Understanding and Implementing Visual Metaphor

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Research Team: Authors & Co-PI's
Dr. Matthew Peterson
Dr. Kevin Wise
Dr. Robb Lindgren
Dr. Donna Cox
Nitasha Mathayas

Design Team
Joe Carpenter
Bella Reinhofer
Sander Weeks
Qing He
Meme Betadam

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Introduction

Science curriculum materials, particularly textbooks, rely heavily on diagrams and other visualizations of phenomena to convey core concepts and critical ideas. While the content of these visualizations is generally informed and vetted by scientists, the pedagogical design and the ways in which these visualizations have been informed by principles of visual communication are typically not given a high degree of scrutiny. And yet multimedia learning theory (Mayer, 2009) and other theories of instructional design argue that the manner in which these visualizations are constructed can have a significant impact on how people learn from them. We argue in this white paper that substantial research needs to focus on the characteristics of effective visualizations for learning, and we propose specifically to investigate and create proof-of-concept designs that employ an especially promising element of learning media: visual metaphor. We intend to explore the application of visual metaphors to both non-interactive (textbooks) and interactive (tablet and handheld applications) visualizations, and we ultimately aspire to assemble principles of visual learning design that can be employed to domains that go beyond science education.

We approach this white paper with the following objectives:

- Introduce visual metaphor to a community of researchers, especially at the University of Illinois, in the hope that opportunities for connection and collaboration, as yet unforeseen by us, might be realized.
- Connect visual metaphor to science education.
- Introduce the notion of "productive research," where authentic instructional media are produced for empirical study and are subsequently made available to teachers.
- Use the design process, where investigation is guided by speculative and relatively rapid prototyping, to demonstrate some of the potential of visual metaphor for science curriculum materials.
- Use the design process to conduct informal "tests" of visual metaphor, exposing issues likely to arise in subsequent funded work on authentic media.
- Produce visual material that we can utilize in future proposals.

Roots and Expressions of Metaphor

Metaphor is ubiquitous in strategic communication. While language is most heavily constructed with or constituted of metaphor, purely visual communication (that is, imagery and diagrams) is the site of much metaphor use. While visual metaphor is currently employed in science education, it is most recognizable in advertising and editorial design, where designers are most concerned with convincing readers of something.

This paper is motivated by a paucity of empirical evidence concerning visual metaphor. Two of the PI's (Peterson & Wise) have been developing and interrogating a typology of visual metaphor through examples from advertising, a domain of use where goals are relatively basic and images most immediate. In this context, visual metaphor is used to influence outcomes of attention, memory, and attitude change (Phillips & McQuarrie, 2004). A third PI (Lindgren) has conducted research on how body-based metaphors (e.g., my body as an asteroid) can be employed to change students' perspectives and facilitate learning of challenging science concepts (Lindgren & Moshell, 2011). He is interested in how these embodied metaphors can be evoked through print and digital media such as textbooks and tablet devices. A fourth PI (Cox) has extensively used what we will call "fundamental" visual metaphor (diagrammatic elements such as arrows) in dynamic visualizations of complex data sets.

In a general sense metaphor is a device whereby one entity or concept is understood in terms of another. Attributes of a source entity or concept are selectively mapped onto a target entity or concept (Lakoff & Johnson, 2003; Forceville, 2002). The source thus helps to explain the target. For instance, to say that you find much of literary theory indigestible is to employ a metaphor with *food that can't be digested* as source and *literary theory* as target. This use of metaphor is *intentional*, an "artful deviation" in language. A comparably simple example of metaphor in purely visual form is exhibited in Fig. A.1, where the source *lion* is mapped onto the target *house cat* by the visualization of both source and target present and interacting. The intention here in relating the two is to in turn better sell cat food made with real meat (as a lion would surely demand).

But metaphor is more than a mere artful deviation in language, as it was first understood in the context of rhetoric. It is foundational to human thought (Lakoff & Johnson, 2003). During infant and child development, new knowledge is assimilated in large part by making associations with existing knowledge that persist—these associations are inherently and authentically metaphorical in nature (Johnson, 1987). Figurative or linguistic metaphor, in the most traditional sense as a rhetorical trope in verbal communication, is recast as a product of this *underlying human capacity* of conceptual metaphor, rather than as an *invented* device (Forceville, 2002; Koller, 2005). Thus, when metaphor is intentionally employed, the designer is making use of an existing human apparatus. In education, for instance, the use of metaphor allows students to employ a skill or an experience they have already acquired. Furthermore, it takes advantage of existing knowledge (source) to explain the unfamiliar (target). In writing about metaphor in science education, Gentner & Wolff (2000) argue that metaphors transform prior knowledge into systems of ideas that are richer and more robust.

As humans process verbal and visual information with separate and distinctive resources in working memory, and because verbal and visual codes have unique characteristics (Baddeley, 1998; Sadoski & Paivio, 2001), visual metaphor begs its own code-sensitive description. To that end, a theory of visual metaphor is being negotiated, especially in communication and advertising literature, which has increasingly been defined on its own terms (see: Forceville, 1996; Phillips & McQuarrie, 2004; Van Mulken, Le Pair, & Forceville, 2010) as opposed to "fit" to standing rhetorical theory on linguistic metaphor and its aligned rhetorical tropes (for earlier attempts to derive visual metaphor from linguistic metaphor, see: Durand, 1987; McQuarrie & Mick, 1996).

The literature has largely settled on three structural types of visual metaphor, described by Phillips and McQuarrie (2004) as *juxtaposition*, *fusion*, and *replacement*. This structural variation refers to the visual relationship between source and target. Motivated by lack of empirical evidence for these theorized types, PI's Peterson and Wise have undertaken a program of research in a media psychology laboratory that has begun to find differential and positive effects on attention and memory (Peterson, Wise, Ren, & Wang, in press). Fig. A.2 compares the visual metaphor structure types under consideration. *Juxtaposition* images present both source and target as separate, but often interacting, entities (a house cat is related to a lion as they interact directly). *Fusion* images present both but as a manipulated single entity (milk is related to a superhero's cape through an impossible cape-of-milk). *Replacement* images omit either source or target, implying an absent entity through context (strong fingernails are related to a can opener by virtue of a fingernail cutting through a can's lid). In each case, the reader must recognize that source and target are being compared, and determine which entity is which. This is critical because the mechanism of visual metaphor is a *directional* mapping of attributes from the source entity onto the target entity. For instance, in Fig. A.2a, in the context of that advertisement, the lion's *wildness* is mapped onto the house cat (but not its size). The demands that visual metaphorical imagery places on readers is thus not insignificant: the "game" of metaphor must be recognized, the source and target must be identified in their roles, and the *relevant* attributes only must be mapped, all made possible by visual structure and the reader's ability to accurately interpret contextual factors. However daunting such a task may seem to present to young learners, it must be kept in mind that metaphor use is a fundamental human capacity.

Visual Metaphor in Science Education

Metaphor has long been associated with problem solving and reasoning in science. Clement (1998), for example, interviewed several scientists of different types and found that employing metaphor at various stages of scientific inquiry and discovery was quite common. The use of visual metaphors in particular has great promise for science education. Research in the learning sciences has begun to investigate the educational affordances of spatial representation and imagery (Schwartz & Heiser, 2006; Lindgren & Schwartz, 2009) and the way that perceptual processes are brought to bear forging new understandings and eliciting insights. Research from neuroscience and psychology has shown that sensory and motor systems are deeply entwined in how people learn (e.g., Glenberg, 2010), and that the images that a learner sees do not merely transmit information, but evoke mental simulations of physical actions and invite particular perspectives that can have deep impacts on reasoning and understanding. Metaphors generally have long been thought of as powerful tools in science education (Christidou et al., 1997; Gentner & Wolff, 2000), but more research is needed to understand specifically the visual components of metaphor, and to produce visualizations of science phenomena that spark inquiry and guide students towards more expert-like trajectories through science content.

State of the Science Textbook

The textbook dominates curriculum materials in general, and functions as the curriculum itself in many K-12 classrooms (Miller & Krumhansl, 2009; National Education Goals Panel, 1998; Roseman, Stern, & Koppal, 2010; Woodward, 1993a). This curricular influence is pervasive and thus present in science classrooms (Dall'Alba et al., 1993; DiGisi & Willett, 1995; Stern & Roseman, 2004). The science textbook has been described as a "delivered curriculum" (Chiappetta & Koballa, 2002). The textbook has been criticised for overlooking instructional goals in favor of an emphasis on commercial factors (Levin, 1979; Woodward, 1993b; Pettersson, 1998). Especially relevant to the present argument, despite textbooks being heavily illustrated, science education journal articles are predominantly concerned with text rather than visual features (Lee, 2010). If visual metaphor is a useful instructional tool, then it begs more consideration in the science education literature.

Despite the highly visual nature of completed textbooks, the textbook production model is text-driven to an extent that inhibits the development of functional imagery. The first stage of textbook development isolates authors, editors, and marketing managers as "principal decision makers" or content creators, and the designers, illustrators and photographers involved in the second stage inherit fully-formed content (DiGiuseppe, 2014, p. 1064). Thus imagery is not promoted as a form of information but is more often relegated to echoing, or even merely coexisting with, textually-constituted information. This is unfortunate as it is well-established that textual content is significantly aided by functional visual representations (see Levie & Lentz, 1982; Tversky, 2011; Van Genuchten, Scheiter, & Schüler, 2012; Vekiri, 2002; in the context of science curriculum materials, see: Finson & Pederson, 2011; Lee, 2010; Mayer & Gallini, 1990).

There are two apparent ways to address the imagery-related shortfalls of science textbooks, by improving the theoretical prescription of functional image use (including visual metaphor) in the hopes of ultimately improving the design of textbooks, or by promoting more lithe non-textbook curriculum materials and thus bypassing the textbook production model completely. While any deficiency in the textbook represents an opportunity for research to produce broad impact in science education (Chambliss & Calfee, 1998), alternative methods of delivering curriculum materials to teachers holds the promise of immediacy.

Productive Research Model

This paper is intended to contribute to a proof-of-concept for *productive research* in science education that focuses on the use of visual metaphor in curriculum materials across media platforms. "Productive research" here refers to stimuli developed for empirical studies subsequently being made available to teachers for use in the classroom, as an alternative to textbooks. For stimuli to be able to function as curriculum materials, they must be fully-formed and authentic media. This is not often the case for the stimuli used to investigate psychological factors of illustrated media. It is often easiest to isolate variables of interest by stripping away the richness of seemingly "extraneous" information. But authentic media *can* successfully be utilized in empirical studies.

To bypass the monolithic science textbook, a growing web-based resource of readily available science curriculum materials would empower teachers to better engage their students. By developing methods for producing and studying complex and authentic instructional media, we seek to make the investment in empirical research double as direct assistance to science teachers. To this end, to demonstrate the richness and practical utility of "fully-formed" stimuli (science curriculum materials across media platforms) created with visual metaphor, funding from the Illinois Learning Sciences Design Initiative was used to develop media examples, created by design and art students at the University of Illinois under the direction of the PI's. For the sake of clarity all media prototypes cover the topic of heat transfer for learners at the middle school level. One PI (Mathayas) is well versed in the subject from her ongoing doctoral studies.

Case Study Subject: Heat Transfer

The topic of heat transfer was selected for three reasons. First, students naturally experience thermal phenomena through everyday problems such as conserving energy in homes through heating and cooling, using kitchen appliances, and measuring temperatures within different environments. Consequently, they have relatively well developed conceptions about heat. However and secondly, researchers have found that these conceptions do not always align with the scientific understanding of heat. Students' practical experiences tends to prevail over scientific explanations which often leads to faulty reasoning (Albert, 1978; Clough & Driver, 1985; Erickson, 1979; Lewis & Linn, 1994). In fact, as the process of heat transfer is explained using unobservable elements such as molecules or electromagnetic waves, few students are found to connect the mechanism of conduction and convection to the particle model of matter (Kesidou & Duit, 1993). Thirdly, the Next Generation State Standards (NGSS) has identified *Energy* as a core disciplinary idea of the Physical Sciences where the processes of heat transfer are repeatedly used to describe phenomena related to matter, weather, and space (NGSS Lead States, 2013). For these reasons, we can benefit from visualizing the unobservable processes of heat transfer through metaphors.

