Visuospatial thinking in science education

Invited talk

UNISA ISTE conference, 23-28 October 2016

Kruger National Park, Mopani Camp

Phalaborwa, Limpopo, South Africa

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Outline of the talk

- History of science, developmental psychology and cognitive science
- Tools of visuospatial reasoning: our research
  - Diagrams
  - Gestures
- Pitfalls of mental imagery
- Working hypotheses for physics education

Childhood anecdotes and introspective reports

James Clerk Maxwell (1831-79)

Constructed mechanical toys, polyhedra, generated ellipse with two pins and loop of thread

Hydrodynamic and mechanical models of electrostatic and magnetic fields, electromagnetic induction

Other examples of scientists with extraordinary visuospatial abilities: Faraday, Helmholtz, Poincaré, Hadamard, Watt, Tesla, Herschel, Kekulé, Watson, Feynman, Hawking... [1]

[1] *Shepard, R. N. (1988). The imagination of the scientist. In K. Egan and D. Nadaner (Eds.) Imagination and education (pp. 153-185). Teacher's College, New York and London.*

Childhood anecdotes and introspective reports

Albert Einstein (1879-1955)

Language disability; arithmetic challenge; fascination with physical devices (magnetic compass, model steam engine); 14 storey house of cards; geometrical proof of Pythagoras theorem before age 10

"early... preoccupation within a relatively private visual-spatial domain, in preference to the socially and institutionally controlled verbal domain" [1]

"the psychical entities which seem to serve as elements in thought are certain signs and more or less clear images which can be 'voluntarily' reproduced and combined... The above mentioned elements are, in my case, of visual and some of muscular type." [2]

[1] *Shepard, R. N. (1988). The imagination of the scientist. In K. Egan and D. Nadaner (Eds.) Imagination and Education (pp. 153-185). New York and London: Teacher's College.*

[2] *Hadamard, J. (1949). An essay on the psychology of invention in the mathematical field. Princeton, NJ: Princeton University Press.*

Model-based reasoning

Science in practice

- Analogies
- Imagistic representations
- Mental simulations
- Thought experiments

- Inscriptions, tools, gestures
- Narration of visual experiences

Nersessian, N. J. (2008). Creating Scientific Concepts. MIT Press, Cambridge, MA.

Developmental psychology

- Cognitive abilities emerge out of early sensorimotor experiences (Piaget)
- Child's intellectual development occurs through convergence of speech and practical activity, including tool use (Vygotsky)
- Gestures are external representations: precursors to drawing and writing (Vygotsky)

Vygotsky, L. S. (1978). Mind in Society: The Development of Higher Psychological Processes. Eds.: Cole, M., John-Steiner, V., Scribner, S., and Souberman, E., Harvard University Press, Cambridge, MA. pp.24, 107-114.

Continuing connections - evidence from neuroscience

- Verbal and visuospatial information is manipulated mutually independently (two parts of working memory).
- Visual perception and mental imagery share common neural mechanisms.
- Category knowledge is processed in modality-specific brain areas.[1]
- Our physical movements affect spatial inferences.

[1] *Smith E. E., and Kosslyn, S. M., (2007). Cognitive Psychology: Mind and Brain. PHI Learning, Delhi, pp 170-4.*

Visuospatial thinking

Two pathways to processing visuospatial information:

- What
- Where/How

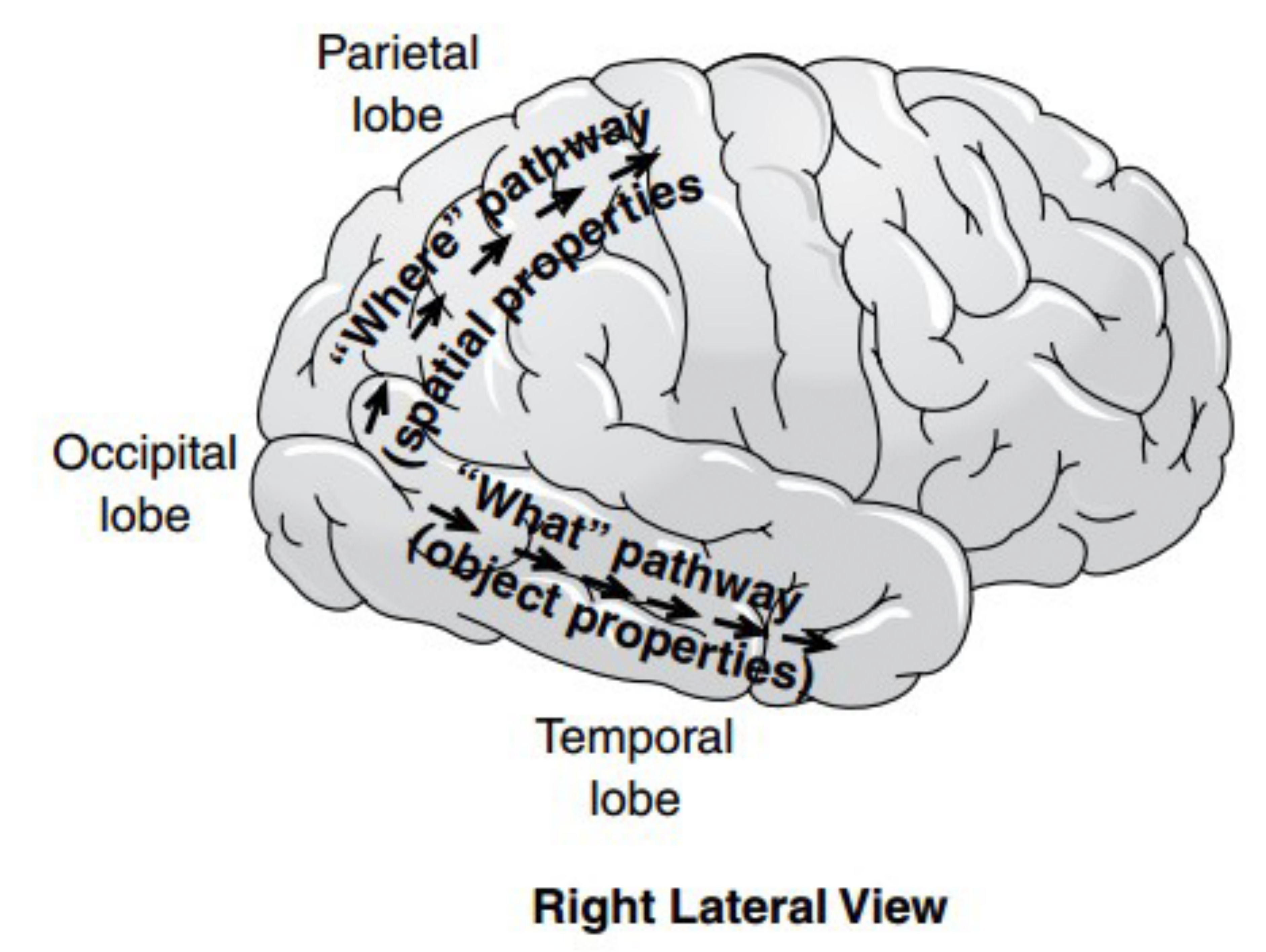


Figure source: Smith E. E., and Kosslyn, S. M., (2007). Cognitive Psychology: Mind and Brain. PHI Learning, Delhi, p 97.

