Defining "Conceptual Understanding" Through Appropriate Constraints on a Knowledge Domain

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Outline

1. Some Discussion of Concepts

   Diverse views

2. A Model of Knowledge Structure

   Conceptual clusters and hierarchies

3. Simple Schematic View of Learning

   Diagrammatic representation

4. Some Empirical Examples

   Entropy and electric fields

Note: Overlapping Work

Many analogous representations and related discussion in:

Michael C. Wittmann, “Using resource graphs to represent conceptual change,” Phys. Rev. Spec. Topics-Phys. Educ. Res. **2**, 020105 (2006).

Some discussion of “concepts”

- *“A scientific concept…is an idea…that is used in thinking about natural phenomena.”*
  - Robert Karplus [AJP **49**, 238 (1982)]

- *“A class of concepts…important in science learning…[consists of] systematically connected ways of getting information from the world.”*
  - A. diSessa and B. Sherin [IJSE **20**, 1155 (1998)]

- *“…one must be able to interpret [identify or generate] a scientific concept unambiguously in any particular instance.”*
  - Frederick Reif [AJP 63, 17 (1995)]

Concepts are diverse

[Robert Karplus, AJP **49**, 238 (1982)]

"It appears useful…to organize scientific concepts into three levels according to their generality…"

1) specific, measurable physical quantities (e.g., *force*, *acceleration*, *charge*);

2) specialized descriptive concepts (e.g., *particle*, *configuration*, *liquid*)

3) general concepts involving explanation, proof, etc. (e.g., *system*, *reference frame*, *evidence*)

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"…the very notion of scientific concept implies a certain position in relation to other concepts, i.e., a place within a system of concepts…any real concept must be taken only together with its system of relations that determine its measure of generality. A concept is like a living cell that must be viewed only together with its offshoots penetrating into surrounding tissue."

– L. Vygotsky, *Thought and Language*, pp. 171-172 (1934/1986)

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“Central to a concept cluster is an empirical or theoretical relationship[*] among several physical variables…there is considerable freedom in the choice of quantities to be defined and derived. The exact choices that are made will determine the structure that is obtained…it would appear that necessary linking of the concepts in a cluster requires teaching that ultimately deals with the entire cluster as an entity.”

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[*e.g., $\boldsymbol{F} = m\boldsymbol{a}$ and $W = \boldsymbol{F}\cdot\Delta\boldsymbol{s}$]

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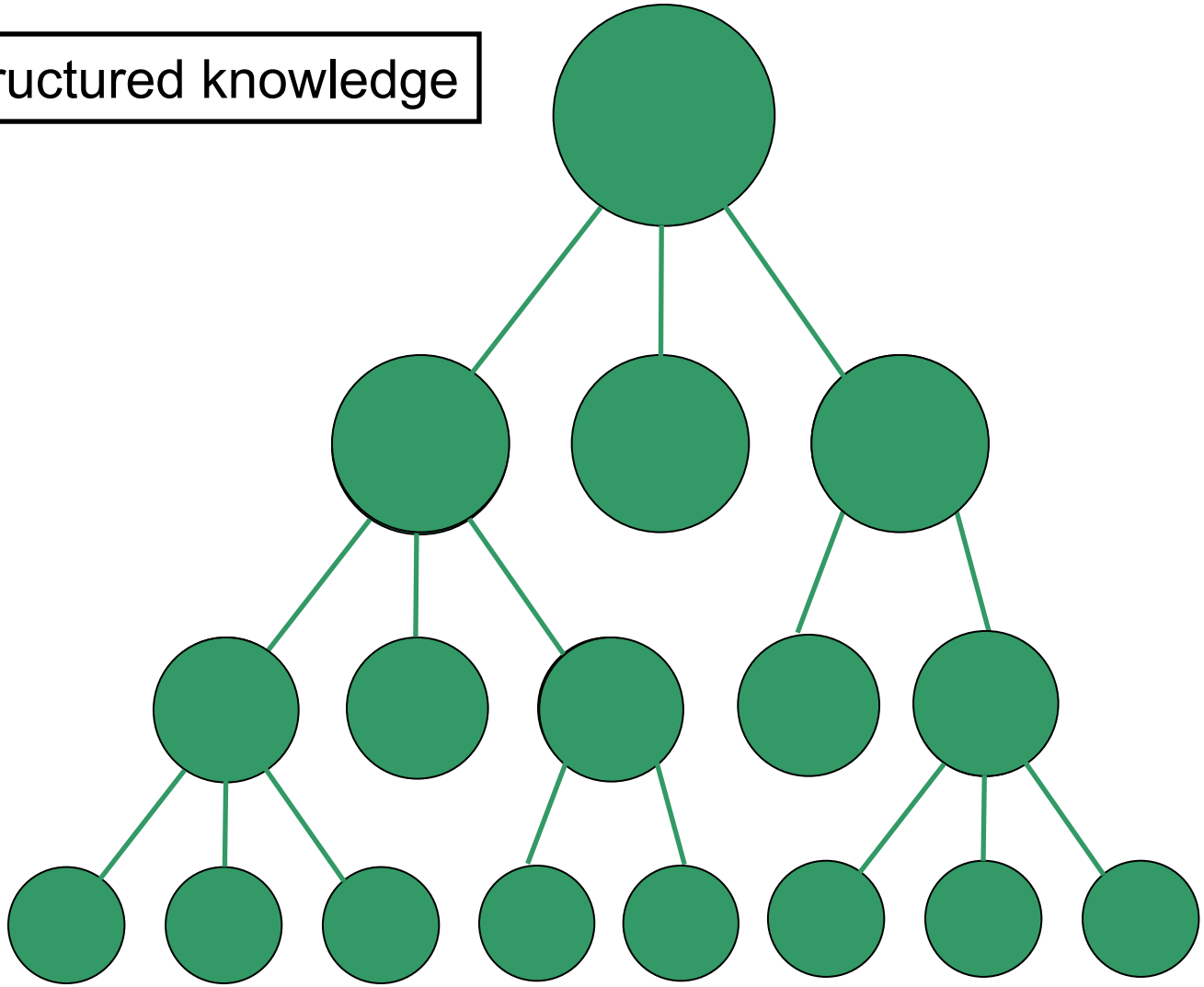
"…instruction can at least try to ensure (a) that students acquire knowledge which is in well-organized hierarchical form, and (b) that they can exploit such organization to help them remember and retrieve pertinent information."

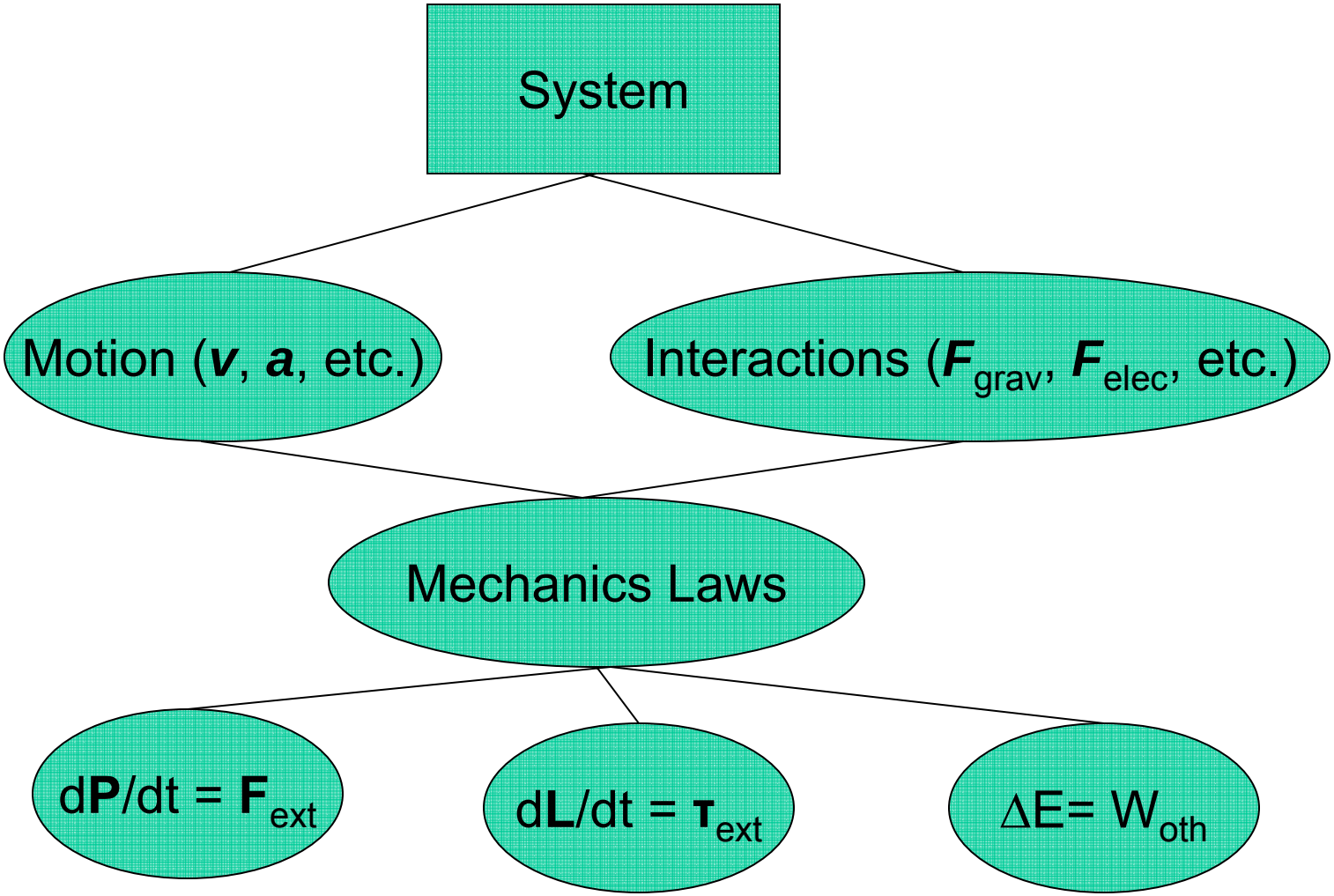
– Frederick Reif [AJP 63, 17 (1995)]

Well-structured knowledge



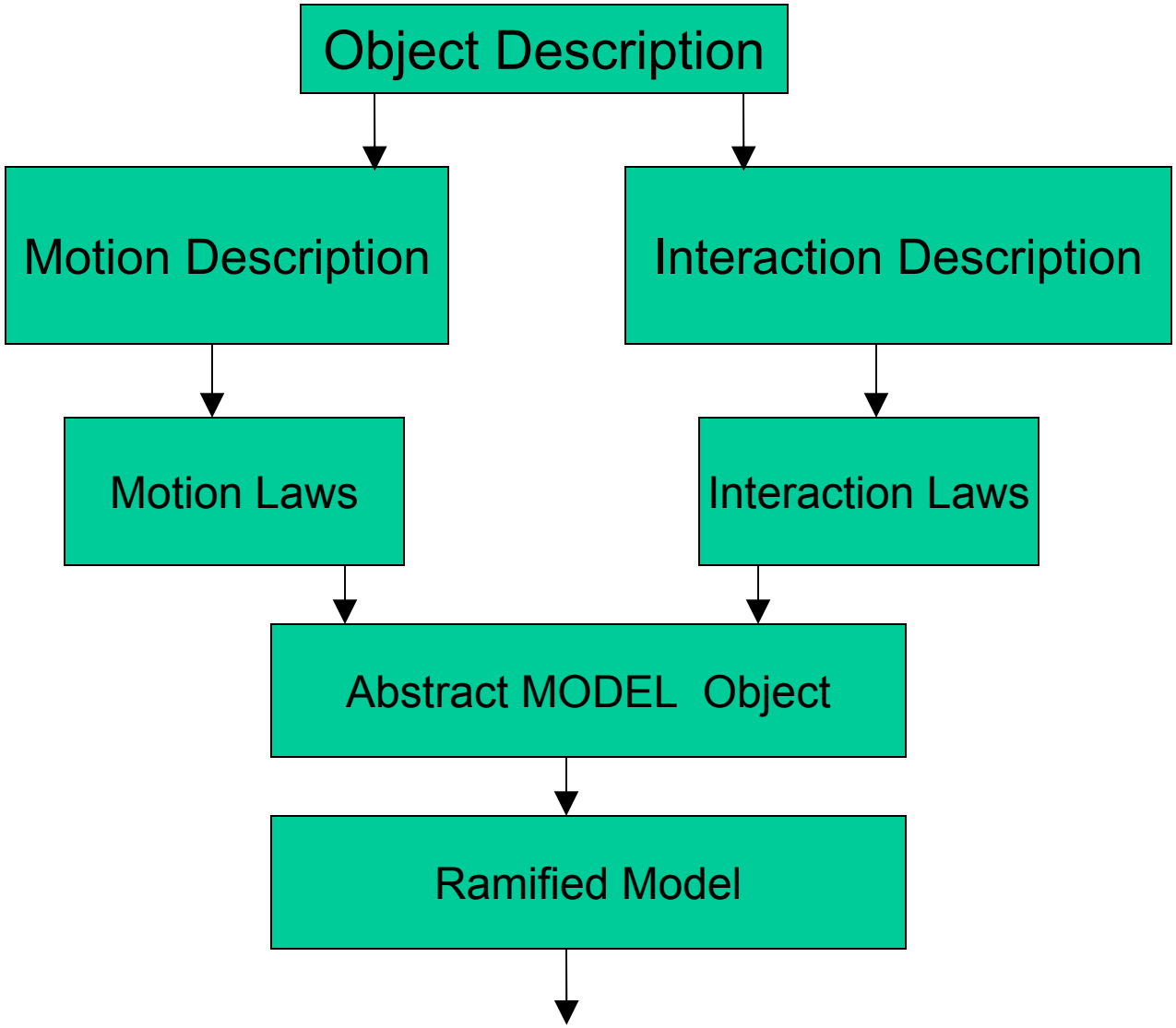
[F. Reif, Am. J. Phys. (1995)]

