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ABSTRACT

This report argues that there exists a pervasive tendency for analogies to contribute to the development of entrenched misconceptions in the form of reducing complex new knowledge to the core of a source analogy. The report presents a taxonomy of ways that simple analogy induces conceptual error and an alternative approach involving integrated sets of multiple analogies. The use of multiple analogies is illustrated in the report by the example of force production by muscle fibers. The report concludes with the argument that the situation of analogy is one instance of a more general pattern of misconception attributable to the use of single knowledge sources when compilation of multiple sources would be more appropriate. (Eight figures illustrating multiple analogies are included, and 21 references are attached.) (RS)

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MULTIPLE ANALOGIES FOR COMPLEX CONCEPTS: ANTIDOTES FOR ANALOGY-INDUCED MISCONCEPTION IN ADVANCED KNOWLEDGE ACQUISITION

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Abstract

A pervasive tendency for analogies to contribute to the development of entrenched misconceptions is identified. The misconceptions have the form of reducing complex new knowledge to the core of a source analogy. A taxonomy of ways that analogies induce conceptual error is presented, with examples of common biomedical misconceptions corresponding to each. In order to combat the tendency toward oversimplification associated with the use of a single analogy, an alternative approach involving integrated sets of multiple analogies is offered. In the multiple analogy approach, additional analogies are introduced that correctly convey information that is incorrectly represented (or not represented at all) in an earlier analogy. Thus, the pedagogical strengths of analogies are retained while their weaknesses are mitigated. The multiple analogy approach is illustrated by the example of force production by muscle fibers. The use of multiple analogy sets is made more tractable by the employment of composite images, with situation-dependent selective instantiation of aspects of the composite. Finally, the situation of analogy is argued to be one instance of a more general pattern of oversimplification-based misconception development attributable to the use of single knowledge sources when compilation of multiple sources would be more appropriate.

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MULTIPLE ANALOGIES FOR COMPLEX CONCEPTS; ANTIDOTES FOR ANALOGY-INDUCED MISCONCEPTION IN ADVANCED KNOWLEDGE ACQUISITION

Few would disagree that analogy is an important tool in the acquisition of new knowledge. Indeed, work in cognitive science and educational psychology in the last dozen years provides ample evidence of the usefulness of analogy in learning and has substantially advanced our understanding of the psychological mechanisms responsible for that utility (e.g., Burstein, 1983; Carbonell, 1983; Collins & Gentner, in press; Gentner, 1983; Gentner & Gentner, 1983; Gick & Holyoak, 1980; Rumelhart & Norman, 1981; Vosniadou & Ortony, 1983). Yet, as this paper will demonstrate, the use of analogies in learning is far from straightforward and surprisingly often results in deeply held erroneous knowledge.

Our intention is to offer a more temporized and cautionary alternative to the general enthusiasm for learning by analogy, especially in its most common form: The use of a single mapping between a source and a target concept (the "topic")--what we will refer to as a "single analogy." (For exceptions that address more complex uses of analogy, see Burstein, 1983; Collins & Gentner, in press.) We argue that single analogies that help novices to gain a preliminary grasp of difficult, complex concepts may later become serious *impediments* to fuller and more correct understandings. Specifically, although single analogies rarely if ever form the basis for a full understanding of a newly encountered concept, there is nevertheless a powerful tendency for learners to continue to limit their understanding to just those aspects of the new concept covered by mapping it to the old one. Analogies seduce learners into reducing complex concepts to a simpler and more familiar analogical core.

Our position is not antagonistic to analogy; again, there is no doubting the value of apt analogies in introducing unfamiliar concepts. However, we are not as sanguine about the benefits of single analogies at later, more advanced stages of learning about complex concepts. Therefore, sensing an unhealthy imbalance in the attention devoted to the nature and benefits of analogical learning, we attempt to address some of the more neglected hazards. On a more positive note, we discuss *two antidotes* for what we have found to be an insidious tendency of analogies to block more advanced knowledge acquisition: (a) pay more attention to the ways that analogies fail or mislead or are incomplete--learners and teachers are more likely to be able to avoid pitfalls if they have explicit warning of what those pitfalls are, and (b) employ integrated multiple analogies to convey more of the necessary complexity of difficult concepts--the more complex and ill-structured the new concept, the greater the need for a finely tuned synthesis of the relations between it and *several* already known concepts.

Overview

We begin with a brief introduction to the overarching orientation that guides our remarks on analogy. Then, in the first main section of the paper we illustrate the danger of misuse of single analogies in the learning of complex concepts, using examples drawn from the biomedical domain. We demonstrate several common misconceptions held by medical students that are traceable to a cognitive (and sometimes instructional) overreliance on single analogies. Eight varieties of analogy-induced misconception are identified. We then examine the circumstances of learning and instruction that promote the uncritical acceptance and entrenchment of learning based on inadequate analogies.

The second section of the paper presents our approach to the use of multiple analogies to correctly, yet manageably, capture the complexity of difficult concepts and illustrates the approach with the example of force production by muscle fibers. In this approach, multiple additional analogies are chosen to correct the problems introduced by any single analogy, without cancelling the beneficial effects of the single analogy. In order to mitigate the additional cognitive load that multiple analogies introduce in learning, we describe a technique for context-dependent "selective and contingent composite imaging" of the productive features of the multiple analogies.

In the third major section we present a more detailed picture of the variety of ways that adding analogies can affect the earlier learning outcomes derived from previously encountered analogies. We develop a nine-part taxonomy of the functions of new analogies and modifications of old analogies in promoting understanding.

Thus the three primary sections of the paper can be thought of as addressing: (a) what can go wrong in the use of single analogies (and often does); (b) how a set of multiple analogies can counter the hazards of single analogies, and how such a set should be selected, integrated, and psychologically managed; and (c) the various functions in promoting understanding accomplished by combining analogies.

The Perspective of Advanced Knowledge Acquisition

The work on analogy that we discuss in this paper is part of a larger program of research concerned with *advanced knowledge acquisition*. Detailed accounts of our theory of advanced knowledge acquisition in complex and ill-structured domains, and applications of the theory to topics other than analogy may be found in Coulson, Feltovich, and Spiro (1986), Feltovich, Coulson, and Spiro (1986), Feltovich, Spiro, and Coulson (in press), Spiro (in press), Spiro, Feltovich, and Coulson (1988), Spiro and Myers (1984, last two sections), Spiro, Vispoel, Schmitz, Samarapungavan, and Boerger (1987), and Spiro and Jehng (in press). Here we present just a bare sketch of some general issues. At the end of the paper, we situate the analogy research within our encompassing theoretical orientation. The use of analogy is just one area of cognition and instruction critically affected by the relative complexity of the material to be learned. Our theoretical approach to the problems posed by complexity takes a similar generic form whether the concern is with analogies, prototype examples, schemata, or overall organizational schemes for the presentation of large bodies of material.

Advanced knowledge acquisition refers to the learning that follows initiation into the rudiments of a knowledge domain and precedes the attainment of expertise. This intermediate stage, falling between the novice and the expert, is often neglected. We argue that this neglect has serious consequences because the aims of advanced knowledge acquisition are different from those of introductory learning, and those differing aims are best attained by qualitatively opposed means--what helps at the introductory stage may hurt at the advanced stage, and vice versa. In other words, success at the introductory stage may sometimes result in forms of entrenched fundamental understanding that interfere with the eventual attainment of expertise.

The main aims of advanced knowledge acquisition are:

1. *mastery of complexity*: the acquisition of those aspects of conceptual complexity that are necessary for a correct understanding of important concepts (rather than the attainment of a superficial familiarity with simplified versions of concepts, which is often the goal at introductory stages of learning in a knowledge domain); and, relatedly,

2. *knowledge applicability*: development of the ability to adaptively apply or transfer acquired knowledge, especially to realistic situations, especially as those situations present aspects of novelty (rather than merely being able to reproduce content material from memory in just the way that it was learned, the criterion too often employed at all stages of learning).

The present paper is concerned with the first aim. We report on misconceptions held by advanced learners (medical students) that all involve a failure to master important complexities in concepts (because of interference from an analogy); and we present an approach to mental representation, learning, and instruction that is designed expressly to address the difficulties posed by complexity.

(Although full apprehension of conceptual complexities is often a necessary but not sufficient condition of knowledge application--the second aim--that issue is not addressed in this paper) Of course, not all concepts are important enough that their complexities must be mastered. However, at some stage in knowledge acquisition a point is reached where certain concepts are so central that they must be correctly understood. Furthermore, we argue that the complexities of a knowledge domain become much more centrally important to the extent that knowledge must be *applied* in unconstrained, naturally occurring situations (rather than learned in the abstract or for application in artificial instructional settings). At some point during the progress of learning in a content area, it becomes important that the learner "get it right," even if the resulting difficulties place burdensome demands on learners and teachers.

