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

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

Comprehensive coverage

Formula for A Successful Keynote Speech

{ ? ! " " _ ^ ∉ -> :-) }

Bold questions

Comprehensive coverage

Formula for A Successful Keynote Speech

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

Provocative assertions

Bold questions

Comprehensive coverage

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Learn from gurus

Provocative assertions

Bold questions

Comprehensive coverage

Formula for A Successful Keynote Speech

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Solid foundations

Formula for A Successful Keynote Speech

{ ? ! " " _ ^ ∉ -> :-) }

Advanced concepts

Solid foundations

Formula for A Successful Keynote Speech

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

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

{ ? ! " " _ ^ ∉ -> :-) }

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

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  - Expected outcome
    = actual execution result

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- What do other researchers do?
- Trim the tree or tame the forest? .

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- 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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The Test Oracle Problem

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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

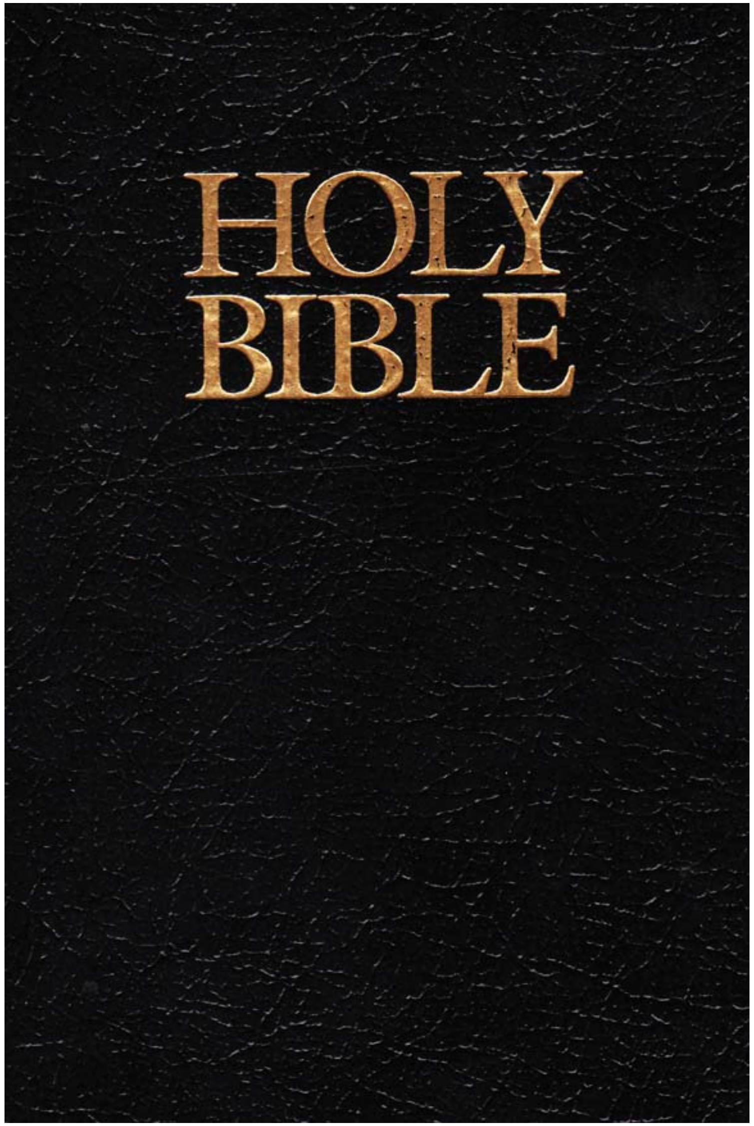
Prof. T.H. Tse
The University of Hong Kong
Pokfulam, Hong Kong

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).

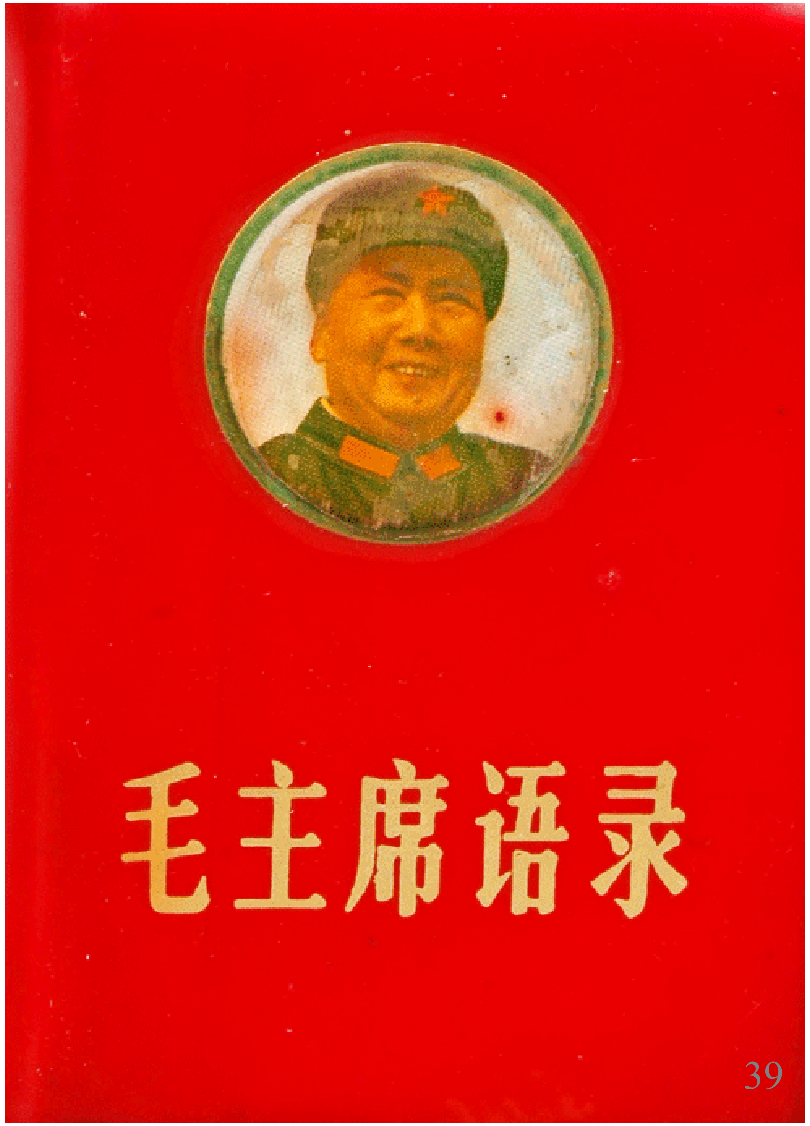
Oracle

- A message supposedly from God's inspiration, usually given by a prophet



Oracle

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



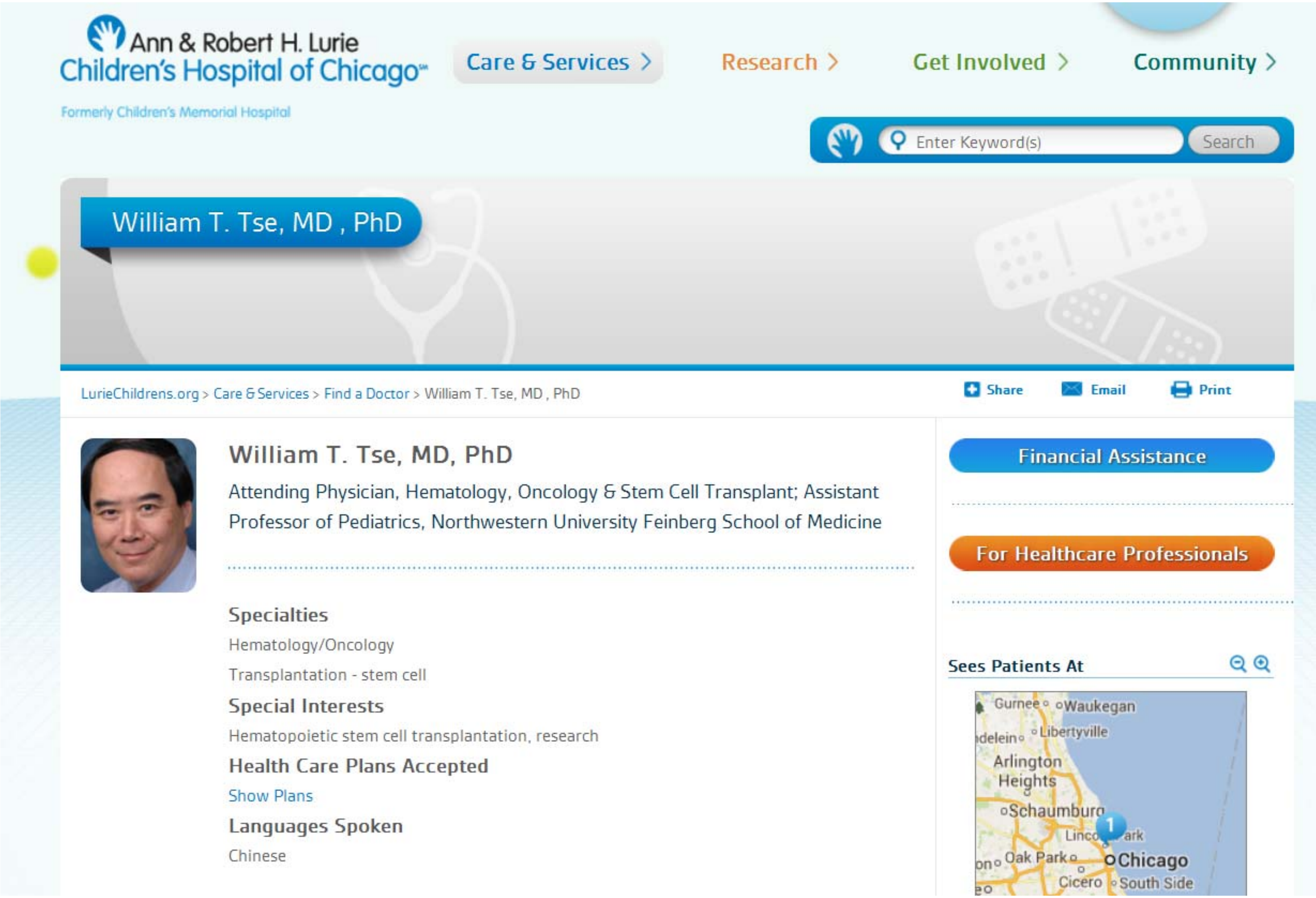
Oracle

- A message supposedly from God's inspiration, usually given by a prophet
- 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

Google

hotel near "children's hospital" chicago

Web Images Maps Books More

About 2,770,000 results (0.74 seconds)

Is 2.77M results correct?

[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**

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 (π – 0.9876)	Expected	?	Actual	0.8347

Metamorphic Testing

sin 0.9876	Expected	?	Actual	0.8347
sin (π – 0.9876)	Expected	?	Actual	0.8347

Metamorphic Testing

sin 0.9876 | Expected ? | Actual 0.8347

sin (π – 0.9876) | Expected ? | Actual 0.8347

Metamorphic Testing

sin 0.9876	Expected ?	Actual	0.8347
sin (π – 0.9876)	Expected ?	Actual	0.8347

Expected ***metamorphic relation***

$$\boxed{\sin 0.9876 = \sin(\pi - 0.9876)}$$

Metamorphic Testing

sin 0.9876

sin (π – 0.9876)

Expected ?

Expected ?

Actual 0.8347

Actual 0.8347

Expected *metamorphic relation*

sin 0.9876 = sin (π – 0.9876)

Metamorphic Testing

sin 0.9876

sin (π – 0.9876)

Expected ?

Expected ?

