

# Transforming Spatial Reasoning Skills in the Upper-Level Undergraduate Geoscience Classroom Through Curricular Materials Informed by Cognitive Science Research

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# Outline

- The problem
- Our solution
  - Insights from cognitive science research
  - Curricular implementation in upper-division geology courses
- Research questions and study design: evaluating our curricular materials
- Data
- Conclusions

# The Problem

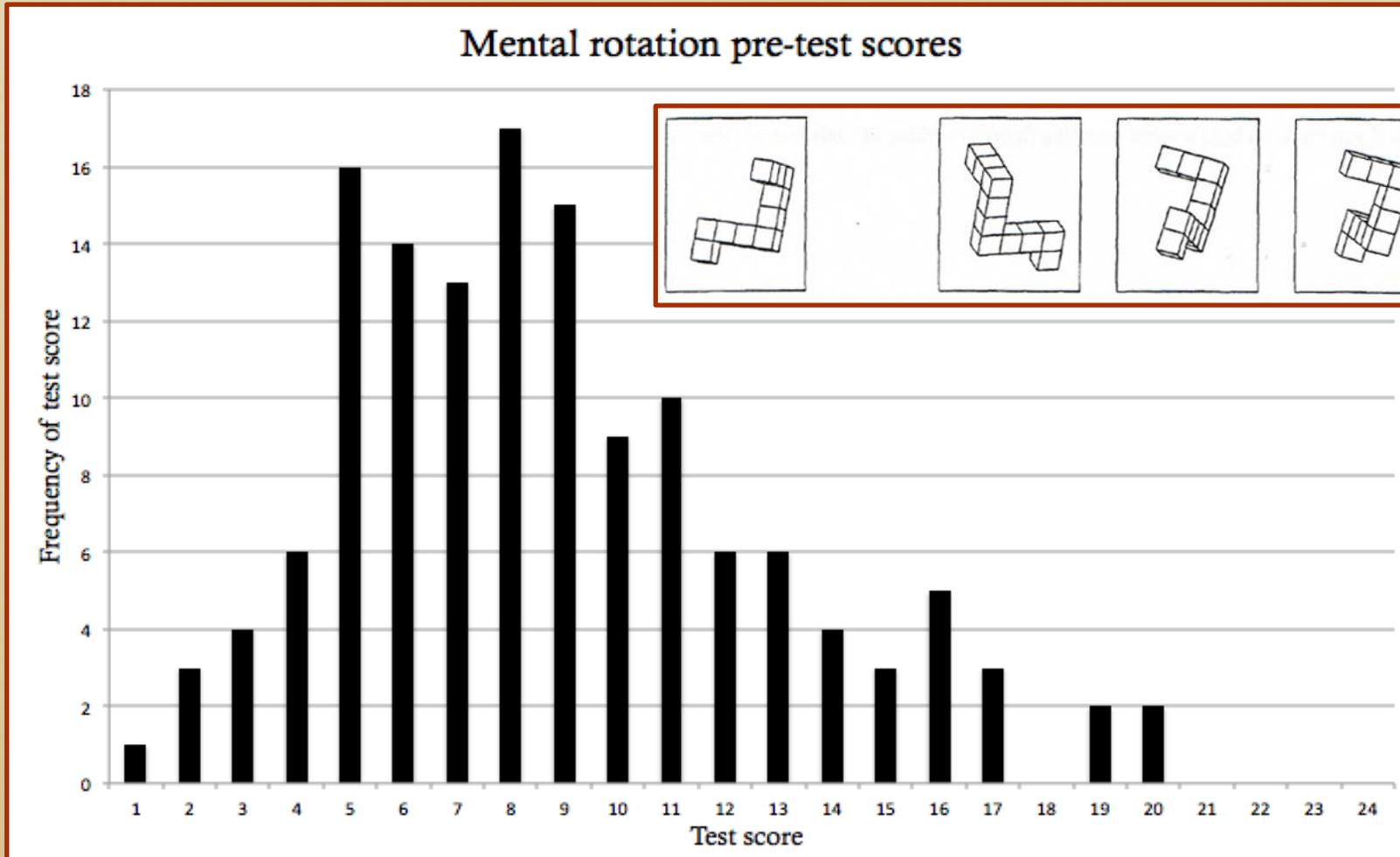
*“Spatial thinking is pervasive: it is vital across a wide range of domains of practical and scientific knowledge; yet it is under-recognized, undervalued, underappreciated, and therefore under-instructed.”*

Learning to Think Spatially, National Research Council, 2006

*“Spatial thinking – you can’t leave home without it.”*

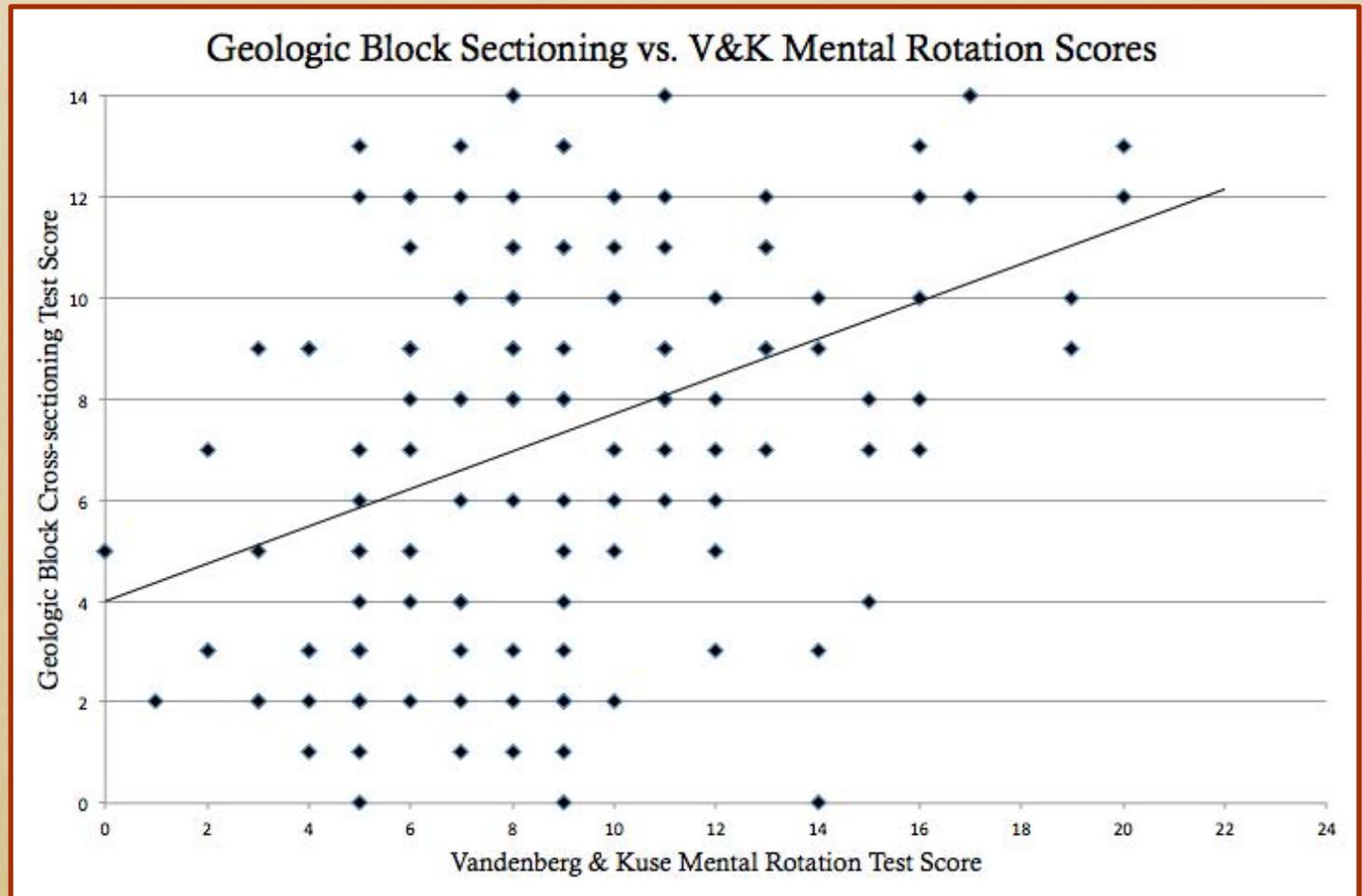
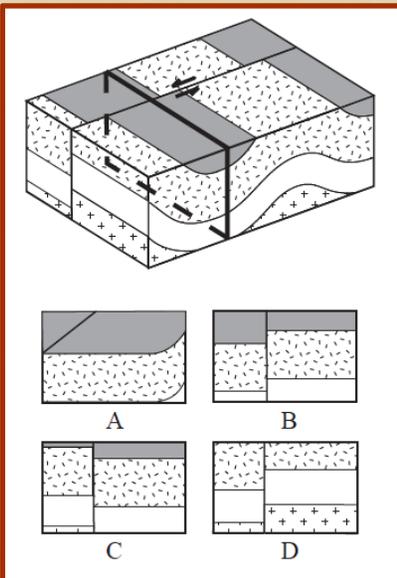
The People’s Guide to Spatial Thinking, Sinton et al., 2013

# The Problem



*Distribution of Vandenberg & Kuse (1978) Mental Rotation pre-test scores for students in Mineralogy, Structural Geology, and Sedimentology/Stratigraphy courses.*

# The Problem



Scores on the Geologic Block Cross-sectioning Test vs. the Vandenberg & Kuse Mental Rotation Test ( $N=142$ ). Although  $R=0.40$ , indicating a statistically significant correlation of these two skills, some students who excel at visualizing a cross-section through a geologic block diagram have weak mental rotation skills.