Other modes of spatial cognition

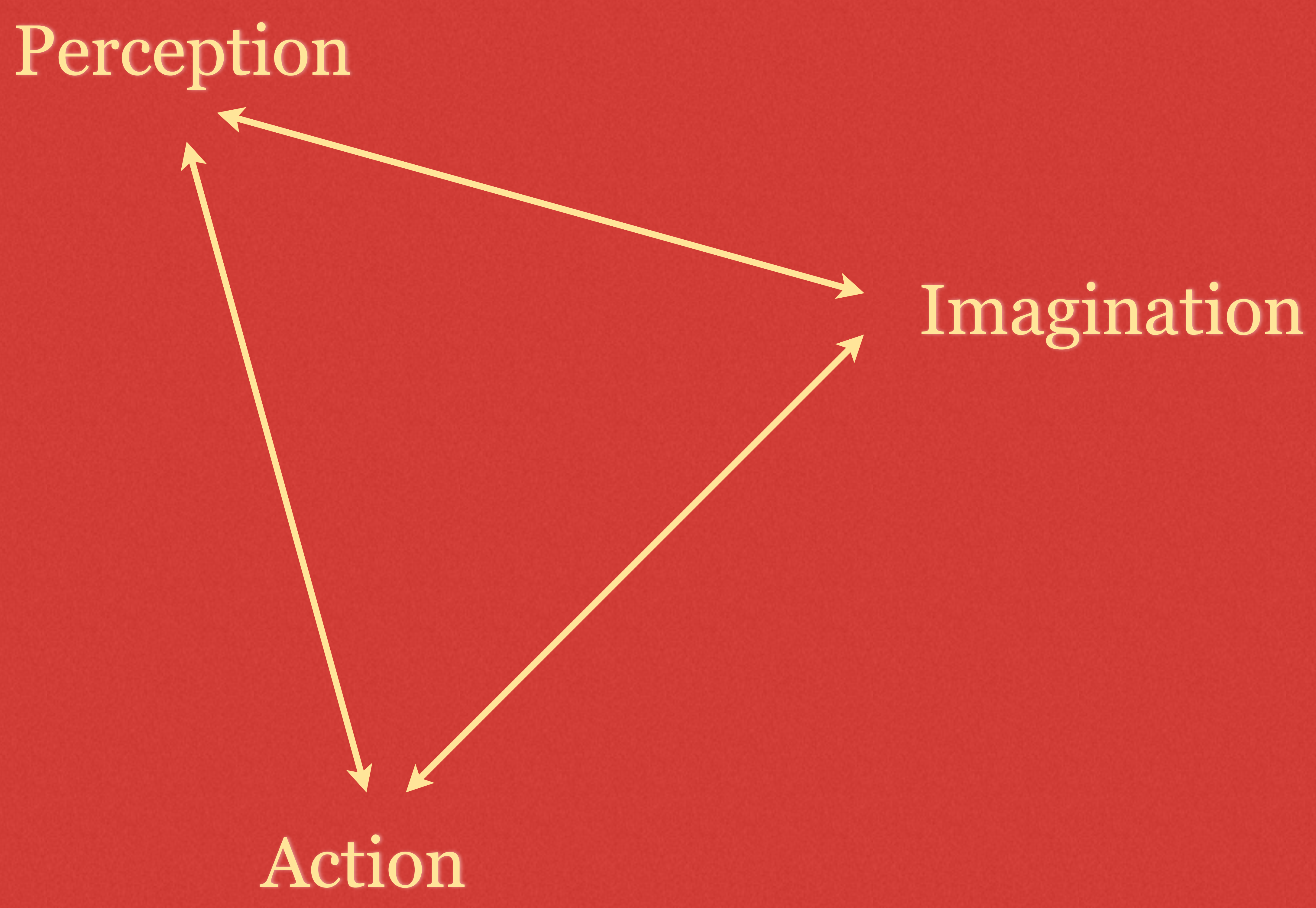
- Kinesthetic (Vestibular + Proprioception)
- Tactile
- Auditory
- Olfactory

Cognition is Embodied

"Cognitive activity takes place in the context of a real-world environment and it inherently involves perception and action ... Even when de-coupled from the environment the activity of the mind is grounded in mechanisms that evolved for interaction with the environment -- that is, mechanisms of sensory processing and motor control." [1]

[1] *Wilson, Margaret (2002). Six views of embodied cognition, Psychonomic Bulletin and Review, Vol 9 (4), pp. 629-36.*

Common coding



Chandrasekharan, S. (2009). Building to Discover: A Common Coding Model. 33, 1059-86.

Tools of visuospatial thinking

- Diagrams and Gestures
  - ~ Facilitate visual, spatial and kinesthethic aspects of mental simulations.
  - ~ Combine depictive (experiential) with schematic (abstract) elements.

Diagrammatic reasoning

- Diagrams are visually economical, moderately precise representations. They encode visual and spatial information, are amenable to transformations.
- Diagrams are efficient external representations for visuospatial reasoning processes. [1]
- Diagrams enable analytical thought, help students work within an abstract context, resulting in responses that are more explanatory than descriptive. [2,3]

[1] *Subramaniam, K. and Padalkar, S. (2009). Visualisation and reasoning in explaining the phases of the moon. International Journal of Science Education, 31 (3), 395-417.*

[2] *Ramadas, J. and Driver, R. (1989). Aspects of secondary students' ideas about light. Leeds: Centre for Studies in Science and Maths Education, University of Leeds.*

[3] *Ramadas, J. and Shayer, M. (1993). Schematic Representations in Optics, In P. Black and A. Lucas (Eds.), Children's Informal Ideas: Towards Construction of Working Theories, Routledge, London.*

'Representative' diagrams

- Children draw schematic diagrams according to problem demands. [1]
- Textbook visuals are illustrative or 'representational'. Visuals for organisation, interpretation and transformation of ideas are missing. [2]

