Cognitive Principles in Tutor & e-Learning Design

Ken Koedinger
Human-Computer Interaction & Psychology
Carnegie Mellon University

CMU Director of the Pittsburgh Science of Learning Center

Lots of Lists of Principles

- Cognitive Tutor Principles
- Multimedia & eLearning Principles
- How People Learn Principles
- Progressive Abstraction or "Bridging" Principles
- Other lists on the web ...
  - See learnlab.org/research/wiki

Overview

- Cognitive Tutor Principles
- Multimedia Principles
  - Theoretical & Experimental evidence
- Building on prior knowledge
  - Need empirical methods to apply
- Summary

Principles on web: See learnlab.org/research/wiki
Cognitive Tutor Principles

1. Represent student competence as a production set
2. Provide instruction in the problem-solving context
3. Communicate the goal structure underlying the problem solving
4. Promote an abstract understanding of the problem-solving knowledge
5. Minimize working memory load
6. Provide immediate feedback on errors

6. Provide immediate feedback on errors

- Productions are learned from the examples that are the product of problem solving
- Benefits:
  - Cuts down time students spend in error states
  - Eases interpretation of student problem solving steps
- Evidence: LISP Tutor
- *Smart* delayed feedback can be helpful
  - Excel Tutor

1. Represent student competence as a production set

- Accurate model of target skill to:
  - Inform design of
    - Curriculum scope & sequence, interface, error feedback & hints, problem selection & promotion
  - Interpret student actions in tutor

- Knowledge decomposition!
  - Identify the components of learning

Feedback Studies in LISP Tutor (Corbett & Anderson, 1991)
Tutoring Self-Correction of Errors

- Recast delayed vs. immediate feedback debate as contrasting "model of desired performance"

- Expert Model
  - Goal: students should not make errors

- Intelligent Novice Model
  - Goal: students can make some errors, but recognize them & take action to self-correct

- Both provide immediate feedback
  - Relative to different models of desired performance

---

Intelligent Novice Condition Learns More

**Coding**

<table>
<thead>
<tr>
<th></th>
<th>Expert Tutor</th>
<th>Intelligent Novice Tutor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concepts</td>
<td>85%</td>
<td>76%</td>
</tr>
</tbody>
</table>

**Concepts**

<table>
<thead>
<tr>
<th></th>
<th>Expert Tutor</th>
<th>Intelligent Novice Tutor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coding</td>
<td>67%</td>
<td>73%</td>
</tr>
</tbody>
</table>

**Retention**

<table>
<thead>
<tr>
<th></th>
<th>Expert Tutor</th>
<th>Intelligent Novice Tutor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concepts</td>
<td>81%</td>
<td>73%</td>
</tr>
</tbody>
</table>

**Transfer**

<table>
<thead>
<tr>
<th></th>
<th>Expert Tutor</th>
<th>Intelligent Novice Tutor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concepts</td>
<td>74%</td>
<td>60%</td>
</tr>
</tbody>
</table>

---

Learning Curves: Difference Between Conditions Emerges Early

- Number of attempts at a step by opportunities to apply a production rule

---

Overview

- Cognitive Tutor Principles
- Multimedia Principles
  - Theoretical & Experimental evidence
- Instructional Bridging Principles
  - Need empirical methods to apply
- PSLC Principles
Media Element Principles of E-Learning

1. Multimedia
2. Contiguity
3. Coherence
4. Modality
5. Redundancy
6. Personalization

Cognitive Processing of Instructional Materials

- Instructional material is:
  - Processed by our eyes or ears
  - Stored in corresponding working memory (WM)
- Must be integrated to develop an understanding
- Stored in long term memory

Multimedia Principle

Which is better for student learning?
A. Learning from words and pictures
B. Learning from words alone
   Example: Description of how lightning works with or without a graphic
A. Words & pictures
   Why?
Students can mentally build both a verbal & pictorial model & then make connections between them

Coherence Principle

Which is better for student learning?
A. When extraneous, entertaining material is included
B. When extraneous, entertaining material is excluded
   Example: Including a picture of an airplane being struck by lightning
B. Excluded
   Why?
Extraneous material competes for cognitive resources in working memory and diverts attention from the important material
Modality Principle

Which is better for student learning?
A. Spoken narration & animation
B. On-screen text & animation
Example: Verbal description of lightning process is presented either in audio or text
A. Spoken narration & animation
Why?
Presenting text & animation at the same time can overload visual working memory & leaves auditory working memory unused.