Example (F. Reif): Mechanics Overview

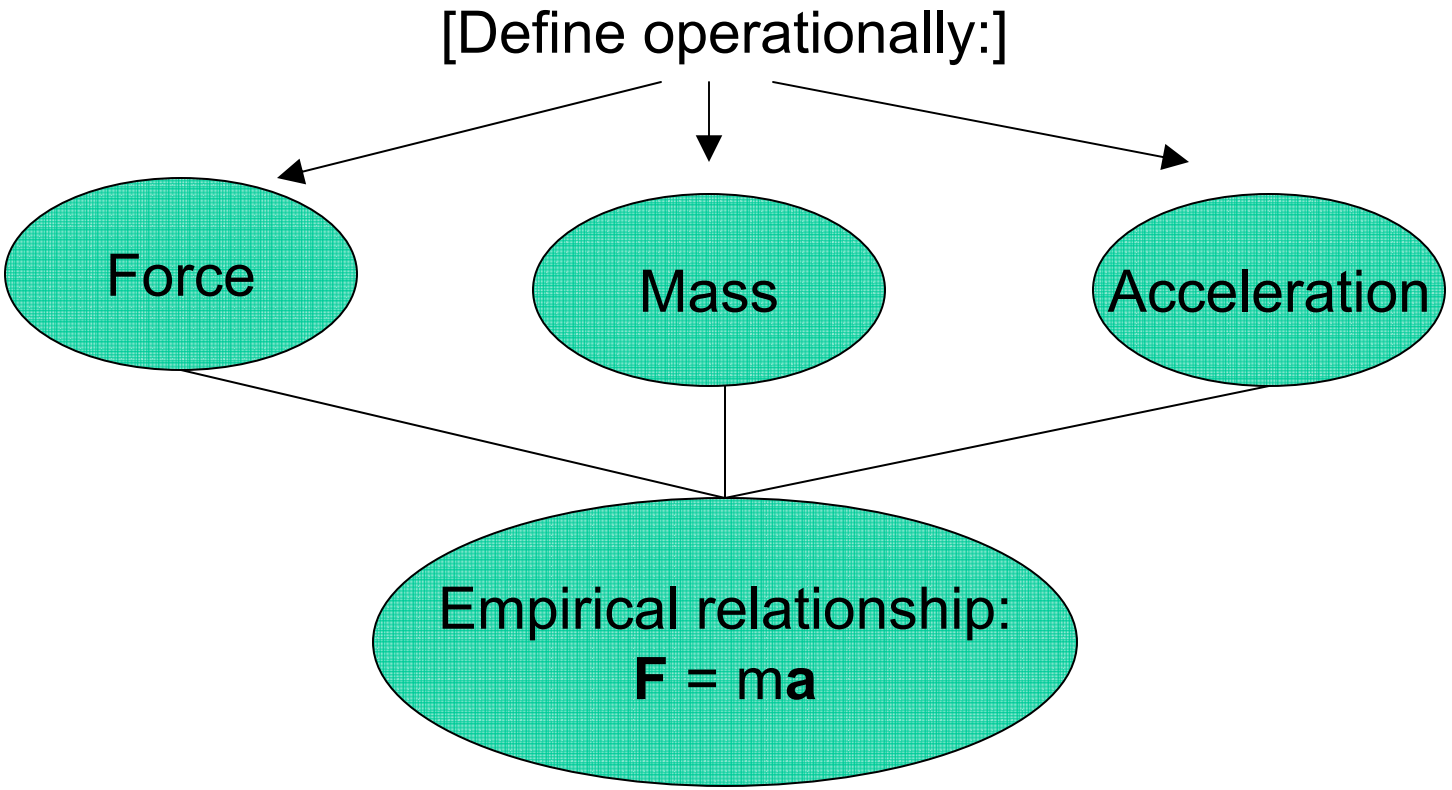


Another Perspective: Model Development

D. Hestenes, AJP *55*, 440 (1987)



Concept Cluster (R. Karplus): Newton's second law



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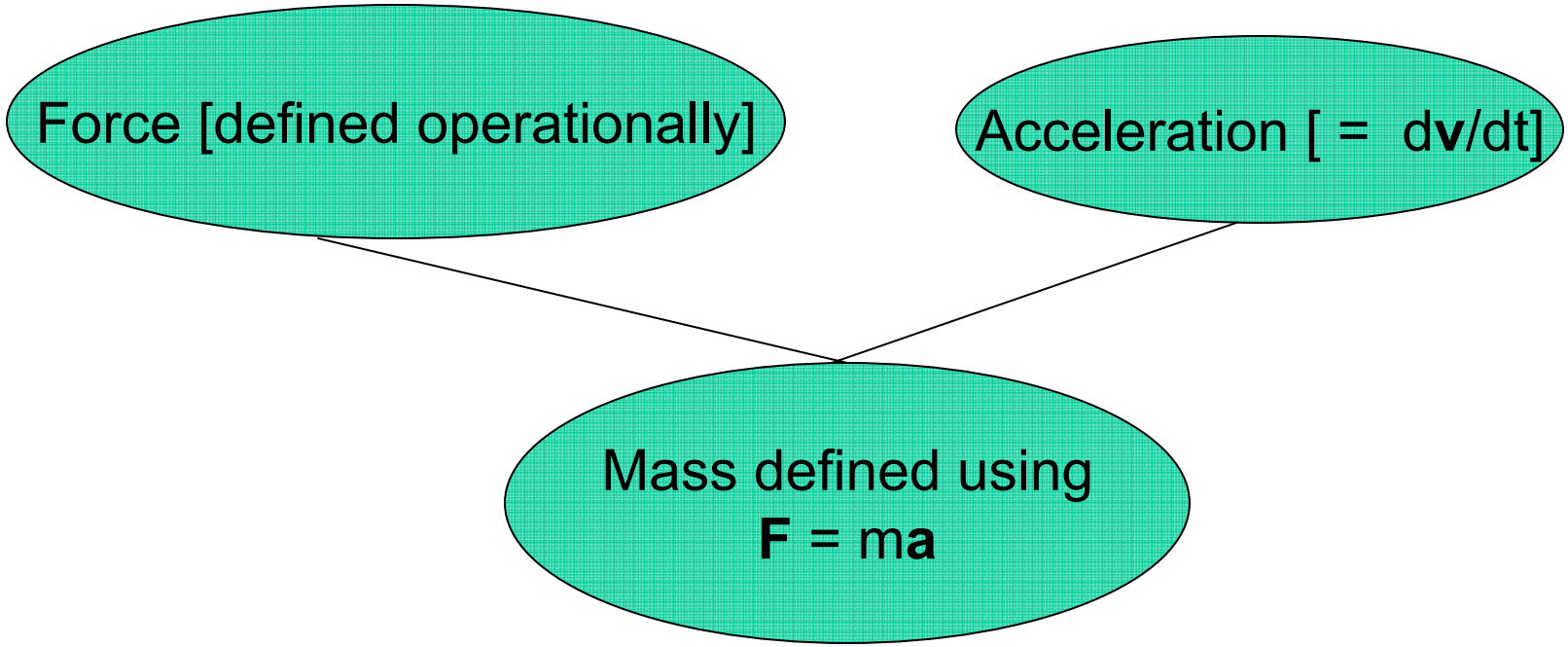
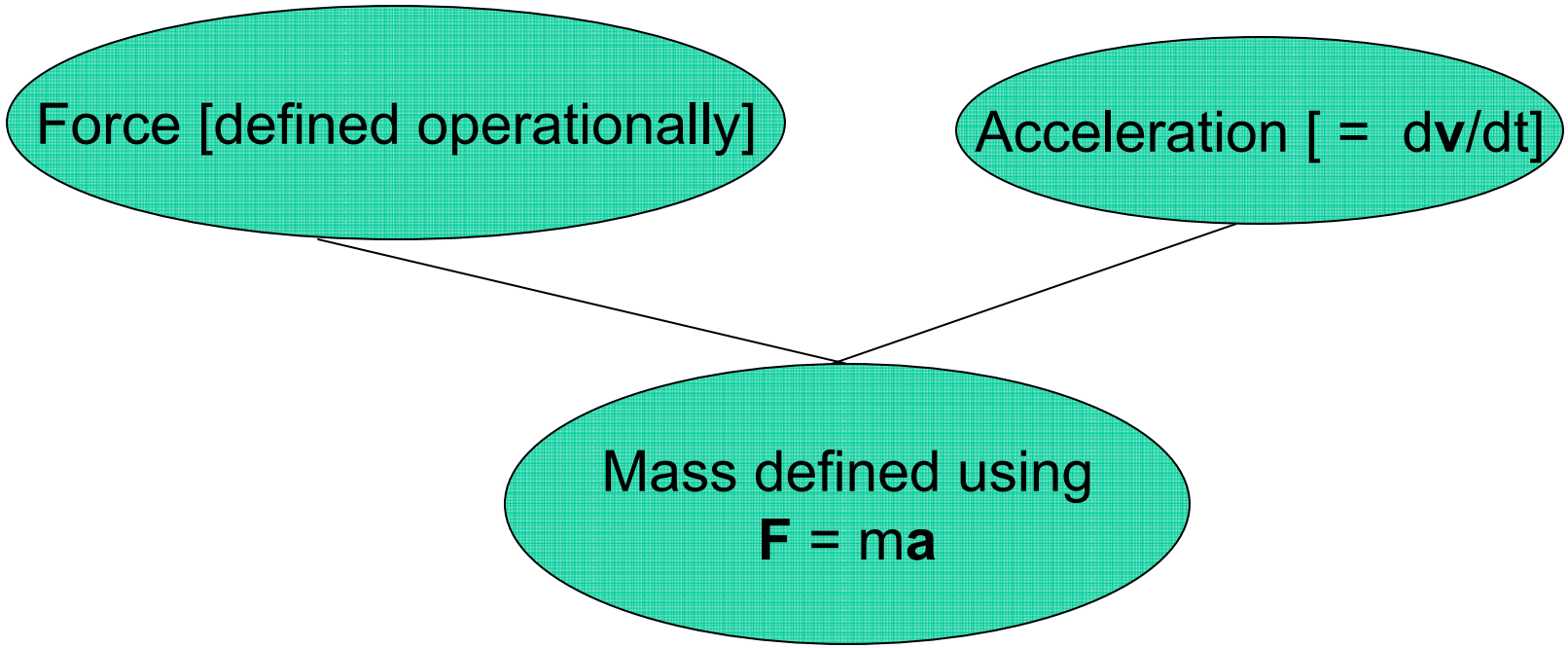
[*alternative concept cluster*]

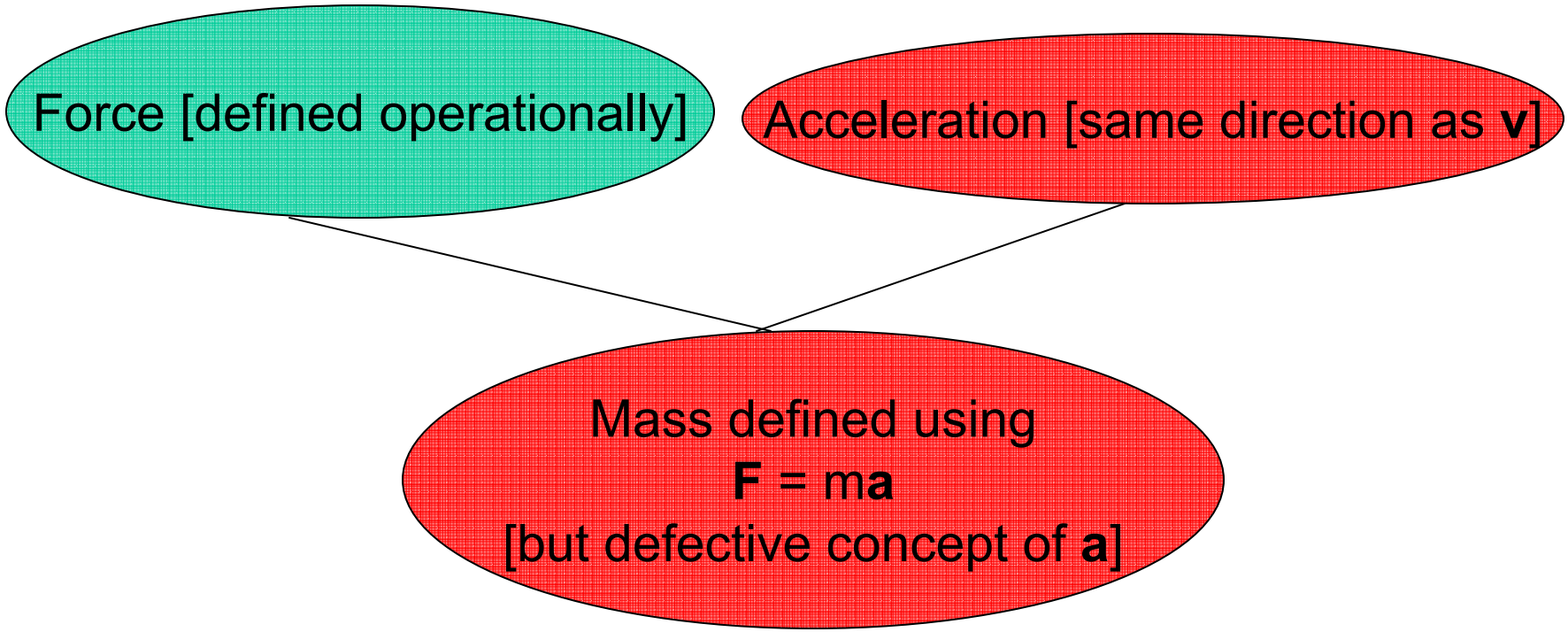


Concept Clusters have diverse representations

[*alternative concept cluster*]



[*flawed concept cluster*]



Learning and Knowledge Structure

- Difficulties in understanding and applying specific physical ideas form obstacles to learning;
- Inadequate *organization* of students' ideas plays a central role in hindering understanding.
- It may be difficult or impossible to differentiate unambiguously between a *difficulty with a specific idea* and *inadequate linking with related ideas*.

