ABDUCTION AND ANALOGY IN SCIENTIFIC MODEL CONSTRUCTION

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Abstract

This study uses qualitative case study methods to study innovative teaching in biology at the middle school level. The findings are then compared to findings from a previous study of learning in electricity at the high school level. By looking for common successful learning processes in two different subject matter domains, we identify teaching strategies that foster conceptual growth and that are candidates for being considered general teaching strategies in science. The teachers in both domains used new approaches to teaching that are innovative in the way that they foster active learning of conceptual models on the part of the student. In order to understand the nature of the teaching and learning processes generated by these teachers, we attempt to develop a finer grained set of concepts and language for describing them.

Framework and Previous Research

Recent work has identified model construction cycles of generation, evaluation, and modification (GEM cycles) as a promising process in conceptual growth (Clement, 2000b; Nunez, et al, 2002). One of the elements still missing is sufficient discussion of cognitive processes of the teacher and students working together while building mental models. This paper will focus on abductive model generation within GEM cycles as defined above. Cognitive science researchers have provided exciting new resources for theory development in this area. For example, Nersessian’s (1990) studies of Faraday and Maxwell have caused a stir in the Cognitive Science and History of Science communities because of her new emphasis on nondeductive processes such as model based abductive theory construction that works in progressive cycles of partially correct models. Peirce (1958) and Hanson (1958) used the term abduction to describe the process of formulating an hypothesis which, if it were true, would provide an explanation for the phenomenon in question.

Settings

This paper examines abductive model generation and the instructional strategies that support it in tutoring studies in two domains: electricity and respiration.

<u>Respiration Lessons</u>. We analyze data from a study using a curriculum that deals with pulmonary and cellular respiration, circulation, and digestion at the 7th grade level. In this curriculum students are asked to play an active role in initiating model construction in small groups via questions like “can you explain using a drawing how blood gets to your big toe?” These initial questions take place before students are given any information about circulation. Later activities foster criticism and revision of the student models. Only after students have developed some models and “own the questions” do they compare their models to targeted models.

<u>Lessons on Electric Circuits</u>. In this curriculum student-drawn color coding of air pressure levels is used as a global analogy to help high school students comprehend an intuitive prototype conception of electric potential as “electric pressure” in a compressible fluid of “charge” in conducting matter. The CASTLE curriculum in electricity has been cited as a proven effective program by the Program Effectiveness Panel (U.S. Dept. of Education), based on data from field testing in 22 U.S. high schools (Steinberg, et al, 2000) and large sections have been adapted by

the Hestenes teacher education effort in physics.

The purpose of both case studies is to describe abductive model revisions and how they are fostered by two different master teachers in tutoring sessions. Similarities across these domains should generate hypotheses for teaching strategies that have considerable generality.

Learning in the Domain of Respiration

The main case study discussed in this paper is a tutoring study of four eighth grade students learning about respiration. The lessons were taught by Mary Anne Rea-Ramirez. The topics covered ranged from pulmonary respiration, to the distribution of oxygen and sugar by the circulatory system, to microscopic respiration in the mitochondria. In this paper we will focus on the **pulmonary respiration sequence** to illustrate the use of analogies and discrepant events in abductive model construction cycles.

Subjects

The study consisted of a pretest, 4 two-hour tutoring sessions, and a posttest. Students had had an introduction to the structure of cells in their previous year's schoolwork, but little of this information was evidenced on the pretest. Two boys (G and L) and two girls (B and Mi), all in eighth grade, were the participants. Of the students, two were Caucasian, one was a Latino special education student, and one was Asian-American

Pre and Post Test

Students completed identical pre and post tests that consisted of two extended problem situations. Students were encouraged to think aloud during the pre and post tests to aid us in understanding their conceptual models. In addition, students were asked to make drawings. The two extended problems were based on situations expected to be familiar to students at this age, one involving a student hiking and one involving a swimmer. These same two problem situations were given as a posttest at the end of the tutoring sessions. These sessions were video and audio taped. For example, the "swimmer" problem was presented as follows:

> Prior to beginning a race one swimmer takes several deep breaths before diving under the water. A second swimmer is late to get to the starting block and dives in without taking any deep breaths. By the end of the race, the second swimmer appears more "out of breath" than the first swimmer and complains of muscle cramps.
>
> Provide an explanation for this occurrence. What is the relationship between the deep breaths and muscle cramps?