Actual 0.8347

Actual 0.8347

Expected *metamorphic relation*

sin 0.9876 = sin (π – 0.9876)

Actual relation

0.8347 = 0.8347

Real-Life Search Engine Example

Apply Metamorphic Testing

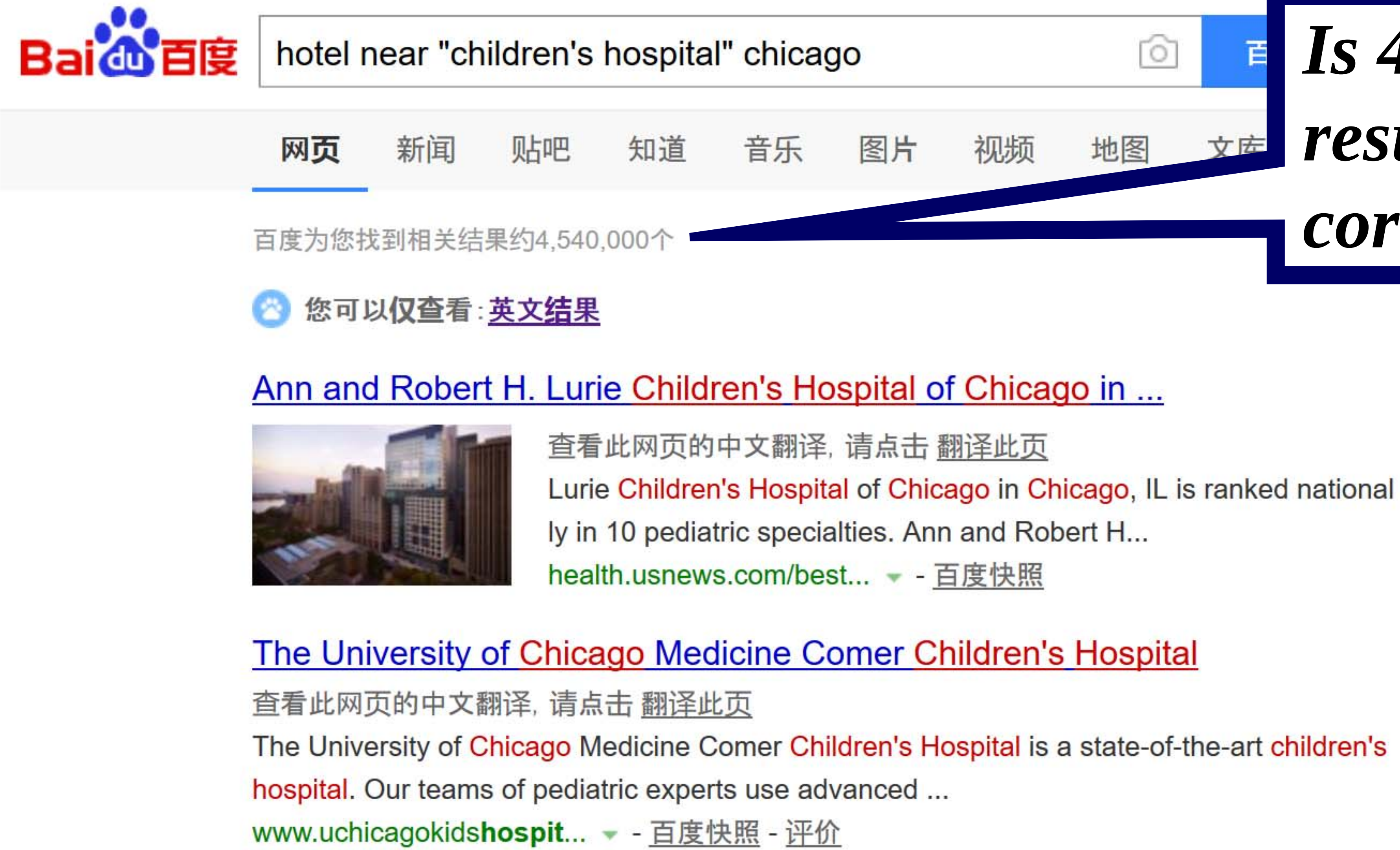
Metamorphic Relation:
More refined search should produce fewer number of entries.

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?

Real-Life Search Engine

Bai du 百度

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 Chicag

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

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Lurie Children's Hospital of Chicago is a unique place where children, families, physicians an d 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.

Recent Track Records

Compilers

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

Recent Track Records

Compilers

- Based on metamorphic testing, an "equivalence modulo inputs" technique identified 147 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

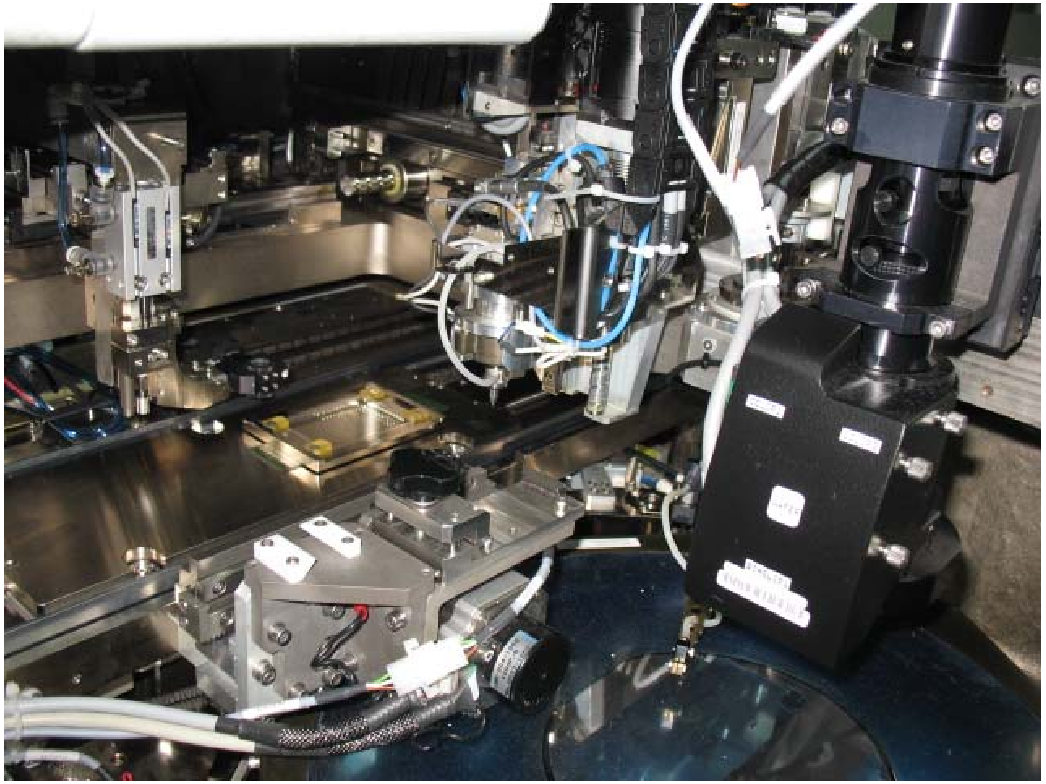
Many Facets of the Test Oracle Problem

Challenge 2:

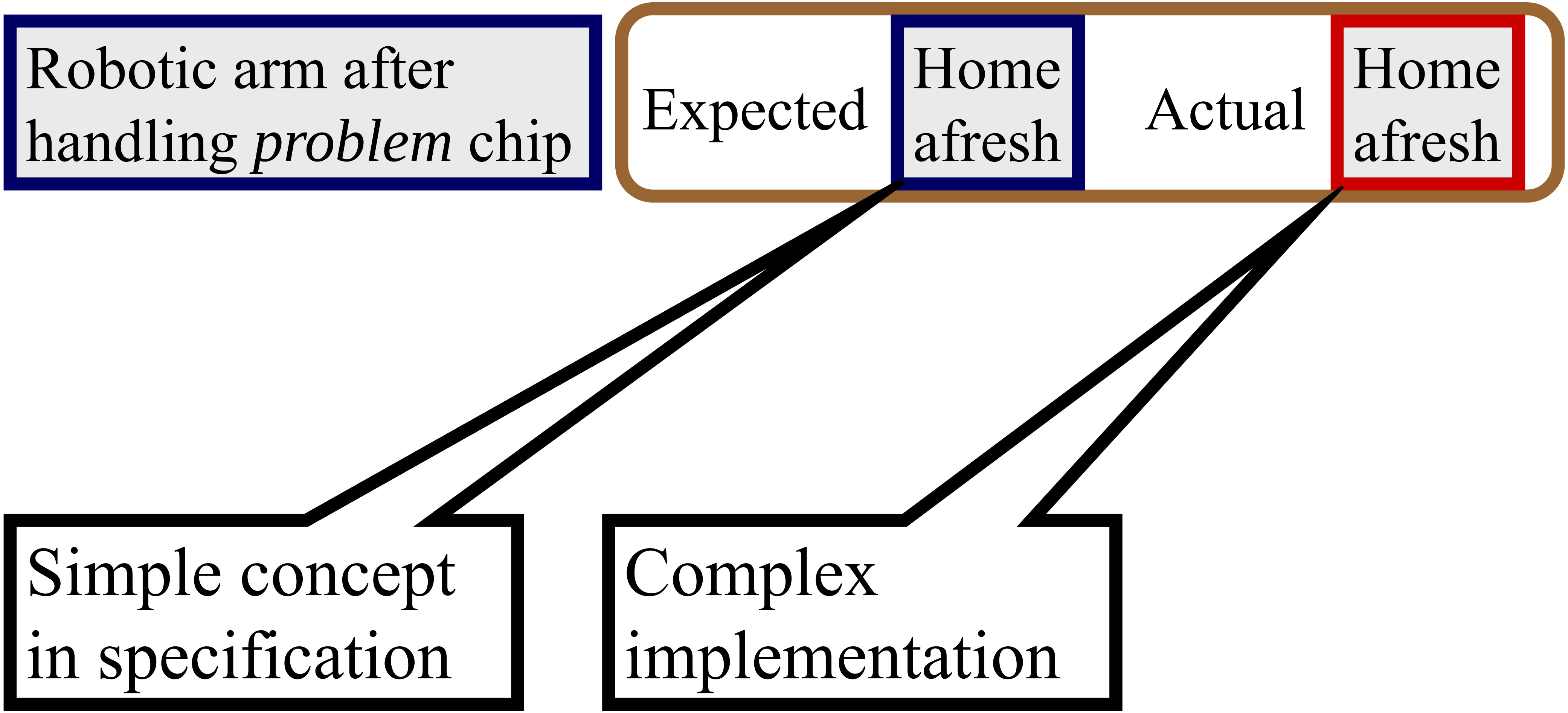
- Expected outcome $\boxed{=}$ actual execution result
- Consider the testing of real-life object-oriented software.

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

Cannot define "=" at two different levels of abstraction.

Mimic Metamorphic Testing?

Robotic arm after handling *problem* chip	Expected	Home afresh	Actual	Home afresh

Mimic Metamorphic Testing?

Robotic arm after handling *problem* chip	Expected	Home afresh	Actual	Home afresh
Robotic arm after handling *standard* chip				

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Mimic Metamorphic Testing?

Robotic arm after handling *problem* chip

Expected Home afresh

Actual Home afresh

Robotic arm after handling *standard* chip

Expected Home afresh

Actual Home afresh

Expected relation

Equivalent

Mimic Metamorphic Testing?

Robotic arm after handling *problem* chip

Expected | Home afresh

Actual | Home afresh

Robotic arm after handling *standard* chip

Expected | Home afresh

Actual | Home afresh

Expected relation

Equivalent

Mimic Metamorphic Testing?

Robotic arm after handling *problem* chip

Robotic arm after handling *standard* chip

Expected | Home afresh

Expected | Home afresh

Actual | Home afresh

Actual | Home afresh

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

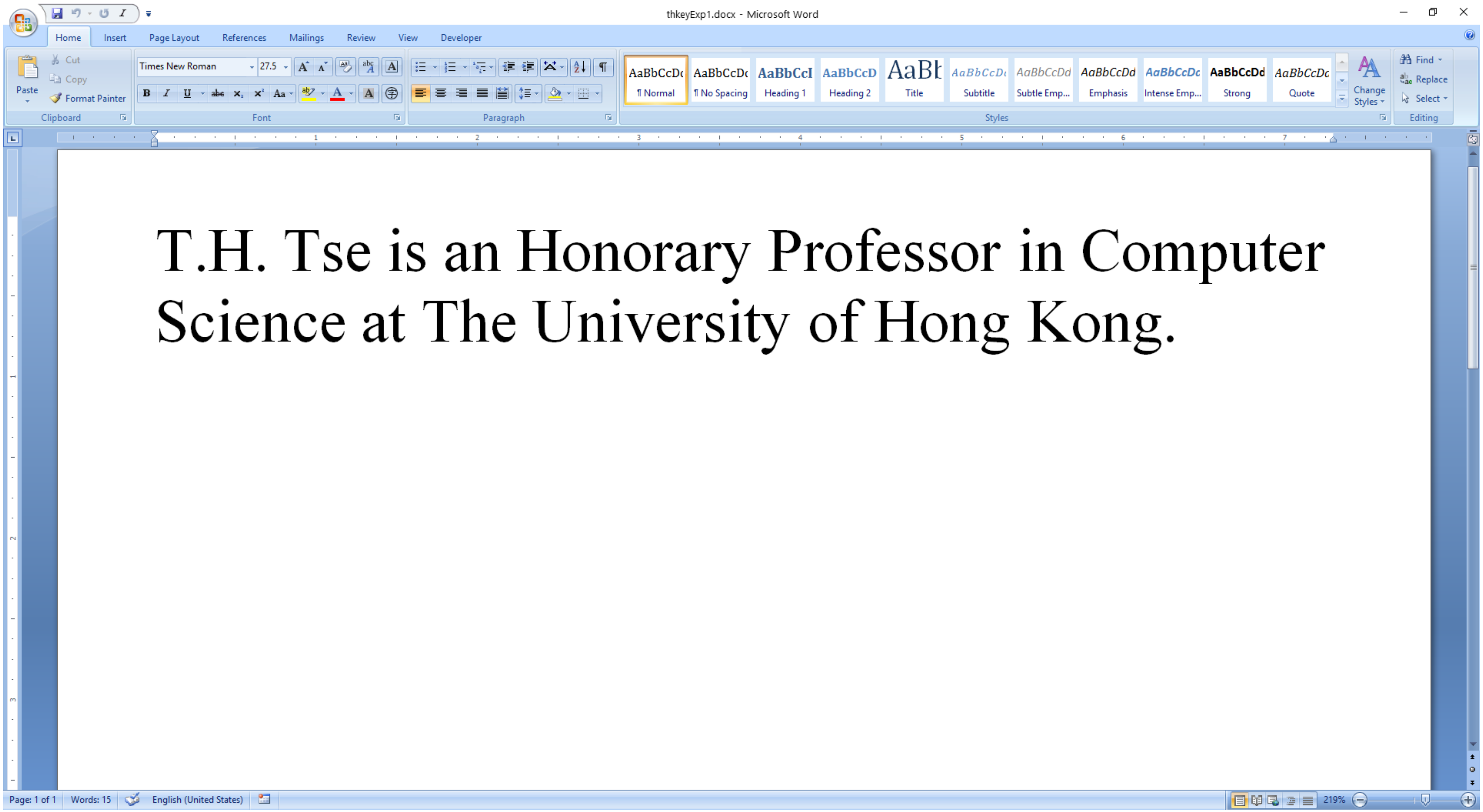
Challenge 3:

- Object A $\boxed{=}$ object B

What is object equivalence?

