

How Abstract is Abstract? Layering meaning in physics.

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Abstract. External representations, including pictures, graphs, text, gestures, and utterances, are key components of all curricular materials in physics. Such representations play a key role in cognitive function, particularly insofar as individuals interpret the meanings of and apply meanings to these representations. We previously proposed a model of how individuals can make meaning of and with external representations through layered analogies and applied this model to learning abstract ideas in physics, i.e. EM waves. [1] [2] We extend this model in two ways. (1) We distinguish individuals' interpretations of representations, which can be highly variable and fleeting, from the physics community's agreed upon interpretations, which are more stable and coherent. (2) We describe these two dimensions of representation use: *abstraction* based on the community consensus of concepts and *salience* based on readily accessible pieces of knowledge for an individual.

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INTRODUCTION

According to the Analogical Scaffolding [1] [2] view of analogy, students presented with an unfamiliar, and perhaps challenging, problem can draw on existing knowledge to solve that problem by analogy. Relevant knowledge may be cued by the student recognizing some similarity between the problem and prior experience, which may include another problem the student has solved previously. If present and prior experiences contain surface features (e.g., signs) that are similar, this can cue the student to make an analogical comparison. For instance, students may consistently solve problems that include inclined planes using kinematics equations, even for problems where the optimal solution method uses conservation of energy. [3] Note that in this case, students use an analogy, albeit the prior knowledge employed may be inappropriate.

The expert framing of a problem including categorizing an inclined plane as a conservation of energy problem can be characterized as relatively abstract, at least compared to other possible framings. However, in practice experts may treat the conservation of energy approach in a fairly concrete way. That is, this more abstract approach is quickly recognized and readily accessible to the expert. In order to better understand this situation, we suggest that this common notion of abstraction, in terms of physics concepts, has a sort of dual-structure. We

denote one of these as *salience*, which applies to individuals. The second dimension, *abstraction*, relates to the shared ideas of a community, e.g. of physicists.

SALIENCE AND ABSTRACTION

The Analogical Scaffolding model [1] [2] builds on existing cognitive models to consider a *mental space* [4] as represented by a triangle with vertices for *sign*, or representation, *referent*, the thing referred to by the sign, and *schema*, a mental construct used to interpret the sign-referent relationship. (See Fig. 1B). [5] We define *salience* [6] as the strength of associations between sign features and schemata. In Fig. 1B we employ a representation using nodes between sign and schema, wherein these nodes represent the number of salient connections (i.e., layers of meaning [7]) relating sign to schema *for an individual*. A sign may be very simply connected to a particular schema, represented by few or no intermediate nodes. For instance, a sine wave representing an oscillating string would be a simple sign-schema relationship (the sign and referent have many corresponding surface features). [8] More complex relationships may require multiple layers of meaning, represented by multiple nodes between sign and schema. For instance, a sine wave representing a sound wave requires several intermediate nodes (a sound wave is longitudinal

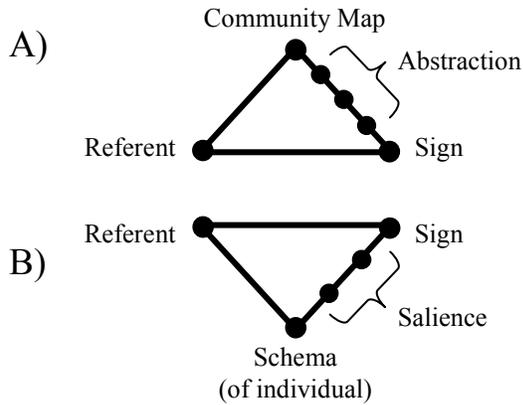


FIGURE 1. A) Sign-referent-community map triangle. B) Sign-referent-schema triangle representing a mental space.

motion of air particles, not at all directly like a sine wave picture). [9]

In Fig. 1A, we introduce a second triangle, similar to that in Fig. 1B but for a community of experts. We represent abstraction in Fig. 1A with a second triangle (top), which has sign and referent vertices that are analogous to vertices in the lower triangle. Schema is replaced with *community map*. [10] Instead of being held by an individual, the community map is a resource that is generated over time and shared by a community of experts. The community map is historically rooted and developed, but can be considered relatively static and stable over short time scales. [11] For example, the physics community’s map for EM waves is not likely to change significantly over the course of a few years or decades. We now use the word *abstraction* to represent the links along the sign-community map leg of the upper triangle in Fig. 1A. In this case, *abstraction* is a measure of the number of layers required to relate a sign to the community map. A community of practice such as the physics community has certain agreed upon interpretations of signs and how these signs relate to referents (i.e., how representations describe phenomena) that are generated, refined, and made canonical over time. What physicists often consider the “correct” interpretation of signs is determined by the community map.

