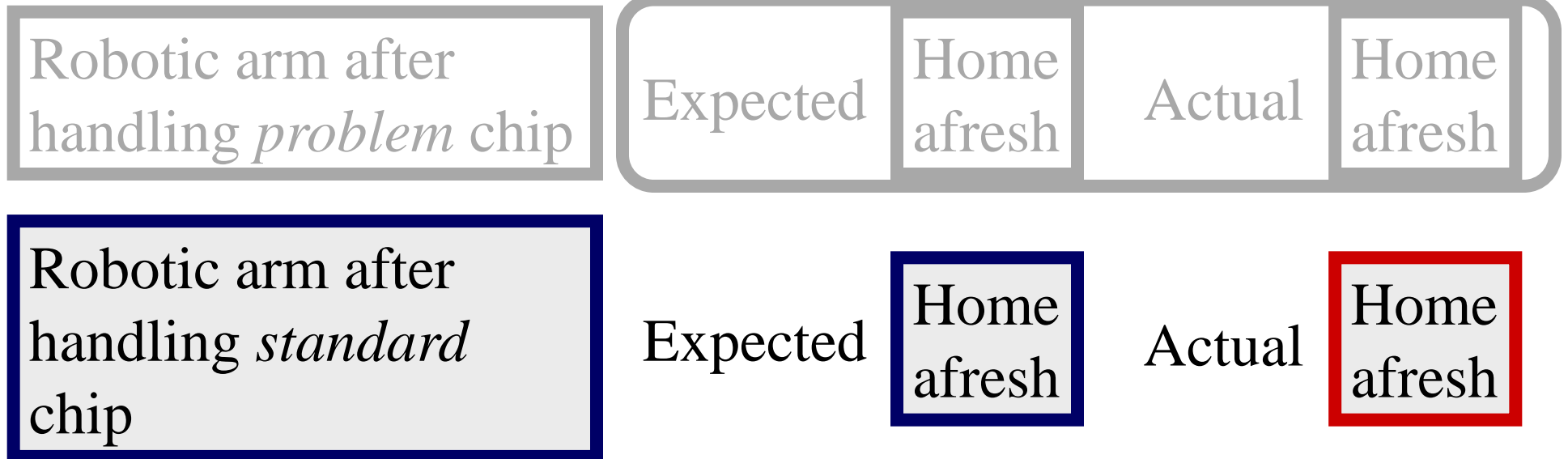
Robotic arm after
handling *standard*
chip

Expected

Home
afresh

Testing of Object-Oriented Software

Mimic Metamorphic Testing?



Testing of Object-Oriented Software

Mimic Metamorphic Testing?

Robotic arm after
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Expected

Home
afresh

Actual

Home
afresh

Robotic arm after
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chip

Expected

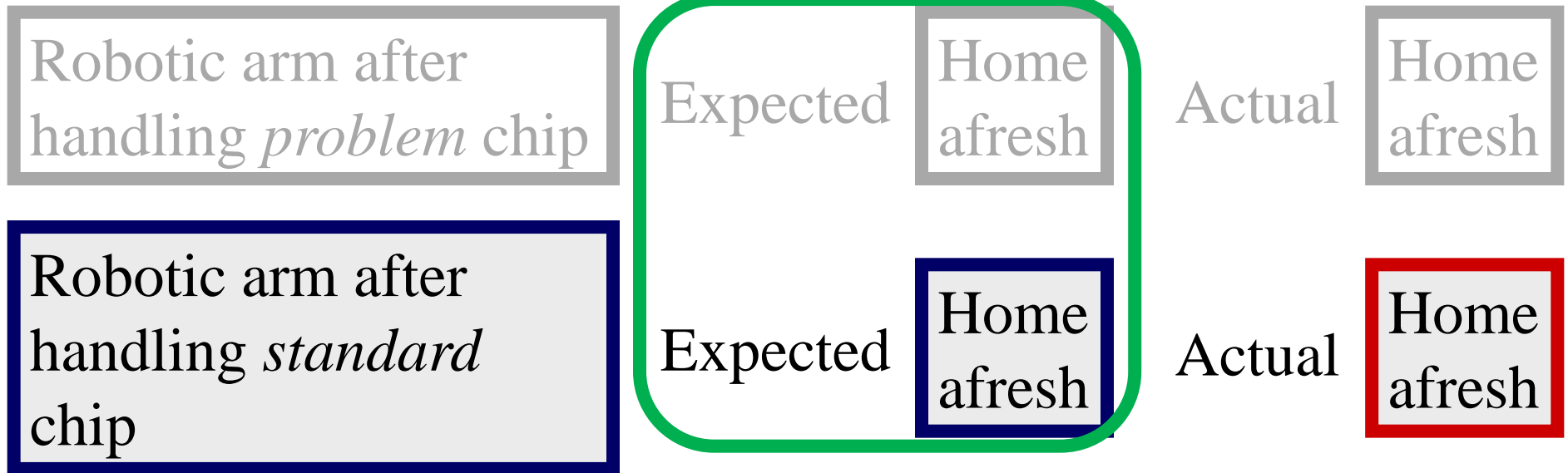
Home
afresh

Actual

Home
afresh

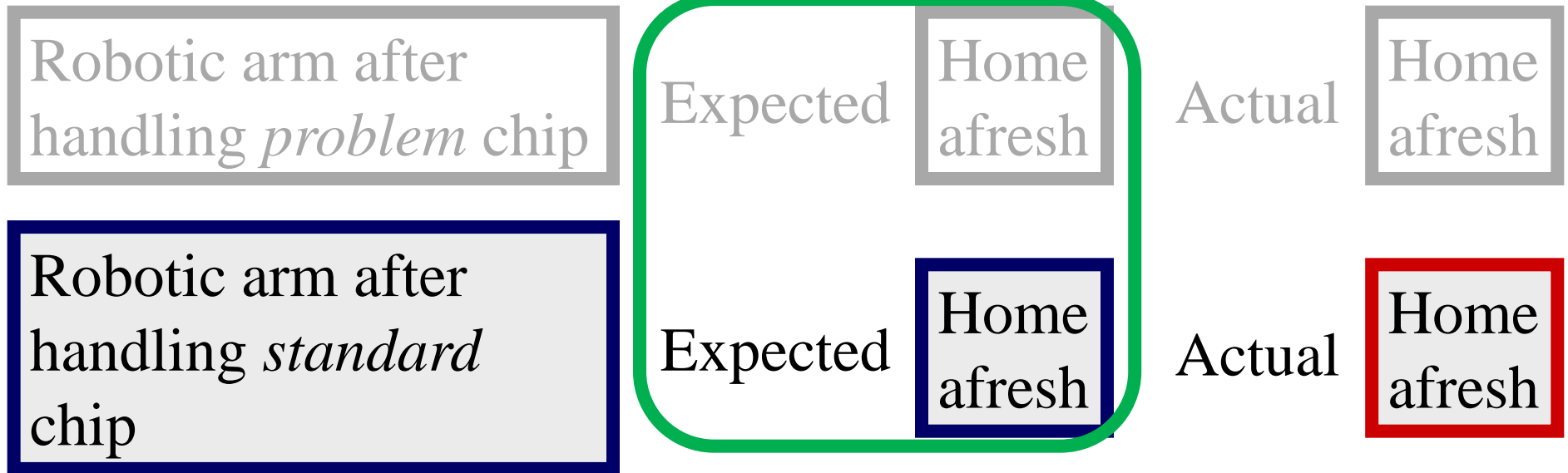
Testing of Object-Oriented Software

Mimic Metamorphic Testing?



Testing of Object-Oriented Software

Mimic Metamorphic Testing?

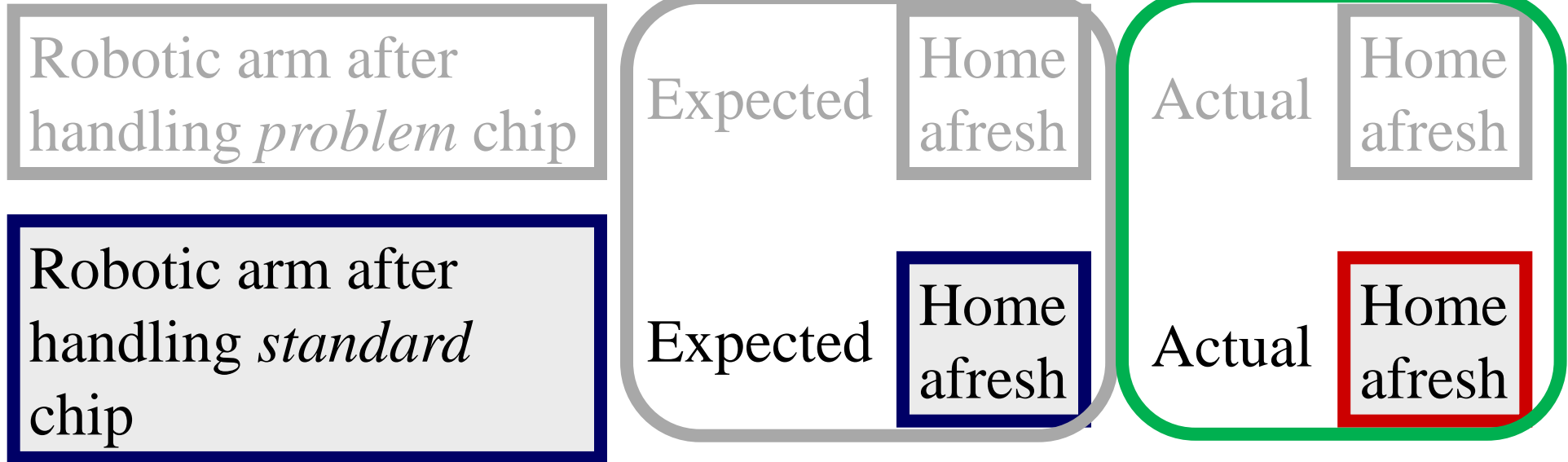


Expected relation

Equivalent

Testing of Object-Oriented Software

Mimic Metamorphic Testing?



Expected relation

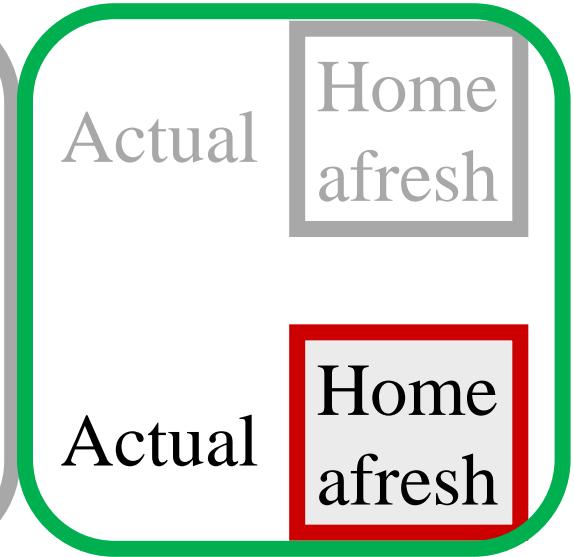
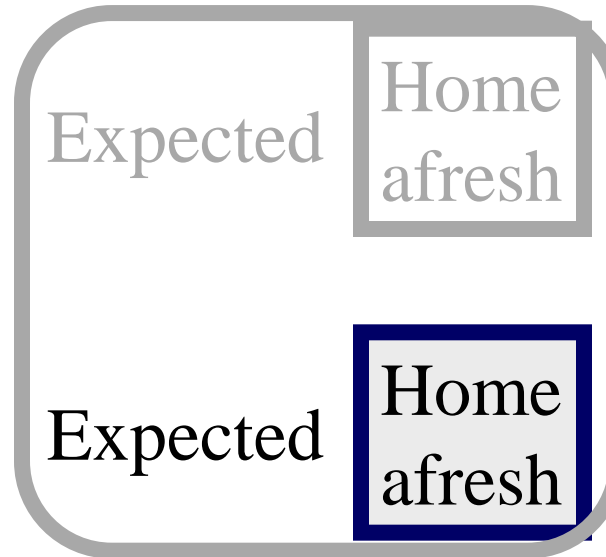
Equivalent

Testing of Object-Oriented Software

Mimic Metamorphic Testing?