To insure our not being misunderstood, it is worth repeating at this point that we are not advocates of complication for its own sake. Well-structured subject matter can and should be taught in much simpler ways than we recommend for more complex and ill-structured material; every kind of reductive use of analogy that we criticize has a counterpart which is a strategy for *usefully* stripping away complexities--either at the early stages of learning some topic (especially for learners who will not be going further in a subject area), or when complicating factors are not especially important. Furthermore, we realize that the *premature* introduction of complexity may confuse learners. However, we do argue that complexity should be introduced as soon as learners are ready for it, because early simple frameworks often act as impediments to grasping complexities introduced later (as we shall see in the next section). Furthermore, new approaches to learning and instruction are now being developed that will advance the time at which learners are ready to deal with complexity--procedures are being created for making the learning and instruction of complex information more tractable at an earlier stage of knowledge acquisition. One example of such a procedure is the use of integrated multiple analogies, made psychologically manageable with composite images; this procedure is dealt with at length in the section after next.

The Reductive Force of Analogy and Analogy-Induced Misconceptions

Those who study analogy offer frequent reminders that the useful applicability of an analogy is never total; only some relational aspects of a source domain may be transported to a target domain (the *topic*). For example, only a subset of the relationships in the domain "solar system" are representative of the domain of "atoms" (Gentner & Gentner, 1983). While this point is obvious to those who study analogy, it unfortunately fails to characterize the state of affairs with respect to the actual employment of analogies in learning and instruction. In fact, as we shall see there is evidence that analogies exert a powerful "reductive force": When a striking, pedagogically efficient analogy is employed that incompletely represents some target of understanding, the incomplete representation often remains as the *only* representation of the target concept. We have found that misconceptions attributable to the reductive effect of analogies occur even when teachers and texts are explicit in stressing the inadequacy of an analogy. In other words, when analogies are used to "start simple," the knowledge ultimately acquired often *stays* simple. Well intended analogies often result in *oversimplified knowledge*.

Analogy-Induced Misconception: A Typology of Varieties, with Biomedical Examples

We have used directed, open-ended discussion probes to assess medical students' knowledge. (The probe procedure is discussed in Coulson et al., 1986, and in Feltovich et al., in press.) The probes have uncovered several instances of commonly held misconceptions connected to cognitive and instructional aspects of the use of analogies. We will simply refer to these misconceptions without presenting methodological details and specific results of the various studies that they have been culled from (i.e., the examples of analogy-induced misconception have been taken from research in which issues related to analogy happened to emerge in the context of probes with a more open-ended focus or a focus directed toward matters other than analogy). More detailed treatments of the misconceptions

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discus d here and the procedures in the studies that revealed them are available elsewhere (Coulson et al., 1986; Feltovich et al., 1986, in press; Spiro et al., 1988).

Eight ways that anlogies can induce misconceptions are identified below. Each type is illustrated by an example of a biomedical misconception that we have observed to be common among medical students (and, occasionally, among physicians and popular medical textbooks). Since the analogy-based misconceptions involve very technical subject matter, our characterizations will stress the form or structure of the fallacious knowledge and how it develops, rather than going into full detail on the specific content of the misconception. (Again, references in which more substantive discussions are provided for each misconception have been provided.)

All of the examples have two features in common: (a) the source (or base) domain information in the analogy is inadequate or potentially misleading for understanding the target domain (the topic), and (b) in practice, the knowledge acquired about the topic is reduced to just that information mapped by (inadequate) analogy from the source domain. This includes both incorrect *overextensions* from the source (derived from misleading aspects) and *omissions* in the source of information important for understanding the topic.

By presenting this list of types of analogy-induced misconception our dual intentions are to call attention to such effects of analogy and, as a step toward prevention, to provide a somewhat detailed analysis of the forms in which these deleterious effects are manifest, thereby making learners and teachers more alert to their occurrence. It is not claimed that the eight types identified form an exhaustive list or that some misconceptions may not be characterizable according to more than one type. Also, the order in which the types are presented is dictated primarily by sequencing requirements related to the biomedical examples, rather than by any natural ordering of the misconception types.

1. **Indirectly misleading properties.** Some salient characteristic of the source domain that is not central to the pedagogical point of the analogy adversely influences understanding of a parallel characteristic in the topic domain. Roughly put in schema-theoretic terms, there is a prominent variable "slot" in the source domain that has a different instantiation in the topic domain (Rumelhart, 1980). As will become clear after the following example, it is not the case that the slot's value is changed in the topic domain to be identical to its value in the source; rather, misconceptions develop regarding the topic that derive from properties *entailed* by the mismatched slot instantiation in the source.

EXAMPLE: A common analogy used to teach opposition to blood flow (impedance) uses rigid pipe systems such as household plumbing as the source domain. This analogy promotes understanding of that aspect of impedance due to resistance, which primarily depends on the radius of the vessel. However, unlike plumbing pipes, blood vessels are flexible. Related to that flexibility is an additional source of impedance, compliant reactance. Further, a third sc e of impedance exists, inertial reactance, which also derives from the pulsatile (beating) nature of the heart, accelerating the mass of blood on every beat. These latter two forms of impedance are jointly referred to as reactance. Aspects of impedance that involve reactances are frequently misunderstood by medical students (Feltovich et al., 1986, in press). The misunderstandings take the form of either ignoring reactance, or (mistakenly) reinterpreting reactance phenomena in terms of their limited aspects that bear resemblance to resistance (where, again, resistance is the only aspect of impedance supported by the plumbing analogy). For example, compliance (the stretchiness of vessels--related to compliant reactance) is erroneously thought to contribute to impedance through the ability of a stretchy vessel to change radius and thereby affect resistance; and blood density, which directly affects inertance (and inertial reactan) is either neglected by students or it is equated with blood viscosity, which is, again, a contributor to resistance. This family of misconceptions connected to the rigid pipes analogy occurs despite the fact that students usually are exposed to a complete account of the factors contributing to impedance.

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It is very important to note that the students do *not* have the misconception that blood vessels are rigid. The misconceptions that we have referred to come from those aspects of the analogy to household plumbing pipes that are *entailed* by their rigidity. So, for example, the rigidity of plumbing pipes (as well as the constant, as opposed to pulsatile, pressure head that is usually associated with plumbing) make resistance the only factor substantially opposing flow, and misconceptions about impedance to blood flow tend to involve the erroneous conversion of nonresistance phenomena to ones that are resistance-like. Thus the effects of the misleading slot instantiation in the source (rigidity) on the development of misconceptions of the topic are *indirect*. Of course, there may be cases where the learner mistakenly adopts for the topic domain the actual value of a mismatching variable slot from the source domain. This would be more likely to happen when the instantiation of the variable slot is not especially important or salient (in contrast to the obvious actual flexibility associated with blood vessels).

2. **Missing properties.** An important aspect or characteristic of the topic domain has no counterpart in the source domain, and that missing aspect or characteristic does not get incorporated in the understanding of the topic.

EXAMPLE: Medical students frequently have trouble attaining a sophisticated understanding of pressure in the cardiovascular system. A contributing factor is, again, the analogy to household plumbing, water taps, and so on. Because these more familiar fluid systems have a constant pressure head, there is no need in these systems to think about the variable acceleration of water. When the plumbing analogy is used in the heat domain, this missing aspect leads students to omit from their thinking contributions to blood pressure deriving from the pulsatile acceleration of blood. The conception of pressure and the factors that influence it are thereby reduced to ones that would be captured by the familiar Ohm's law, applicable in plumbing.

3. **Exportation of base domain properties.** A salient characteristic of the source domain that has no analogue in the topic domain is nevertheless exported to the topic. A non-existent "slot" is *created* in the topic to correspond to a slot in the source.

EXAMPLE: Starling's relationship between end diastolic *volume* in the heart and cardiac *output* is seen as analogous to the relationship between the *length* to which an individual muscle fiber is stretched and the *tension* it can produce. This is partly because the graphs of both relationships (volume-output and length-tension) have similar ascending left limbs and plateaus. However, while the length-tension relationship for an individual (skeletal) fiber has a descending limb reflecting decreased tension at long lengths, the Starling relationship (in the *in vivo* heart) has no corresponding descending limb at large volumes. A common error made by medical students, physicians, and some medical texts is to asume that the Starling relationship has a descending right limb like that of the length-tension curve for skeletal muscle (Coulson et al., 1986)

This mistaken importation of the source domain's descending limb has serious consequences, playing a central role in the development of a major misconception about the nature of congestive heart failure. Heart failure is erroneously attributed to "falling off the plateau of the Starling curve" as the collection of individual muscle fibers get stretched too far (thus losing tension), resulting in reduced cardiac output, further stretching because of blood accumulation in the heart, further reduced output, and so on. In fact, there are physiological limitations preventing the cardiac muscle fibers from reaching a "descending limb" on the Starling curve (for an *in vivo* heart). In contrast to this misconception, the heart enlarges due to hypertrophic mechanisms while it weakens as a result of the breakdown of muscle activation mechanisms--the heart does not fail because it is geting enlarged (stretched too far), as the analogy to the individual skeletal muscle fiber length-tension relationship mistakenly suggests; it gets enlarged in response to its failing. (See Coulson et al., 1986, for further explication.)

