# Learning Chemistry through Inquiry: Engaging Underprepared Math Students

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# Miami University

- Oxford, OH
- 14,500 undergrads & 1500 grad students
- 11 Ph.D. programs of selective excellence
- Ph.D. in chemistry education
- Top 25 Initiative

# Miami University


ΑΦ
12 . 05 . 2009

# Laboratory Procedure

- The procedure is not difficult. First, bring 1 liter of water to a state where it has undergone partially a phase transition in which the vapor pressure of the steam that is formed is equal to the pressure of the atmosphere. Then add 1.0g of the mixture of chemical known as camillea thea. The important ingredient in this mixture is 3,7-dihydro-1,3,7-trimethyl-1H-purine-2,6-dione. Allow the mixture to stir for 5 minutes. Finally, filter the undissolved solids and collect the liquid.

# Making Tea

- The procedure is not difficult. First, bring 1 liter of water to a state where it has undergone partially a phase transition in which the vapor pressure of the steam that is formed is equal to the pressure of the atmosphere. Then add 1.0g of the mixture of chemical known as camillea thea. The important ingredient in this mixture is 3,7-dihydro-1,3,7-trimethyl-1H-purine-2,6-dione. Allow the mixture to stir for 5 minutes. Finally, filter the undissolved solids and collect the liquid.

# The Mole

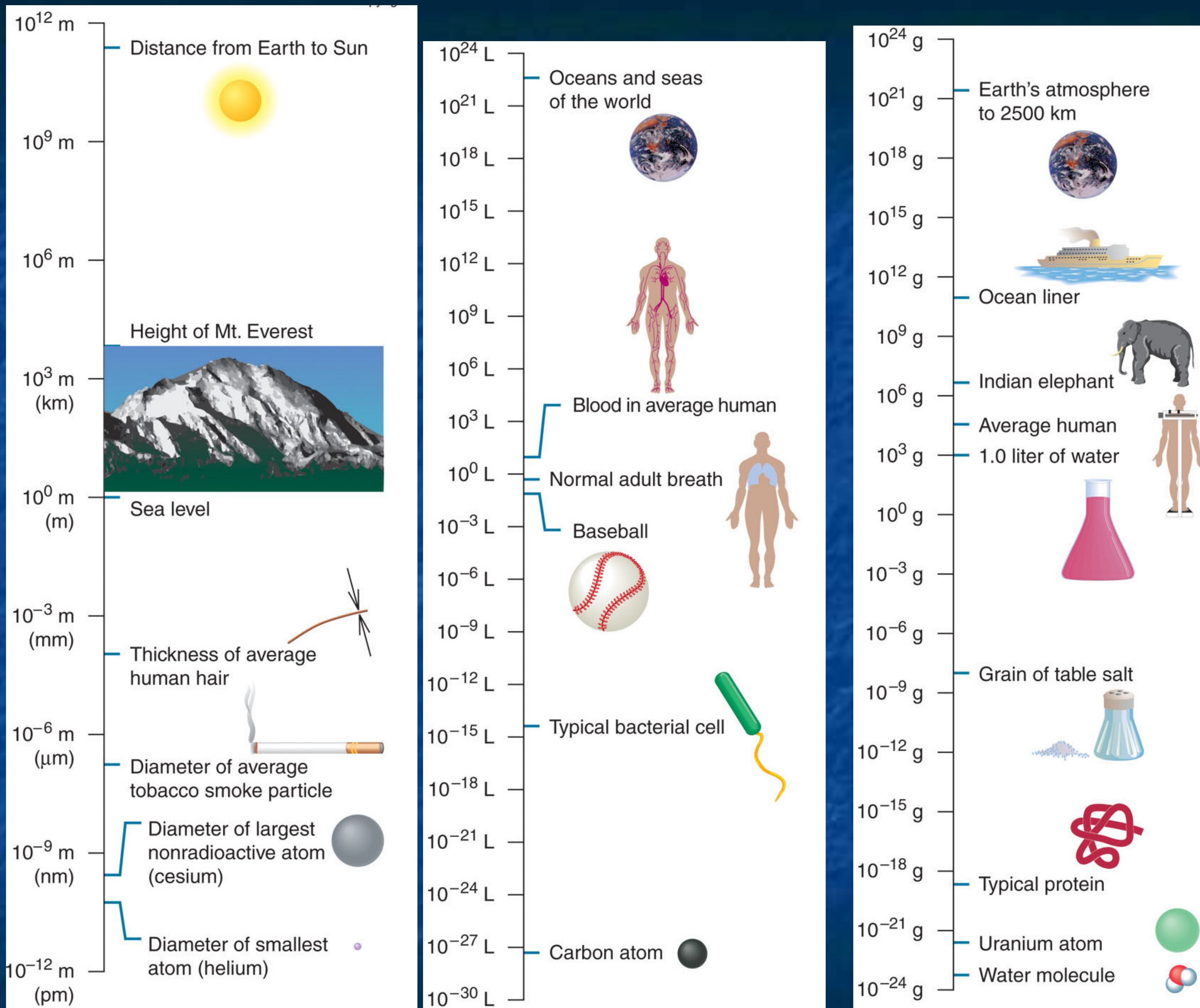
Where did this number come from?

C-12 has only 6p, 6n (no isotopes)

Mass of 1 atom C-12 (6p + 6n) = $1.992648 \times 10^{-23}$g

$$12.0\text{g} \times \frac{1 \text{ atom}}{1.992648 \times 10^{-23}\text{g}} = 6.02 \times 10^{23} \text{ atoms}$$

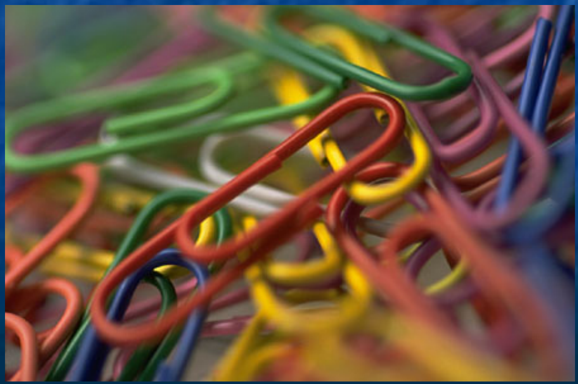
One mole (1 mol) contains $6.02 \times 10^{23}$ entities
(to four significant figures)



$10^{12}$ m
Distance from Earth to Sun
$10^{9}$ m
$10^{6}$ m
Height of Mt. Everest
$10^{3}$ m (km)
$10^{0}$ m (m)
Sea level
$10^{-3}$ m (mm)
Thickness of average human hair
$10^{-6}$ m (µm)
Diameter of average tobacco smoke particle
$10^{-9}$ m (nm)
Diameter of largest nonradioactive atom (cesium)
Diameter of smallest atom (helium)
$10^{-12}$ m (pm)
$10^{24}$ L
Oceans and seas of the world
$10^{21}$ L
$10^{18}$ L
$10^{15}$ L
$10^{12}$ L
$10^{9}$ L
$10^{6}$ L
Blood in average human
$10^{3}$ L
$10^{0}$ L
Normal adult breath
Baseball
$10^{-3}$ L
$10^{-6}$ L
$10^{-9}$ L
$10^{-12}$ L
Typical bacterial cell
$10^{-15}$ L
$10^{-18}$ L
$10^{-21}$ L
$10^{-24}$ L
$10^{-27}$ L
Carbon atom
$10^{-30}$ L
$10^{24}$ g
$10^{21}$ g
Earth's atmosphere to 2500 km
$10^{18}$ g
$10^{15}$ g
$10^{12}$ g
Ocean liner
$10^{9}$ g
Indian elephant
$10^{6}$ g
Average human
$10^{3}$ g
1.0 liter of water
$10^{0}$ g
$10^{-3}$ g
$10^{-6}$ g
Grain of table salt
$10^{-9}$ g
$10^{-12}$ g
$10^{-15}$ g
$10^{-18}$ g
Typical protein
$10^{-21}$ g
Uranium atom
Water molecule
$10^{-24}$ g

# Will a mole of paperclips stretch around the world?

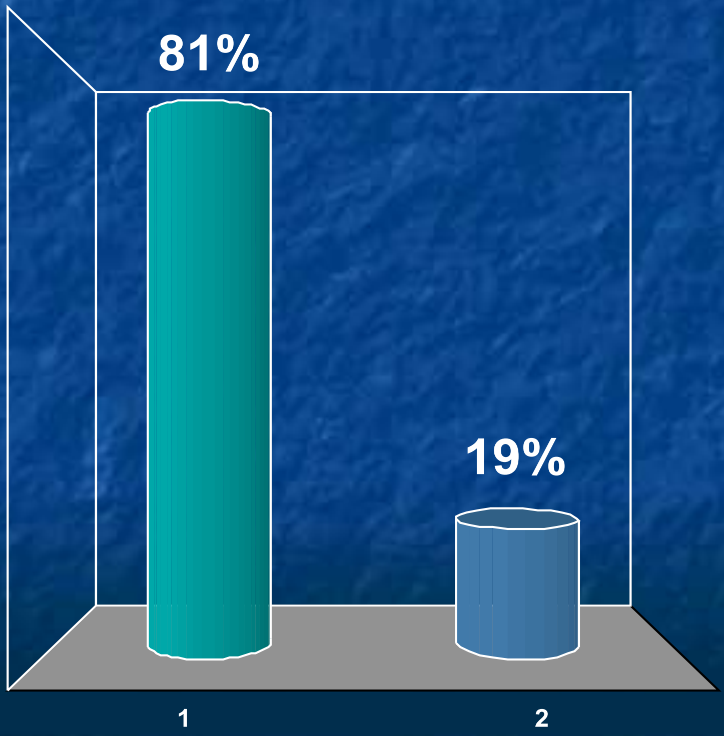
1. Yes
2. No




1 2

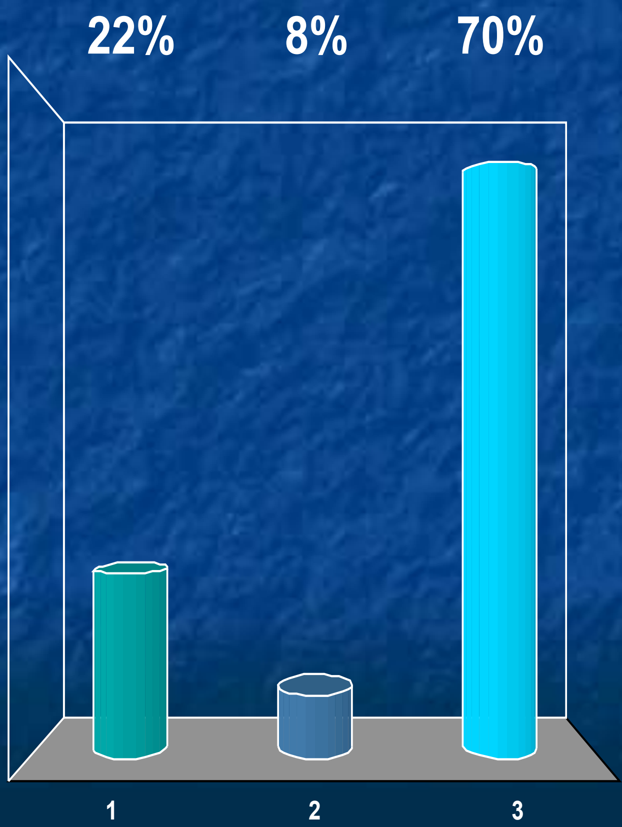
# If you were given a mole of money 4.5 billion years ago, and you spent $1million every second, would you have any money left?

