

Bioactive Cellulose Nanocrystal Reinforced 3D Printable Poly(ϵ -caprolactone)
Nanocomposite for Bone Tissue Engineering

Jung Ki Hong

Dissertation submitted to the faculty of the Virginia Polytechnic Institute and State
University in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
In
Macromolecular Science and Engineering

Maren Roman, Chair
Kevin J. Edgar
Charles E. Frazier
Scott H. Renneckar
Abby R. Whittington

February 6, 2015
Blacksburg, Virginia

Keywords: cellulose nanocrystal, poly(ϵ -caprolactone), nanocomposite,
biomineralization, 3D printing, porous bone scaffold, mechanical performance,
biocompatibility

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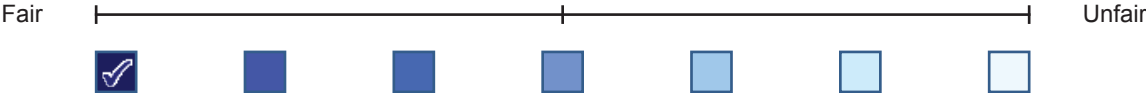
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Title of Work Used:	Figure 2.1. Prevalence of self-Reported Primary Medical Conditions for Persons Aged 18 and over, United States 2005.
Copyright Holder:	Joshua J. Jacobs, G.B.J.A., John-Erik Bell, Stuart L. Weinstein, John P. Dormans, Steve M. Gnatz, Nancy Lane, J. Edward Puzas, E. William St. Clair, Edward H. Yelin.
Publication Status:	Published
Publisher:	The Burden of Musculoskeletal Diseases in the United States.
Place of Publication:	Online
Publication Year:	
Description of Work:	
Date of Evaluation:	May 3, 2015
Date of Intended Use:	May 5, 2015

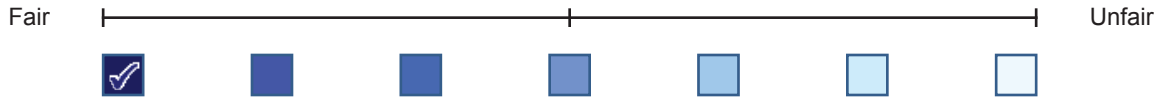
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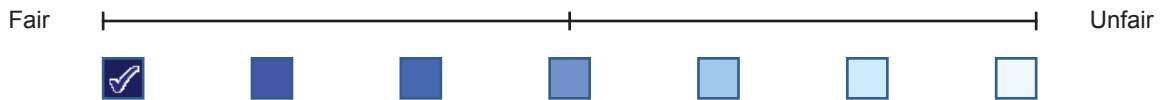
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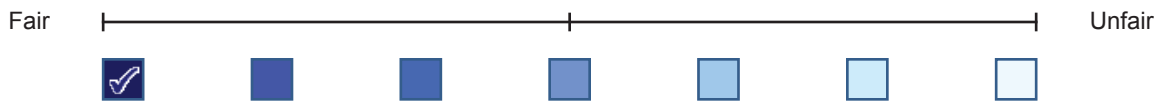
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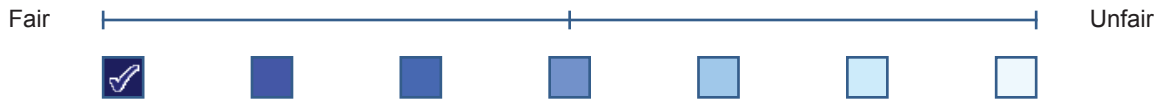
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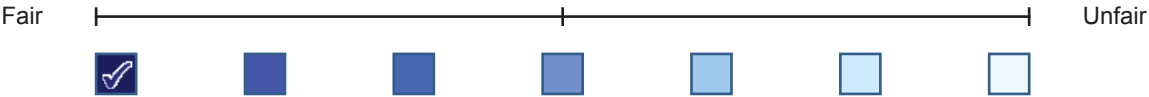
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Institution:	Virginia Polytechnic Institute and State University
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Copyright Holder:	Encyclopædia Britannica, Inc.
Publication Status:	Published
Publisher:	Encyclopædia Britannica, Inc.
Place of Publication:	Online
Publication Year:	
Description of Work:	
Date of Evaluation:	May 3, 2015
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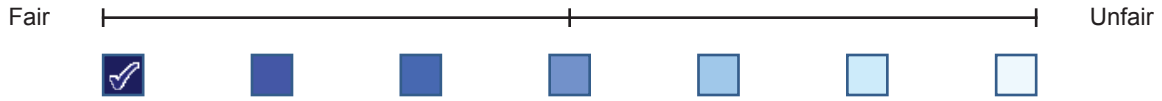
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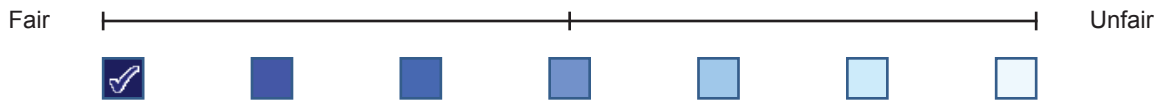
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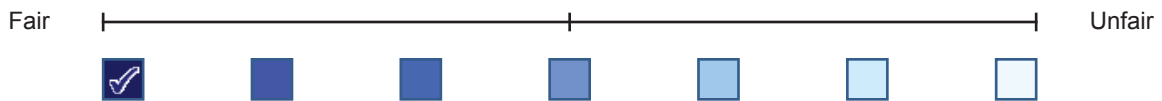
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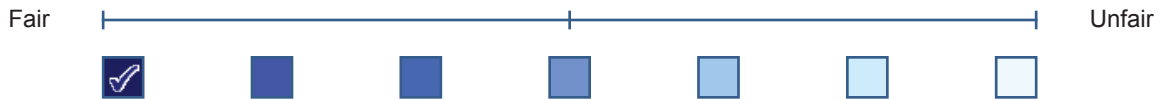
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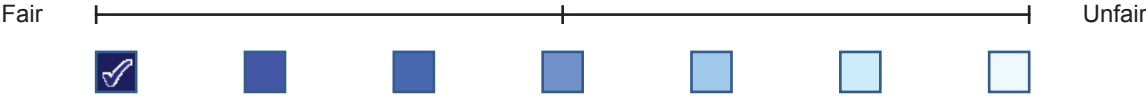
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Institution:	Virginia Polytechnic Institute and State University
Title of Work Used:	Figure 2.3. Hierarchical structural organization of bone.
Copyright Holder:	Rho, J.Y., L. Kuhn-Spearing, and P. Zioupos
Publication Status:	Published
Publisher:	Journal of Medical Engineering & Physics
Place of Publication:	
Publication Year:	1998
Description of Work:	
Date of Evaluation:	May 3, 2015
Date of Intended Use:	May 5, 2015

