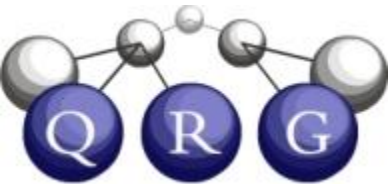# Integrating Sketch Worksheets into GIFT

## Kenneth D. Forbus, Thomas Hinrichs, Samuel Hill, & Madeline Usher

Qualitative Reasoning Group

Northwestern University

# Computer Tutors need Spatial Capabilities

- Intelligent tutoring systems have provided valuable benefits for education
  - Immediate feedback, potentially any time, anywhere
- But rarely in spatially rich subjects (e.g., geology, engineering)
  - How to create human-like visual processing is a hard scientific question
  - Need to model the spatial & conceptual reasoning involved
- Sketch understanding software is changing this
- Time is right to explore more ways to build sketch-based intelligent tutoring systems

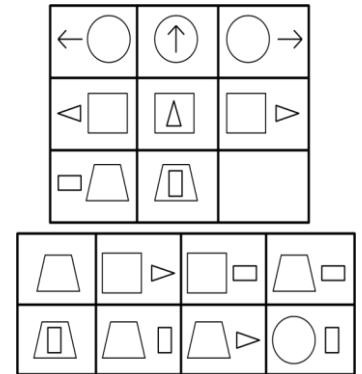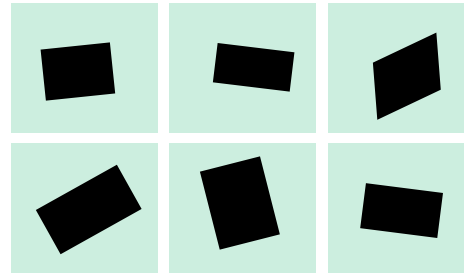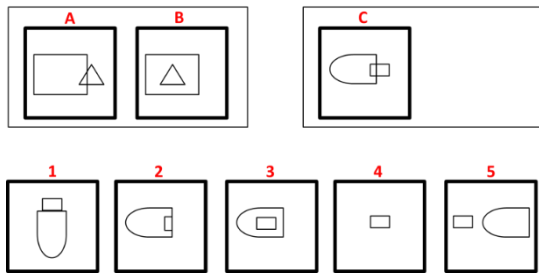Ultimate goal: Software that understands sketches as you would
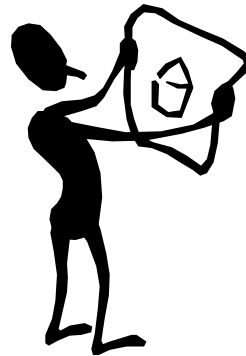
Overview

- Motivation ✓
- CogSketch
- Sketch Worksheets
- Integration into GIFT
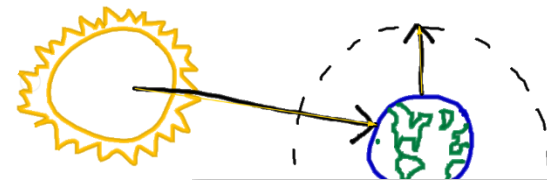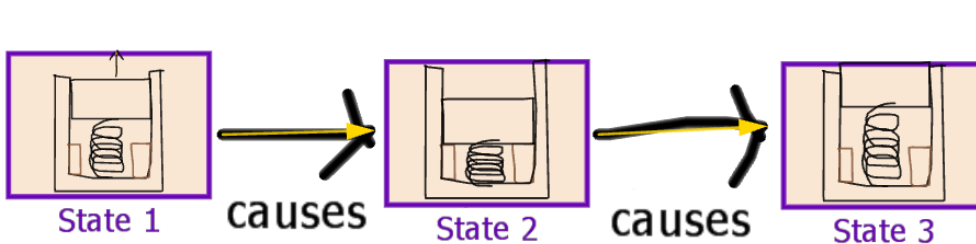- Testbed: Simple Machines Tutor
- Future Work
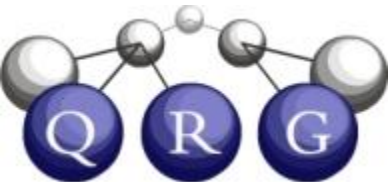
CogSketch

- Cognitive Science Research Instrument
 - Models aspects of human visual and spatial representations and processing

- A platform for new kinds of educational software

State 1   causes   State 2   causes   State 3

Sketch Worksheets

Tutor Suggestions

Suggestions for Sketch greenhouse-effect

- From what you've drawn, I can't see how the atmosphere helps warm the planet. Do the greenhouse gases in the atmosphere emit radiation? What kind of radiation? Is this radiation lost to the system or does the planet absorb it?

QRG
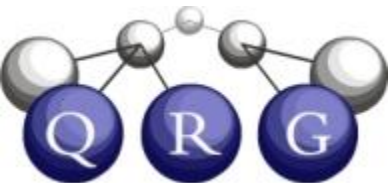
Sketch Understanding >> Recognition

- Some educational systems use recognition
  - Each system works only in one small part of a single domain
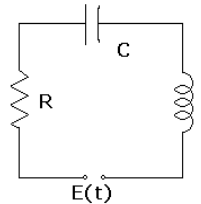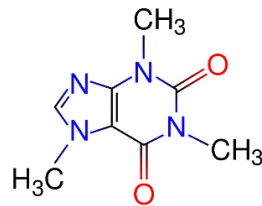
  Cooper et al. 2009; DeSilva et al 2007;Lee et al. 2007; Valentine et al. 2012