Robotic arm after handling *problem* chip

Robotic arm after handling *standard* chip



Expected relation

Equivalent

Actual relation

Equivalent

Target of OO Software Testing

- ◆ 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* .

Many Facets of the Test Oracle Problem

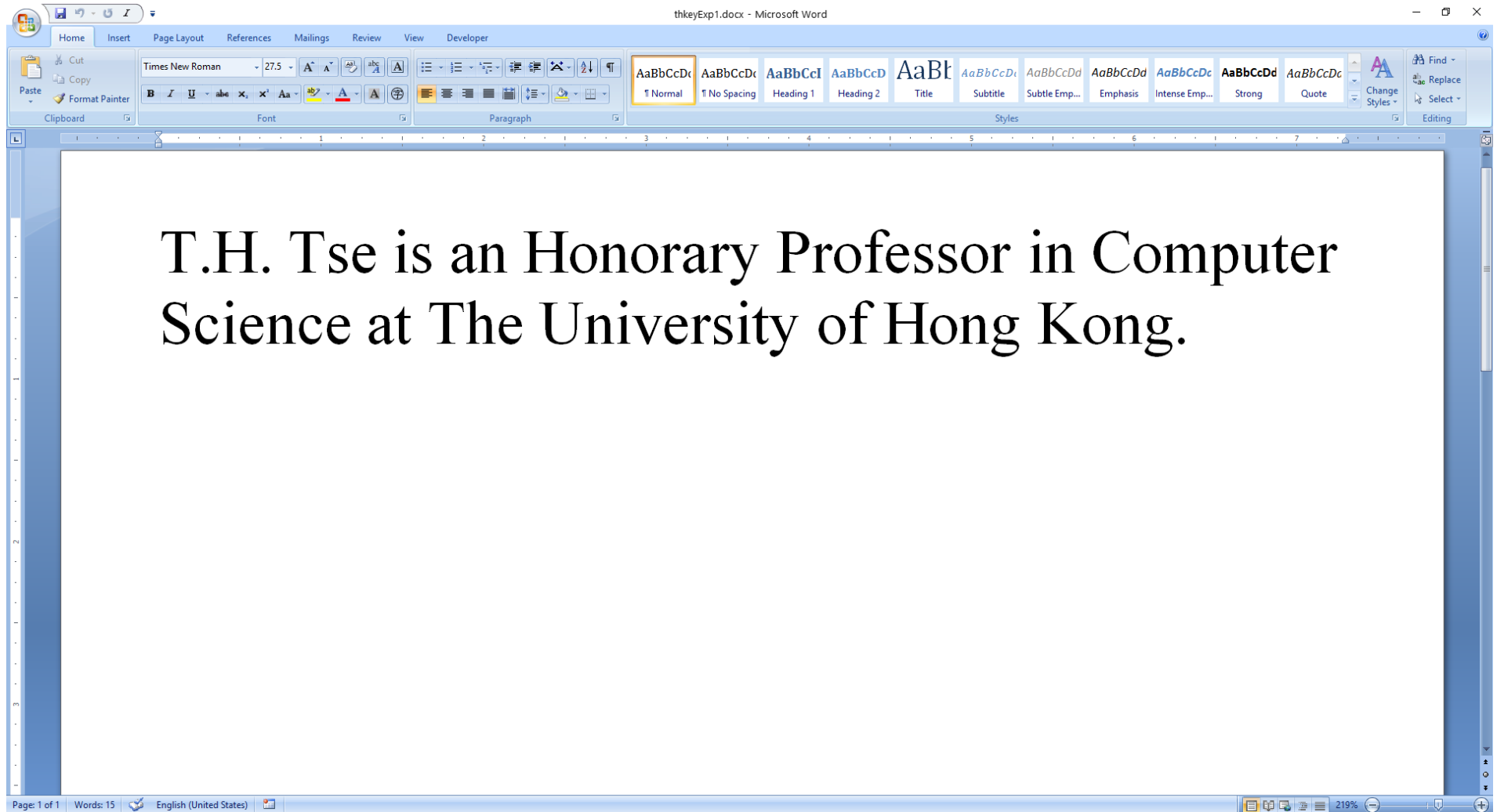
Challenge 3:

- ◆ Object A = object B

What is object equivalence?

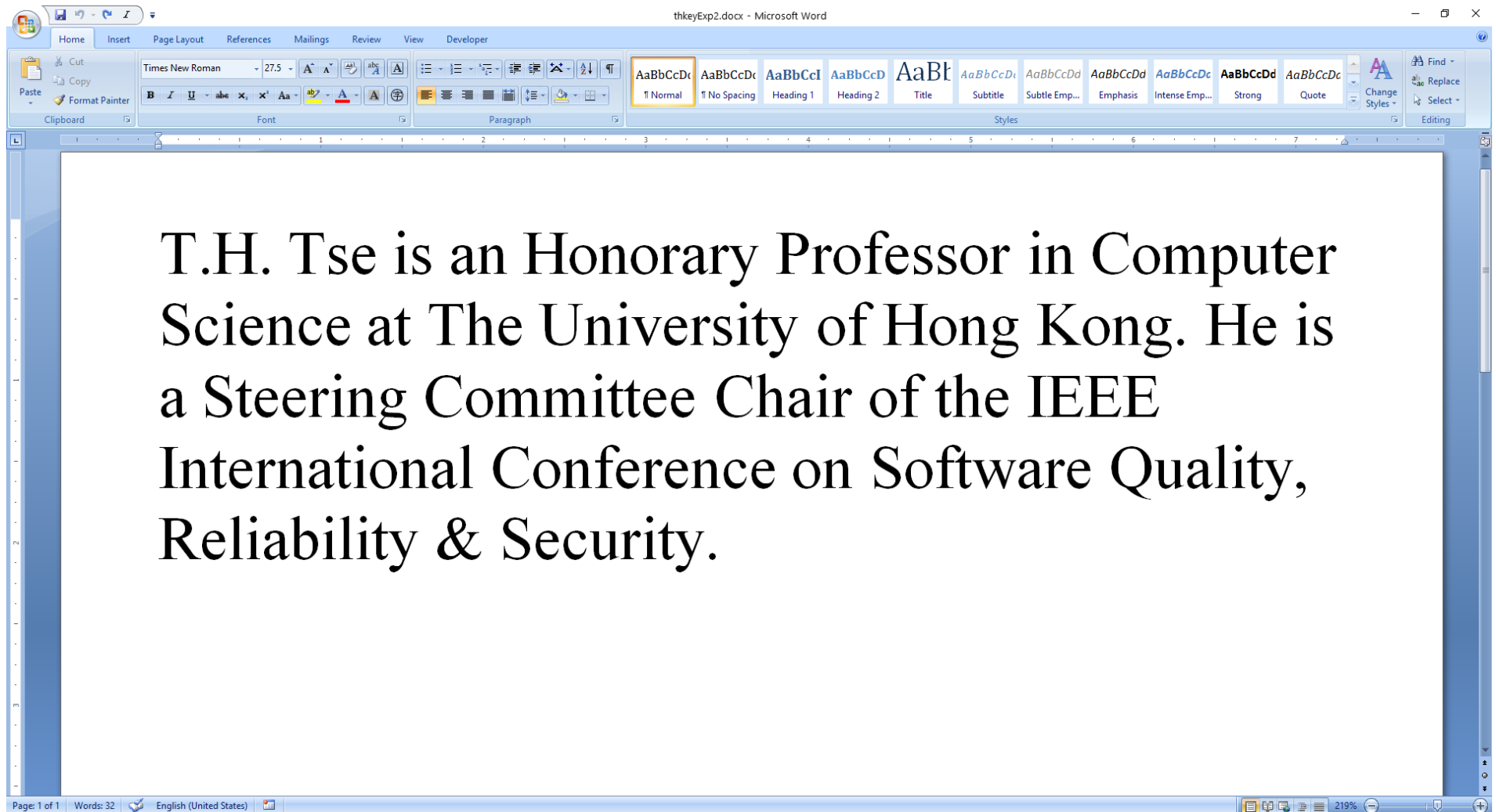
What is Object Equivalence?

Real-Life Word Processing Example



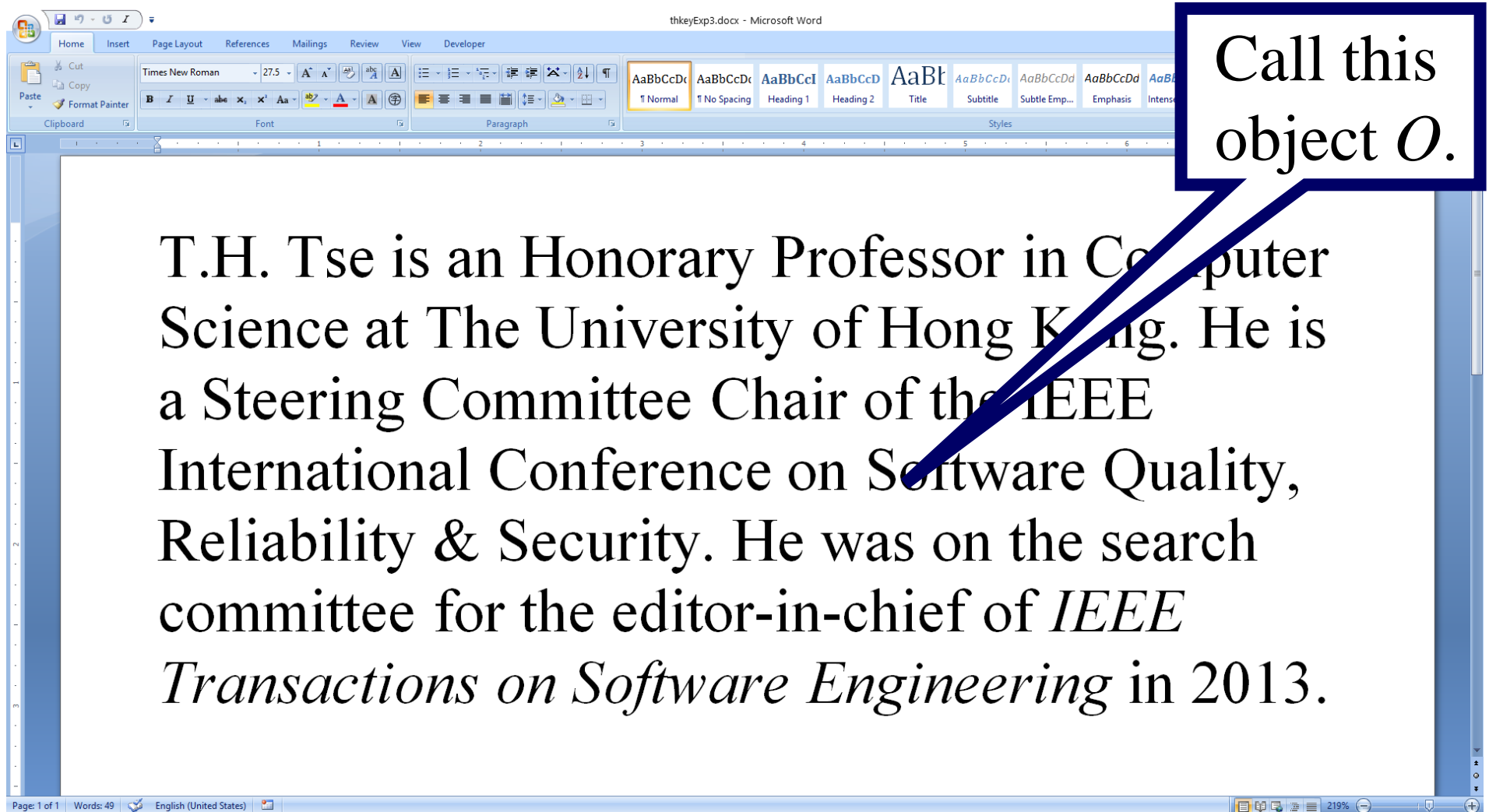
What is Object Equivalence?