1. Yes
2. No



# A mole of water…

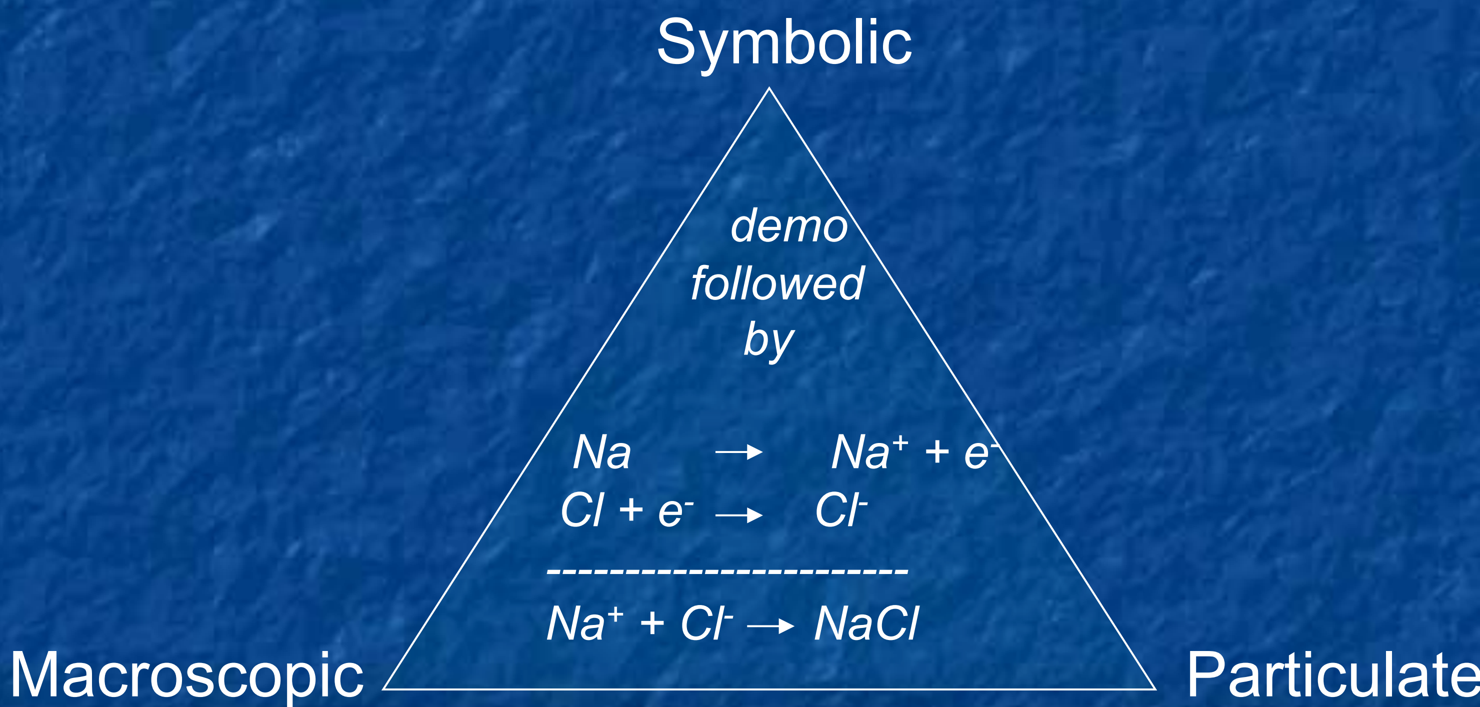
1. Is a quick drink
2. Could fill a swimming pool
3. Approximately Hurricane Katrina



# Take a Breath Answers…

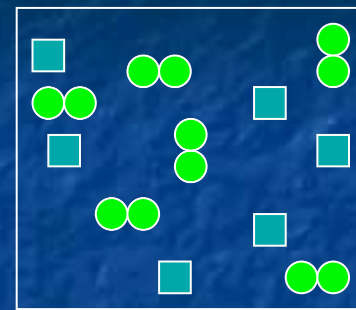
- 792 L
- 13,593.6 L
- 12,960 L
- 76809.6 mL
- 864,000 $in^3$
- 1,929,145.681 $cm^3$

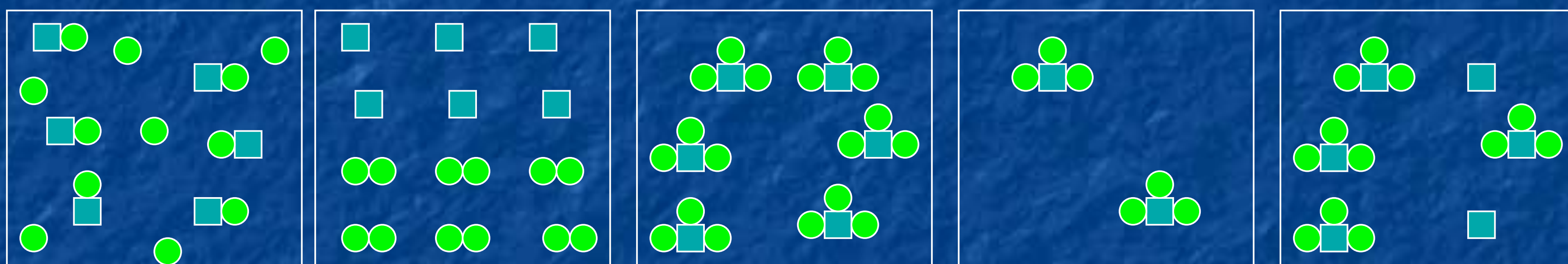
# Johnstone's Domains



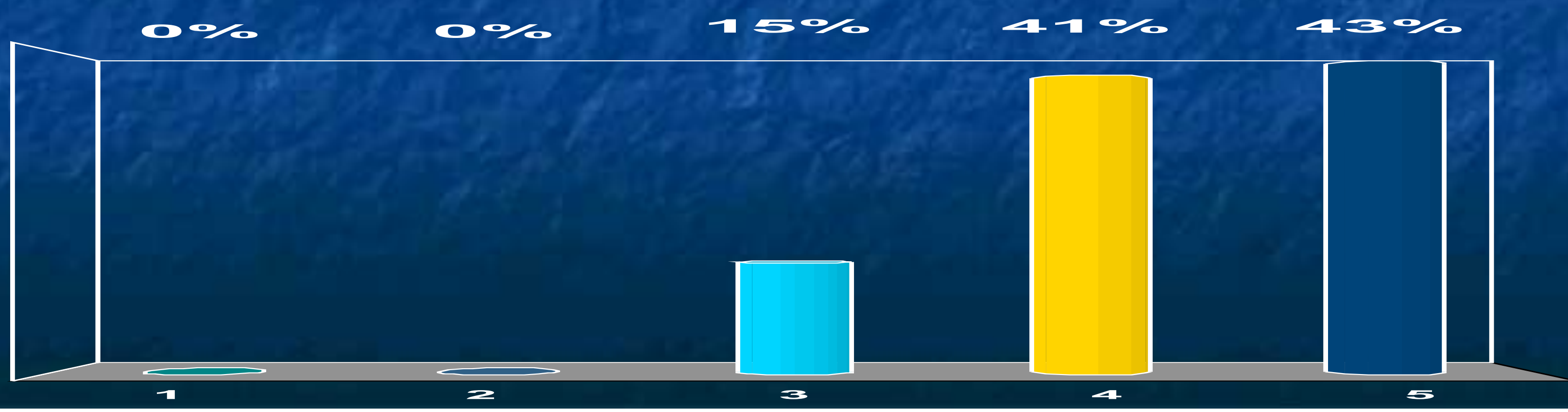

Johnstone, A. H. *Journal of Computer Assisted Learning*, **1991**, *7*, 75-81.

The equation for a reaction is $2S + 3O_2 \longrightarrow 2SO_3$.
Consider the mixture of S(□) and $O_2$(●●) in a closed container as illustrated:
Which represents the product mixture?

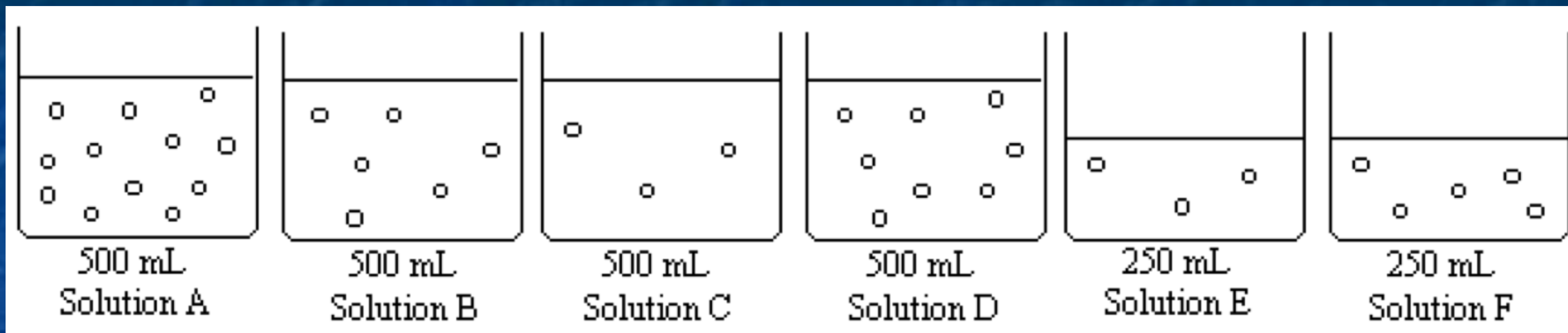




1 2 3 4 5



The drawings below represent beakers of aqueous solutions. Each "o" represents a dissolved solute particle. Which statement is false?