Only one out of four students mentioned lungs on the pretest in the oral interview. The others mentioned oxygen and its possible relationship with cramps but the explanations were incomplete and vague. They were also asked to complete a Human Survey Interview and only two of the students drew lungs. Another student drew air going directly into the heart and the fourth student did not include air at all in her drawing. (Later during tutoring it was found that alternative conceptions of the structure and function of the lungs were particularly persistent.)

Instructional Sequence

I. Pretest interview
   A. Swimmer situation
   B. Hiker situation
II. Models
   A. what they are
   B. how we use them
   C. examples from students
III. Cells
   A. exploration with microscope
   B. models
   C. computer simulation of cell respiration
IV. Circulation and digestion
   A. how does sugar and oxygen get to the cell
   B. diffusion
   C. trace circulation using computer simulations
V. Pulmonary respiration
   A. getting oxygen into the body for delivery by circulatory system
   B. most efficient structure of lungs
   C. mechanism of lungs
   D. gas exchange
VI. Posttest
   A. Swimmer
   B. Hiker

Table 1: OUTLINE FOR TUTORING INTERVENTION

Tutoring Procedure

Each session was audio- and videotaped. After the pre test, an instructional sequence was used with the group of four students, using tactics like analogies, discrepant events, model building, occasional hands-on activities, and computer generated animations. These were further supported by scaffolding and probing questions,. Throughout the sessions students were encouraged to describe what they were thinking, imagining, and questioning. Four teaching sessions were conducted of about 120 minutes each. These were video and audio taped for later analysis using dual cameras to capture the details of participants' discussions and drawings. The topics addressed are outlined in Table 1.

During the teaching of each individual target model, the instructor asked the students to draw their initial ideas about the target model. She then promoted model construction in the students with teaching strategies such as analogies, hands-on activities, discussion, and drawings. Throughout the process, the teacher encouraged the students to question and revise their own and other students' models. At the end of this process, the students were presented with a computer animation that contained a simplified version of the accepted scientific model (the target model). Finally, the students were asked to go back to their initial drawings and revise them.

Summative Evaluation

Learning was assessed through analysis of the pre- post-test performance, including occurrence of alternative conceptions and target conceptions. Coding criteria were determined by prior research and experts in the field of biology. Answers were scored for each of pulmonary, circulatory, and cellular subsystems, represented as a series of major target conceptions to form a learning pathway. To obtain a full score the student had to show knowledge and understanding of the basic structure, the function, and the integration between systems showing cause and effect as expressed through discussion of the problem situations. This indicated that the student had a conceptual understanding of not only isolated factual information but how the system worked in real world situations.

Results. Transcript data from the post-test indicated that all four students in this study were successful in constructing mental models of a complex concept, respiration, and had some success in applying these mental models to transfer problems. Multiple aspects of the test responses were coded for one of four levels of understanding. Analysis of the post-test suggested that individual students learned at differing levels. Despite these individual differences, all students achieved an understanding of respiration at least at the target level that allowed them to give an integrated explanation of how and why oxygen travels from outside the body to the mitochondria. The difference in the pre-test and post-test means was significant at the $p = .004$ level (Mean Diff= 10.400; sd=2.668) and was greater than three standard deviations in size.

Case Study of Pulmonary Respiration Learning

In this paper we will focus on an example of the approach used in the *pulmonary respiration sequence* to illustrate some of the model construction strategies used by the teacher. This summary is highly condensed from the original, which took about 90 minutes. Here I want to examine some of the different strategies a teacher can use to promote content goals when they allow student ideas, both correct and incorrect, to be taken seriously in classroom discussions (where by 'correct' I mean largely compatible with the target model for the lesson).