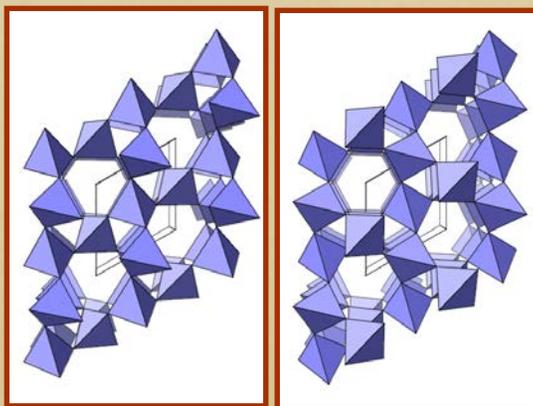
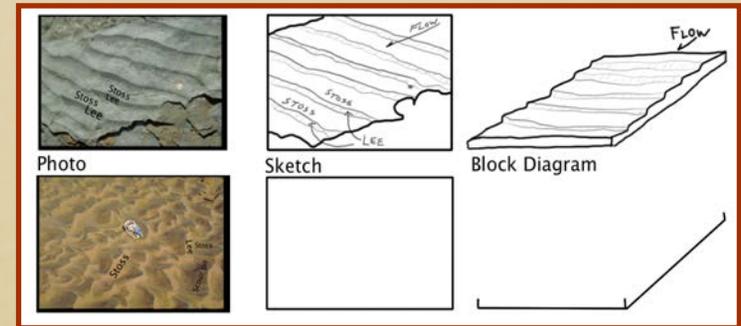
# Context

- Spatial visualization is a key skill for understanding and solving many geological problems
- Undergraduate geoscience students, including students in upper-level courses, bring a wide range of spatial skills to the classroom
- Spatial skills are malleable (e.g., Sorby, 2009; Uttal et al., 2013)
- SILC (the Spatial Intelligence & Learning Center) studies the development of spatial thinking skills and is particularly interested in spatial thinking in the geosciences



# Our solution: curricular materials informed by cognitive science research (the Spatial Workbook)

- Premise: Use strategies/tools from cognitive science research (e.g. Gentner and Markman, 1994; Goldin-Meadow, 2011) to develop curricular materials that will boost students' spatial skills
  - 3D sketching and prediction
  - Gesture
  - Analogical reasoning
  - Progressive alignment\*



\* **Progressive alignment** is the process of moving from the comparison of very similar to less similar objects, in order to identify salient differences.

# Our Research Questions

- Can curricular materials informed by cognitive science research boost students' **domain-general** spatial thinking skills (their ability to perform abstract spatial tasks)?
- Can these materials boost students' **domain-specific** spatial thinking skills (their ability to reason about spatially complex geological concepts and problems)?
- Will these gains be **greater than** the improvement we typically see over the course of a semester?



# Our solution: curricular materials informed by cognitive science research (the Spatial Workbook)

Strategies/tools from cognitive science research:

3D sketching and prediction

Gesture

Analogical reasoning

Progressive alignment



Upper-level geoscience courses:

Mineralogy

Structural Geology

Sedimentology &

Stratigraphy

# Our solution: curricular materials informed by cognitive science research (the Spatial Workbook)

Teaching Activities

serc.carleton.edu/dev/spatialworkbook/activities.html

## Spatial Thinking Workbook

Spatial Thinking Workbook > Teaching Activities

### Teaching Activities

The activities in this collection are designed to help undergraduate geoscience students develop the skills, and particularly their penetrative thinking skills: the ability to visualize spatial relations in 3D. These exercises are the [Spatial Thinking Workbook](#).

Search:

Help  
Results 1 - 20 of **21 matches**

**Fault Separation**  
Students use gestures to explore the relationship between fault slip direction and fault separation by varying the geometry of faulted layers, slip direction, and the perspective from which these are viewed.

**Contractional Strain**  
Students use gesture to describe the bulk deformation and local deformation apparent in images of a contractional analog experiment. Students then calculate bulk shortening and bulk thickening for the experiment and describe the structures accommodating that strain.

**Miller Indices**  
Students use one hand to gesture crystallographic axes and the other hand to represent planes designated by Miller Indices.

**Linear and Planar Features**  
Students gesture the orientations of linear and planar features. In the first part of the exercise, students can only see one surface of a wooden block, and are asked to speculate about how planes are oriented in the interior. Later, they uncover the other faces of the block and gesture the actual orientations.

Go to "<http://serc.carleton.edu/spatialworkbook/index.html>"

### Refine the Results

**Subject: Geology**

- [4 matches](#) General/Other
- Mineralogy [8 matches](#)
- Structural Geology [8 matches](#)
- Sedimentary Geology [2 matches](#)

**Spatial Thinking: Instructional Strategies**

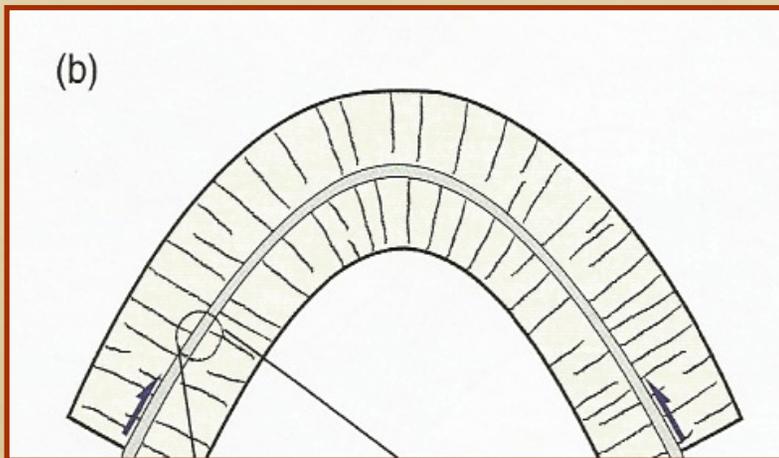
- [2 matches](#) General/Other
- Comparison [13 matches](#)
- Gesture [10 matches](#)
- Sketching [5 matches](#)

**Resource Type: Activities**

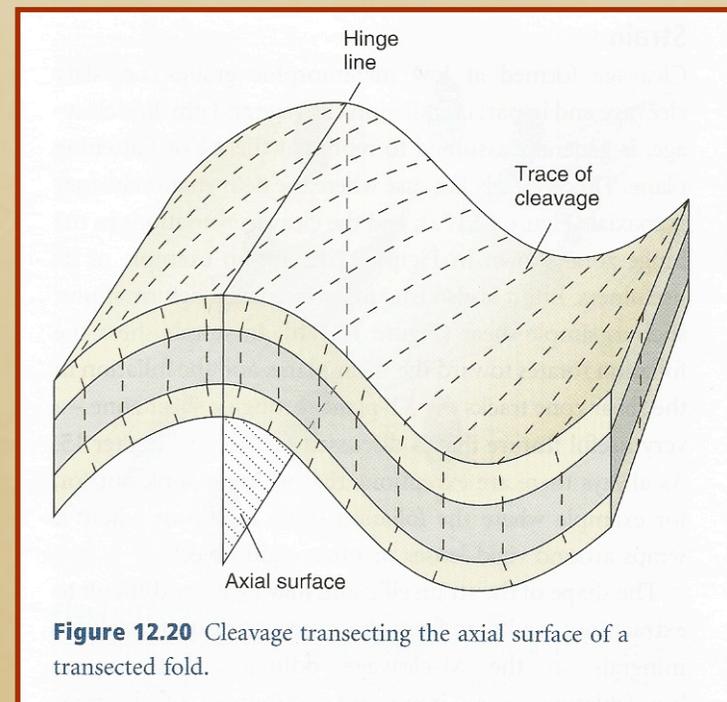
- [2 matches](#) General/Other
- Problem Set [11 matches](#)
- Classroom Activity [9 matches](#)
- Lab Activity [5 matches](#)

# Examples from the Workbook

- 3D cleavage patterns around folds:
  - Sketch bedding/cleavage intersections, in outcrop view
  - What would you look for, in the field, to distinguish transecting cleavage from axial planar or fanning cleavage?



Images from the course textbook, *Structural Geology*, Haakon Fossen (2010), University Press



**Figure 12.20** Cleavage transecting the axial surface of a transected fold.

# Examples from the Workbook

Folds and Cleavage

serc.carleton.edu/spatialworkbook/activities/folds.html

Reader

## Spatial Thinking Workbook

[Spatial Thinking Workbook](#) > [Teaching Activities](#) > Folds and Cleavage

Spatial Thinking Workbook

- Teaching Activities
- About this Project
- Prior Research
- Publications

### Folds and Cleavage

Laurel Goodwin, UW-Madison, and Carol Ormand, SERC at Carleton College [Author Profile](#)

#### Summary

In this exercise, students explore the geometric relationship between bedding/cleavage intersections and fold axes for axial planar, fanning, and transecting cleavage.