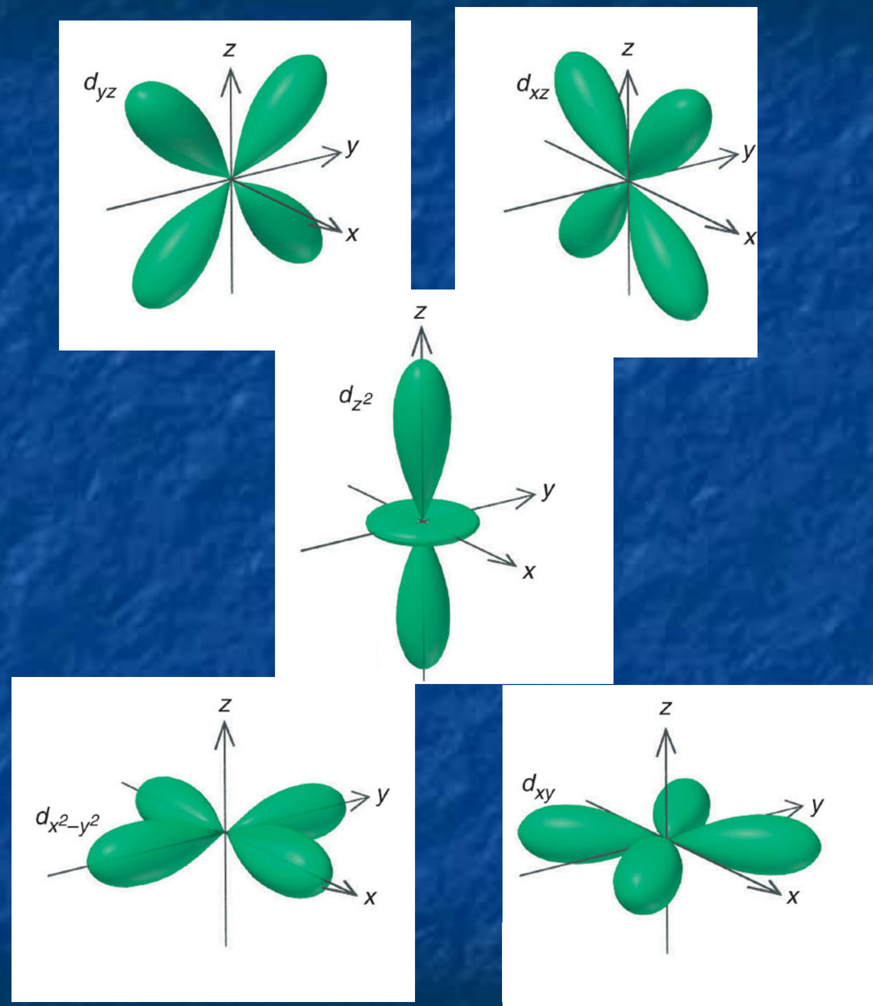



1. Solution C is least concentrated. — 7%
2. Solutions B & E have the same concentration. — 17%
3. When Solutions E & F are combined, the resulting solution has a higher concentration than Solution D. — 61%
4. If you evaporate half the water in Solution B, the resulting solution has the same concentration as Solution A. — 15%

The 3d orbitals

$3d_{xy}$ $3d_{yz}$ $3d_{xz}$

$3d_{x2-y2}$ $3d_{z2}$



# Rank these ions in order of increasing size $S^{2-}$, $Cl^-$, $K^+$

44% 1. $S^{2-} < Cl^- < K^+$

7% 2. $S^{2-} > Cl^- > K^+$

31% 3. $K^+ < Cl^- < S^{2-}$

18% 4. $K^+ > Cl^- > S^{2-}$

**Boyle's Law** $V \;\text{a}\; \frac{1}{P}$ n and T are fixed

$V = \text{constant} / P$

**Charles's Law** $V \;\text{a}\; T$ P and n are fixed

$V = \text{constant} \times T$

**Avogadro's Law** $V \;\text{a}\; n$ P and T are fixed

$V = \text{constant} \times n$

**combined gas law** $V \;\text{a}\; \frac{T}{P}$ $V = \text{constant} \times \frac{nT}{P}$ $\frac{PV}{nT} = \text{constant}$

$$PV = nRT$$

$$R = \frac{PV}{nT} = \frac{1atm \times 22.414L}{1mol \times 273.15K} = \frac{0.0821atm*L}{mol*K}$$

# General Chemistry I: CHM 141

- Gateway course >1000 students per year
- 3 lectures per week
- 200 - 250 student per lecture
- no recitation
- lab separate course

# Research Literature

- Mathematics single best predictor of success
  - Hovey, N.H.; Crohn, A. Predicting failures in general chemistry. *J. Chem. Educ.* **1958**, 35, 507-509.
  - Spencer, H. Mathematical SAT test scores and college chemistry grades. *J. Chem. Educ*. **1996**, 73, 1150-1153.
  - Mason, D.S.; Verdel, E. Gateway to success for at-risk students in a large-group introductory chemistry class. *J. Chem. Educ*., **2001**, 78, 252.
  - Pienta, N.J. A placement examination and mathematics tutorial for general chemistry. *J. Chem. Educ*., **2003**, 80, 1244.
  - Wagner, E.P.; Sasser, H.; DiBiase, W.J. Predicting students at risk in general chemistry using pre-semester assessments and demographic information. *J. Chem. Educ*. **2002**, 79, 749

# Math Placement Test

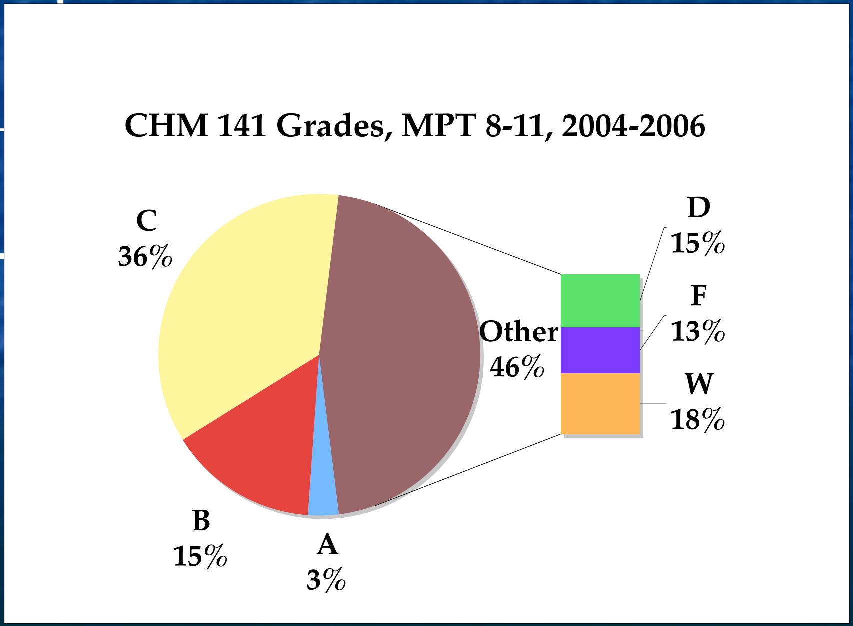
| MPT 1 Score | Years HS Math | Miami Course |
|---|---|---|
| 0-7 | < 3 years | Intermediate algebra |
| 8-11 | < 3 years | Precalc w/ algebra |
| 12-15 | 3-4 years w/ trig | Precalc |
| 16-25 | 3-4 years w/ trig | Calc I |

required of all incoming Miami freshmen

# Math & General Chemistry at Miami

- Students with MPT<13:

| CHM141 Grade | Majority Students | Minority Students |
|---|---|---|
| C- or lower | 35% | 60% |
| F | 10% | 25% |



# Research Question

- Can POGIL *reduce attrition* and *increase performance* for weaker math students in general chemistry?

# POGIL

- Process Oriented Guided Inquiry Learning
- http://www.pogil.org
- Processes
  - Information processing
  - Critical thinking
  - Problem solving
  - Teamwork
  - Communication

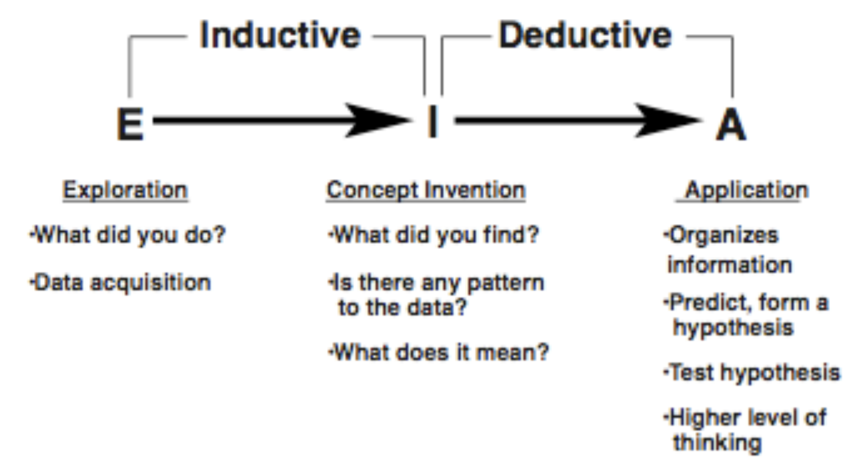


Figure 1. The learning cycle.

Spencer, *J. Chem. Educ.*, 1999, 566 - 569

# CHM 141.R Lectures

- Fixed lecture hall seats
- Clicker questions
- *Mastering Chemistry*
- Demonstrations
- Traditional order of topics (*math first!*)
- Judicious elimination
  - Limiting reagents w/ one reactant in excess
  - Bomb calorimetry
- Guided by student questions from “recitations”

# POGIL "Recitations"

- Graduate student teaching assistant
- 6 sections of 20 students
- All meet on Thursday
- Teams *not heterogeneous* w/r/t math ability
- 10 minute quiz + 40 minute POGIL activity
- *Precede* Friday, Monday, & Wednesday lectures
- End with students generating questions

# Representative Student Questions from Recitation

- What is the difference between amu and grams?
- What is this 'mole thingy?'
- How do you know which ions are present?
- How do you know how many ions are present?
- Direct inverses are confusing!

# Representative Student Questions from Recitation

- How do you calculate $\Delta H$ ?
- Is $\Delta H$ the same thing as specific heat?
- If two samples gain the same amount of heat, why do they experience a different $\Delta T$?
- What does bond strength have to do with $\Delta H$ ? How do you determine which bonds are stronger?

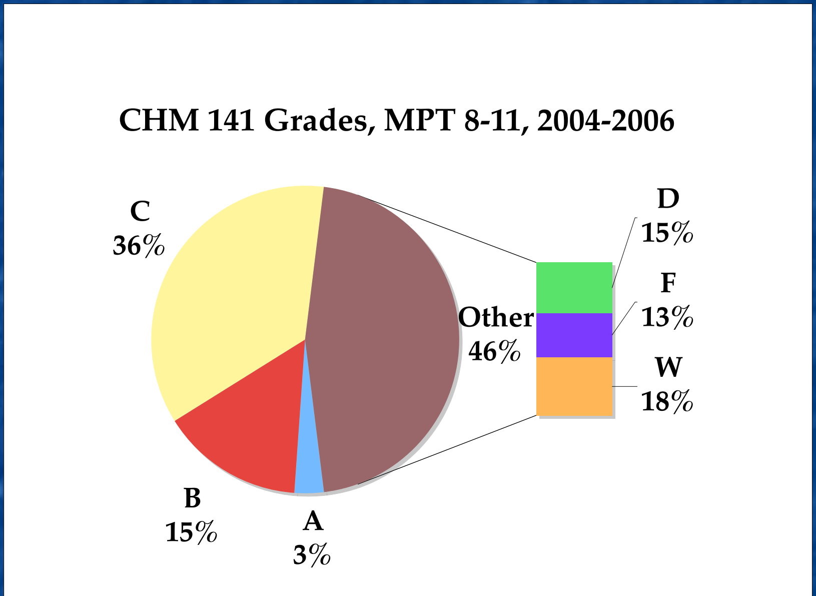
# Representative Student Questions from Recitation

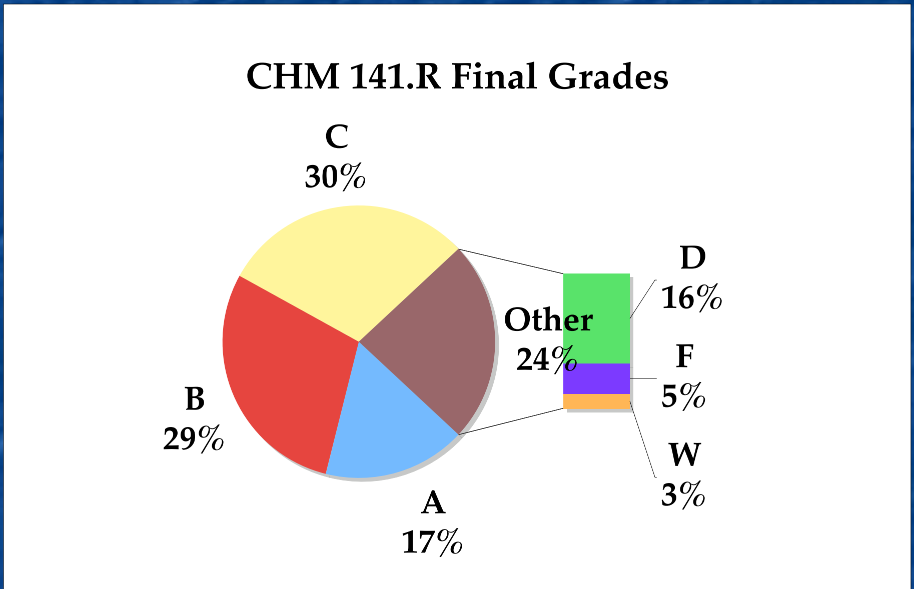
- How do you calculate IE of an electron? Are IEs constant numbers?
- Does IE apply to single electrons, or to all in a subshell?
- Why is IE low for high energy electrons?
- How does a dipole moment generate stronger intermolecular forces?
- What is hydrogen bonding? How do I know if it exists?