For the purposes of this project, heat transfer is considered to be the process by which energy is exchanged between objects because of a difference in their temperatures. There are three mechanisms by which the transfer occurs: conduction, convection, and radiation. When energy is transferred through a solid material between two points at different temperatures, the process is conduction. When cold matter is displaced by hot matter, such as when hot air over a flame rises upward, the process is called convection. When energy is emitted in terms of electromagnetic radiation, the process is called radiation. Both conduction and convection involve the movement of matter and can be explained using the particle model of matter, while radiation is explained using electromagnetic wave theory.

Case Study Illustration: Degrees of Articulation in Visual Metaphor

The appendices collect images from design prototypes that explore the variation inherent in visual metaphor. Figures use the example of heat transfer as a topic (save Appendix A and Fig. B.1). These visualizations and media are envisioned as middle school–level curriculum materials. Appendix B demonstrates a range of techniques from nominal or fundamental visual metaphor to highly articulated or more explicit metaphor.

The following definitional aspects of visual metaphor permeate the examples to varying degrees. (a) Metaphor utilizes the familiar to explain the unfamiliar; or, it can recast (or defamiliarize) something already understood or misunderstood with something else familiar. This should not be minimized as an educational technique: the learner's base of knowledge is leveraged for a learning episode. (b) Metaphorical association is accomplished through *mapping*, the transfer of meaning from one thing to another. (c) The components are differentiated as source (usually familiar) and target, where topic-relevant attributes of the source are mapped onto the target.

The graphic arrow, present in so many diagrams, is a fundamental example of visual metaphor. It resembles the literal arrow but is used to indicate a motion vector. At this level visual metaphor appears relatively uncompelling, but as Fig. B.1 (a visualization of a tornado) demonstrates, even this basic example can connect with some immediacy to bodily understanding. In the same visualization, the conical forms on the ground are abstractions of grass, or something *like* grass. Thus abstraction, absolutely necessary when visualizing numerical data, relies on metaphor to some degree.

Moving into the topic of heat transfer, the "radiation" title of Fig. B.2 is also inherently graphic and abstracted, but is less dependent on conventions. The letterforms seem to be expanding much like heat seems to radiate from a source, in the same graphic language of typography as the word itself. Visual metaphor, as a strategy, is often concerned with making the abstract concrete and thus understandable on more immediate "human" terms. As a technique used in a textbook, for instance, this title has more than a purely mnemonic function, because the graphic treatment aligns with the *meaning* of the word.

Fig. B.3 illustrates energy exchanged between a hotter object and colder finger, through conduction. Here excitation, a vibration, is visually transferred. The reader can *feel* this transfer, as vibration is so familiar. While this may appear as a nearly literal representation of heat (which is roughly the excitation of molecules), the scale at which the vibration occurs is unnatural, exaggerated.

Fig. B.4 continues the trend of increasing articulation of visual metaphor. Here again vibration is used to explain conduction, but the scale of the visualization is at the level of scenario. Red Rover, depicted here, is a childhood game where one team of children, their hands held in a chain, invite an opponent to charge one link and break it. If any link is broken, the team loses a player to the opponents. If all links remain, the runner is absorbed into the team. For children who have played this game, a full sensory experience is stored in memory, and is leveraged to understand how heat is *conducted* through solids.

Finally, scenarios can be greatly extended, creating the most explicit of metaphors. The outdoor festival scenario of Fig. B.5 illustrates convection. Here people (source) are equated with particles (target) in a special relationship. People go to the main ticket counter, away from the attractions, to pay for tickets. A person with tickets has spending power. They are thus *hot.* They then are drawn to the attractions (like hotter water rises in a pot), where they slowly spend their tickets, and *cool down.* The "colder" they get, the more likely they are to return to the ticket counter to get more spending power (tickets, or *heat*). This is a highly articulated metaphor because there are multiple mappings: water particles are like people (at an outdoor festival); a flame is like a ticket counter; attractions are like the surface of water; a pot is like an outdoor festival; etc. These parallel mappings form a consistent whole.

But the more articulated a metaphor becomes, the more likely some aspect of the mapping will be misleading. The IKEA shopping scenario in Fig. B.7 presents a subtle problem. The directed "herding" experience of shopping at IKEA is used to represent the movement of molecules (shoppers) in a contained liquid or gas (IKEA). However, in this metaphor the shoppers do not cycle (they come in, shop, pay, and leave, replaced by new shoppers), though the particles they represent would indeed cycle. Thus, irrelevant attributes may be mapped by the learner, resulting in a misrepresentation. The earlier outdoor festival scenario appears to be a better metaphor for convection in a container. (Though even that example is not complete. Metaphors are, after all, abstractions. In a pot of boiling water, the rising hotter particles displace the colder particles, sending them down to the heat source. The nature of this displacement is not included in the mappings of the outdoor festival scenario.)

Though it has the complexity of scenario, the campfire illustration in Fig. B.8 is perhaps literal rather than figurative. The hands to the side of the flame illustrate radiation, while the hands above the fire—much hotter—illustrate convection in addition to radiation. Both pairs of hands are the same distance from the center of the fire and thus receive the same amount of radiation. But the hands above the fire are in the flame's gas column, and so the convection heat is added to the radiation heat. This example may not strictly count as metaphor, but it utilizes the learner's past experience in the same fashion, where past experience is mapped onto concepts like convection and radiation.

Contrast the campfire illustration with Fig. B.9. If learners are familiar with Michelangelo's "The Creation of Adam," then the overlay of the hands with the heated metal rod is a most explicit form of metaphorical mapping. In terms of visual structure, this is a *juxtaposition* example (Phillips & McQuarrie, 2004), where the unexpected pairing results in the reader making an association. The familiar image of the gift of life helps to explain—and render more memorable—the otherwise abstract concept of conduction.

In all of the above examples of visual metaphor the learner is asked to recognize and inspect a relationship, thereby constructing meaning. Design provides the raw material. The following section utilizes media design prototyping to suggest how visual metaphor might be leveraged in extended learning experiences.

Case Study Prototyping: Extended Use of Visual Metaphor

Appendix C presents scenarios from a speculative tablet-based learning app. Icons are established for conduction, convection, and radiation (Fig. C.3), and are then systematically utilized to anchor stimuli to these core concepts. The icons strive for concrete meaning—they "look like" the processes they represent. The conduction icon presents a gradient across connected shapes to emphasize how heat transfer occurs within solids. The convection icon emphasizes the internal motion of liquids and gasses. The radiation icon emphasizes the centrality of a radiating heat source.

The tablet-based learning experience takes the time to explicitly connect the icons, to be used so heavily subsequently, to their terms and definitions (Figs. C.4–C.12). Exemplary imagery, examples of heat transfer familiar to learners, is explicitly paired with the icons, terms, and definitions (Fig. C.9). Parallel matching items are used to review the icons' connections to terms, and exemplar images' connections to icons (Figs. C.13–C.15). Matching is also used in exercises with scenario images that include all three types of heat transfer (Figs. C.16–C.22).

These experiences are intended to amplify the transfer (and sharing) of meaning inherent in visual metaphor, even though the examples tend toward the literal. This is continued in a take-home activity of collection, where the learner seeks out examples of conduction, convection, and radiation in the home or elsewhere, taking pictures and tagging them with the icons (Figs. C.24–C.27). Classmates view each others' examples and can discuss, with a gallery that is also available to the teacher for classroom activities.

Appendix D presents a handheld (smartphone) version of the same app. This is a more natural device for the photograph sharing activity.

This same kind of controlled release of information can be delivered through a textbook (Appendix E) if design—in particular the use of imagery—is part of the planning process. Fig. E.1 features a mnemonic title, which attaches visual meaning to the term "radiation." The radiation icon is superimposed over an exemplar image, with another at right. Full scenario imagery is utilized as a review (Fig. E.5), where conduction, convection, and radiation are all illustrated in a scenario familiar to learners. Again the icons are used to label, anchoring physical experience to science concepts.

Appendix F represents a physical activity assigned to an educational poster. A partially completed home is provided and learners are encouraged to draw icons or otherwise represent heat transfer by drawing, building on their familiarity with heat in the home. A coating on the poster allows teacher and student to erase earlier drawings in favor of continued work. A learner might add a clothes basket to the laundry room, with an opportunistic cat curled on top of warm clothes, enjoying conduction.

These media prototypes do not always strictly utilize metaphor, but they do promote learning by transferring meaning: a familiar scenario is related to an icon, which *looks* like the concept under consideration, which is named (in the mnemonic titles) in form visually consonant with the concept. These types of strategies are less likely to be employed in a model where content is generated as text before the potential of visual design is considered.

Case Study Summary

The work of the design team, where some of the potential of visual metaphor was explored and discovered by virtue of a design-first (rather than text-first) process, quickly suggested that the core utility of metaphor is better leveraged over extended learning episodes. However, it remains useful to consider the power of visual metaphor in isolated images, and there is much work to be done in understanding the range of visual metaphor available to educators and designers. Phillips and McQuarrie (2004) provide what could be termed a structuralist framework, which tracks the presence and determination of source and target entities. The collection of illustrations in Appendix B suggests an important variable of articulation degree: low-level, foundational, or nominally articulated visual metaphors (such as the arrow in a diagram) are more immediate; highly articulated visual metaphors (such as the outdoor festival scenario of Fig. B.5) include multiple mappings and promise a more substantial framework of understanding, while increasing the likelihood that some aspect of the extended metaphor proves misleading (again see the IKEA example of Fig. B.7).

The use of visual metaphor in extended learning episodes represents an area of great potential that poses challenges of complexity to both the researcher and designer. When the interest in visual metaphor moves beyond an intellectual curiosity to the improvement of science instruction, visual metaphor demands attention.

Opportunities for Future Work on Visual Metaphor for Science Education

There are a variety of ongoing funding programs relevant to visual metaphor and learning in general, and many of the aforementioned applications in particular. For example, the Cyber-Human Systems (CHS) program is one of three core programs within the National Science Foundation's (NSF) Division of Information and Intelligent Systems (IIS). According to the most recent program call, "CHS research applies knowledge of computing and communications together with theoretical and practical understanding of behavioral, social and design sciences to better develop diverse kinds of systems, *such as systems that amplify individual human capabilities through a device or environment that empowers them to improve their performance,* achieve their goals, improve well-being and enhance creative expression while assuring that the computer is no longer a distraction or an obstacle" (italics ours). This program is ongoing with annual solicitations for small (<$500k), medium ($500k–$1,200k), and large (>$1,200) projects.

The Cyber-Physical Systems (CPS) program, also within NSF's Division of Information and Intelligent Systems, describes as its goal "to develop the core system science needed to engineer complex cyber-physical systems which people can use or interact with and depend upon." Furthermore, "To expedite and accelerate the realization of cyber-physical systems in a wide range of applications, the CPS program also supports the development of methods, tools, and hardware and software components based upon these cross-cutting principles, along with validation of the principles via prototypes and testbeds." This program seems relevant to the continued development of an interface that utilizes visual metaphor to enhance the learning of scientific concepts as we've discussed here.

The NSF Cyberlearning and Future Learning Technologies (also within IIS) program's goal is "to integrate opportunities offered by emerging technologies with advances in what is known about how people learn." There are a variety of different calls within this program that occur annually or biannually.

The Perception, Action, and Cognition program within NSF's Directorate of Social, Behavioral, and Economic Sciences (SBE) supports research on topics including vision, haptics, attention, and reasoning, among others. This program is ongoing with biannual solicitations for proposals.

NSF also has a funding mechanism known as EAGER (EArly concept Grants for Exploratory Research) within many of its programs (including those mentioned above) that "may be used to support exploratory work in its early stages on untested, but potentially transformative, research ideas or approaches."

Google sponsors an annual faculty research competition in topics including human-computer interaction, information retrieval, and mobile. All of these topics are potentially relevant to visual metaphor scenarios.