#### Learning Goals

After successfully completing this exercise, students will be able to

- Define axial planar, fanning, and transecting cleavage;
- Use gesture to describe and illustrate axial planar, fanning, or transecting cleavage; and
- Describe the geometric relationship between bedding/cleavage intersections and fold axes for each type of cleavage.

#### Context for Use

We use this exercise as a homework exercise to help students review/learn the cleavage patterns most commonly associated with folding. Students complete the exercise shortly before a field trip in which they will observe two of the cleavage patterns.

#### Description and Teaching Materials

In this exercise, students explore the geometric relationship between bedding/cleavage intersections and fold axes for axial planar, fanning, and transecting cleavage. They do this via gestures, sketching, and short answers to questions.

[Folds and Cleavage homework](#) (Microsoft Word 2007 (.docx), 649kB, Apr10, 14)



Folded bedding with axial planar cleavage in the Taconic Mountains of western Vermont 

# Examples from the Workbook

- Misconception: Strain is (always) 2-dimensional
- Exercise: Calculate the cross-sectional area of deformed layers at different stages of deformation. Is the area constant? Why or why not?
- Students compare 2 sets of images: 2D and 3D strain

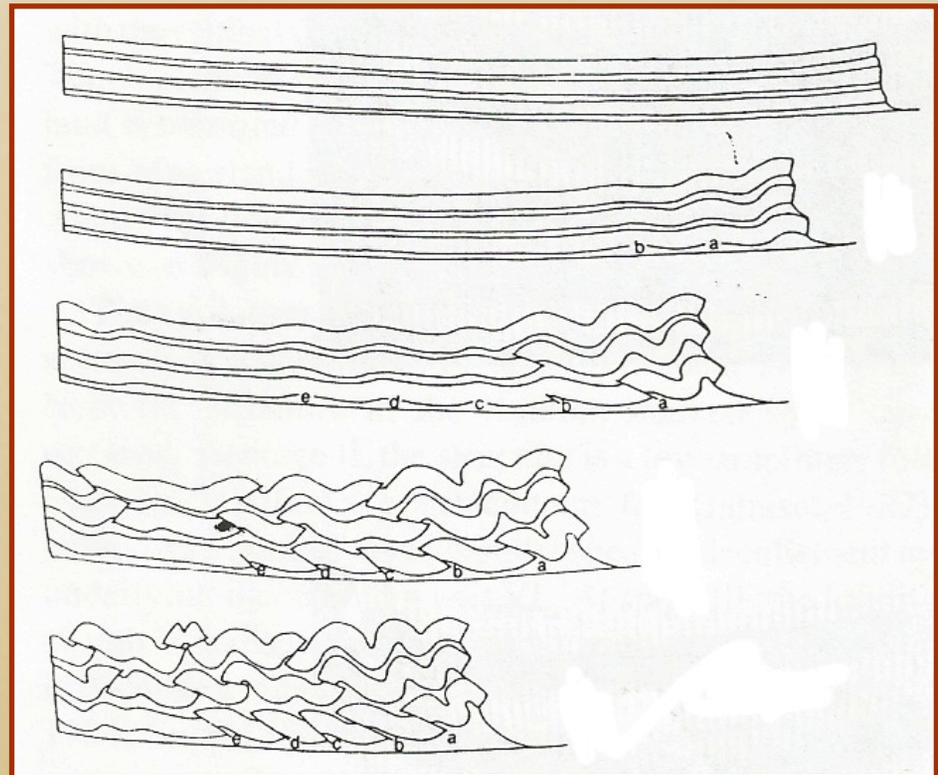


Image from Dixon, John M. and Liu, Shumin, Centrifuge modeling of the propagation of thrust faults, *in Thrust Tectonics* (Ken R. McClay, ed.), 1992

# Examples from the Workbook

Contractional Strain

serc.carleton.edu/spatialworkbook/activities/contractional\_strain.html

Reader

## Spatial Thinking Workbook

Spatial Thinking Workbook > Teaching Activities > Contractional Strain

### Spatial Thinking Workbook

- Teaching Activities
- About this Project
- Prior Research
- Publications

## Contractional Strain

Laurel Goodwin, UW-Madison, and Carol Ormand, SERC at Carleton College [Author Profile](#)

### Summary

In this exercise, students use gesture to describe the bulk deformation and local deformation apparent in images of a contractional analog experiment. Students then calculate bulk shortening and bulk thickening for the experiment and describe the structures accommodating that strain.

### Learning Goals

At the end of this exercise, students will:

- Be able to describe and calculate the bulk strain within a foreland fold-and-thrust belt, if the undeformed geometry is known.
- Be able to use gesture to illustrate the deformation within a contractional tectonic setting.
- Recognize that horizontal shortening within a lithological layer can be accommodated by multiple mechanisms, including vertical thickening.

### Context for Use

This exercise accompanies a lecture on contractional fault systems, convergent tectonics, and strain, in an undergraduate Structural Geology course. It is helpful, but not necessary, for students to know something about folds and reverse faults prior to this exercise.

If students complete the extra credit exercise at the end of this problem set, they will compare these contractional deformation experiments to extensional deformation experiments shown here: [Evolution of Normal Fault Systems During Progressive Deformation](#). In that case, students should be able to analyze these two types of deformation for similarities and differences. This makes an excellent introduction to extensional deformation.



Photograph of re-folded folds.

# Examples from the Workbook

Slices Through 3D Objects

serc.carleton.edu/spatialworkbook/activities/3D\_slices.html

Reader

## Spatial Thinking Workbook

Spatial Thinking Workbook > Teaching Activities > Slices Through 3D Objects

### Slices Through 3D Objects

Carol Ormand, SERC at Carleton College [Author Profile](#)

#### Summary

In this exercise, students identify and draw slices through an ice cream cone, a pyramid, and a beverage six-pack.

#### Learning Goals

This exercise is intended to provide a little bit of practice in identifying and sketching slices through 3D objects.

#### Context for Use

This exercise is designed to be used early on in a course that requires a lot of mental slicing (imagining cross-sections through sedimentary deposits or deformed rocks, for example). It may be most useful as a diagnostic tool, to discover which students will struggle to draw cross-sectional diagrams.

#### Description and Teaching Materials

In this exercise, students identify and draw slices through an ice cream cone, a pyramid, and a beverage six-pack.

[Slices through 3D objects](#) (Microsoft Word 291kB Apr10 14)

#### Teaching Notes and Tips

I would use this exercise primarily as a diagnostic tool, to see whether drawing cross-sectional diagrams will be challenging for a significant number of students in a class that will require visualizing slices through 3D objects.

#### Assessment



Photographic image of a slice through coffee and donuts. Image by Beth Galton, photographer (<http://bethgalton.com/>) and Charlotte Omnes, food stylist (<http://charlotteomnes.com>).

# Examples from the Workbook

Deciphering Mineral Diagrams

serc.carleton.edu/spatialworkbook/activities/mineral\_diagrams.html

## Spatial Thinking Workbook

Spatial Thinking Workbook > Teaching Activities > Deciphering Mineral Diagrams

### Deciphering Mineral Diagrams

Barb Dutrow (Louisiana State University) and Carol Ormand (SERC at Carleton College) [Author Profile](#)

#### Summary

Mineral structures can be represented using several different types of diagrams, including ball-and-stick, space filling, and polyhedral. Each of these visual representations encodes spatial information, showing the 3D relationships of atoms and bonding within the mineral. In addition, mineral structures are viewed from multiple angles in addition to using different types of representations. It is important to be able to "read" these diagrams: to visualize the atoms and bonds within the mineral from the diagram. In this exercise, students practice comparing mineral diagrams to gain familiarity with (1) the same mineral structure shown from multiple points of view and (2) the same mineral shown in different types of diagrams.

#### Learning Goals

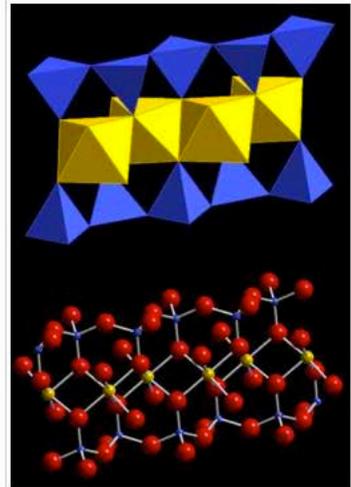
After successfully completing this exercise, students will be able to

- Compare ball-and-stick, space filling, and polyhedral diagrams to determine whether they show the same or different mineral structures.
- Find the structural differences between similar minerals, illustrated in ball-and-stick, space filling, and/or polyhedral diagrams.

#### Context for Use

This exercise is designed for use early in a Mineralogy course, where students will be exposed to a wide variety of diagrams of mineral structures. It is intended to help students understand those diagrams.

#### Description and Teaching Materials



Polyhedral and ball-and-stick models of identical mineral structures. Image constructed using screenshots from the CrystalMaker software program.