What is Object Equivalence?

Real-Life Word Processing Example



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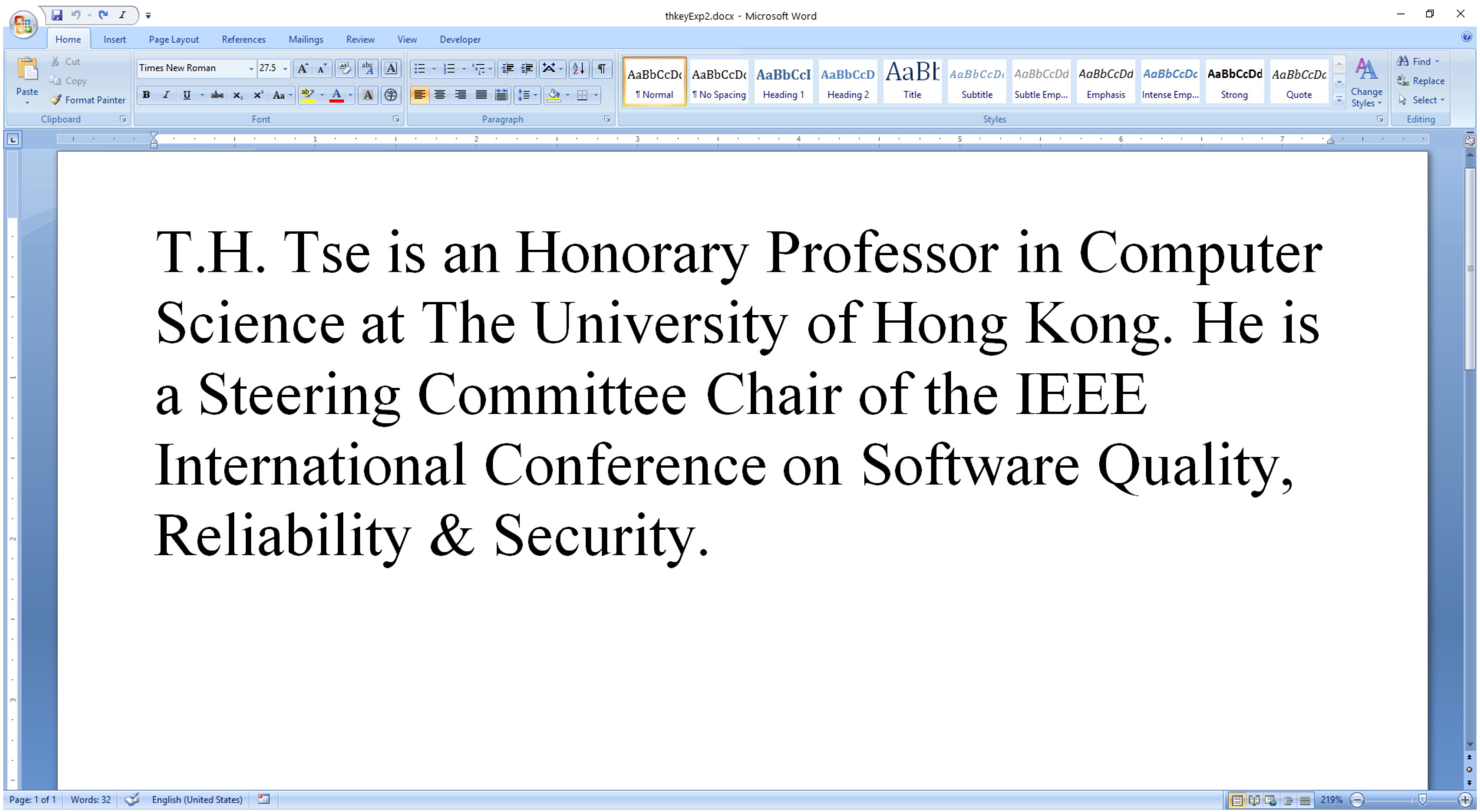
Real-Life Word Processing Example



What is Object Equivalence?

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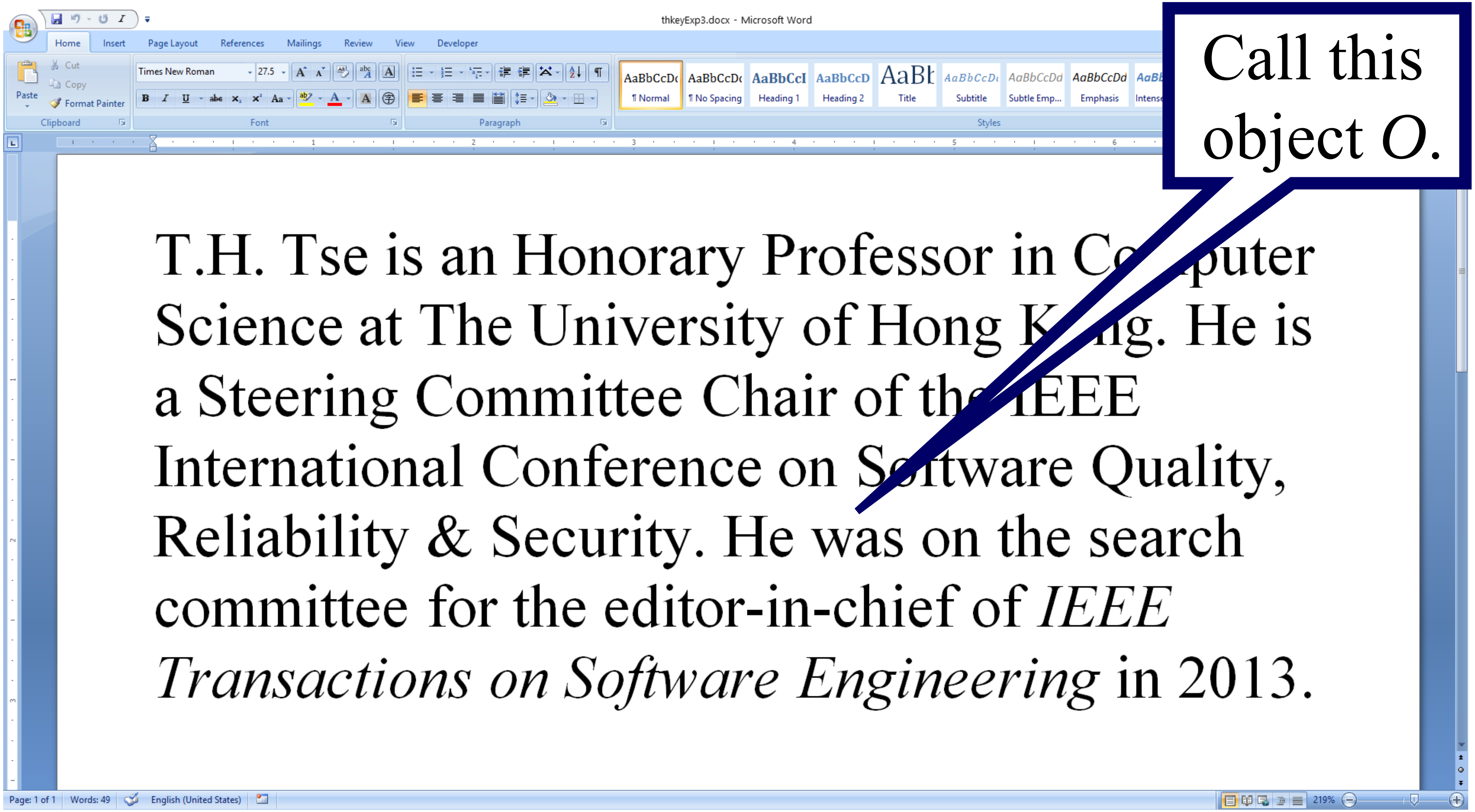
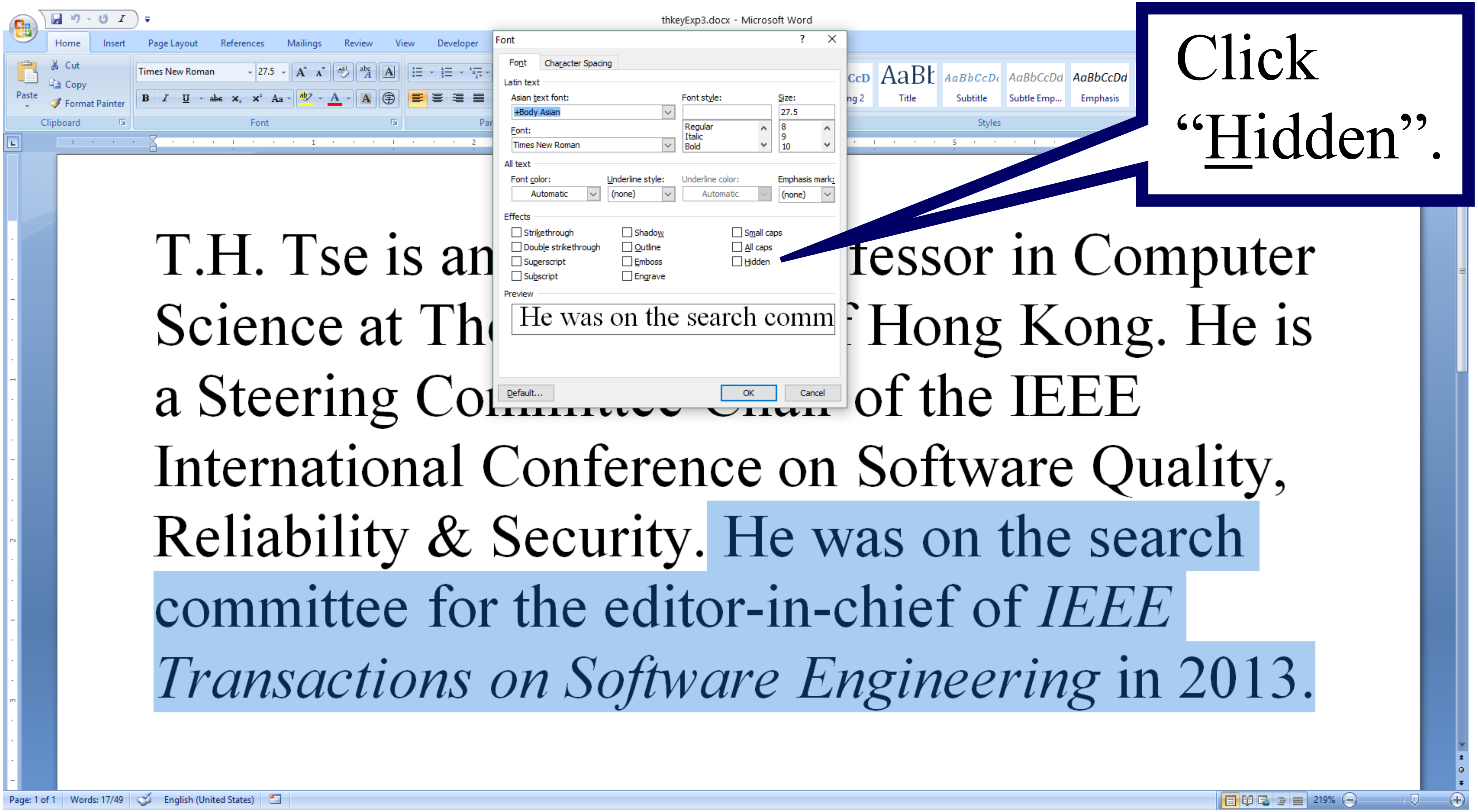