EXTENDING ANALOGICAL SCAFFOLDING

Potentially, this teasing apart of abstraction and salience has considerable explanatory power. A physicist may, for example, describe an EM wave (represented by a sine wave) as highly abstract based on the tacit recognition that the relationship between

the sine wave and an EM wave is richly layered and complex. We can operationalize this tacit sense of complexity by ascribing multiple layers of meaning for the sine wave with each layer represented by a node along the sign-community map axis. We may differentiate abstraction in this (more-or-less) absolute sense from how a sign is interpreted by an individual.

This interpretation can lead to an explicit goal of instruction. Specifically, enculturation or adoption of cultural norms and beliefs [11] can be considered the coordination, cross-mapping, and alignment of schemata with the community map, where the latter has been generated and agreed upon by a surrounding culture. Note that we do not assume a complete mapping, or that this mapping will always occur. Importantly, the nodes of salience need not be *the same as* the nodes of abstraction. In our view, a constructivist model of learning will be satisfied by a correspondence between the two sets of nodes, recognizing that each individual may hold their own unique interpretations and still legitimately participate in a community (e.g., physics).

We can employ our new notion of salience to argue that it is not the surface features of a sign that are salient *per se*, but the associations made with those surface features. Salience depends on the individual and context. A student presented with a sine wave may associate that sign with a material object (e.g., a wave on a string or a water wave), while a physicist may associate the same sine wave with a graph (e.g., of electric field strength oscillating in time). Both the student and physicist cue on surface features – where the sine wave goes up, *something* goes up – but *what goes up* is very different.

We propose *building associations* as a mechanism of changing salient nodes for an individual. Building associations is the explicit linking of ideas to representations in a layered fashion. [7] Consider, for example, the idea of a *plane wave*. This complex idea can be broken into several constituent ideas, such as propagation, vector space, 3D, and relation of these ideas to a representation such as a sine wave. Individuals build associations in a layered fashion in order to interpret a representation of a plane wave (e.g., a sine wave). In a representation like Fig. 1B, the number of salience nodes represents the number of built up associations that are simultaneously held by the individual and that serve as an interpretive mechanism.

In terms of instructional practice, the extended Analogical Scaffolding model suggests productive ways of scaffolding students’ use of analogy by capitalizing on associations that are already salient for students and layering these associations toward more expert-like ideas.

In order to delve into this new framing of abstraction, consider an EM wave represented by a sine wave and vectors (the canonical representation). An EM wave represented in this way can be considered highly abstract. According to our extended framing we should represent this with several nodes along the sign-community map leg in Fig. 1A. Those particular nodes are those arrived at by the community and often built into the curricula used to teach students. The interpretation of the EM wave sign (sine wave and vectors) by the individual, or student, can now be treated separately. While the highly abstract and multiply-layered sign-community map relation can be considered a goal of instruction, students will not begin in this expert-like interpretive state. We suggest that Analogical Scaffolding is a useful model for describing and promoting student learning in communities with established sign-referent relations, and the intention here is to enhance the resolution of the model.

LAYERING MEANING

We apply this model to unpack the community map of EM waves (goal of instruction) and the associations a student makes in interpreting the relevant representations during a clinical interview. Fig. 2 shows a segment of transcript from a student interview (left) and associated Analogical Scaffolding diagram (right). Shown top left of the diagram in Fig. 2 is a community interpretation of a sine wave representation (upper triangle). Each node between

sign (lower right vertex) and community map (top vertex) is labeled with a particular interpretative phrase. For instance, this sine wave is a physical representation drawn in the x - y plane. Shown at the upper right is a similar representation for a pictorial representation of sound. These two spaces blend, [1] and at the bottom of Fig. 2 (upper triangle of lower box) is a layered space which uses a sine wave to represent sound (which is a 3D, longitudinal movement of air particles). We note that the diagram in Fig. 2 represents one layer of many. The top two spaces are the result of prior blending of other mental spaces, constituting prior layers (which, incidentally, also have preceding layers in a sort of fractal pattern).

In this representation, the top vertex of each upper triangle stands for a community map, while the nodes along the upper-right leg demarcate discrete layers of meaning that relate a given sign to an associated community map. Note that the upper triangle at the bottom (blended space) of Fig. 2 uses five nodes between sign and community map, whereas the two upper triangles at the top (input spaces) each use four nodes. The representation in Fig. 2 makes explicit constituent parts of a community map that may be used as a unitary object. An expert may use such a unitary object in such a way that she is not explicitly aware of the multiple associations that are built into the community map. The constituent parts of the community map can be unpacked by examining scientific papers, textbooks, etc.