(As we will see in the next section of the paper, "The Analogical Bias," "length-tension: Starling's volume-output" is a false analogy--the circumstances of its mistaken adoption will be discussed later. Our present point only examines its consequences *after* it has been mistakenly adopted.)

4. **Directly misleading properties.** A nonsalient aspect of the source domain in an analogy has a different value than the parallel aspect of the topic domain. The variable slot in the topic is incorrectly assigned the instantiated value of the slot in the source.

EXAMPLE: Recall the misconception that heart failure is due to collective (ventricular) overstretching of individual muscle fibers, "falling off the plateau of the Starling curve," in much the same way that such "falling off" could be achieved in an individual skeletal muscle fiber's length-tension curve (Coulson et al., 1986). The correct explanation involves biochemical *activation* or energizing of the components of the system. One reason that activation is neglected by medical students as a possible cause of heart failure is that cardiac muscle fibers are understood by analogy to skeletal muscle fibers. The implicit assumption is that "all striated muscles are alike." In reality, the two kinds of muscle differ greatly in their activational properties, in ways that are important with regard to heart failure. Skeletal muscle always functions at full activation, so that the activation level of the muscle is not an issue. If cardiac muscle is taken to be like skeletal muscle, and the level of activation is not an issue for skeletal muscle, then it follows that activation is not an important issue for cardiac muscle either. Unfortunately, in contrast to skeletal muscle, the degree of activation of cardiac muscle is *variable*. And degree of activation is the key to the correct account of heart failure (in a way that would not be similarly manifested in skeletal muscle failure). The analogy of cardiac to skeletal muscle brings along with it an incorrect instantiation of the variable slot, "type of activation," and adopting that property of the source domain for the topic has serious ramifications.

5. **Focus on surface descriptive aspects with corresponding mistreatment of underlying causation.** Some analogies are very effective at characterizing surface features and relationships, but gloss over underlying causal mechanisms. The result is that learners are susceptible to either filling in a convenient but incorrect causal account of their own, or just leaving the causal mechanism unexplained, as a kind of "black box." (It might be said that a comparison based primarily on surface descriptive aspects is more metaphorical than analogical. However, our point here is that an underlying relational structure is indeed transferred--that is, people have a tendency to interpret metaphor analogically.)

EXAMPLE: The failing heart is often compared by medical students to a stretched out, saggy balloon (or to overstretched "silly putty"). In fact, this analogy gives a very good picture of representational correlates in the two domains; both heart and balloon get big, but the heart gains passive tension while the balloon loses it. The stretched out balloon, when underinflated for its enlarged size, exhibits floppy walls (low tension); but in the enlarged heart, while each individual fiber exhibits the low active tension associated with heart failure, the increased mass of the enlarged heart and the decreased compliance of pathological origin allows the bearing of increased tension in the walls (via the law of Laplace). However, the analogy is pitched to mere description, and leaves the causal mechanisms in both the balloon and heart situations unaddressed. Medical students then fill the causal vacuum by employing the convenient assumption that the stretching in the heart causes the failure, as it causes the failure in the balloon. As was indicated earlier, activational problems are responsible for heart failure; enlargement (mistakenly likened to overstretch) is merely a later *consequence* of a variety of processes which are associated with failure. Corrrelation can easily be mistaken for causation in this case because causation is not represented in the analogy.

6. **Magnification to the wrong grain size.** An important aspect of the topic domain is missed because the analogy is pitched at the wrong level of magnification or elaboration. It is not that the source domain does not address the aspect, as in #2, but rather that the analogy is cast in such a way that the relevant aspect is not noticed.

EXAMPLE: Certain applications of the Law of Laplace to lung function are demonstrated using an analogy to soap bubbles. In particular, soap bubbles are used to demonstrate what does *not* happen in the lungs (due to an agent secreted by the lungs called surfactant): Little air sacs of the lung do not empty into larger air sacs, as happens when small and large soap bubbles are in communication. However, it is difficult to understand why this does not happen in the lungs without knowing why it does happen in soap bubbles. And it is here that grain size is a problem. You would need to magnify considerably the structure and dynamics in the *walls* of the soap bubble to appreciate what happens differently in the lungs (due to the surface tension lowering effects of surfactant). The magnification would focus on the nature of the wall as two concentric circle layers with fluid in between them. In other words, the important lesson is in the "fine grain of the soap bubble wall rather than in the typical, grosser image of soap bubbles connected by a pathway.

7. **Misleading properties derived from common language meanings of technical terms.** Ordinary language concepts are often employed analogically as technical terms. Their everyday, "public" connotation is overextended to their technical use in the topic domain.

EXAMPLE: In its technical usage the "compliance" (stretchiness) of vessels in the cardiovascular system is important as it contributes to the vessels' ability to exchange potential and kinetic energy, to ensure smooth movement of blood under the influence of the pulsatile beating of the heart. Students develop misconceptions that reflect the adoption of analogies for compliance that are consistent with common, ordinary language uses of "compliance" and that clash with its technical meaning. These include analogies of compliance as a "giving-way" (surrender) of vessels under the onslaught of blood, and even analogies that reflect the vessels' willingness to respond to orders from the nervous system (to, for example, dilate or contract, Feltovich et al., 1986).

(This misconception type, as well as #8, might be considered to be based more in metaphor than analogy. However, because the metaphorical descriptions lead to the adoption of specific source exemplars the features of which are mapped to the topic, the designation of these misconception types as analogical seems appropriate.)

8. **Misleading properties due to connotations of nontechnical descriptive language.** Inappropriate analogies are induced by the loose use of poorly chosen, connotatively loaded nontechnical descriptors.

EXAMPLE: The arterial vessels and other sections of the circulation are active contributors to blood flow. During the period of the heart's ejection (systole), blood from the heart is stored under pressure in the distended walls of the arterial vessels, so that when the heart is no longer actively ejecting (diastole) the recoil of these elastic vessels continues to propel blood. Perhaps to make a contrast to the period of active ejection of blood from the heart, diastole is often referred to loosely in instruction as a period of "run-off" or "drainage." These terms do not convey active motive force but, rather. passive flow from a region of high to low static energy density. Students tend to think of the arterial vessels as passive receptacles and also tend not to consider adequately the active propulsion of blood during diastole, viewpoints more consistent with a notion of passive "seepage" than with the reality of blood flow during diastole.

It is interesting to note that a similar misconception occurs on the venous side of blood circulation due to the use in instruction of such language as "pooling" of blood in the veins, a term that carries the connotation of stagnation, or lack of interaction with the surround. Students develop the notion that some major components of the circulation can (at least temporarily) be removed from the active stream of circulation. Components of the venous circulation take on characteristics of reservoirs, "pools" that can be augmented and drained according to circumstantial needs for blood delivery, but that are not continuous parts of the overall circulation of blood.

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9. **Multiply based misconceptions.** A single analogy may in fact lead to a variety of misconceptions, each involving a different influence from the list above.

EXAMPLE: The analogy of a rowing crew is commonly used to represent the functioning of the contractile units (sarcomeres) of muscle fibers. This analogy captures some aspects of the topic domain of muscle function well, particularly anatomic aspects of force production by oar-like ratcheting elements within the fiber. At the same time, the analogy (a) *Indirectly Misleads* (#1) with regard to some aspects of muscle ultrastructural function (e.g., conveying erroneously that the force producing units act in synchrony), (b) *Misses* (#2) some aspects (e.g., sarcomere characteristics related to their width as opposed to their length), and (c) *Exports* (#3) yet other misleading aspects (e.g., the idea that the force-generating units can get entangled, and thus fail to produce force). Much more will be said about the strengths and weaknesses of this particular analogy in the later section on multiple analogies.

Summary of analogy-induced misconception. Several ways that analogy can induce misconceptions have been presented. Although they differ in many respects, they have in common the characteristic that students' understanding of a topic domain is too exclusively determined by properties of an analogous source domain. In the various ways that we have illustrated, the mental representation of the topic domain is *reduced* to the source domain. It is in that sense that the misconceptions involve *Reductive Analogies*. In the next section we address the influences that contribute to the ready acceptance of analogical reductions.

The Analogical Bias: Patterns of Psychological Support for the Uncritical Acceptance of Deficient Analogies

Where do maladaptively reductive analogies originate? We have observed three sources. In the first, teachers and textbook authors recognize the pedagogical value of analogies in introducing difficult concepts and employ a conventional analogy for just that introductory purpose (while providing disclaimers about the limitations of the analogy and descriptions of appropriate corrections). They then find that their students have simplified their understanding of later, more advanced treatments of the concept to just what was covered by the introductory analogy. The second source is teachers and textbook authors who themselves have misconceptions. These may be associated with mistaking conventional approaches to introducing a complex concept for complete accounts of the concept. In the third scenario, learners independently adopt analogies that, despite being both unconventional and incorrect, are nevertheless seductive in some way.