T.H. Tse is an Honorary Professor in Computer Science at The University of Hong Kong. He is a Steering Committee Chair of the IEEE International Conference on Software Quality, Reliability & Security. He was on the search committee for the editor-in-chief of *IEEE Transactions on Software Engineering*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

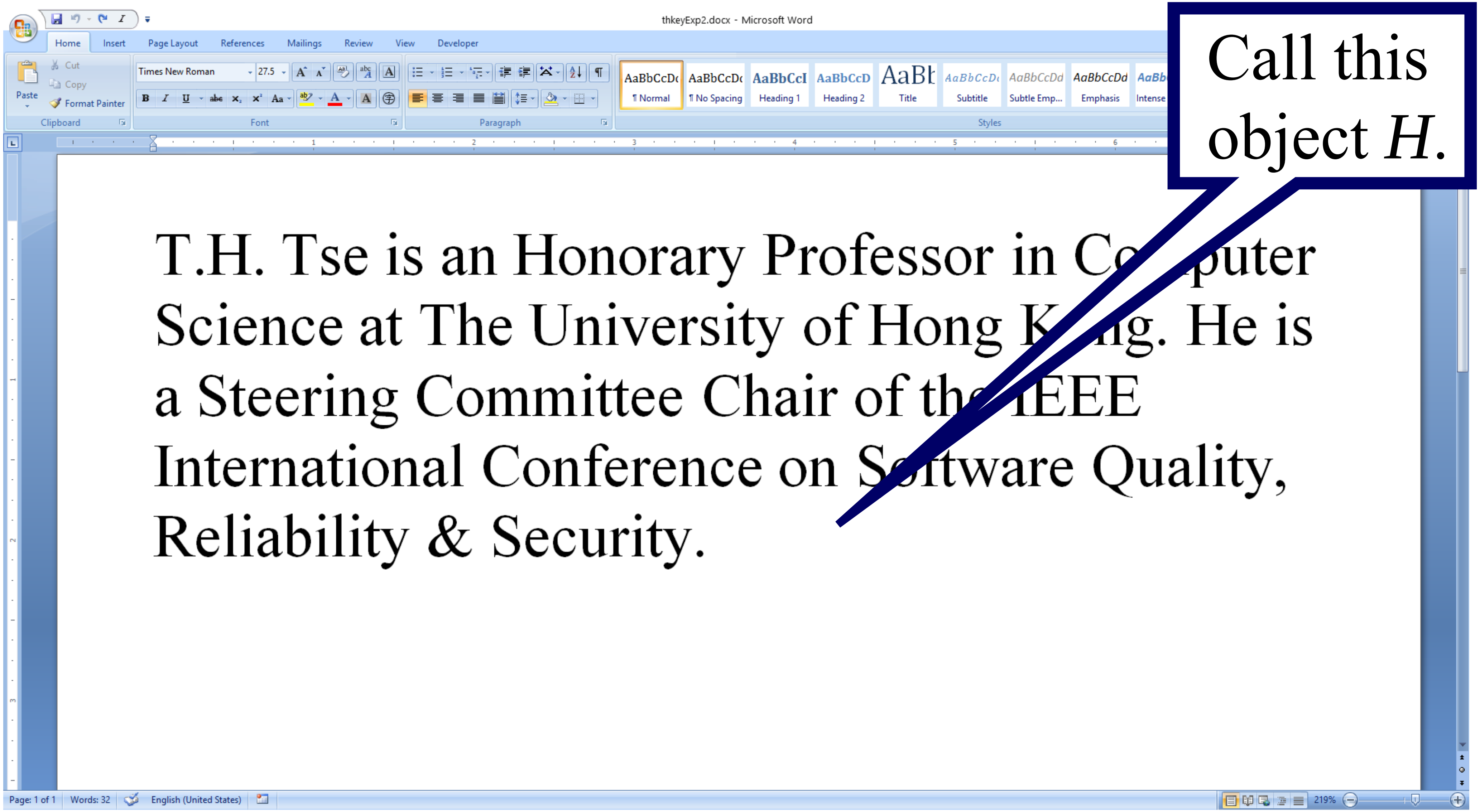
What is Object Equivalence?

Real-Life Word Processing Example



What is Object Equivalence?

Real-Life Word Processing Example



Call this object *H*.

What is Object Equivalence?

Output from Object *H*

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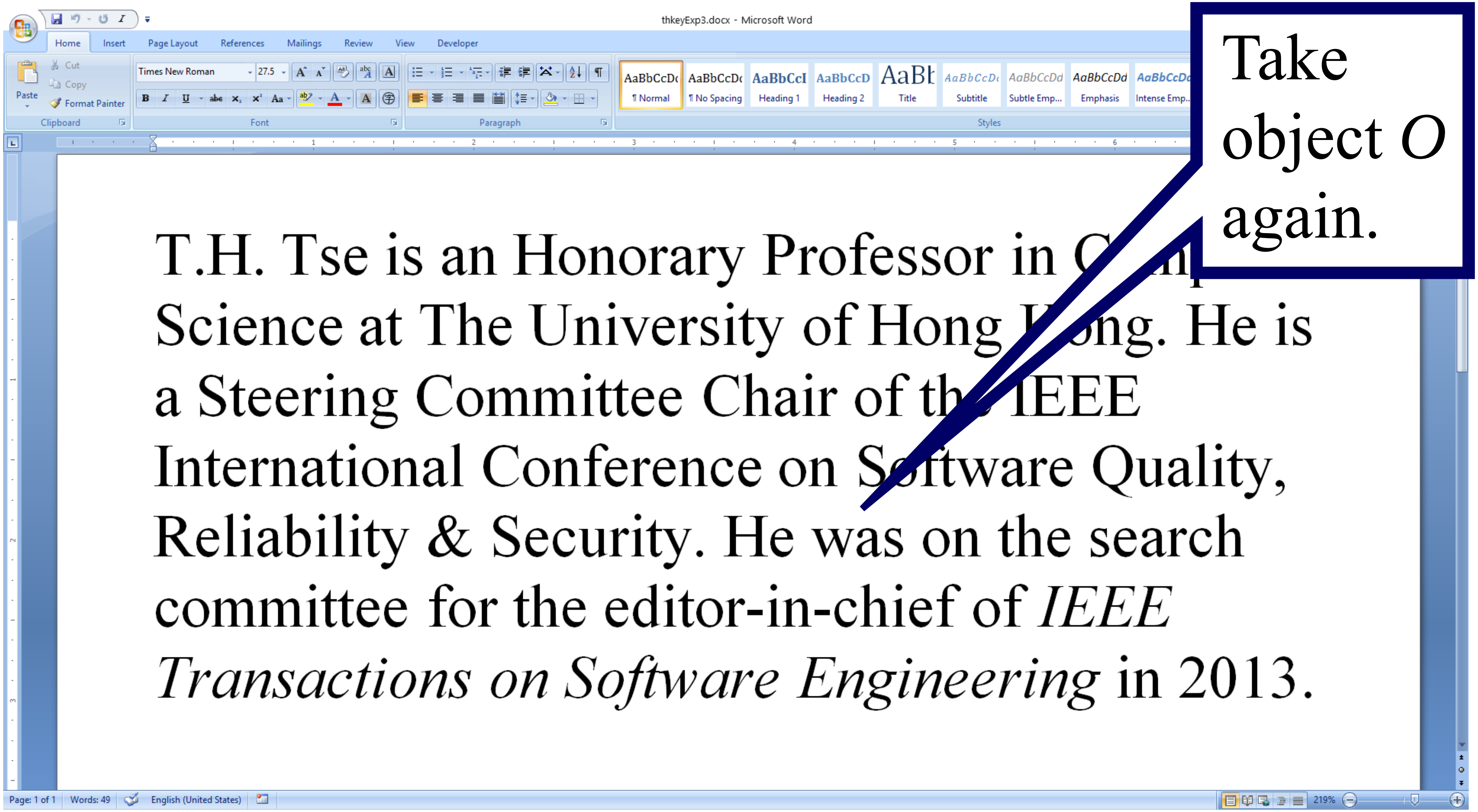
What is Object Equivalence?

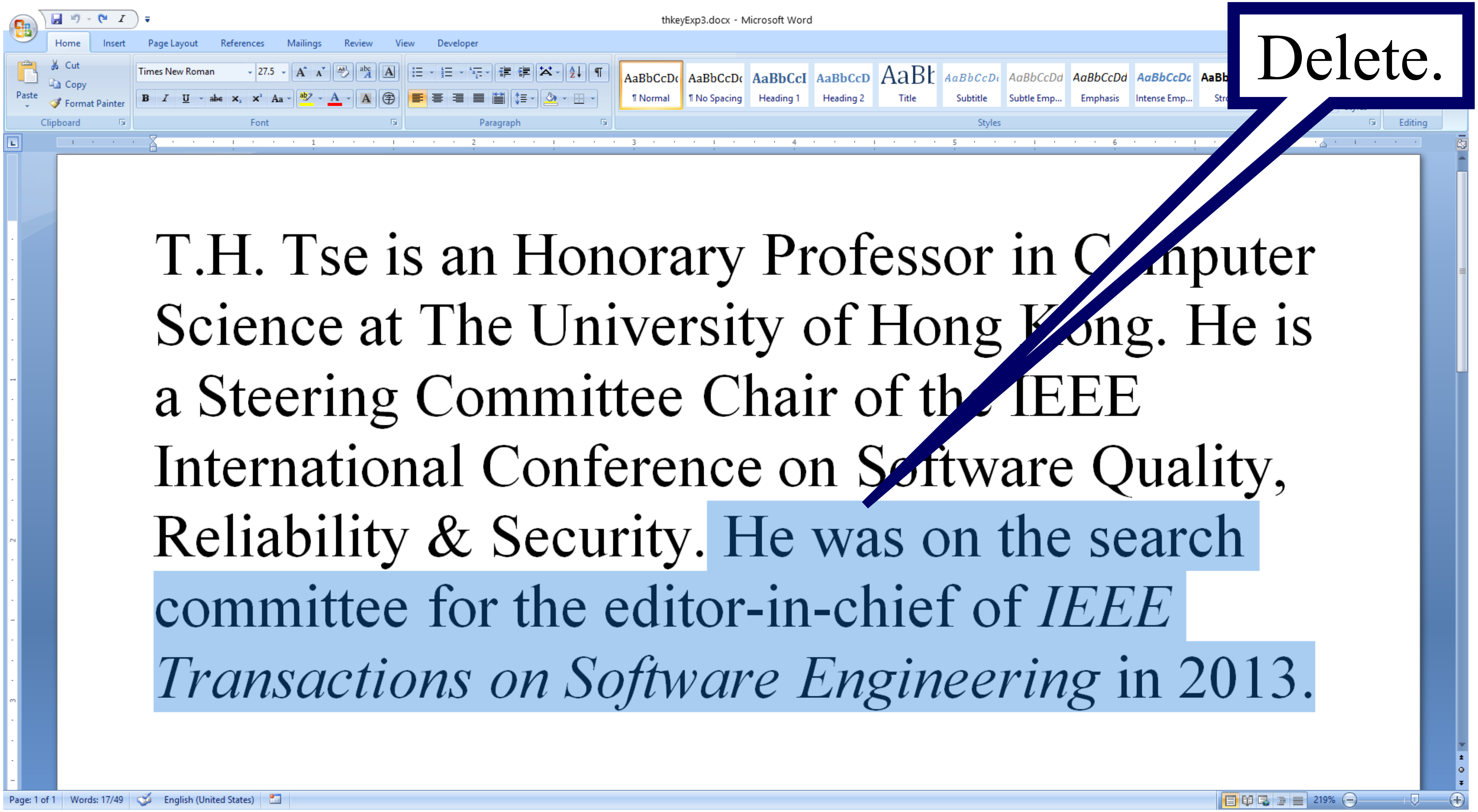
Real-Life Word Processing Example



Take object *O* again.