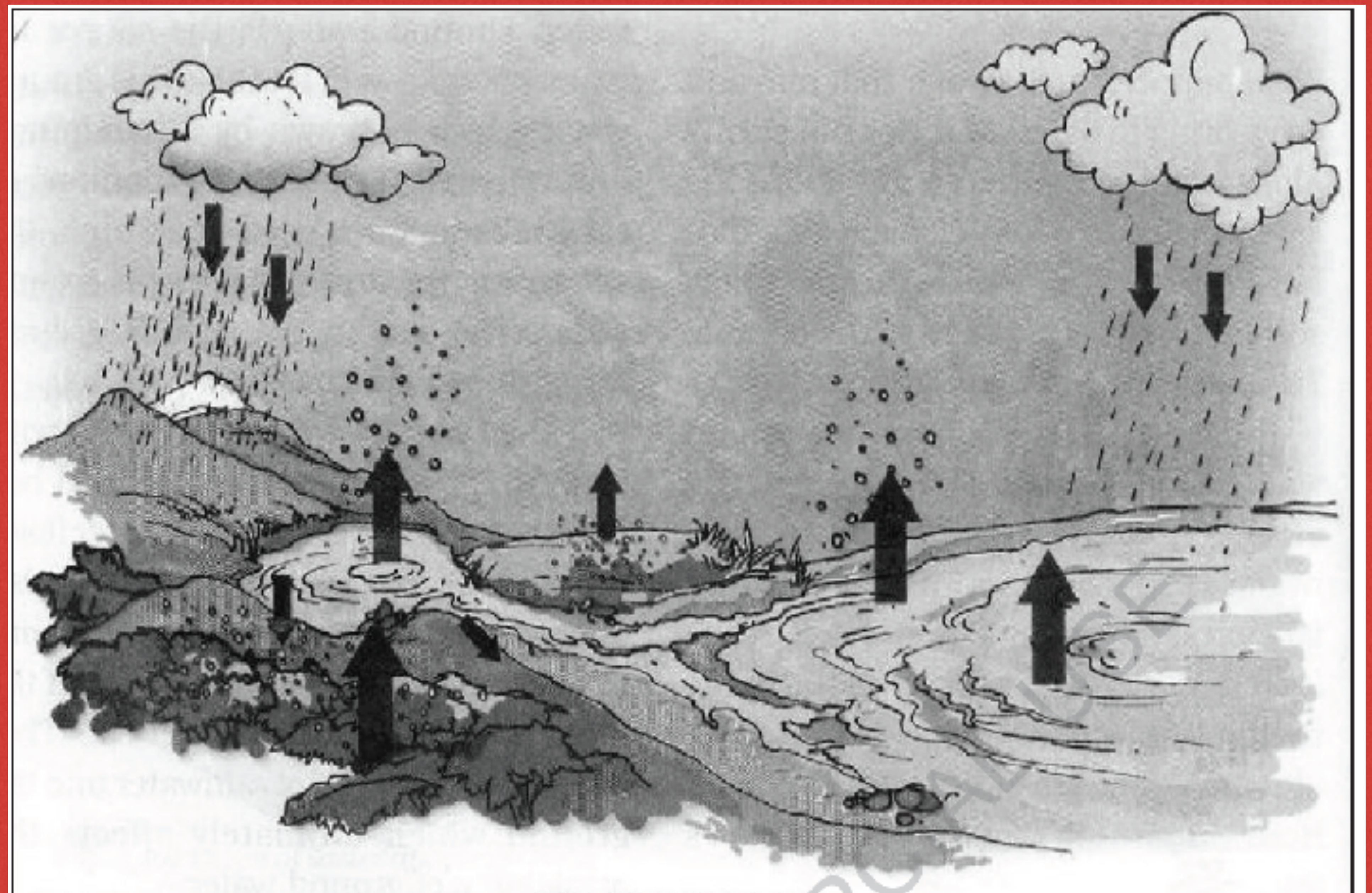


Fig. 14.9 Water cycle

[1] *Ramadas, J (1990). Motion in children's Drawings, In I. Harel (Ed.), Constructionist Learning: A 5th Anniversary Collection of Papers, MIT Press, Cambridge, MA.*

[2] *Vinisha, K. and Ramadas, J. (2013). Visual representations of the water cycle in science textbooks, Contemporary Education Dialogue, 10 (1), 7-36, 2013.*

Figure source: Science - Textbook for Class 6, NCERT, 2006

'Transformative' diagrams

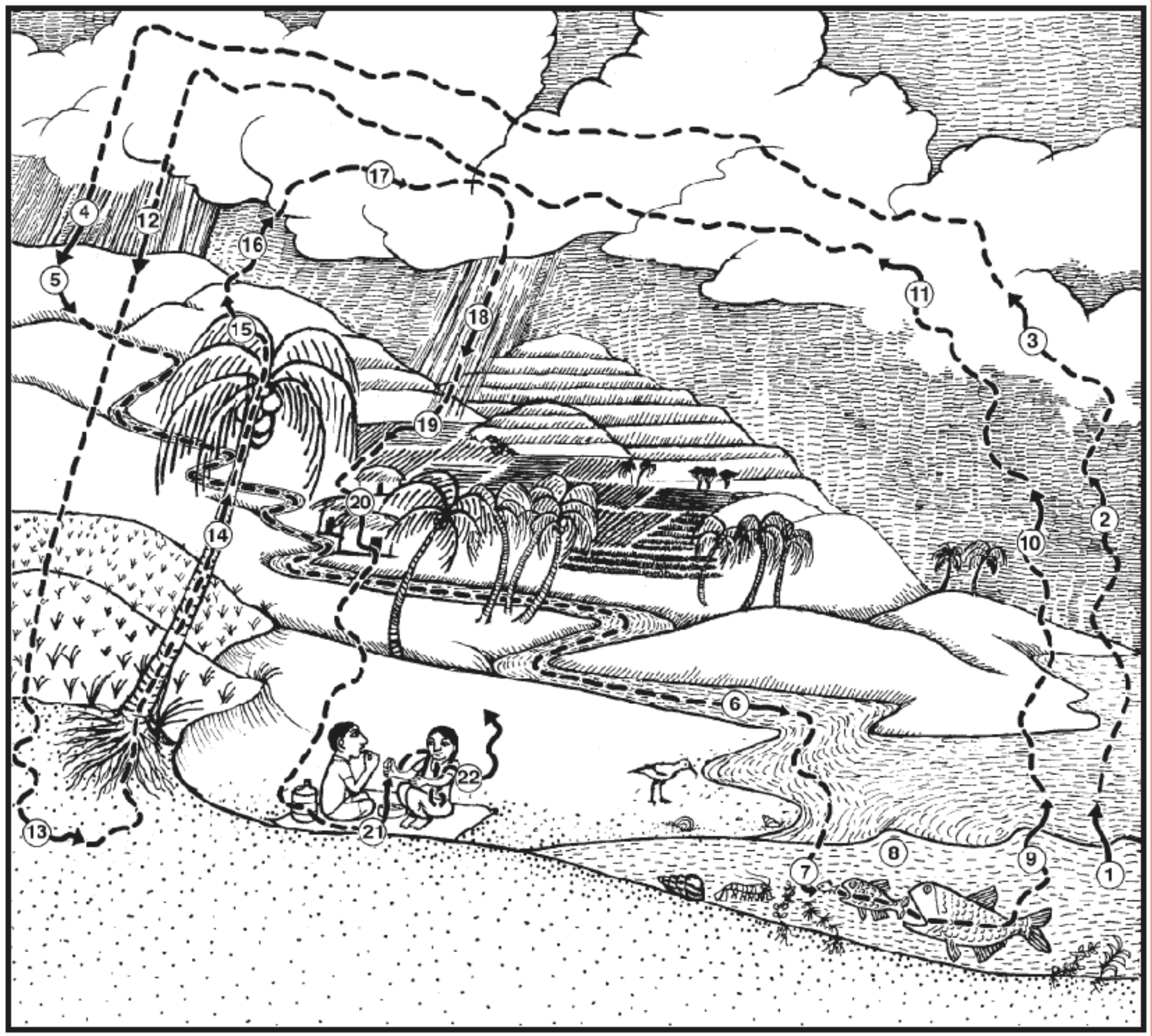
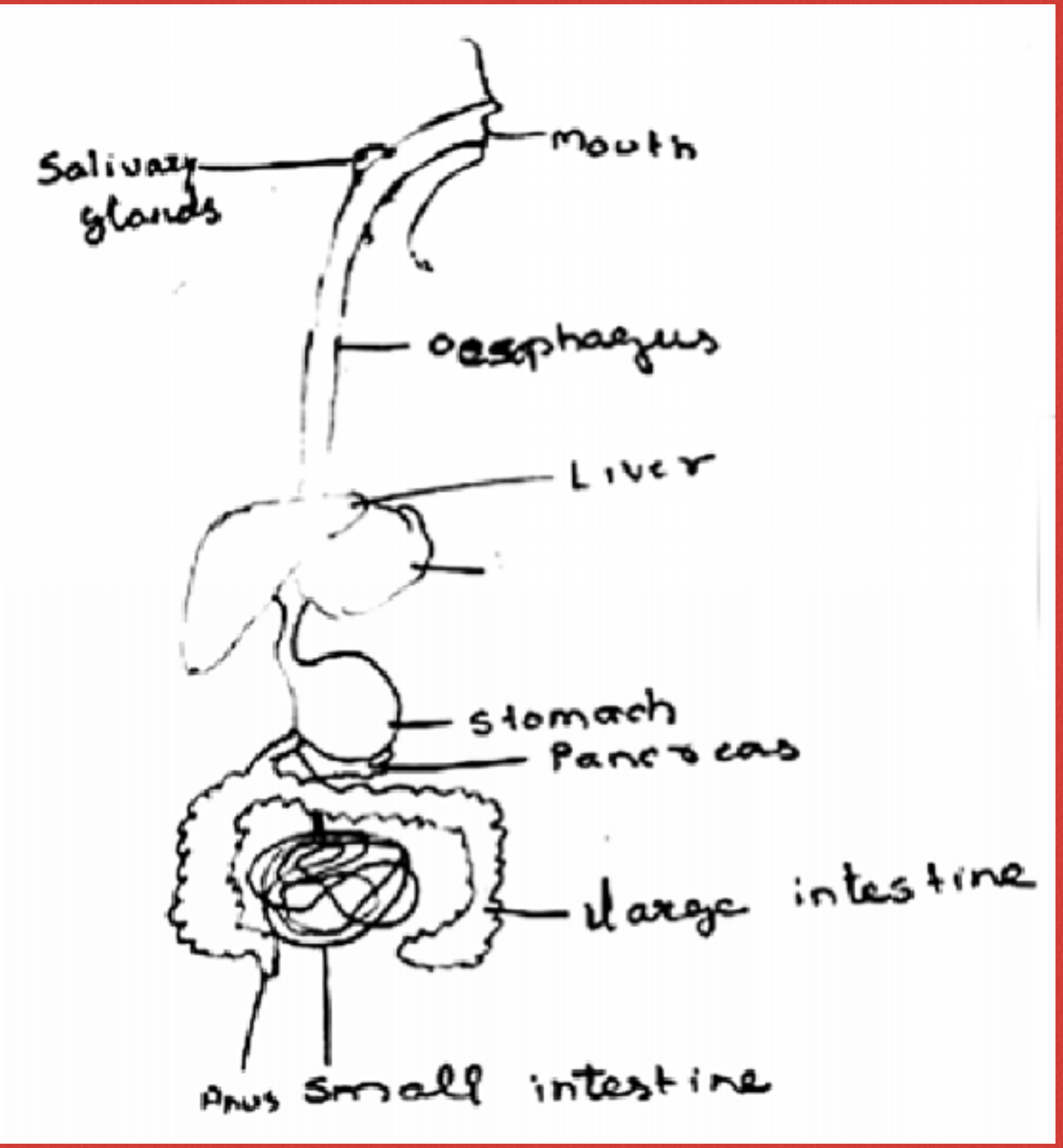