However, regardless of their origin, reductive analogies all share certain features. All of the scenarios involve a *bias* to overrely on analogies: in the first case by students/learners in their implicit strategies for assimilating externally provided instructional information, in the second case by teachers, and in the third case by students/learners as regards their self-generated cognitive strategies. A further feature of the reductive analogies that we have observed is that they seem to lull the learner into an unquestioning acceptance that leads to a durable entrenchment of the misconception. Why, then, are maladaptively reductive analogies so readily adopted and so durably held? We will offer a partial account of the factors contributing to this bias, including its motivational origins and the methods implicitly employed for its self-justification. We will take an example of the third kind, an inappropriate analogy that is frequently adopted spontaneously. Understanding of the sources of such especially maladaptive analogies will also provide clues to why reductive analogies seem to be held so uncritically; that is, why they are so *seductive* of the belief that a full and accurate understanding has been achieved.

Support for false analogy in the Starling/Length-Tension example. The *length-tension* relationship of a single skeletal muscle fiber (studied in the laboratory, isolated from other muscles it normally interacts with *in vivo*) is essentially *irrelevant* to Starling's relationship between ventricular *volume* and cardiac *output* for the *whole* heart *in vivo*. (See the earlier discussion of #3 in the typology of ways analogies induce misconceptions.) Thus, when people adopt the analogy, they are doing it largely on their own. Despite its irrelevance, students give no sign that they consider the analogy at all

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controversial. What contributes to this unquestioning acceptance? More specifically, why would students want the analogy to be a useful one, and what causes them not to be suspicious of it? The following is a partial set of contributing forces.

1. **Bolstering due to similar appearing objects.** Volume is like length; force that produces ventricular (cardiac) output is like tension.

2. **Bolstering due to similar appearing relations.** The graph of the relationship between cardiac volume and output (Starling) has a similar shape to that of the relationship between skeletal muscle length and tension: They both have ascending slopes to a plateau.

3. **Reciprocating effects of separate bolstering elements.** The extent to which the similar appearing objects in the source and the topic bolster the analogy (#1) is increased by the fact that those similar objects also have a similar pattern of relationship in the source and the topic (#2). In a circular fashion, each is used to increase the credibility of the other.

4. **Bolstering due to assumptions of ontological similarity.** Why does it sound so initially plausible that the collective function of muscle fibers in the whole heart would be analogous to that of individual, isolated muscle fibers? Here we have what can fairly be described as a fundamental ontological assumption about the natural world, namely that the world is structured in such a way that it is legitimately reducible by analogy: *Wholes are like parts*. The relational functioning of collections of fibers will be analogous to that of individual fibers (even though the objects involved, hearts and heart muscle cells, are markedly dissimilar): They will have the same shaped curve mapping their size aspects (i.e., length/volume) to their force aspects (i.e., tension/output), and the latter relationship will have the same theoretical explanation invoking the same mechanism (in particular, the sliding filament theory of muscle contraction--see Coulson et al., 1986).

Note further that this ontological bias can be reached through presuppositions deriving from two different ways of theorizing about the world: organicism and mechanism (Pepper, 1942). Organicistic accounts are noted for their attention to the symmetry of relationships found in microcosms and macrocosms (here, wholes are like parts). Mechanistic accounts would reach the same conclusion via such presuppositions as additivity and atomism: The collective Starling function "sums over" individual fiber length-tension functions (additivity); and individual fibers function the same when placed in context (*in vivo*) as when they are studied in isolation (atomism; i.e., the primary units of analysis are the individual components of a system and not the whole system itself--a fundamental bias of mechanistic approaches).

5. **Indirect bolstering by convenience of explanation.** In students' learning about heart failure, the well known "sliding filament" account of the length-tension relationship has a plausible sounding (but incorrect) extension to volume-output relationships in the heart. In other words, you do not need to learn a new underlying mechanism. Furthermore, you get to use a well-learned concept; the situation is akin to that of the person trying to improve his or her vocabulary who learns a new word and then orchestrates opportunities to use it. The conveniently overextended sliding filament theory then invokes a theme of overstretching for heart failure which (misleadingly) corresponds to a prominent and well known clinical sign of heart failure, enlargement.

6. **Indirect bolstering by elimination of potential analogy blockers.** We have seen that activational/energizing operations are neglected, in favor of mechanical overstretching operations (sliding filament theory), in the account of heart failure commonly preferred by medical students and by some physicians and popular textbooks. This elimination of activation cleans up a bit of potential untidiness in adopting the "length-tension: volume-output (Starling)" analogy. The absence of an activational component reinforces the idea that only mechanical factors are involved, and are involved in the same way, in the production of the two curves. That is, if heart failure is a mechanical phenomenon, and it is caused by "falling off the Starling curve," then mechanical rather than

ERIC

activational factors account for Starling. This consideration of Starling as being entirely mechanical makes it easy to ignore fundamental differences between the length-tension relationship and the Starling relationship that are due to the role of activation. Without an understanding of the differential roles of activation in the two curves, the "length-tension: volume-output" analogy gains strength.

But how does activation become neglected in the first place? One contributing factor is presented in #7.

7. **Bolstering due to shared name.** Degree of activation of muscle is not an issue if cardiac muscle is taken to be like skeletal, since skeletal muscle fibers always function at *full activation* (tetanic activation). So, if cardiac is like skeletal, variable activation is not an issue. Unfortunately, in this respect cardiac muscle fibers are *not* analogous to skeletal muscle fibers--the former are in fact *variably activated* (twitch activation).

So, the anlogy between length-tension and volume-output is supported by the overreliance on the analogy of skeletal and cardiac muscle, which in turn is supported by the implicit (and reductive) bias that is described in the header of this sub-section and may be roughly instantiated in the present case as the belief that "all muscles are alike."

This neglect of activation in the cardiac volume-output relationship of course contributes to the mistaken acceptance of the "length-tension: volume-output (Starling)" analogy: without activation as an alternative account of volume-output and heart failure, volume-output is left with no competition for the mechanical overstretching account derived from the length-tension relationship.

8. **Bolstering due to overall convergence of support.** When many factors converge to support an analogy, as in the present "length-tension: volume-output (Starling)" example, the analogy is bolstered to a greater degree than if it had fewer supporting factors. "If so many things point to it, it must be right."

Summary

We have argued in this section that (a) single analogies induce misconceptions involving the reduction of the topic domain to the source, and (b) there are certain mutually reinforcing biases that increase the likelihood that such reductive analogies will be uncritically adopted. If one adopts reductive analogies, they cause trouble; and one is likely to adopt them.

Antidotes for Analogy-Driven Misconception: Multiple Analogies and Composite Images

What should be done to counter the tendencies toward oversimplification that come with the use of analogy and lead to misconceptions. The reductive force of analogies appears to be so great that it is not enough merely to tell people what the limitations of an analogy are. When teachers or texts provide such caveats for an instructional analogy, the result over time tends to be the same: The analogical core is what is retained. The remedy that we propose is to combat the power of a limited analogy with *another powerful analogy* that counteracts the limitations of the earlier one. In general, the antidote to *any* kind of Reductive Analogy might be the use of appropriately integrated *multiple analogies*, designed to vitiate the effects of three generic types of shortcomings in the use of single analogies (for a more detailed treatment of such shortcomings, see the earlier section on Analogy-Induced Misconceptions): (a) information that is *missing* from the source, (b) information in the source that is *misleading* about the topic, and (c) information that is *inappropriately focused* in the source. In this section we discuss an approach for *selecting, integrating, and managing* multiple analogies to promote full understanding of complex concepts in advanced stages of knowledge acquisition.

ERIC

The discussion of our multiple analogy approach uses as an example the concept of muscle function introduced earlier. When the topic of force generation in a muscle is taught using the analogy to rowing teams, we saw that the resulting knowledge contained the seeds for various misconceptions. Some could be attributed to what the analogy *misses* (e.g., reduction in width with elongation of a muscle fiber) and some to aspects of the analogy that *mislead* (e.g., the synchronicity of movement across rowers).

Our approach to using multiple analogies is simply to introduce new analogies targeted at emending the missing, misleading, or misfocused information contained in earlier analogies. Then, as we will see in the next subsection, the various analogies are integrated in a *composite image* that has selective instantiations of the correct and useful information found in each analogy, but suppresses the inappropriate information. In other words, our procedure permits the retention of each analogy's strengths while discarding its weaknesses.

A Multiple Analogy Set for Muscle Fiber Function

We begin with a brief treatment of some of the more essential features of muscle fiber function, with reference to the muscle fiber portrayed in Figure 1.

[Insert Figure 1 about here.]

The contraction of a muscle ultimately is accomplished by micro-structures within the muscle called cross-bridges. Cross-bridges are tiny "arms" that reach from one part of the muscle (myocin) out to an adjoining muscle structure (actin). The cross-bridges deliver the pulling force that accomplishes the contraction of a muscle. During a shortening contraction (non-isometric) each cross-bridge head releases from its site on the actin and moves to the next slot, possibly just vacated by its neighbor, while another cross-bridge pulling elsewhere prevents backsliding. The actin structures are thus pulled in towards the center of the myocin filament (see Figure 2). Each release and rebinding is called a "cross-bridge cycle." After a cross-bridge releases and rebinds, the cycle repeats until muscle deactivation occurs. That is, cross-bridge cycling continues over and over unless activating material (e.g., calcium) and/or usable energy (ATP) needed to energize the releases and rebindings become limited. The duration of the contraction is dependent on the degree of availability of these materials. The strength depends upon the number of cross-bridges pulling on actin filaments at any instant during the contraction. The somewhat simplified description presented here does not do justice to the real complexity of the process. The mechanisms by which the repeated cross-bridge cycles are accomplished involve intricate electrostatic, chemical, and physical processes and exchanges.