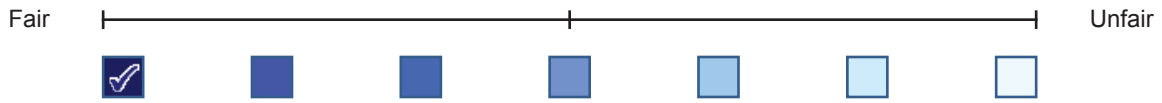
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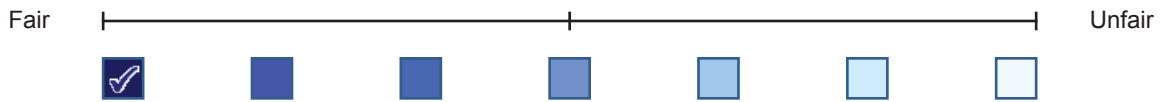
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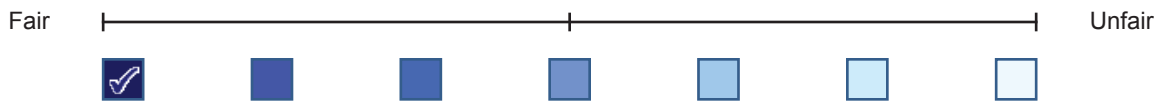
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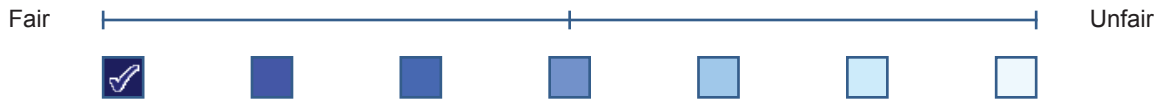
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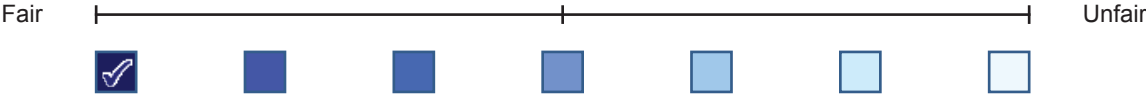
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Job Title:	Graduate student
Institution:	Virginia Polytechnic Institute and State University
Title of Work Used:	Figure 2.4. The microscopic structure of cortical and cancellous bone.
Copyright Holder:	U.S. National Institutes of Health
Publication Status:	Published
Publisher:	
Place of Publication:	Online
Publication Year:	2006
Description of Work:	
Date of Evaluation:	May 3, 2015
Date of Intended Use:	May 5, 2015