Illustration of the water cycle by Karen Haydock: Ramadas, J. (2001). Small Science, Text Book for Class 4, Homi Bhabha Centre for Science Education, Mumbai, p.52.

Mental simulation in biology

- Imagery experiments - mental rotation and scanning; mental manipulation of images
- Human body systems - not normally visible
  - Structure (static) - Function (dynamic)
  - Drawings from novel viewer / object orientation
  - Manipulating structure to infer effect on function
  - Describing a transformation
- Mental visualisation could be expressed verbally, while drawings (like text) could be learnt by rote.[1]



[1] *Mathai, S., & Ramadas, J. (2009). Visuals and visualization of human body systems. International Journal of Science Education, 31 (3), 439-458.*

Visualising DNA structure

Textbook representations (Maharashtra State, Class XII)

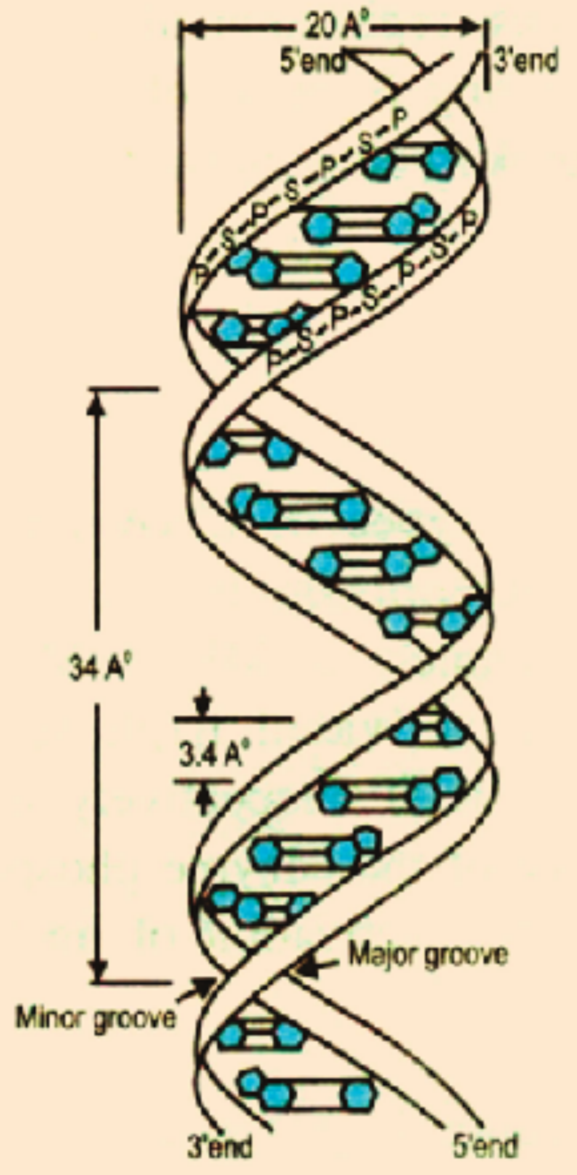


Fig 2.1 (A) Structure of DNA : Watson and Crick's model

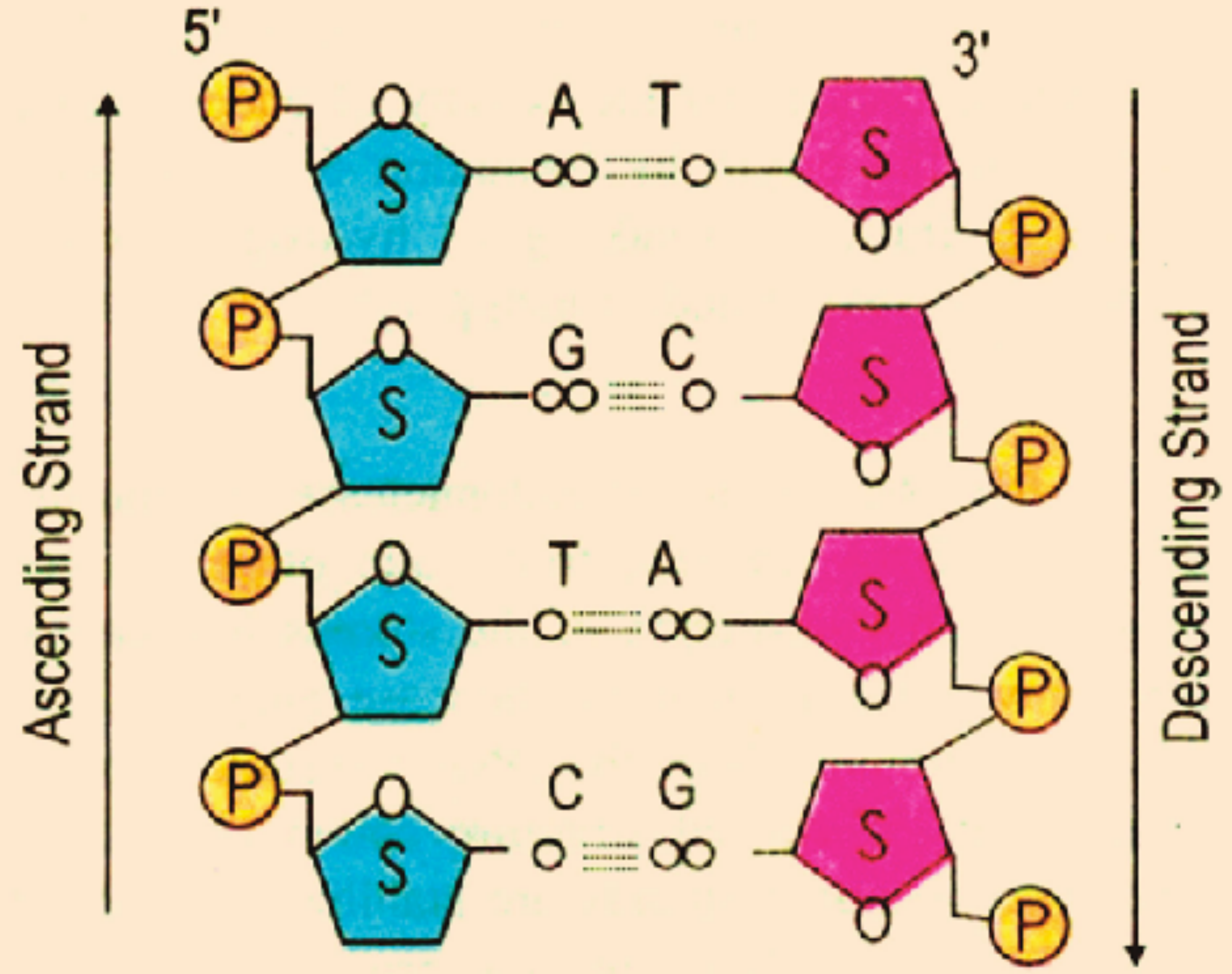


Fig 2.1 (B) Diagrammatic representation of DNA molecule

Gesture with mental simulation

- DNA skeletal structure; molecular structure
- Familiar diagram --> Gesture the configuration of base pairs (diagnostic) --> Ladder analogy --> Gesture --> Simulate the act of climbing --> Gesture
- Model --> Gesture --> Simulation / Animation --> Gesture