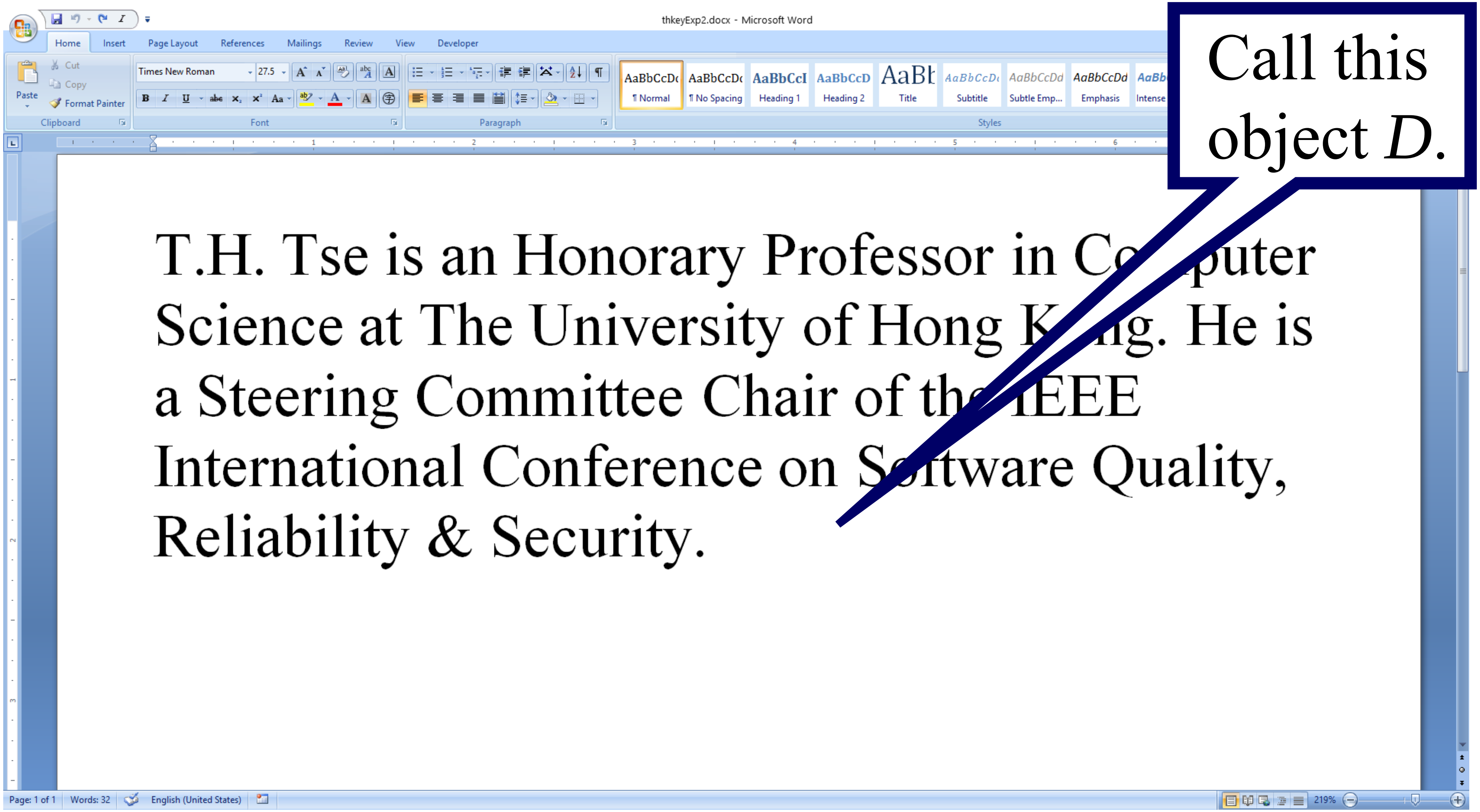
What is Object Equivalence?

Real-Life Word Processing Example



What is Object Equivalence?

Real-Life Word Processing Example



Call this object *D*.

What is Object Equivalence?

Output from Object *D*

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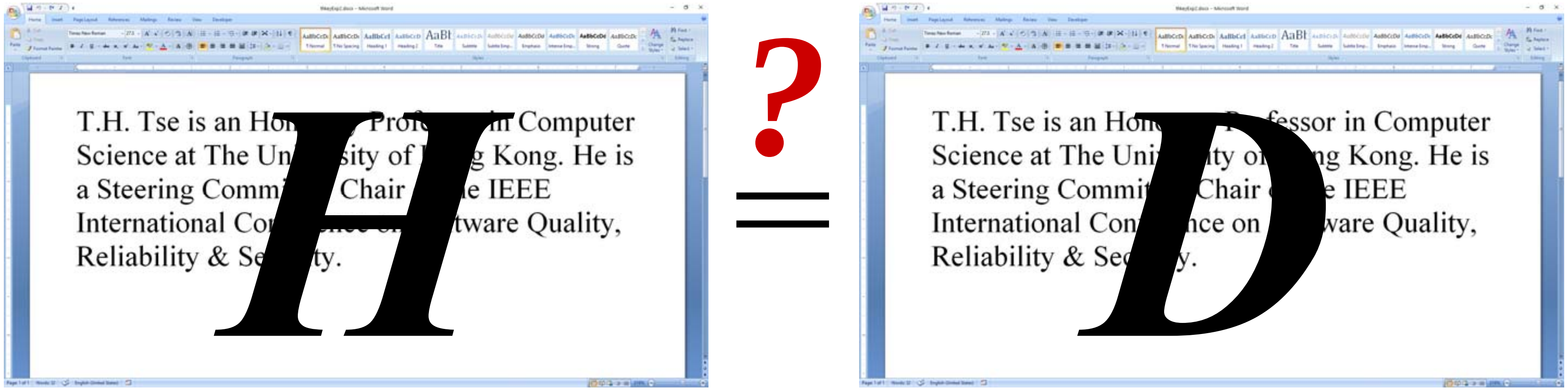
What is Object Equivalence?

Attributive Equivalence



- Two objects will be ***attributively equivalent*** if they have the exactly the same ***visible attributes***

What is Object Equivalence?

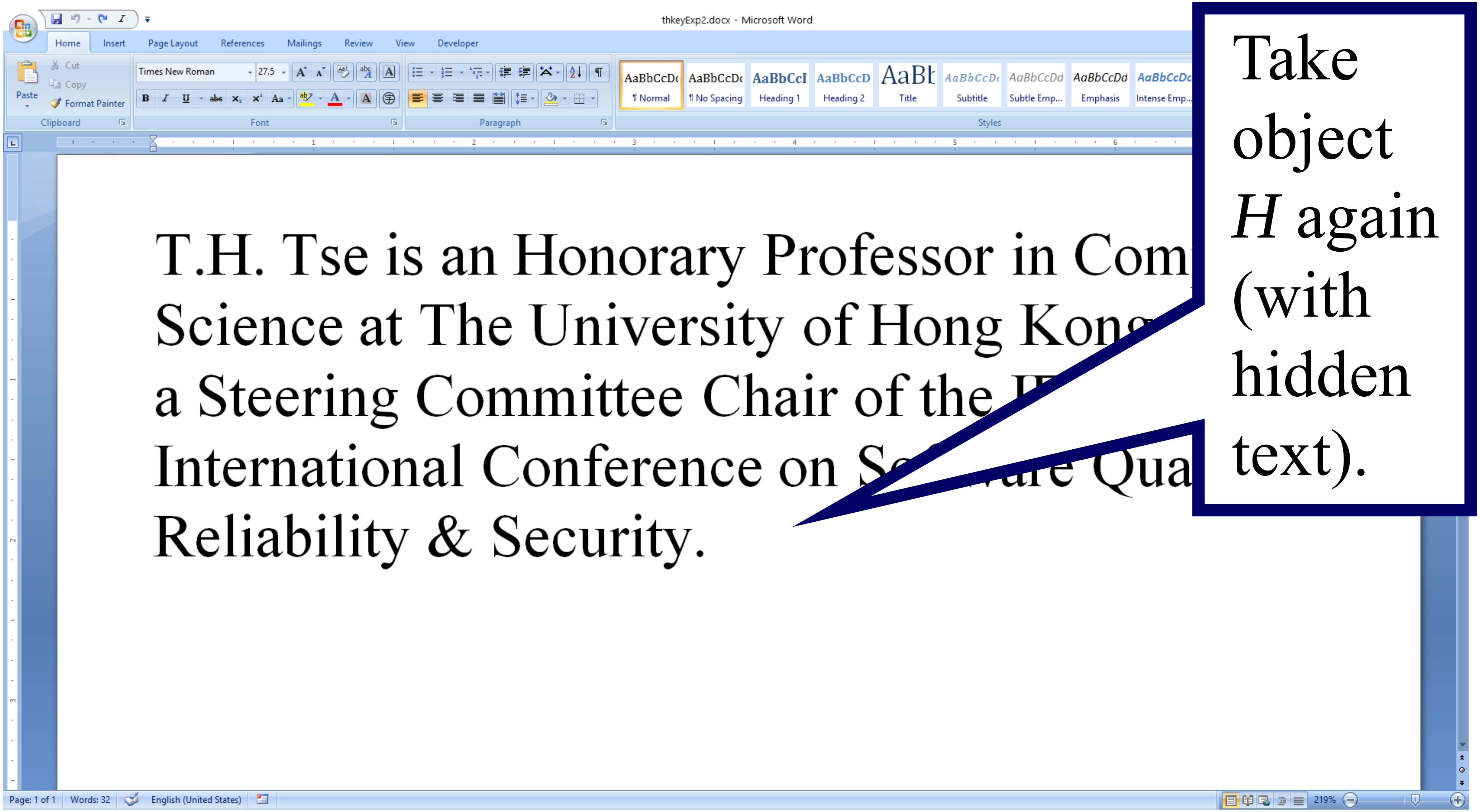
Attributive Equivalence

H	=	*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.	=	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.

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

What is Object Equivalence?

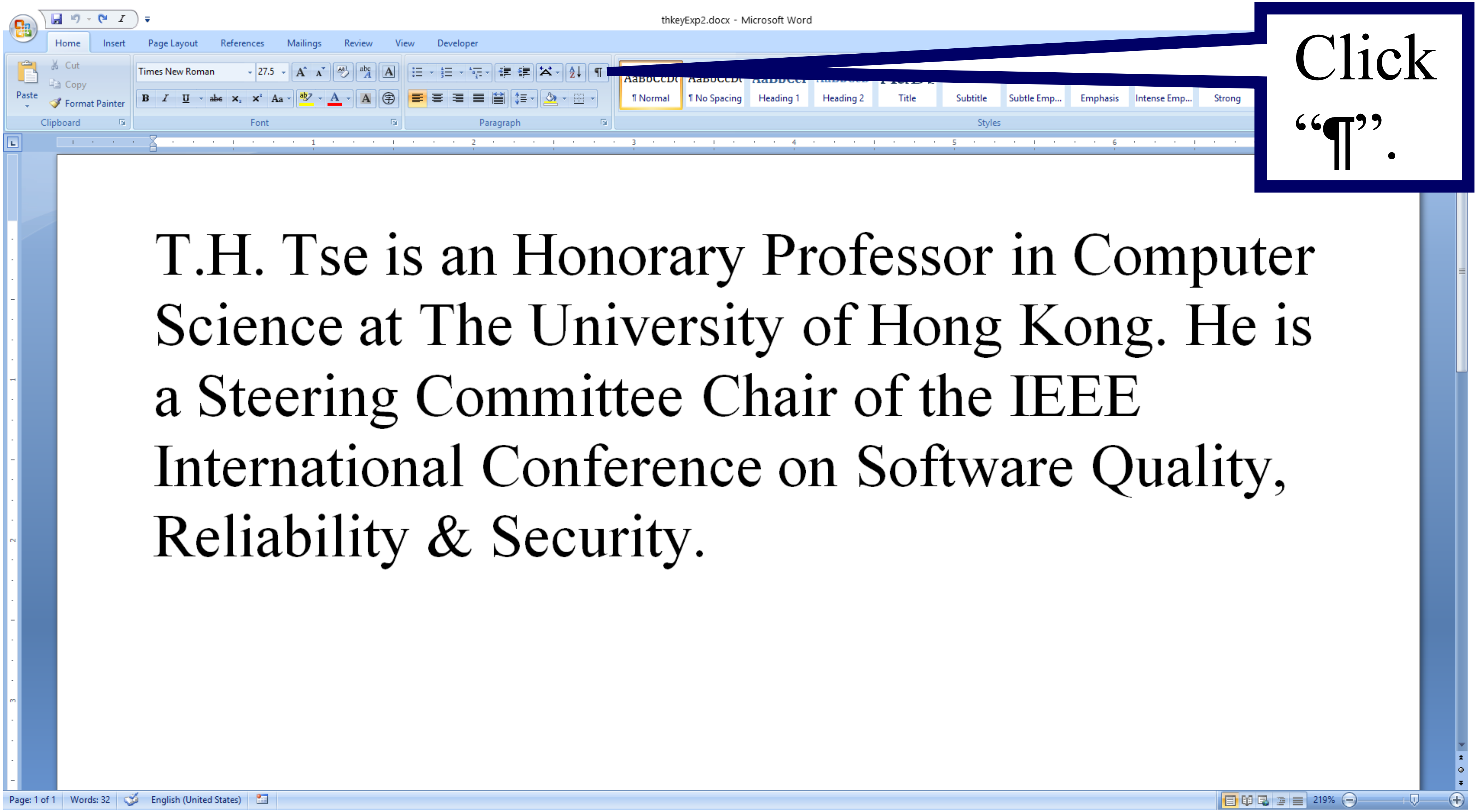
Real-Life Word Processing Example



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

What is Object Equivalence?