- Most STEM domains involve more than visual symbols
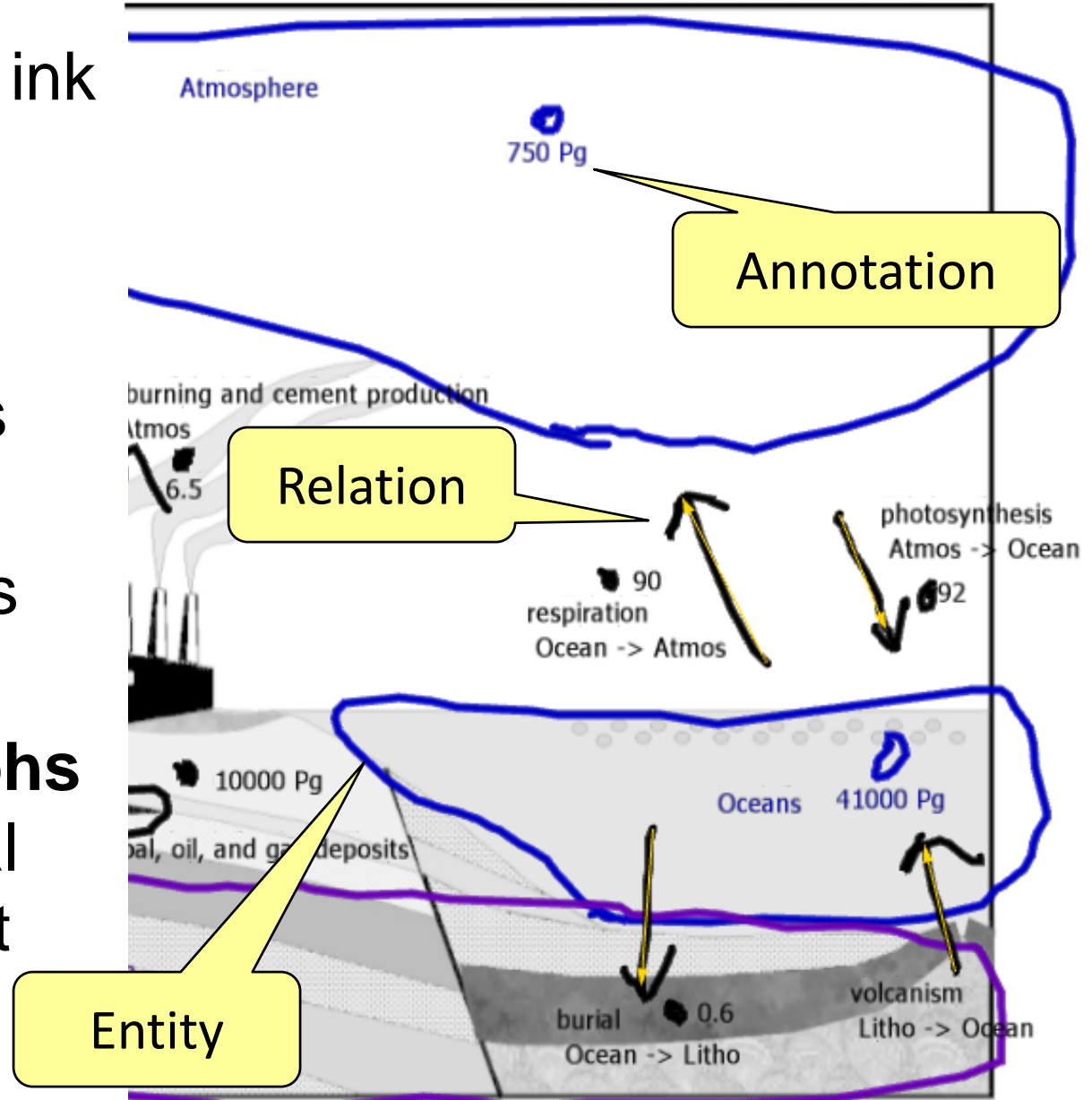
- Concept/Depiction mapping is many:many

Our Approach: Open-domain Sketch Understanding

- Observation: People typically talk when they are sketching
  - They verbally identify what they are drawing
  - Recognition is a catalyst, not a necessity
- In open-domain sketch understanding
  - You draw *glyphs* to depict things
  - They can be anything CogSketch has a concept for
  - You tell CogSketch what they mean by labeling them
- CogSketch models aspects of human visual and spatial representations and reasoning
 - Goal: It sees our sketches as we see them

Kinds of Glyphs

- **Glyphs** combine ink with what it represents
- **Entity glyphs** represent objects
- **Relation glyphs** describe relations between objects
- **Annotation glyphs** provide additional information about other glyphs

Atmosphere

750 Pg

Annotation

burning and cement production
Atmos

6.5

Relation

photosynthesis
Atmos -> Ocean

90
respiration
Ocean -> Atmos

92

10000 Pg

Oceans   41000 Pg

al, oil, and gas deposits

Entity

burial   0.6
Ocean -> Litho

volcanism
Litho -> Ocean

Sketch Worksheets

- Sketching is a valuable way of learning spatial relationships.

- Feedback on pencil and paper worksheets is delayed.

- CogSketch provides on-the-spot feedback

- Sketch Worksheets can be built by instructors
 - Facilitates translation, dissemination
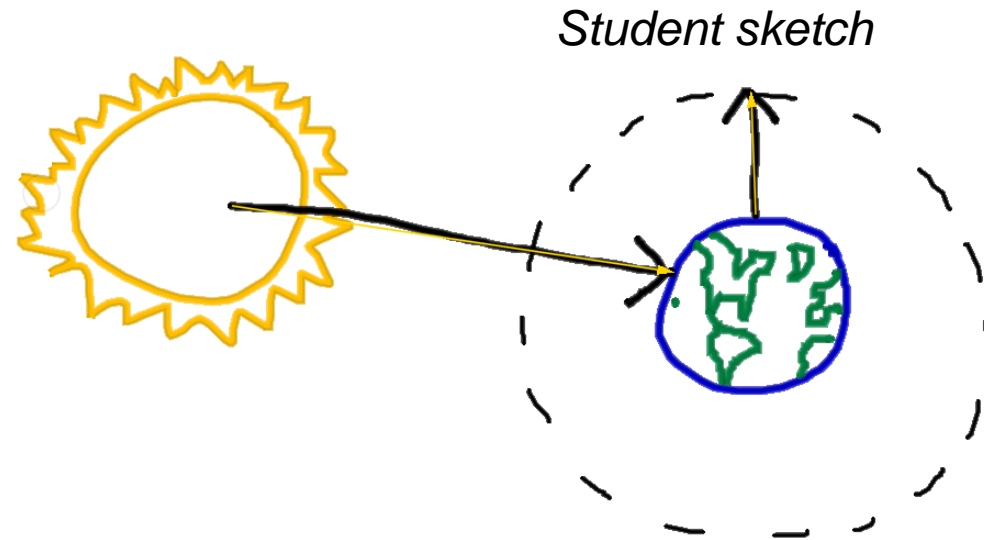
Student sketch

Tutor Suggestions

Suggestions for Sketch greenhouse-effect

• From what you've drawn, I can't see how the atmosphere helps warm the planet. Do the greenhouse gases in the atmosphere emit radiation? What kind of radiation? Is this radiation lost to the system or does the planet absorb it?

Sketch Worksheets: What's Inside?