Real-Life Word Processing Example



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.

Page: 1 of 1 Words: 49 English (United States) 219%

What is Object Equivalence?

Real-Life Word Processing Example

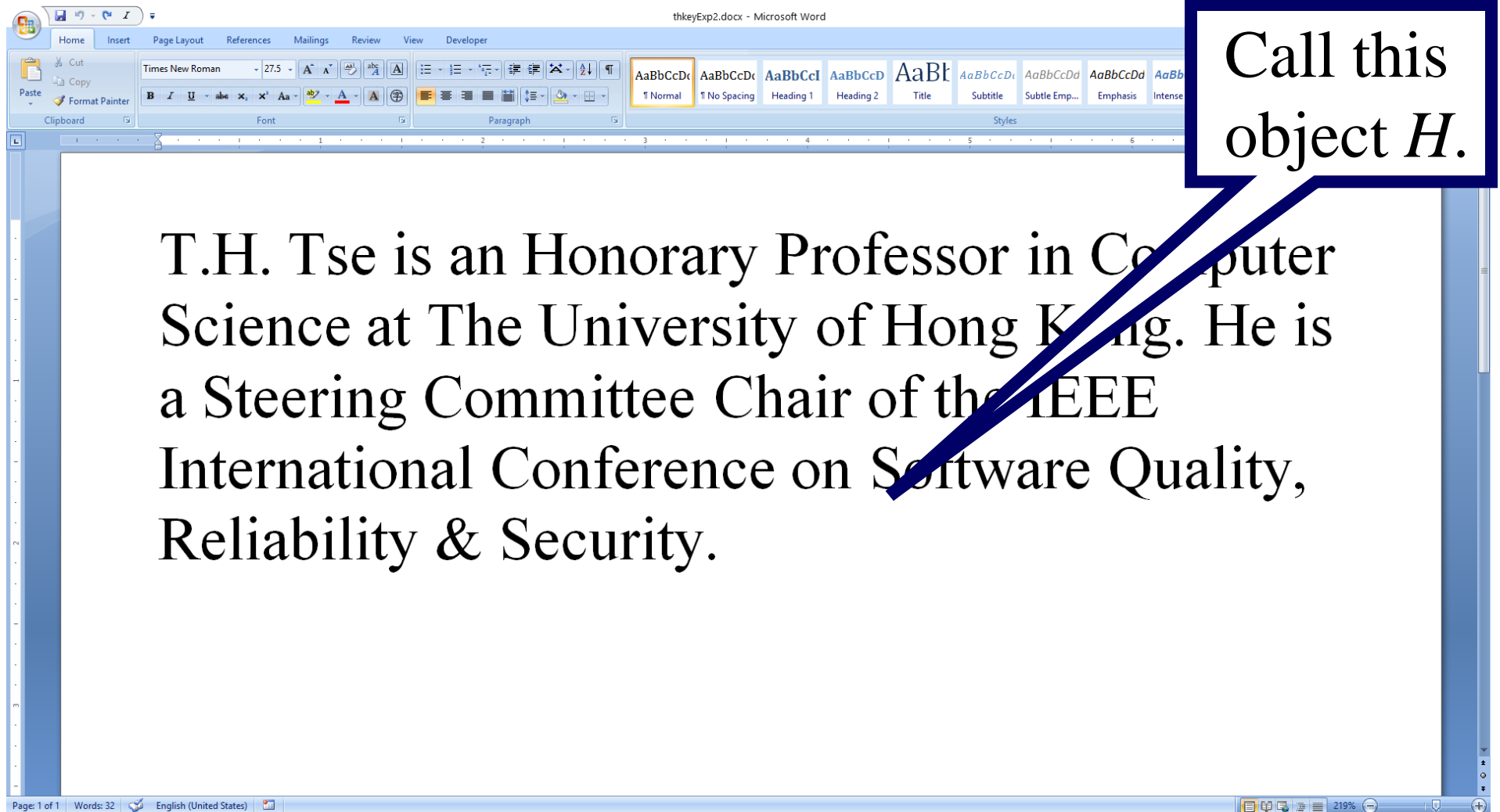
The image shows a screenshot of Microsoft Word with a document titled 'thkeyExp3.docx'. The document text is: "T.H. Tse is an Professor in Computer Science at The Hong Kong. He is a Steering Committee of the IEEE International Conference on Software Quality, Reliability & Security. He was on the search committee for the editor-in-chief of *IEEE Transactions on Software Engineering* in 2013." A blue callout box points to the 'Hidden' checkbox in the Font dialog box, which is open to the 'Character Spacing' tab. The 'Hidden' checkbox is checked. The text 'Click "Hidden"' is written inside the callout box. The status bar at the bottom shows 'Page: 1 of 1', 'Words: 17/49', 'English (United States)', and '219%'.

Click "Hidden".

T.H. Tse is an Professor in Computer Science at The Hong Kong. He is a Steering Committee 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



The image shows a screenshot of the Microsoft Word interface. The title bar indicates the document is named "thkeyExp2.docx". The ribbon is set to the "Home" tab, showing the Font, Paragraph, and Styles groups. The text in the document is "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." A blue callout box with a white background and a blue border points to the letter 'H' in "T.H. Tse". The callout box contains the text "Call this object *H*." The status bar at the bottom shows "Page: 1 of 1", "Words: 32", "English (United States)", and "219%".

Call this object *H*.

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.

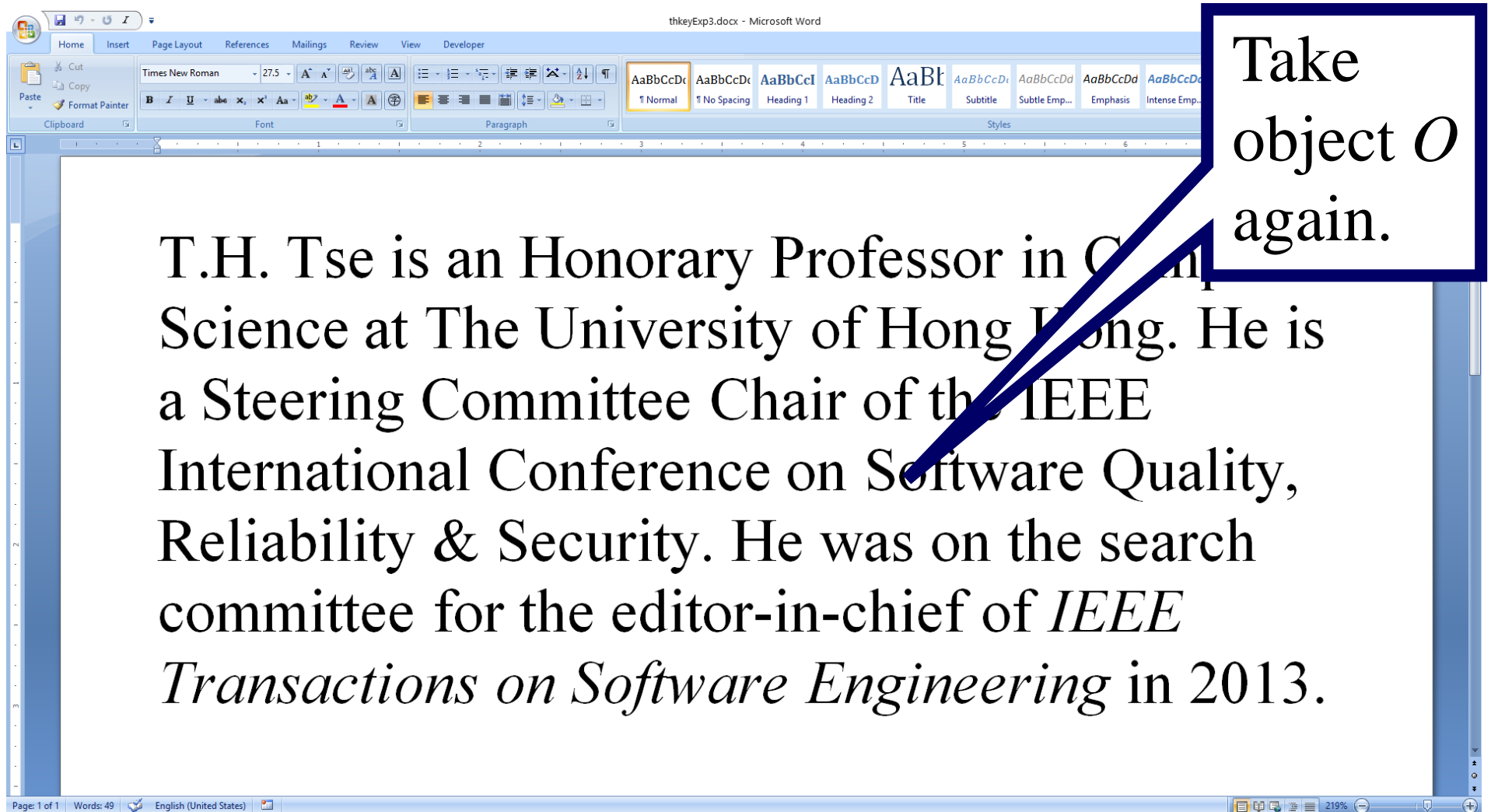
What is Object Equivalence?