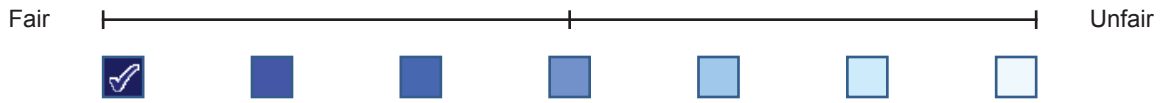
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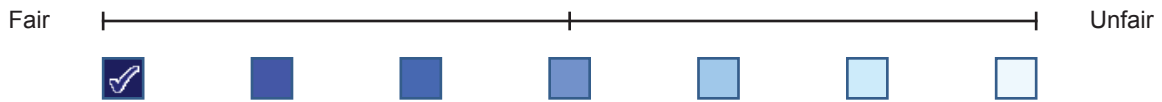
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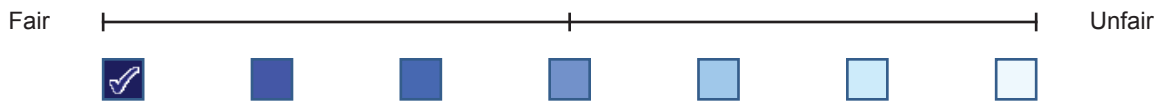
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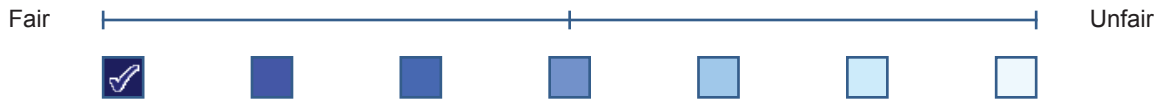
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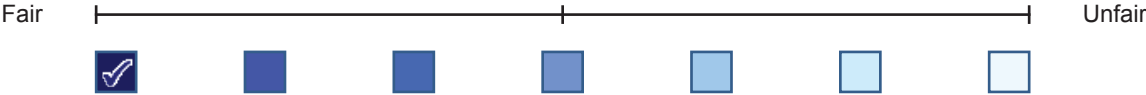
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Title of Work Used:	Figure 2.5. Schematic representation of the topographic relationship among bone cells.
Copyright Holder:	Marks, S.C. and S.N. Popoff
Publication Status:	Published
Publisher:	American Journal of Anatomy
Place of Publication:	
Publication Year:	1988
Description of Work:	
Date of Evaluation:	May 3, 2015
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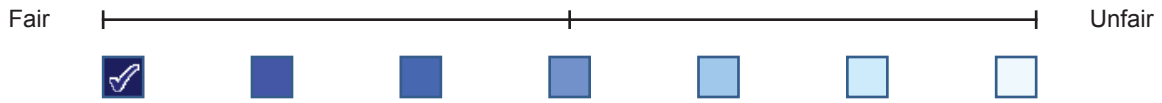
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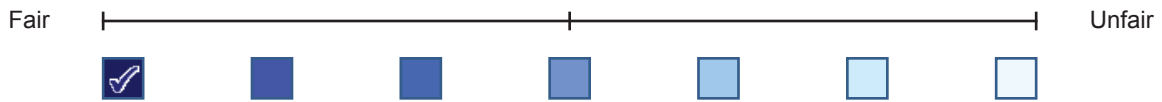
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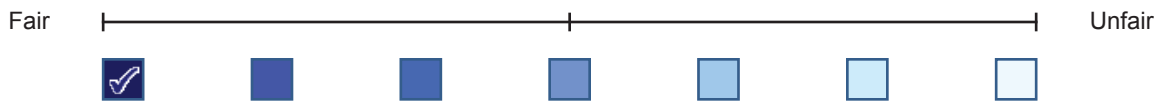
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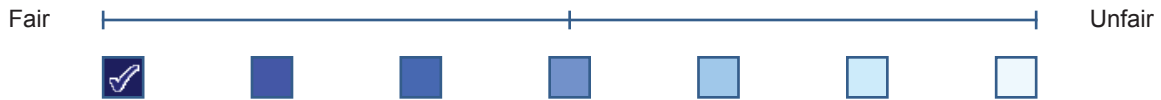
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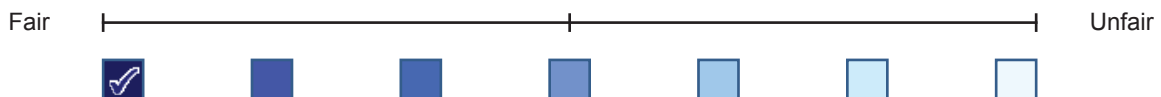
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Copyright Holder:	Labet, M. and W. Thielemans
Publication Status:	Published
Publisher:	Chemical Society Reviews
Place of Publication:	
Publication Year:	2009
Description of Work:	
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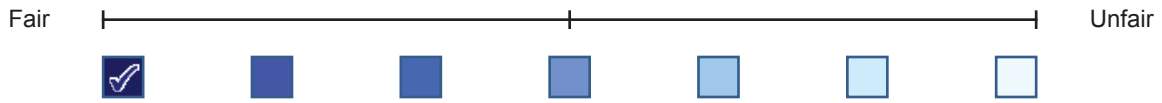
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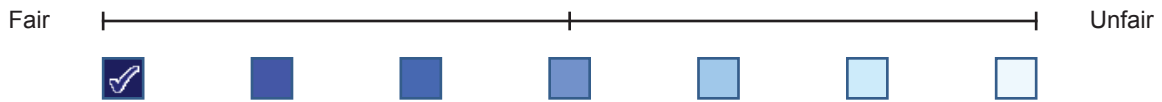
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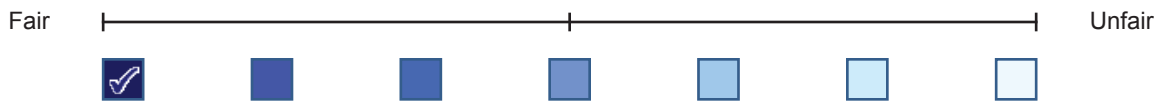
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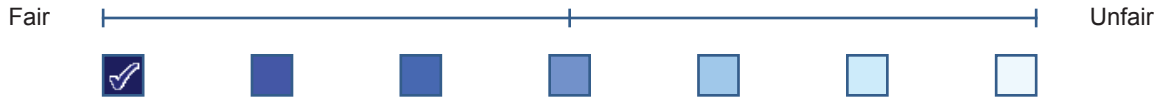
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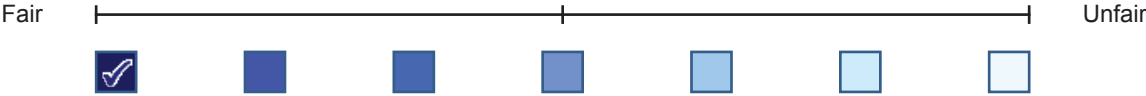
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Institution:	Virginia Polytechnic Institute and State University
Title of Work Used:	Figure 2.7. The degradation mechanism of PCL via hydrolysis
Copyright Holder:	Woodruff, M.A. and D.W. Hutmacher
Publication Status:	Published
Publisher:	Progress in Polymer Science
Place of Publication:	
Publication Year:	2010
Description of Work:	
Date of Evaluation:	May 3, 2015
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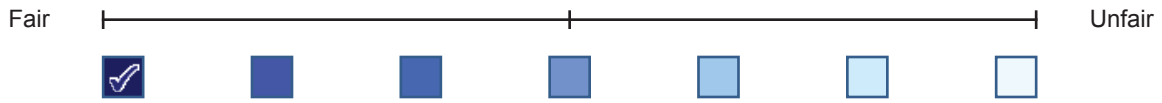
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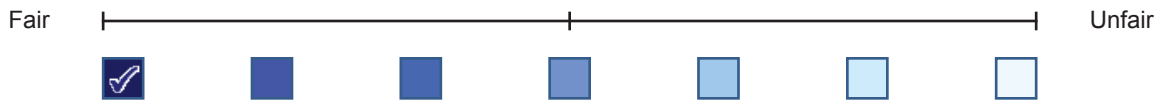
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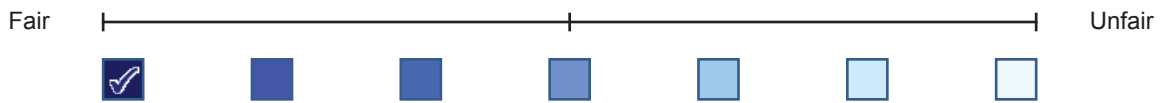
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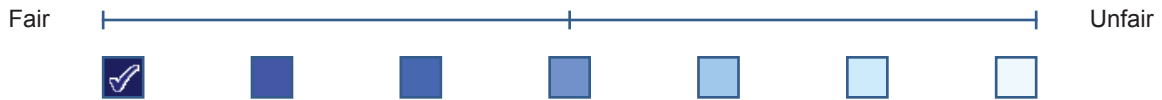
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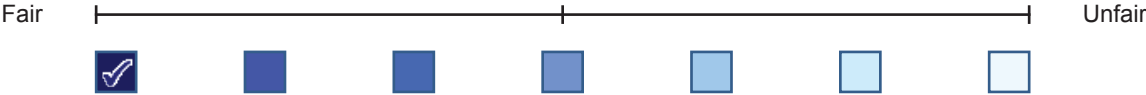
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Job Title:	Graduate student
Institution:	Virginia Polytechnic Institute and State University
Title of Work Used:	Figure 2.9. Schematic diagram of surface-directed mineralization of calcium phosphate in simulated body fluid
Copyright Holder:	Dey, A., et al., Colfen, H.
Publication Status:	Published
Publisher:	Nature Materials
Place of Publication:	
Publication Year:	2010
Description of Work:	
Date of Evaluation:	May 3, 2015
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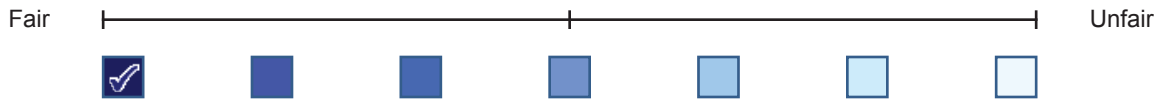
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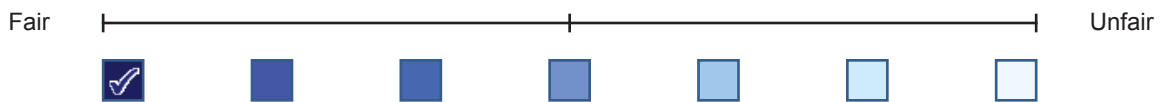
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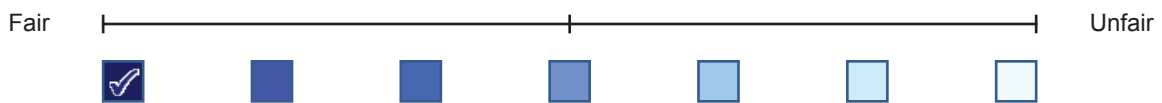
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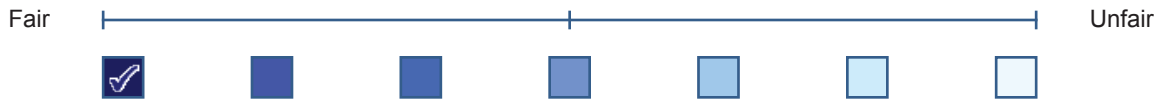
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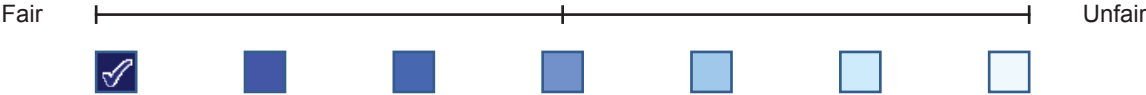
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Job Title:	Graduate student
Institution:	Virginia Polytechnic Institute and State University
Title of Work Used:	Figure 2.10. Various interaction modes between calcium phosphate ions and surface functional groups as an initial step for apatite formation.
Copyright Holder:	Tanahashi, M. and T. Matsuda
Publication Status:	Published
Publisher:	Journal of biomedical materials research
Place of Publication:	
Publication Year:	1997
Description of Work:	
Date of Evaluation:	May 3, 2015
Date of Intended Use:	May 5, 2015