# Data Collection

- Success (Grade = A, B, or C) vs. DFW rate
- Attrition & Retention for both Gen Chem I & II
- Enrollment in organic chemistry
- Historical comparison with MPT 8-11 students
- ACS General Chemistry 1st Semester Exam
- CHEMX (Grove & Bretz)
- Semantic Differential (Bauer)
- TOLT (Tobin)
- MCA-I (Cooper & Sandi-Urena)

# Results – Cognitive Learning

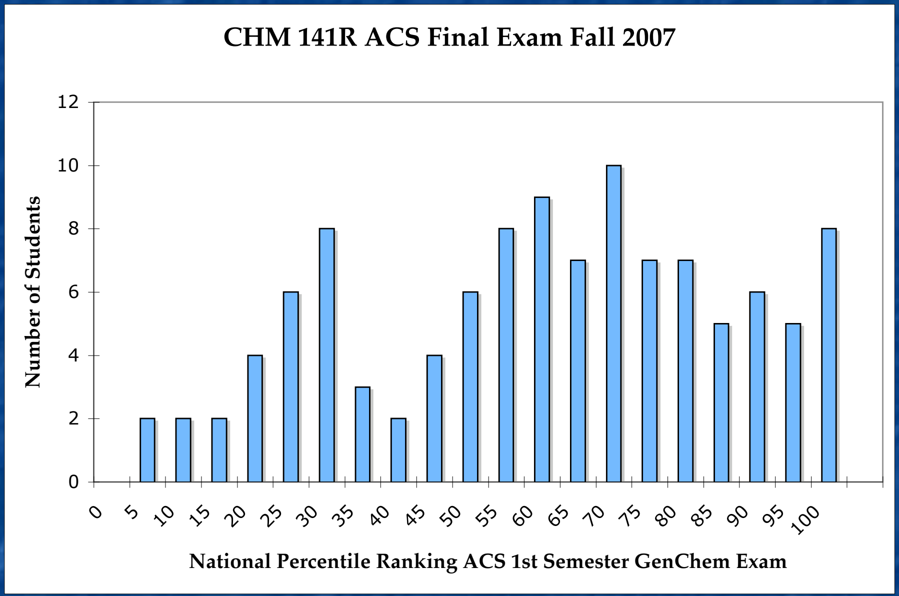



- *Was the course simply made easier?*
  - Syllabus still "covered"
  - Slower pace facilitated by introducing new material in recitations

# Results – Content Knowledge

- MPT 8-11, POGIL
  - mean = 45/70 questions (60th percentile)




- MPT 12+, no POGIL
  - mean = 48/70 questions (65th percentile)

# Results – Attrition & Retention

| | Gen Chem I | | |
|---|---|---|---|
| | N | ABC vs. DFW | Attrition |
| MPT 8-11 No POGIL 2004-2006 | 355 | 54.0% vs. 46.0% | N=77 (17.5%) |
| MPT 8-11 POGIL 2007-2008 | 117 | 76.0% vs. 24.0% | N=4 (3.4%) |
| MPT 12+ No POGIL 2007-2008 | 738 | 70.5% vs. 29.5% | N=71 (9.6%) |

# Results – Attrition & Retention

| | Gen Chem I | | | Gen Chem II | | | |
|---|---|---|---|---|---|---|---|
| | N | ABC vs. DFW | Attrition | N | Retention | ABC vs. DFW | Attrition |
| at risk No POGIL historical | 355 | 54.0% vs. 46.0% | N=77 (17.5%) | 145 | 40.8% | 59.0% vs. 41.0% | N=22 (15.2%) |
| **at risk w/POGIL** | **117** | **76.0% vs. 24.0%** | **N=4 (3.4%)** | **57** | **50.4%** | **53.0% vs. 47.0%** | **N=10 (17.5%)** |
| not at risk no POGIL | 738 | 70.5% vs. 29.5% | N=71 (9.6%) | 375 | 50.8% | 62.0% vs. 38.0% | N=61 (16.3%) |

# Results – Attrition & Retention

| CHM 142 Enrollments | | | | |
|---|---|---|---|---|
| | Fall 2008 cohort | Continued to CHM 142 Spring 2009 | Fall 2009 cohort | Continued to CHM 142 Spring 2010 |
| CHM 141 | 745 | 419 (56.2%) | 737 | 384 (52.1%) |
| CHM 141.R | 189 | 108 (57.1%) | 191 | 110 (57.6%) |

**Chi-square test of independence results**

$\chi^2$ (1, $N$ = 1862) = 1.24, $p$ = .266

**T-test results on Gen Chem II Grades**

CHM 141 ($M$ = 2.80, $SD$ = 1.00) vs. CHM 141R ($M$ = 2.29, $SD$ = 1.09)

$t$(471) = 3.58, $p$ < .001

# Results – Attrition & Retention

| Organic Enrollments | | | | |
|---|---|---|---|---|
| | Fall 2007 cohort | Continued to CHM 241 Fall 2008 | Fall 2008 cohort | Continued to CHM 241 Fall 2009 |
| CHM 141 | 772 | 210 (27.2%) | 745 | 216 (29.0%) |
| CHM 141.R | 116 | 25 (21.6%) | 189 | 39 (20.6%) |

**Chi-square test of independence results**

$\chi^2$ (1, $N$ = 1822) = 6.51, $p$ = .011

**T-test results on Organic Grades**

CHM 141 ($M$ = 2.80, $SD$ = 1.00) vs. CHM 141R ($M$ = 2.29, $SD$ = 1.09)

$t$(471) = 3.58, $p$ < .001

# Results – Cognitive Learning

- *Did students' expectations about learning chemistry improve?* (CHEMX)
  - No significant change during Gen Chem I
  - Gain in math cluster ($p=0.003$)
  - Gain in concepts cluster ($p=0.055$)
  - Decline in lab cluster ($p<0.000$)
  - Decline in outcomes cluster ($p=0.006$)

Grove, N.P.; Bretz, S.L. *J. Chem. Educ.*, 2007, 84, 1524-1529

# Results – Affective Learning

- *Did students' attitudes about chemistry improve?* (Bauer's Semantic Differential)
- 7 point scale, polar adjectives
- 20 items:
  - Interest and utility
  - Anxiety
  - Intellectual accessibility
  - Fear
  - Emotional satisfaction

Bauer, C.F. (2008). *J. Chem. Educ.* 85(10), 1440-1445

# Semantic Differential v. 2

**CHEMISTRY IS**

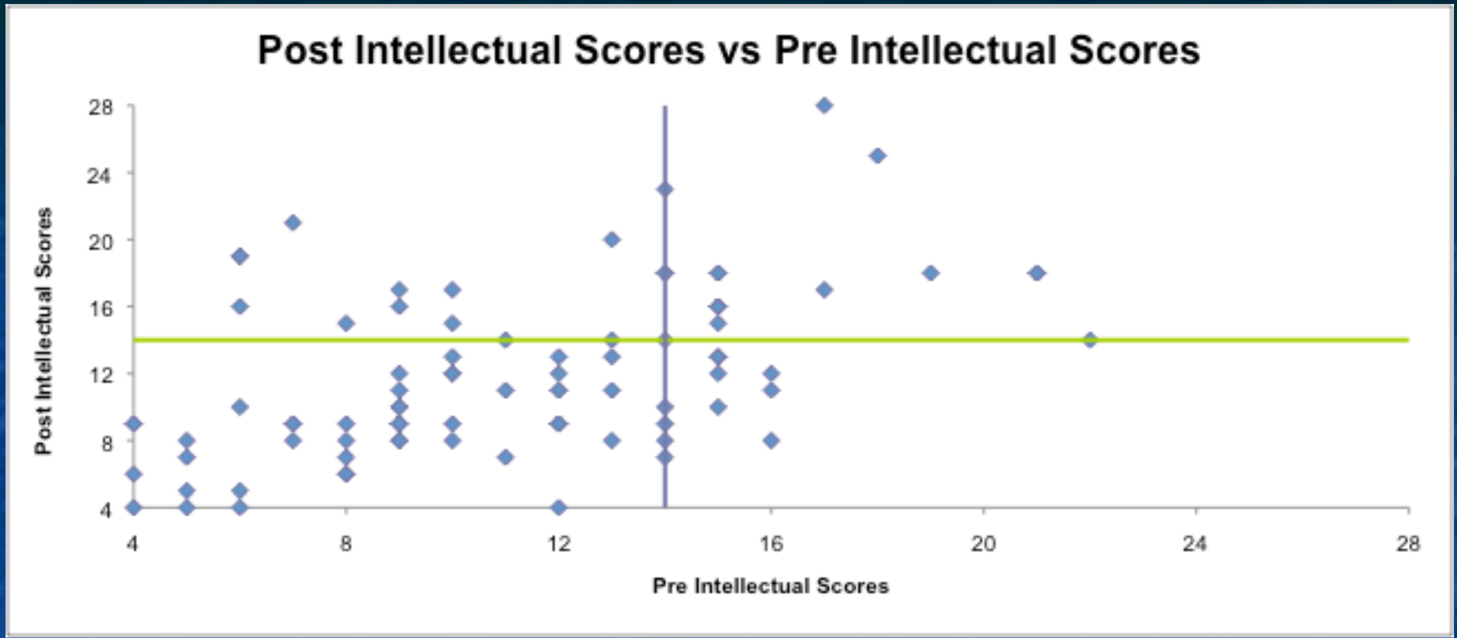
| | | | |
|---|---|---|---|
| 1 | easy | \|__1__\|__2__\|__3__\|__4__\|__5__\|__6__\|__7__\| | hard |
| | | middle | |
| 2 | complicated | \|__1__\|__2__\|__3__\|__4__\|__5__\|__6__\|__7__\| | simple |
| 3 | confusing | \|__1__\|__2__\|__3__\|__4__\|__5__\|__6__\|__7__\| | clear |
| 4 | comfortable | \|__1__\|__2__\|__3__\|__4__\|__5__\|__6__\|__7__\| | uncomfortable |
| 5 | satisfying | \|__1__\|__2__\|__3__\|__4__\|__5__\|__6__\|__7__\| | frustrating |
| 6 | challenging | \|__1__\|__2__\|__3__\|__4__\|__5__\|__6__\|__7__\| | not challenging |
| 7 | pleasant | \|__1__\|__2__\|__3__\|__4__\|__5__\|__6__\|__7__\| | unpleasant |
| | | middle | |
| 8 | chaotic | \|__1__\|__2__\|__3__\|__4__\|__5__\|__6__\|__7__\| | organized |