Teaching Approach. In the Energy in the Human Body curriculum, a principle teaching method used to aid model construction is to have students invent models of body systems that could perform functions like breathing or delivery of nutrients to a limb. They are asked to do this on their own initially before receiving information from the teacher. Almost always this involves making drawings. The teacher then uses the students' initial models (including misconceptions contained therein) as a starting point to foster a series of model criticisms and improvements. Eventually enough changes are made to approach the target model for the lesson.

Description of Lesson Episodes

Students' Initial Model

Figure 1 shows a simplified summary of the sequence of models constructed during the lungs teaching interaction. The sequence starts from a hollow lung, progresses to lungs filled with blood vessesls in tissue, and finally features vessells in microscopic contact with large numbers of air-filled alvioli. The teacher first asked students to make individual drawings of what the inside of the lungs might look like. She then asked them to make a collective drawing. In their initial model in Figure 1a the lung is mostly hollow with veins on the interior surface There is also a hole at the bottom of the lung.

First Modification

The teacher then asks what we call a "discrepant question" I have this little question here because you have this sort of space here that all the air can sink out of, what do you want to do about that?" [661]. The students then begin to worry about air leaving the lung there and decide to modify their model by closing the hole as in Figure 1b. One of the students said that it did not make sense to have the hole because the air will go out inside of the body and that the air was instead going out through the mouth. To support her idea she breathed in and out several times and put her hand in front of her mouth to detect the air that was coming out. This is an example of an indirect and mild but focused intervention by the teacher. The intended purpose of a discrepant question is similar to that of a discrepant event--to promote dissonance with the current model (and if it is repairable, to provide a guiding constraint for modifying it.)

Figure 2 shows a notation system for tracking the evolution of the model being generated by the teacher and students working together. We modeled the hypothesized effects of the discrepant questions as internal dissonance with an existing conception. These are shown as labeled arrows.

Second Modification

Following Figure 2 into the next episode, the teacher is interested in helping the students construct an exchange mechanism where the blood can receive oxygen from the air in the lungs. The teacher and students discussed the fact that oxygen has to be provided for a huge number of cells in the whole body and that much of the space in the middle of the lung was not being used for anything. She also introduced an analogy, reconstructing with the students a mechanism they had learned about earlier--how the oxygen goes from the capillaries to the cells in the rest of the body. The teacher said, "remember how it got out of the bloodstream …you have blood cells and then you have oxygen on them how do you get out the oxygen into these cells?' [989-991-993-1009] A student answered that the oxygen "seeps through the walls," and immediately a student said loudly "so why can't it do that in the lungs!!!!" [994-997] To enable this to happen, the teacher drew blood vessels spread everywhere in the lungs as in Figure 1c. In this way model 2 that showed a mostly empty lung with some blood vessels in the walls was transformed into a lung full of blood vessels in model 3.

Earlier, the students had discussed how the air might end up in "little circles [cavities] inside the lung" but they had no connection to the trachea. Thus, the students were not ready to integrate the "seeping" imagery at a microscopic level suggested by the capillary to cell oxygenation analogy, so this topic was deferred until after an air distribution mechanism was developed.

Third Modification

The teacher confirmed that there were little round cavities in the lung. She then asked the students for more details about connections that would say where air goes in the lungs: “it has to go.. somewhere…” Then she asked, referring to the little cavities of air: ”You have to attach them some where, what are you going to attach them to?” We model the effect of these questions as the establishment of a “Gap” in the existing model--a missing part of the explanation. Inagaki & Hatano, (1986)refer to this as “discoordination” to distinguish it from dissonance. A student suggested “grapes on vine…” This student generated analogy led the teacher to draw Model 4 as the next modification in the model. Other students said

> “Looks like a tree attached”
>
> Attach a vine there”
>
> That is starting to look kind of right”

Fourth Modification

The teacher then moved to a more microscopic level of modelling and re-asked the basic question of how oxygen was going to get into the blood. She asked for a blow-up drawing of the round cavities and vessels: “can you put those little round things and the oxygen together in any way[with the blood vessels]?” We model this simply as a request for explanation pointing to a gap in the model. The teacher cautioned that the blood cannot get into the cavities. As a consequence, a student drew Model 5. He explained that in his model “the oxygen passes through them…they have little holes that the oxygen goes through…and that blood vessels are running by little attachments and then they just seep through and climb onto the blood vessels” . The small size of these attachment tubes apparently prevents the larger blood cells from leaking into the air cavities.