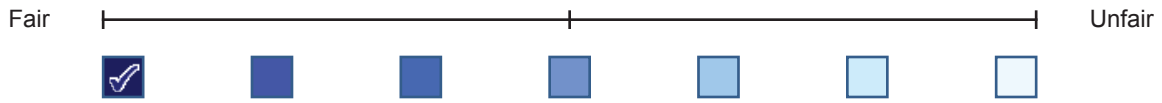
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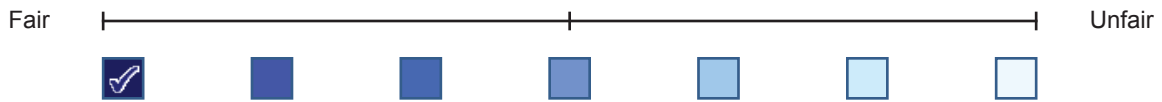
Describe the **Nature** of Your Intended Use of the Copyrighted Work:

[+] Work to be used has been previously PUBLISHED



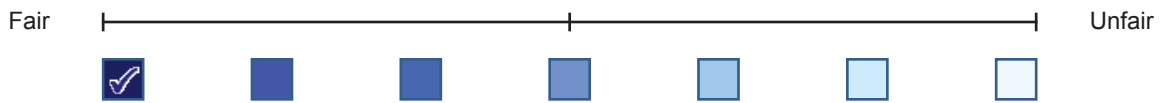
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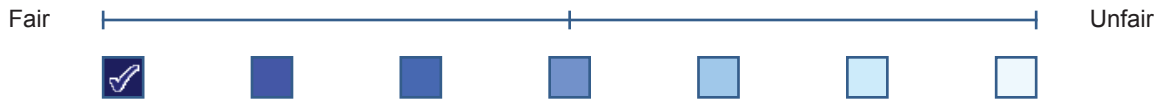
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The Average **"Fairness Level,"** Based on Your Rating of Each of the 4