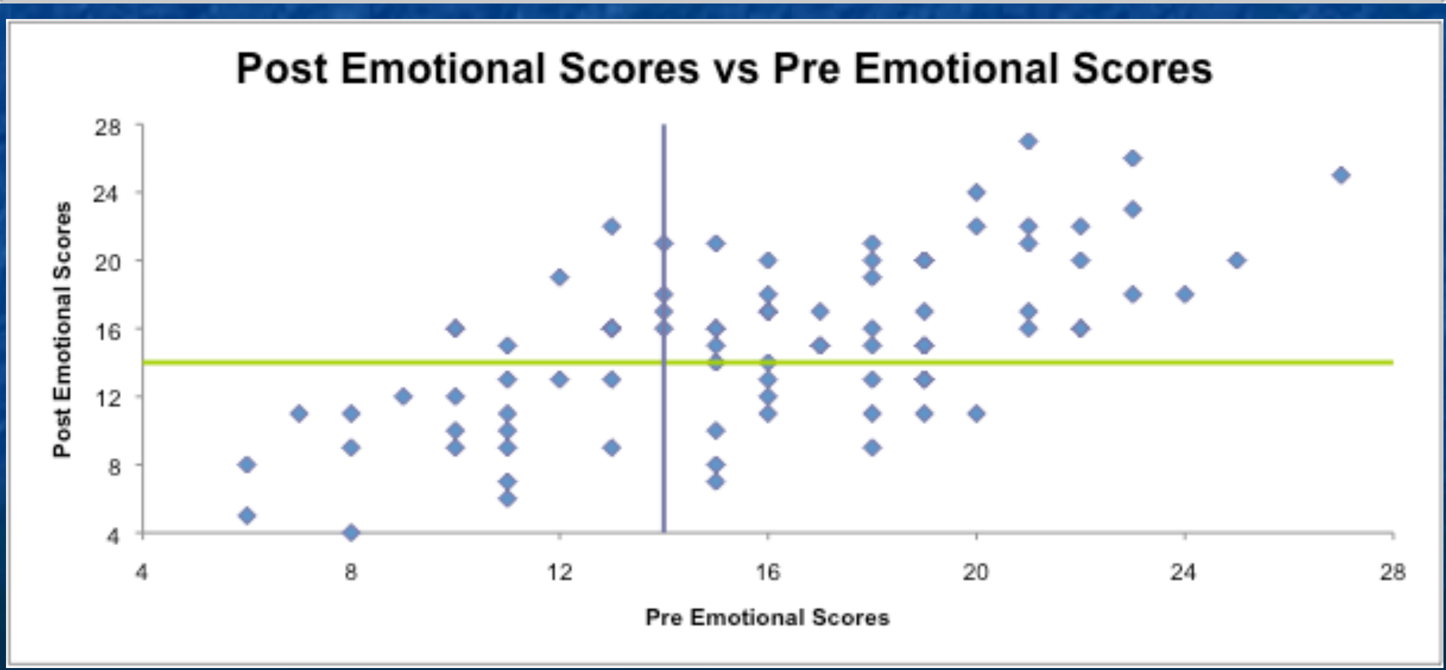
- Intellectual accessibility scale: items 1, 2, 3, 6
- Emotional satisfaction scale: items 4, 5, 7, 8

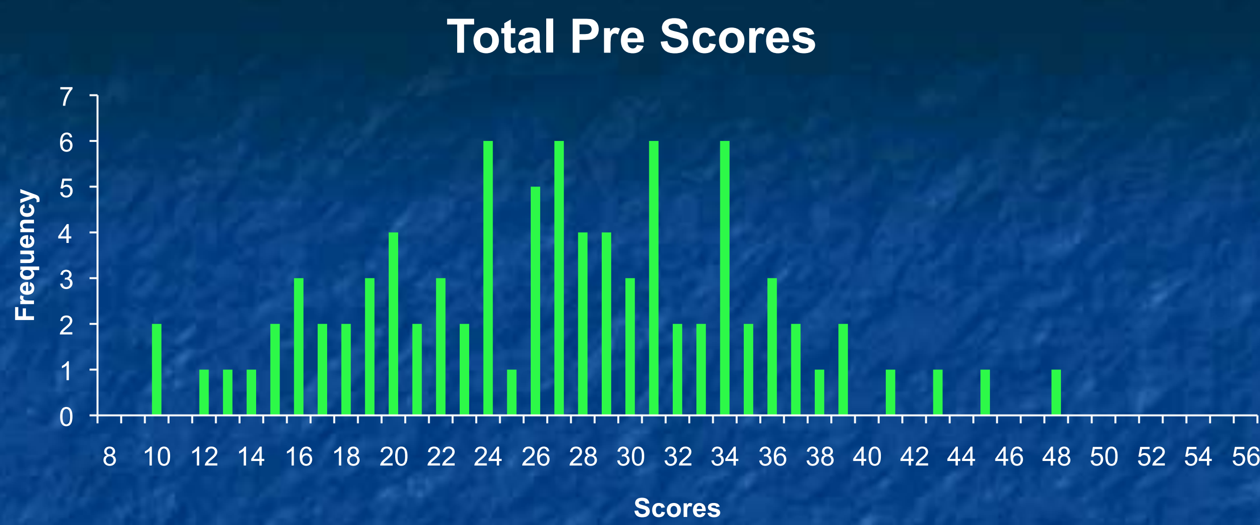
# Semantic Differential v. 2

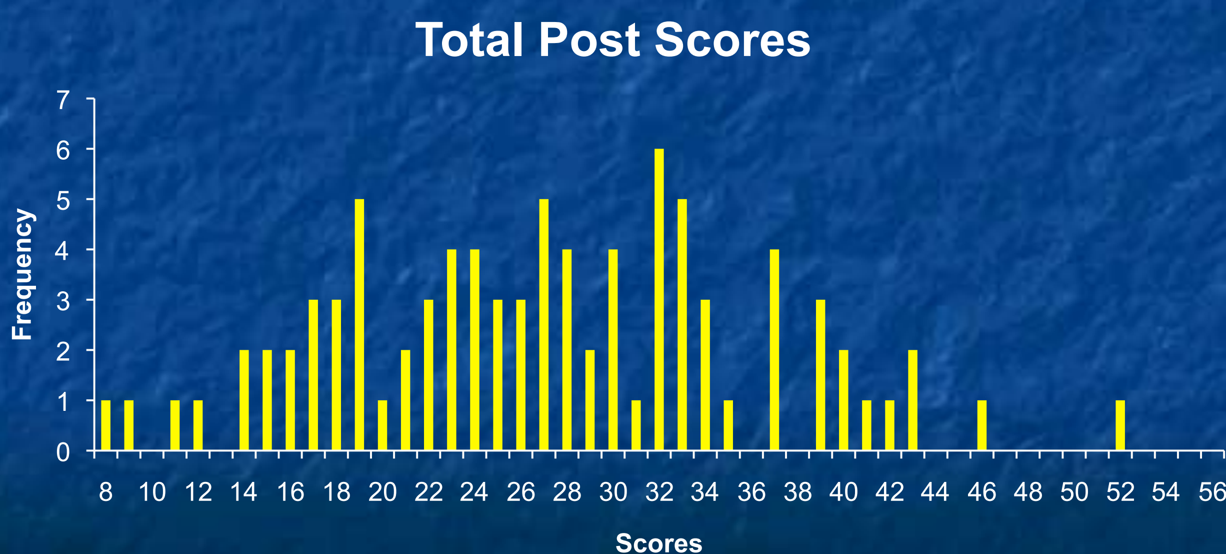
| **N=87**<br>**Item (*reversed)** | | **PRE**<br>**Mean ± St. Dev.** | **POST**<br>**Mean ± St. Dev.** |
|---|---|---|---|
| *hard | easy | 2.90 ± 1.29 | 2.80 ± 1.43 |
| complicated | simple | 2.61 ± 1.32 | 3.09 ± 1.61 |
| confusing | clear | 3.36 ± 1.44 | 3.57 ± 1.54 |
| *uncomfortable | comfortable | 3.63 ± 1.43 | 3.79 ± 1.54 |
| *frustrating | satisfying | 3.87 ± 1.58 | 3.40 ± 1.78 |
| challenging | not challenging | **2.26 ± 1.13** | **2.44 ± 1.38** |
| *unpleasant | pleasant | 4.00 ± 1.28 | 3.67 ± 1.37 |
| chaotic | organized | **4.29 ± 1.38** | **4.37 ± 1.53** |

Higher score = intellectually accessible, emotionally satisfying
Item 8 highest score = students feel chemistry is organized
Item 6 lowest score = students feel chemistry is challenging

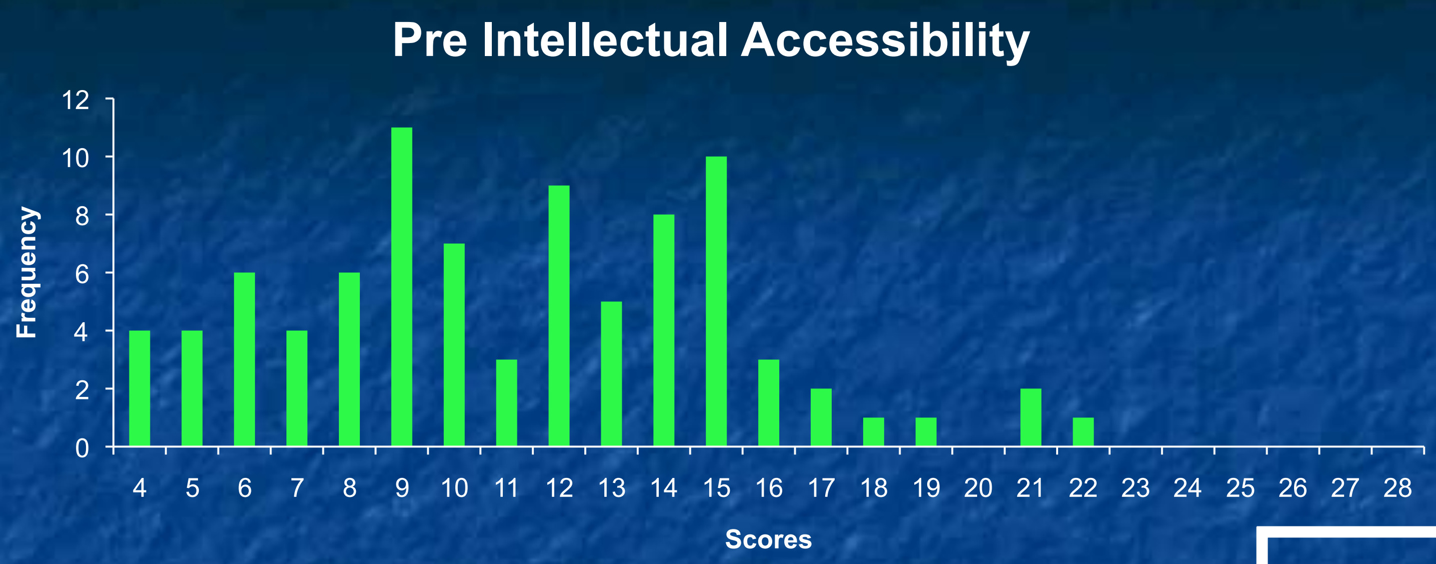

Post Intellectual Scores vs Pre Intellectual Scores
Post Intellectual Scores
Pre Intellectual Scores
4
8
12
16
20
24
28