Feedback

Assessment data
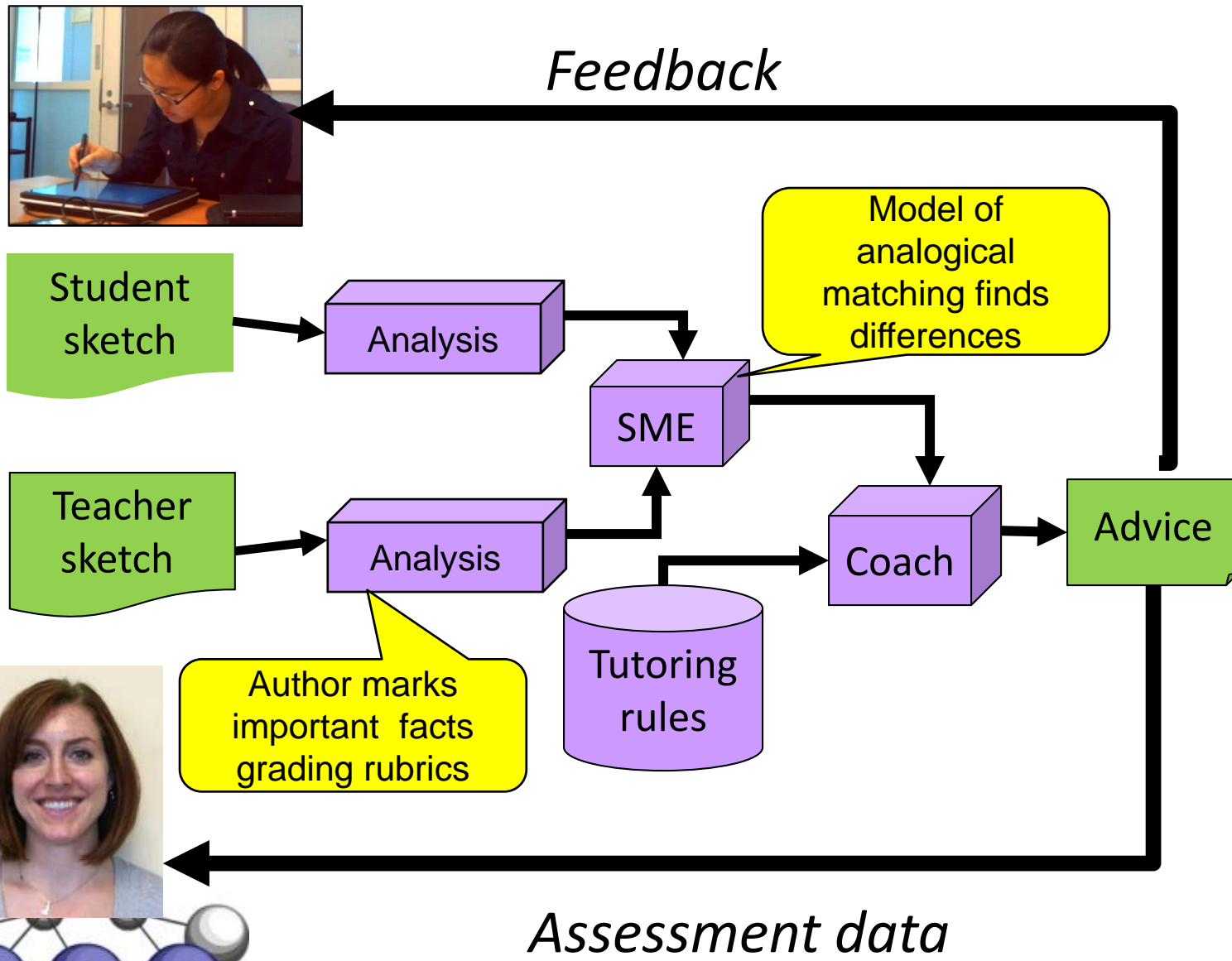
Coaching via Analogy

- Instructor and student sketches are compared via the Structure-Mapping Engine (SME)
- Candidate inferences provide differences
- Advice is tied to differences

Analogical Matching Provides Flexible Authoring & Interpretation

- Facts not marked as important can vary
  - Irrelevant spatial aspects are ignored in coaching
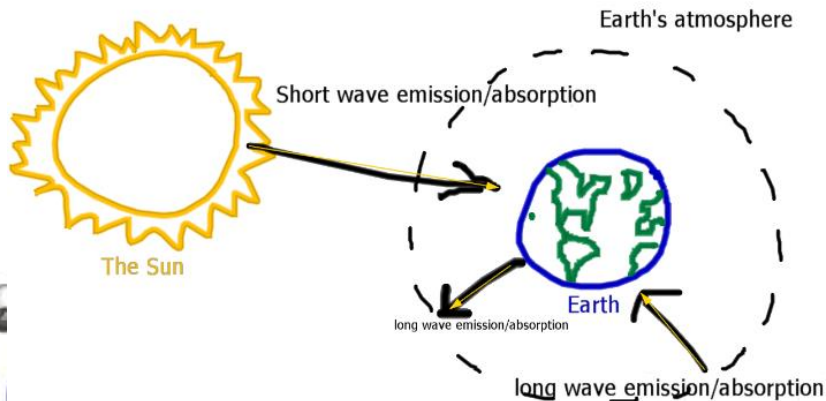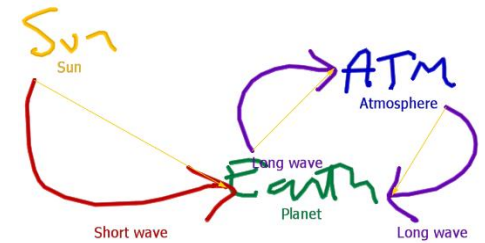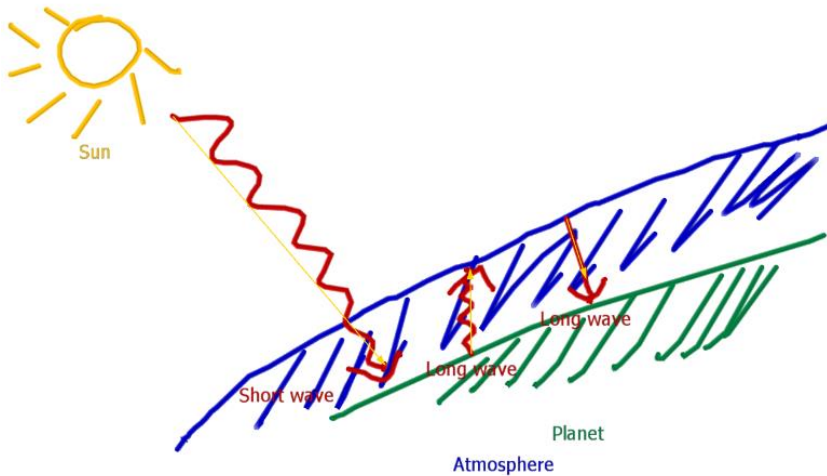
Three Correct Solutions to the Greenhouse Effect Worksheet
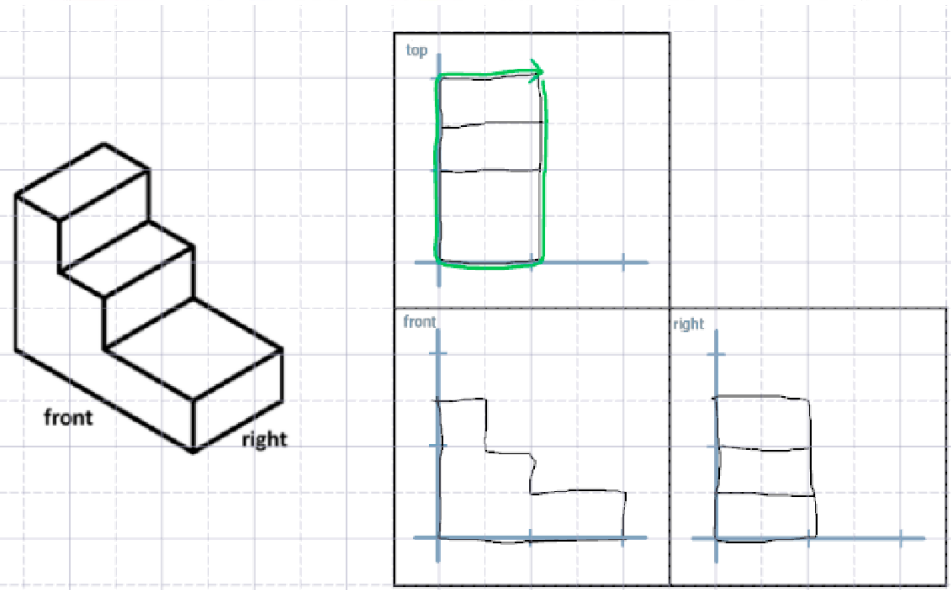
Quantitative Ink Constraints