Factors, Is:

[see tool disclaimer for important clarifying information]:



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Signature: Jung Ki Hong

Date of Signature: 5/5/2015

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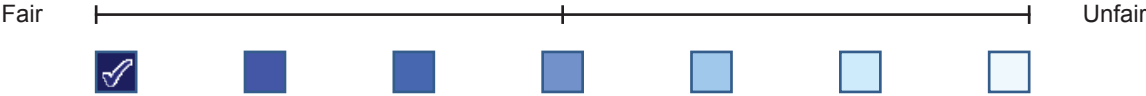
Fair Use Evaluation Documentation

Compiled using the **Fair Use Evaluator** [cc] 2008 Michael Brewer & the Office for Information Technology Policy, <http://librarycopyright.net/fairuse/>

Name:	Jung Ki Hong
Job Title:	Graduate student
Institution:	Virginia Polytechnic Institute and State University
Title of Work Used:	Figure 2.12. Mechanical properties between dense and porous materials.
Copyright Holder:	Rezwan, K., et al.
Publication Status:	Published
Publisher:	Journal of Biomaterials
Place of Publication:	
Publication Year:	2006
Description of Work:	
Date of Evaluation:	May 3, 2015
Date of Intended Use:	May 5, 2015

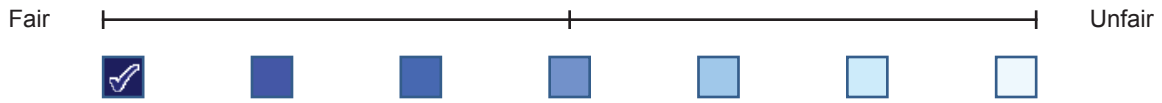
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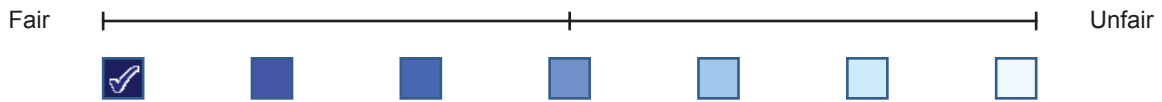
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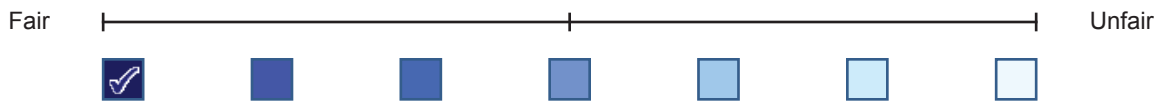
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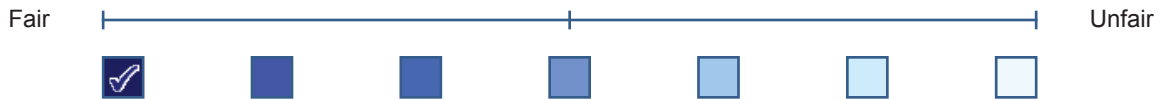
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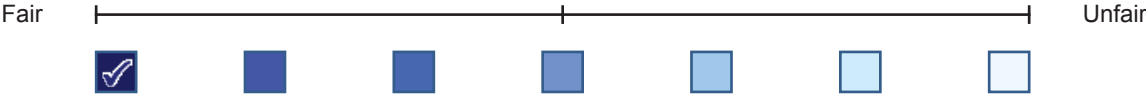
Fair Use Evaluation Documentation

Compiled using the **Fair Use Evaluator** [cc] 2008 Michael Brewer & the Office for Information Technology Policy, <http://librarycopyright.net/fairuse/>

Name:	Jung Ki Hong
Job Title:	Graduate student
Institution:	Virginia Polytechnic Institute and State University
Title of Work Used:	Figure 2.13. 3D porous scaffolds fabricated by different techniques.
Copyright Holder:	Cima, L.G., Mikos, A.G., Schugens, C., Mooney, D.J., Sui, G., Zein, I., et al.
Publication Status:	Published
Publisher:	Journal of Biomechanical Engineering-Transactions of the Asme, Journal of Polymer, Journal of biomedical materials research, Journal of Biomaterials
Place of Publication:	
Publication Year:	1991, 1994, 1996, 2002, 2007
Description of Work:	
Date of Evaluation:	May 3, 2015
Date of Intended Use:	May 5, 2015

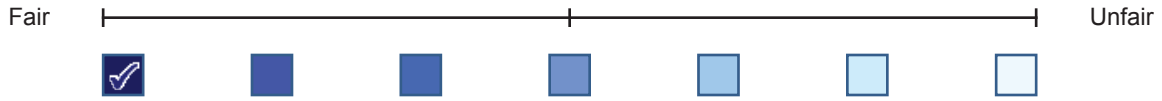
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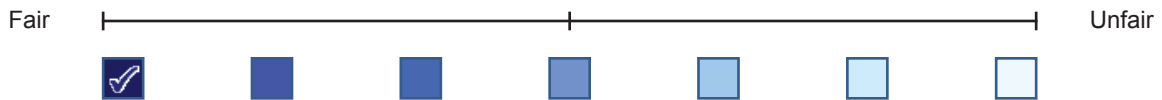
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[+] Work to be used has been previously PUBLISHED