[Insert Figure 2 about here.]

The processes of muscle function are clearly quite complex. As we have already seen, much of this complexity is not captured by the rowing team analogy (although the anlogy is very helpful for conveying some of the anatomical aspects). Some strengths and weaknesses of the rowing team analogy are listed in the left and right columns, respectively, of Figure 3. Analogies relevant to other aspects of muscle fiber function are found in Figures 4-8, each with the same two-column structure of strengths and weaknesses.

[Insert Figure 3 about here.]

The missing, misleading, and inappropriately focused information found in the right column of each of the analogy figures guides the selection of additional analogies used to promote fuller understanding; new analogies are chosen which convey the correct knowledge not conveyed by the old analogies. For example, one of the misconceptions engendered by the Rowing Team analogy concerns the nature of the gross movement of the main structures in relationship to each other. To produce contraction the "oars" must in fact pull something toward the center. Figure 4 modifies the analogy in Figure 3 to correct this incorrect aspect.

[Insert Figure 4 about here.]

However, the analogy in Figure 4 still has the problem that it misses the crucial notion of attachment of the cross-bridges to some structure (the actin; see Figure 1) that gets pulled toward the middle--oars, in contrast, slip through water. This shortcoming suggests the analogy of the Turnbuckle (Figure 5). This analogy captures the correct idea of something being pulled toward the middle, without any change in the length of the structure doing the pulling (the myocin) or the structure being pulled (the actin). It also conveys the notion that there is a limit to the shortening process, which has also been missed by the earlier analogies. However, the Turnbuckle analogy has nothing corresponding to the cross-bridge anatomy depicted so well by the Rowing Team analogy; hence the new analogy is not a complete substitute for the old one. It is for such reasons that multiple analogies must often be maintained, rather than new ones simply supplanting old ones.

[Insert Figure 5 about here.]

Another failing of the Turnbuckle analogy is that it provides no useful guidance on the limits to *lengthening* of the fiber (an aspect that is important, for example, in understanding heart failure). Here the analogy of the Chinese Finger Cuffs (Figure 6) provides a (partial) corrective: The double-wound spiral structure of the muscle covering (the collagen and elastin) produces a length limit (a kind of "wall"). Here again, some of the elements that the new analogy is weak in conveying are covered by earlier analogies (e.g., the anatomical information about individual force producers covered well by the Rowing Team analogy and the limits to shortness covered by the Turnbuckle).

[Insert Figure 6 about here.]

We have now progressed considerably from the initial Rowing Team analogy, but essential information has still not been conveyed. Most prominently, there is still nothing about the recruitment of force producers (rowers and oars) to act in any given contraction cycle; not all force producers need act on any cycle and there is a process of selection from those available. (Note also how this analogy might serve to correct a notion that all rowers must be rowing at any one time, which is conveyed by the Rowing Team analogy.) This variable recruitment aspect of the topic is conveyed by the Slave Ship analogy in Figure 7.

[Insert Figure 7 about here.]

More could be added about how muscle cells work. For example, the metabolic and energetic "life processes" of the muscle's force producers have not been addressed (Figure 8). (These processes are important in understanding muscle activation, which, in turn, is important in understanding cardiac failure.) Furthermore, analogies for them are not even easily created. (Note, however, that we have been talking about the force producers as *people* rowing. This may actually be a fairly good analogy for the processes under discussion here.)

[Insert Figure 8 about here.]

At this point of the analysis a plateau of sorts has been reached. Many essential aspects of the topic have been covered. And if one considers that much of what medical students understand (and misunderstand) about muscle function is guided by the Rowing Team analogy, the advance in understanding easily enabled by the additional analogies is very substantial indeed. A complex topic that typically is oversimplifed can now be more readily grasped.

ERIC

Integrating Multiple Analogies

The most important step in the integration of multiple analogies has already been covered by the selection procedure discussed in the previous section. The multiple analogies in a set are *interlocking*, since each new analogy is chosen to correct the negative aspects (the right-columns in Figures 3-7) of the preceding analogies. The remaining discussion of integration is merely an unpacking of the integrative machinery implicit in the procedure for selecting analogies.

Once a set of analogies has been selected, such that the unproductive missing, misleading, or poorly focused information for each analogy has been modified or canceled out by some aspect of a succeeding analogy, then the multiple analogy set must be integrated. There are two main ways of adding new analogies to earlier analogies. These will have an impact on how the additions function to produce new understanding. (A more detailed taxonomy of the functions of new analogies and modification of old ones is presented in the next section. Although there are relationships between the *functions of new analogies* discussed there and the *patterns of combination* described here, they are distinct topics. We restrict ourselves here to the smallest number of types of combination necessary for introducing the composite imaging procedure in the next section.) In one of the two combination patterns, *Modified Analogies*, new analogies merely amend an earlier one (e.g., correcting the Rower analogy to have two sets of rowers pulling toward the middle; Figures 3 & 4). In the second way, *New Analogies*, a totally new analogy is added (e.g., introducing the Turnbuckle analogy following the Rower analogy).

The class of Modified Analogies contains two subtypes: *Simple* and *Complex*. With the addition of a Simple Modified Analogy there is no need to retain the old analogy; the new analogy emends incorrect information from the old one but loses none of its essential information. This type of Modified Analogy is the easiest to deal with. First, the modified analogy is merely *substituted* for the earlier one (e.g., replace the drawing in Figure 3 with that in Figure 4). Second, the critical new aspect of the substituted Modified Analogy is accentuated. For instance, the image of two sets of rowers *facing each other* and *rowing toward the middle* is marked for special notice. This may be accomplished, for example, by suggesting to students that they envision one of the sets of rowers as colored red and the opposed set as blue; or by placing eye-glasses on the rowing team members to accentuate the directions they are facing. The point, again, is to accentuate the features of the Modified Analogy that constitute the main change from the prior analogy.

In a Complex Modified Analogy, the analogy used for correction of the earlier analogy contains seeds of misconceptions that are best mitigated by *maintaining* an aspect of the earlier analogy. Here the prior analogy cannot simply be "updated." Analogies of this type do not occur in our muscle fiber example. However, integration would be handled by the same *selective instantiation* feature of our composite imaging technique that is illustrated with New Analogies, discussed next.

Making Multiple Analogy Representations Cognitively Tractable: Composite Images With Context-Dependent Selective Instantiation

How should one keep track of several analogies and the complicated pattern in which they are combined (i.e., the patterns by which the left-columns of Figures 3-7 are retained and the right-columns overridden as successive analogies are introduced)? The cognitive demands are considerable. To make the psychological management of this complexity more tractable, we introduce the technique of "Composite Imaging with Selective Contingent Instantiation" (CISCI). The remainder of this section is devoted to a description of the CISCI procedure. However, although conventional means of teaching concepts will not receive attention, it must be emphasized at the outset that *the composite images are perceptual adjunct aids that supplement rather than replace verbal instruction*.

In the CISCI procedure, a complete set of images, each corresponding to one of the multiple analogies (other than those superceded by a Simple Modified Analogy), is available in a latent state. That is, all of the images that are to be combined are represented as potentials in a state of readiness for instantiation. (We intend for these representations to refer both to latent mental images and to displayable external images, e.g., computer graphical displays. Thus our discussion refers *both* to mental representation and its parallel in instructional support systems.) Which of the latent images (analogies) of the total composite image are actually instantiated at any one time is *aspect-dependent*. That is, a component of the (latent) total composite image will be a part of an actual instantiated composite image as a function of the aspects of muscle fiber function under consideration. For example, in contexts where it is important to focus on the way muscle fiber is affected by longer lengths and length limitations, the Chinese Finger Cuffs image would become salient; when thinking is directed at muscle functioning under short lengths and toward the limits to shortening, the Turnbuckle image would be "programmed" for high salience. Component images that are not activated are suppressed; they may either not be visible (in "the mind's eye" or in an external support system) or, preferably, they may be instantiated very faintly, as a kind of background to the aspect-dependent focal images.

Finally, at the same time that either the Turnbuckle or the Chinese Finger Cuffs (continuing the last example) is relatively salient within the instantiated CISCI, images corresponding to the other analogies that are not being actively suppressed (i.e., that retain their usefulness for the conceptual aspect under consideration) will simultaneously be superimposed within the total image. So, if the Chinese Finger Cuffs are active, that image would be overlaid by the Double Rowing Team image; an image of two sets of rowers pulling toward the center would be superimposed on the cylinder of the finger cuffs, enabling the positive properties of both analogies to make a simultaneous contribution.