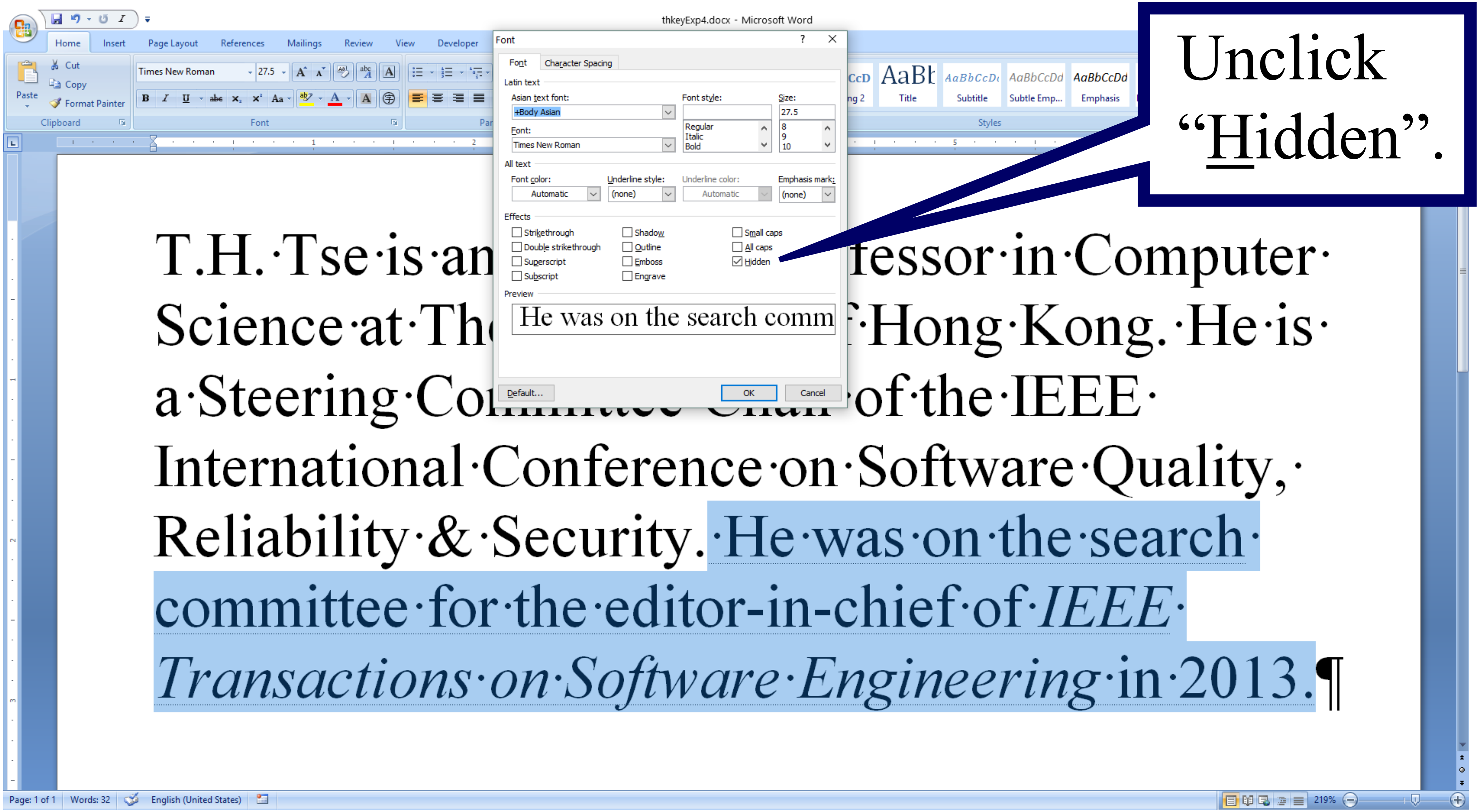
Real-Life Word Processing Example



Click "¶".

What is Object Equivalence?

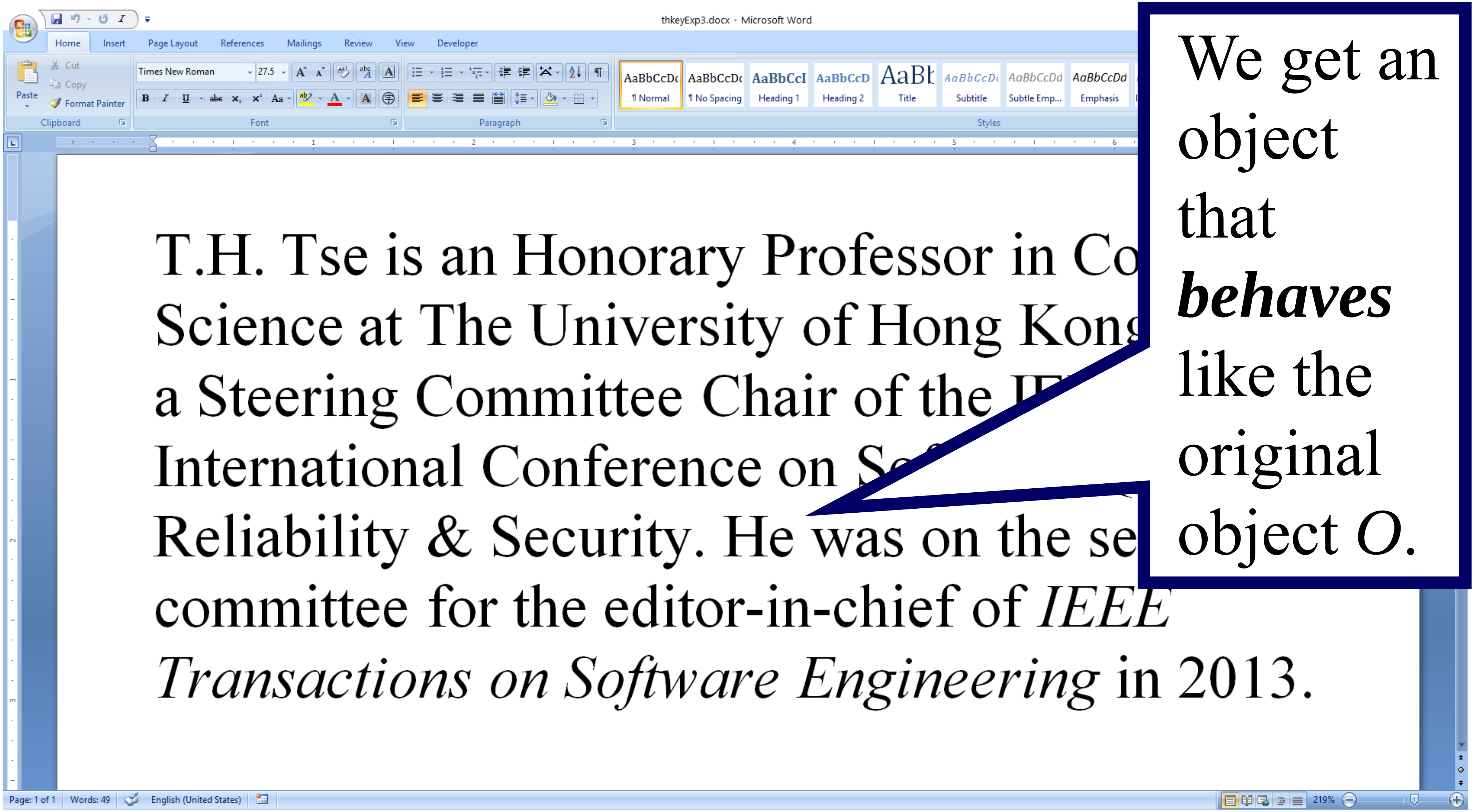
Real-Life Word Processing Example



Unclick "<u>H</u>idden".

What is Object Equivalence?

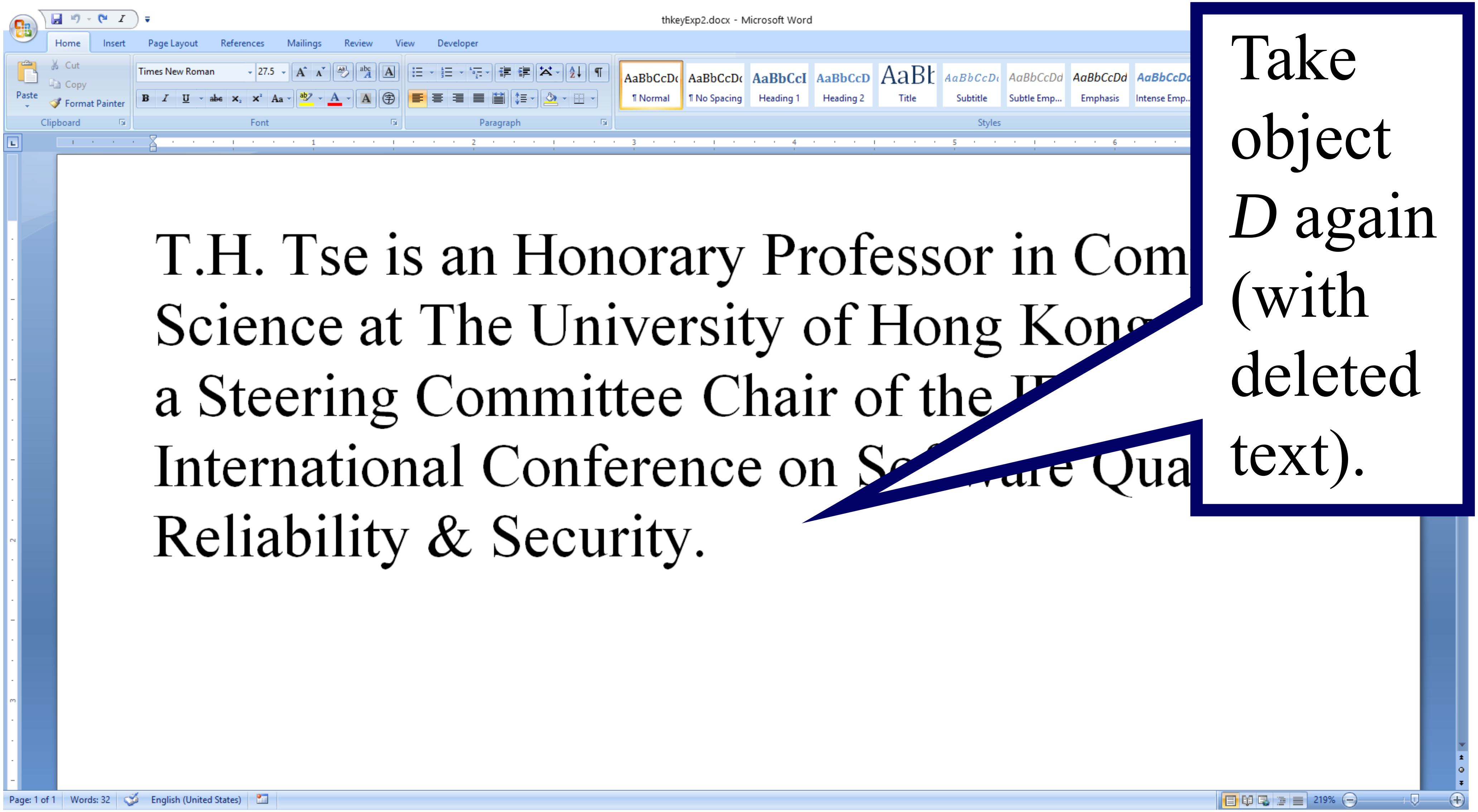
Real-Life Word Processing Example



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

What is Object Equivalence?