  - ~ From diagnostic to pedagogic
  - ~ Gesture in air more effective than with model

Srivastava, A. & Ramadas, J. (2013). Analogy and Gesture for Mental Visualization of DNA Structure. In Treagust, D. F. & Tsui, C.-Y. (Eds.), Multiple Representations in Biological Education. Dordrecht, The Netherlands, pp. 311-329.

Astronomy - from phenomenon to mental model

- Pedagogical gestures in elementary astronomy [1]
  - to internalise a phenomenon: e.g. tracing observed path of the sun, extrapolating to different latitudes and different seasons
  - to internalise a model: e.g. shapes, configurations, relative motions of earth and sun
- Other possibilities - spatial structures at large and small scales, molecular structures, vector quantities - velocity, acceleration, forces; fields

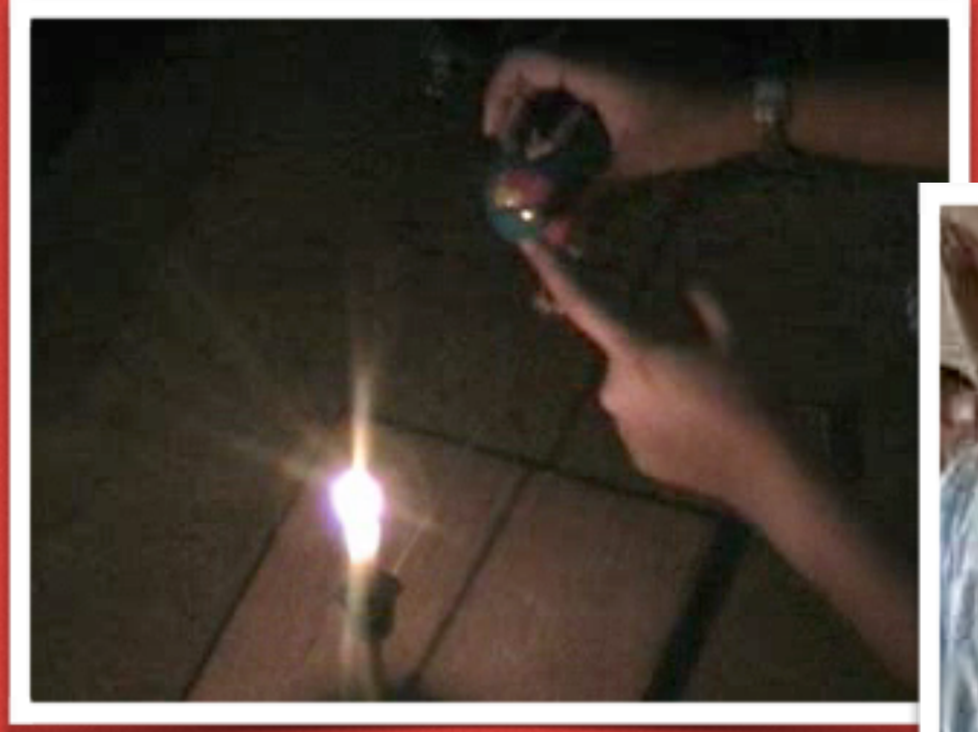
[1] *Padalkar, S., & Ramadas, J. (2011). Designed and spontaneous gestures in elementary astronomy education. International Journal of Science Education, 33 (12), 1703-1739.*

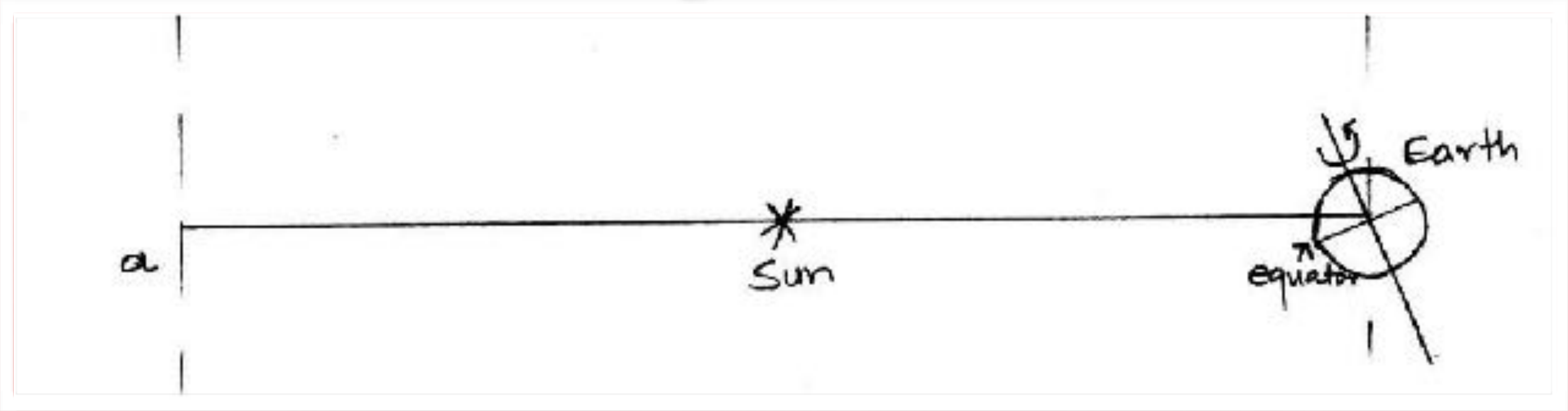
http://web.gnowledge.org/pedagogic-gestures/

From concrete model to diagram

- Gestures done in the presence of concrete model help link it to a diagram - e.g. right hand thumb rule for rotation of earth; tilt of earth's axis wrt orbital plane