- Author draws desired outline

- Indicates error tolerances

- Advice can be based on directions as well as non-overlap
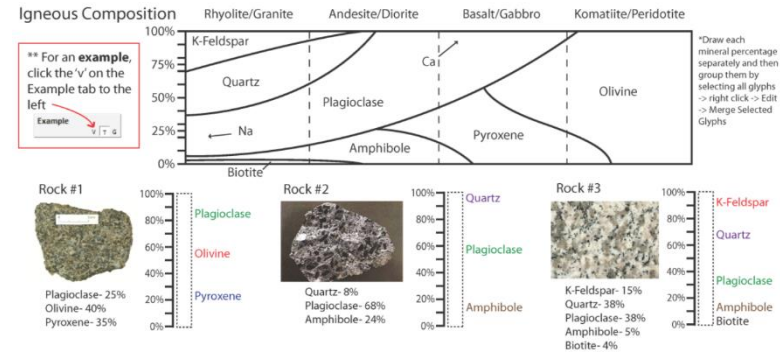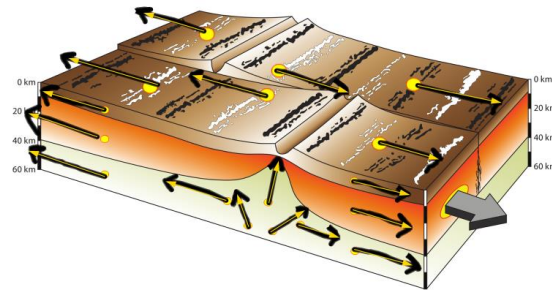
Overall Sketch

- You haven't drawn any glyphs on the construction lines layer yet.

- The top view should be wider than it is tall. You probably have it rotated 90 degrees from its correct position.
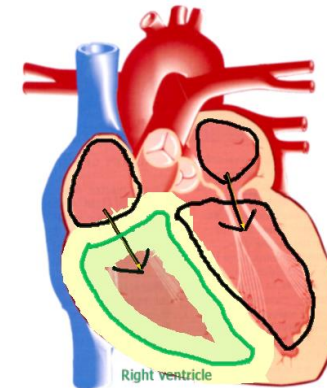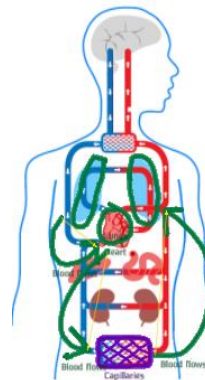
Sketch Worksheet Experiments
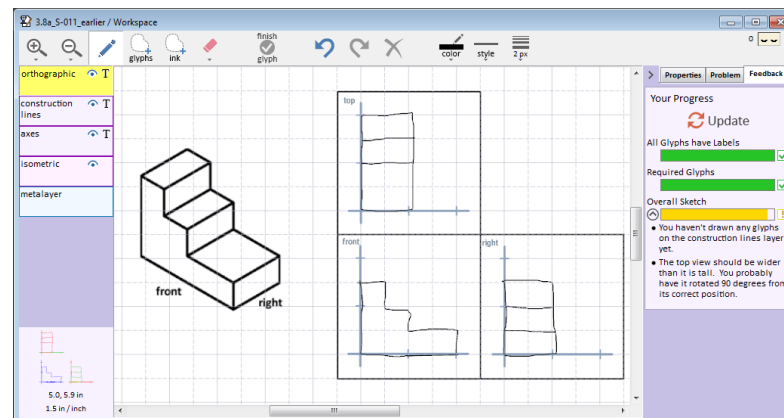
- **Geoscience**
  - NU
  - Carleton
  - Madison
  - https://serc.carleton.edu/

- **Biology**
  - UCLA (lab)
  - Temple
    - 5th grade classroom

- **Engineering**
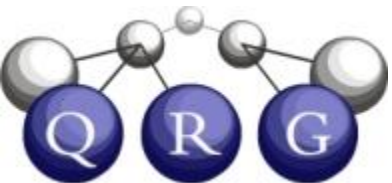 - NU DTC

Deployments

Geoscience

- 26 Worksheets, covering an entire introductory course
  - Authored by a geoscience graduate student
- Grading efficiency
  - Paper: ~1.5 min/W
  - CogSketch: ~0.11 min/W

See Forbus et al. 2018, IAAI

Knowledge Representation

- Four worksheets
  - Authored by Forbus
- Grading efficiency
  - ~0.34 min/W
- Feedback effectiveness
  - Mean # Requests: 40
  - 78% got perfect scores
 - w/o feedback, similar complexity: 38%

GIFT Integration

- Treat Sketch Worksheets as a new media type
  - Goal: Anyone can use Sketch Worksheets for their GIFT-based tutors
    - Non-commercial: Need Franz license to commercialize