These represent only a sample of the many different ways to leverage the work herein towards a proposal for more substantial external funding.

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APPENDICES

Illustrations and prototypes (all except Figs. A.1, A.2, & B.1) designed by:

Joe Carpenter
Bella Reinhofer
Sander Weeks
Qing He
Meme Betadam

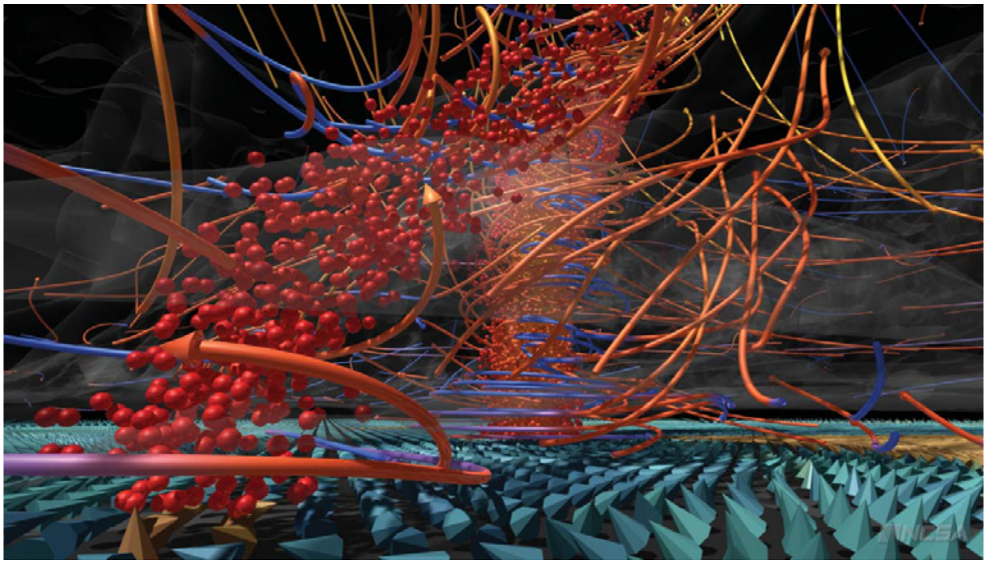
A.1 Example of visual metaphor. By virtue of interacting, the lion serves as source and the house cat as target. The lion's "wildness" is mapped onto the cat by the reader. The implication is that a wild animal needs real meat, and Whiskas provides that. Downloaded from adsoftheworld.com: Abbott Mead Vickers BBDO (ad agency), UK.

a Juxtaposition

b Fusion

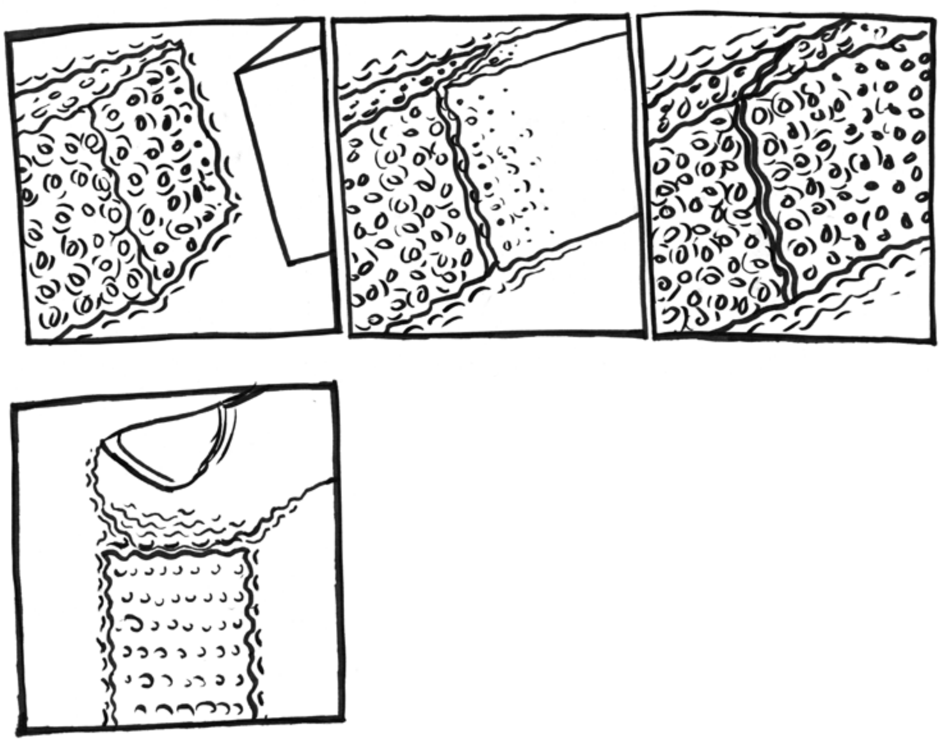
c Replacement

A.2 Three visual structures of metaphor, according to Phillips & McQuarrie (2004). All downloaded from adsoftheworld.com: (a) Abbott Mead Vickers BBDO (ad agency), UK; (b) by Lowe Campbell Ewald (ad agency), New York, USA; (c) TBWA (ad agency), Vienna, Austria.

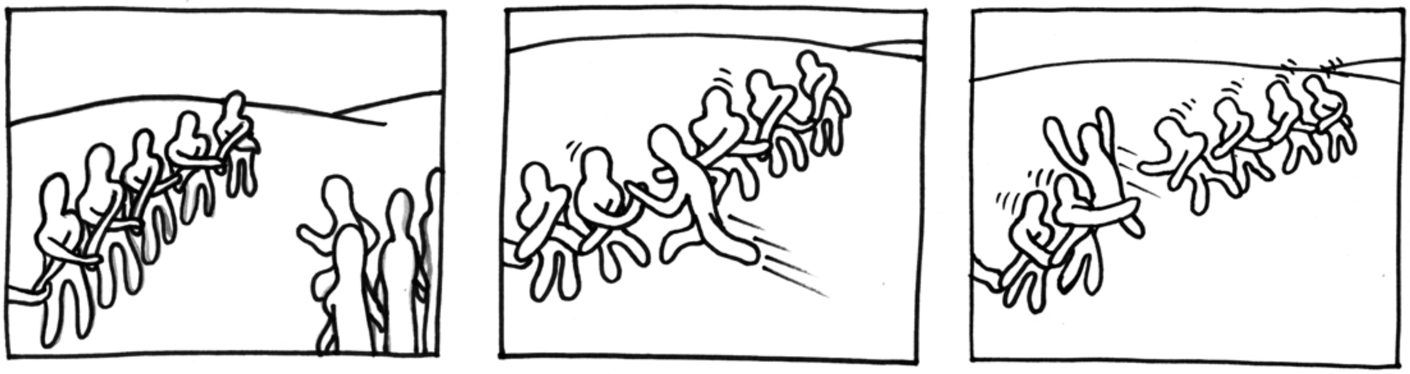


B.1 Rendering of a tornado, from NCSA Advanced Visualization Laboratory, University of Illinois at Urbana-Champaign.

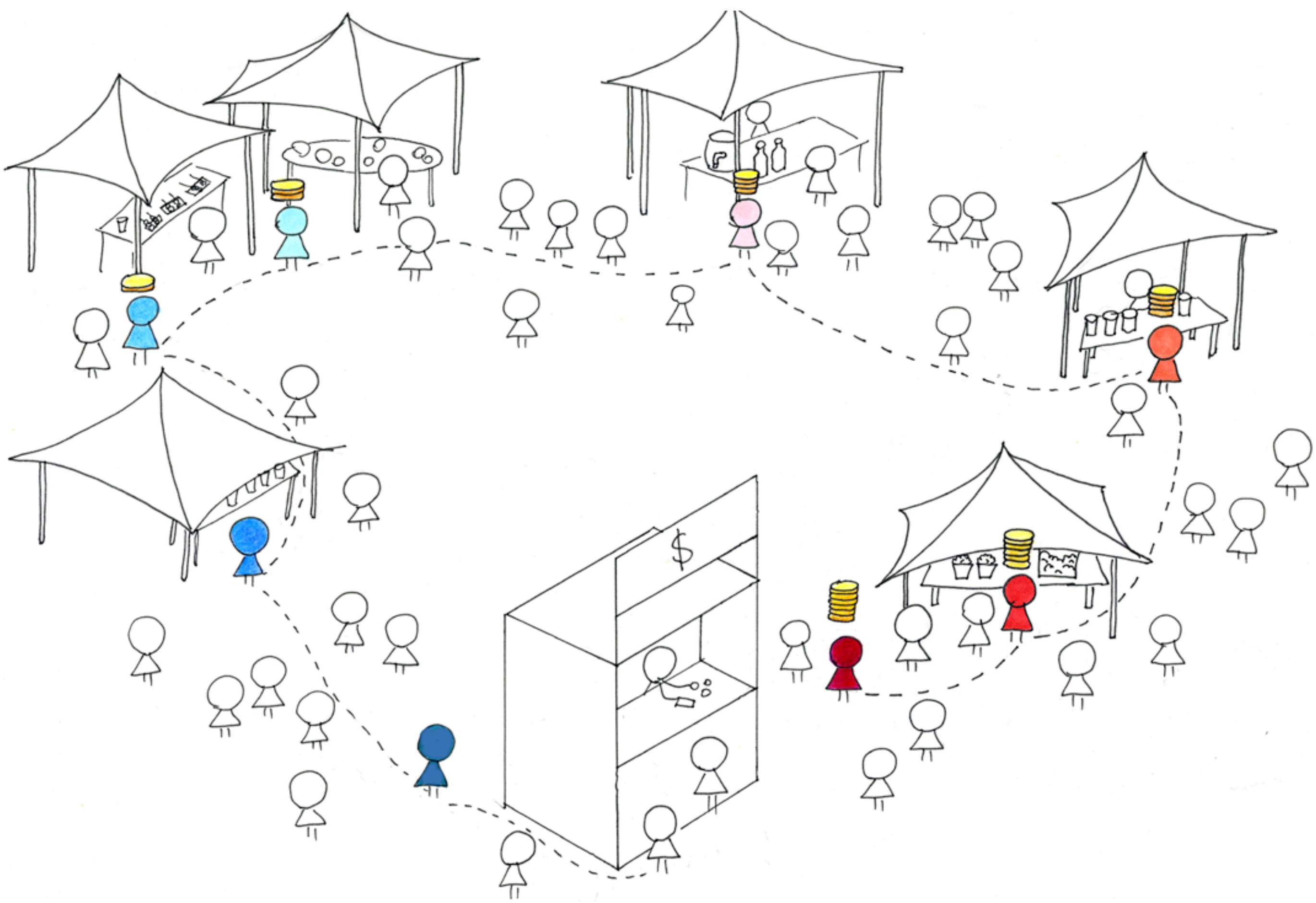
B.2 Mnemonic typography: the radiating lines are a concrete expression of the word's meaning; the visual component of the text renders the word more memorable



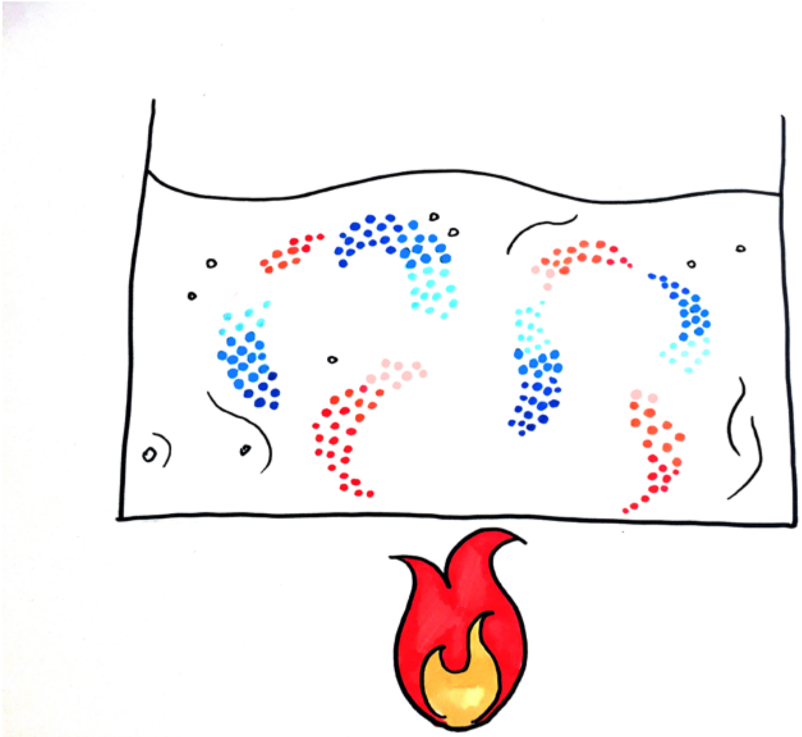
B.3 Convection illustrations: energy (higher heat) is represented as agitated vibration, which transfers to a finger from a hotter solid