# Examples from the Workbook

Miller Indices

serc.carleton.edu/spatialworkbook/activities/Miller\_Indices.html

Reader

## Spatial Thinking Workbook

Spatial Thinking Workbook > Teaching Activities > Miller Indices

### Spatial Thinking Workbook

- Teaching Activities
- About this Project
- Prior Research
- Publications

## Miller Indices

Barb Dutrow (Louisiana State University), Kinnari Atit (Temple University), and Carol Ormand (SERC at Carleton College) [Author Profile](#)

### Summary

In this exercise, students use one hand to gesture crystallographic axes and the other hand to represent planes designated by Miller Indices. This uses embodied learning to reinforce how Miller Indices are used to convey spatial information.

### Learning Goals

At the conclusion of this exercise, students will be able to use gestures to communicate about Miller Indices.

### Context for Use

This exercise follows a short lecture on Miller Indices and an assignment to determine Miller Indices of forms on wooden blocks, in an undergraduate Mineralogy course. It is intended to give students practice using Miller Indices to communicate about the orientations of surfaces.

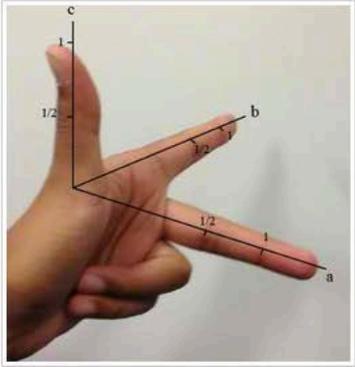
### Description and Teaching Materials

In this exercise, students use one hand to gesture crystallographic axes and the other hand to represent planes designated by Miller Indices. This uses embodied learning to reinforce how Miller Indices are used to convey spatial information.

[Student handout for Miller Indices gesture exercise](#) (Microsoft Word 2007 (.docx) 487kB Mar11 13)

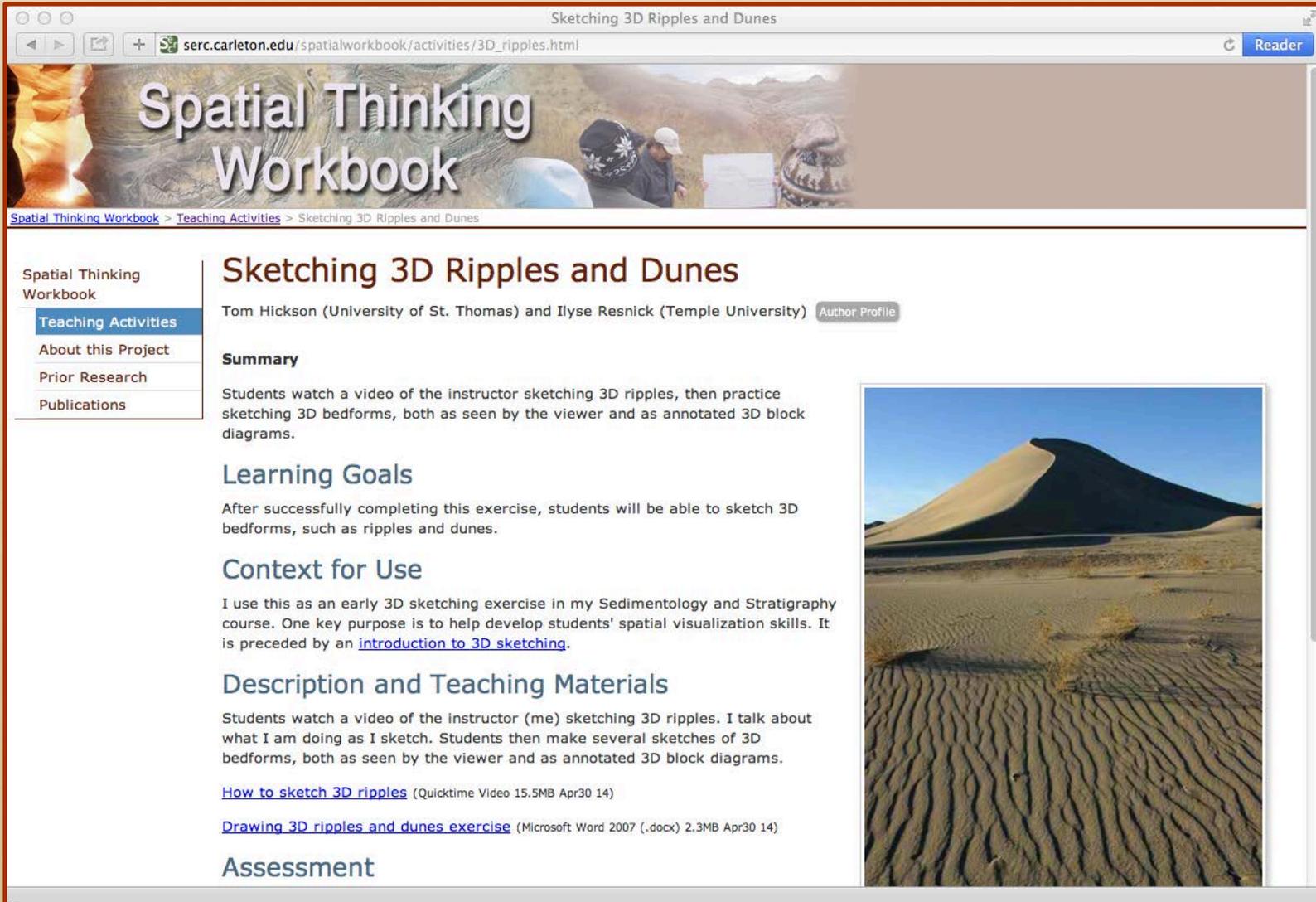
### Assessment

I walk around the room and verbally quiz students as they are doing the exercise to assess their understanding.



Using gesture to represent crystallographic axes 

# Examples from the Workbook



The screenshot shows a web browser window with the address bar displaying `serc.carleton.edu/spatialworkbook/activities/3D_ripples.html`. The page title is "Sketching 3D Ripples and Dunes". The main header features the text "Spatial Thinking Workbook" over a background image of people in a desert landscape. A breadcrumb trail reads "Spatial Thinking Workbook > Teaching Activities > Sketching 3D Ripples and Dunes".

**Spatial Thinking Workbook**

- Teaching Activities
- About this Project
- Prior Research
- Publications

## Sketching 3D Ripples and Dunes

Tom Hickson (University of St. Thomas) and Ilyse Resnick (Temple University) [Author Profile](#)

### Summary

Students watch a video of the instructor sketching 3D ripples, then practice sketching 3D bedforms, both as seen by the viewer and as annotated 3D block diagrams.

### Learning Goals

After successfully completing this exercise, students will be able to sketch 3D bedforms, such as ripples and dunes.

### Context for Use

I use this as an early 3D sketching exercise in my Sedimentology and Stratigraphy course. One key purpose is to help develop students' spatial visualization skills. It is preceded by an [introduction to 3D sketching](#).

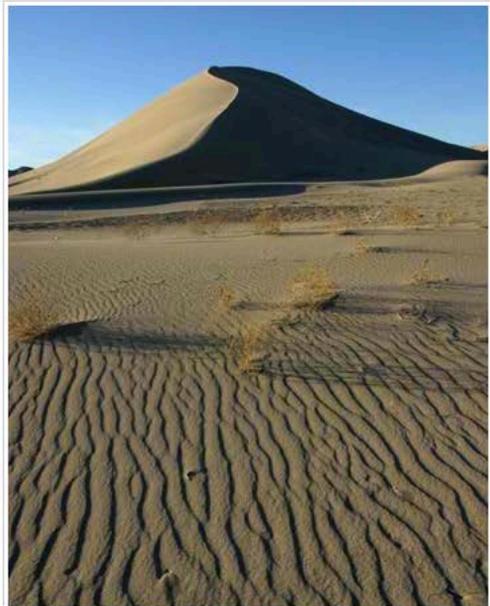
### Description and Teaching Materials

Students watch a video of the instructor (me) sketching 3D ripples. I talk about what I am doing as I sketch. Students then make several sketches of 3D bedforms, both as seen by the viewer and as annotated 3D block diagrams.

[How to sketch 3D ripples](#) (Quicktime Video 15.5MB Apr30 14)

[Drawing 3D ripples and dunes exercise](#) (Microsoft Word 2007 (.docx) 2.3MB Apr30 14)

### Assessment



# Outline

- The problem
- Our solution
  - Insights from cognitive science research
  - Curricular implementation in upper-division geology courses
- Research questions and study design: evaluating our curricular materials
- Data
- Conclusions

# Our Research Questions

- Can curricular materials informed by cognitive science research boost students' **domain-general** spatial thinking skills (their ability to perform abstract spatial tasks)?
- Can these materials boost students' **domain-specific** spatial thinking skills (their ability to reason about spatially complex geological concepts and problems)?
- Will these gains be **greater than** the improvement we typically see over the course of a semester?