- Use LTI as connection medium
  - Provide feedback number based on # rubrics completed
  - Also provide side-channel access to more detailed data gathered by CogSketch

- Docker swarm
  - Currently hosted on NU server
 - Will port to AWS so groups can run their own
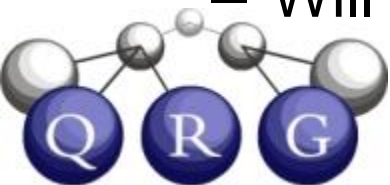
System Architecture
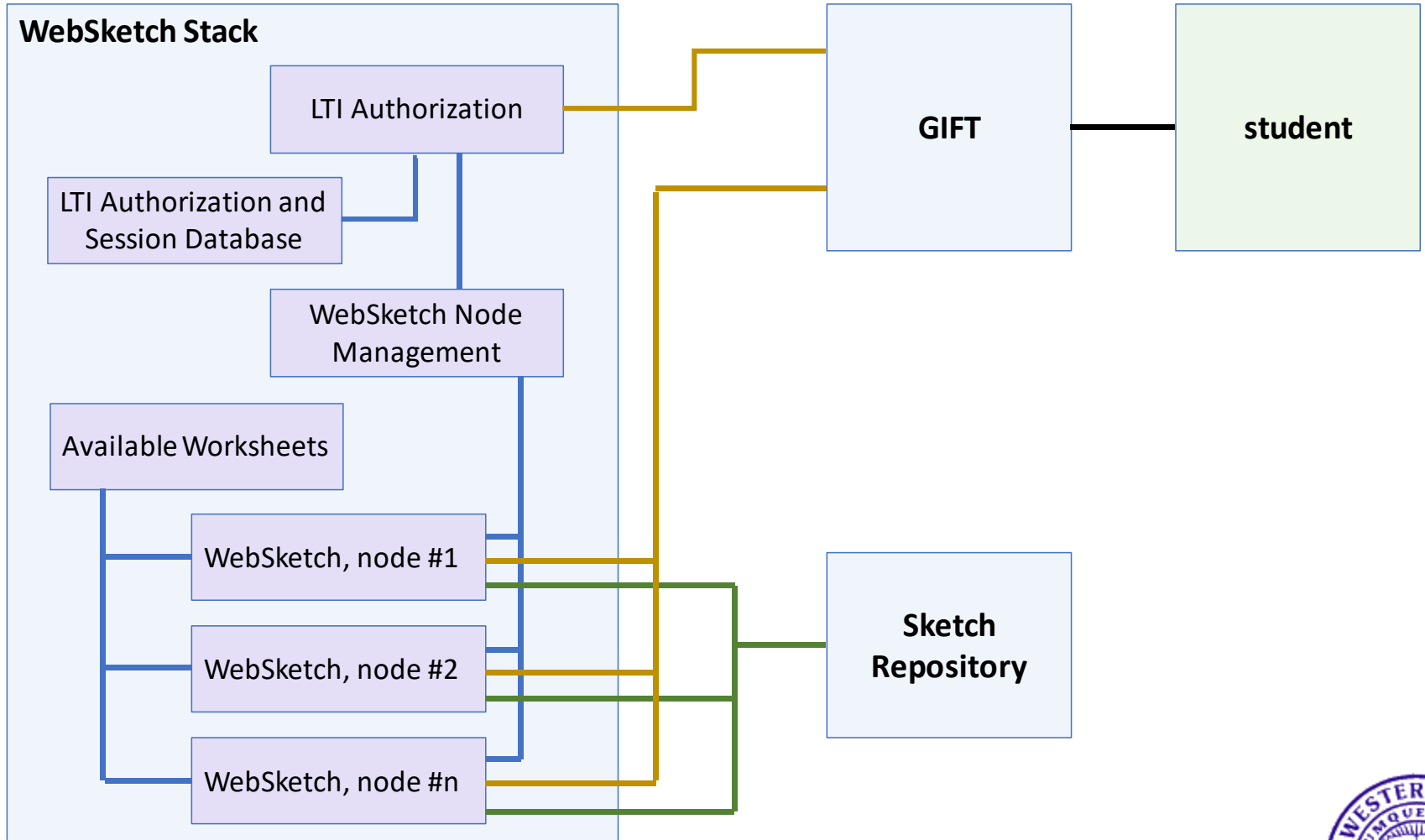
Simple Machines Tutor

- ## Testbed for experimentation
  - Relevant to STEM education, military training

- ## Learning goals
  - Understand the kinematics and force dynamics of simple machines
  - Recognize components and relationships relevant to their operation
  - Recognize simple machines in the everyday world
  - Understand tradeoffs between force, distance, and work
  - Understand how mechanisms will behave, both qualitatively and quantitatively
  - Understand space of alternate designs to achieve a given effect
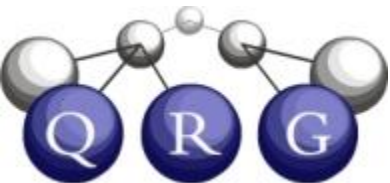
Example: Levers

Task: Identify the parts of each lever by circling and labeling them. Identify what type of lever it is as well.

Tutor Development Progress

- Initially focused on levers
  - Multiple sketch worksheets, authored in CogSketch
  - Explanatory material authored in GIFT

- Pre/post test questions
  - Built bank of > 90 questions
  - Selected 20 for pretest, 20 for posttest, balanced for contents and difficulty
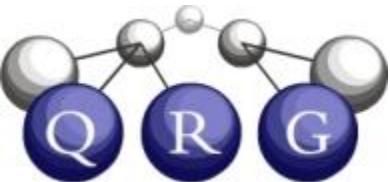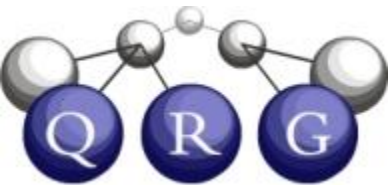
First-Class Lever

# Second Class Lever Worksheet
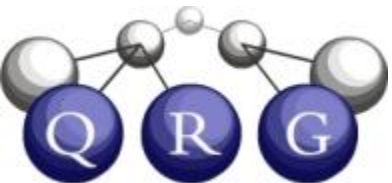
Future Work

- Start user testing with Simple Machines Tutor
  - Incrementally build out content to cover whole curriculum
- Start field-testing
  - GIFT cloud, NU server
- Run experiment (predictions in italics)

	No Sketching	Sketching
Non-Adaptive	*Least learning*	*In between*
Adaptive	*In between*	*Most learning*