A Schematic Model for Students' Knowledge Structure

[E. F. Redish, *AJP* (1994), *Teaching Physics* (2003)]

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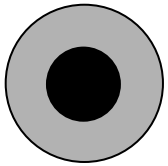

- Central black bull's-eye: what students know well
  - *tightly linked network of well-understood concepts*
- Middle "gray" ring: students' partial and imperfect knowledge [Vygotsky: "Zone of Proximal Development"]
  - *knowledge in development: some concepts and links strong, others weak*

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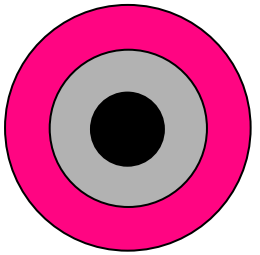

- Central black bull's-eye: what students know well
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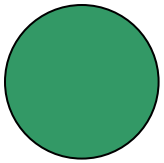
- Middle "gray" ring: students' partial and imperfect knowledge [Vygotsky: "Zone of Proximal Development"]
  - *knowledge in development: some concepts and links strong, others weak*
- Outer "white" region: what students don't know at all
  - *disconnected fragments of poorly understood ideas*

Knowledge in Development: “Flawed” Models

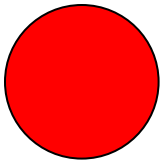
“A flawed mental model may share a number of propositions with a correct mental model, but they are interconnected according to an incorrect organizing principle.”

– M. Chi and R. Roscoe, in *Reconsidering Conceptual Change* (2002), p. 7.

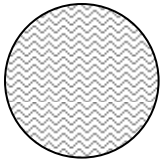
Schematic Representation of Knowledge Structure…



“correct” and stable knowledge element



“incorrect” or unstable knowledge element

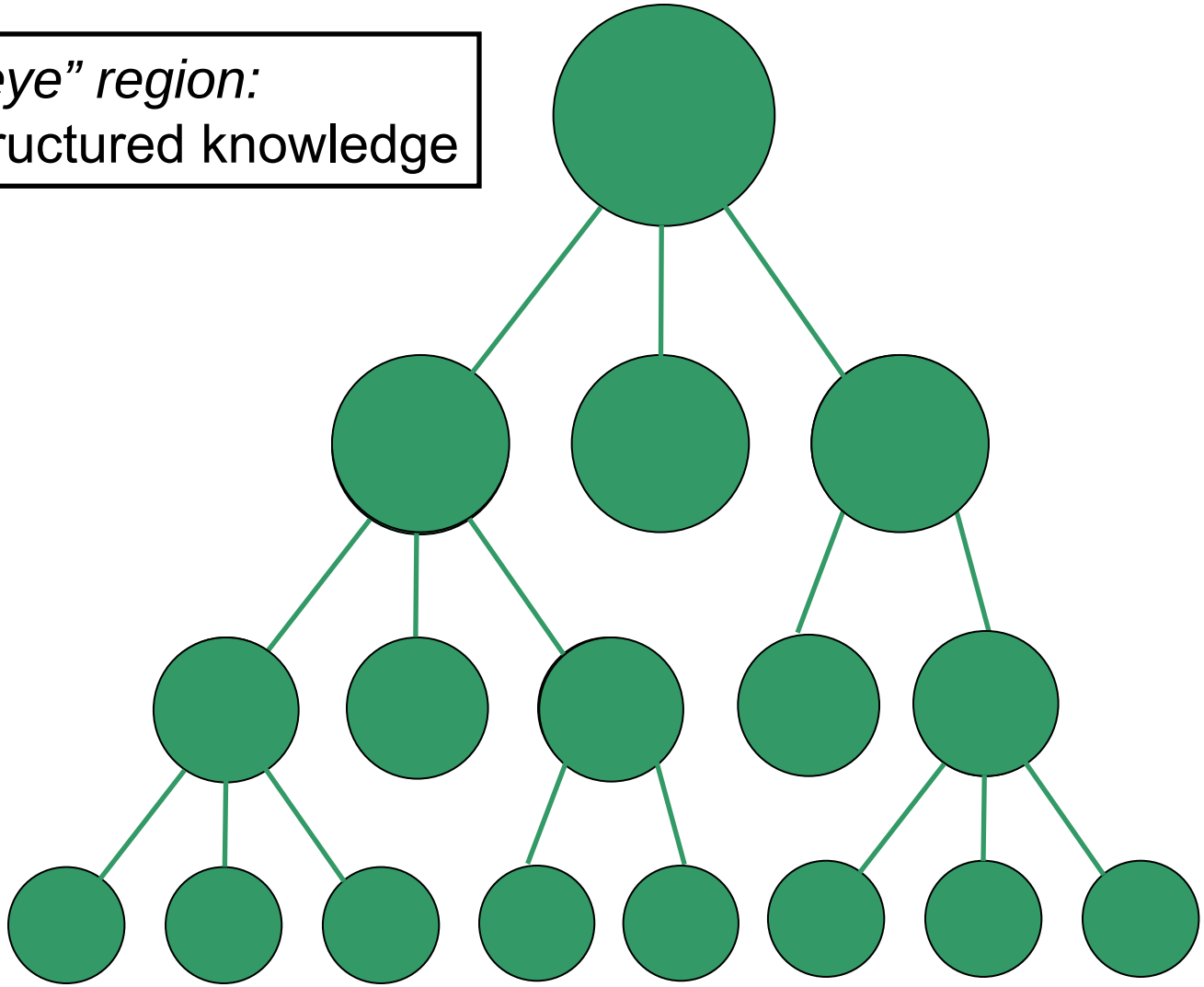


ill-defined idea, highly unstable

consistent, reliable link

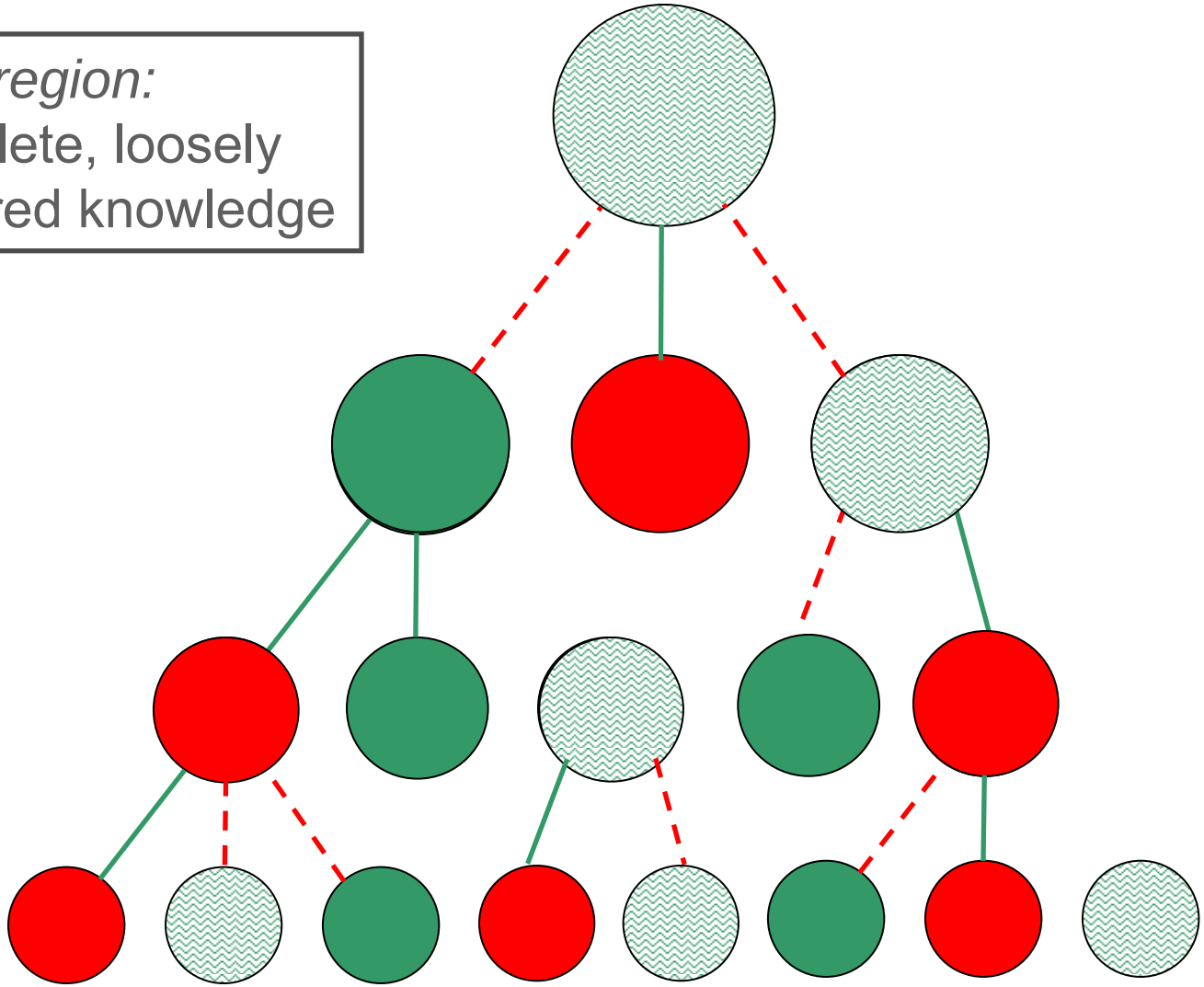
inconsistent or “incorrect” link

"Bulls-eye" region:
Well-structured knowledge



[F. Reif, Am. J. Phys. (1995)]

“Gray” region:
incomplete, loosely structured knowledge



“White” region:
incoherent ideas

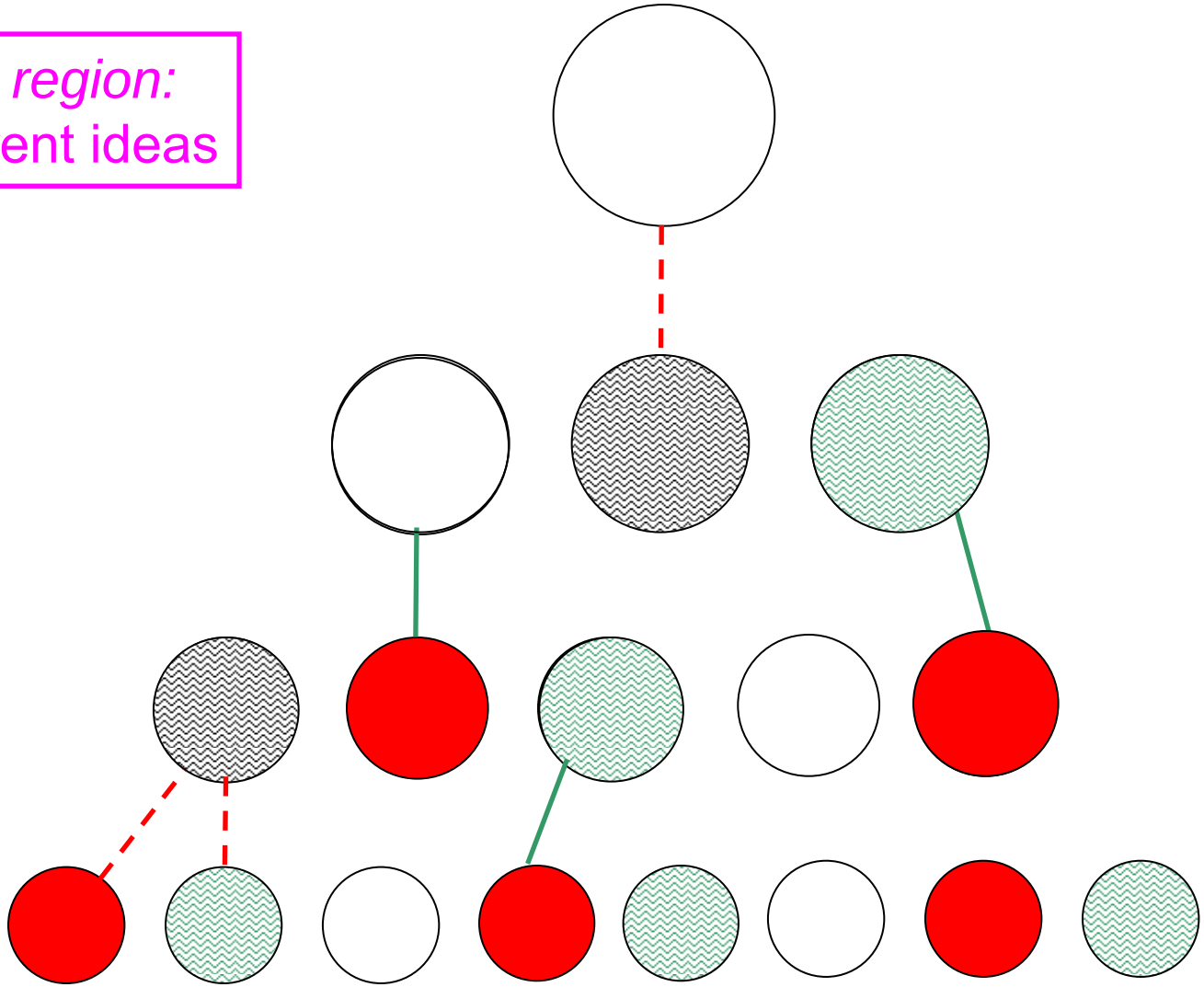


Diagram Coding

"Knowledge elements" (ovals) may represent:

- well-defined, stable concepts
- models "correct" within a certain context (e.g., particle model)
- simple naïve ideas or intuitive rules (e.g., "closer means stronger")
- "correct" but unstable and inconsistent ideas
- well-defined but incorrect ideas (e.g., $\mathbf{v} \propto \mathbf{F}$)
- vague, poorly defined notions

Diagram Coding

“Links” (lines) may represent:

- valid theoretical or empirical relationship ***with*** strong association, i.e.: high probability of one knowledge element being accompanied by the other
- invalid but strong association
- valid, but inconsistent or unreliable association

Teaching Effectiveness, Region by Region

- *In central black region:* difficult to make significant relative gains
- *In white region:* learning gains minor, infrequent, and poorly retained.
- *Teaching most effective when targeted at gray:* Analogous to substance near phase transition; a few key concepts and links can catalyze substantial leaps in student understanding.

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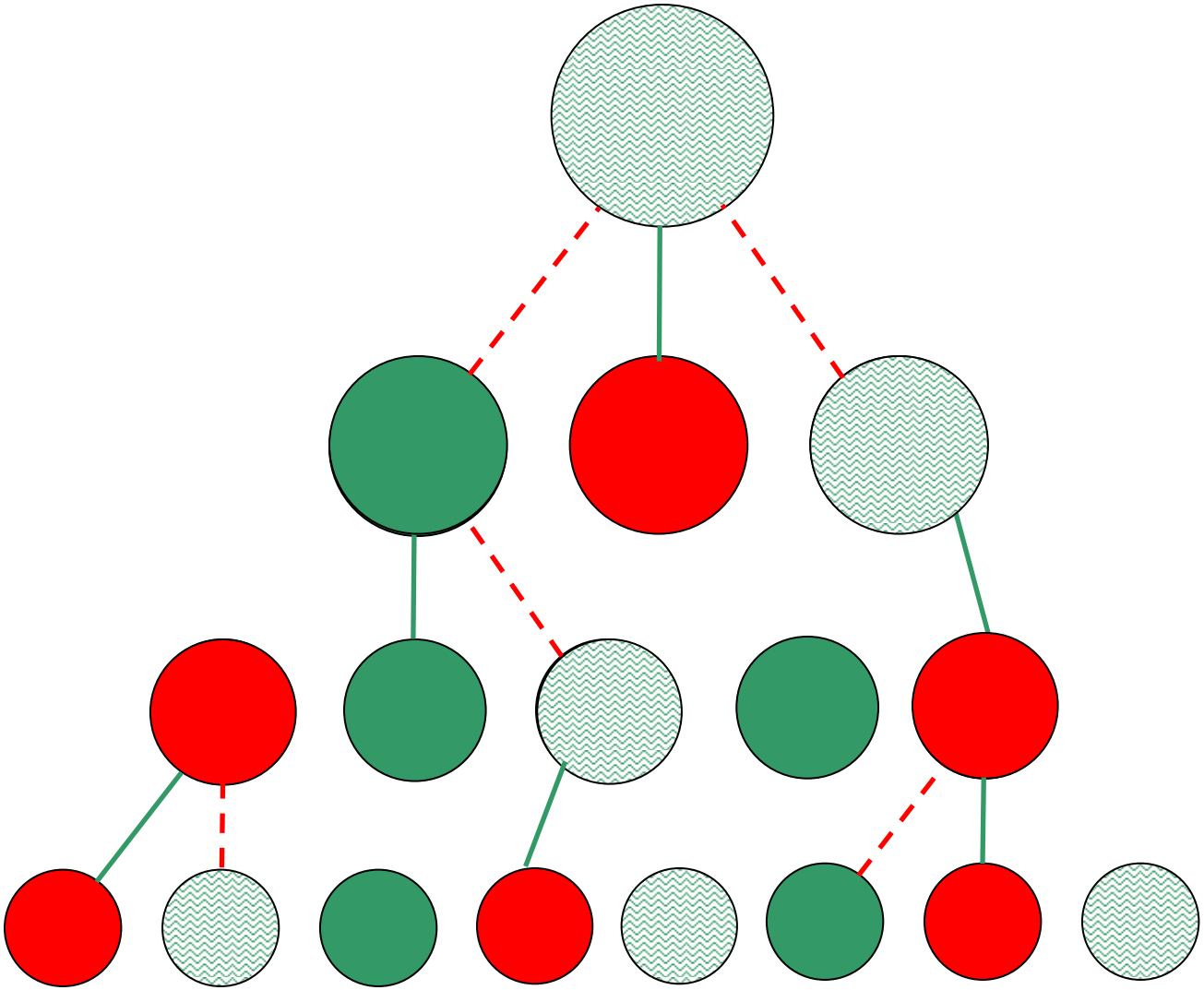
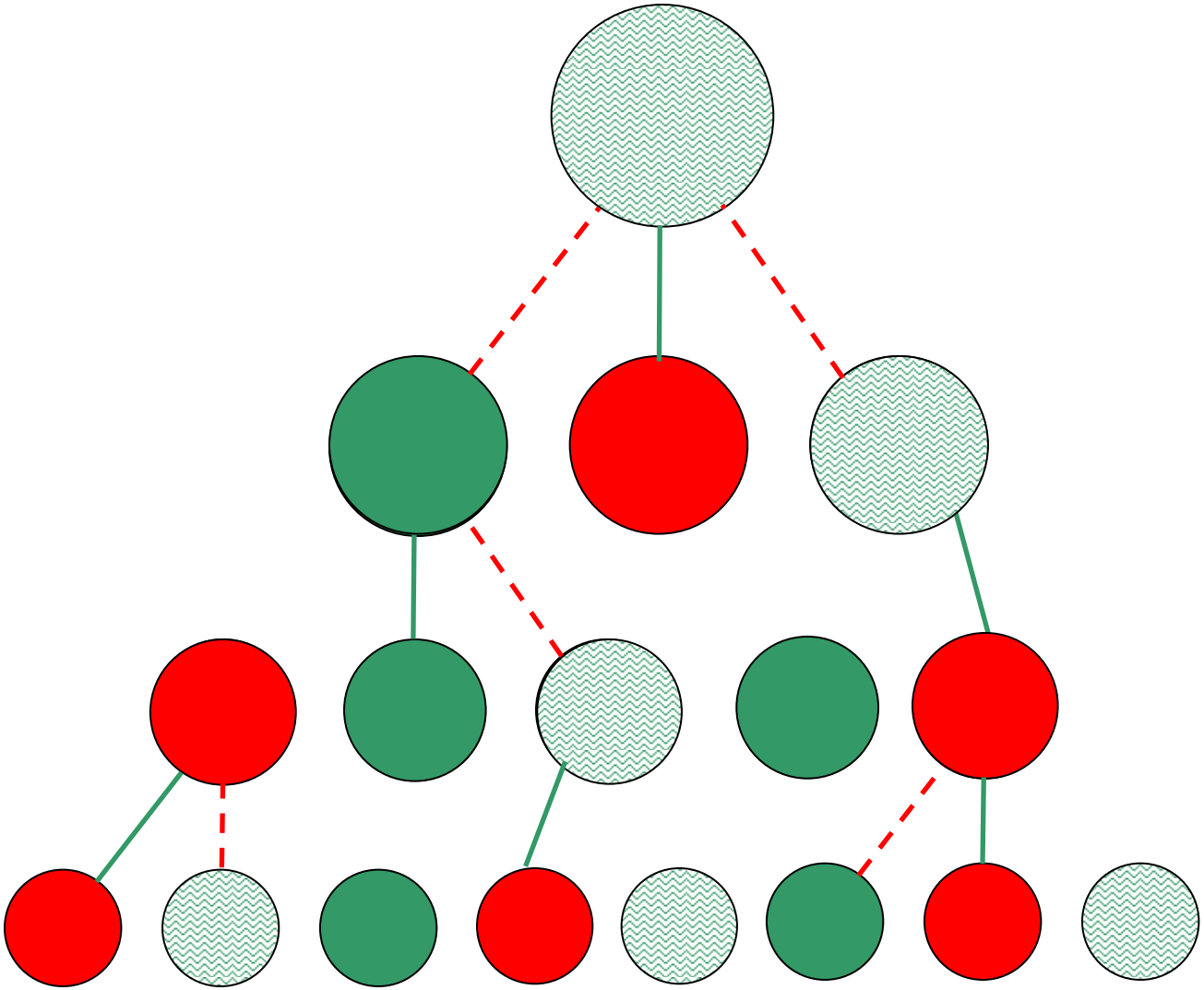
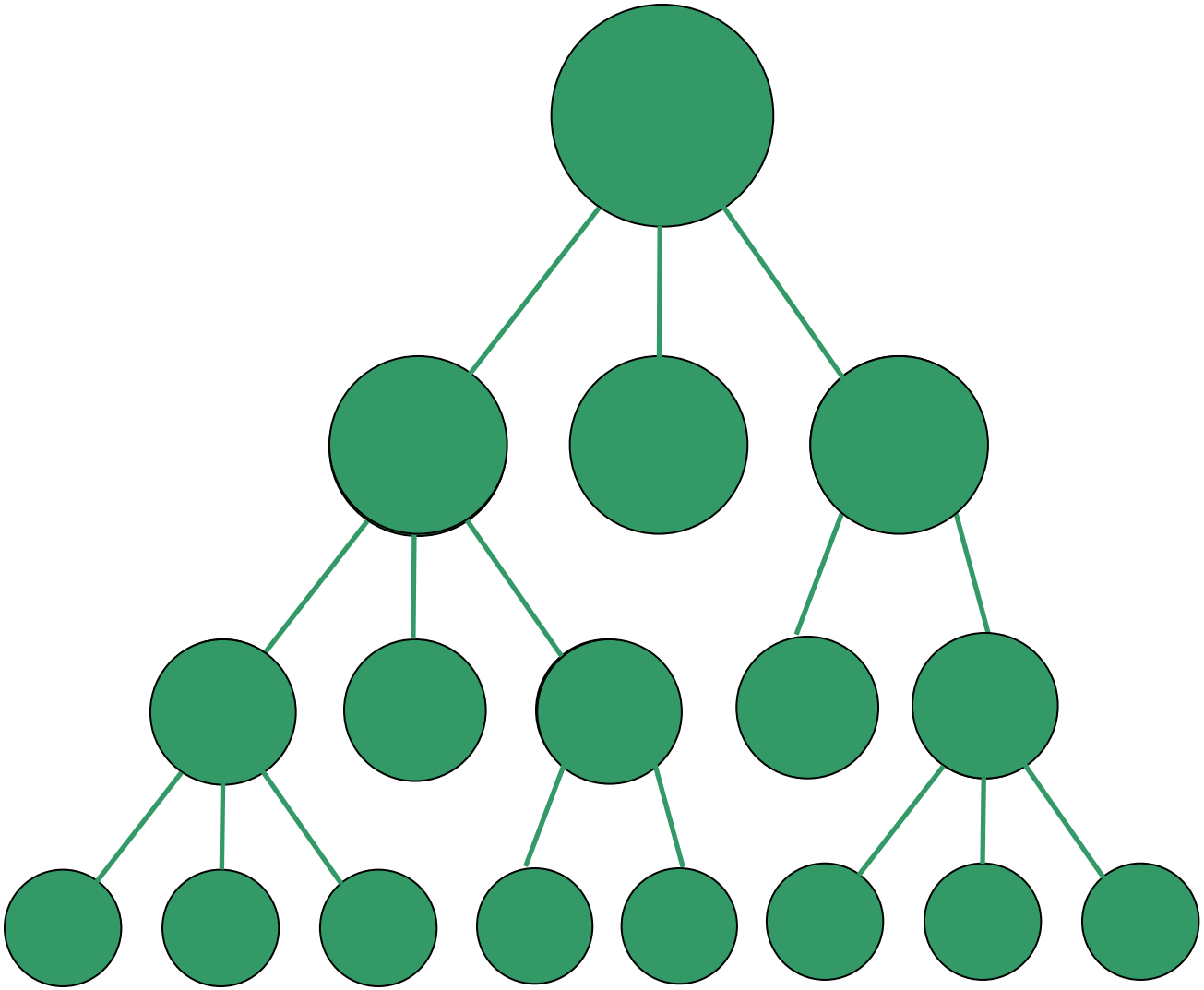