# Classroom Study Design

## Participants:

- Structural Geology at UW-Madison (N = 31; N = 34; N = 32)
- Mineralogy at Louisiana State University (N = 15; N = 17; N = 26)
- Sedimentology & Stratigraphy at the University of St. Thomas (N = 18; N = 8)

## All courses, all years:

- Administer **pre- and post-tests of spatial thinking skills**, focusing on mental rotation and penetrative thinking (visualizing interiors)
- Document instructional strategies, materials
- Collect data from student performance on **embedded assessments** (e.g., exam questions that require discipline-based spatial thinking)
- Collect student data from registrars (SAT/ACT scores, GPAs, course grade)

## Timeline:

- 2011-2012: **Baseline year**; no changes in instruction
- 2012-2013: **Pilot implementation**; draft exercises in Mineralogy and Structure
- 2013-2014: **Full scale implementation** in all 3 courses

# Spatial Thinking Tests

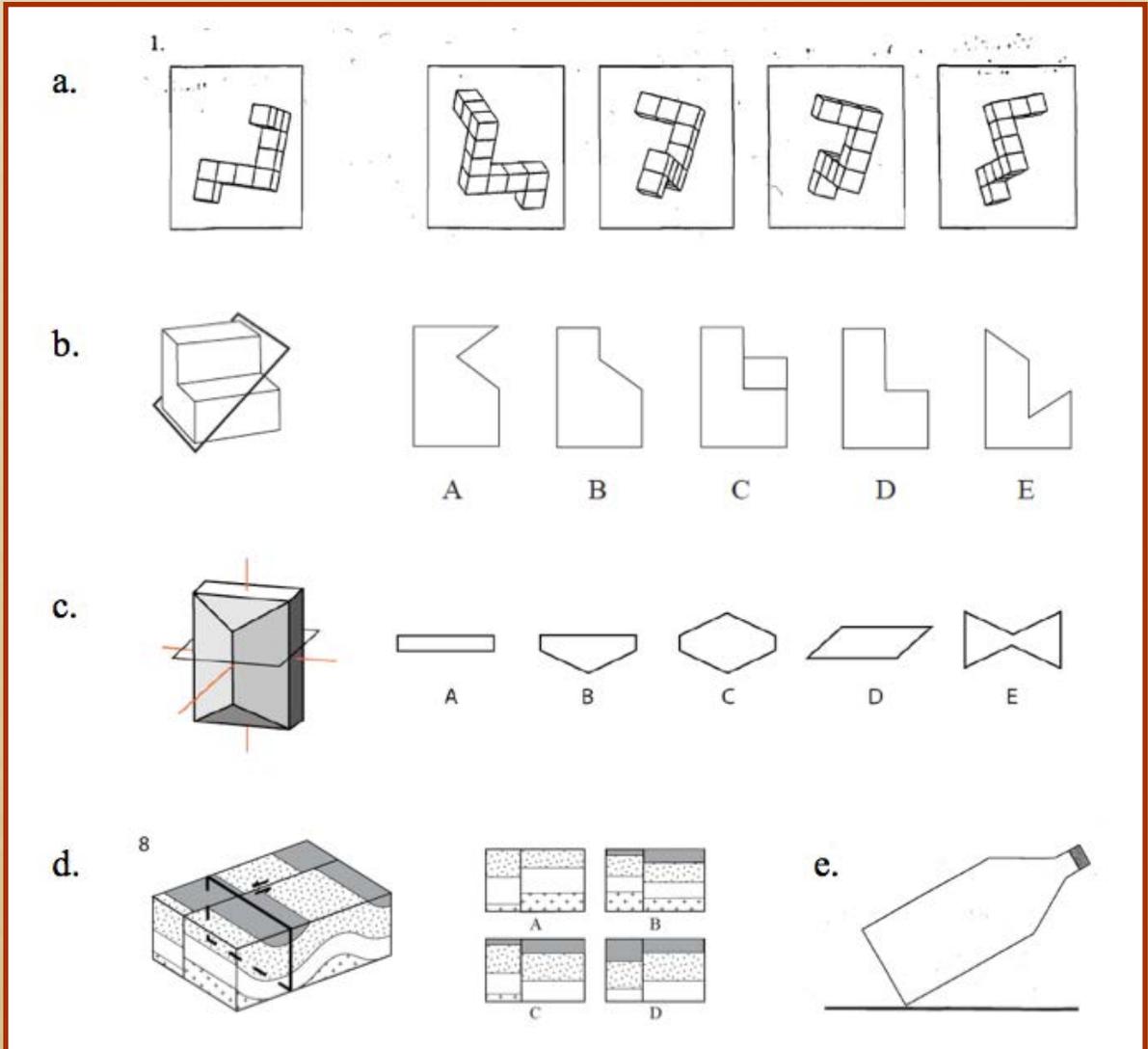
a. Mental rotation (MRT-A)

b. Mental slicing: geometric solids (Planes of Reference)