- Start design work on Companion/GIFT integration

Details
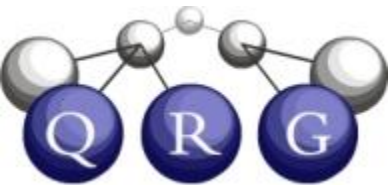
Sketch Worksheets in a Knowledge Representation class
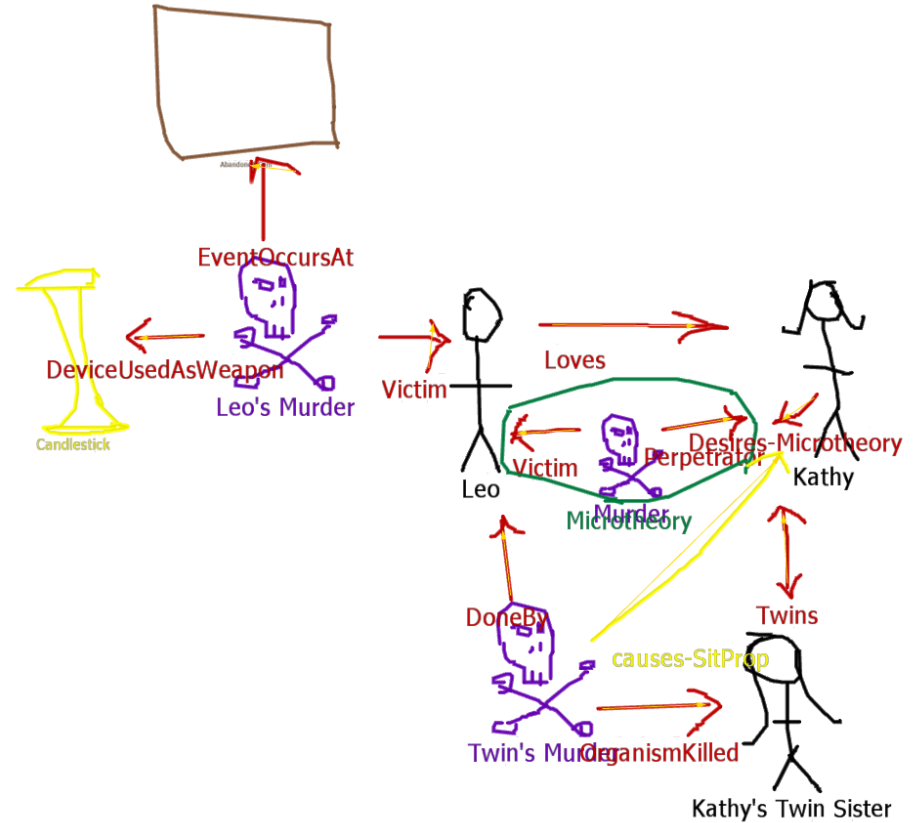
Students used feedback heavily: ~40 requests/student on soap opera worksheet
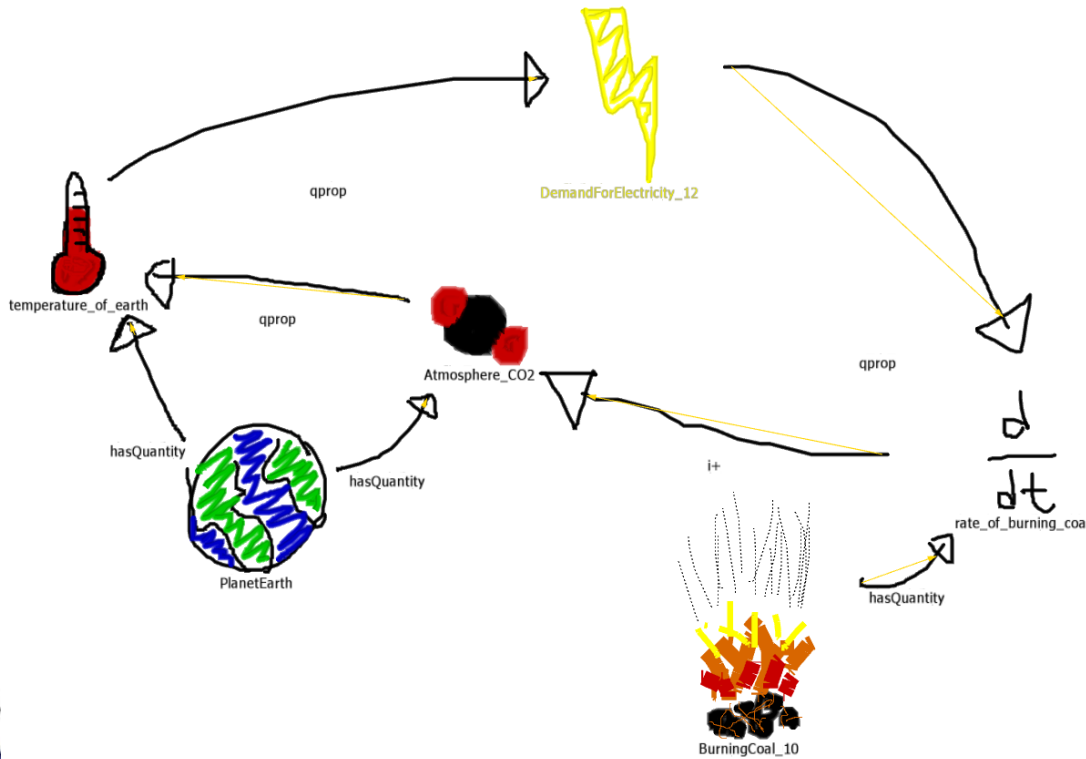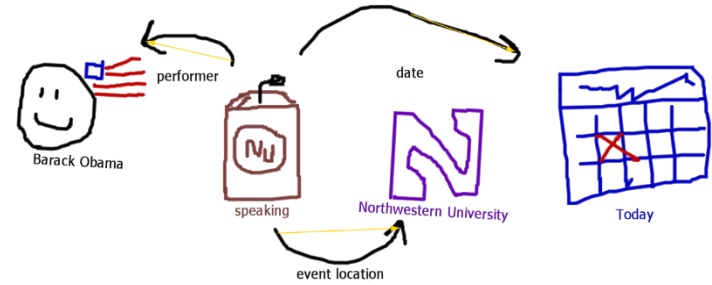*Feedback helped: 78% of students got a perfect score*
*No feedback on a similarly complex worksheet: Only 38% got a perfect score*

Sketch Worksheets in Introduction to Cognitive Modeling

"Barack Obama gave a speech at Northwestern today"