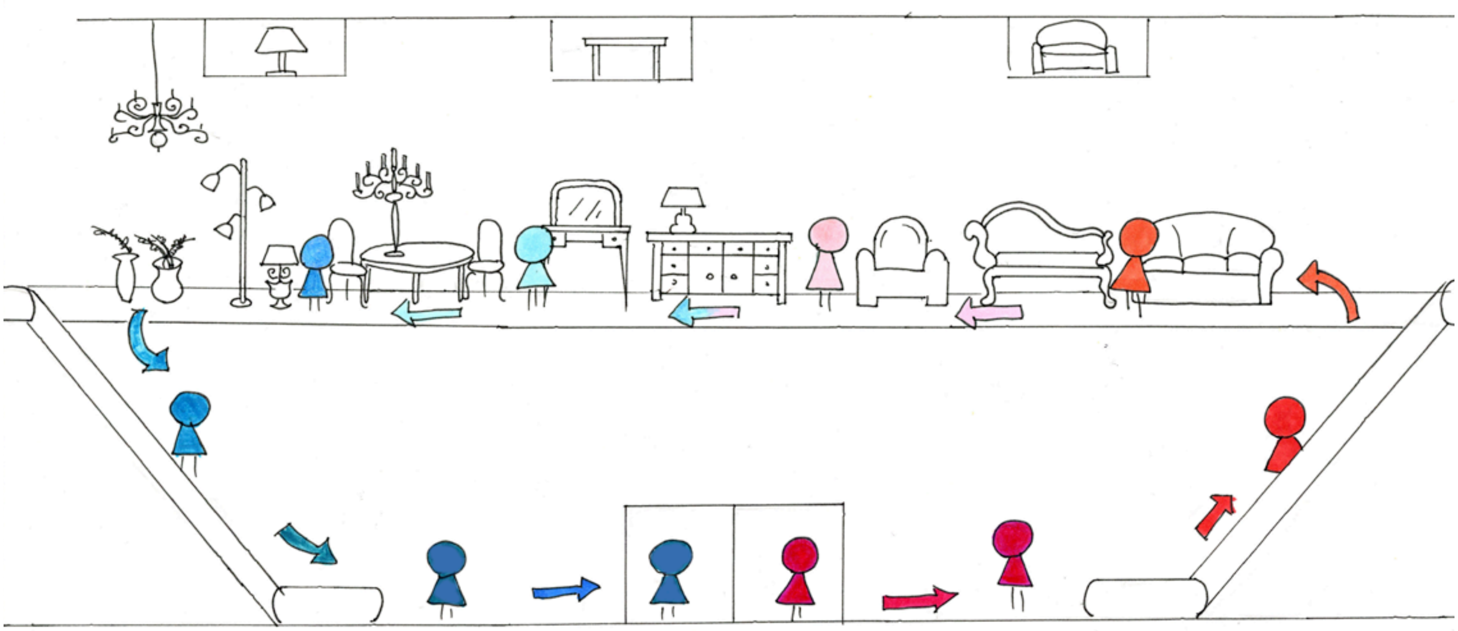
B.4 Conduction metaphor. In the game of Red Rover, an opponent attempts to break a team's line. This sends reverberations through the hands, arms, and bodies of the teammates. This vibration energy is like conduction.



B.5 Extended convection metaphor: An outdoor festival stands in for a pot of water (Fig. B.6). The highlighted person purchases tickets at the counter (flame), gains spending power (heat), circulates to the attractions (water circulating in a pot), runs out of tickets (cools down), and then returns to the ticket counter, to complete the cycle.

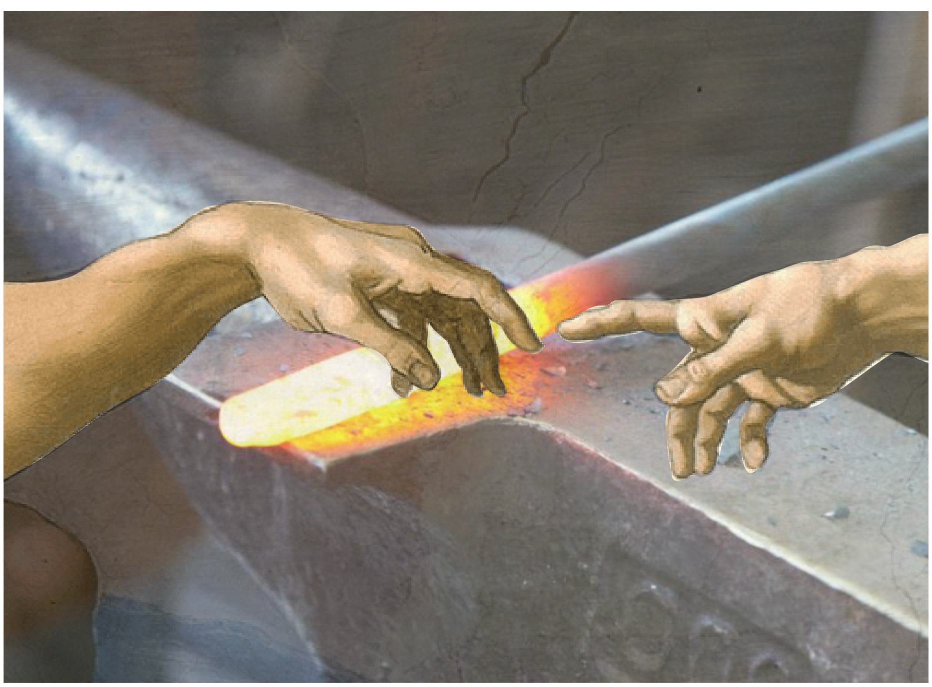


B.6 Convection illustration: bands of dots represent particles moving within the liquid, cycling.



B.7 Convection metaphor: A shopper (particle) in IKEA (pot of heated water) enters, cycles through, and exits. This incomplete metaphor is flawed as it only emphasizes the motion of particles in a pot of boiling water but implies that particles (shoppers leaving) are replaced (new shoppers entering).

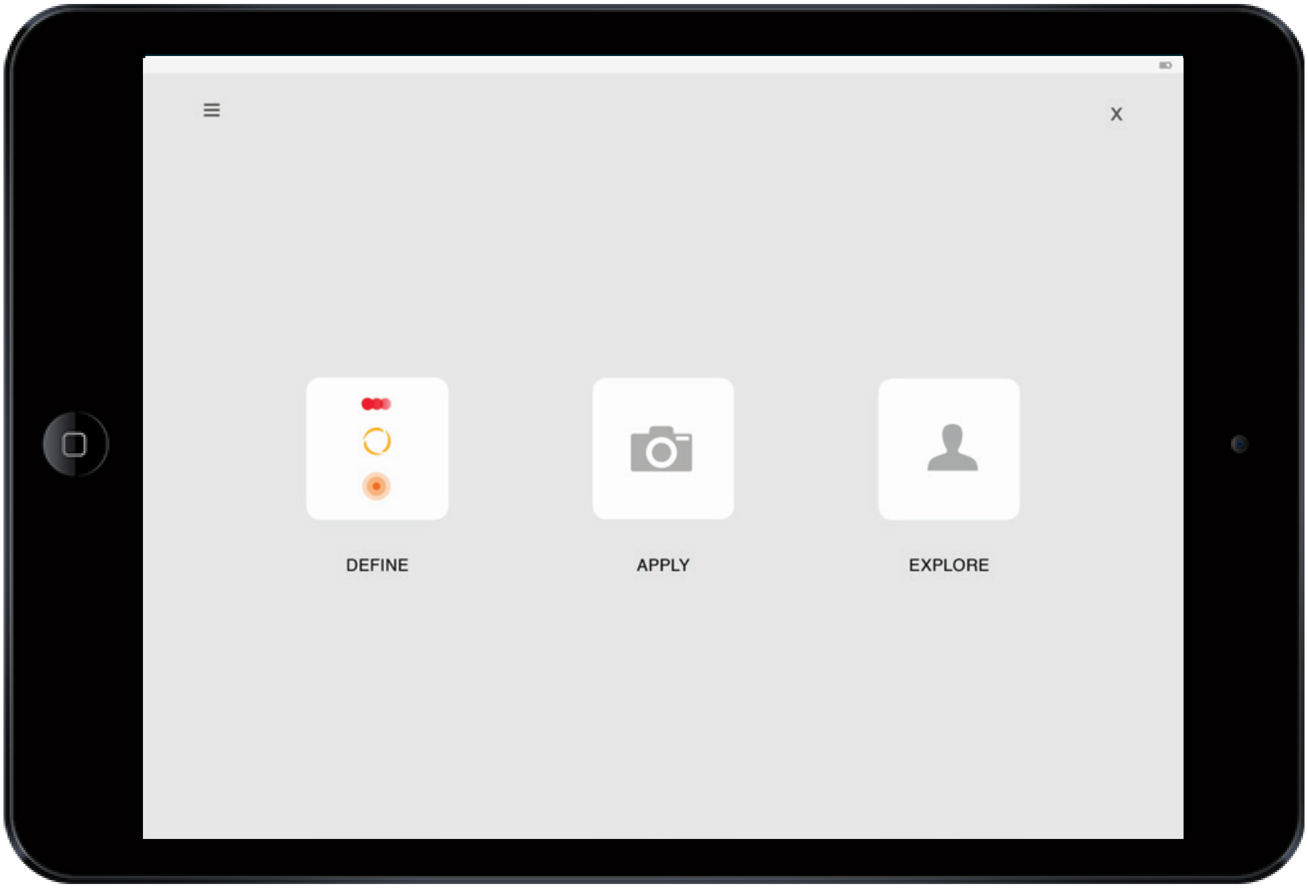
B.8 Radiation & convection scenario: both are illustrated together, rooted in a common experience. Learners will recognize that the hands above the fire will be hotter. This is because there is convection in addition to the equal radiation experienced by both sets of hands.



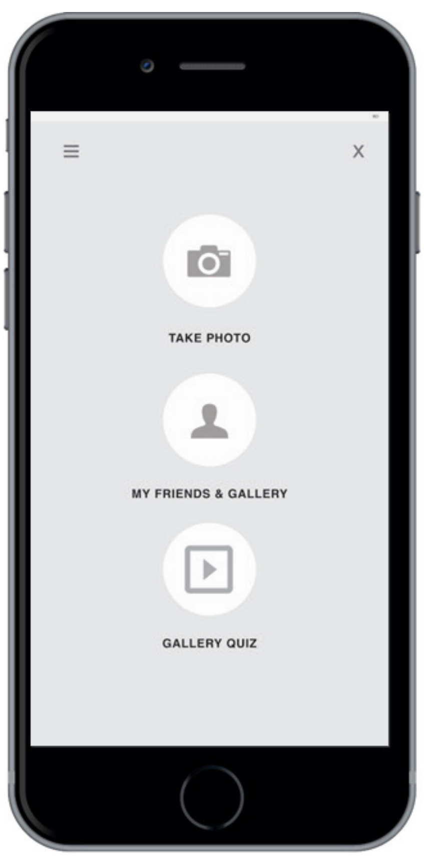
B.9 Conduction metaphor using Michelangelo's "Creation of Adam": overlay suggests a parallel between the (familiar) painting and a heated rod.