Summary of Media Element Principles of E-Learning
1. Multimedia: Present both words & pictures
2. Contiguity: Present words within picture near relevant objects
3. Coherence: Exclude extraneous material
4. Modality: Use spoken narration rather than written text along with pictures
5. Redundancy: Do not include text & spoken narration along with pictures
6. Personalization: Use a conversational rather than a formal style of instruction

Scientific Evidence (mostly lab) that Principles Work

<table>
<thead>
<tr>
<th>Principle</th>
<th>Percent Gain</th>
<th>Effect Size</th>
<th>Number of Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multimedia</td>
<td>89</td>
<td>1.50</td>
<td>9 of 9</td>
</tr>
<tr>
<td>Contiguity</td>
<td>68</td>
<td>1.20</td>
<td>5 of 5</td>
</tr>
<tr>
<td>Coherence</td>
<td>82</td>
<td>1.17</td>
<td>10 of 11</td>
</tr>
<tr>
<td>Modality</td>
<td>80</td>
<td>1.17</td>
<td>4 of 4</td>
</tr>
<tr>
<td>Redundancy</td>
<td>79</td>
<td>1.24</td>
<td>2 of 2</td>
</tr>
<tr>
<td>Personalization</td>
<td>67</td>
<td>1.24</td>
<td>5 of 5</td>
</tr>
</tbody>
</table>
Applying principles depends on a quality domain analysis

- Example: See Davenport pages on PSLC wiki
- Three studies indicate dependency
  - Applied multimedia principle in College Chemistry course -- added diagrams to existing text
    - No impact on learning!
  - Did cognitive task analysis of domain & redesigned course materials
    - Big impact on learning!
  - Reapplied multimedia principle with new materials -- added diagrams to modified text
    - New principle worked: Big impact on learning

Overview

- Cognitive Tutor Principles
- Multimedia Principles
  - Theoretical & Experimental evidence
- Building on prior knowledge
  - Need empirical methods to apply
- Summary

How People Learn Principles

How People Learn book
1. Build on prior knowledge
2. Connect facts & procedures with concepts
3. Support meta-cognition


But:
What prior knowledge do students have?
How can instruction best build on this knowledge?
Algebra Student Results: Story Problems are Easier!

Story Problems: As a waiter, Ted gets $6 per hour. One night he made $66 in tips and earned a total of $81.90. How many hours did Ted work?

Word Problem: Starting with some number, if I multiply it by 6 and then add 66, I get 81.90. What number did I start with?

Equation: \( x \times 6 + 66 = 81.90 \)

What do these results imply for instruction?

- Focus instruction on story problems
- Focus instruction on equations
- Start with story then go to equations
- There are no direct implications
- Other?

Instructional Bridging Principles

1. Situation-Abstraction
   Concrete situational <-> abstract symbolic reps

2. Action-Generalization
   Doing with instances <-> explaining with generalizations

3. Visual-Verbal
   Visual/pictorial <-> verbal/symbolic reps

4. Conceptual-Procedural
   Conceptual <-> procedural

Recent results suggest going abstract yields better transfer


- Idea: Abstractions help students develop deeper encodings that better transfer
- Are abstractions always better? Is there a role for concrete examples?
Assistance Dilemma

- How to optimize learning outcomes?
  - Can there be too little instructional assistance (i.e., too hard for students)?
  - Can there be too much assistance (i.e., too easy)?
- Yes to both, yields inverted U function

Open questions:
- What is the shape of this function?
- What parameters & conditions drive it?

General form of “assistance formula”

- If $P$ = probability of success during instruction then:
  - Robust Learning Efficiency gain =
    $$P \times \text{SuccessBenefit} + (1-P) \times \text{FailureBenefit}$$
  - $P$, SuccessBenefit, ... depend on level of assistance
- Assumptions that yield inverted U
  - Higher the assistance $\Rightarrow$ higher chance of success ($P$)
  - Lower benefit of succeeding (SuccessBenefit)
  - SuccessBenefit > FailureBenefit
  - SuccessCost $\leq$ FailureCost

Applying assistance formula to concrete-abstract dimension

- Success during instruction is higher for concrete ($P_c > P_a$)
  - Success means understanding instruction or getting practice exercises correct
- If success, robust learning is higher for abstract ($S_{Ba} > S_{Bc}$)
  - Abstract encoding is more general
- Often, robust learning is better for abstract ($P_a \times S_{Ba} > P_c \times S_{Bc}$)
- How about concreteness fading?
  - Is concrete to abstract: $P_c \times S_{Bc} + (P_a+(1-P_a)) \times S_{Ba}$
    better than 2 abstract: $2 \times P_a \times S_{Ba}$