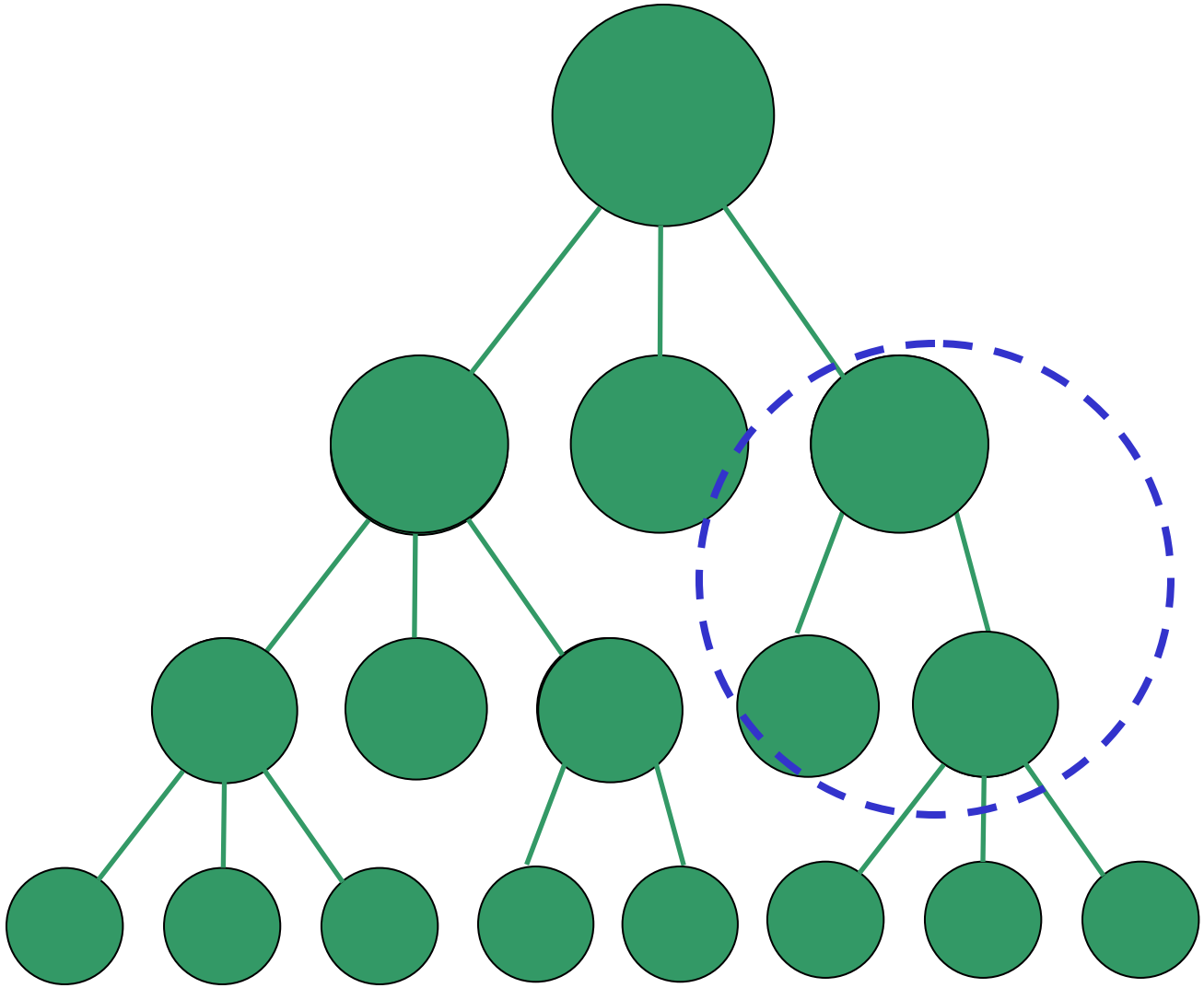
Research Task: map out gray region



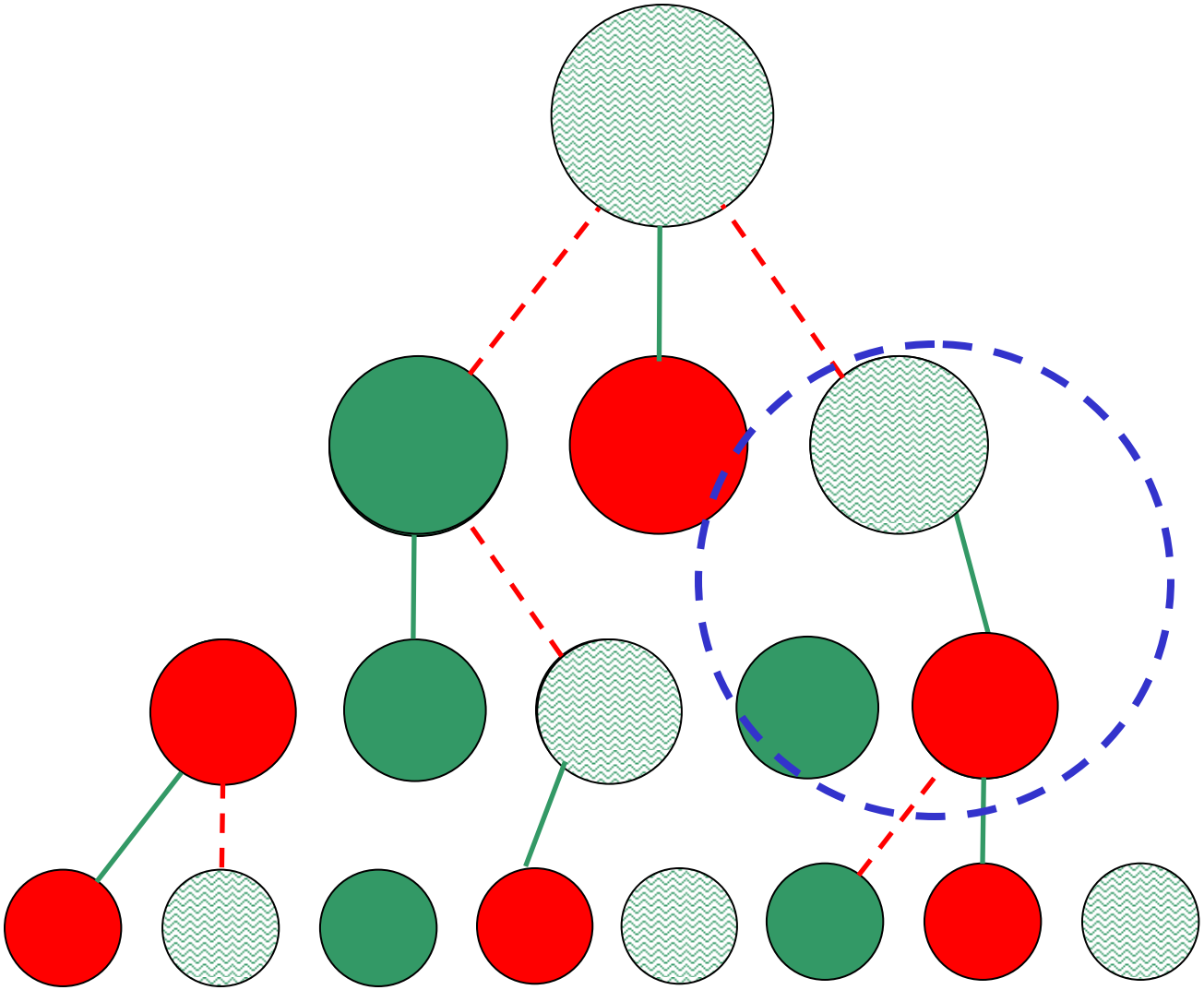
Instructional Task: address difficulties in gray region



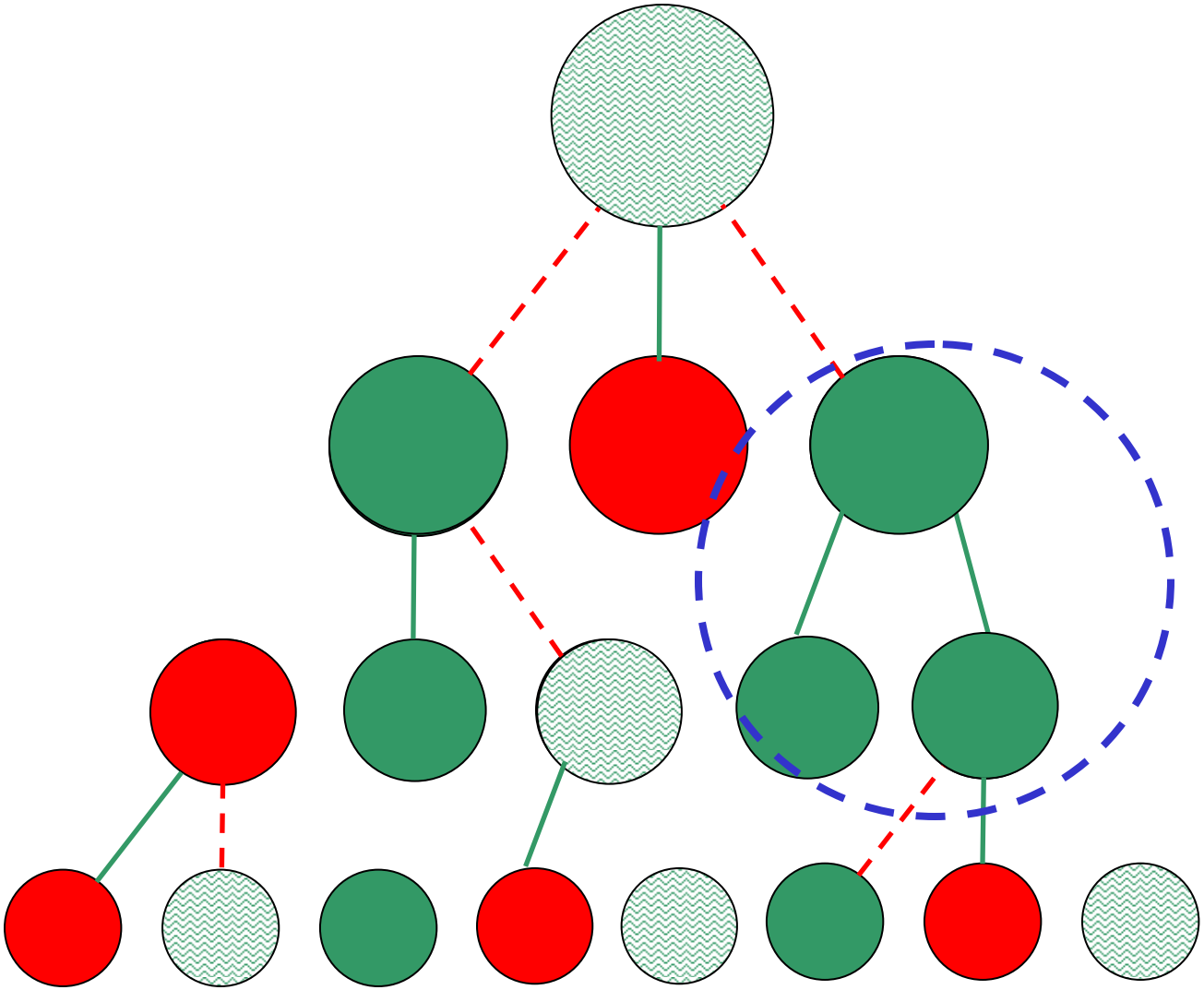
Instructional Goal: well-organized set of coherent concepts



Instructional Task #1: identify a target concept cluster



Research Task: probe targeted cluster



Instructional Task #2: address and resolve obstacles to learning

Dynamic View of Knowledge Elements

- Each knowledge element is inherently linked to multiple other knowledge elements
- Each knowledge element and its links are in a continual process of development
- Since an element is partially *defined* through its links, its intrinsic character evolves along with its linking network

Knowledge Structure Develops Continually

- Even the “expert” knowledge structure for a given individual can continue to develop.
- It is therefore highly probable that *any* arbitrarily circumscribed concept cluster (i.e., set of elements + links) will itself evolve in time.
- The instructional implication is that the detailed nature of a specific “target” concept cluster (e.g. “magnetic interaction”) is linked inseparably to a specific educational level (e.g., middle-school vs. graduate school).