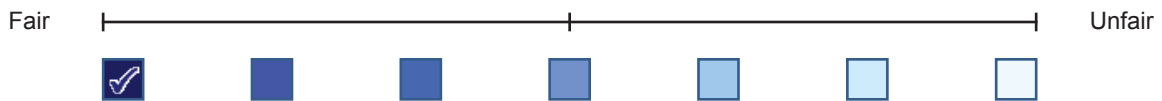
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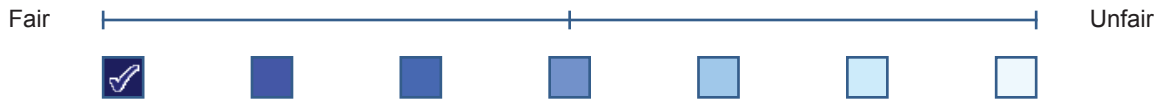
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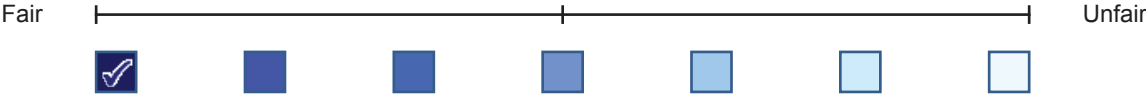
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Name:	Jung Ki Hong
Job Title:	Graduate student
Institution:	Virginia Polytechnic Institute and State University
Title of Work Used:	Figure 2.14. 3D printing process for customized bone scaffolds for critical sized defects.
Copyright Holder:	Schieker, M., et al.
Publication Status:	Published
Publisher:	European Journal of Trauma
Place of Publication:	
Publication Year:	2006
Description of Work:	
Date of Evaluation:	May 3, 2015
Date of Intended Use:	May 5, 2015

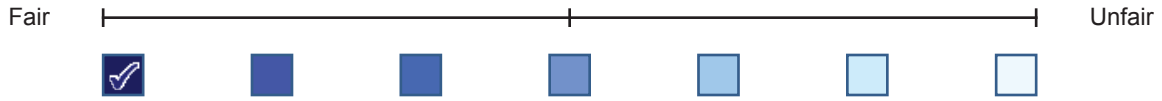
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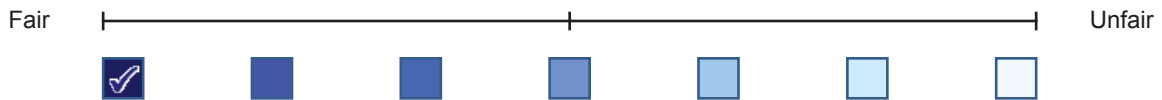
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[+] Work to be used has been previously PUBLISHED



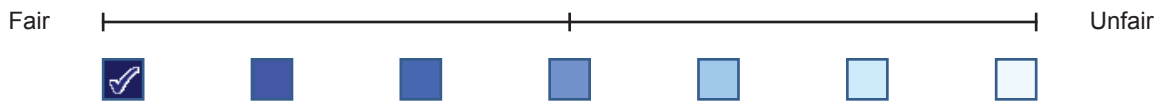
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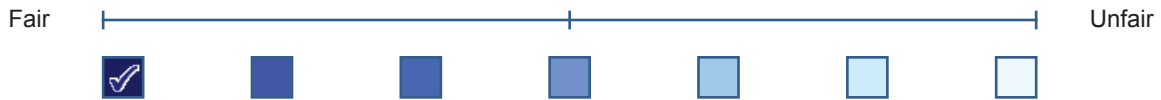
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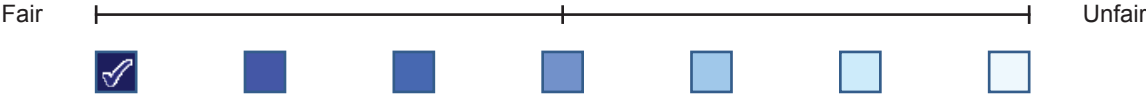
Fair Use Evaluation Documentation

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Name:	Jung Ki Hong
Job Title:	Graduate student
Institution:	Virginia Polytechnic Institute and State University
Title of Work Used:	Table 2.1. Mechanical properties of human bone
Copyright Holder:	Athanasίου, K.A., et al.
Publication Status:	Published
Publisher:	Journal of Tissue Engineering
Place of Publication:	
Publication Year:	2000
Description of Work:	
Date of Evaluation:	May 3, 2015
Date of Intended Use:	May 5, 2015

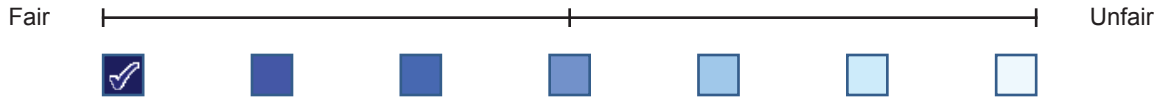
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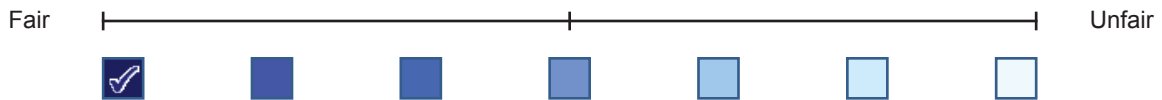
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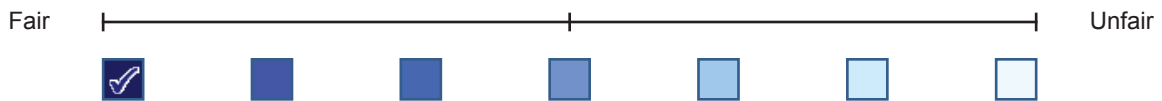
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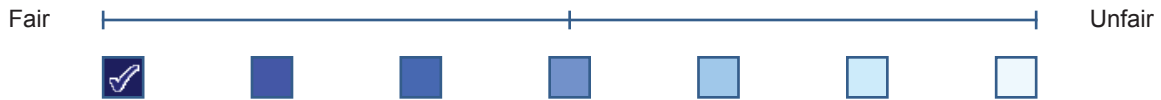
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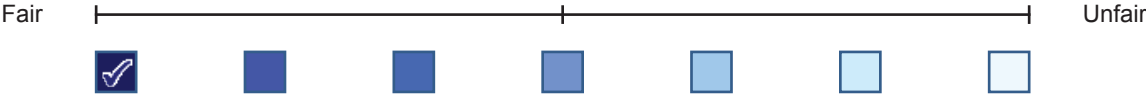
Fair Use Evaluation Documentation