c. Slicing: minerals

d. Slicing: geologic block diagrams

e. Water level

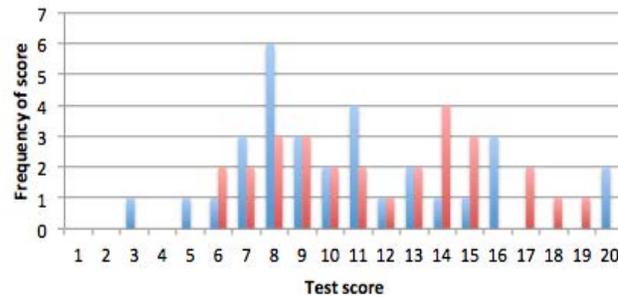


# Baseline data, Structural Geology, UW-Madison

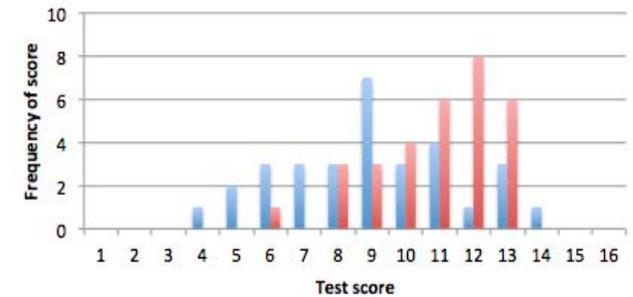
N = 31

■ Pre-test  
■ Post-test

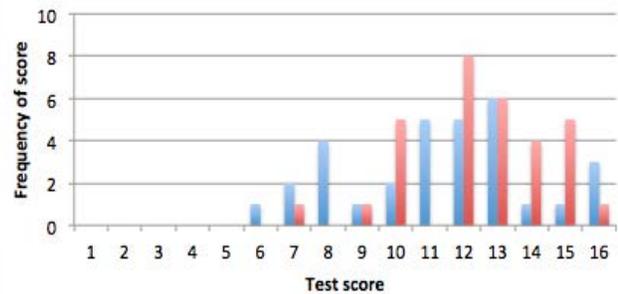
**Mental rotation test**



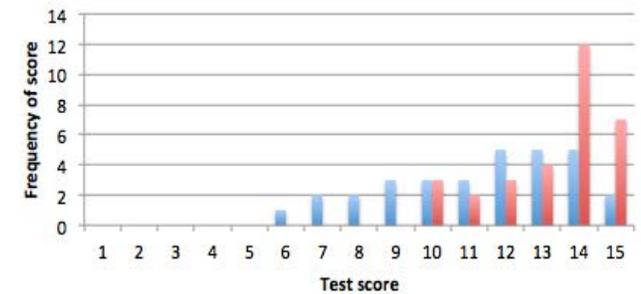
**Psychometric mental slicing test**



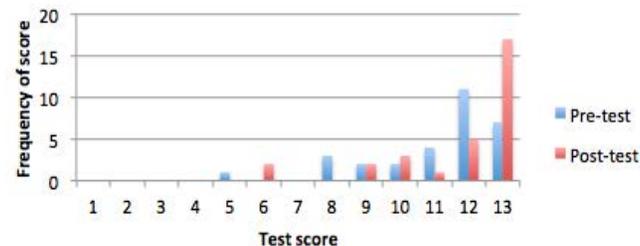
**Mineral slicing test**



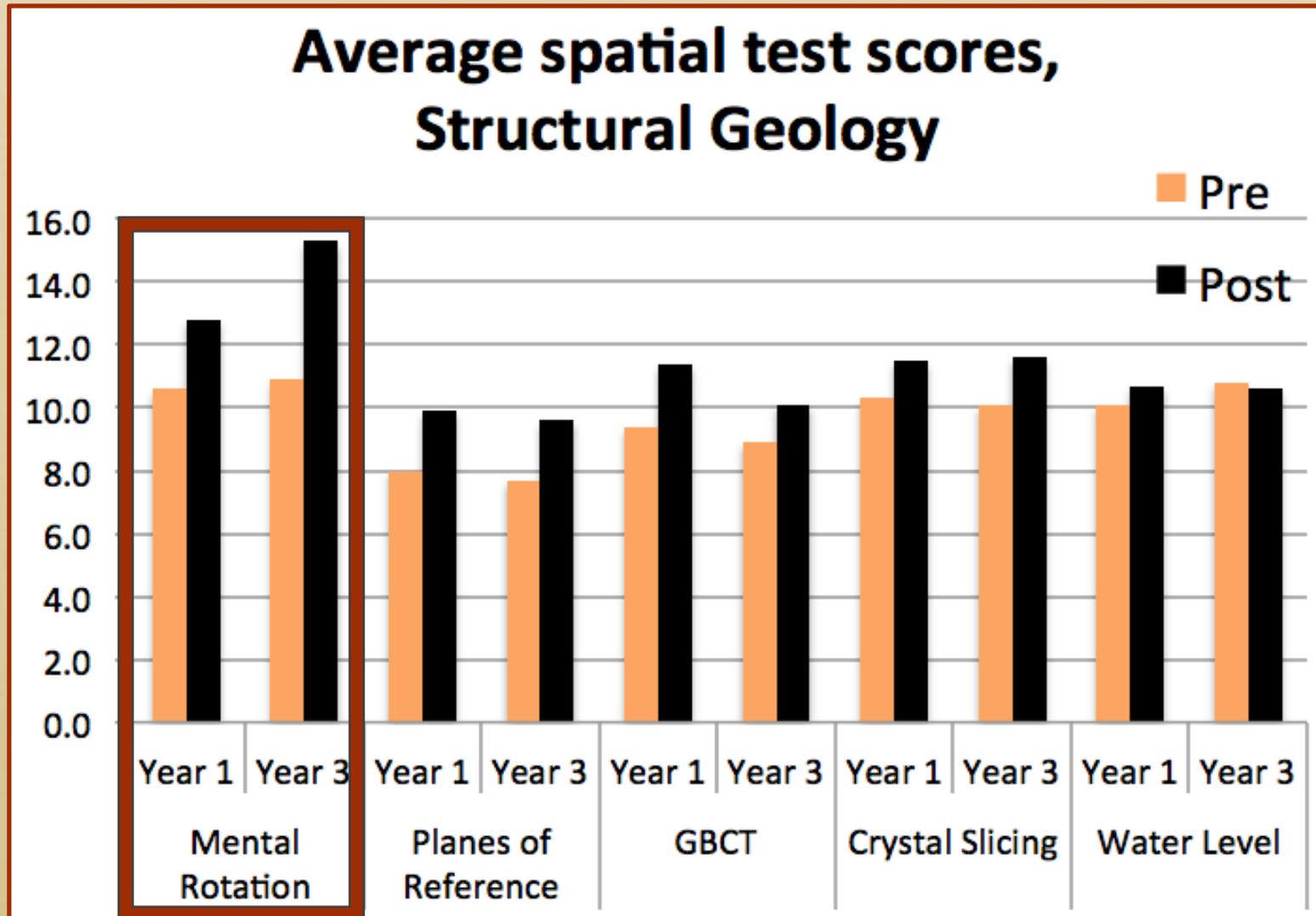
**Geologic block slicing test**



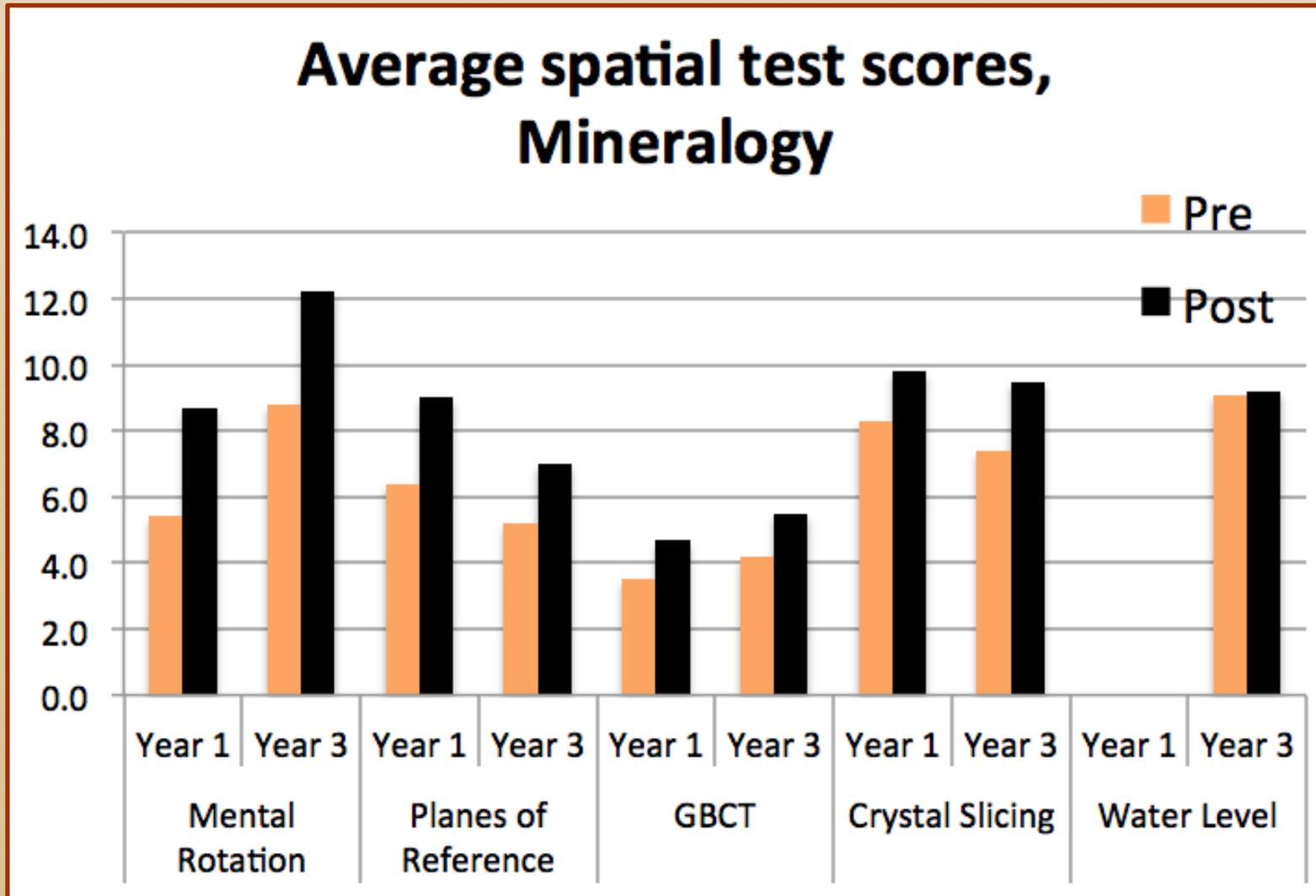
**Water level test**



# Spatial test scores, Structural Geology, baseline vs. implementation

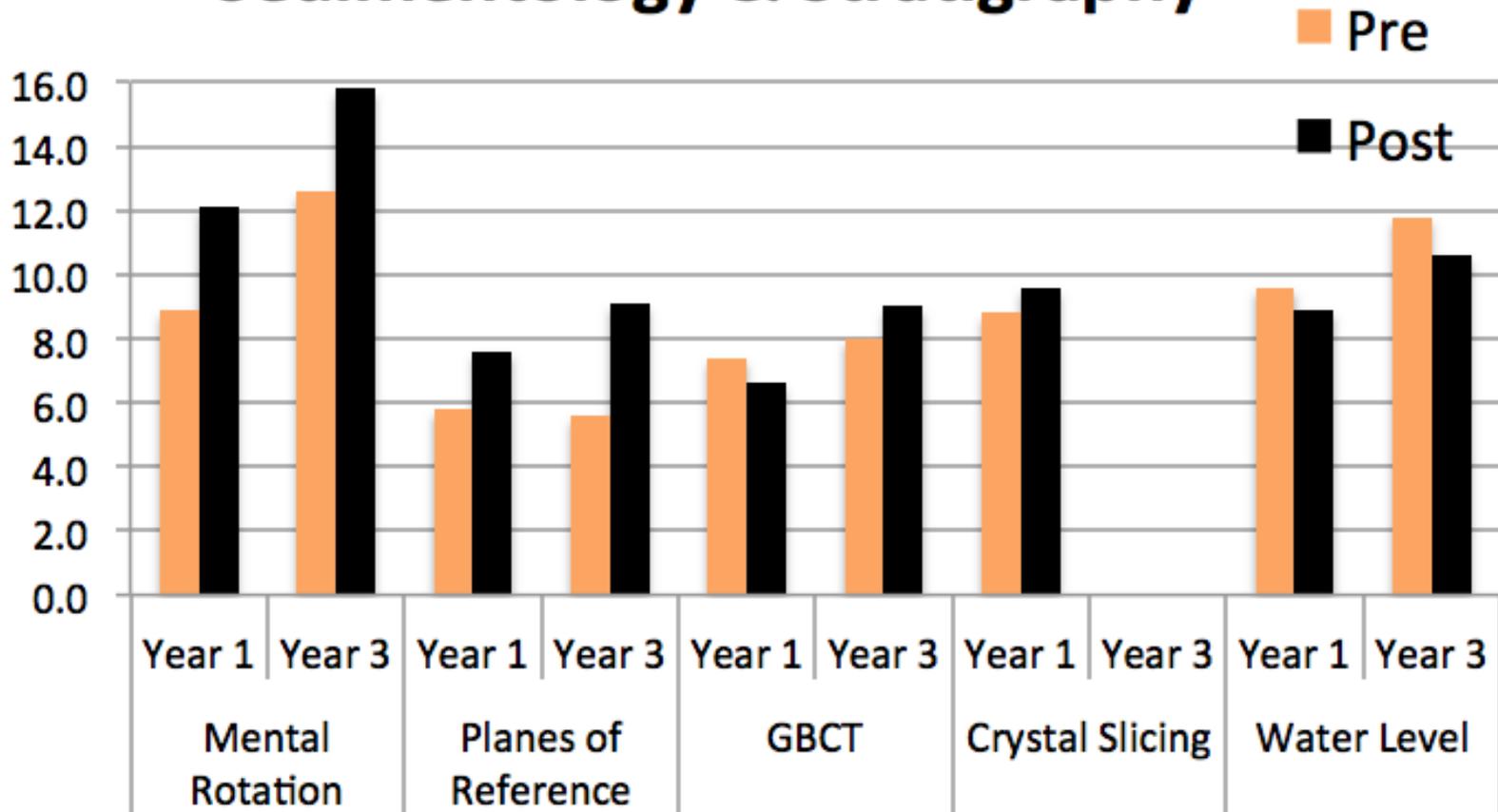


# Spatial test scores, Mineralogy, baseline vs. implementation



# Spatial test scores, Sed/Strat, baseline vs. implementation

## Average spatial test scores, Sedimentology & Stratigraphy



# Our Research Questions

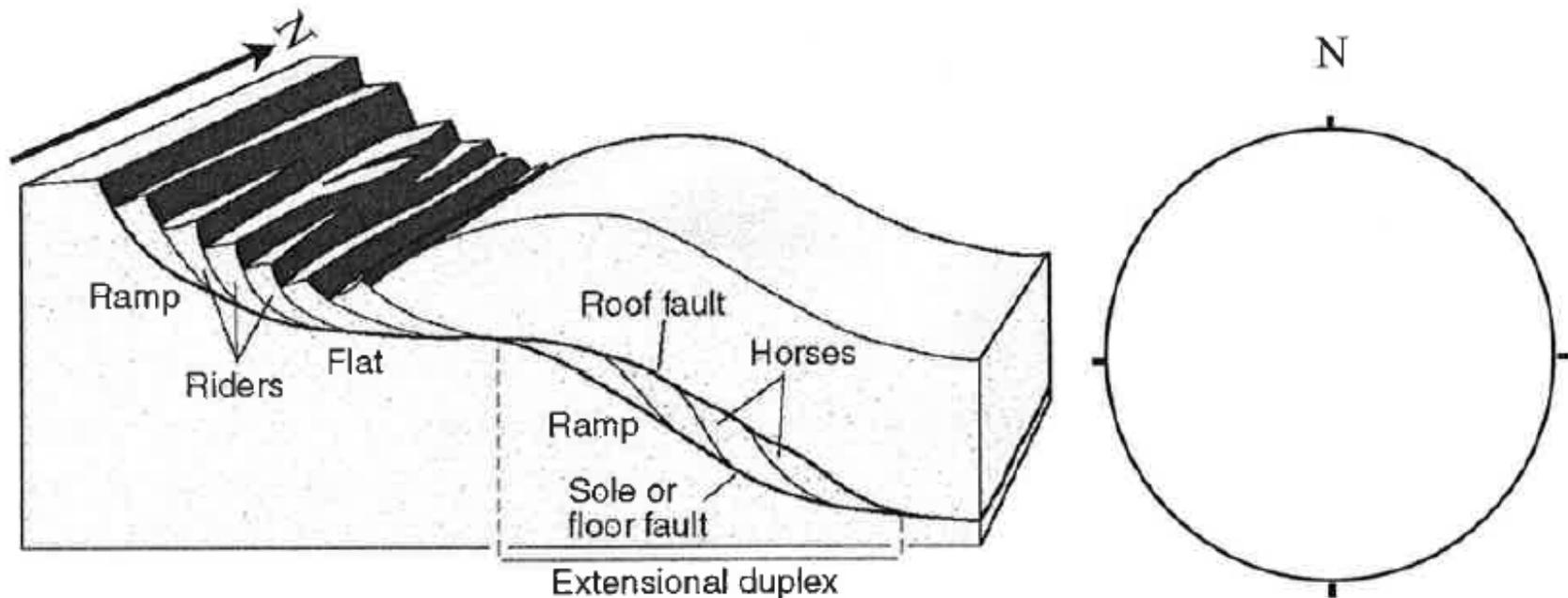
- Can curricular materials informed by cognitive science research boost students' **domain-general** spatial thinking skills (their ability to perform abstract spatial tasks)?
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# Embedded assessments, Structural Geology, UW-Madison

What is it we want students to be able to DO after this course?