A *Better* (More Complete) Coding

G. Nicoll, J. Francisco, and M. Nakhleh, IJSE **23**, 863 (2001)

"Links" (arrows) may be:

useful *(correct or generally sound)*

wrong *(contain wrong information)*

incomplete *(lack critical information)*

emerging *(vague, tentative, and/or uncertain)*

defined *(well-defined, consistent, confident)*

more…

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↑ useful links may be:

Level #1: examples or similar items

Level #2: fundamental fact (simple, basic, memorizable)

Level #3: complex and/or have predictive power

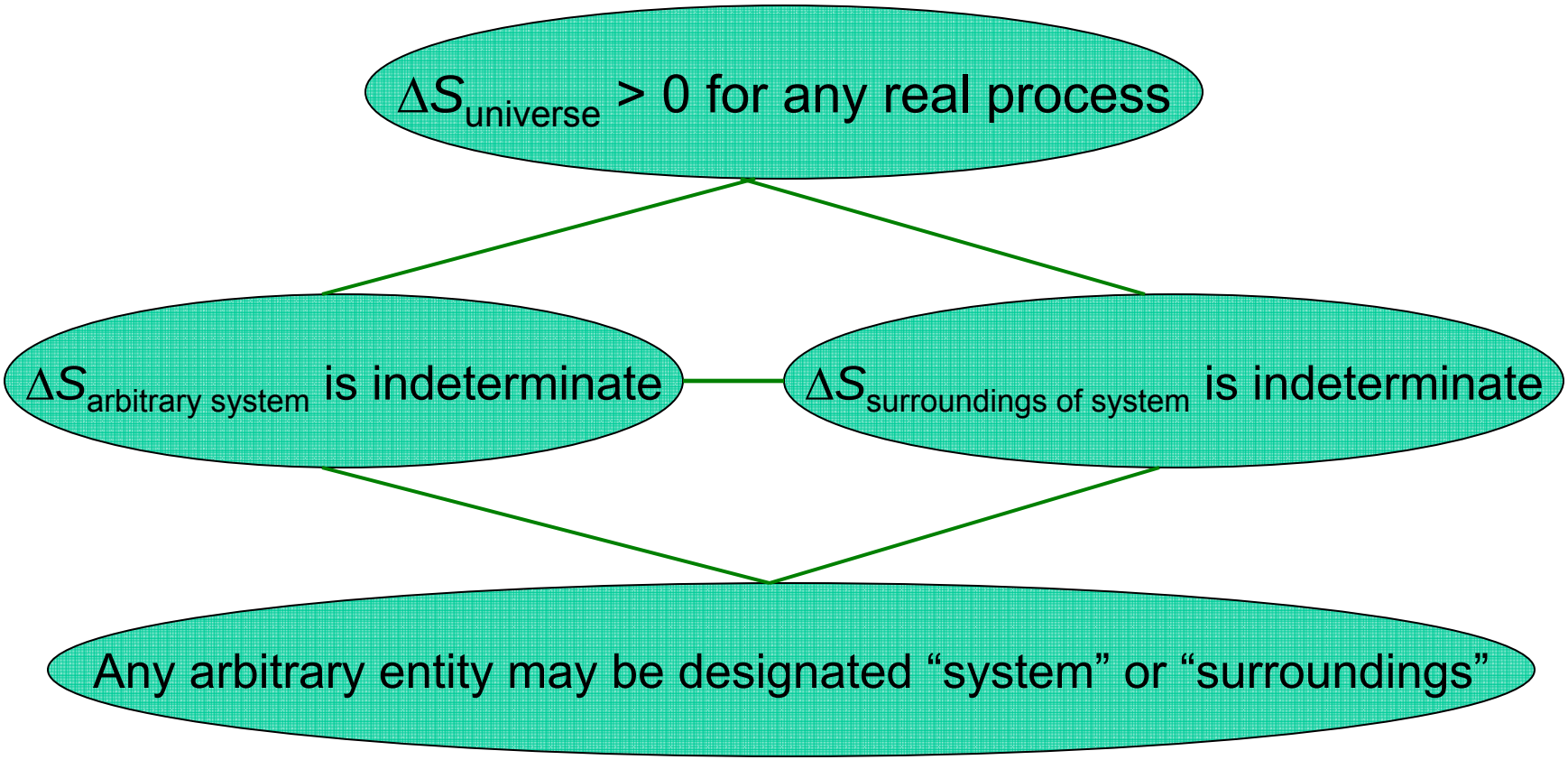
Some Empirical Examples

- Entropy and Second Law of Thermodynamics
  - from Ph.D. work of Warren Christensen

- Electric Fields and Forces

[Data from Iowa State University (ISU)]

Entropy-Increase Concept Cluster



"General-Context" Question

For each of the following questions consider a system undergoing a naturally occurring ("spontaneous") process. The system can exchange energy with its surroundings.

A. During this process, does the entropy of the **system** [S_{system}] *increase*, *decrease*, or *remain the same*, or is this *not determinable* with the given information? ***Explain your answer.***

B. During this process, does the entropy of the **surroundings** [$S_{surroundings}$] *increase*, *decrease*, or *remain the same*, or is this *not determinable* with the given information? ***Explain your answer.***

C. During this process, does the entropy of the system *plus* the entropy of the surroundings [$S_{system} + S_{surroundings}$] *increase*, *decrease*, or *remain the same*, or is this *not determinable* with the given information? ***Explain your answer.***

"Concrete-Context" Question

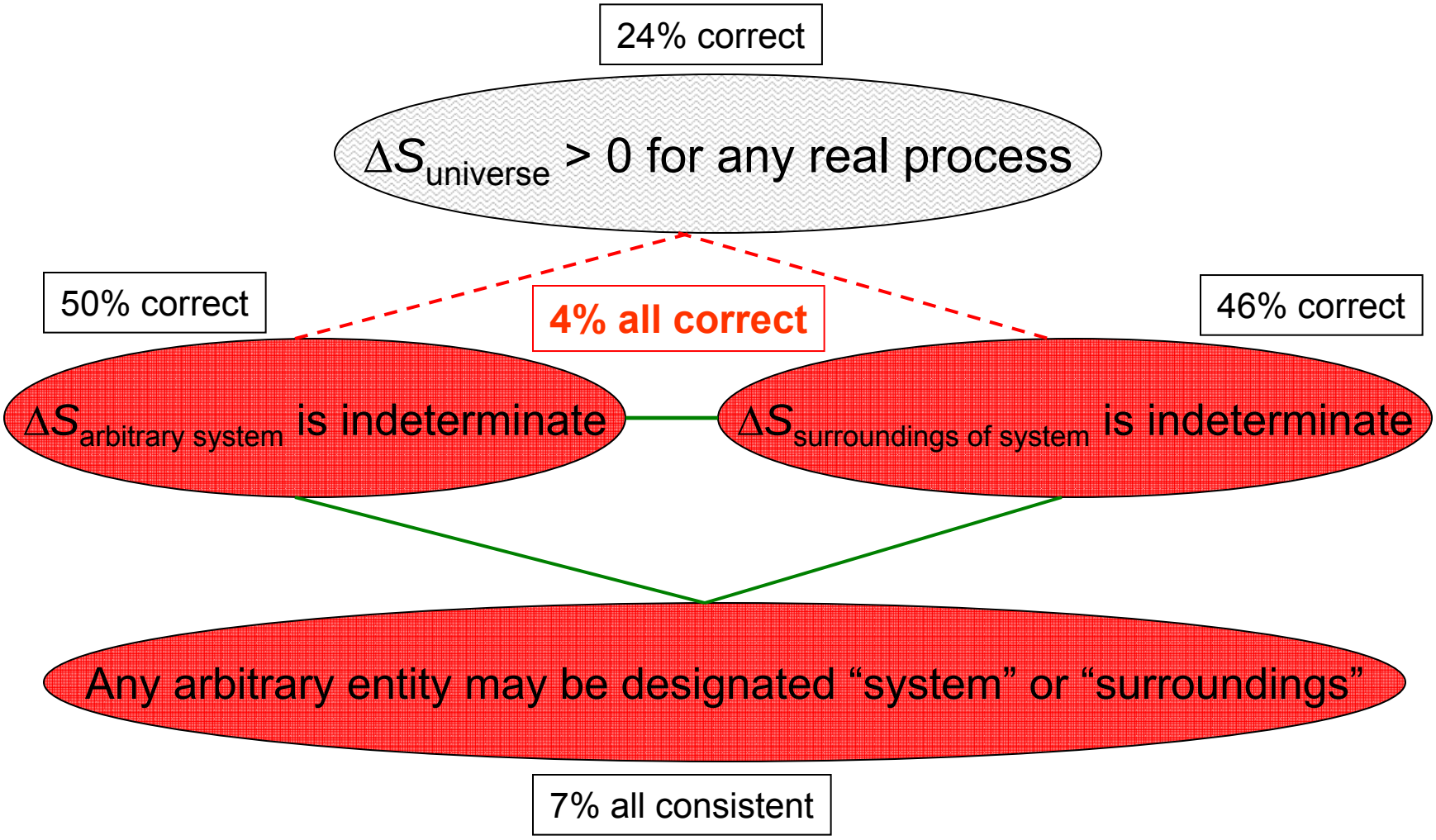
An object is placed in a thermally insulated room that contains air. The object and the air in the room are initially at different temperatures. The object and the air in the room are allowed to exchange energy with each other, but the air in the room does not exchange energy with the rest of the world or with the insulating walls.

A. During this process, does the entropy of the **object** [S_{object}] *increase*, *decrease*, *remain the same*, or is this *not determinable* with the given information? ***Explain your answer.***

B. During this process, does the entropy of the **air in the room** [S_{air}] *increase*, *decrease*, *remain the same*, or is this *not determinable* with the given information? ***Explain your answer.***

C. During this process, does the entropy of the object *plus* the entropy of the air in the room [$S_{object} + S_{air}$] *increase*, *decrease*, *remain the same*, or is this *not determinable* with the given information? ***Explain your answer.***

Pre-Instruction Structure



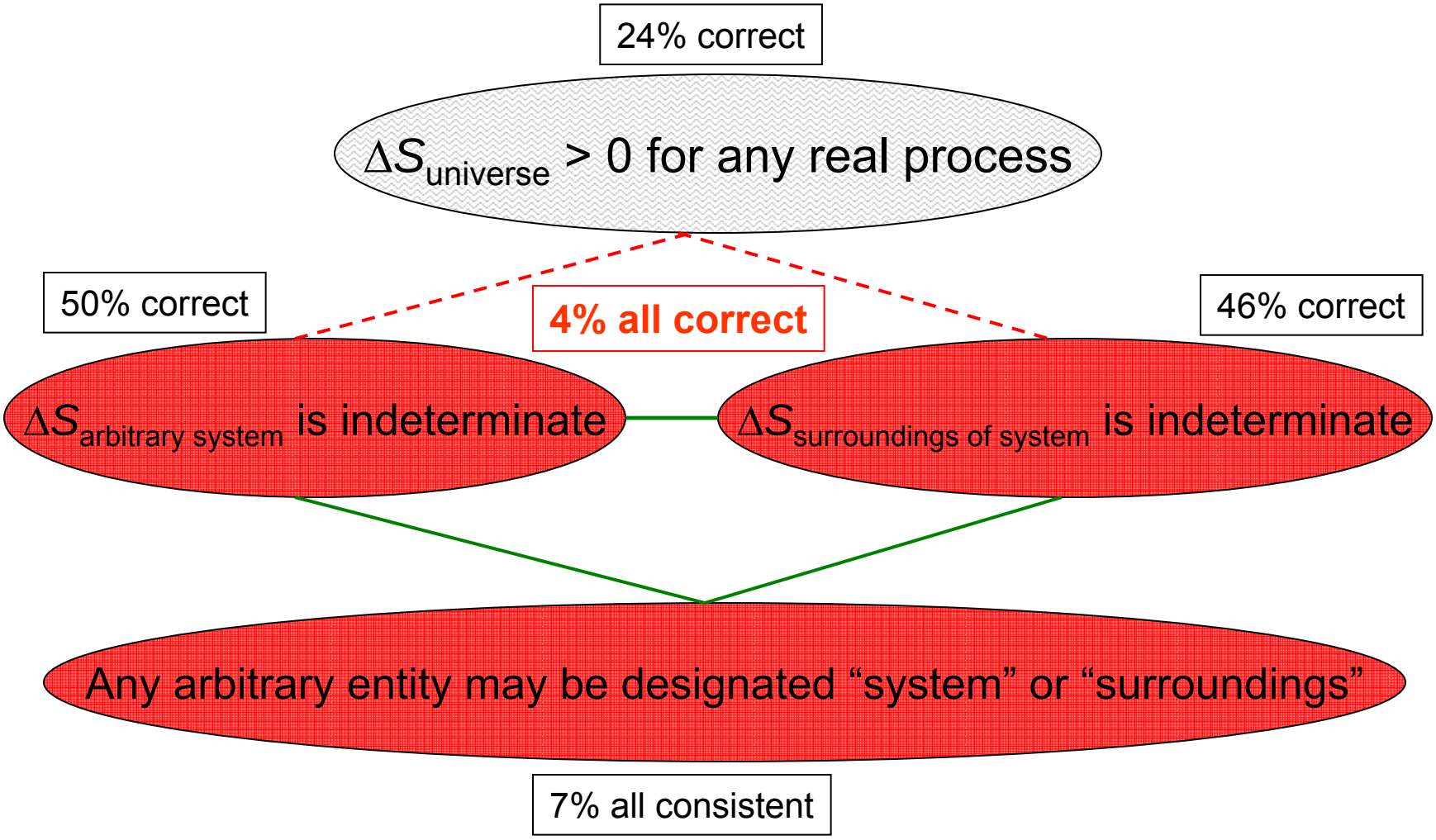
Introductory Physics Students' Thinking on Spontaneous Processes

- Tendency to assume that "system entropy" must *always* increase

- Slow to accept the idea that entropy of system plus surroundings ***increases***