Output from Object H

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



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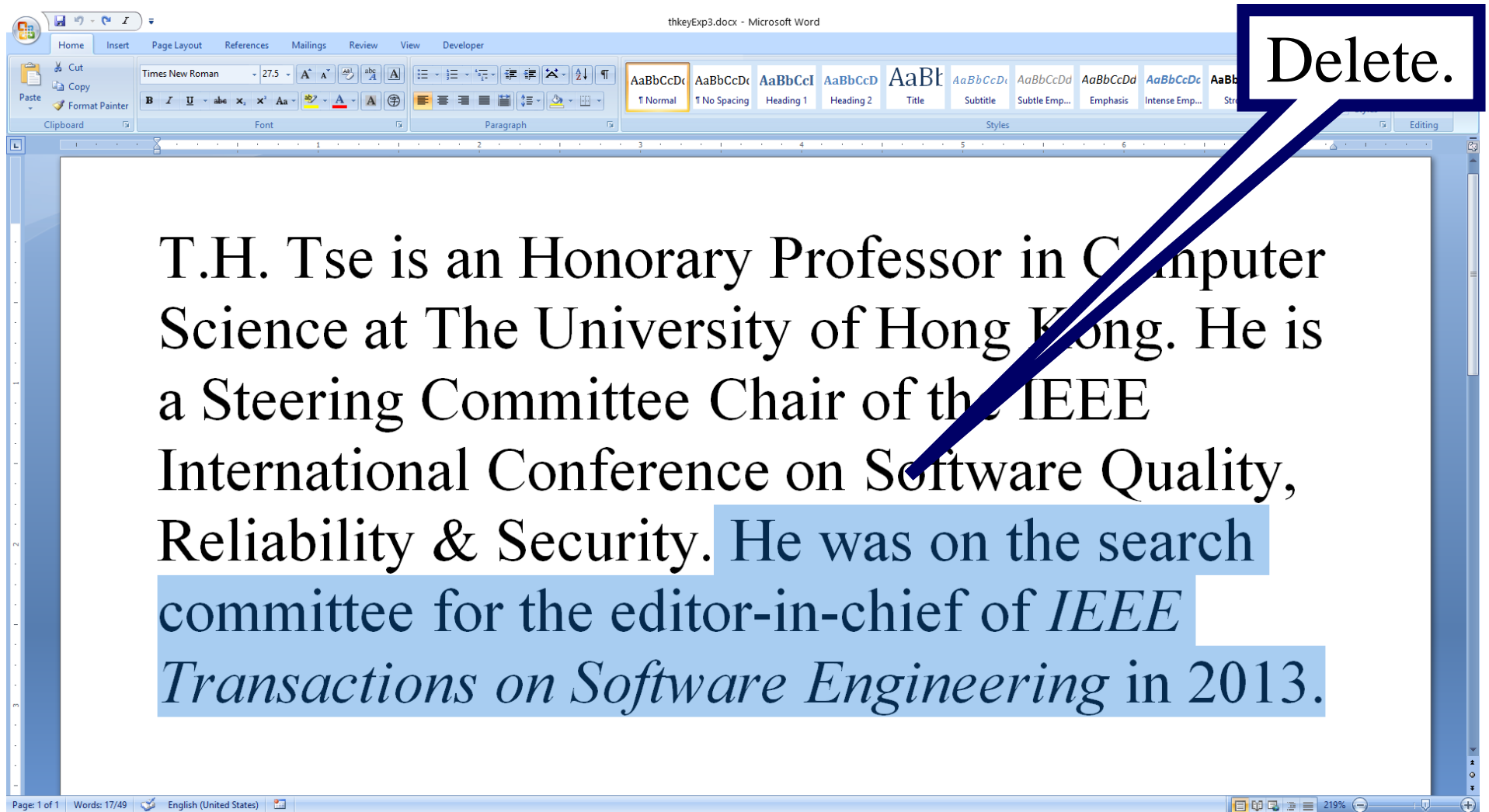
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A callout box with a blue border and a blue arrow pointing to the word "object" in the text contains the text: "Take object O again."

Page: 1 of 1 | Words: 49 | English (United States) | 219%

What is Object Equivalence?

Real-Life Word Processing Example

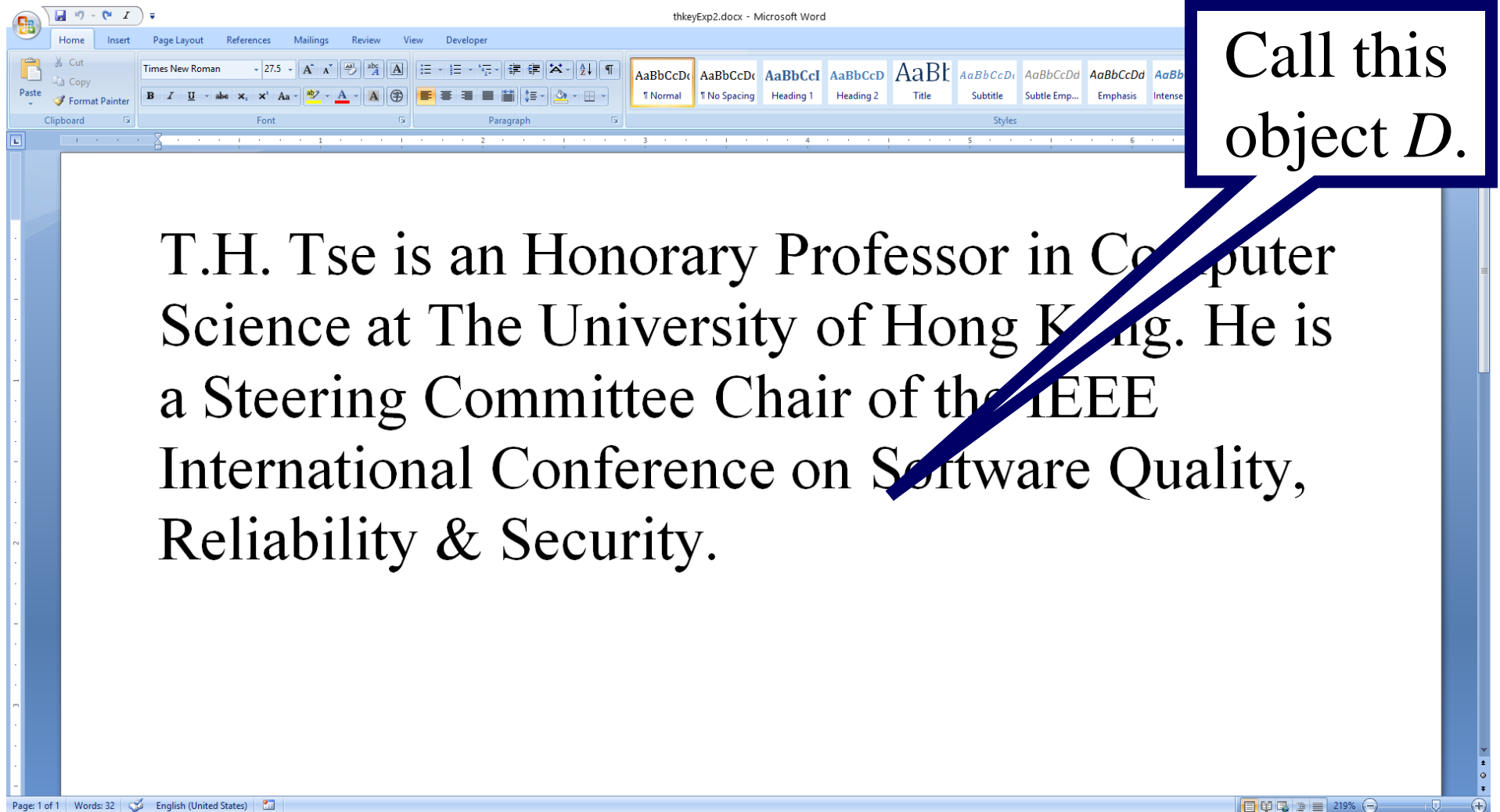


The image shows a screenshot of the Microsoft Word interface. The document title is 'thkeyExp3.docx'. The ribbon is set to 'Home', and the 'Font' group is active, showing 'Times New Roman' font and size '27.5'. A paragraph of text is highlighted in blue. A callout box with a blue border and a white background, containing the word 'Delete.', is positioned above the highlighted text. The status bar at the bottom indicates 'Page: 1 of 1', 'Words: 17/49', and 'English (United States)'.

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



The image shows a screenshot of the Microsoft Word interface. The title bar indicates the document is named "thkeyExp2.docx". The ribbon is set to the "Home" tab, showing the "Font" and "Paragraph" groups. The font is "Times New Roman" in size 27.5. The paragraph contains the following text:

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.

A callout box with a blue border and a blue arrow points to the italicized letter 'D' in the word "Quality". The callout box contains the text: "Call this object *D*."

At the bottom of the window, the status bar shows "Page: 1 of 1", "Words: 32", "English (United States)", and a zoom level of "219%".

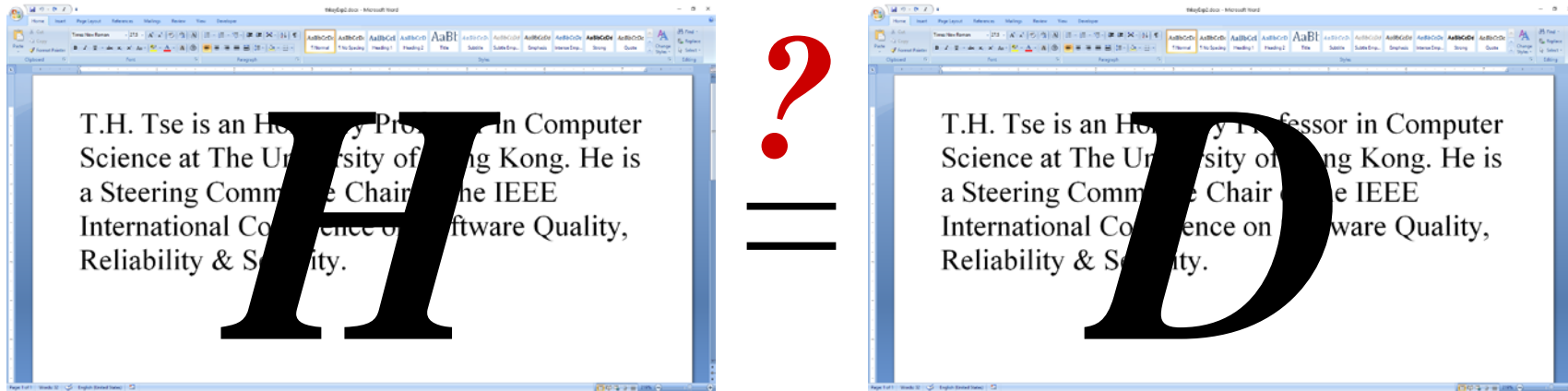
What is Object Equivalence?

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

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.