- Gestures strip away the concrete details, hence promote generalisation



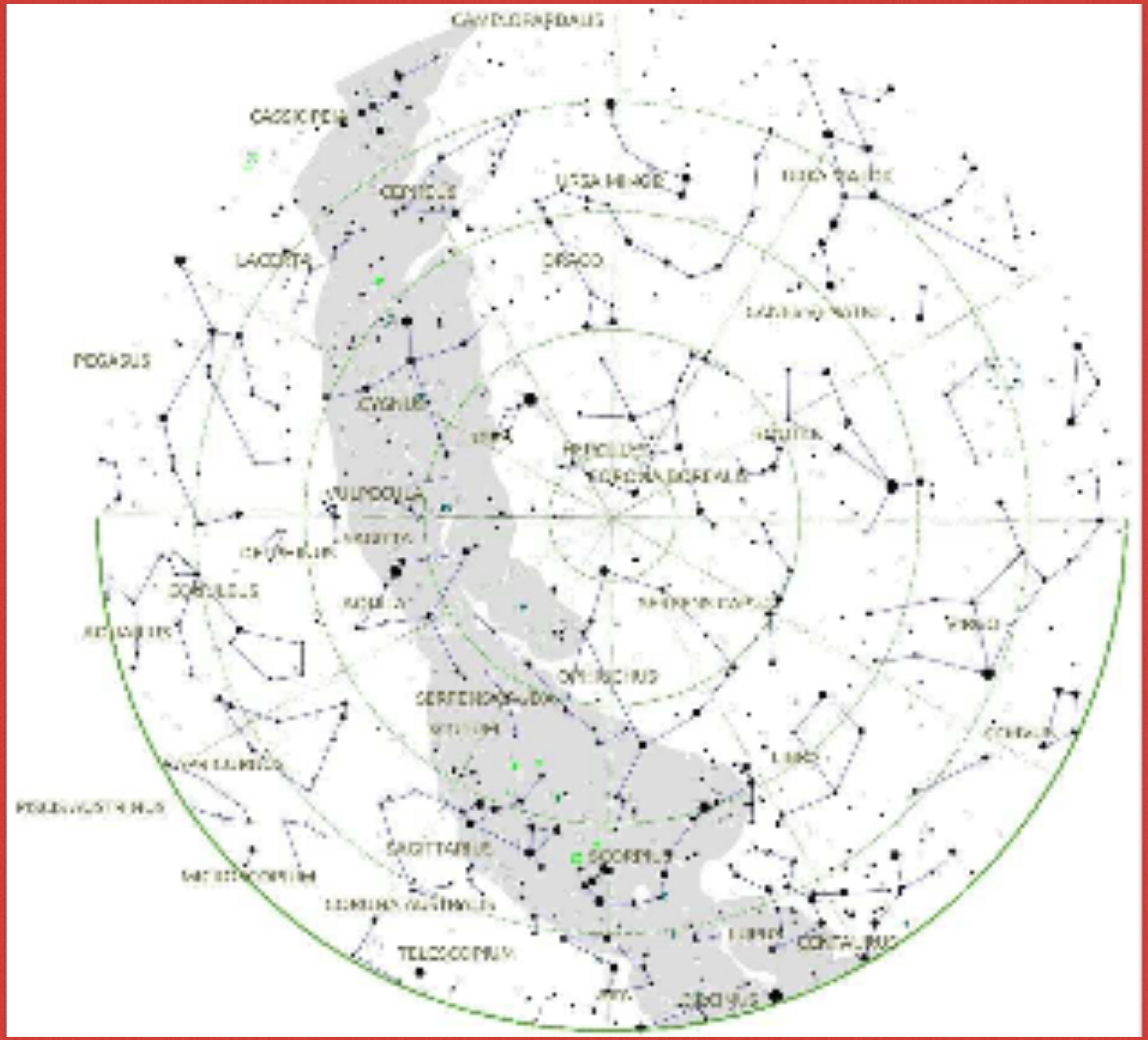


Padalkar, S., & Ramadas, J. (2011). Designed and spontaneous gestures in elementary astronomy education. International Journal of Science Education, 33 (12), 1703-1739.

http://web.gnowledge.org/pedagogic-gestures/

When gestures become redundant

- Mapping an alt-azimuth projection sky chart to the 'dome' of the sky
- Question from INAO 2014
- 20 Students from JS-OCSC - 8 Junior Astronomy / 12 Junior Science
- Interviews - 3-11 minutes (average 6 min)



http://olympiads.hbcse.tifr.res.in/olympiads/wp-content/uploads/2016/09/inao2014-Q-S.pdf

When gestures become redundant

- Interview questions
  - ~ Mark N/S/E/W on the map, why?
  - ~ Zenith, Horizon
  - ~ Position of Sun
  - ~ Position of Moon

- Reasoning and Inference
  - ~ On sky map (2nd diagrammatic reasoning; Deictic gestures)
  - ~ Gestures in space (Metaphorical gestures)
  - ~ Recalling prior knowledge (Terminology, Zodiac signs)

Students' strategies

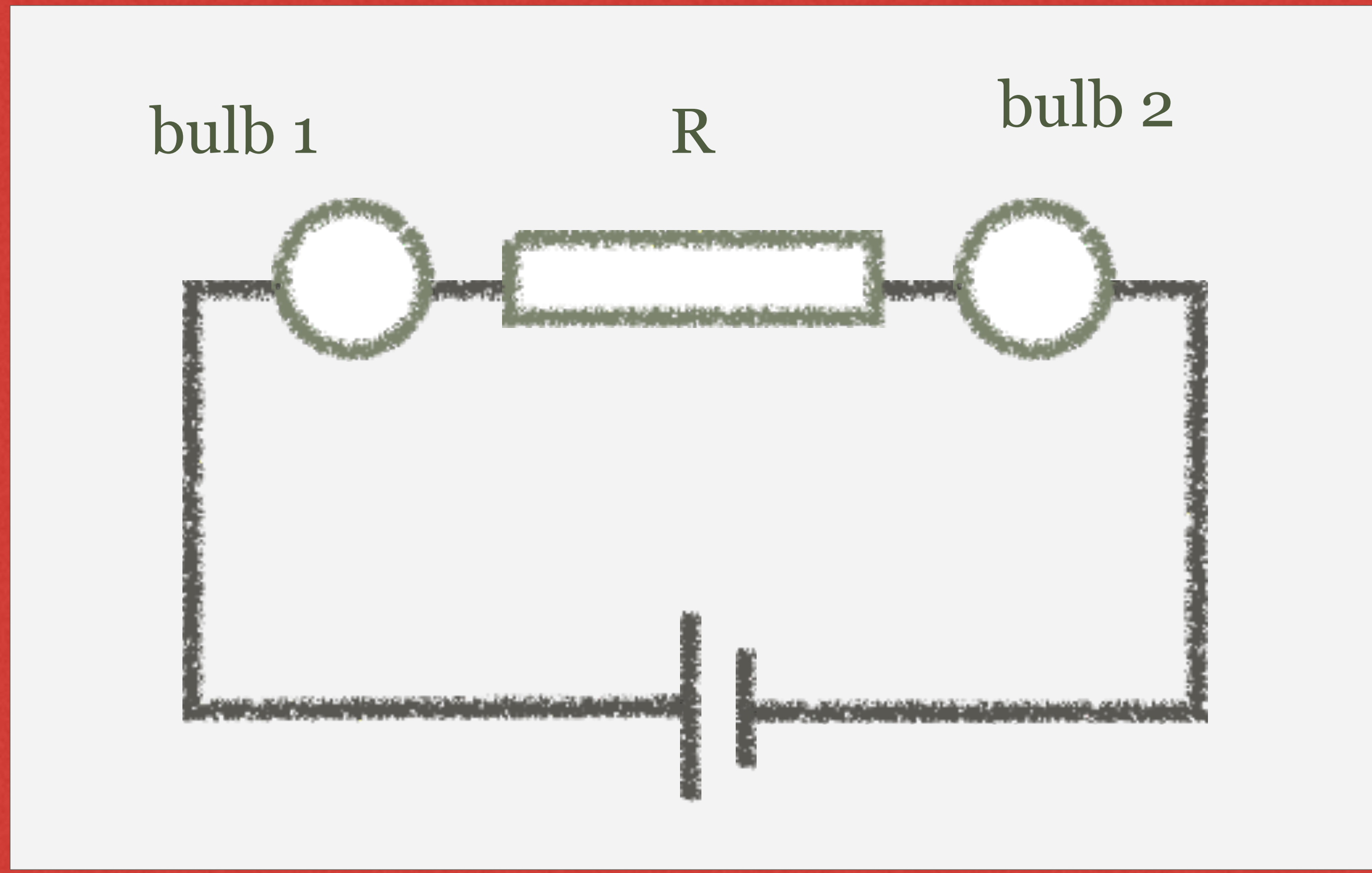
- Syntax - mapping chart to dome of sky
  - E/W reversal - challenge for JS; easy for JA
  - Zenith, Horizon - as above; terminology unfamiliar to JS
- Reasoning
  - Position of sun - 10/12 JS from time of day; 7/8 JA from ecliptic
  - Position of moon
- Gestures in space (Metaphorical)
  - East-West reversal - 11/12 JS ; 6/8 JA
  - Zenith: 11/12 JS ; 1/8 JA
  - Horizon: 8/12 JS ; 1/8 JA
  - Position of the moon: 6/12 JS ; 6/8 JA