The Earth's temperature depends on the amount of CO_2 in the atmosphere.
Burning coal increases the amount of carbon in the atmosphere.
As the Earth's temperature rises, the amount of electricity people need rises.
The rate at which coal is burned depends on the demand for electricity.
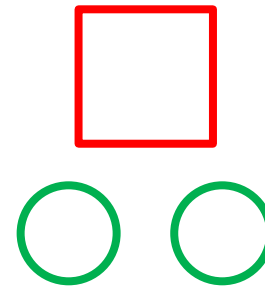
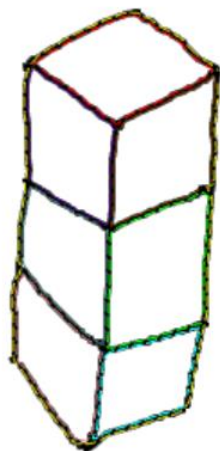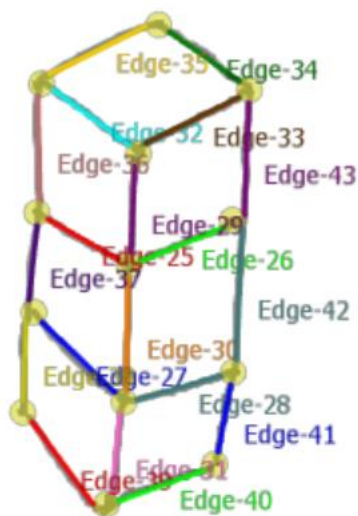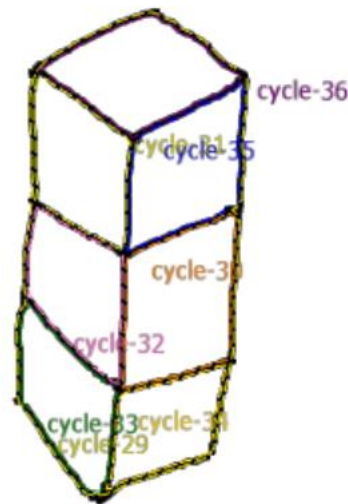# CogSketch uses Hierarchical Representations
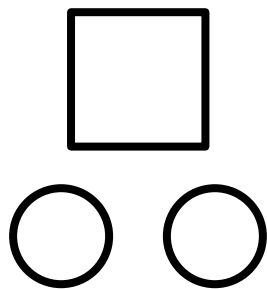
Original
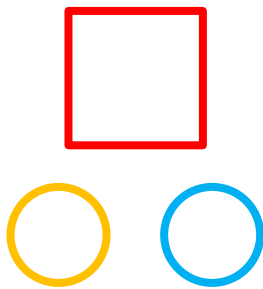
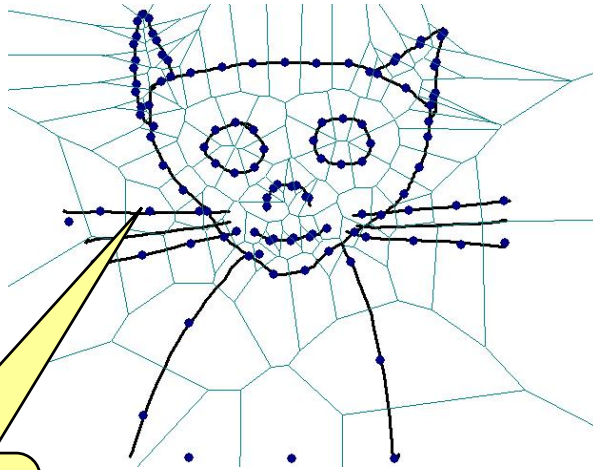Object level

Group Level

Original
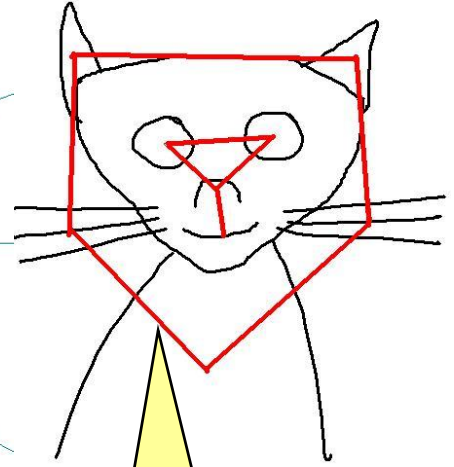
Edge Level

Edge Cycles

Edge Cycle Objects

(Marr & Nishihara, 1978; Palmer, 1977; Hochstein & Ahissar, 2002)

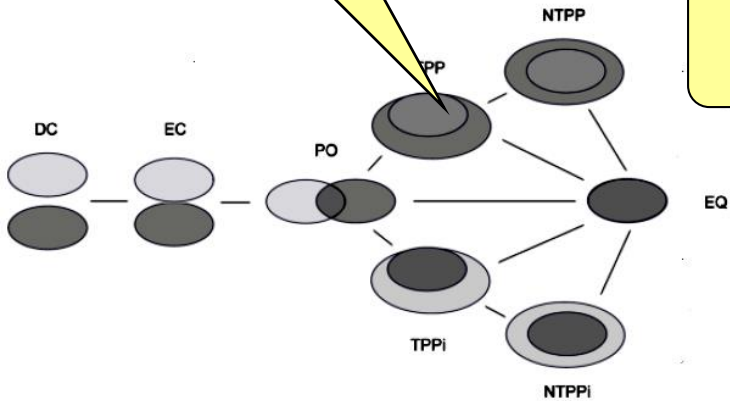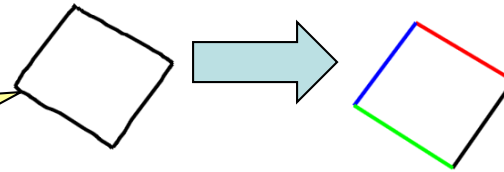# Additional CogSketch Spatial Computations

Grouping

Voronoi diagrams

Positional relations
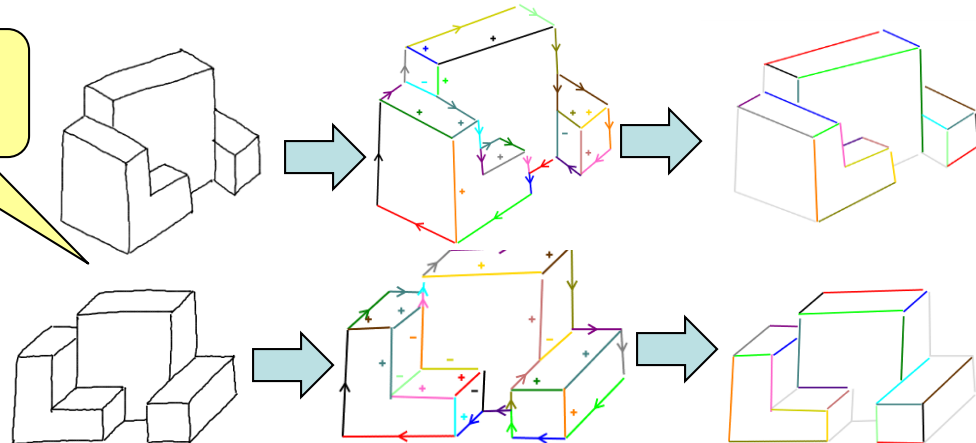
Qualitative Topology