H

=

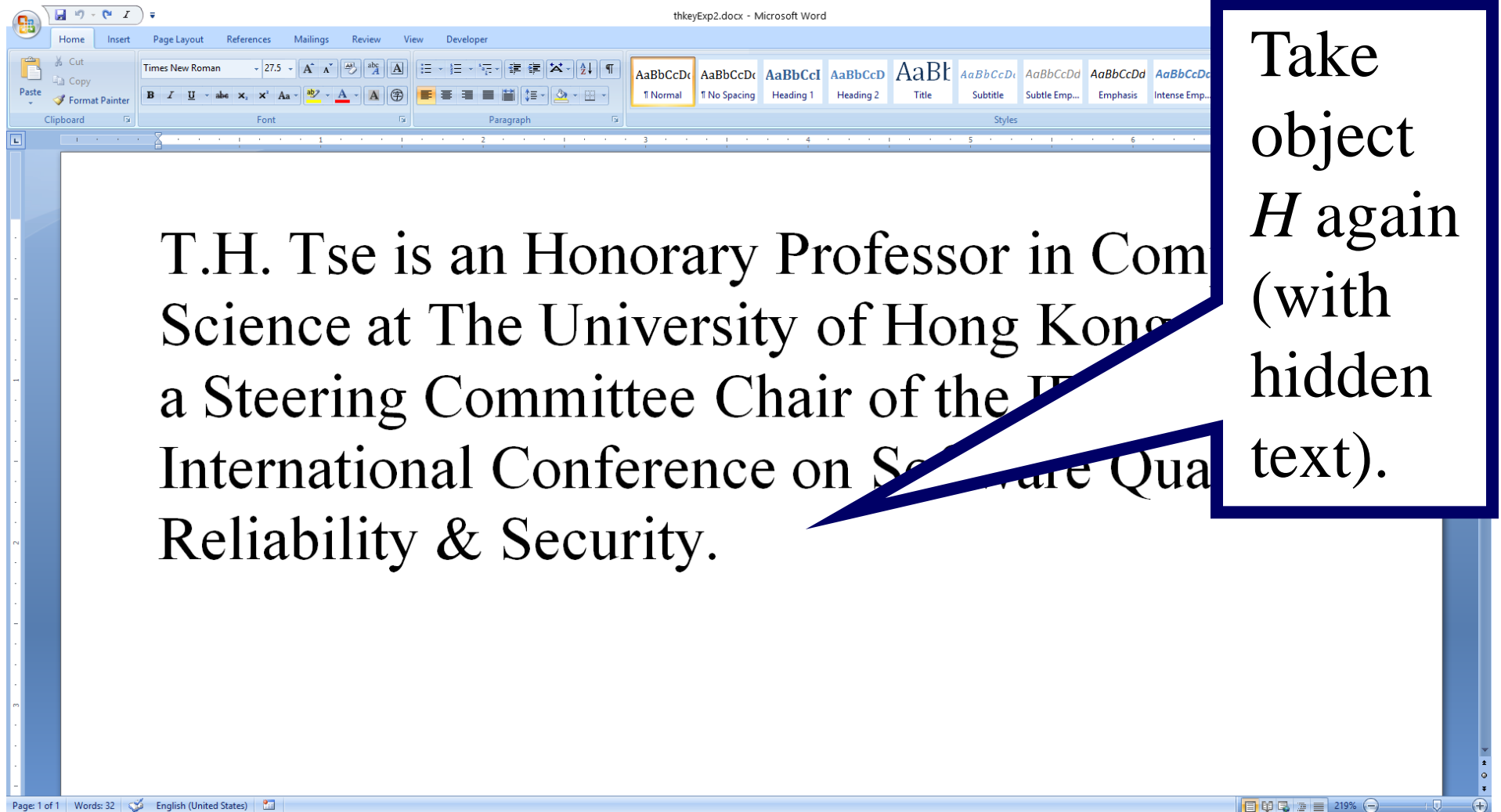
T.H. Tse is an Honorary Professor in Computer Science at The University of Hong Kong. He is a Steering Committee Chair of the IEEE International Conference on Software Quality, Reliability & Security.

D

- ◆ Simple to test
- ◆ *But* the definition is too weak to be useful ...
- ◆ Why? .

What is Object Equivalence?

Real-Life Word Processing Example



The image shows a screenshot of the Microsoft Word interface. The title bar reads "thkeyExp2.docx - Microsoft Word". The ribbon is set to the "Home" tab, showing the Font, Paragraph, and Styles groups. The main text area contains the following text:

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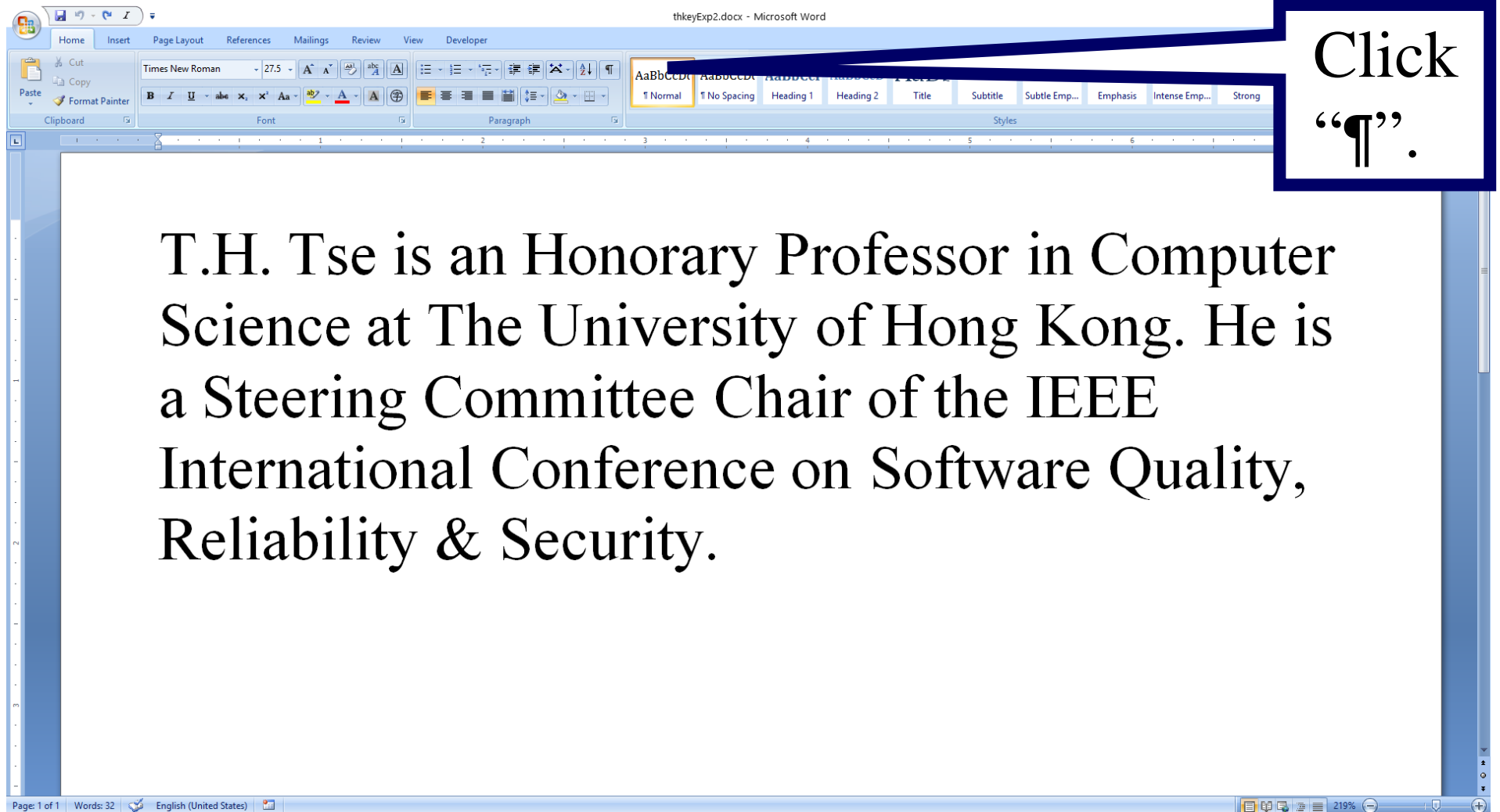
A callout box with a blue border and a pointer to the text contains the following text:

Take object *H* again (with hidden text).

The status bar at the bottom indicates "Page: 1 of 1", "Words: 32", "English (United States)", and "219%".

What is Object Equivalence?

Real-Life Word Processing Example



The image shows a screenshot of the Microsoft Word interface. The document title is "thkeyExp2.docx - Microsoft Word". The ribbon is set to "Home", and the "Styles" task pane is visible, showing the "Normal" style selected. A callout box with a blue border and a white background points to a specific character in the text. The callout box contains the text "Click '¶'." The text in the document is "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." The status bar at the bottom indicates "Page: 1 of 1", "Words: 32", "English (United States)", and "219%".

Click "¶".

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What is Object Equivalence?

Real-Life Word Processing Example

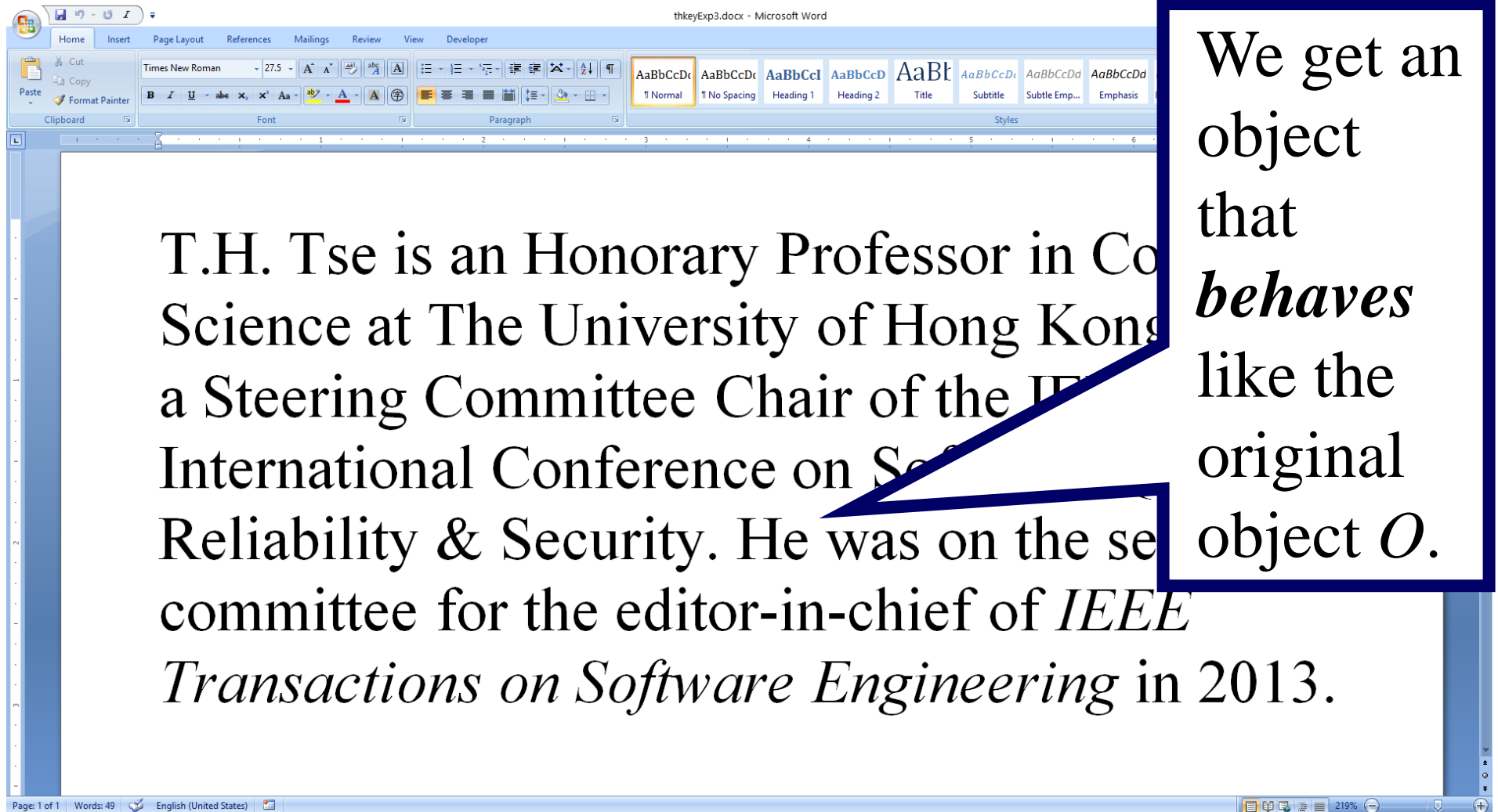
The image shows a screenshot of Microsoft Word with a document containing text with a 'Hidden' font style. A 'Font' dialog box is open, showing the 'Character Spacing' tab. The 'Hidden' checkbox is checked under the 'Effects' section. A callout box points to the 'Hidden' checkbox with the text 'Unclick "Hidden"'. The document text is: 'T.H. Tse is an Professor in Computer Science at The Hong Kong. He is a Steering Committee 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.' The text is highlighted in blue, and the 'Hidden' checkbox is also highlighted in blue.

Unclick "Hidden".