Compiled using the **Fair Use Evaluator** [cc] 2008 Michael Brewer & the Office for Information Technology Policy, <http://librarycopyright.net/fairuse/>

Name:	Jung Ki Hong
Job Title:	Graduate student
Institution:	Virginia Polytechnic Institute and State University
Title of Work Used:	Table 2.2. Definitions of biodegradable and bioresorbable by Vert.
Copyright Holder:	Vert, M., et al.
Publication Status:	Published
Publisher:	Journal of Materials Science-Materials in Medicine
Place of Publication:	
Publication Year:	1992
Description of Work:	
Date of Evaluation:	May 3, 2015
Date of Intended Use:	May 5, 2015

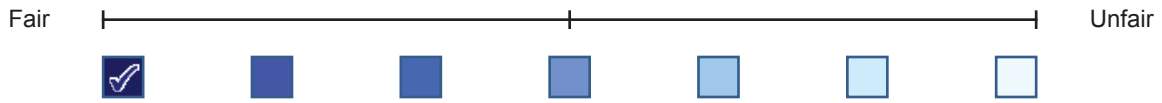
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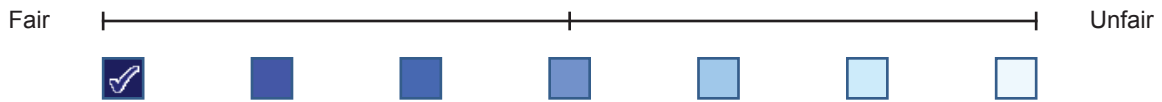
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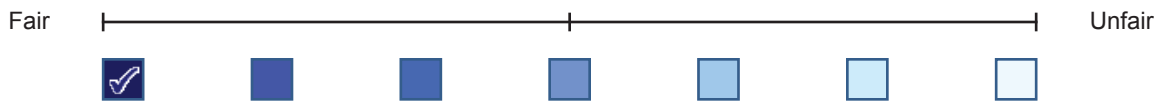
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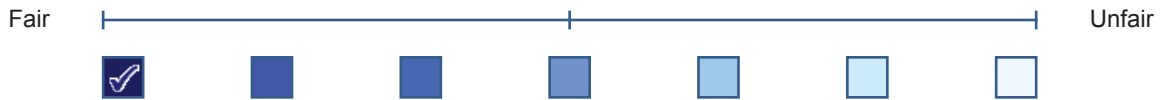
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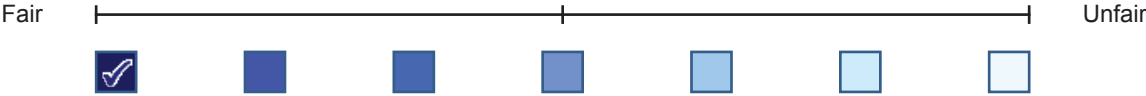
Fair Use Evaluation Documentation

Compiled using the **Fair Use Evaluator** [cc] 2008 Michael Brewer & the Office for Information Technology Policy, <http://librarycopyright.net/fairuse/>

Name:	Jung Ki Hong
Job Title:	Graduate student
Institution:	Virginia Polytechnic Institute and State University
Title of Work Used:	Table 2.3. Classification of polymeric biomaterials.
Copyright Holder:	Ikada, Y. and H. Tsuji
Publication Status:	Published
Publisher:	Macromolecular Rapid Communications
Place of Publication:	
Publication Year:	2000
Description of Work:	
Date of Evaluation:	May 3, 2015
Date of Intended Use:	May 5, 2015

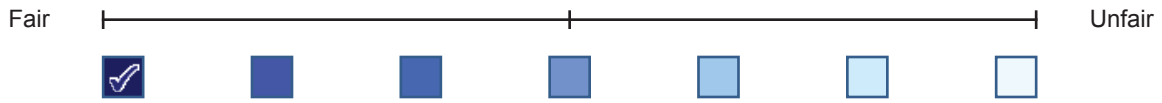
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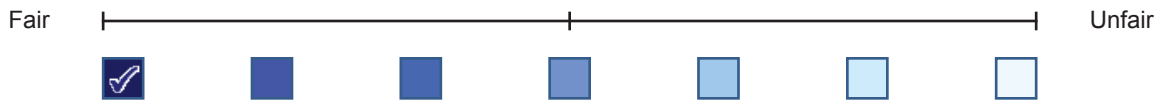
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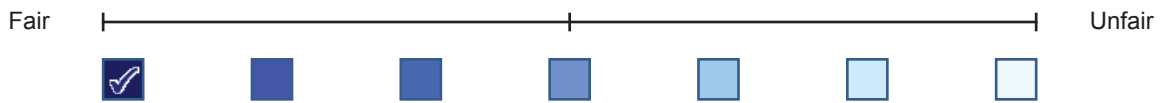
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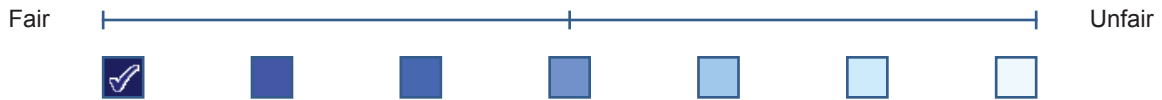
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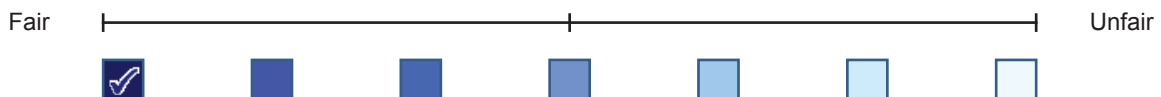
Fair Use Evaluation Documentation