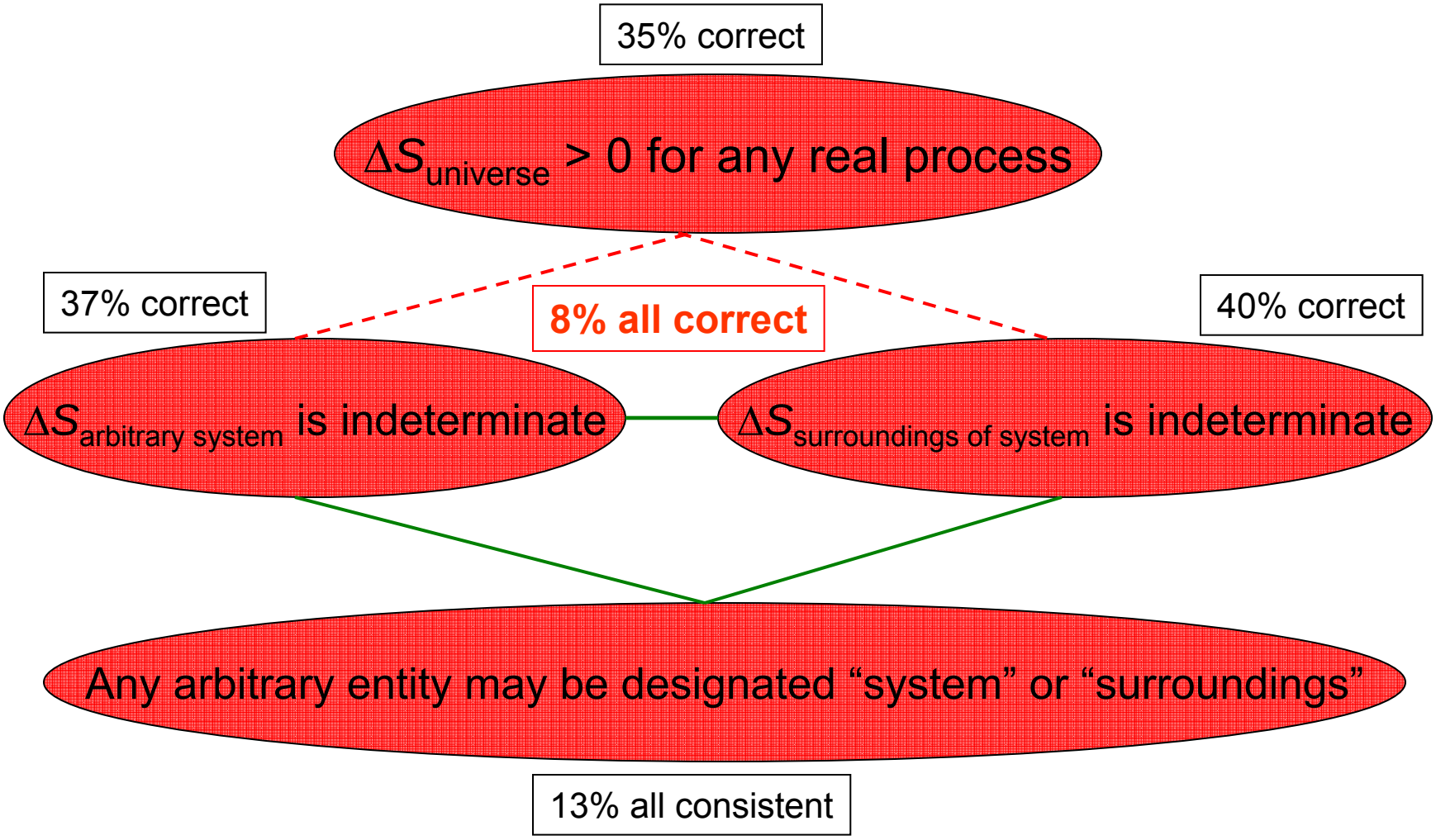
  - *Most students give incorrect answers to all three questions*

Pre-Instruction Structure



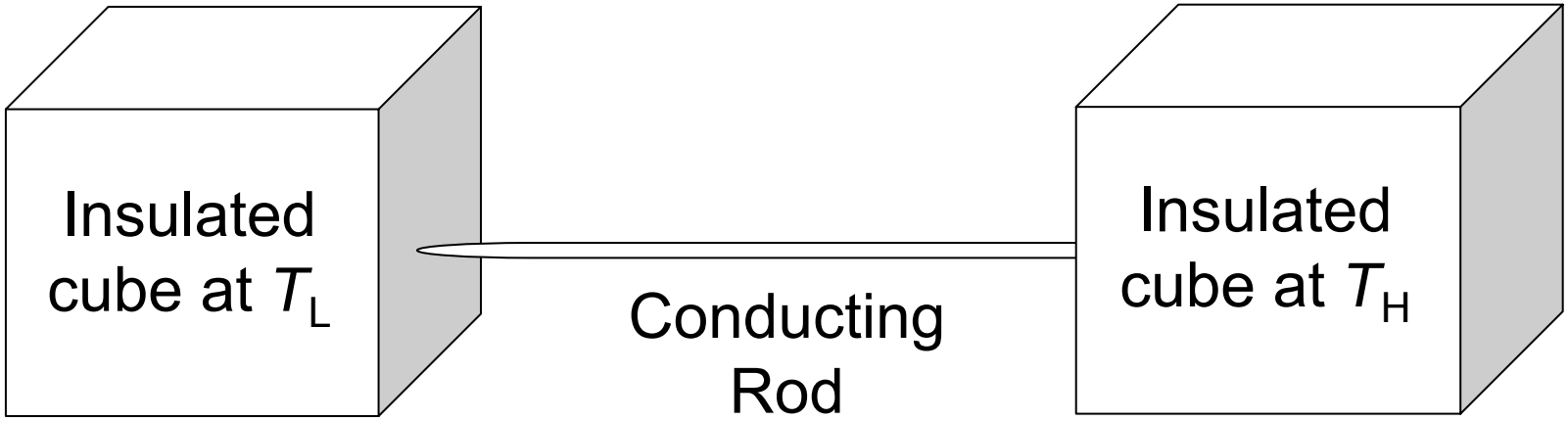
Post-Instruction, Tutorial #1

["Entropy State-Function" Tutorial, W. Christensen and DEM]



“Entropy Spontaneous-Process” Tutorial

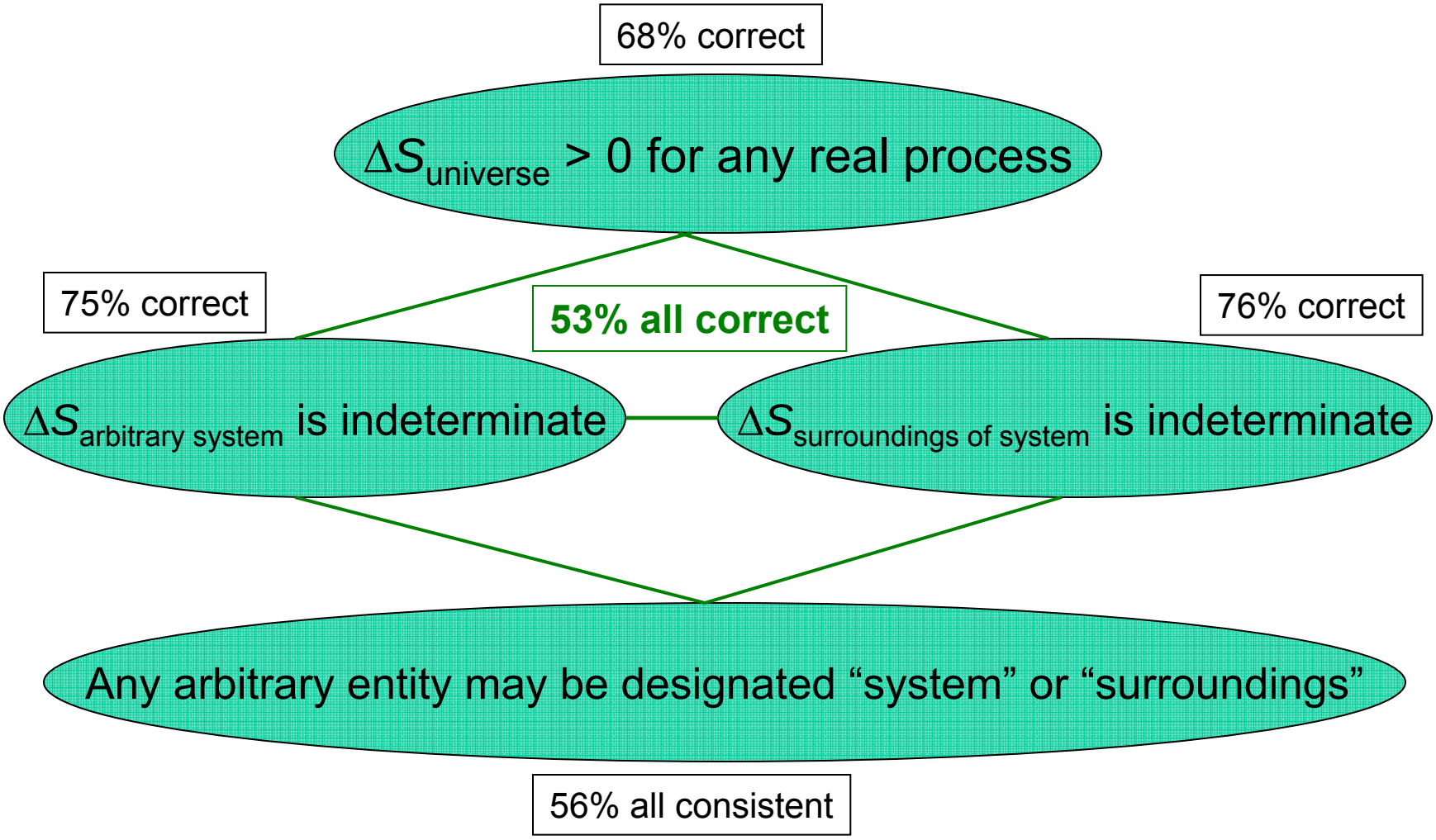
(draft by W. Christensen and DEM, undergoing class testing)



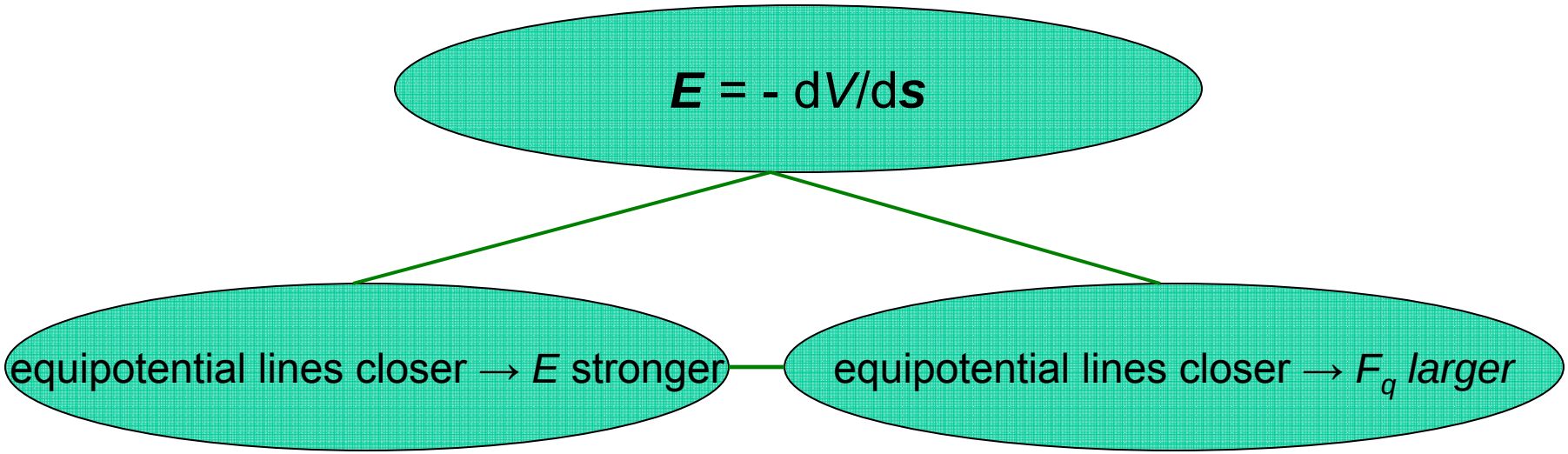
- Consider slow heat transfer process between two thermal reservoirs (insulated metal cubes connected by thin metal pipe)
  - ➢Does total energy change during process? *[No]*
  - ➢Does total entropy change during process? *[Yes]*

Post-Instruction, Tutorial #2

["Entropy Spontaneous-Process" Tutorial]