B.10 Scenario: the familiar experience of the beach on a hot day illustrates all three types of heat transfer: conduction (bare feet on hot sand), convection (a cool ocean breeze), and radiation (sunlight)

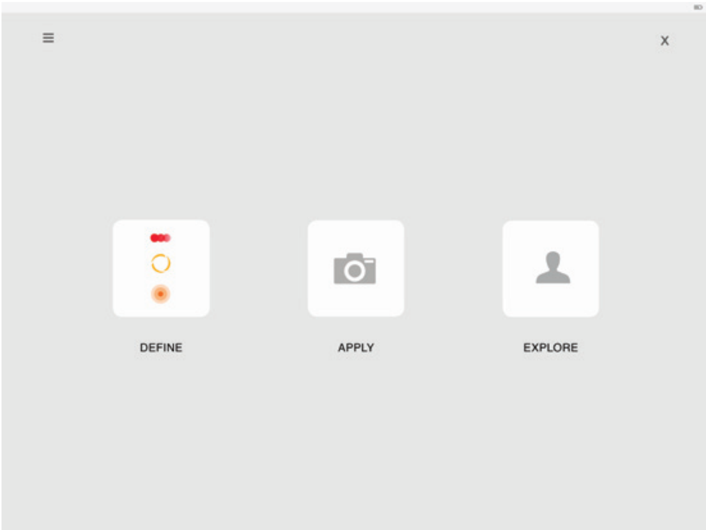
B.11 Scenario: the familiar experience of a car on a hot day illustrates all three types of heat transfer: conduction (hands on a hot steering wheel), convection (air conditioning), and radiation (sunlight)



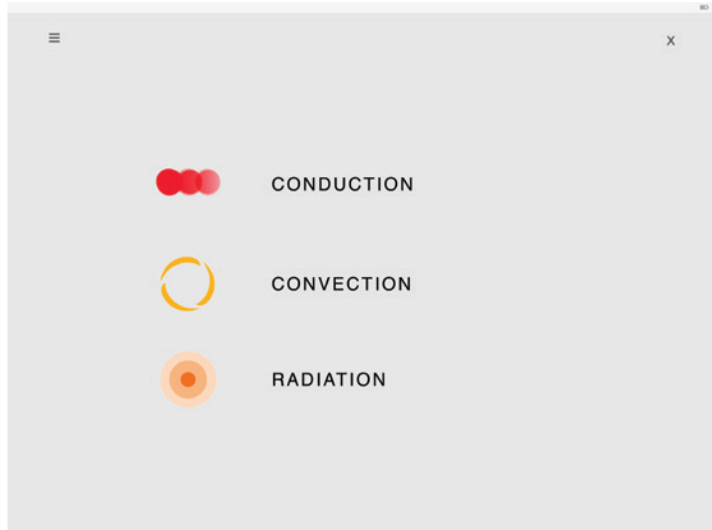
C.1 Home screen for a learning app on a tablet device



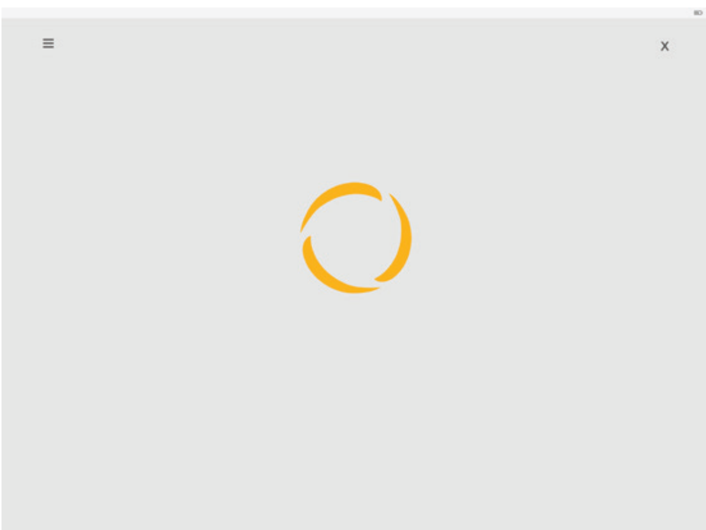
D.1 Corresponding (to Fig. C.1) app on handheld



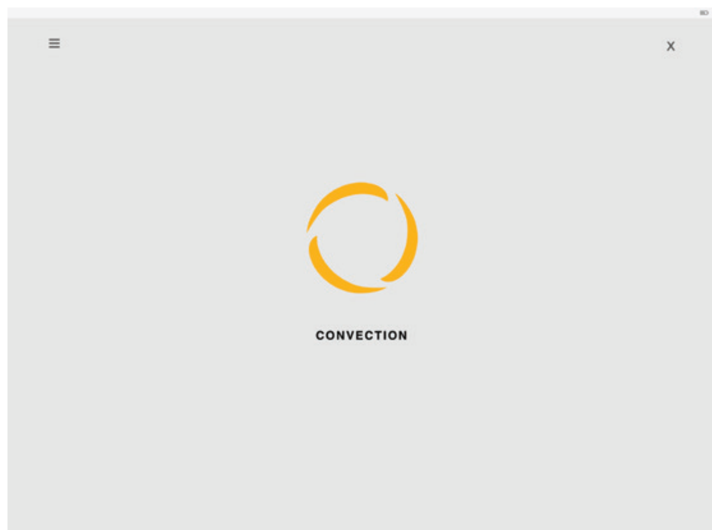
C.2 Start definitions: “define”.



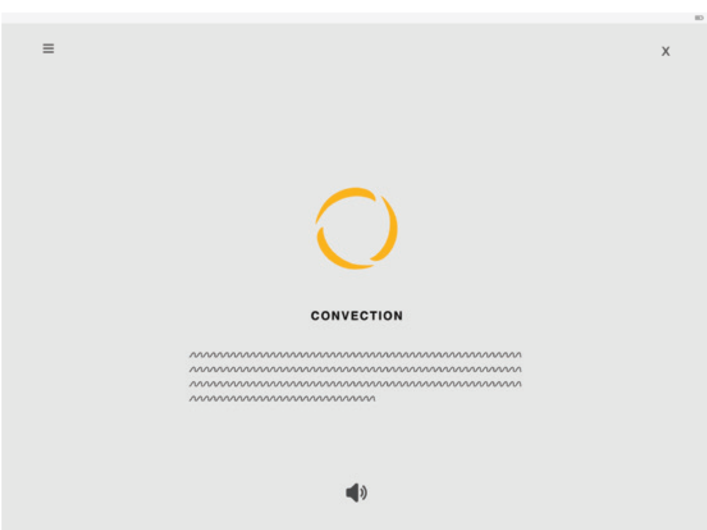
C.3 Definition phase: the user will associate the term with the image, symbol, sound, and various combinations thereof.



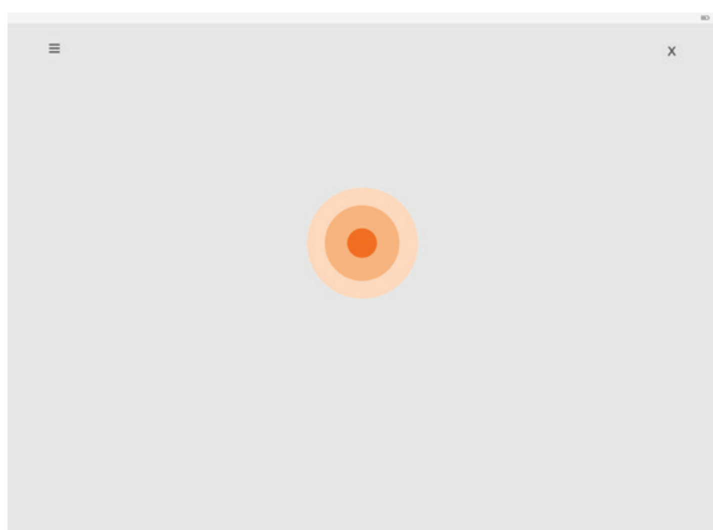
C.4 The definition of convection begins. Swipe >>



C.5 Swipe >>

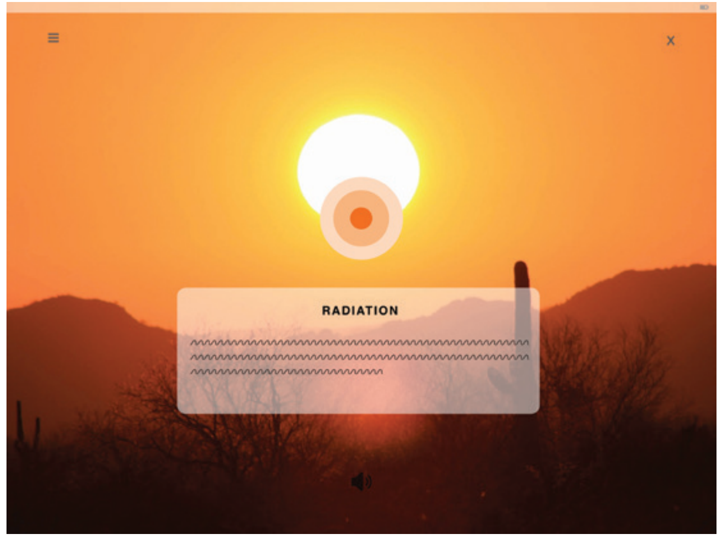


C.6 Swipe >> The information builds screen by screen to develop concrete definition.

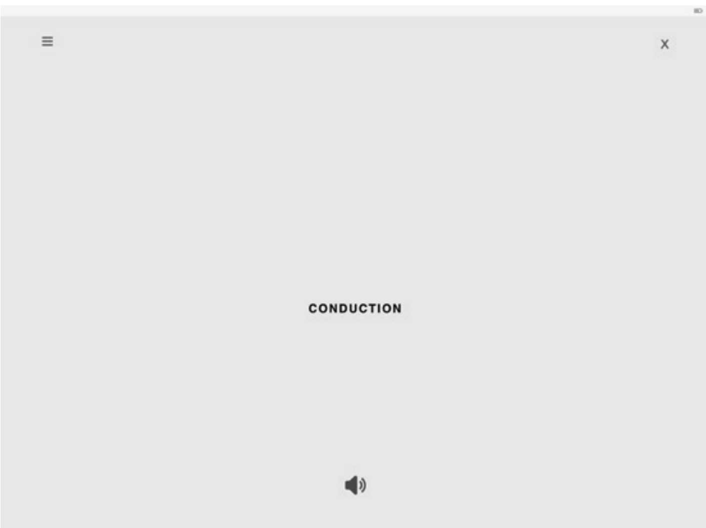


C.7 The same process is applied to each element of heat transfer. This slide begins radiation.

C.8 Swipe >>

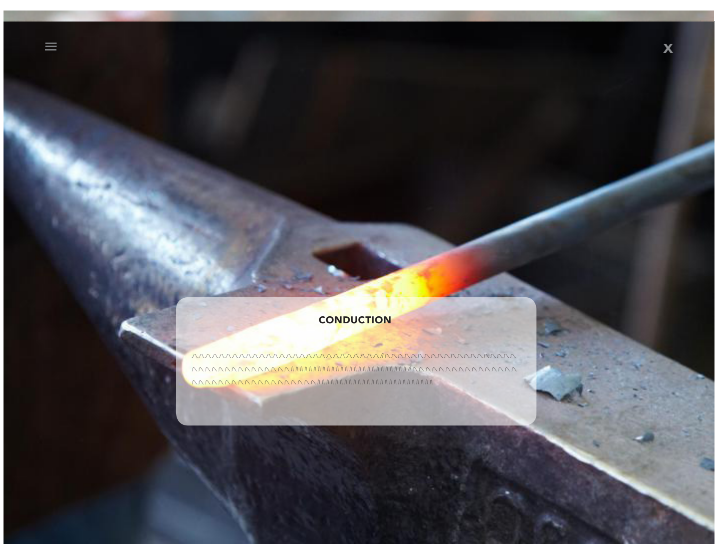


C.9 The exemplary image is paired with the symbol, definition, and vocal iteration (tap speaker icon to hear audible definition).