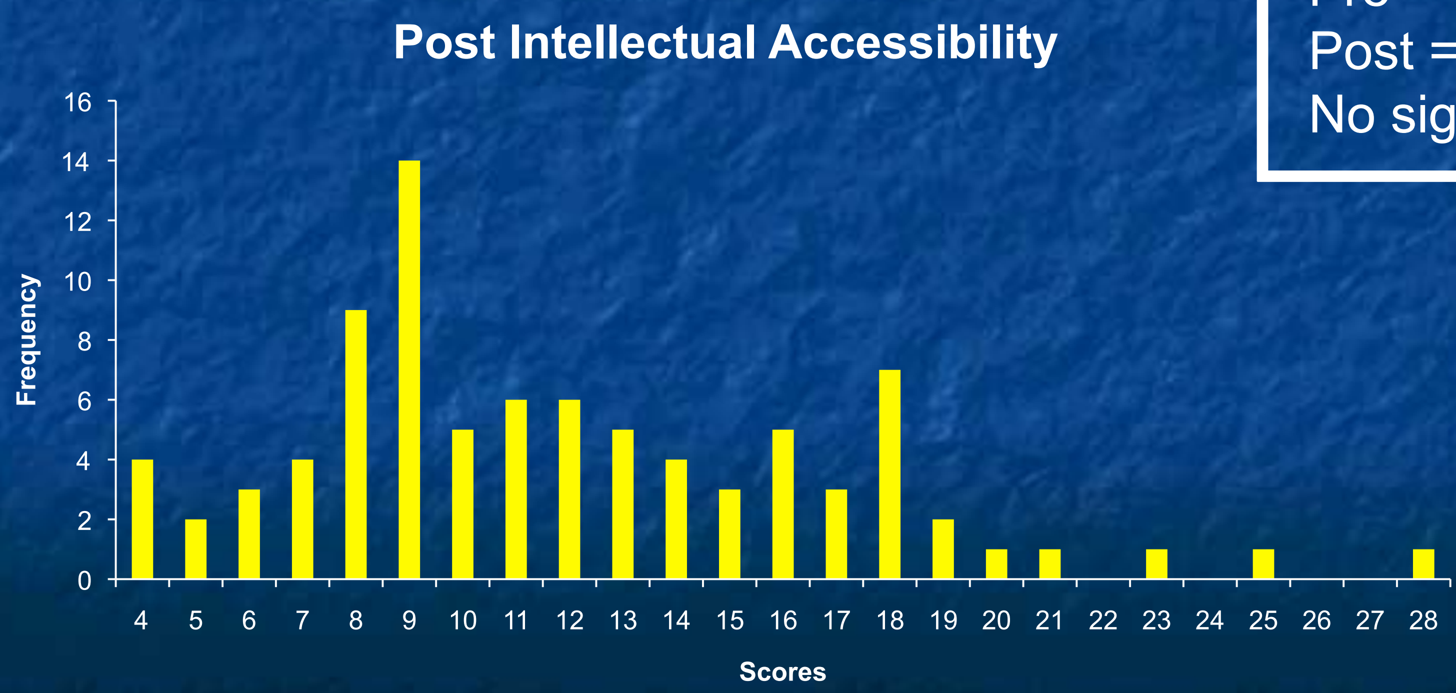

Post Emotional Scores vs Pre Emotional Scores
Post Emotional Scores
Pre Emotional Scores
4
8
12
16
20
24
28