	Eclipse explanation	Correct explanation	Total students
JS	8	1	12
JA	2	4	8

Visuospatial Reasoning in using Projective Sky Maps (Unpublished): Presentation at the International Conference on Physics Education, Beijing, China, August 10-15, 2015. Authors: S. Jawkar, A. Sule, S. Padalkar, J. Ramadas (presenting author) http://www.hbcse.tifr.res.in/resources/talks-by-hbcse-members/icpe15-jr-hbcse.pdf

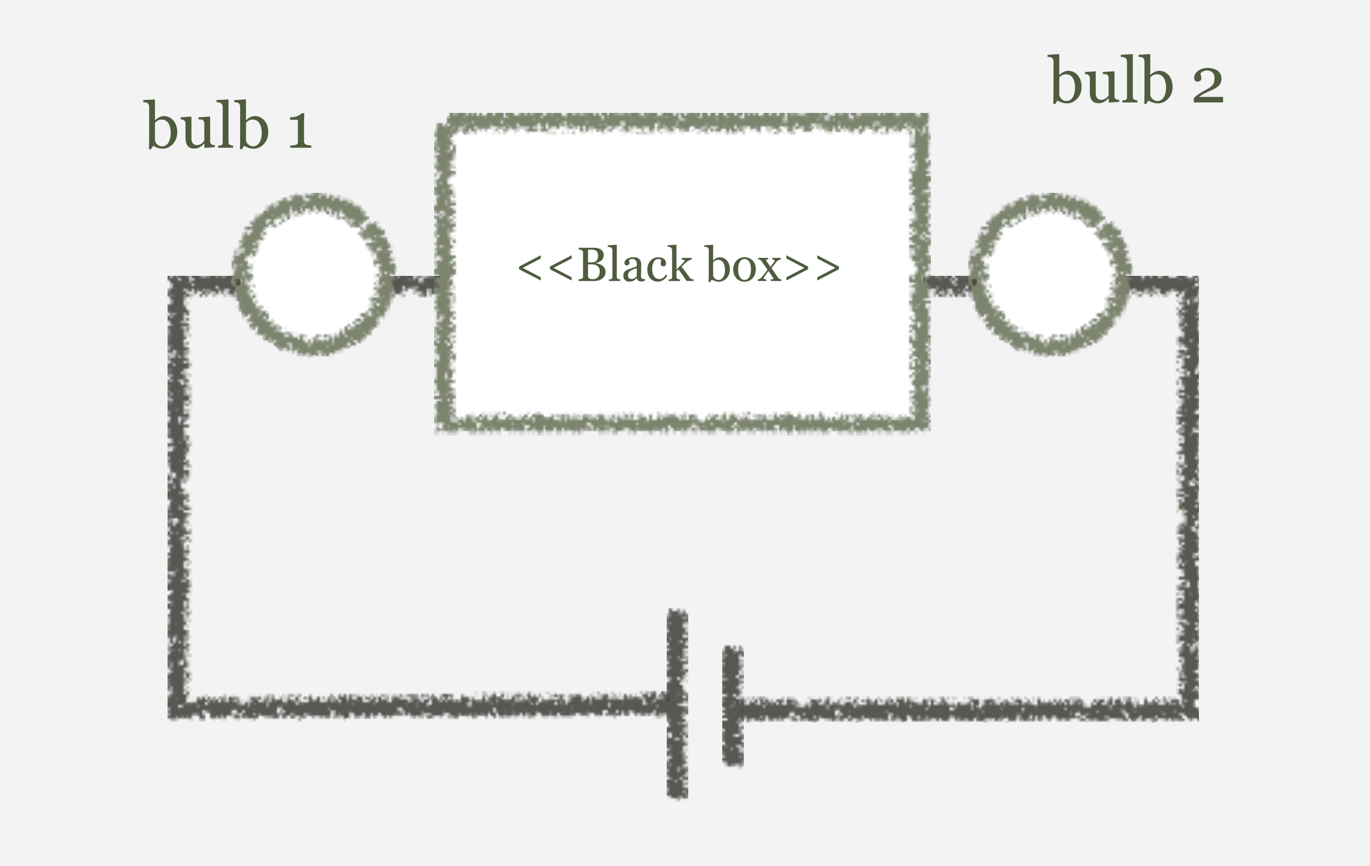
Pitfalls in mental imagery

Situation 1



"Bulb 2 shines less brightly."