Shape decomposition

Mental Rotation

DC EC PO TPP NTPP EQ TPPi NTPPi
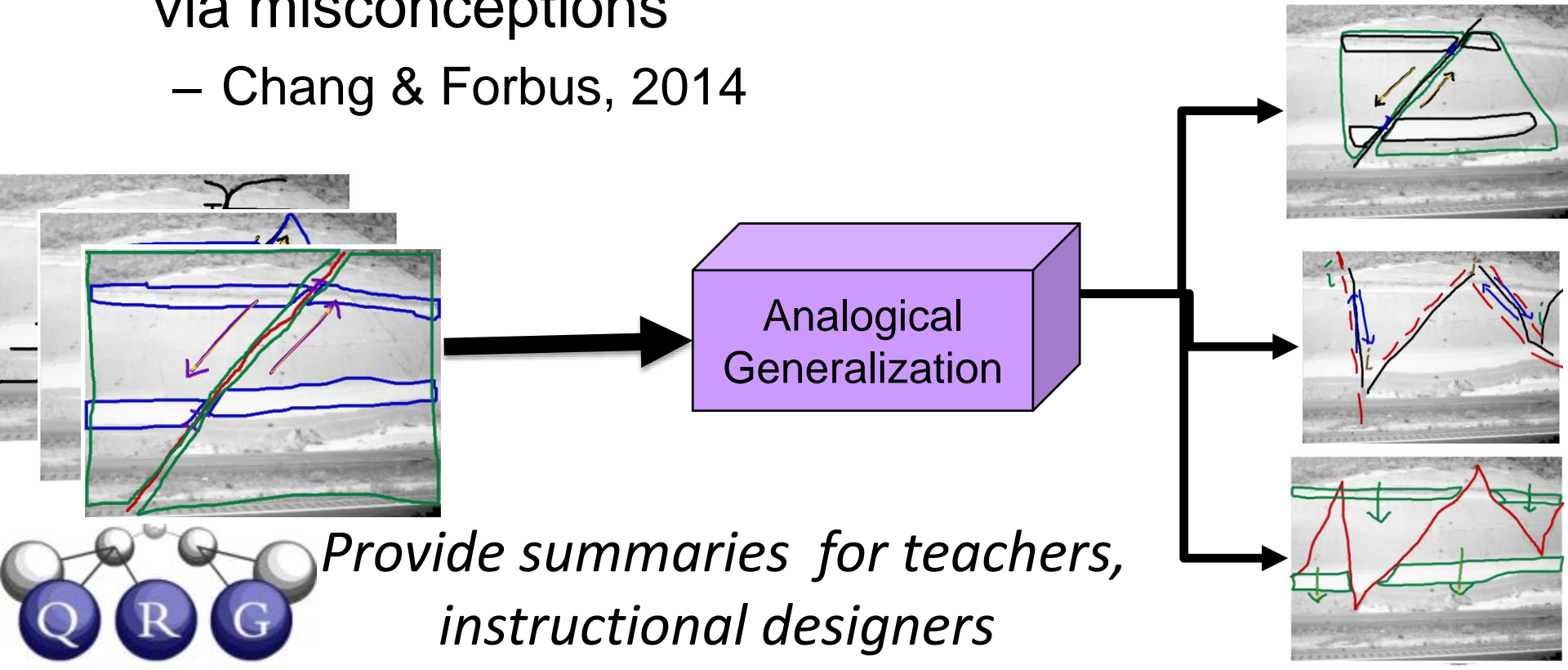
Sketching As Assessment

- Even copying sketches can help measure expertise
  - Jee et.al. 2014

- Idea: Use analogical learning to cluster sketches via misconceptions
  - Chang & Forbus, 2014

Analogical Generalization

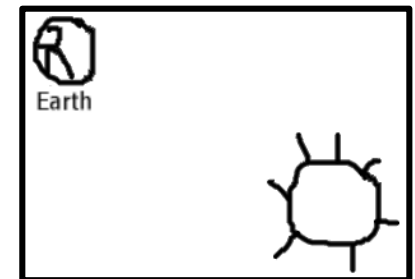*Provide summaries for teachers, instructional designers*

Other Analysis Tools

- Timing data
  - View glyph ordering
  - View ink stroke ordering
  - Sketch playback
- History data
  - Detailed history and ink data exported to comma separated values (*.csv) format
  - HTML reports detailing user actions with screenshots

Useful assessment data (Miller et al. 2014)
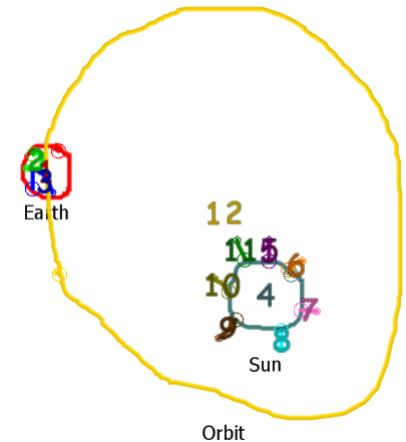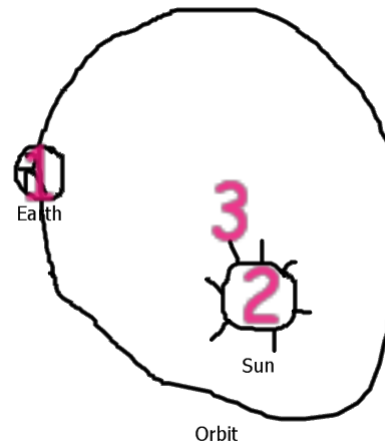
- 48) Created glyph #7820 ("Sun")
  - Start:
    - clock time: 2014-08-22 15:43:03.174
    - sketch timestamp (seconds): 2178.186
  - Finish:
    - clock time: 2014-08-22 15:43:19.092
    - sketch timestamp (seconds): 2194.104
  - Elapsed time (seconds): 15.918
  - user / source: George Washington

- 49) Changed conceptual labels for glyph #7820 ("Sun")
  - clock time: 2014-08-22 15:43:20.729
  - sketch timestamp (seconds): 2195.741
  - user / source: George Washington
  - Removed: Entity
  - Added: Sun
  - All conceptual labels assigned at this time: Sun