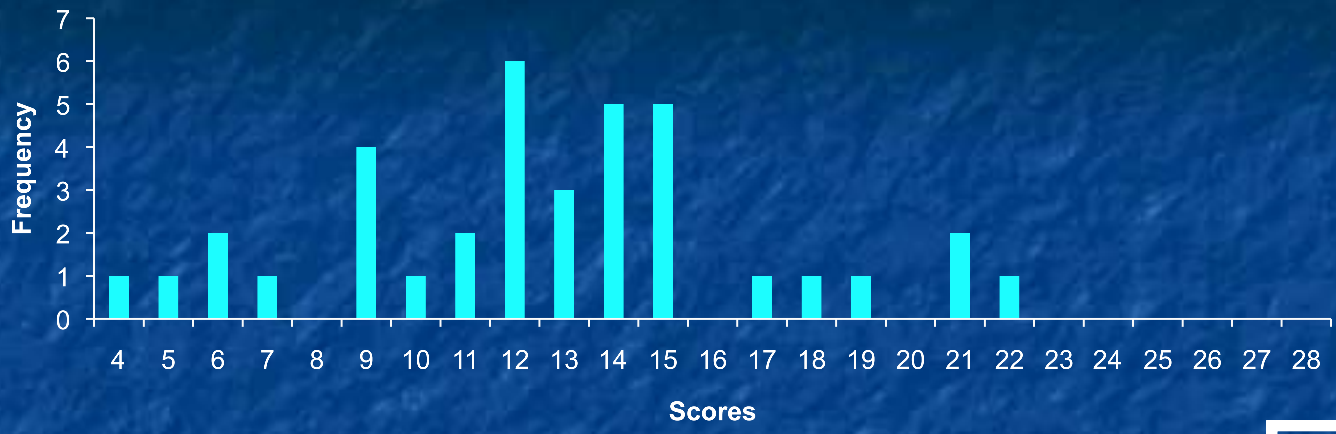

Pre = 26.9 ± 8.0
Post = 27.1 ± 9.0
No sig. difference



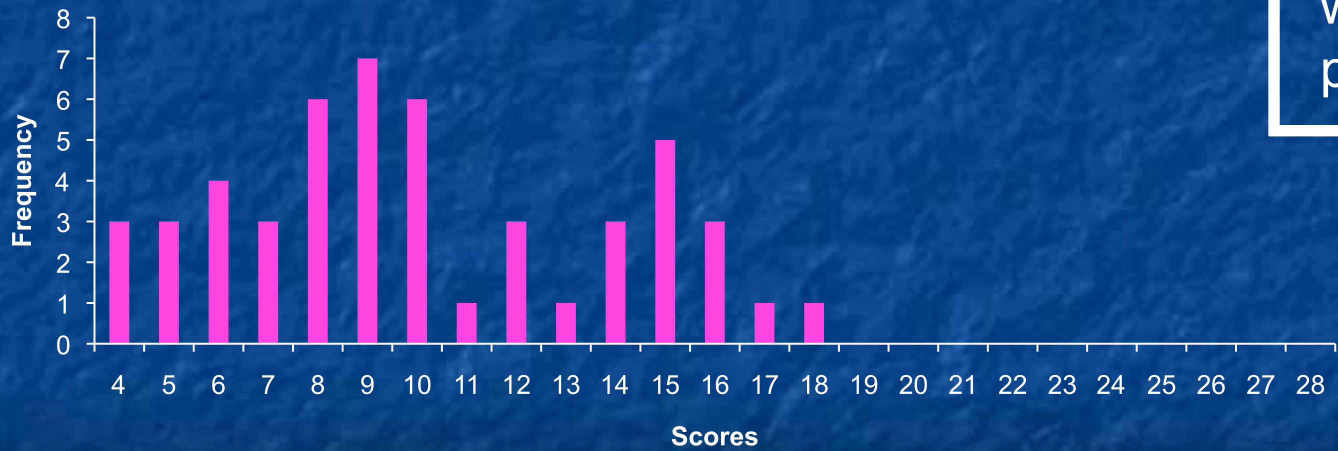




Pre = 11.1 ± 4.2
Post = 11.9 ± 4.9
No sig. difference

## Men (N=37) Pre-Intellectual Accessibility

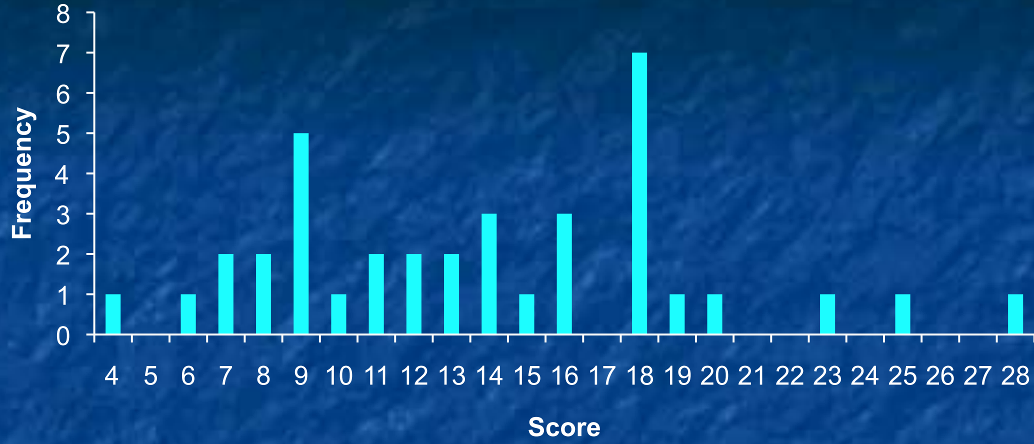



## Women (N=50) Pre-Intellectual Accessibility

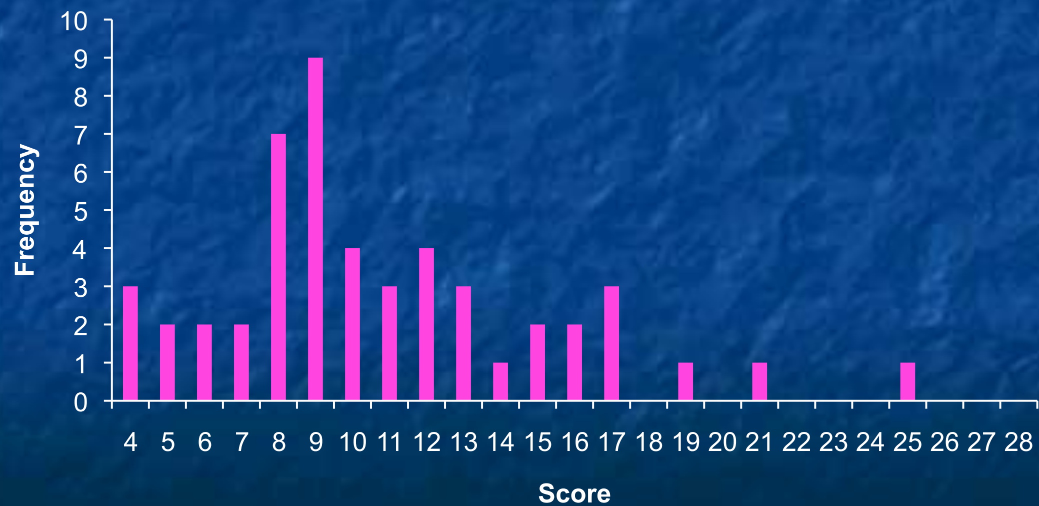



men =12.7 ± 4.3
women=10.1 ± 3.8
$p<0.01$

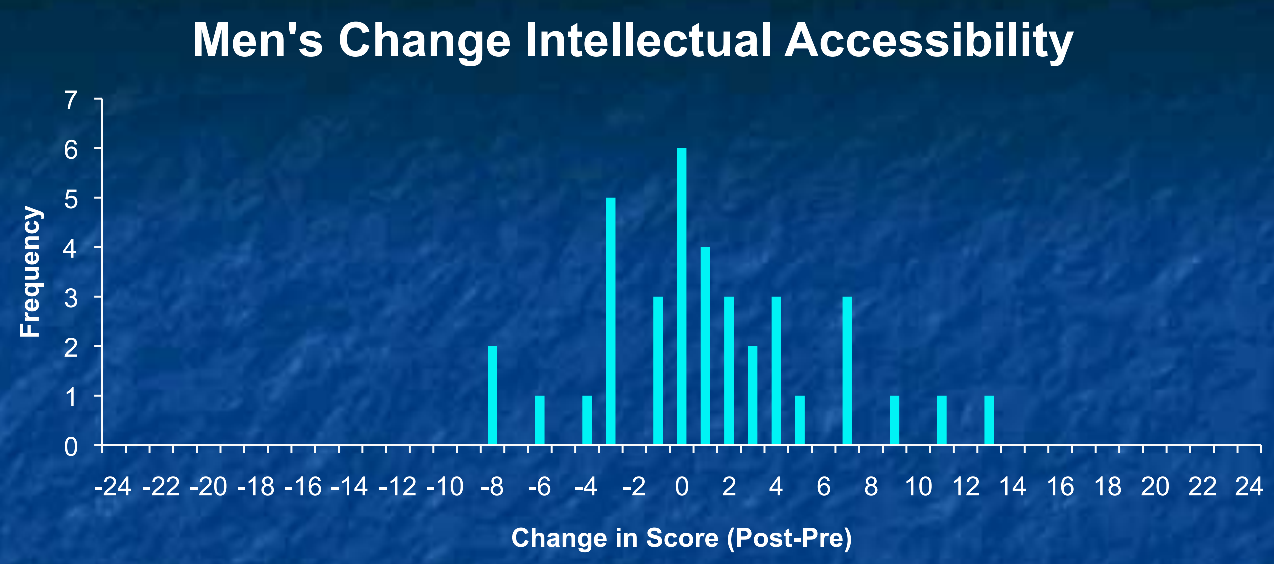
## Men Post-Intellectual Accessibility

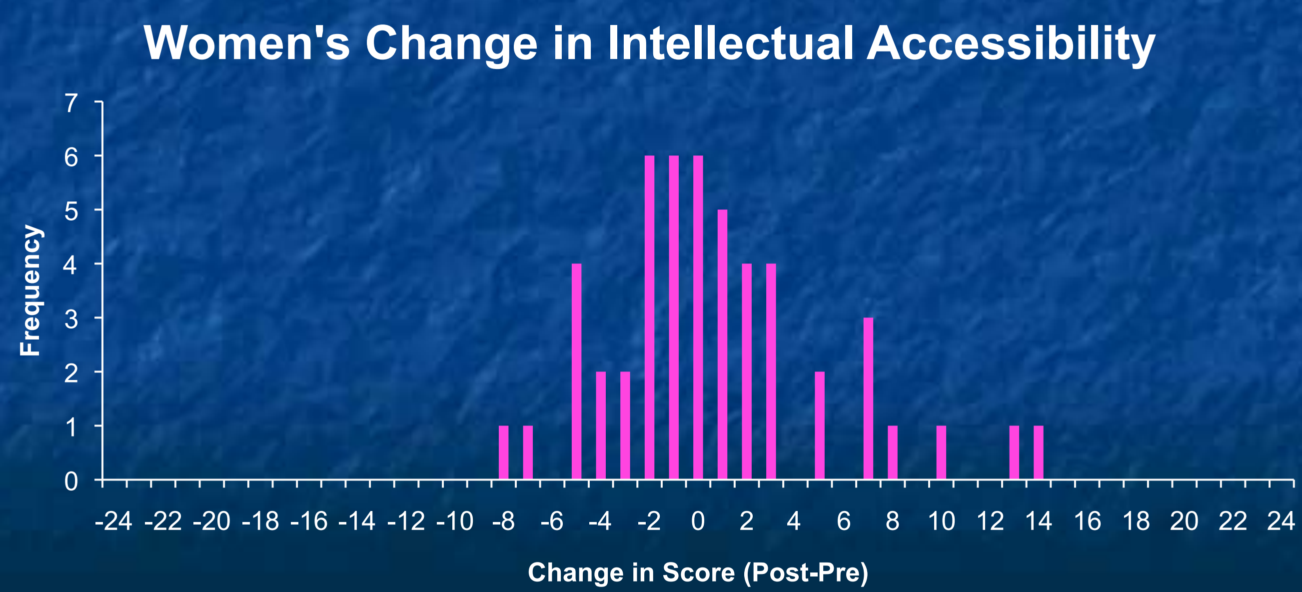


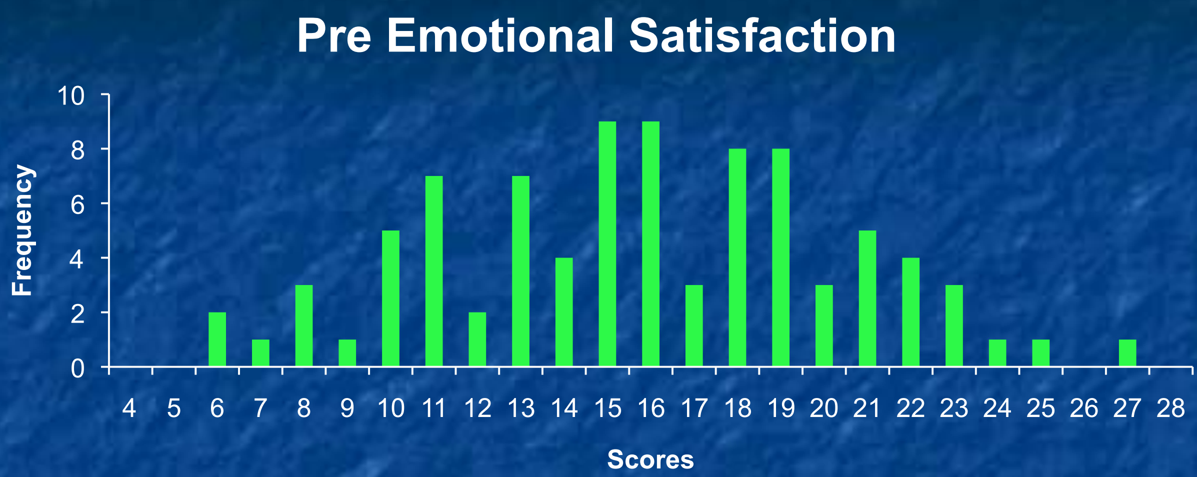

## Women Post-Intellectual Accessibility

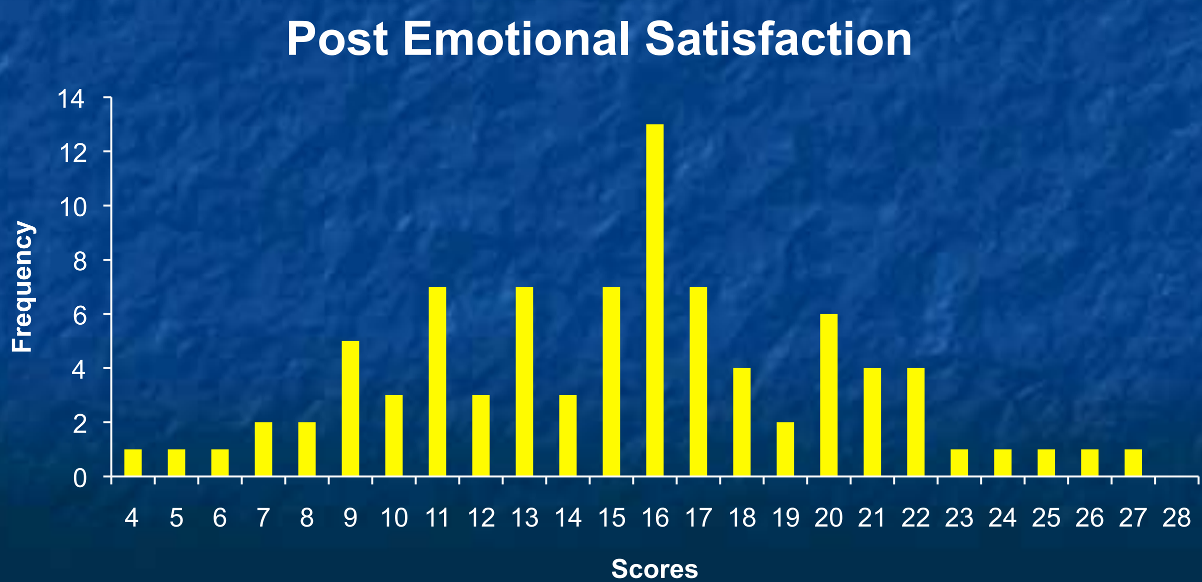



men =13.9 ± 5.5
women=10.7 ± 4.5
$p<0.01$

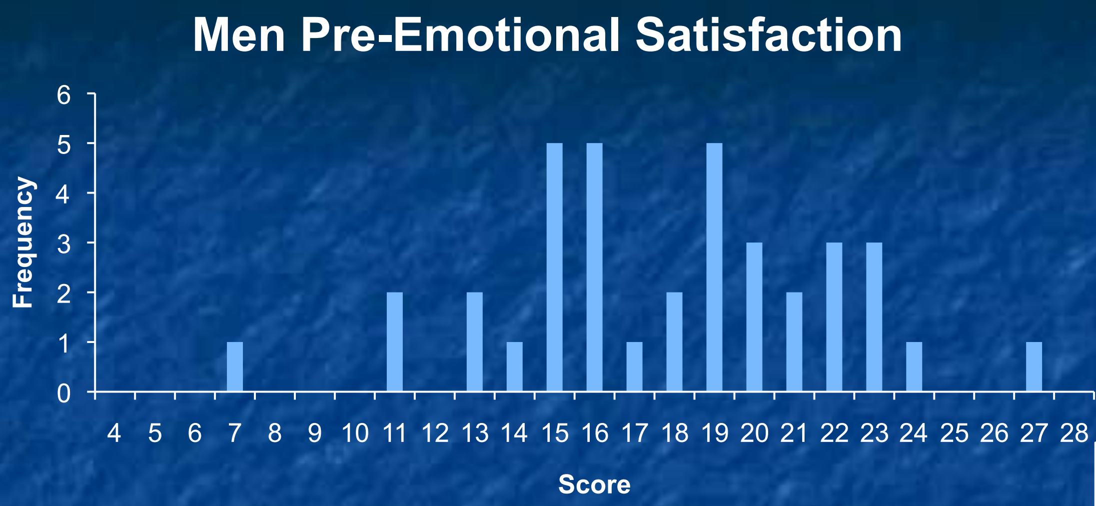

Men's Change Intellectual Accessibility
Frequency
0 1 2 3 4 5 6 7
-24 -22 -20 -18 -16 -14 -12 -10 -8 -6 -4 -2 0 2 4 6 8 10 12 14 16 18 20 22 24
Change in Score (Post-Pre)