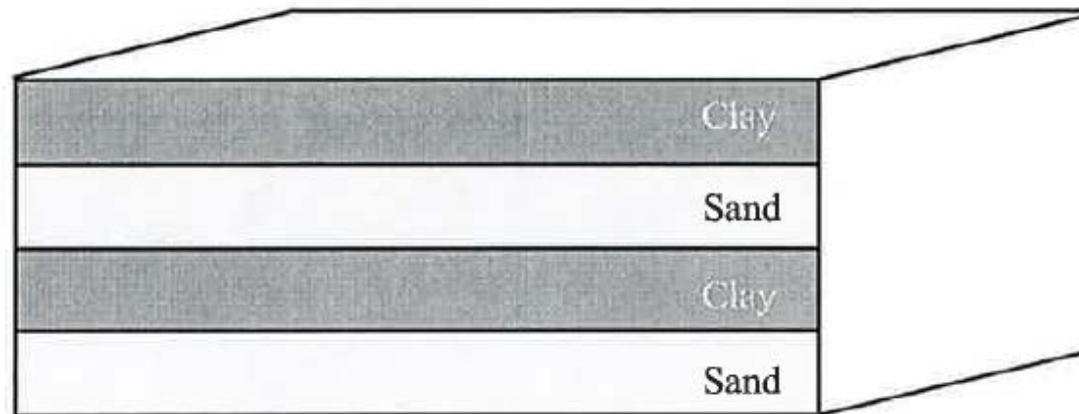
- b.** The fold shown in the block diagram below is a \_\_\_\_\_. (2 pts) Plot the fold hinge (which is a line) on the equal area net to the right. (3 pts). What caused the fold to form? (4 pts)



# Embedded assessments, Structural Geology, UW-Madison

What is it we want students to be able to DO after this course?

**g.** Fill in the blank sides of the block diagram below, and show the expected orientation(s) of a normal fault crosscutting a layered sequence of the sand and clay on which the above analyses were made. *You do not have to show displacement.* (6 pts)

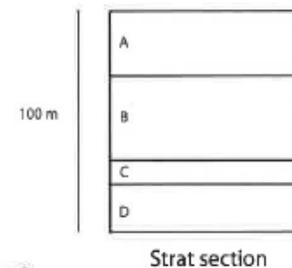
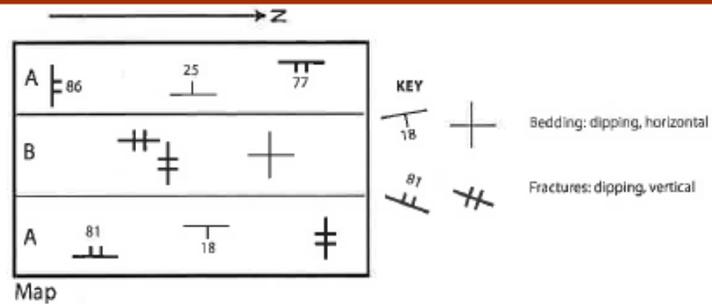


**On the same diagram, show** the expected orientations of all three principal stresses with respect to the normal fault. (6 pts)

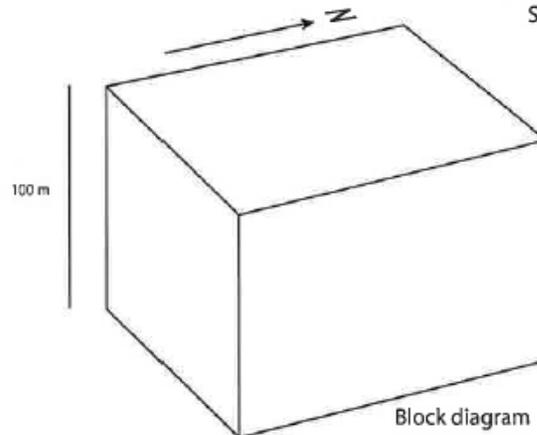
# Embedded assessments, Structural Geology, UW-Madison

What is it we want students to be able to DO after this course?

9. The map to the right shows the orientations of bedding and dominant fractures in the center of an anticline. The stratigraphy of the area is shown at the same scale below. Units A, B, and D are sandstones; unit C is a shale. The interface between A and B is quite strong, such that A and B form a single mechanical unit.