T.H. Tse is an Professor in Computer Science at The Hong Kong. He is a Steering Committee 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



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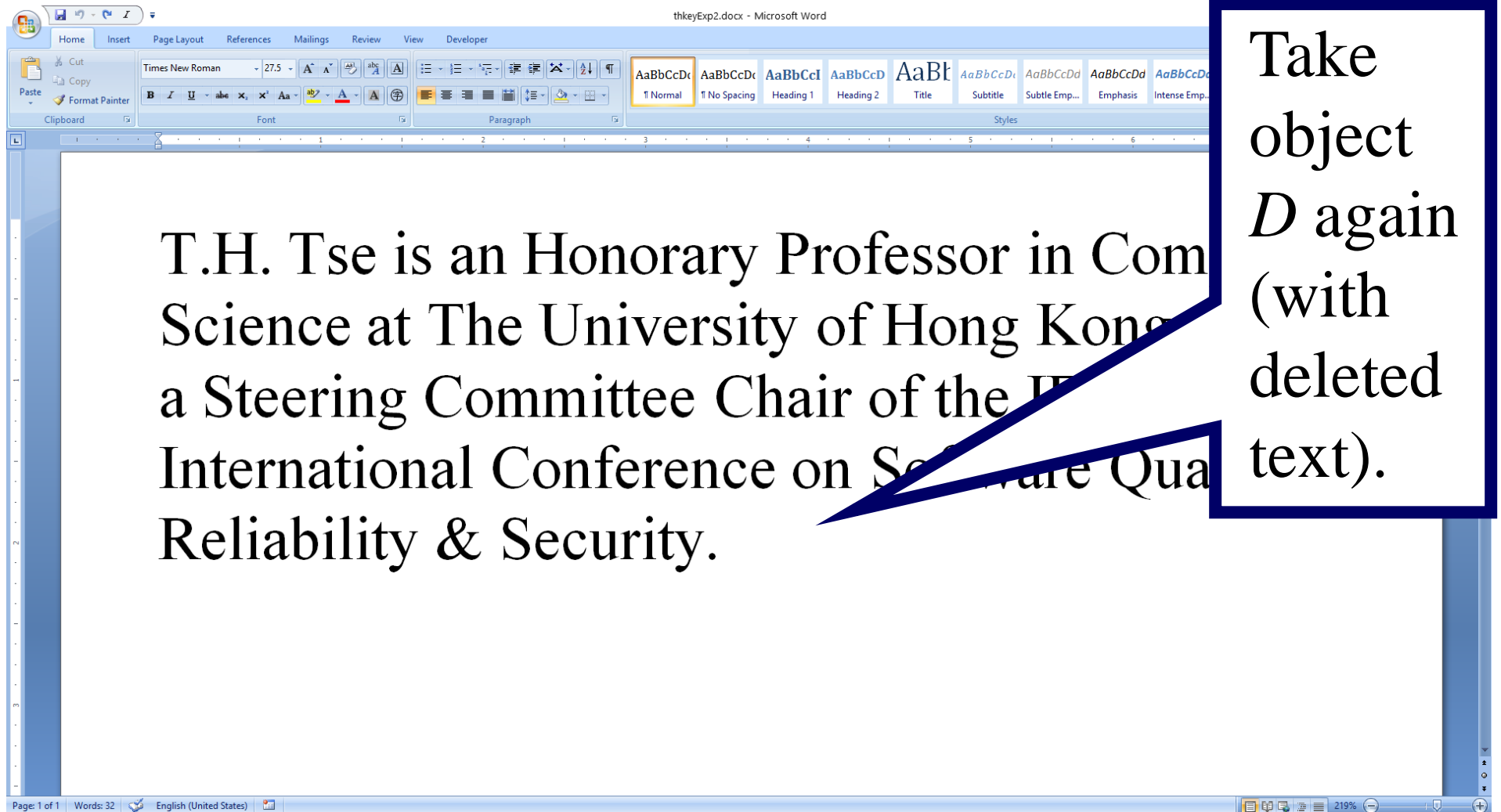
A blue-bordered callout box on the right side of the document contains the following text:

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

The callout box is connected to the word "behaves" in the document text by a blue arrow. The word "behaves" in the document is italicized, matching the word in the callout box. The callout box also contains the word "original" and the letter "O" in italics, which correspond to the italicized text in the document.

What is Object Equivalence?

Real-Life Word Processing Example



The image shows a screenshot of the Microsoft Word interface. The title bar indicates the document is named "thkeyExp2.docx". The ribbon is set to the "Home" tab, showing the Font, Paragraph, and Styles groups. The main text area contains the following text:

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

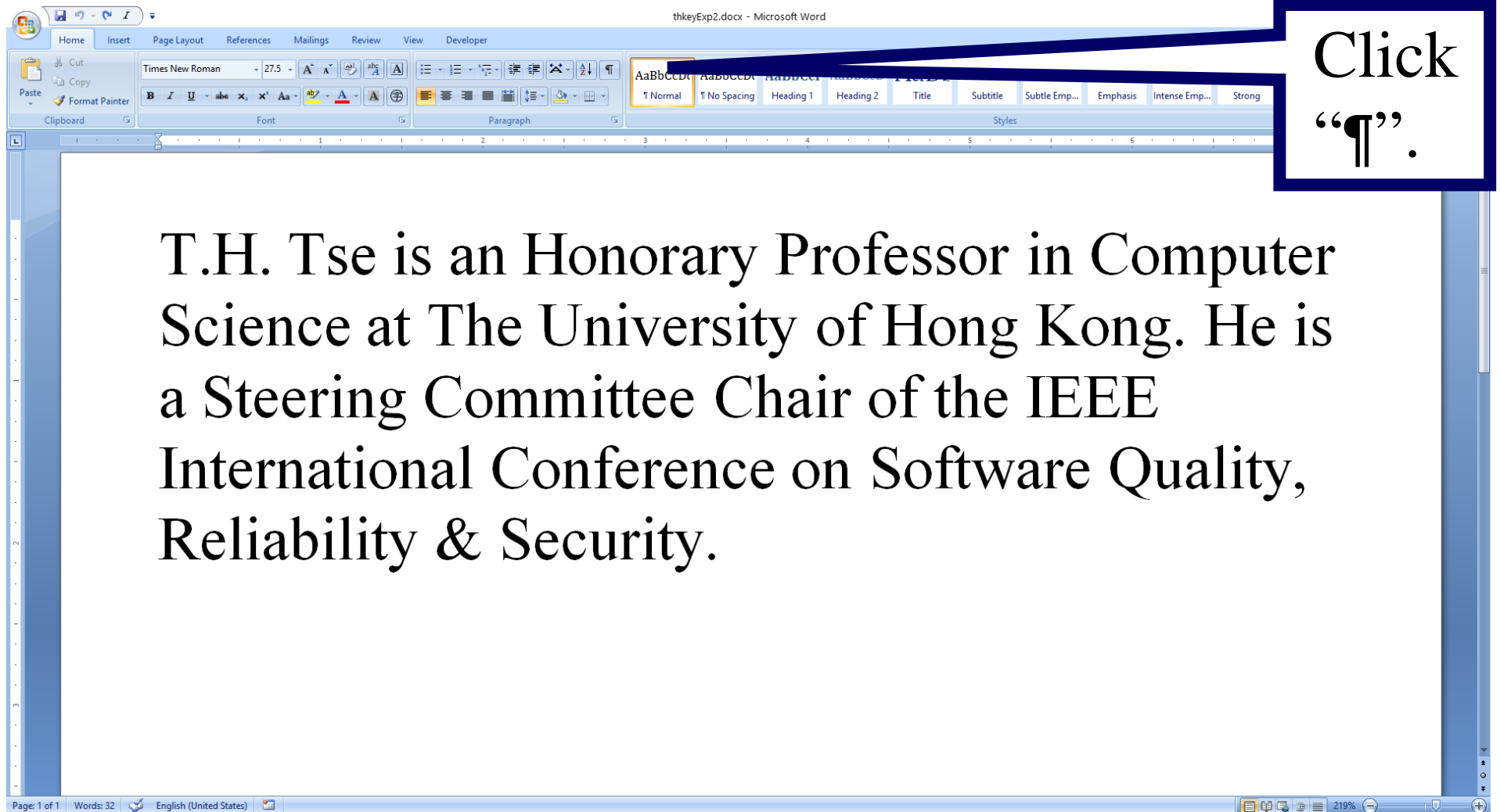
A callout box with a blue border and a pointer to the text contains the following text:

Take object *D* again (with deleted text).

The status bar at the bottom shows "Page: 1 of 1", "Words: 32", "English (United States)", and "219%".

What is Object Equivalence?

Real-Life Word Processing Example



The image shows a screenshot of the Microsoft Word interface. The document title is "thkeyExp2.docx - Microsoft Word". The ribbon is set to "Home" with the "Font" group selected. The text in the document is "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." A callout box with a blue border points to the character "¶" in the text, with the text "Click '¶'." inside the box. The status bar at the bottom shows "Page: 1 of 1", "Words: 32", "English (United States)", and "219%".

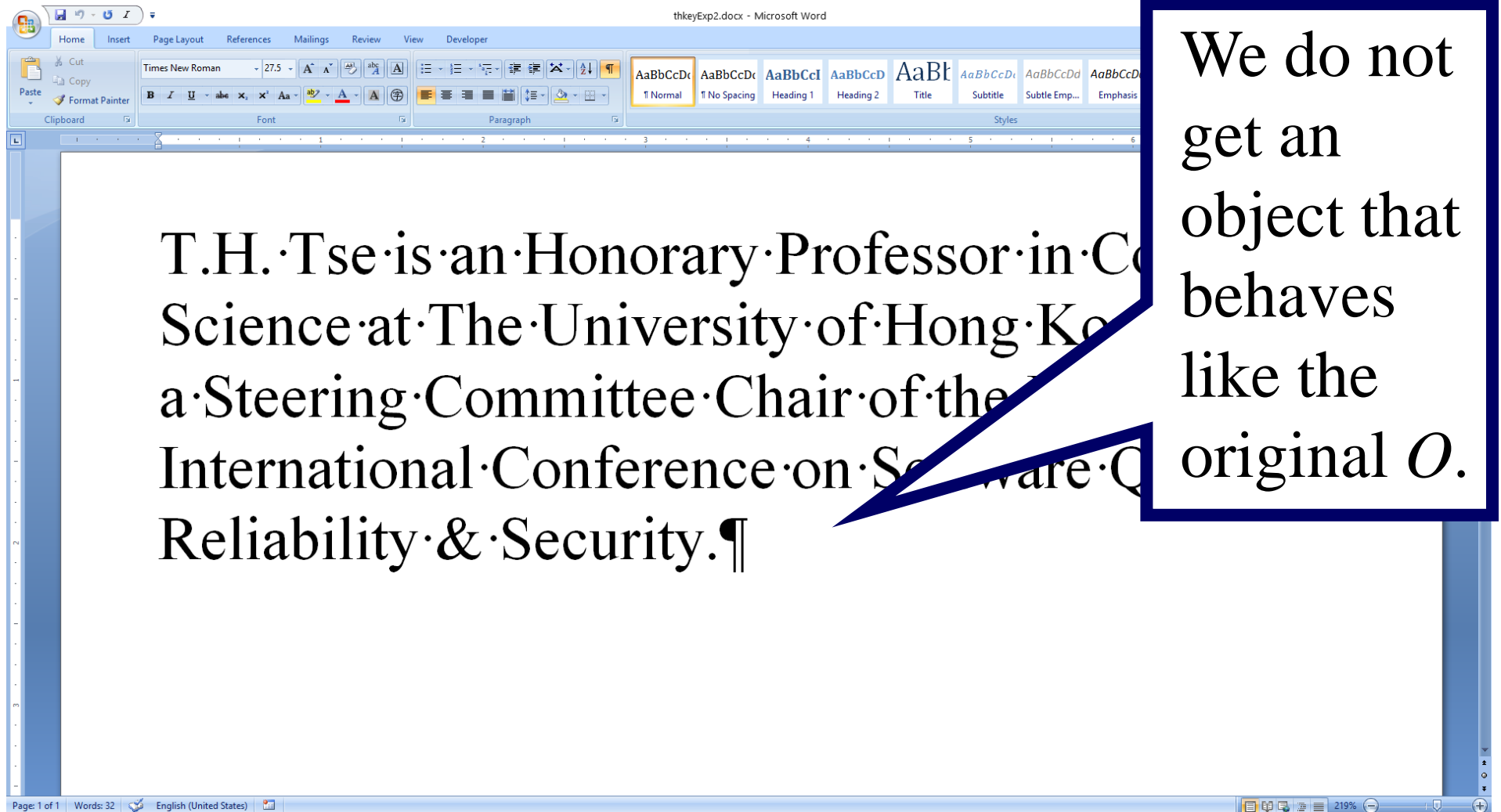
Click
“¶”.