Fifth Modification

The teacher realized that the model proposed by the students was different from the target model in that it still had vestiges of a direct piping system for air from the cavities to the bloodstream and that the blood vessels were too far from the air cavities. The teacher introduced another analogy to a previous topic by reminding the students how close the blood vessels were to the edge of the villi in the intestine. She said, “remember when we talked about the intestine and how close the blood vessels had to be to the intestine to pick up the stuff”. A student suggested that they were very close. This analogy suggested the modification appearing in another student drawing (Model 6) in which the blood vessels were very close to the little circles that contained the oxygen. The recurrence of the “seeped through the walls” terminology here suggests that the students may also have been influenced here by the earlier analogy to the previously studied topic of cells being oxygenated by capillaries. That analogy did not seem to lead anywhere in the discussion when it was first introduced. The possible deferred effect of this analogy is shown as a long diagonal line from the top to the middle row in Figure 2.

Sixth Modification

The teacher then helped the students wrap lots of string around some plastic grapes as a physical model analogy for the vessel/alvioli structure and played an animation that showed the internal structure of the lungs. After these were discussed the students drew their final individual models of the internal structure of the lungs, such as the one shown in Model 7.

Analysis of Learning Session

Model Evolution. In looking at the instructional sequence as a whole, several aspects of Figure 2 are noteworthy:

- Discrepant questions or focussed requests for explanation were used to motivate model revisions.

- Analogies were used to tap into useful prior knowledge structures already possessed by the students.

- The sophistication of the students' explanations grew steadily during the instructional treatments. We can view the students' conceptual changes here as producing a sequence of progressively more expert-like models. This suggests a view of learning that has model evolution as its central feature, where students are able to build on knowledge that they had developed in earlier sections.

- Figure 2 is designed to illustrate the idea of teacher/student co-construction (Rea-Ramirez, 1999; Steinberg & Clement, 2001; Clement & Steinberg, in press) in which both teacher and students contribute ideas and evaluations of ideas to the model construction process. There the row labeled "Students" shows student generated contributions, and the row labeled "Teacher" shows the guiding questions and occasional direct contributions of ideas introduced by the teacher.

- The overall idea is to keep students in a "Reasoning Zone". Building on Vygotsky's ideas, one can think of the Reasoning Zone as an area of discussion where students can reason about ideas and construct new ideas productively (or at least contribute to its production in a group). Not all student generated ideas move in the direction of the target, but if thinking in the Reasoning Zone includes idea evaluation and modification, then progress toward the target should occur. If the question or topic chosen by the teacher is too large or too hard, it will be outside of this zone. Here the art of teaching via co-construction is to provide just enough support in the form of a leading question, hint, new observation, reference to an earlier comment, discrepant question, etc. in order to get student reasoning going again.

In the next section we investigate the nature of this reasoning; we examine the sense in which much of this reasoning takes place via abduction, as opposed to induction or deduction.

Abduction

As stated earlier, Peirce (1958) and Hanson (1958) used the term abduction to describe the process of formulating an hypothesis which, if it were true, would provide an explanation for the phenomenon in question. In their view the hypothesis could even be a guess about a hidden mechanism at work in the system as long as it explained the observations collected so far. Magnani (1999) has proposed two different meanings for the term Abduction:

- **A Narrower Sense**: the formation of explanatory hypotheses (we will call this 'generative abduction')
- **A Broader Sense**: Inference to the best explanation, including hypothesis generation, evaluation, and revision cycles and comparisons between rival hypotheses. (Here we will use the term 'model evolution' for this larger set of processes.)

We will focus first on the narrower process of generative abduction within a single cycle of model generation (or revision). Generative abduction is thought of as being a complementary and different process from hypothesis evaluation at some level.

A number of student model construction actions are labeled abductions in Figure 3. This figure shows the same instructional sequence as Figure 2, but the rows have been reorganized somewhat.