Bridge from concrete to abstract

- Combining abstract text & diagrams (concrete) enhances transfer (Mayer, 2002)
  - Non-dependent info from alternative sources reduces ambiguity in constructing concepts
  - Like co-training theory (Blum & Mitchell, 1998)
- Progressive formalization/concreteness fading (Goldstone & Son, 2005; Kotovsky & Gentner, 1996; Nathan, 1998)
  - Gradually shift from concrete to abstract
  - Goldstone: “Initial concrete grounding facilitates interpretation of model elements”
  - Subsequent abstraction helps stress deep features

Bridging assumption: Partially correct concept created from concrete instruction reduces credit assignment ambiguity in processing abstract instruction
Study 1: Bridge from concrete to abstract


Inductive Support idea

Use activities that bridge from existing concrete modes of thinking to more sophisticated abstract modes of thinking

Test in domain of “algebra symbolization”

Forester Textbook Problem

Drane & Route Plumbing Co. charges $42 per hour plus $35 for the service call.

1. Create a variable for the number of hours the company works. Then, write an expression for the number of dollars you must pay them.

2. How much you would pay for a 3 hour service call?

3. What will the bill be for 4.5 hours?

4. Find the number of hours worked when you know the bill came out to $140.

Inductive Support Version

Drane & Route Plumbing Co. charges $42 per hour plus $35 for the service call.

1. Create a variable for the number of hours the company works. Then, write an expression for the number of dollars you must pay them.

2. How much you would pay for a 3 hour service call?

3. What will the bill be for 4.5 hours?

4. Find the number of hours worked when you know the bill came out to $140.
Unpacking **bridging assumption** in algebra symbolization domain

- **Story -> algebra symbols**
  - Requires A) english comprehension, B) combining operations, C) producing symbols
  - Learning all 3 at once: big credit assignment challenge
- **Concrete solution requires only A & B**
- **Hardest is learning C (Heffernan & Koedinger, 1998)**
  - Shallow algebra “grammar” knowledge can produce simple expressions, 3*42, 126+35, but not 3*42+35
- **Concrete first means C is isolated in abstract phase, credit assignment is much easier**

---

**Study 2: Bridge from concrete to abstract**

### Goldstone & Son results on assistance curve

Do concrete tasks always provide more assistance than abstract ones?

That is, are concrete tasks always easier than matched abstract tasks?

- Concreteness fading balances costs & benefits of instructional assistance/difficulty
Which is easier, situation or analogous abstract problem?

<table>
<thead>
<tr>
<th>Situation</th>
<th>Abstract</th>
</tr>
</thead>
<tbody>
<tr>
<td>Show 5 different ways that you can give Ben $4.07. [Place value table given.]</td>
<td>List 5 different ways to show the amount 4.07. [Place value table given.]</td>
</tr>
<tr>
<td>You had $8.72. Your grandmother gave you $25 for your birthday. How much money do you have now?</td>
<td>Add: 8.72 + 25</td>
</tr>
<tr>
<td>You work at a candy store. Your boss has asked you to figure out the different ways she could package the jelly beans and chocolate eggs, and she wants to know all the possible ways. If there are 64 jelly beans and 40 chocolate eggs and she wants each package to be the same, what are the different numbers of packages you could make?</td>
<td>The common factors of 64 &amp; 40 are:</td>
</tr>
</tbody>
</table>

%correct
- Situation 61%
- Abstract 20%

Abstract
- List 5 different ways to show the amount 4.07. [Place value table given.]
Add: 8.72 + 25

%correct
- Abstract 35%

Key Point: Design principles require empirical methods to successfully implement

Overview
- Cognitive Tutor Principles
- Multimedia Principles
- Building on prior knowledge
- Need empirical methods to apply
- Summary
Summary of Learning Principles

- Lots of lists of principles...
  - 6 Cognitive Tutor Principles
  - 6 Multimedia Principles
  - See PSLC wiki for others...
- Should be Based on both:
  - Cognitive theory
  - Experimental studies
- Need Cognitive Task Analysis to apply
  - Domain general principles are not enough
  - Need to study details of how students think & learn in the domain you are teaching

Organizing Instruction and Study to Improve Student Learning

- Produced by US Department of Education, Institute for Education Sciences (IES)
  - Goal: Get high quality science into practice
- Expert panel goals
  - Extract recommendations from scientific literature
  - Be conservative, even painfully honest, about status of evidence

Panel:
Harold Pashler (Chair), University of California-SD
Patrice M. Bain, Columbia Middle School, Illinois
Brian A. Botting, University of Wisconsin-Madison
Arthur Graesser, University of Memphis
Ken Koedinger, Carnegie Mellon University
Mark McDaniel, Washington University in St. Louis
Janet Metcalfe, Columbia University

Principles on web: See learnlab.org/research/wiki