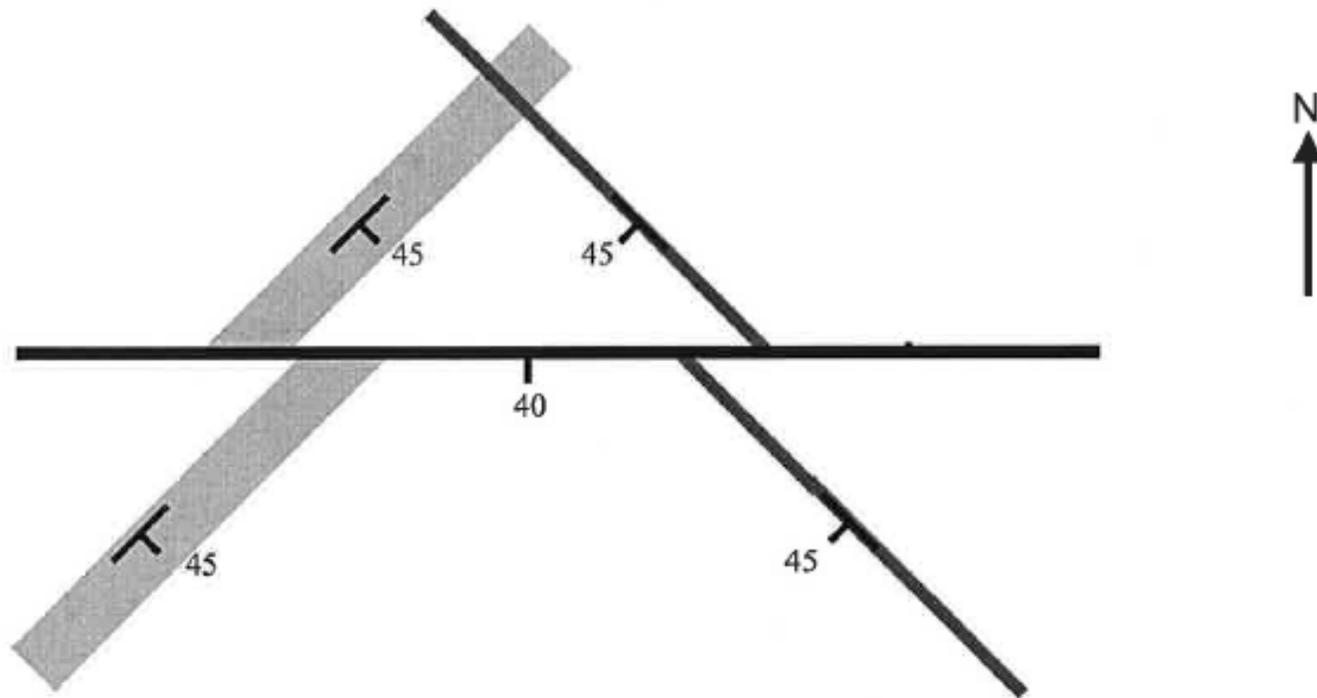
a. Using the stratigraphic column and map data showing bedding orientations, show what the fold looks like in the block diagram to the right. Label stratigraphic units. (6 pts)



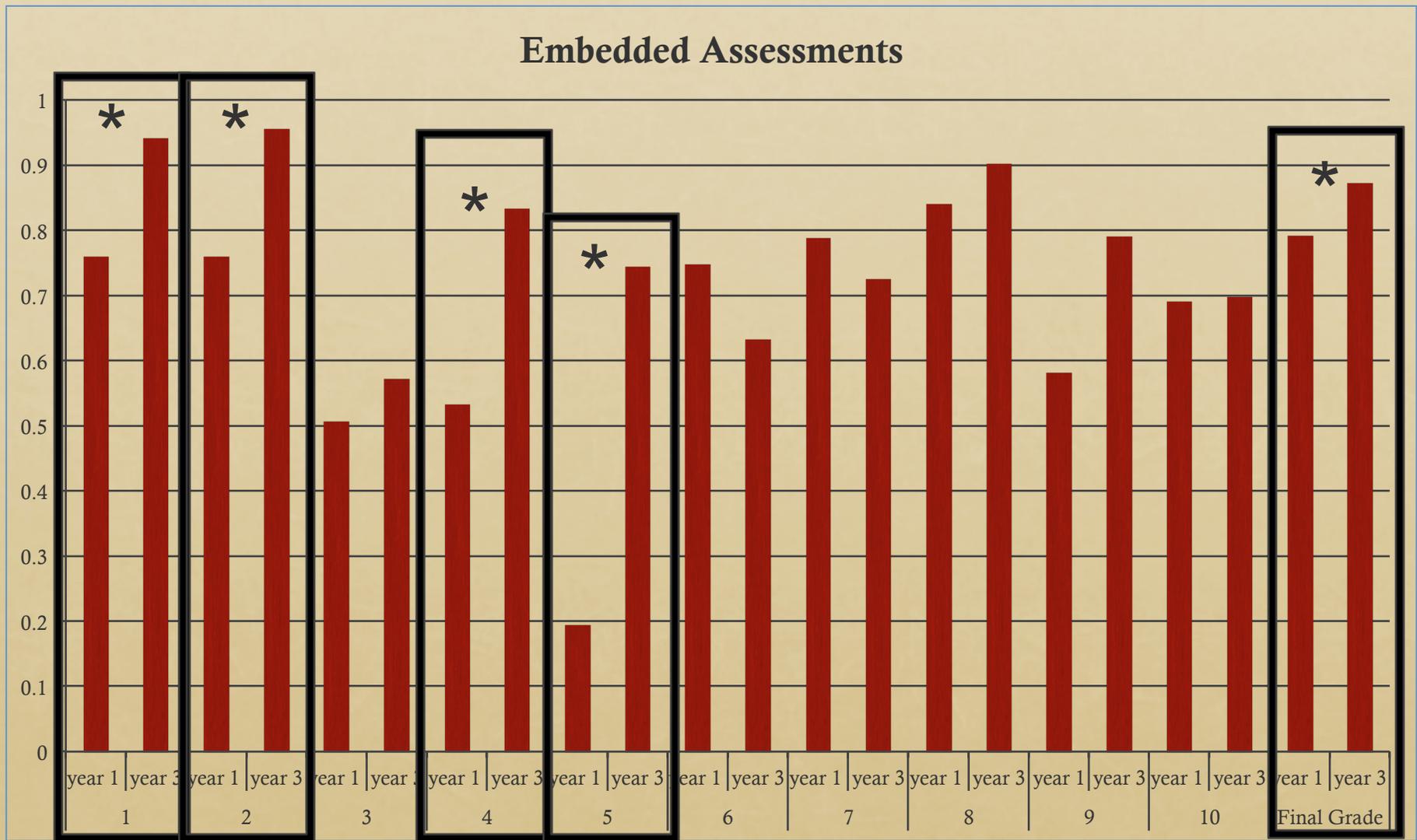
# Embedded assessments, Structural Geology, UW-Madison

What is it we want students to be able to DO after this course?

4. You have just mapped an area in which a fault which strikes 270 and dips 50 N intersects a limestone bed (45, 45 SE) and a dike (135, 45). Your map is shown below.

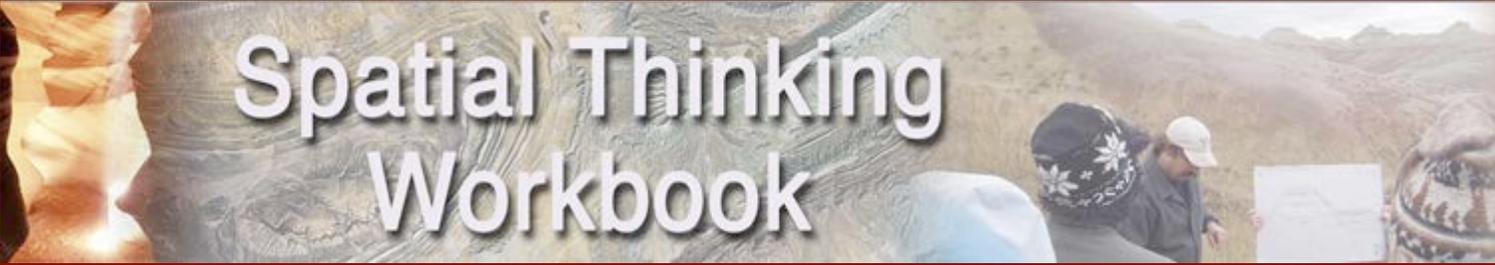


# Embedded assessment scores, UW-Madison Structure, baseline vs. implementation



# Conclusions

- We can boost students' **domain-specific** spatial thinking skills, beyond the gains they would “normally” get from taking geoscience courses. While students' **domain-general** spatial skills also show improvement, these gains are statistically the same as the gains we see in our baseline data.
- Teaching spatial thinking in the context of discipline-based exercises has the potential to transform undergraduate STEM education by removing one significant barrier to success.

A banner image for the Spatial Thinking Workbook. It features a collage of spatial-related images: a golden, textured object on the left, a topographic map in the center, and a group of people in a field looking at a map on the right. The text "Spatial Thinking Workbook" is overlaid in white, bold, sans-serif font.

# Spatial Thinking Workbook



<http://serc.carleton.edu/spatialworkbook/index.html>

# References

Gentner, D., and Markman, A.B. (1994). Structural alignment in comparison: No difference without similarity. *Psychological Science*, v. 5, pp. 152-158.

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National Research Council (2006). Learning to think spatially—GIS as a support system in the K-12 curriculum. Washington DC: National Academies Press. 313 pp.

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