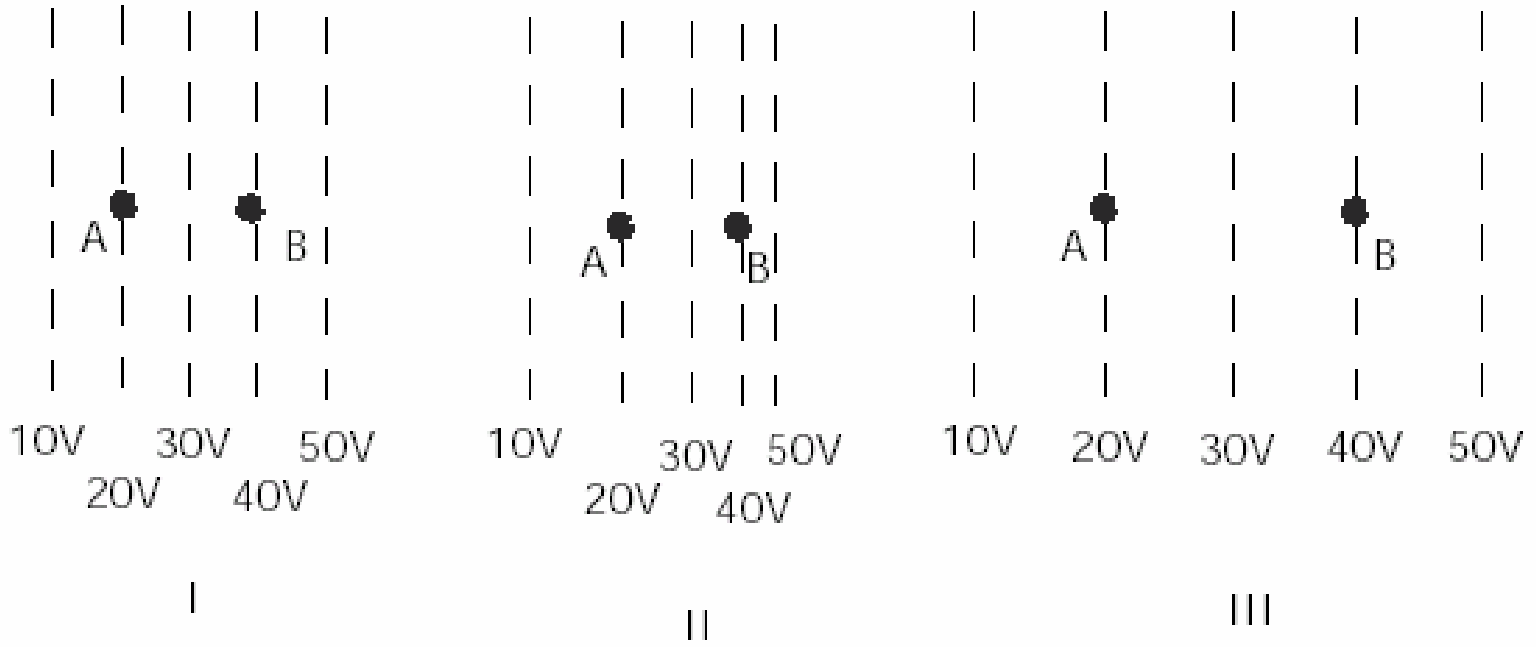
Electric Potential/Field Concept Cluster



D. Maloney, T. O'Kuma, C. Hieggelke, and A. Van Heuvelen, Am. J. Phys. **69**, S12 (2001).

#18

In the figures below, the dotted lines show the equipotential lines of electric fields. (A charge moving along a line of equal potential would have a constant electric potential energy.) A charged object is moved directly from point A to point B. The charge on the object is +1 μC.



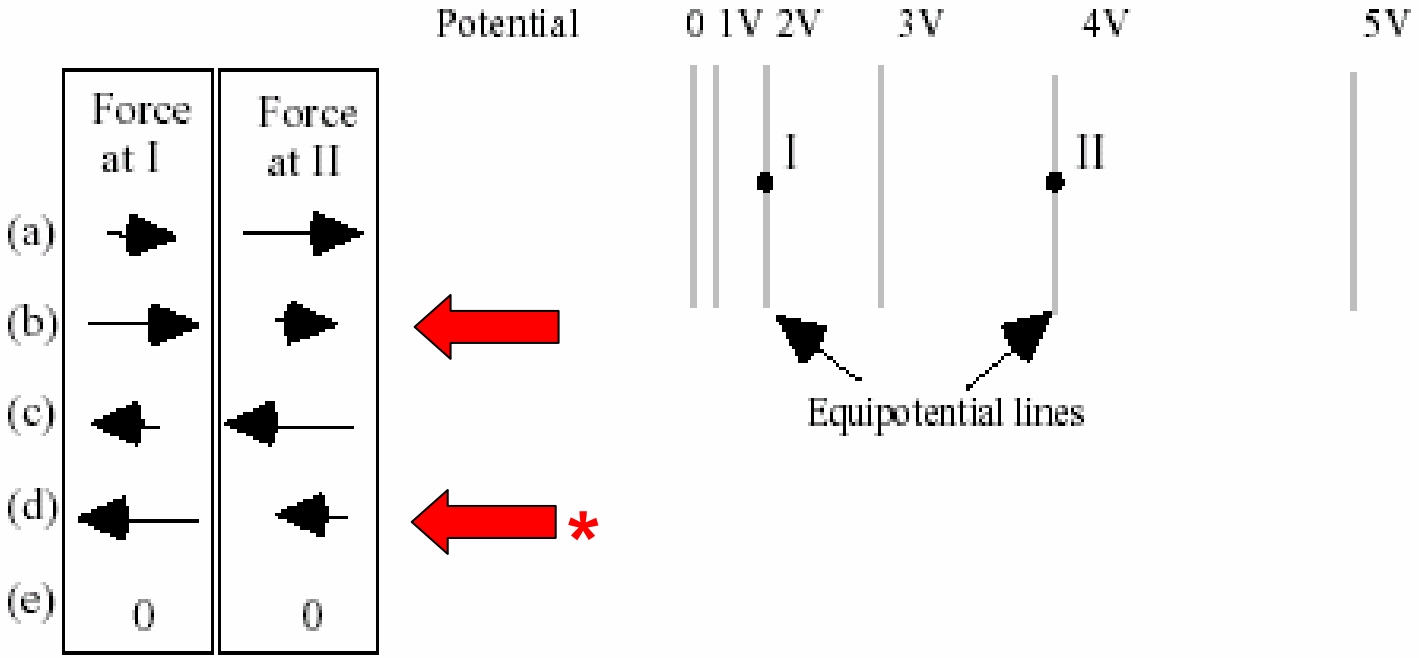
How does the magnitude of the electric field at B compare for these three cases?

(a) I > III > II
(b) I > II > III
(c) III > I > II
(d) II > I > III **[correct]**
(e) I = II = III

closer spacing of equipotential lines ⇒ larger magnitude field

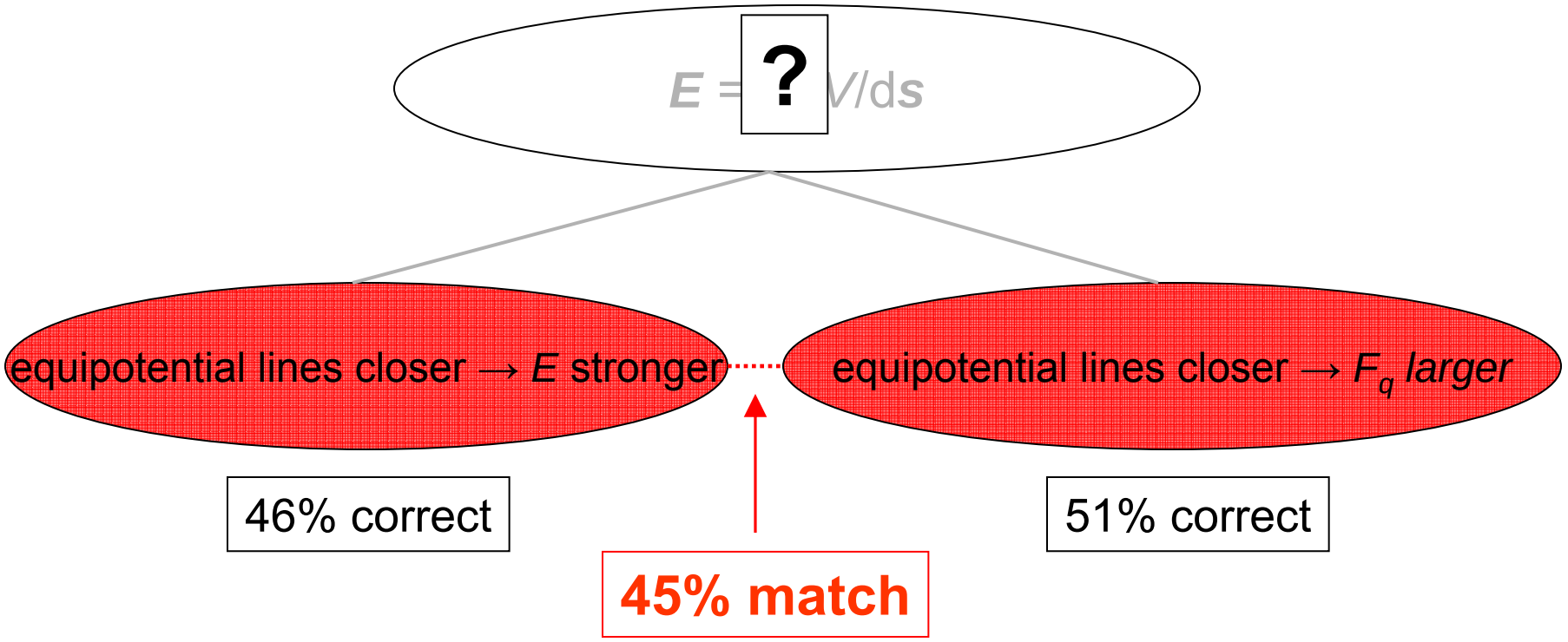
#20

A positively-charged proton is first placed at rest at position I and then later at position II in a region whose electric potential (voltage) is described by the equipotential lines. Which set of arrows on the left below best describes the relative magnitudes and directions of the electric force exerted on the proton when at position I or II?

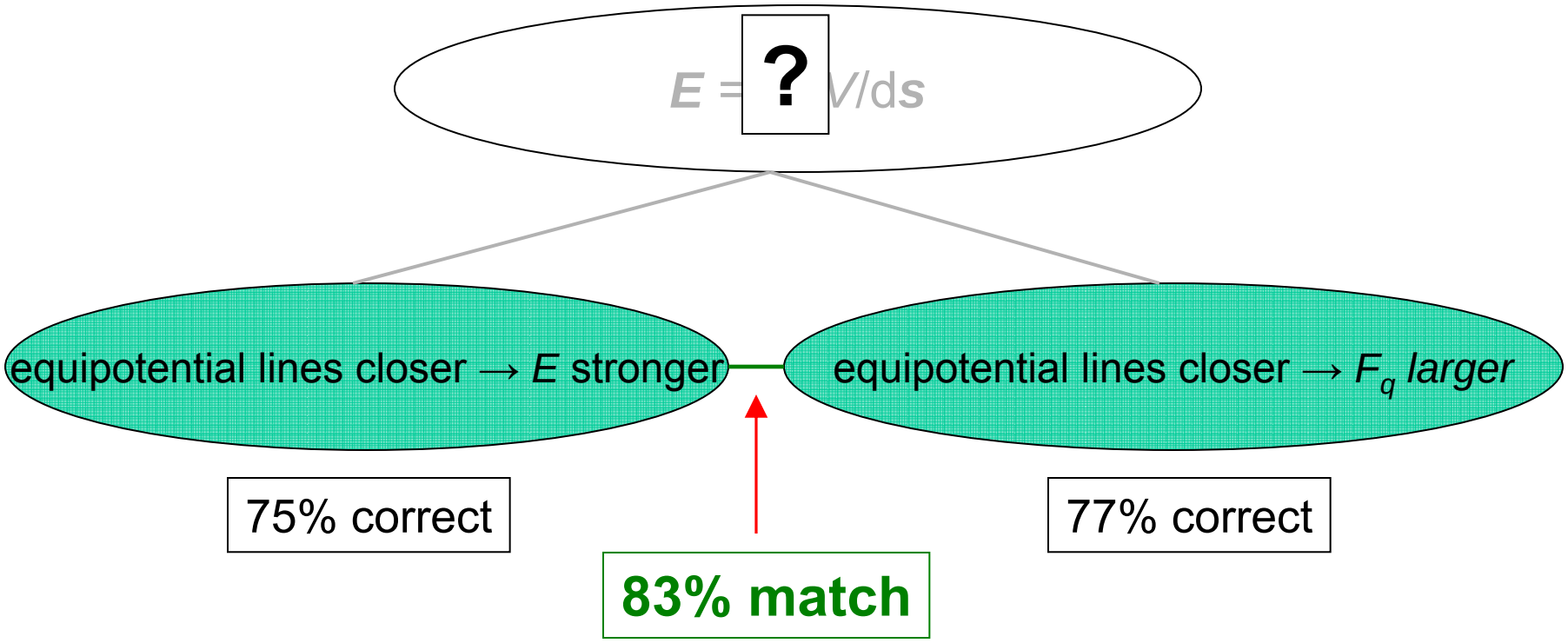


(b) or (d) consistent with correct answer on #18

Pre-Instruction, ISU (1998-2001)



Post-Instruction, ISU (1998-2001)



Summary

- A “concept” can be considered as an arbitrarily circumscribed portion of an interlinked array of knowledge elements.
- Assessment of conceptual understanding implies probing a specific set of knowledge elements along with their links, broadly defined.
- The practical definition of a particular concept (or concept cluster) is determined by a specific target population at a specific point in their learning trajectory.