In sum, the characteristic of aspect-dependent *selective and contingent instantiation* of component images (along with the initial motivation and basis for selecting each of the analogies, that is, overcoming some inappropriate information in an earlier analogy--the right columns in Figures 3-7), makes it possible for understanding of the concept to be supported only by the correct and productive features of each analogy, with the incorrect and unproductive features cancelled out. The CISCI can be thought of as a *montage* of simultaneous ways that muscle fiber function can be "*seen as*" (Wittgenstein, 1953) something else. Parts of the montage are emphasized in visualization as a function of the productive left column information that needs to be stressed and the unproductive right column information that needs to be suppressed, given the conceptual aspects under consideration at any one time.

The CISCI method we have described is thus one of *nonabstractive integration*. By using a *composite* of several analogies, understanding is not abstractively reduced either to a superordinate system or to any one of the analogies acting as privileged with respect to the others. In contrast, in *abstractive integration* the individual elements are *replaced* by a subsumptive abstraction that *stands for* the elements and/or their combinations. By presenting the composite analogies as simultaneously overlapping images, the composite leads to a *perceptual* integration. Thus, as in the perception of complex objects like human faces, a whole is psychologically graspable without loss of information about parts--although one's image of the face of a close friend is typically perceived as a simultaneous physiognomy, the components of the face are recoverable (i.e., perceptual focus can shift to individual facial features, such as the size of the nose or the distance between the eyes). The physiognomy is perceptually integrated while the component parts continue to make their contributions individually (in contrast to the supplanting of individual elements in an abstractive integration).

The kind of perceptual composites or "integral visual displays" for representing nonreducible multidimensional information that we are proposing have been receiving increasing support in recent years (Chernoff [illegible]; Spiro, 1982; Spiro et al., 1987; Spiro & Myers, 1984; Wainer & Thissen, 1981). The more [illegible]ly structured the domain, the more it becomes impossible in principle to conceptually [illegible] large groups of information; so, instead of a conceptual chunking of information to lessen the cognitive load, we employ a perceptual chunking.

Although formal experimental tests of the CISCI procedure have not yet been completed, there is evidence from its informal employment that the procedure is both (a) effective in fostering in novices a sophisticated understanding of the complexities of force production by muscle fiber (think about the effects on you the reader of having stepped through the figures and having received just partial guidance as to how to compose an image of the set) and (b) easily managed psychologically.

Regarding psychological manageability, it should not be suprising that such a small number of analogy images and aspectual contingencies can be grasped and memorized fairly readily. Furthermore, the component images are fairly familiar ones (rowing crews, Chinese finger cuffs, and so on). Also, the *incremental* introduction of the analogies (see also Burstein, 1983) leads to only gradual increases in the complexity of the target concept; by the time the final analogy is introduced, the concept will already be comprehended fairly well. Then, when the CISCI is introduced, support for learning it will come from the conceptual understanding of the concept already established (through the incremental procedure). That is, incremental introduction of multiple analogies that are individually pedagogically effective helps the understanding of the complex concept, and understanding of the complex concept helps to then durably encode the CISCI that corresponds to the concept--the composite image is not arbitary. The concept supports the initial acquisition of the CISCI, and then the CISCI supports the concept. (It should be quite clear from what we have said that CISCI is very dissimilar to the "method of loci," which involves memorizing lists of unrelated items by placing them against the backdrop of familiar sequentially ordered scenes; Yates, 1966.)

A Taxonomy of Functions of Additional Analogies in Promoting Conceptual Understanding

There are a variety of reasons that new analogies might reasonably be introduced to augment earlier analogies in promoting understanding. Earlier, for purposes of illustrating the mechanics of the composite imaging technique, we presented a very simple clasification of the kinds of analogy additions that can be made. Here we offer a more detailed accounting of the ways that additional analogies can contribute to understanding. A preliminary and nonexhaustive classification of such functions of multiple analogy is given below (mostly carrying over examples from muscle fiber function).

1. **Supplementation** (with New Analogy). Aspects of a topic domain that are *missed* by earlier analogies are covered by a supplementary analogy. (Also see Burstein, 1983.) EXAMPLE: Adding the Turnbuckle analogy to cover the information missing from the Rowing Crew analogy about attachment to some structure that gets pulled (Figure 5).

2. **Correction** (with New Analogy). Aspects of a source domain that *mislead* about the topic domain are corrected (without altering the correct information in the earlier analogy). EXAMPLE: Replacing the Turnbuckle with Chinese Finger Cuffs in the context of understanding muscle fiber function at *long* lengths (Figure 6).

3. **Alteration** (of an Earlier Analogy). Sometimes an incorrect element in an earlier analogy can be dealt with by modifying or "patching" it, rather than by fundamentally changing it or replacing it altogether. EXAMPLE: Modifying the Rowing Crew analogy to have the crew split in half and row towards the center (Figure 4).

4. **Enhancement** (of an Earlier Analogy). A refinement of an earlier analogy that *deepens* the understanding of the topic domain--that overcomes some earlier superficiality, without either altering the existing components of the earlier analogy (#3, Alteration) or changing its magnification (#5, Magnification). EXAMPLE: Having the cockswain call out the numbers of the rowers (recruitment of cross-bridges) to convey the notion of asynchronous movement and degrees of recruitment (Figure 7). Note that the Enhancement impresses an appropriate new layer of mechanism on the phenomenon. As a side effect, the Enhancement also repairs a misleading implication of an earlier analogy (Figure 3; first item in the right column), without repairing the earlier analogy itself. Thus it differs from #3,

Alteration. In terms of the rules for constructing Composite Images, this is a Simple Modified Analogy, whereas Alteration is a Complex Modified Analogy.

5. **Magnification (or Elaboration).** An aspect of the topic domain that is not correctly captured because of the "grain size" of the analysis (and corresponding image) evoked by the source analogy is addressed by scale alterations (i.e., changes in grain size). EXAMPLE: While the introduction of the cockswain (Figure 7) captures the notions of recruitment of force producers and asynchronous movement, it is simply opaque regarding the biochemical life processes involved in variably energizing the force producers. Perhaps the best way to remedy this problem is by a many-times magnification of an individual rower in the rowing crew (i.e., "people," and their intake, breakdown, and utilization of energy, as an analogy for the metabolic aspects of the force producers).

Note that there are two possibilities following Magnification: introduction of a *new* analogy for the magnified section of the old analogy and retention of the *old* analogy on a different scale. An example of Magnification involving the retention of an earlier analogy but with change of scale was encountered earlier in the Law of Laplace example, where magnification of the soap bubble wall was a key step.

Of course, when a more synoptic view is required, grain size may be decreased in a "reverse magnification." Also, a function related to Magnification would be served by rotating the image of the source domain so that previously obscured elements are brought into view (e.g., as would happen if the first image involved the front of a thing and one needed to augment understanding by later looking at the back of the thing).

6. **Perspective Shift.** Complex domains can often be thought of in fundamentally different ways. In such cases, a new analogy may convey a different perspective than that conveyed by earlier ones. EXAMPLE: The Rowing Crew represents well the perspective of *movement production*. The Finger Cuffs represent well the perspective of *limits to movement.*

A related use of new analogies for contributing to understanding involves the introduction of an analogy that addresses underlying causal mechanisms after an earlier analogy that was more concerned with the surface form of a situation. EXAMPLE: When heart failure is taken as analogous to an overstretched balloon that has lost its tensile strength, some aspects of superficial similarity are captured: two things have gotten big and have lost their ability to produce force. However, as we saw when this kind of reductive analogy was discussed earlier, despite the fact that the underlying causes are greatly different, students mistakenly assume they are the same. Introduction of an analogy that more correctly characterizes the cause of heart failure (e.g., a dying car battery) would make it less likely that students would mistake gross "input-output" correlation for causation in the development of the misconception about heart failure.

7. **Competition.** More than one analogy competes as an overall account of the same domain. One analogy eventually supercedes its competitor, which is discarded. Only one analogy occupies a specific analogical niche. EXAMPLE: A common analogy employed by medical students in understanding congestive heart failure is that of an overstretched, "bagged out" balloon incapable of generating force (Coulson et al., 1986; also see the earlier discussion of the false analogy between the length-tension relationship for individual muscle fibers and Starling's relationship between cardiac volume and output). Since heart failure is really due more to impotence within energetic activational factors of cardiac muscle than to anything related to mechanical overstretching, a more appropriate overall analogy would involve something like the dying battery (or perhaps a fouled spark plug or broken distributor wire) introduced in the last section.

8. **Sequential Collocation.** Successive stages in a process are each represented by an analogy. In other words, a single analogy is used for each identifiable "segment" of a phenomenon, and the analogies are simply collocated (without any integration being necessary).

The last two categories are the main ones addressed by Collins and Gentner (in press) in one of the few discussions of multiple analogies in the literature (see also Burstein, 1983). A brief discussion of their work on evaporation models will help to clarify our own approach. Again, Collins and Gentner deal with multiple analogies in two different ways. In the first, they divide up the water cycle into successive stages (e.g., what happens in bodies of water; what happens in the sky; and so on). This is #8, Sequential Collocation. A multiple analogy set would then be the group of analogies for each stage. Their second use of multiple analogies involves choosing the best analogy for each stage. That is, they discuss alternate analogies for each stage (e.g., alternate analogies for what happens in bodies of water), with the ultimate goal of selecting the most appropriate analogy for that stage. This is #7, Competition.