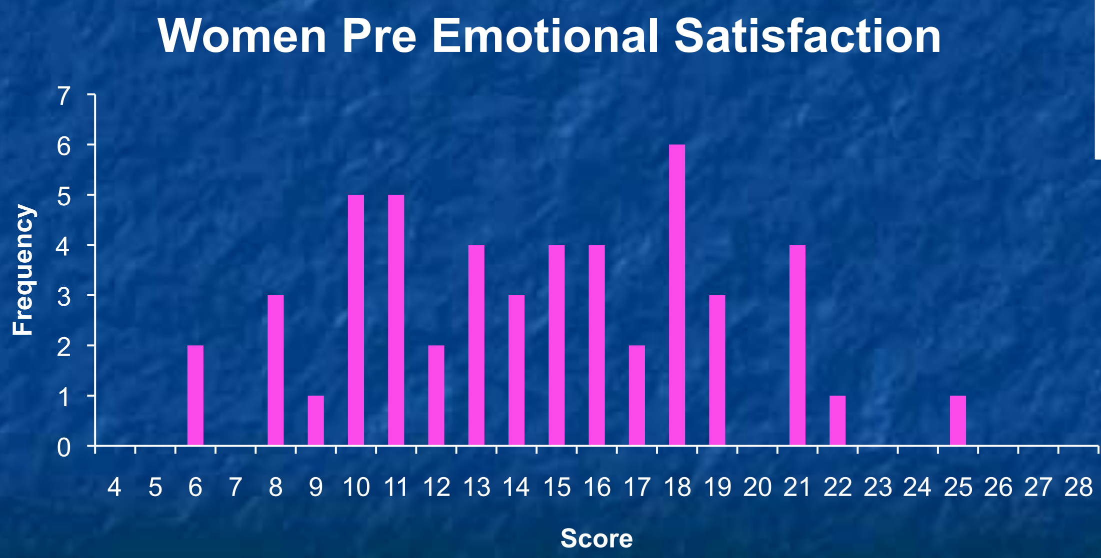

Women's Change in Intellectual Accessibility
Frequency
0 1 2 3 4 5 6 7
-24 -22 -20 -18 -16 -14 -12 -10 -8 -6 -4 -2 0 2 4 6 8 10 12 14 16 18 20 22 24
Change in Score (Post-Pre)



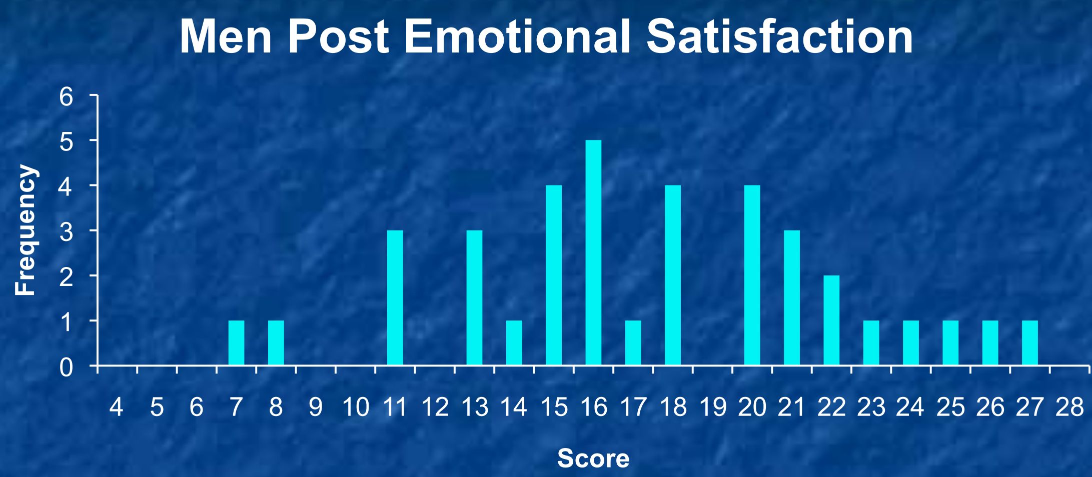



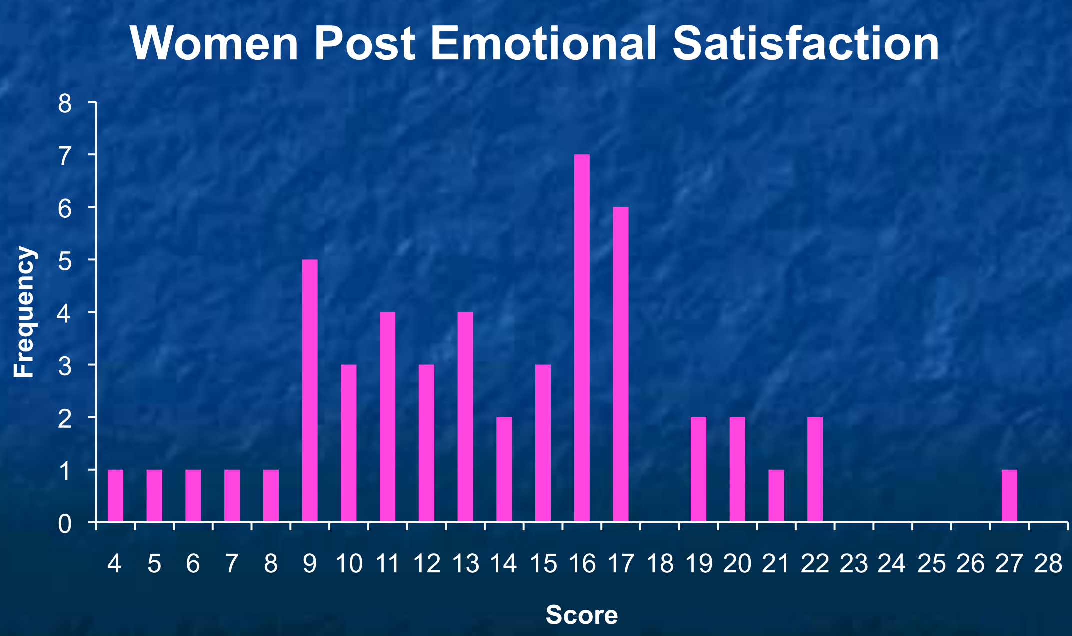

Pre = 15.2 ± 4.9
Post = 15.8 ± 4.6
No sig. difference



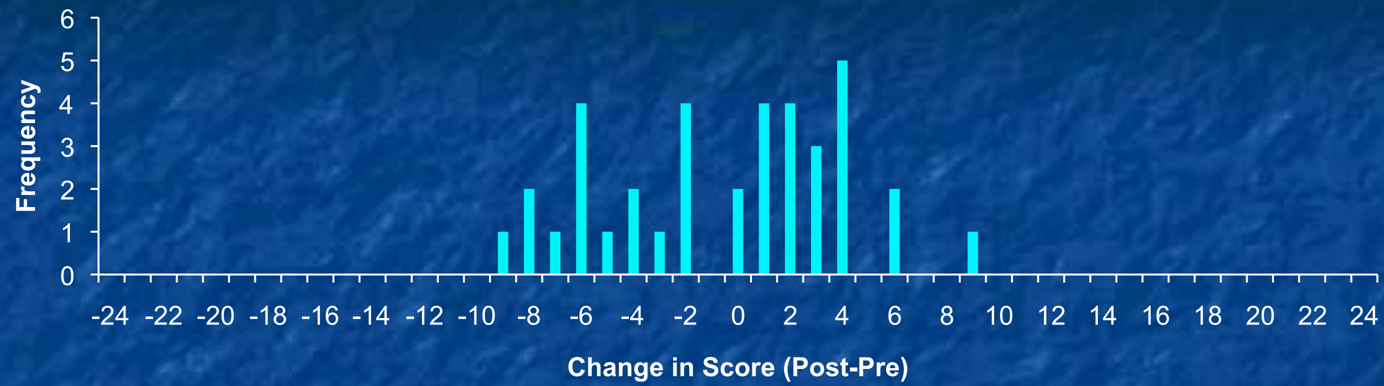

men =17.8 ± 4.2
women=14.4 ± 4.5
$p<0.001$



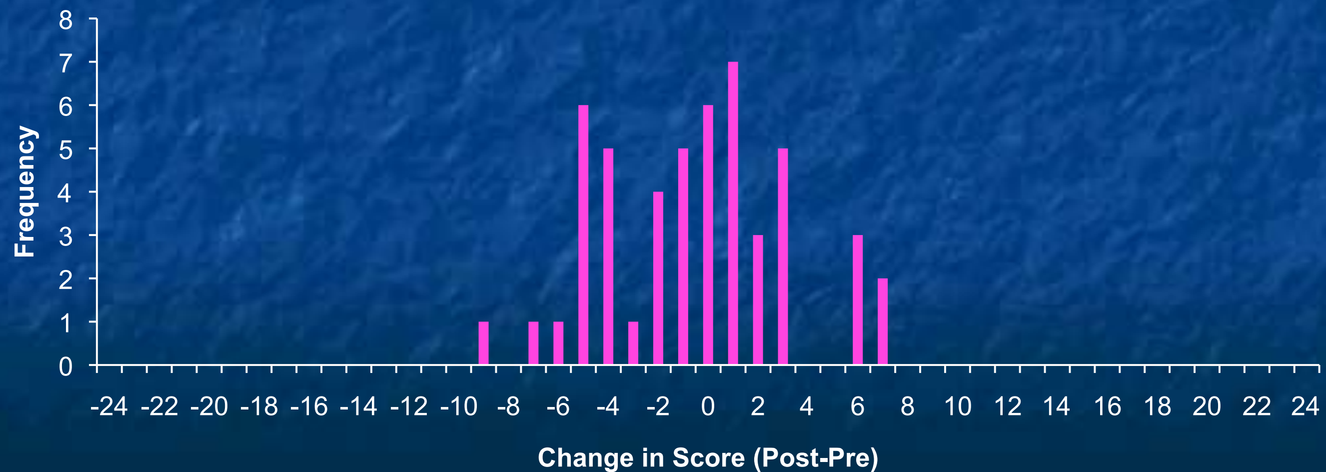




men =17.4 ± 4.8
women=13.9 ± 4.8
$p<0.001$

## Men's Change in Emotional Satisfaction




## Women's Change in Emotional Satisfaction



# Conclusions

- Conceptual understanding & guided inquiry offer access to cognitive learning of chemistry.
- Weaker math students find chemistry
  - More emotionally satisfying
  - Less intellectually accessible
- Gender differences
- Next steps –
  - TOLT & Metacognition
  - Assessment fatigue

# Acknowledgements


- Mary O’Donnell
- Michael Fay
- Allie Brandriet
- Rick Moog, Franklin & Marshall College
- Jennifer Lewis, University of South Florida
- Maria Oliver-Hoyo, North Carolina State U.
- Beatriz D’Ambrosio

# Acknowledgements

- Tom Holme (PI), Melanie Cooper, Jennifer Lewis, Norb Pienta, Angelica Stacy, Ron Stevens, Marcy Towns
- National Science Foundation, CCLI Program #0817297/0817409/0817257/0817279/0817594, "A Model for Data-Driven Reform"
- "Enhancing the Role of Assessment in Curriculum Reform in Chemistry," *Chem. Educ. Res. Prac.*, 2010, 11, 92-97, DOI: 10.1039/C005352J