Abduction is essentially open ended design under constraints, here applied to explanations for pulmonary oxygenation of the blood. The first example occurs when students collectively design a model of the lungs at the left of the drawing. Model modifications also count as student abductions if they are a hypothesis coming from the students, so the first modification in the second "column" is also an abduction.

The Role of Analogy in Abduction and Model Construction

The second row in Figure 3 shows sources that tap prior knowledge in the student, no matter whether they were initiated by the student, another student, or the teacher. For example a teacher-suggested analogy may activate the student's prior knowledge about a phenomenon in a prior lesson. This row provides the "raw material" for abductions that produce model modifications. This clarifies the relationship between analogy and abduction: analogies can activate schemata that provide raw material for abductive model modifications. In this view analogies provide supporting input to the somewhat more complex process of model revision via abduction.

Explanatory Models vs Analogies.

This view also clarifies the distinction between an explanatory model and an analogy: One attempts to draw certain features selectively from each analogy in order to add a component to the evolving model. Although some researchers have tended to treat a model and a source analog as equivalent, we believe that researchers, teachers, and students need to distinguish an explanatory model from the particular analogies that contribute elements to its construction. This is seen most clearly in the case where multiple analogies are used, and the model develops successively from each one.

The bottom row in Figure 3 on the other hand shows other ideas and stimulating questions coming from the teacher. These serve other roles in guiding model construction.

In summary, when viewed in this way, we see from Figure 3 that most of the episodes in this sequence involve student abductions. These are generative abductions in the narrow sense defined earlier. Since the students articulate several of the model revisions before the teacher does, we believe that they are doing some generative abductions, although the context for these is certainly set up by the teacher. So in this case we refer to “teacher-supported” or “scaffolded” abductions.

Model Evolution Complements Generative Abduction

Abduction in the broad sense on the other hand, as defined earlier, is the larger process of inference to the best explanation, including hypothesis generation, evaluation, and revision cycles and comparisons between rival hypotheses. It is the larger model construction enterprise. An important point is the idea that the model revisions can utilize the previous criticisms as new constraints to guide the direction of the revision. This makes them “intelligent” revisions that contrast with a pure “series of random guesses” process such as that used in a simple model of biological evolution. Thus we hypothesize that repeated evaluation and revisions cycles can make up for the possible missteps in any particular generative abduction. This is a sense in which a weak type of inference--generative abduction-- can become strong when complemented by the evaluation and revision process. This gives added meaning to relationships between the various teaching strategies shown in Figure 3, where analogies supporting generative abductions of newly revised models are coordinated with discrepant events that evaluate the models, promote revisions, and provide new constraints for the next abduction.

Learning in the Domain of Electricity

Parallel results to those above --from a case study of an electricity tutoring experiment-- are provided in Steinberg and Clement (2001) and Clement and Steinberg (2002). I will summarize some of their findings briefly here.

The database for the Electricity study is a set of tutoring interviews with a student who was called Susan who was 16 years old and had completed her junior year in high school. Susan had not yet taken a course in physics. In Susan’s first session she was asked to think aloud as she completed a pretest on electric circuits. She did this again with an identical posttest in her last session. All sessions were video taped. The five intervening tutoring sessions were spread over a period of two weeks and lasted from 60 to 120 minutes each. During the tutoring Susan was asked to think aloud as she set up and observed experiments with circuits, explained events, solved problems, reacted to the tutor’s comments, and completed color coding for “electric pressure” (potential) values in circuit diagrams. In this curriculum student-drawn color coding of air pressure levels is used as a global analogy to help students comprehend an intuitive prototype conception of electric potential as “electric pressure” in a compressible fluid of “charge” in conducting matter. Students interact with many bulb lighting experiments, gradually revising their models of electric current and potential. Care was also taken over several instructional sessions in this tutoring experiment to develop an imagable model by working from concrete analogue examples (e.g. a leak in a tire).