The fundamental difference from our approach should be clear: Our multiple analogies are all applied to the *same* stage of a process, and all of the analogies in the set are *partially correct*--they are all "best" at conveying something about the topic domain. More generally, we claim that for most domains of any complexity the "pieces" (e.g., stages, sectors, aspects, etc.) that the domain is divided into will each need to be covered by more than one analogy. And this is what our "aspect-dependencies" do. However one compartmentalizes a complex domain, the pieces cannot usually be effectively treated with a single analogy. (A related issue that we have not addressed here concerns the extent to which "pieces" of a complex domain can be adequately treated separately from each other at all.)

Recapitulation

There are two main conclusions to be derived from the work that we have presented. First, there are serious hazards involved in the use of analogies. In particular, the employment of a single analogy for a complex concept may impede the acquisition of more advanced understandings of that concept and to engender misconceptions. Second, access to a fuller and more immediate comprehension of conceptual complexities may be achieved by the systematic employment of integrated sets of multiple analogies.

With regard to the first conclusion, a theme of our recent research has been the recurring empirical observation of a pervasive tendency in cognition and instruction towards oversimplification of complex concepts (Coulson et al., 1986; Feltovich et al., 1986, in press; Spiro, et al., 1988; Spiro, et al., 1987). This tendency, which we have referred to as the "Reductive Bias," has been identified in both biomedical and historical domains and has been shown to take a great variety of forms. In this paper we have confined our inquiry to just one cognitive arena, analogical learning, where we have provided several illustrations of the reductive force of analogies and the ramifications of that reductive force in the development of fallacious knowledge. Eight different ways that analogy can induce misconception were identified, and each was illustrated by an important misconception commonly held by medical students who have already had courses in the relevant content area.

This demonstration clearly indicates that analogies must be used with great caution. Even when they are used judiciously to initiate learners into a difficult subject area with appropriate caveats about their limitations, reduction of the topic domain to the source domain appears to be a too common occurrence. It is hoped that our typology of ways that analogy can induce misconception can serve to alert learners and teachers to these potential hazards. However, the reductive force of analogies appears to be so great that even very detailed warnings are probably not sufficient by themselves. More positive measures may be needed, which brings us to the second main conclusion of this paper.

Analogies have traditionally been seen as a powerful *positive* force in learning new material. We have shown a countervailing tendency: In more advanced forms of knowledge acquisition, the power of analogies is often *negatively* exercised. We have argued that the best way to counter this powerful negative force is with equally powerful positive forces--in order to combat the elements that induce misconceptions in an otherwise useful single analogy, import new analogies that powerfully convey the correct knowledge.

In order to lay the groundwork for such an approach, we have offered a detailed conceptualization of the diverse functions of multiple analogies in learning, a procedure for selecting and integrating multiple analogy sets so that they convey complexity without inducing misconceptions, and a composite imaging technique to lessen the cognitive load of working with a multiple analogy set. Taken together, these elements constitute a comprehensive program for the employment of multiple analogies in support of advanced forms of complex knowledge acquisition.

A Final Note: Simplicity and Complexity in Advanced Knowledge Acquisition

This paper dealt explicitly with the reductive force of single analogies in the development of misconceptions and with the role of multiple analogies in promoting correct understandings of complex concepts. However, it has a more general purport as well. This paper can also be treated as a kind of apologue about learning in complex domains. The detailed treatment of hazards of analogy use and remedies for them has close parallels in the use of *any* mode of cognitive support for complex new learnings. In the findings of our other studies, the maladaptive reductive force of single analogies is paralleled by misconception-inducing reductive forces of a single schema, single mode of organization, single line of argument, single precedent example, single prefigurative "world view," and so on. The antidote for these maladaptive forces of simplification is in each case the *systematic assembly of multiple knowledge sources*--integrated multiple analogies, compiled fragments from diverse schemata, re-presentations of the same information under different organizational schemes, multilinear lines of argument, and multiple precedent examples. So, it could be said that this paper, besides being about analogy per se, is also, in an important sense, about the seductive force of all singular approaches to complex learning, the prevalent role of oversimplification in the development of entrenched fallacies of conceptual understanding, and the general importance of assembling multiple knowledge sources to support the mastery of complex concepts at advanced stages of knowledge acquisition.

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Figure Captions

Figure 1. Schematic representation of the sarcomere. The sarcomere is the functional contractile unit of the muscle cell (fiber). The sarcomere is usually thought of as the unit contained between two of the z divisions in the (a) diagram. Actually a great many actin filaments are attached to each z disc and a great many myosin filaments are interspered among them. A schematic cross-section through a muscle fiber is presented in the (b) diagram. It shows a hexagonal array in which each myosin filament is surrounded by actin filaments and each actin filament is surrounded by myosin filaments.

Figure 2. Schematic representation of a sarcomere during shortening. The illustrations (a)-(d) represent the sarcomere at various stages of a shortening contraction, between the rest length (a) and the maximum shortened length (d). The sarcomeres in a muscle cell (fiber) fill the cell from end to end. When they all shorten at once, the whole cell shortens.

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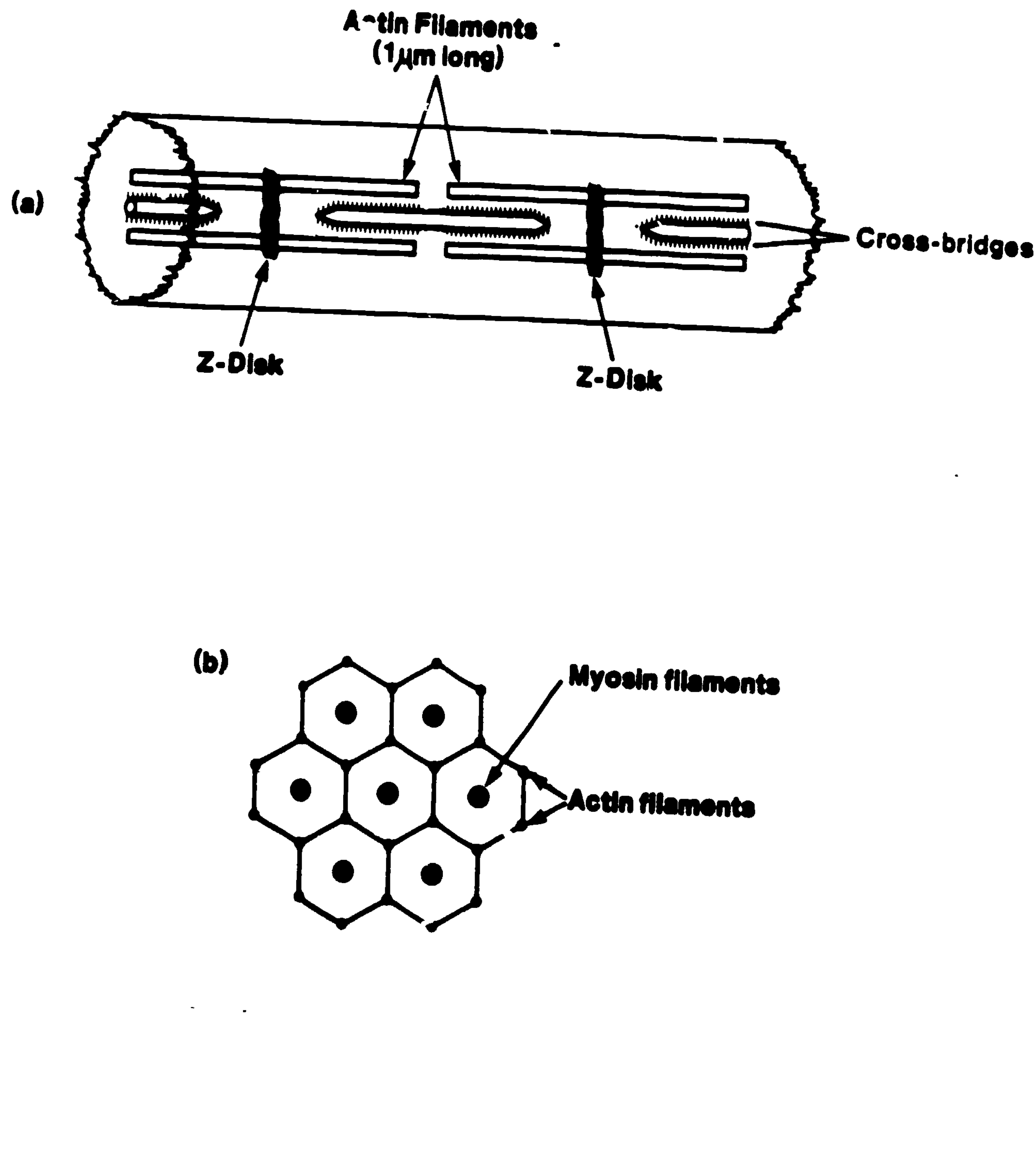