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Page: 1 of 1 Words: 32 English (United States) 219%

What is Object Equivalence?

Real-Life Word Processing Example



The image shows a screenshot of a Microsoft Word document titled "thkeyExp2.docx". The document content is a paragraph of text with spaces between every character, including spaces between words and punctuation. A blue-bordered callout box on the right side of the document contains the text: "We do not get an object that behaves like the original *O*." The callout box has a pointer pointing to the text in the document.

thkeyExp2.docx - Microsoft Word

Home Insert Page Layout References Mailings Review View Developer

Cut Copy Paste Format Painter Clipboard

Times New Roman 27.5 A A abc A

Font Paragraph Styles

AaBbCcDc AaBbCcDc AaBbCcDc AaBbCcDc AaBbCcDc AaBbCcDc AaBbCcDc AaBbCcDc

¶ Normal ¶ No Spacing Heading 1 Heading 2 Title Subtitle Subtle Emp... Emphasis

T.H.·Tse·is·an·Honorary·Professor·in·Co
Science·at·The·University·of·Hong·Ko
a·Steering·Committee·Chair·of·the
International·Conference·on·Software·Q
Reliability·&·Security.¶

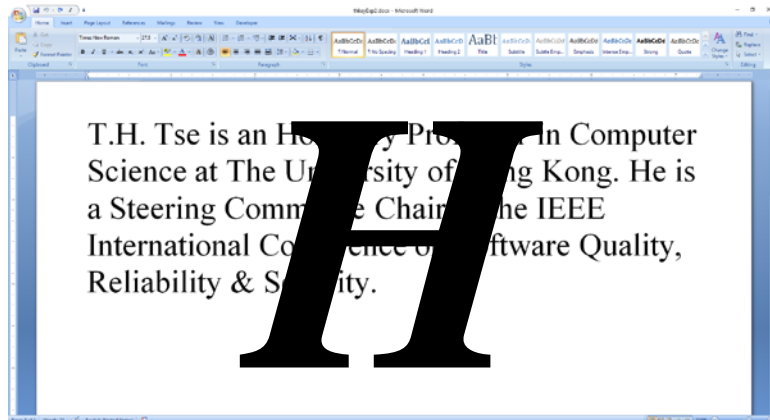
We do not get an object that behaves like the original *O*.

Page: 1 of 1 Words: 32 English (United States) 219%

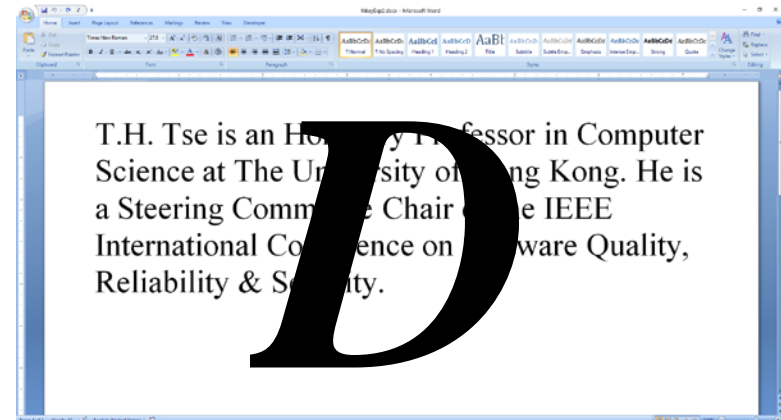
What is Object Equivalence?

Observational Equivalence

- ◆ Two objects will be *observationally equivalent* if they have the exactly the same *visible attributes* and *behavior*

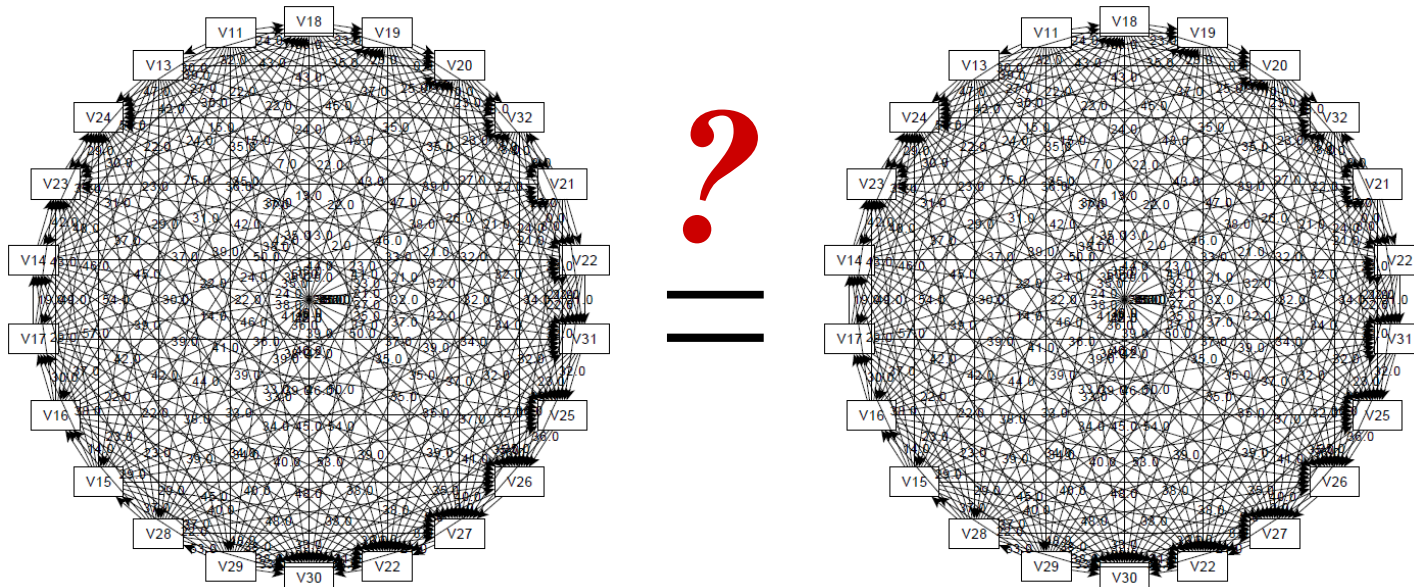


≠



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
 - `show(HKU QRS hide(TSE))`
- ◆ An *axiom* is a rule that specifies the refinement of a term
 - `hide(D D') = hide(D) hide(D')`
 - `show(D D') = show(D) show(D')`
 - `show(hide(D)) = show(D)`
 - `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*

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show(HKU QRS hide(TSE))

Algebraic Specification

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

`show(HKU QRS hide(TSE))`

`→ show(HKU) show(QRS) show(hide(TSE))`

`show(D D') = show(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*

`show(HKU QRS hide(TSE))`

→ `show(HKU) show(QRS) show(hide(TSE))`

→ `show(HKU) show(QRS) show(TSE)`

`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*

`show(HKU QRS hide(TSE))`

→ `show(HKU) show(QRS) show(hide(TSE))`

→ **`show(HKU) show(QRS) show(TSE)`**

→ **`HKU QRS TSE`**



`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*

`show(HKU QRS hide(TSE))`

→ `show(HKU) show(QRS) show(hide(TSE))`

→ `show(HKU) show(QRS) show(TSE)`

→ **HKU QRS TSE**

Normal form.

Denotational Semantics

- ◆ Mathematical meaning
- ◆ Like simultaneous equations

$$2x + 3y = 4$$

$$5x + 6y = 7$$

- “=” means “equals”
- The order of the equations is not important.

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.

Canonical Algebraic Specification

- ◆ An algebraic specification is *canonical* if every sequence of rewrites of a ground term produces a unique normal form

Canonical Algebraic Specification

- ◆ An algebraic specification is *canonical* if every sequence of rewrites of a ground term produces a unique normal form

show(HKU) show(QRS) show(hide(TSE)**)**

→ show(HKU) show(QRS) show(TSE)

→ HKU QRS TSE

Canonical Algebraic Specification

- ◆ An algebraic specification is *canonical* if every sequence of rewrites of a ground term produces a unique normal form

`show(HKU) show(QRS) show(hide(TSE))`

→ `show(HKU) show(QRS) show(TSE)`

→ `HKU QRS TSE`

`show(HKU) show(QRS) show(hide(TSE))`

→ **`HKU QRS show(hide(TSE))`**

→ **`HKU QRS TSE`**

Canonical Algebraic Specification

- ◆ For a *canonical* specification, the operational semantics agrees with the denotational semantics.

Target of OO Software Testing

According to Real-World Practice

- ◆ An implementation P is *correct with respect to the specification S_p* if and only if

Target of OO Software Testing

According to Real-World Practice

- ◆ 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, **hide**(TSE) and **delete**(TSE) are attributively equivalent.

Target of OO Software Testing

According to Huo Yan Chen et al. (1998)

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

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

For example, **hide**(TSE) and **delete**(TSE) are observationally nonequivalent.

Targets of OO Software Testing

AE

Real-world short-cut, but too weak to be useful

?

A jungle of proposals by various researchers.

OE U OE'

Real-world correctness, but *very very very very very very very very very very* difficult to test.

Target of OO Software Testing

According to Bernot et al. (1991), Le Gall and Arnould (1996), Machado (1998, 2000), Machado and Sannella (2002), Aiguier et al. (2006)

- ◆ 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

Target of OO Software Testing

According to Doong and Frankl (1994), Gaudel (1995), Zhu (2003)

- ◆ 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

Target of OO Software Testing

According to Doong and Frankl (1994), Gaudel (1995), Zhu (2003)

- ◆ 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.