Situation 2

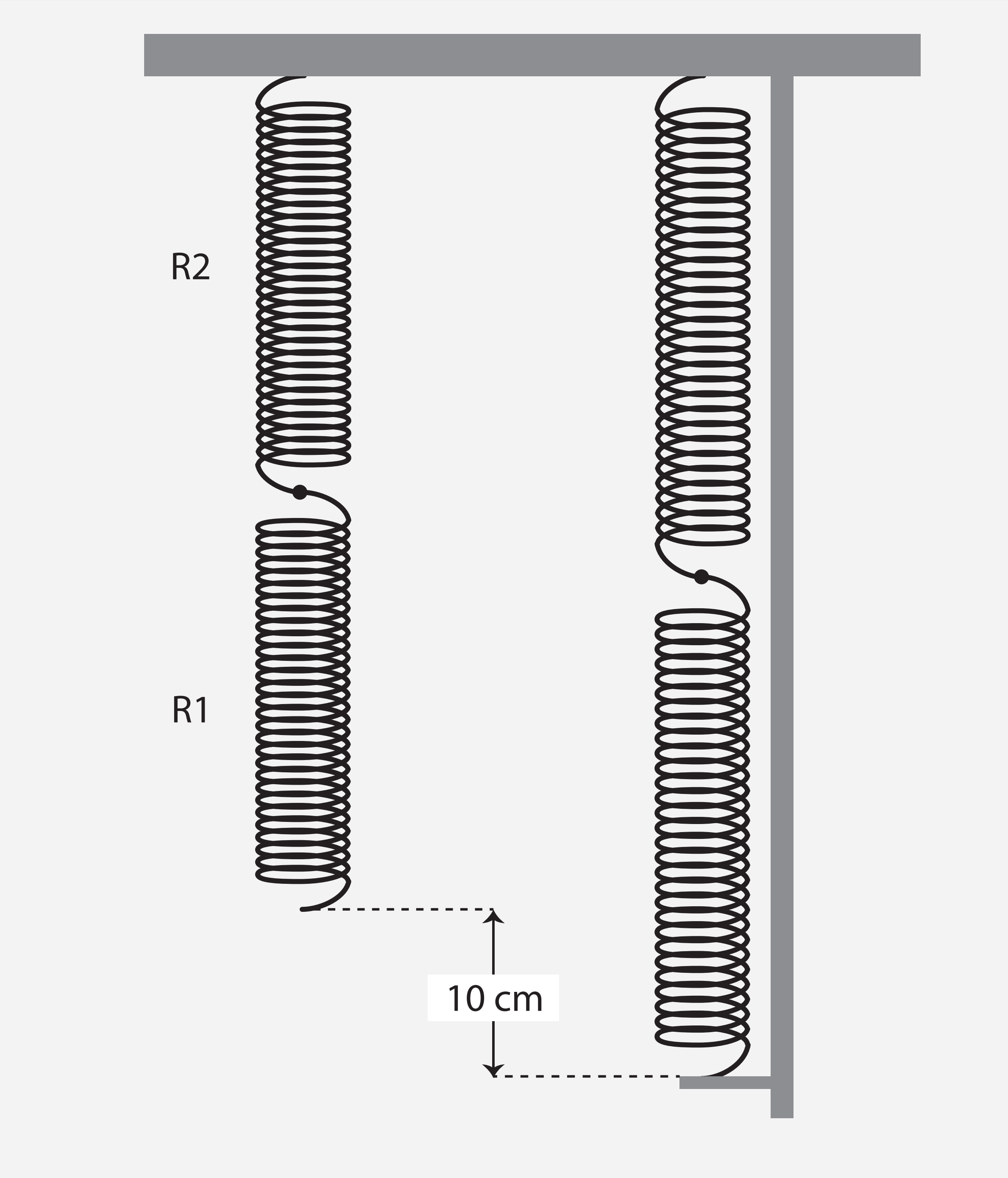


"For the two bulbs to shine equally there should be no battery in the box."

Viennot, L. (2001). Reasoning in Physics: The Part of Common Sense. Dordrecht: Kluwer Academic Publishers. p.100.

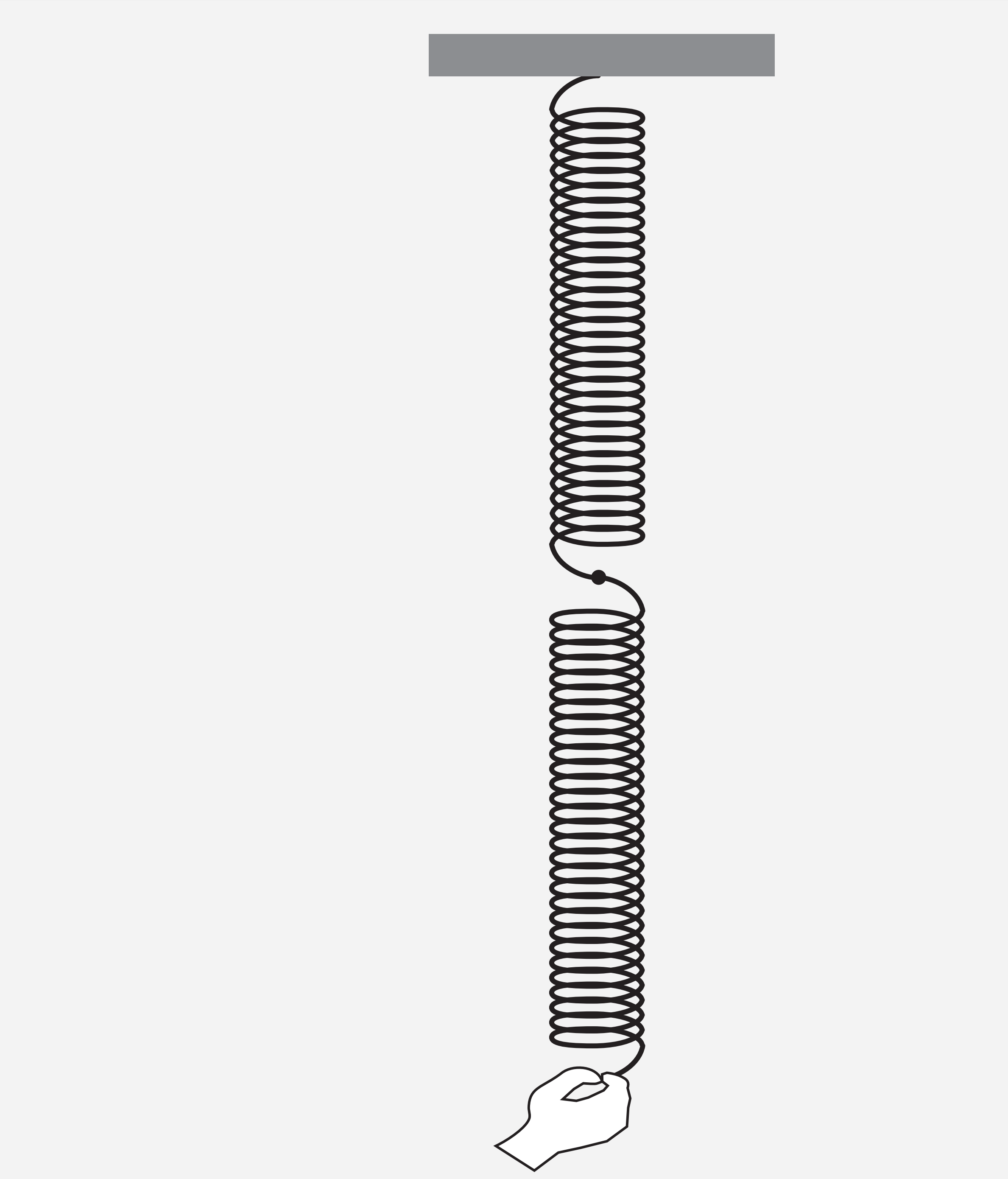
Pitfalls in mental imagery

Situation 1



What is the difference in the length of the upper spring?

Situation 2



Displacement of the junction point?

Viennot, L. (2001). Reasoning in Physics: The Part of Common Sense. Dordrecht: Kluwer Academic Publishers. pp 96-7.

Working hypotheses for physics education

- Commonsense models of reality are grounded in our visual-spatial-temporal experiences in the world. These experiences are characterised by agency, effect and a sequential chronology of events.

- In contrast, the laws of physics (Newton’s laws, Maxwell's equations, Schrödinger's equation) are local in space and time.

- Reasoning in the quasi static situations common in physics requires one to arrest the mind's natural sequential flow in time (imagery or mental simulation) and focus on a single body, or its contact point, or a point in its trajectory (in mechanics), or a component of a circuit… significantly, tapped by tests of spatial thinking.

Pedagogy as design

- Core principles in physics are often operationalised through diagrams (e.g. free body diagrams). Diagrams are a tool for reasoning and communication.
- Diagrams with gestures (external representations) could couple effectively with internal mental models / representations with the required visuospatial and temporal properties.
- Low-tech science pedagogy for all could develop best in collaboration with designers.

Thanks

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- Manoj Nair