Figure 1

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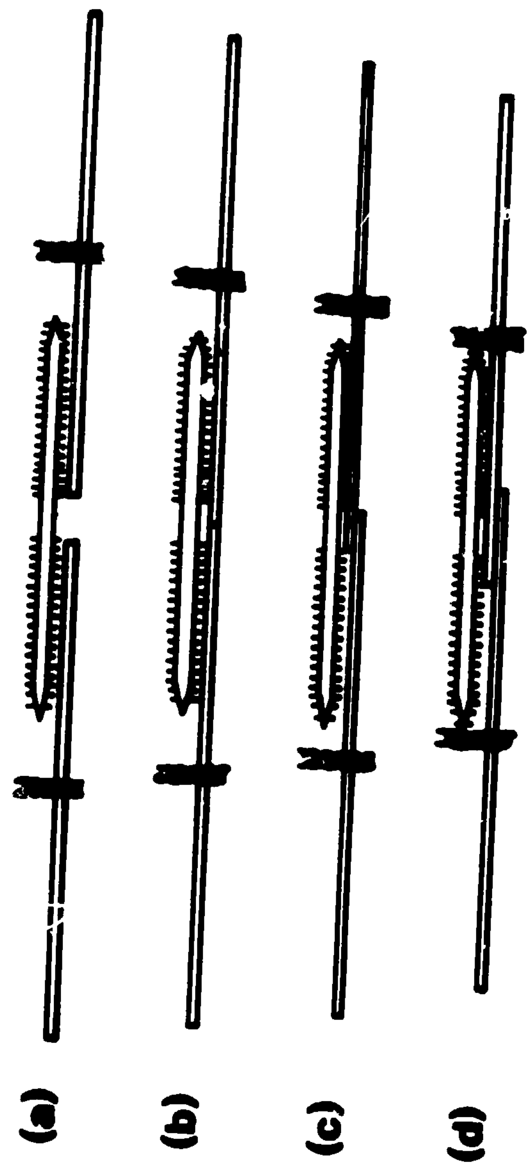
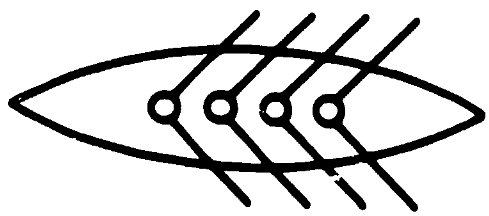


Figure 2



Rowing Crew

Figure 3. Force production to create movement (contraction): the rowing crew analogy

CAPTURES

(1) Anatomy of force producers: the little arms

(2) Nature of the movement of the force producers: back and forth, hitting a resistance

(3) Lots of individual force producers

MISSES OR MISLEADS

(1) Conveys synchronicity: idea that all producers act in unison

(2) Conveys notion that oars can get tangled (e.g., if boat too short)

(Locus of L-T Bug)

(3) Misses actual nature of gross movement (see Figure 4)

(4) Misses things related to Width (see Figure 6)

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Figure 4. The nature of overall gross movement of parts in relation to each other (pulling toward the middle): the analogy of two crews facing each other in a long boat.

CAPTURES

(1) Notion that action tends to pull something toward middle (the water)

MISSES

(1) Attachment to some <u>structure</u> that gets pulled toward middle

(Problem is that oars slip through water)

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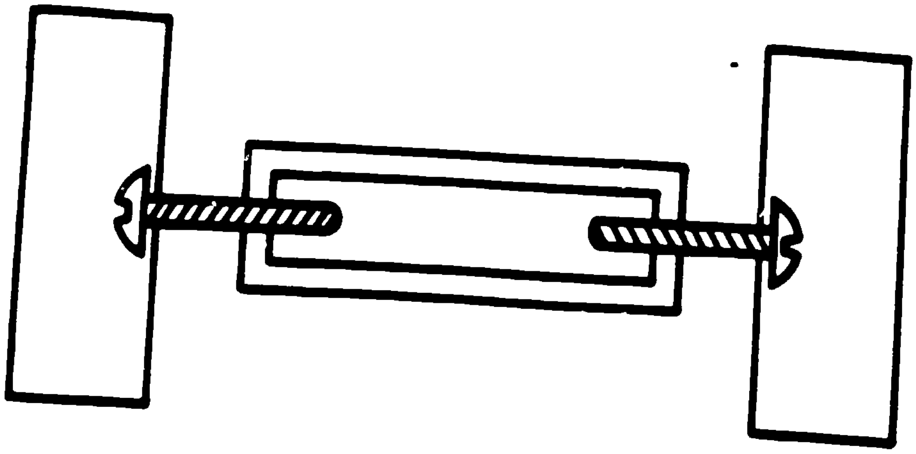

Figure 5. The nature of overall gross movement: the turnbuckle analogy.

CAPTURES	MISSES
(1) Notion that action pulls something toward middle, with no change in length of puller	(1) Cross-bridges
(2) Notion that there are limits to shortening	(2) Individual force producers
	(3) Weak on limits to lengthening (see Figure 6)

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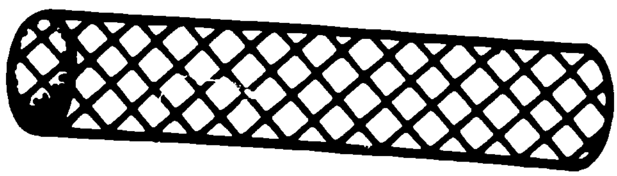

Chinese Finger Cuffs

Figure 6. Structure and function of the casing (elastin) surrounding the force producers (i.e., sarcomeres are contained within the casing: the Chinese finger cuffs analogy.

CAPTURES

(1) Anatomy of the covering: the double wound spiral

(2) Thinning with stretch (the dimension missed in Figure 3

(Important in right-side L-T function-squashing)

(3) Limits to length

A. "Wall" beyond which you can't go

B. At "wall," will break before it lengthens

MISSES

(1) Anything about force producers, etc.

(2) Anything about the stuff inside the casing

(Where's the beef?)

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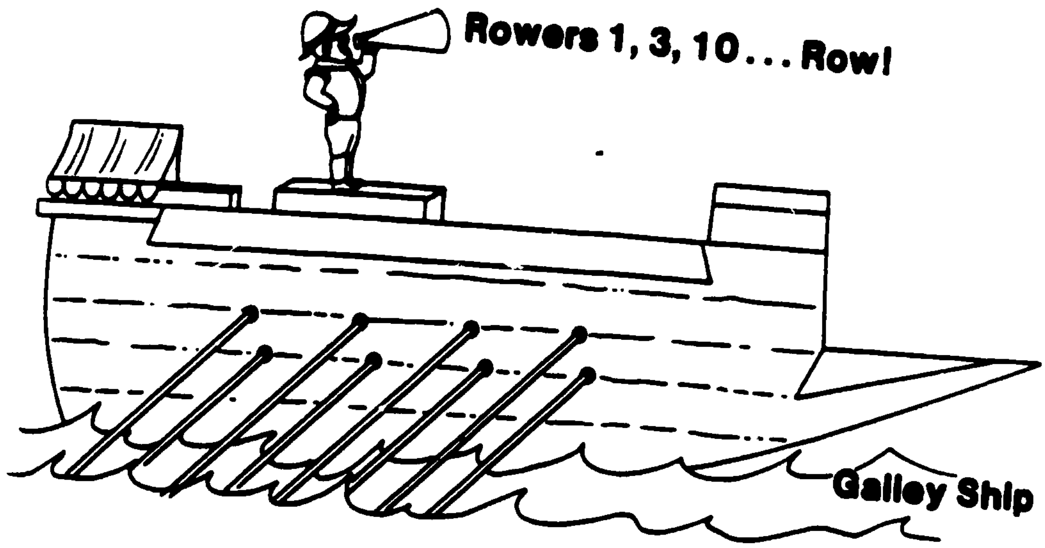

Figure 7. Recruitment of force producers: the galley ship analogy.

CAPTURES

(1) Control that selects and recruits which force producers are to work (on any stroke)

(2) Recruitment aspects of activation

MISSES

(1) Communication mechanisms

(2) Anything about internal metabolic, energetic, life processes of the force producers

(The galley ship rowers)

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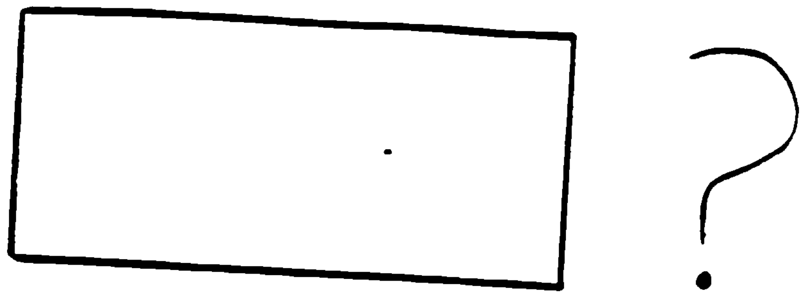

Figure 8. The biochemical life processes of the force producers. How they get energy, nutrition, expend it, etc.--how they get "juiced up." This is the ATP energy cycle of the muscle and all its components.

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