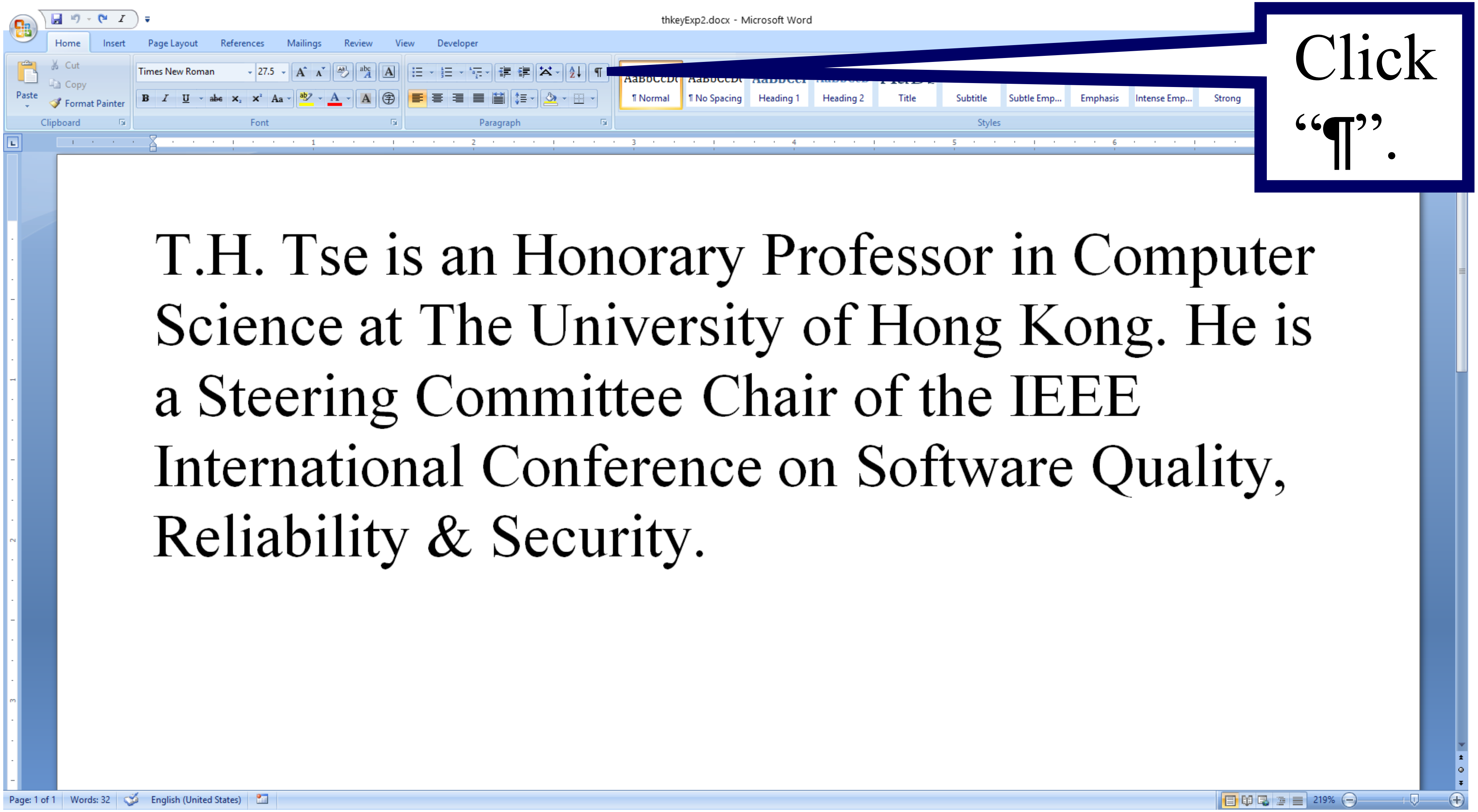
Real-Life Word Processing Example



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

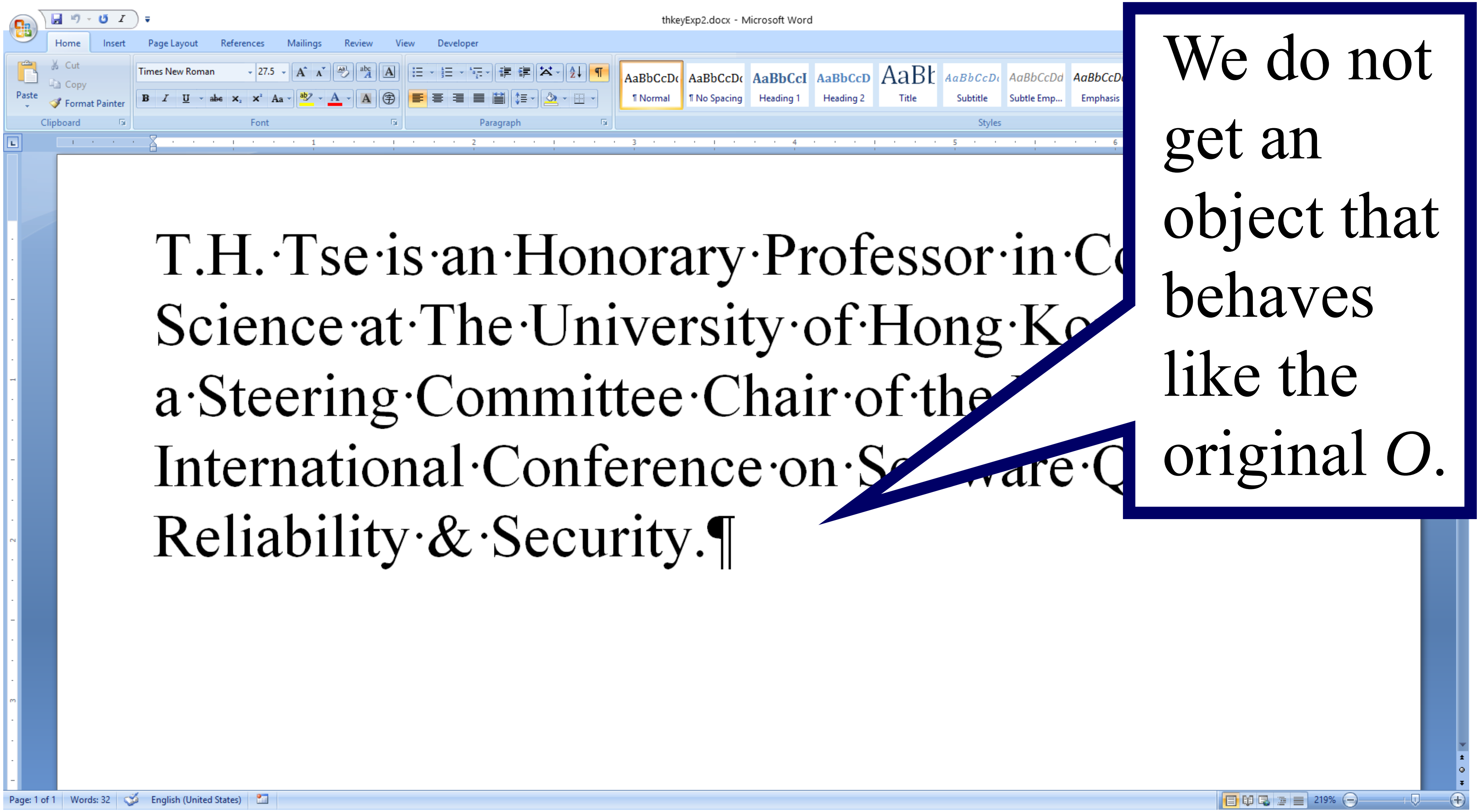
What is Object Equivalence?

Real-Life Word Processing Example



What is Object Equivalence?

Real-Life Word Processing Example

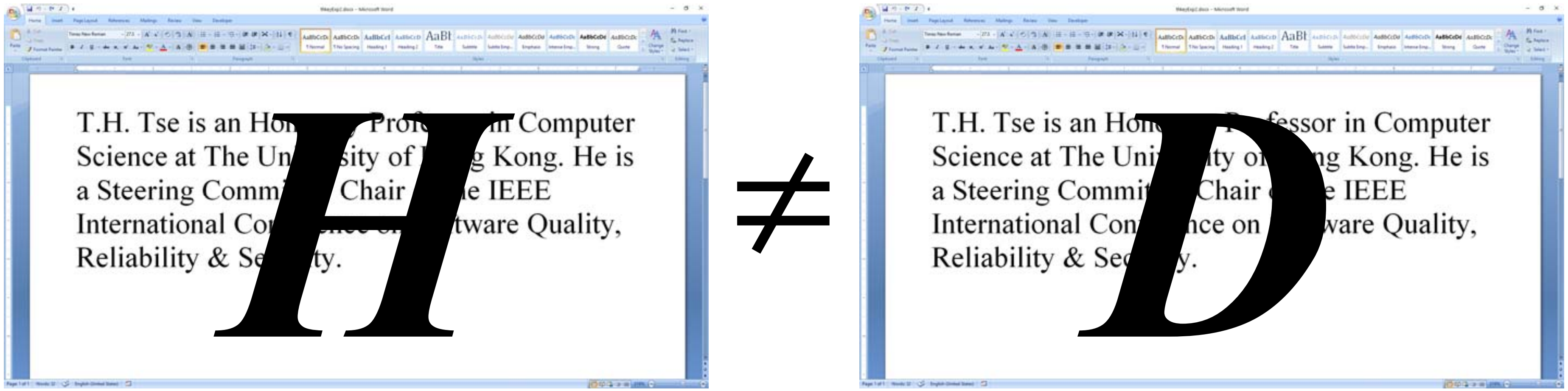


We do not get an object that behaves like the original *O*.

What is Object Equivalence?

Observational Equivalence

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



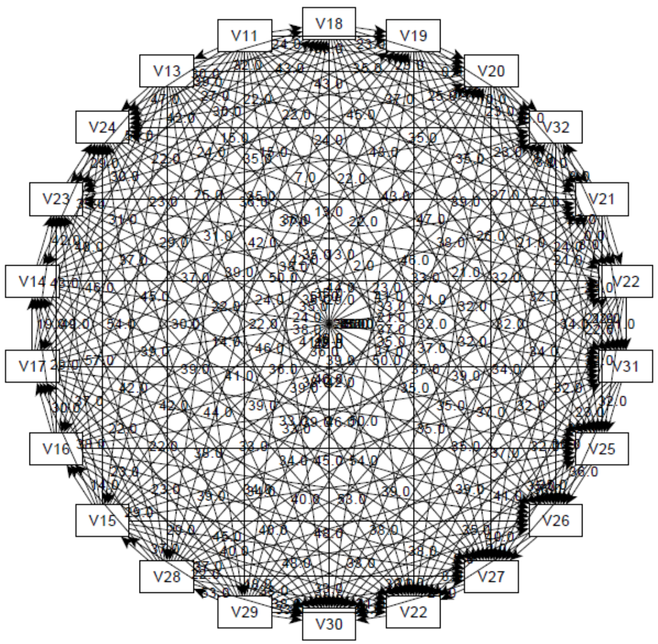
What is Object Equivalence?

Observational Equivalence

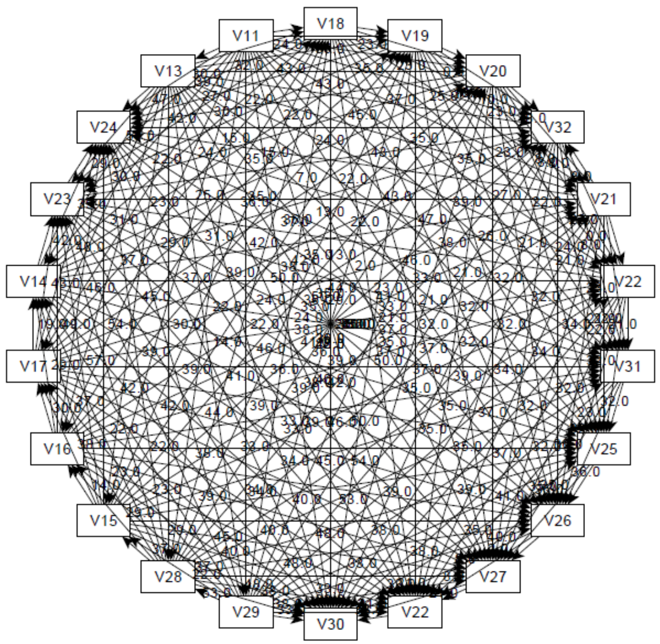
- Ideal criterion in object-oriented software testing
- ***But*** *very very very very very very very very very very very very very very very very very very very very very very very very very very very very very* difficult to verify:
  - Need to check an infinite combination of possible behavior for 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