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Name:	Jung Ki Hong
Job Title:	Graduate student
Institution:	Virginia Polytechnic Institute and State University
Title of Work Used:	Table 2.4. Classification of aliphatic polyesters.
Copyright Holder:	Ikada, Y. and H. Tsuji
Publication Status:	Published
Publisher:	Macromolecular Rapid Communications
Place of Publication:	
Publication Year:	2000
Description of Work:	
Date of Evaluation:	May 3, 2015
Date of Intended Use:	May 5, 2015

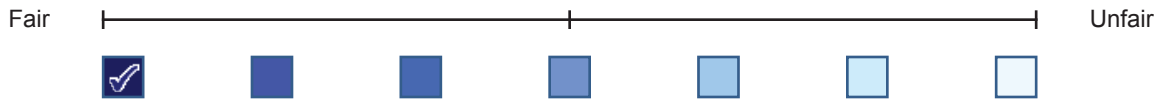
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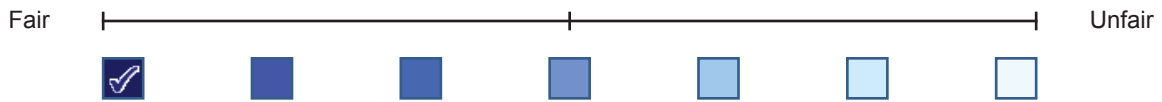
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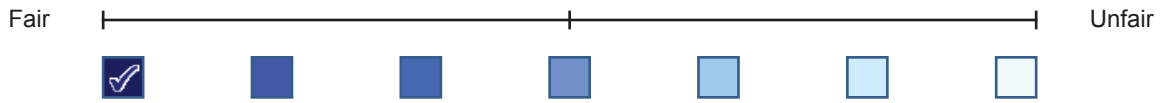
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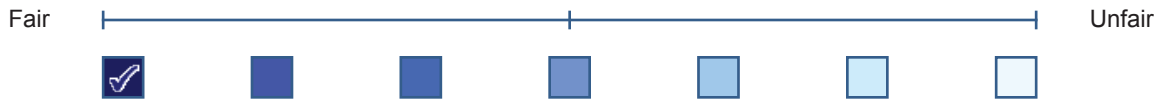
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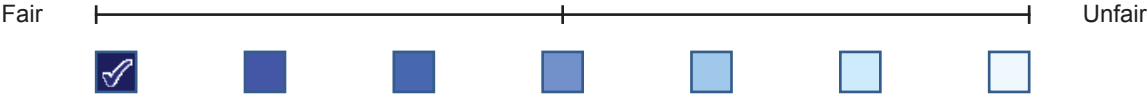
Fair Use Evaluation Documentation

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Name:	Jung Ki Hong
Job Title:	Graduate student
Institution:	Virginia Polytechnic Institute and State University
Title of Work Used:	Table 2.5. Total ion concentrations (mM) of human blood plasma and SBFs
Copyright Holder:	Kokubo, T. and H. Takadama
Publication Status:	Published
Publisher:	Journal of Biomaterials
Place of Publication:	
Publication Year:	2006
Description of Work:	
Date of Evaluation:	May 3, 2015
Date of Intended Use:	May 5, 2015

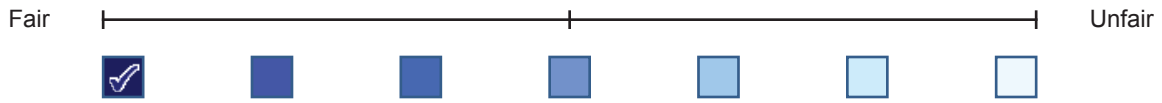
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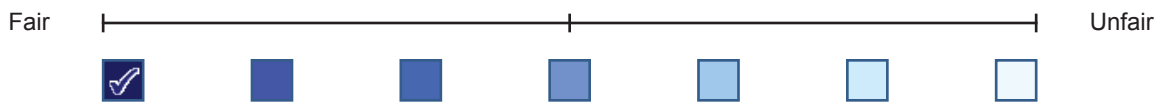
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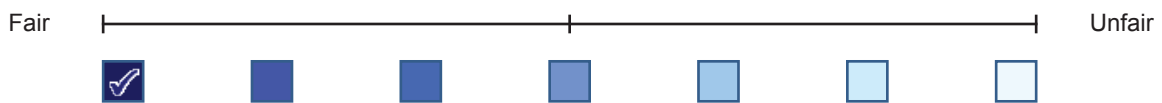
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[+] Only limited and reasonable portions will be used



Describe the **Effect** of Your Intended Use on the Potential Market or Value of the Copyrighted Work:

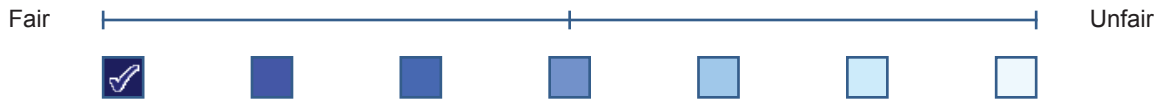
[+] The work is NOT currently under commercial exploitation (out of print, no licensing available, etc.)



The Average **"Fairness Level,"** Based on Your Rating of Each of the 4

Factors, Is:

[see tool disclaimer for important clarifying information]:



Based on the information and justification I have provided above, I, Jung Ki Hong, am asserting this use is **FAIR** under Section 107 of the U.S. Copyright Code.

Signature: Jung Ki Hong

Date of Signature: 5/5/2015

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