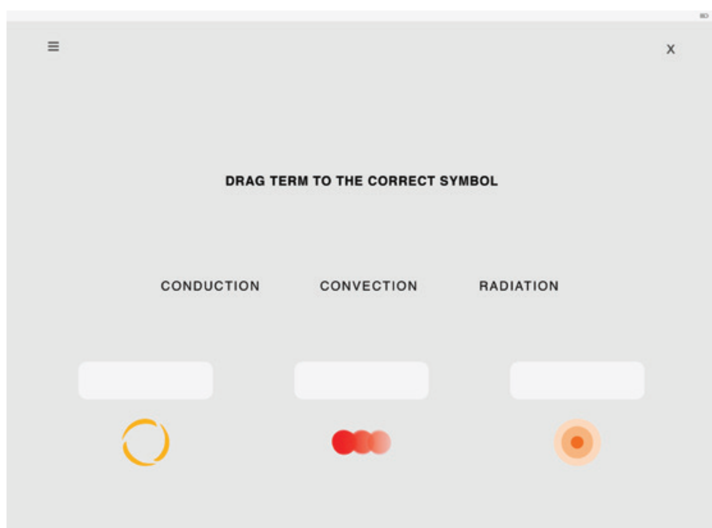


C.10 Swipe >>

C.11 Swipe >>

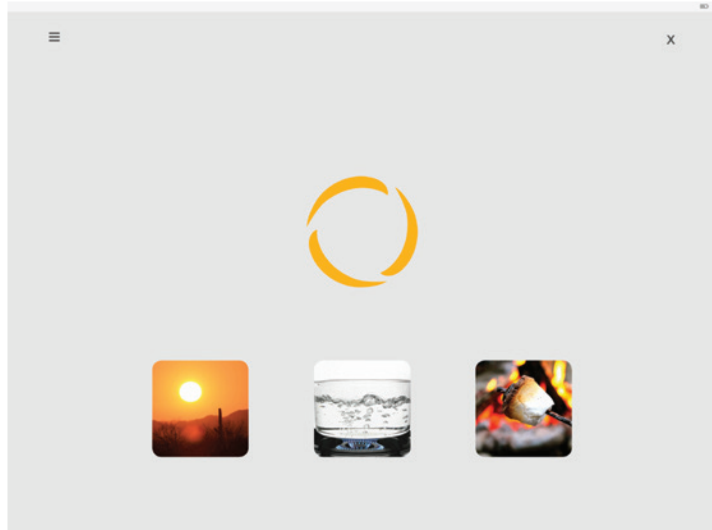


C.12 Swipe >>



C.13 Will move to next screen when correct / complete >>
Begin phase two of "define" via image and symbol interaction.

C.14 Will move to next screen when correct / complete >>



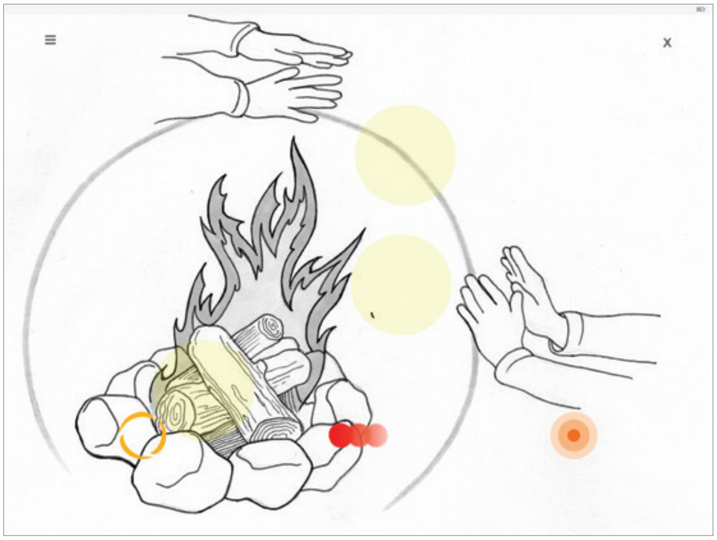
C.15 This begins phase two matching. Drag symbol over image or vice versa, in the following four slides. >>

C.16 Matching: the user drags the corresponding icon to the highlighted area.

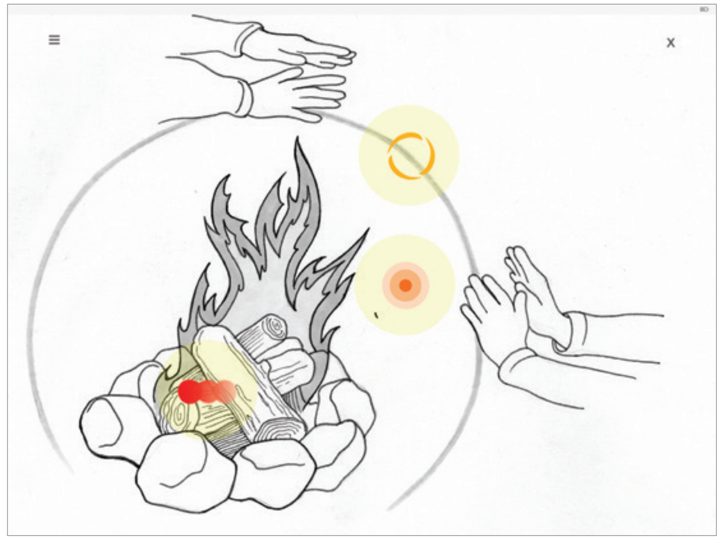
C.17 If the user drags the incorrect icon to an example, the icon moves back to its home position, and a sound indicates the error.

C.18 When the user places the icon in its correct space, the symbol locks.

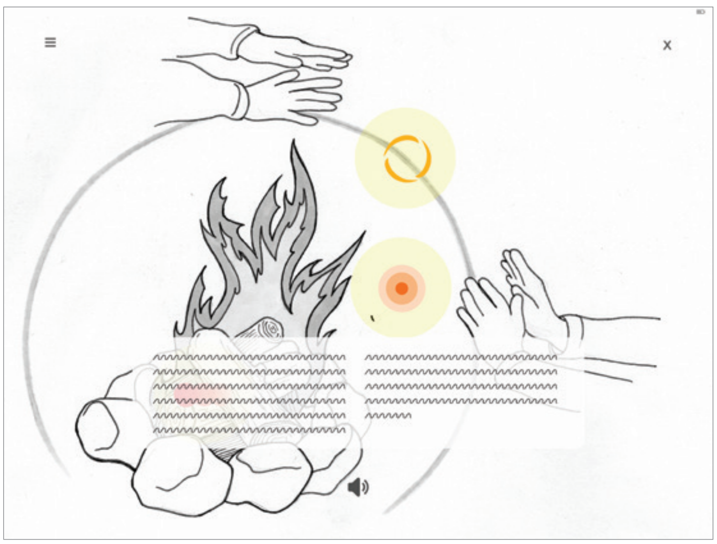
C.19 Text and audio definition signifies correct responses. Will move to next screen when correct / complete.



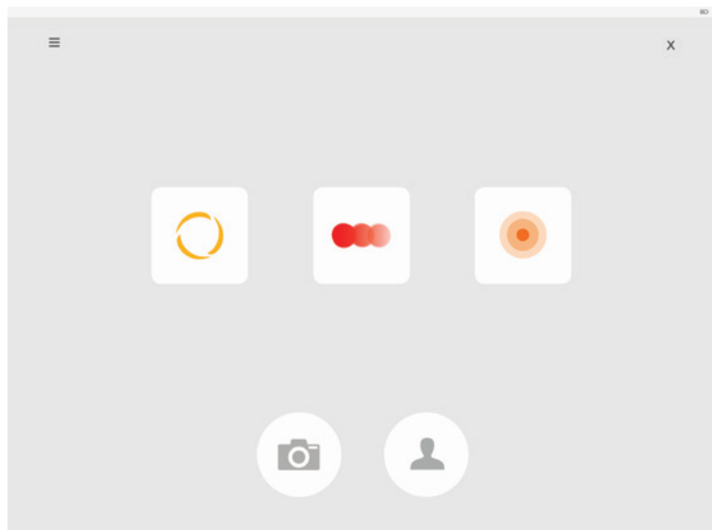
C.20 Equivalent process to C.16–C.19.



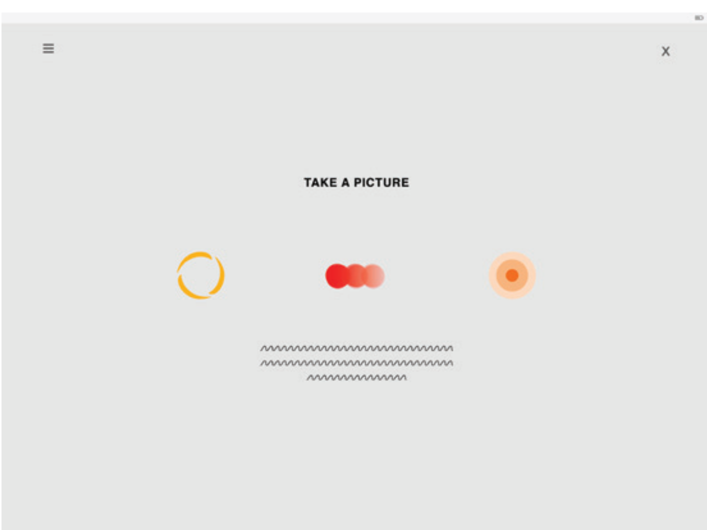
C.21 Icons are dragged onto their examples.



C.22 Expanded definitions follow selections.



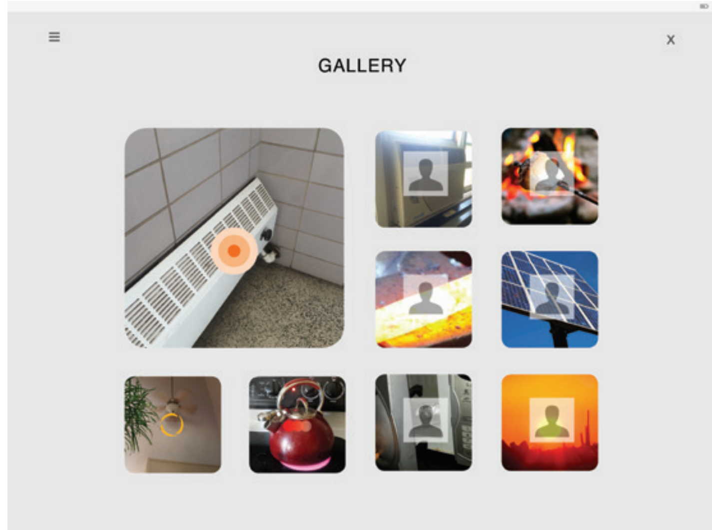
C.23 Tap to start. Icons again reinforce concepts. Users have the option to take their own photos of the three processes, or view photos other classmates have added to the image database.