$\stackrel{?}{=}$



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***

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))
```

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.

Algebraic Specification

Denotational Semantics

- Mathematical meaning
- Like simultaneous equations

$$2x + 3y = 4$$
$$5x + 6y = 7$$

  - "=" 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.

Canonical Algebraic Specification

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

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  → show(HKU) show(QRS) show(TSE)
  → HKU QRS TSE
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Canonical Algebraic Specification

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

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   → show(HKU) show(QRS) show(TSE)
   → HKU QRS TSE
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   → 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 Sp* 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)

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- 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* ∪ *OE′

Real-world correctness, but *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

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

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  - ***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 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*

Target of OO Software Testing
According to Aiguier et al. (2006)

- 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

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

- 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)

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  - 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”

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What is Empirical Study?

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  - 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 tre or tame the fore

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

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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 Reseachers 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

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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)

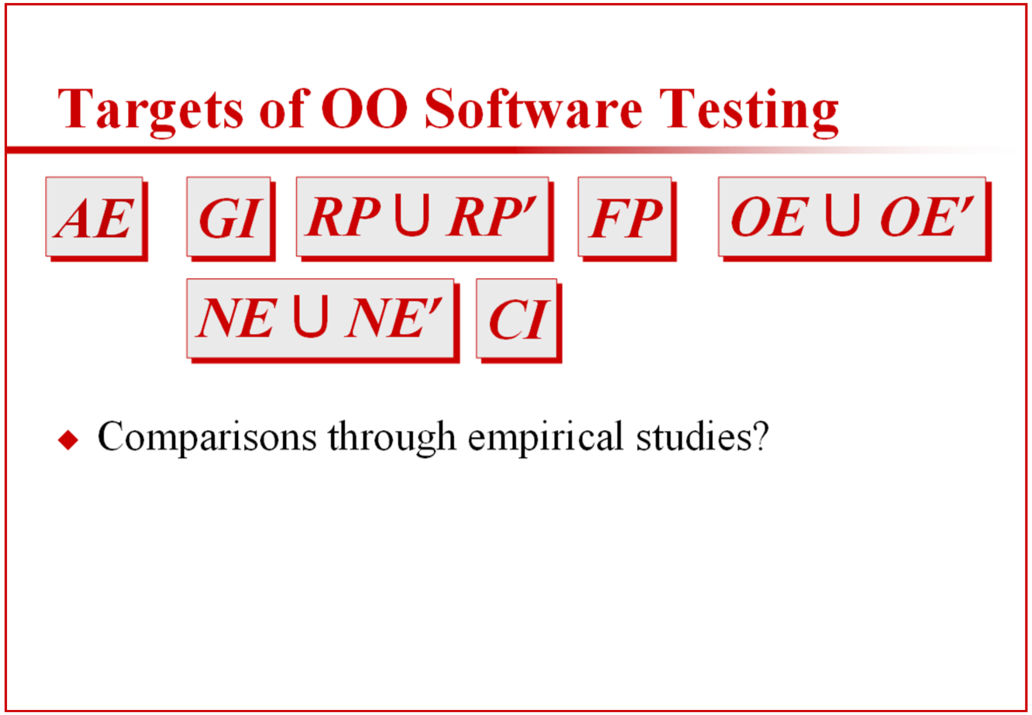
- Prove that no test case generation technique can be better than random testing by more than 50%
  - in the absence of further information on possible locations of failure-causing inputs
- Adaptive random testing is close to this theoretic limit.

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!



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 satisfies AE) $\Rightarrow$ (P satisfies OE) $\Rightarrow$ (P satisfies NE) $\Rightarrow$ (P satisfies RP) $\Rightarrow$ (P satisfies GI) $\Rightarrow$ (P satisfies CI) $\Rightarrow$ (P satisfies FP) and

Not helpful.

- (P satisfies $OE \cup OE'$) $\Rightarrow$ (P 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 *Sp* 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 *Sp* with ***proper imports*** and a ***complete*** implementation *P*
  - (*P* satisfies *AE*)
    $\Leftrightarrow$ (*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* satisfies *AE*)
    $\Leftrightarrow$ (*P* satisfies *OE*) $\Leftrightarrow$ (*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 satisfies AE)
    $\Leftrightarrow$ (P satisfies OE) $\Leftrightarrow$ (P satisfies OE')
    $\Leftrightarrow$ (P 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 satisfies AE)
    $\Leftrightarrow$ (P satisfies OE) $\Leftrightarrow$ (P satisfies OE')
    $\Leftrightarrow$ (P satisfies $OE \cup OE'$)
    $\Leftrightarrow$ (P satisfies NE) $\Leftrightarrow$ (P satisfies RP)
    $\Leftrightarrow$ (P satisfies GI) $\Leftrightarrow$ (P satisfies CI)
    $\Leftrightarrow$ (P satisfies FP).

Tame the Forest

In short

- Given a ***canonical*** specification *Sp* with ***proper imports*** and a ***complete*** implementation *P*
  - (P satisfies AE) $\Leftrightarrow$ (P 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 = $\boxed{\text{actual execution result}}$

Ubiquitous Computing

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

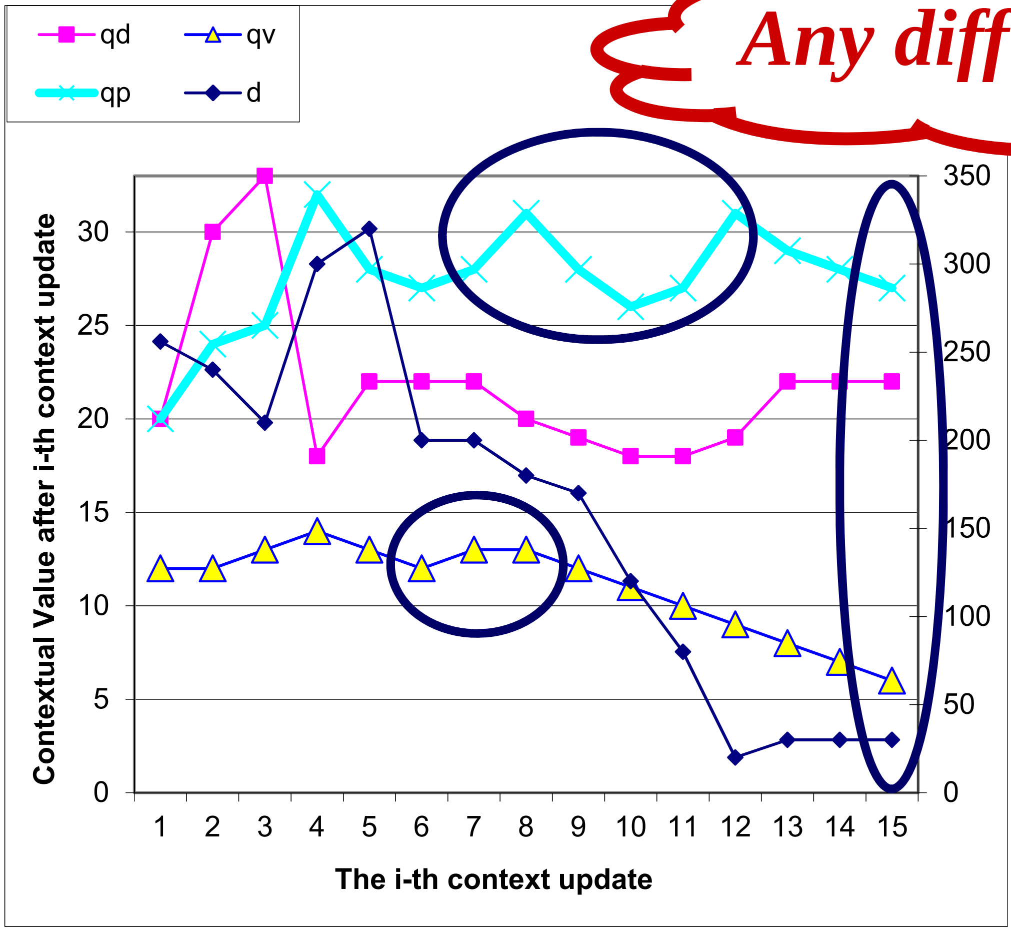
Ubiquitous Computing

- 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!

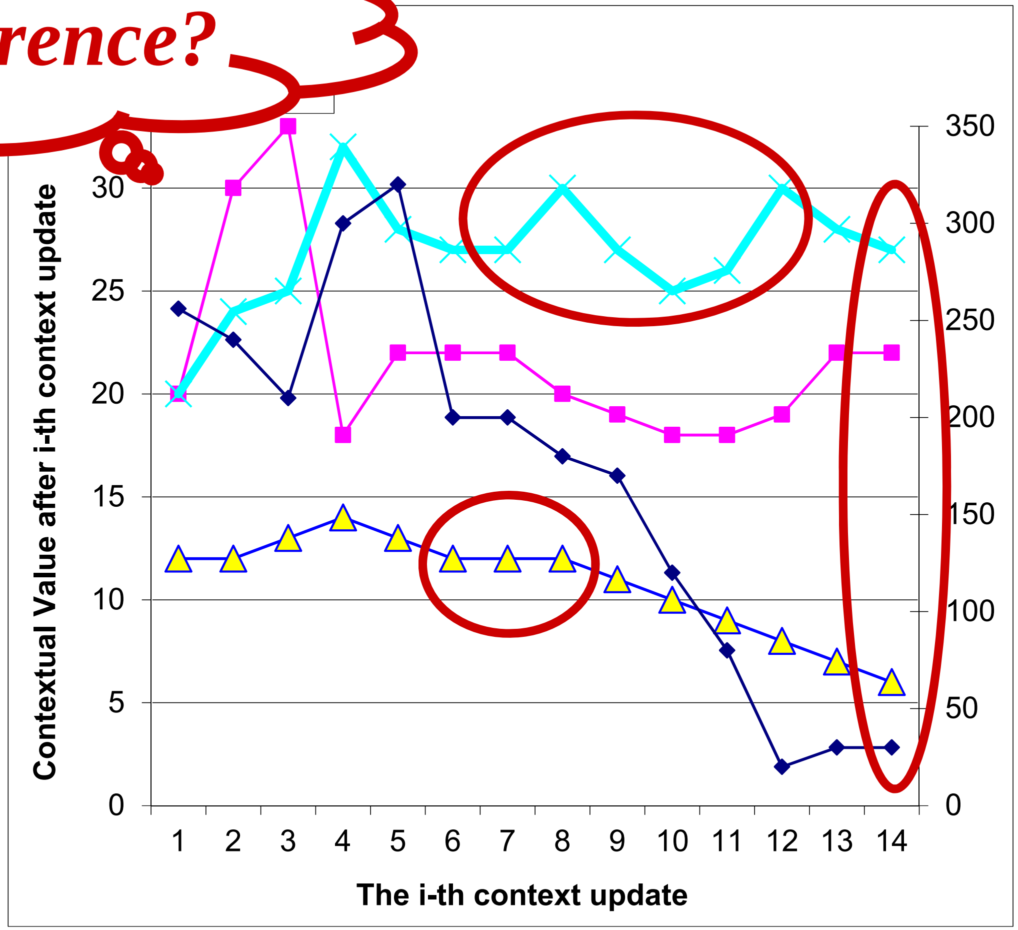
Ubiquitous Computing

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 = $\boxed{\text{actual execution result}}$
- 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
  - $\boxed{\text{Expected outcome}}$ = 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

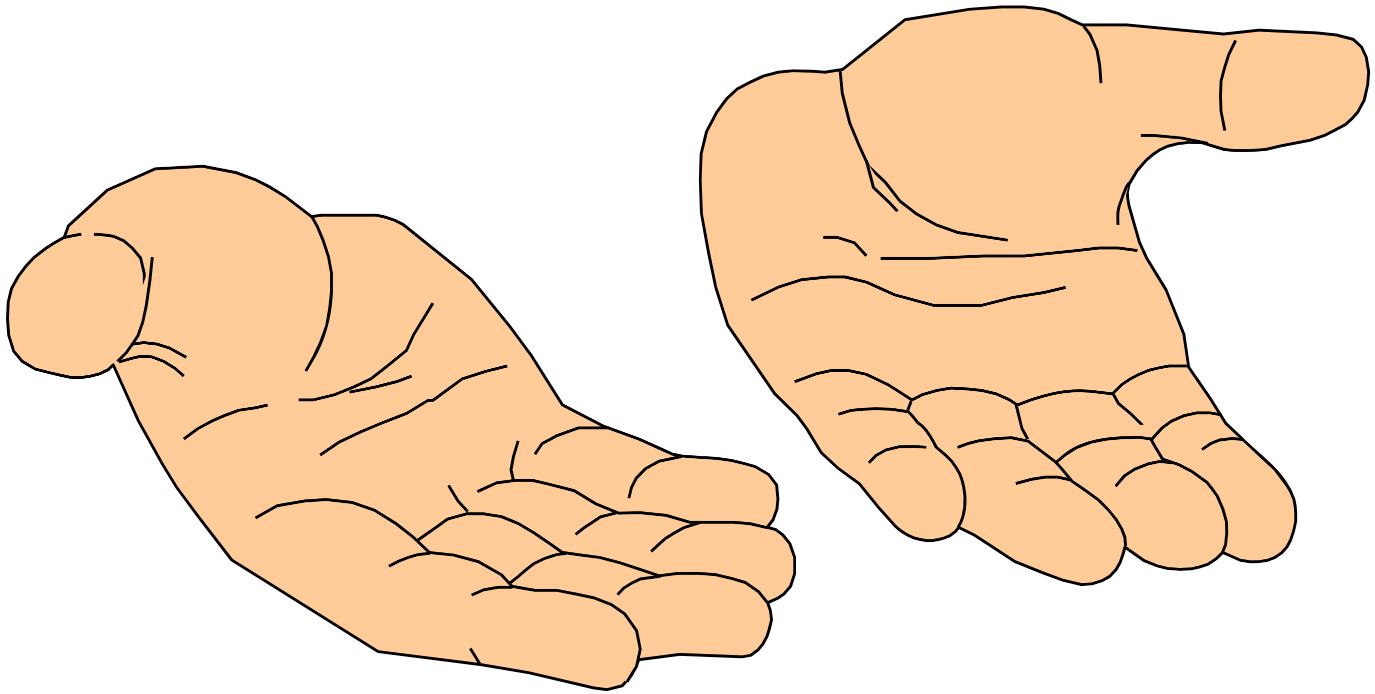
- Many facets of the test oracle problem
  - $\boxed{\text{Expected outcome}}$ = actual execution result
  - Expected outcome $\boxed{=}$ actual execution result
  - Expected outcome = $\boxed{\text{actual execution result}}$

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