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
 - P satisfies the set (***FP***) of all *fundamental pairs* in Sp

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 (***NE***) of all *normally equivalent* ground pairs in Sp

Target of OO Software Testing

According to Huo Yan Chen et al. (1998)

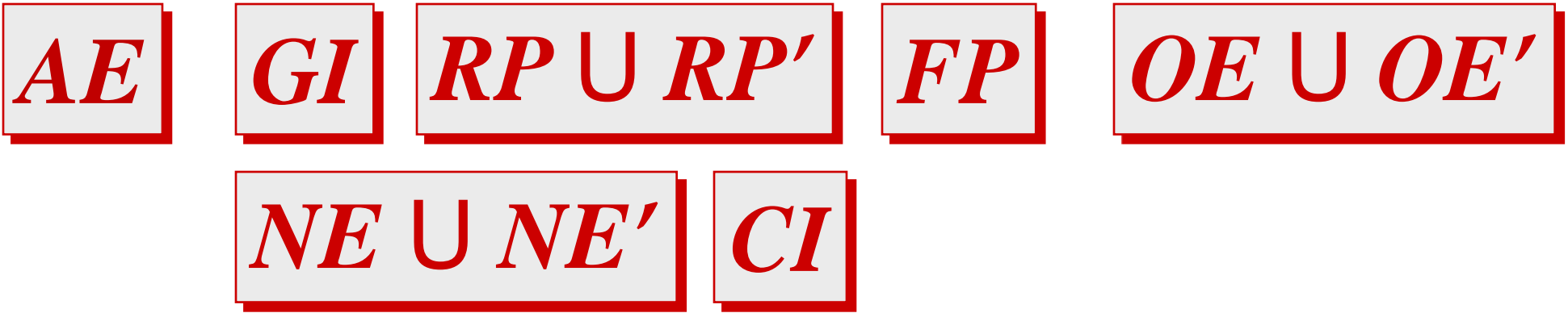
- ◆ An implementation P is *correct with respect to the specification S_p* if and only if:
 - ***Equivalence Criterion***
 P satisfies the set (NE) of all *normally equivalent* ground pairs in S_p
 - ***Non-Equivalence Criterion***
 P satisfies the set (NE') of all *normally nonequivalent* ground pairs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

Target of OO Software Testing

According to Aiguier et al. (2006)

- ◆ An implementation P is *correct with respect to the specification S_p* if and only if
 - P satisfies the set (**CI**) of all ground instances of every axiom in S_p 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?

What Do Others 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

◆ Tame the forest!

space time curvature



Albert Einstein

What Do Other Researchers Do?

Spectrum-Based Fault Localization

◆ Risk evaluation formulas

AMPLE2

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

AMPLE2 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



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!

Targets of OO Software Testing

AE *GI* *RP* \cup *RP'* *FP* *OE* \cup *OE'*
NE \cup *NE'* *CI*

- ◆ 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

Not helpful.

Not helpful.

◆ $(P \text{ satisfies } OE \cup OE') \Rightarrow (P \text{ satisfies } OE)$

Ultimate Target of OO Software Testing

Tame the Forest

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

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)
 - ↔ (P 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
 - $(P \text{ satisfies } AE)$
 $\Leftrightarrow (P \text{ satisfies } OE) \Leftrightarrow (P \text{ satisfies } OE')$

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
 - $(P \text{ satisfies } AE)$
 - $\Leftrightarrow (P \text{ satisfies } OE) \Leftrightarrow (P \text{ satisfies } OE')$
 - $\Leftrightarrow (P \text{ satisfies } OE \cup OE')$

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
 - $(P \text{ satisfies } AE)$
 - $\Leftrightarrow (P \text{ satisfies } OE) \Leftrightarrow (P \text{ satisfies } OE')$
 - $\Leftrightarrow (P \text{ satisfies } OE \cup OE')$
 - $\Leftrightarrow (P \text{ satisfies } NE) \Leftrightarrow (P \text{ satisfies } RP)$
 - $\Leftrightarrow (P \text{ satisfies } GI) \Leftrightarrow (P \text{ satisfies } CI)$
 - $\Leftrightarrow (P \text{ satisfies } FP).$

Ultimate Target of OO Software Testing

Tame the Forest

In short

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

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

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Ubiquitous Computing

- ◆ Computing everywhere and at any time
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- ◆ 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!

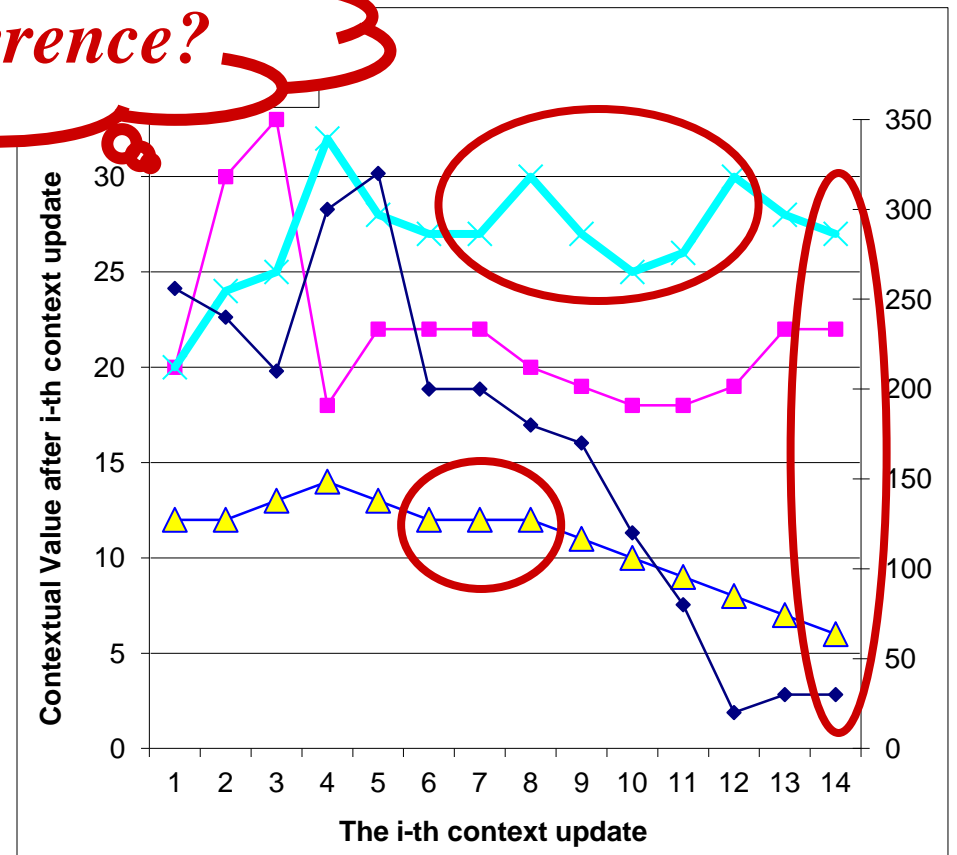
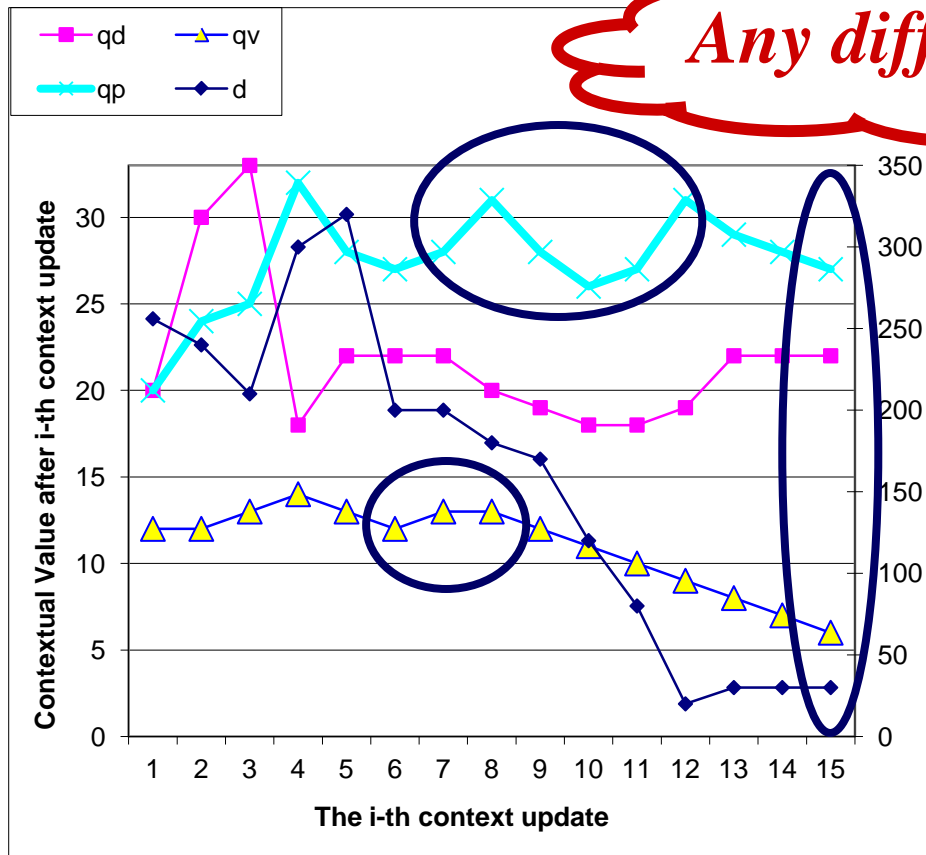
Ubiquitous Computing

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



Metamorphic testing



Many facets of
metamorphic testing.

Conclusion

- ◆ 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

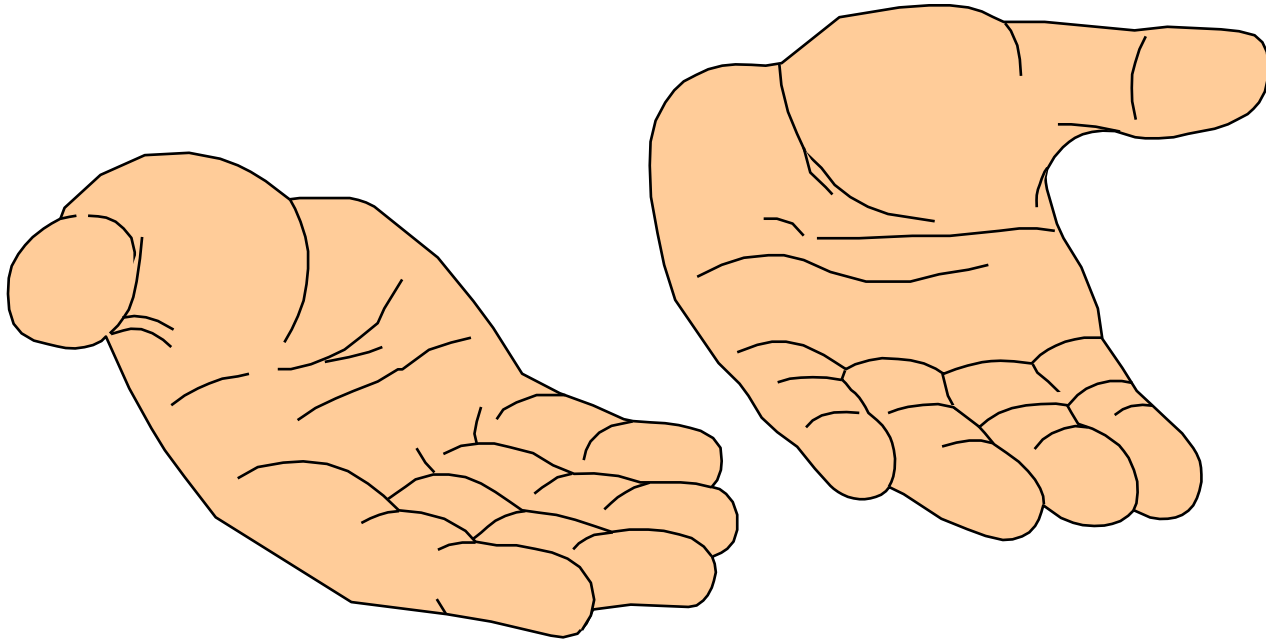
- ◆ Many facets of the test oracle problem
 - Expected outcome = actual execution result
 - Expected outcome = actual execution result
 - Expected outcome = actual execution result

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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