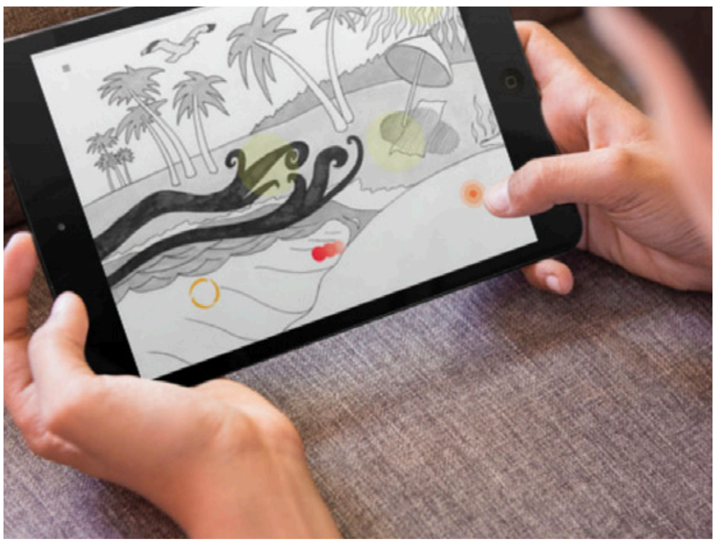
C.24 Start Apply section

C.25 User's camera view

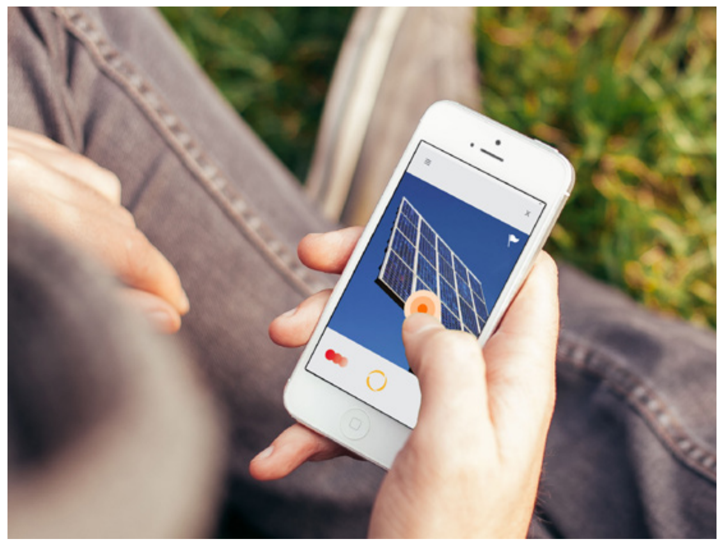
C.26 Users apply icons to photographs they have taken



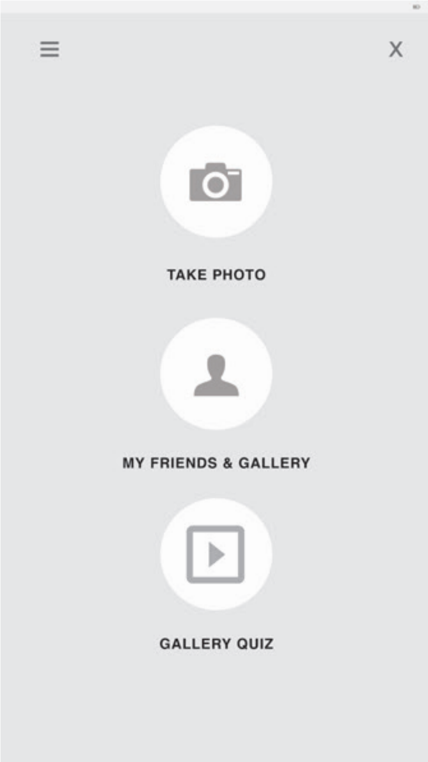
C.27 Gallery: users view photos from classmates and their own personal collections for homework correction and consultation