Meanwhile, a student may initially use a direct interpretation of a sine wave, a 2-D substance-like

Interviewer (I) directs student (S) to sound representations show at right	
16:48	S This is saying, like, the signal almost, the signal is strong, well, I mean they're once again its another physical representaion of the sine . So just looks like it's strongest here, [points to dense area of particles] so at the high point it'd be strongest . [points to peak of sine wave]
17:05	I Mm hmm.
17:10	S And, when you come down negative there's the least particles . [points to trough of sine wave] So it'd be weakest.
I directs S to EM an wave concept question using a sine wave representation	
17:37	S That, um, 1 and 4 are actually gonna be greater because this is gonna be a stronger signal . [points near dense particles on sound rep] Essentially like the sound wave. There's more particles into the peak. Greater signal.
17:52	I OK. Greater signal than...
17:54	S Than, like, 3 which is out here. [points near rarefied particles on sound rep] There'd be less particles .
17:59	S 2 I'm still kind of confused on. It seems like, well maybe it'd be the same 'cause if you look, if you look, um, at this high point [points at dense area in sound rep], there's a lot of particles all the way down . [sweeps pencil up/down over dense area of pictorial representation] Seems to follow it.

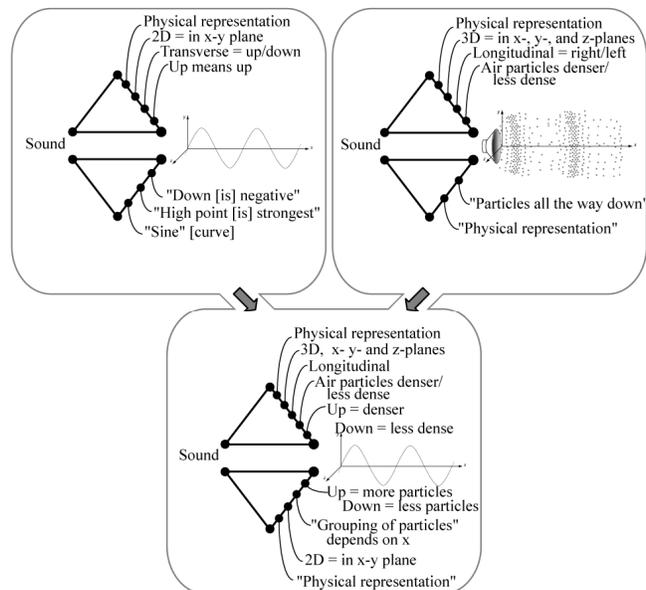


FIGURE 2. Transcript segment from student interview (left). Accompanying Analogical Scaffolding diagram (right). Quotes from the transcript in bold (left) are used in the lower triangles of the diagram (right).

interpretation of this representation – perhaps a *wave on a string*-like interpretation. We represent this student interpretation with one inter-vertex node between sign and schema in the lower triangle of the left input space in Fig. 2, indicating that the salient interpretation of the sine wave utilizes few apparent layers – up means up, for example. In Fig. 2, we use quotes from the transcript to represent some schema elements in the lower triangles. Note that the number of nodes is inversely related to how salient the sign is to the schema. The number of nodes is an indicator of the number of layers that are simultaneously accessed by an individual at a particular time. In a later layer, we might introduce the sine wave as standing for a sound wave, a 3-D longitudinal wave in air. Such is the case in the interview segment shown in Fig. 2. In this interview, student S was presented with both sine wave and air particle pictures (top of Fig. 2). The two mental spaces at the top of Fig. 2 combine to form a new layer, wherein the sine wave stands for a 3-D longitudinal wave in air. Note that this interpretation is not a direct reading of the sine wave (which is depicted as 2-D and transverse). The student learns this community interpretation of the sine wave through a layering process involving the coordination of different representations of the same phenomenon (sound).

DISCUSSION

The framework we have described allows the reframing of particular flavors of constructivist learning. So-called *misconceptions* [12] views may be reinterpreted in several ways. We might view a misconception as the condition in which the set of abstraction layers (call these set A) and the set of salience layers (call these set B) are disjoint, or at least where the union of A and B is only a subset of either set A or set B. A fine-grained approach [8] [13] to constructivism takes a somewhat similar relativist stance, wherein student ideas are “correct” only insofar as these student ideas align with expert views. In other words, apparent misconceptions may be more usefully described as a condition in which a student builds schemata in alignment with a prior community map, say, everyday experience, but these schemata do not align with a new community map (i.e., the physics community map).

Analogical Scaffolding provides a dynamic model of learning. Student ideas are not static structures, even on time scales of minutes or seconds under certain conditions. Our model allows for the dynamic representation of student reasoning and learning of abstract ideas in physics. We have applied our newly modified model of analogy to explore the community

representation of the material used to teach students EM waves, here focusing on a segment of this curriculum using sound waves, and the dynamics of student reasoning around the curriculum.

The results above support the notion that student knowledge is no unitary or stable across contexts, such as different representations. However, we have found productive ways of using existing student knowledge, initially fractured, to build towards more expert-like knowledge. We see student learning redefined as mapping student nodes of salience to nodes of the community. Finding productive ways of promoting such mapping is a task for researchers and instructors in physics education. Unpacking expert knowledge into constituent pieces is a challenging but attainable goal. We have found that Analogical Scaffolding can be productively employed towards such efforts.

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