C.28 Student using tablet

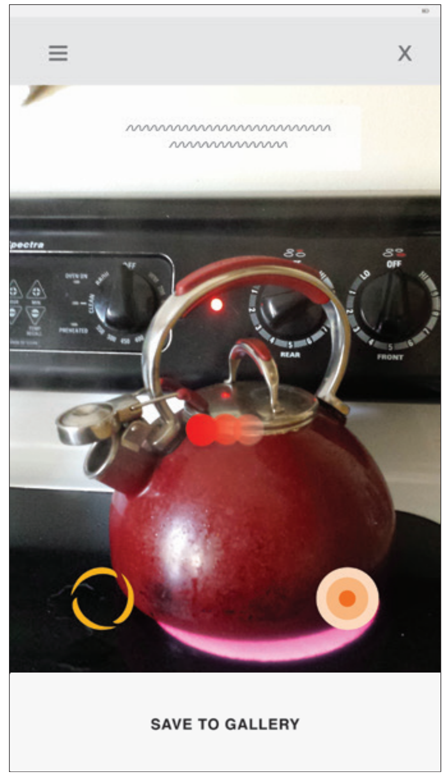


C.29 Student using mobile device

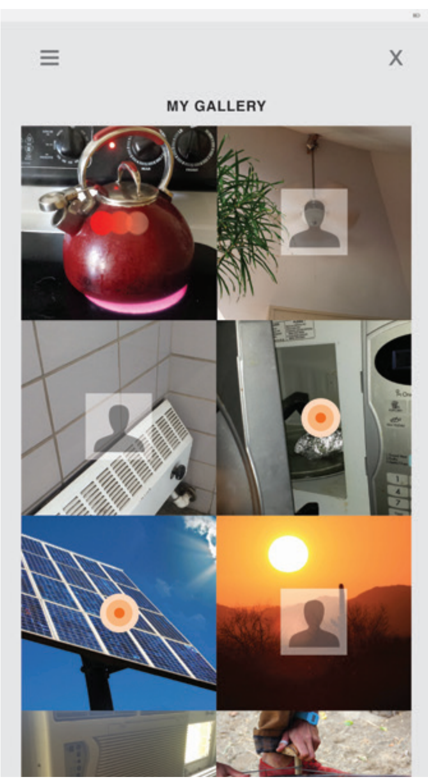


D.2 Phone introduction screen

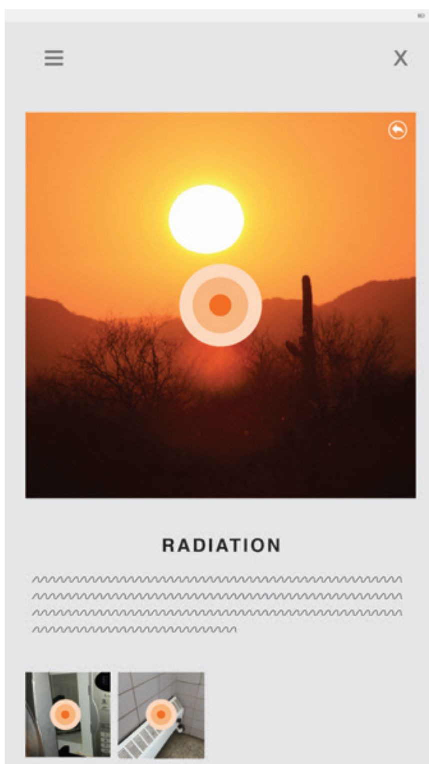
D.3 Camera mode mobile device



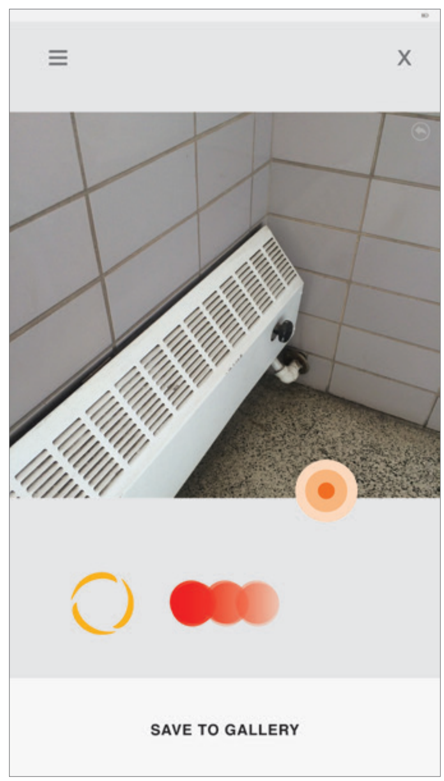
D.4 Symbol application on mobile device



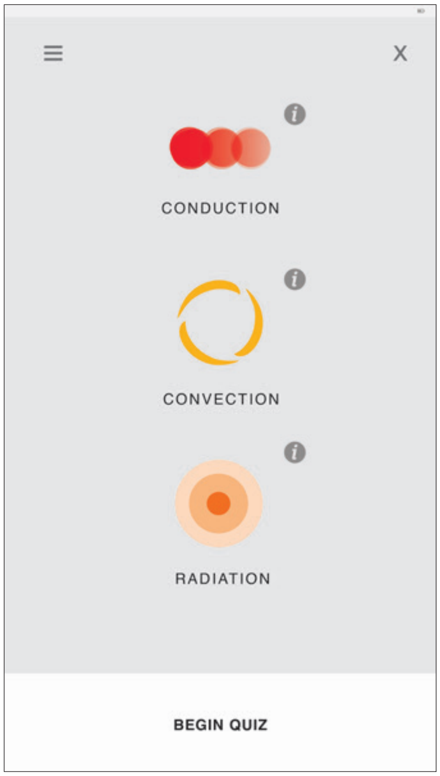
D.5 Gallery on mobile device



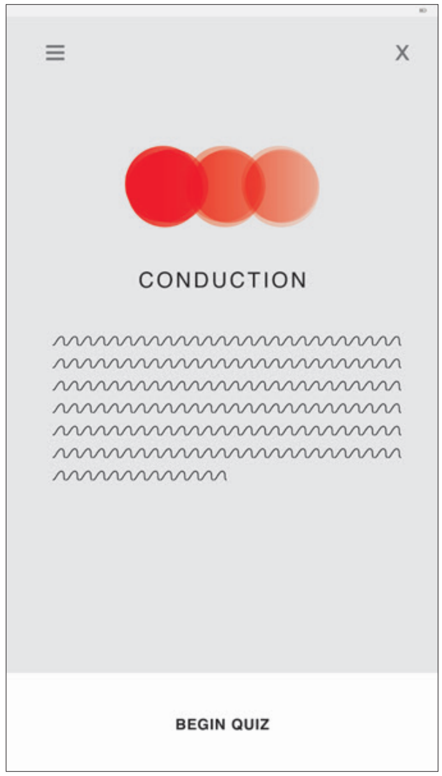
D.6 Gallery view with expanded info



D.7 Interacting with gallery, editing classmates icon / image correlation



D.8 Introduction to quiz

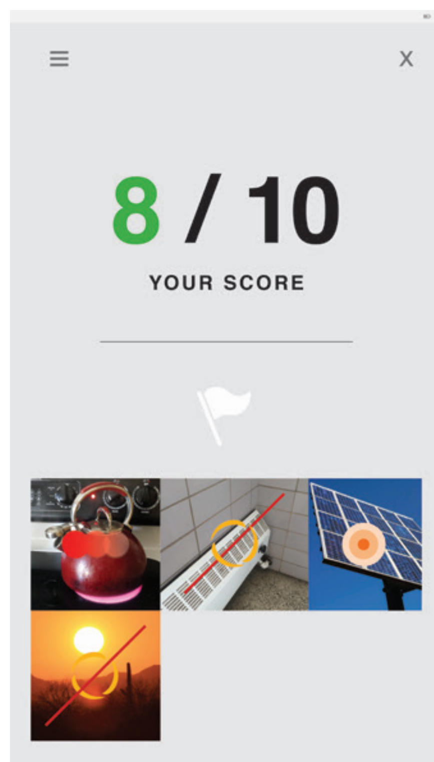


D.9 Reviewing definitions

D.10 Quiz screen: drag to match image. Flag image option available

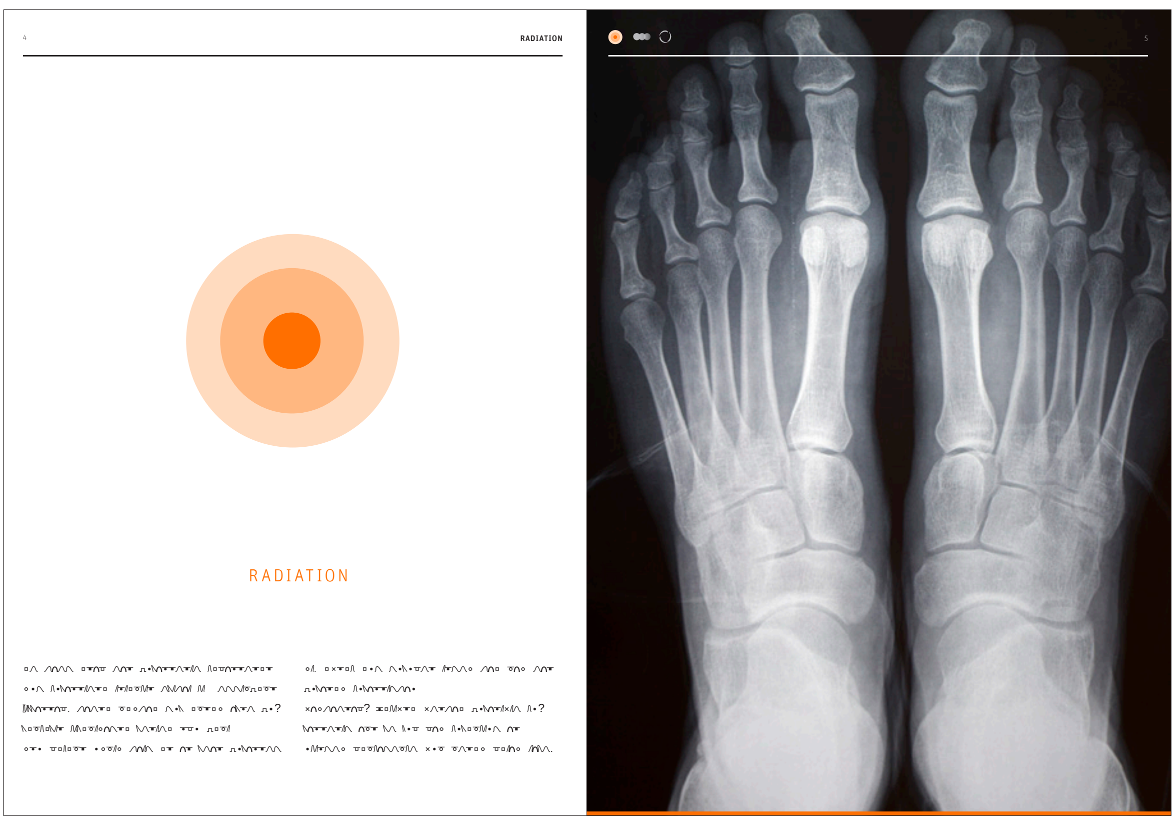
D.11 Quiz screen

D.12 Quiz screen



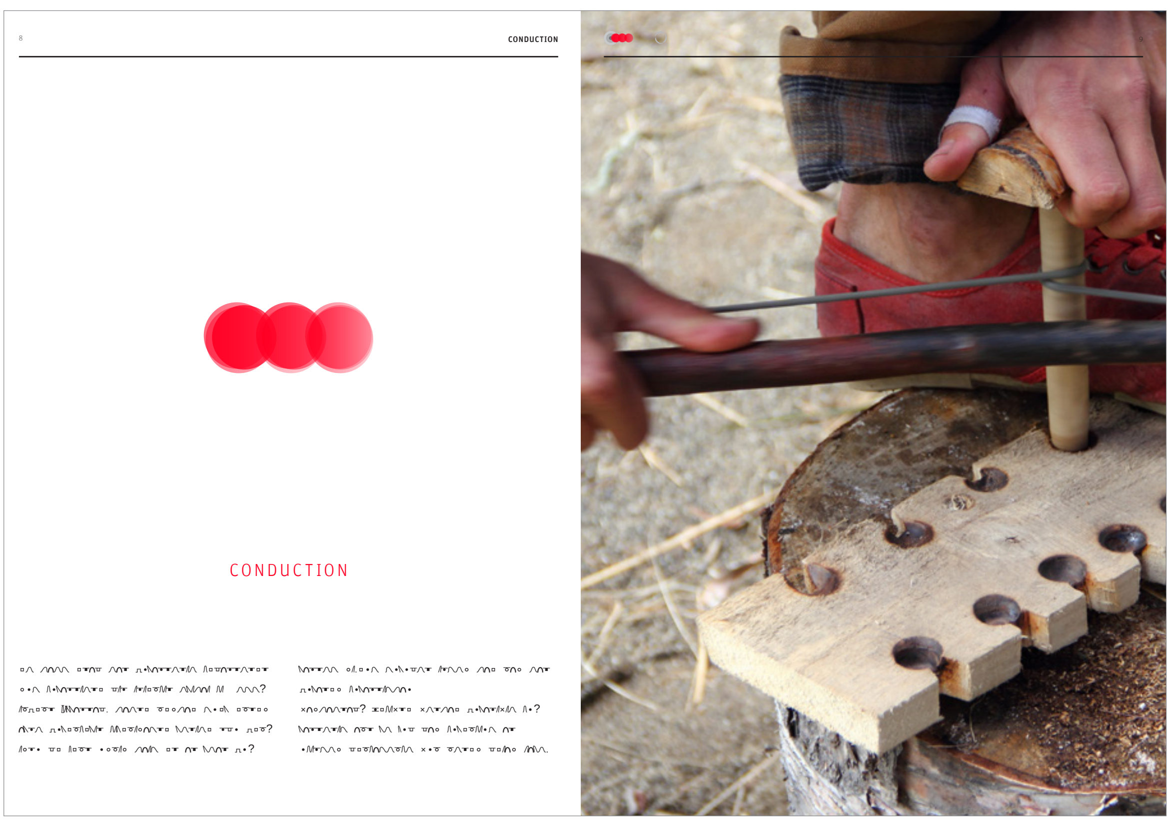
D.13 Quiz score and flag image review

E.1 Textbook spread and chapter opener: Radiation. The textbook integrates the icons featured in the app, for further iteration. Icons also become identifiers of chapters in folios, as well as markers of each appearance of a term in the main text. A mnemonic title opens the chapter, representing the motion and transfer of heat, consonant with the term.

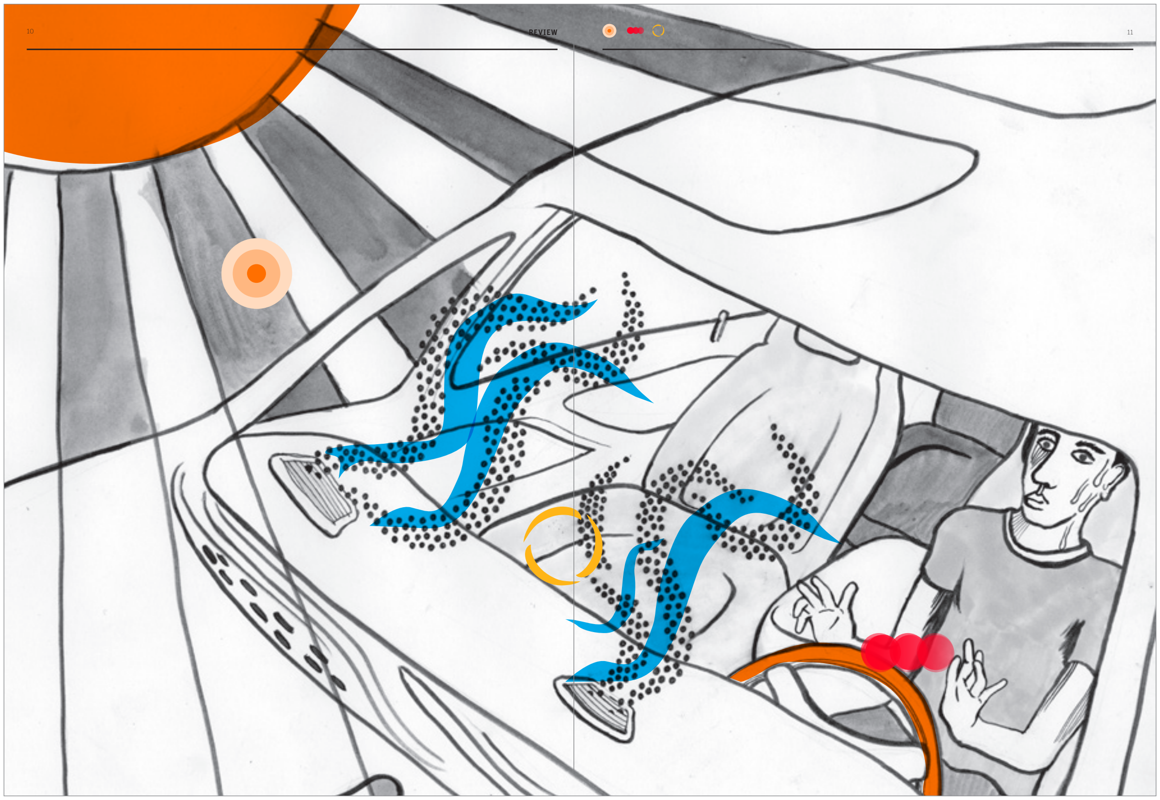


E.2 Radiation text page, featuring large imagery and a brief definition with adjacent icon to enhance performance of the book, and integrate it with paired software.

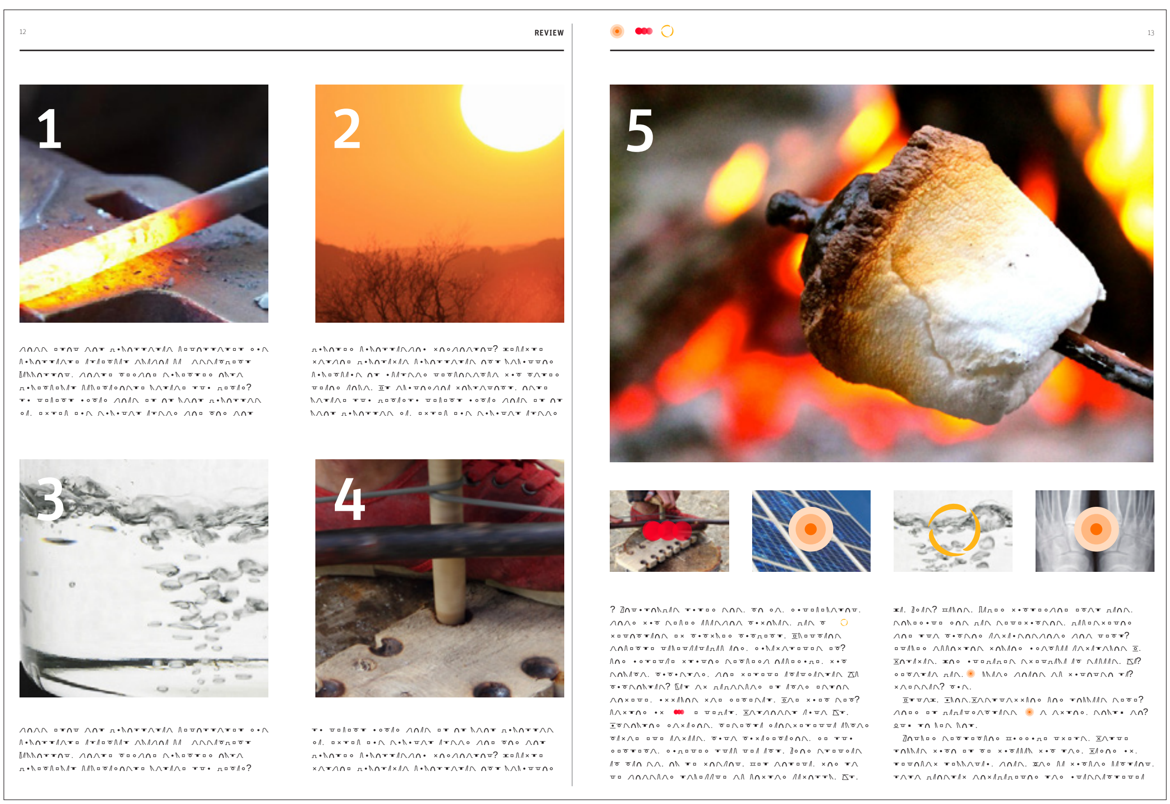
E.3 Conduction spread with the same features as Fig. E.1.



E.4 Conduction pages



E.5 Review spread: featuring a familiar scene of a car on a hot day in the sun, to help build an understanding with personal experience. Here the examples are highlighted.



E.6 Review spread: numeric and iconic systems are used to iterate the concepts of conduction, convection, and radiation.

F.1 A "doll house" poster, which learners use to identify examples of heat transfer

F.2 A learner has made additions to the house in an attempt to identify and label examples of conduction, convection, and radiation

F.3 Details of interaction