The subject in the electricity case study was able to demonstrate an ability to solve complex problems on the post test that required an impressive degree of concept integration and flexible transfer. The main body of the study then focussed on attempting to model from transcript data why this occurred. The analysis focused on episodes where the subject indicated some surprise in a new observation or finding as places where the most intensive learning may have occurred, and these were transcribed.

Abduction

In particular, findings on abduction included evidence that**:**

> -Susan was able to generate and evaluate abductions when the context was set up by the tutor
>
> -Analogies contributed to generative abduction
>
> -Abduction can form models that generate imagistic simulations
>
> -Conjectural abduction processes can be successful when backed up by a larger evaluation and revision process

Thus there are a number of parallels between the electricity study and the present study.

Transfer of Runnability

The subject was able to map and apply an air pressure analogy used for building up a model of electric potential and continued to exhibit traces of it in a posttest interview on a relatively far transfer problem after instruction. The subject's spontaneous use of similar depictive hand motions during the instruction and during the posttest provided evidence that the instruction fostered development of a dynamic mental model of fluid-like flows of current caused by differences in "electric pressure", that could generate new imagistic simulations for understanding relatively difficult transfer problems. This led the authors to describe the core of her new knowledge as runnable explanatory models at an intermediate level of generality. They also hypothesized a transfer of runnability from the analog pressure conceptions to the electric potential model, and the consequent benefit of the model being able to run simulations of transfer problems. This study suggests that the transfer of runnability achieved by grounding a new model in runnable prior knowledge schemas may foster a type of model flexibility that aids its use in transfer problems. At present we lack data at this last level of detail in the respiration study, but the electricity study is suggesting ways to collect and analyze it. Model flexibility and runnability would seem to be a very important feature of scientific knowledge for both experts and students.

Summary of Results

Summary of Analyses of Learning Processes

Analyses of the tutoring sequences from both the respiration and electricity studies generated a number of hypotheses, including the following:

- GEM (model generation, evaluation, and revision) cycles were found in each of the instructional sequences.

- Students were found generating abductions in each study. That is, they invented designs for models of body systems and electrical current flows. However these were usually in response to questions from the teacher, and therefore we refer to them as scaffolded abductions.

- Not all abductions were correct, but this fit the instructional approach of using GEM cycles in that the students were expected to evaluate and reject or revise most abductions.

- Thus GEM cycles can make up for the conjectural nature of individual abductions by evaluating and improving them.

The above patterns have also been observed in expert reasoning (Clement, 1989; Nersessian, 1990, 2001) leading to hypotheses about expert novice similarities (Clement, 1998).

Engagement and comprehension in the cycle was fostered by small step sizes for revisions from using multiple “small” discrepant questions or events built into the lessons. In this way the teachers appeared to be able to avoid discouraging students while still obtaining the benefits of motivation from dissonance.

We would like to create more diagramed models of other processes that clarify for researchers the learning mechanisms involved. Simpler versions of these diagrams should help teachers comprehend new aspects of learning processes.

Further Research

Abductive model generation is a poorly understood process that appears to be a the very center of model construction processes in science. We need to expand the theory developed in this paper to include new descriptions and models of general pedagogical strategies that are effective, including:

- Teacher questioning strategies

- Special techniques for using analogies and discrepant events

- Prompts for sustaining discussion modes that foster model construction

- Larger macro-strategies for model construction cycles that coordinate the above strategies

The identification of core concepts for describing the processes involved in these techniques is a first step in this task.

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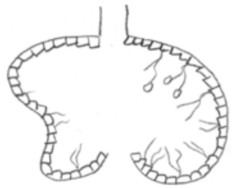

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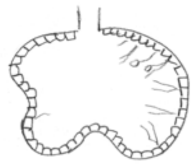

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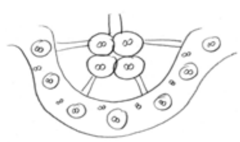

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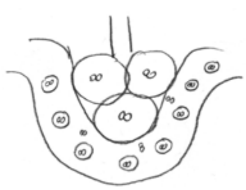

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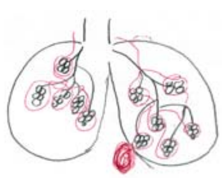

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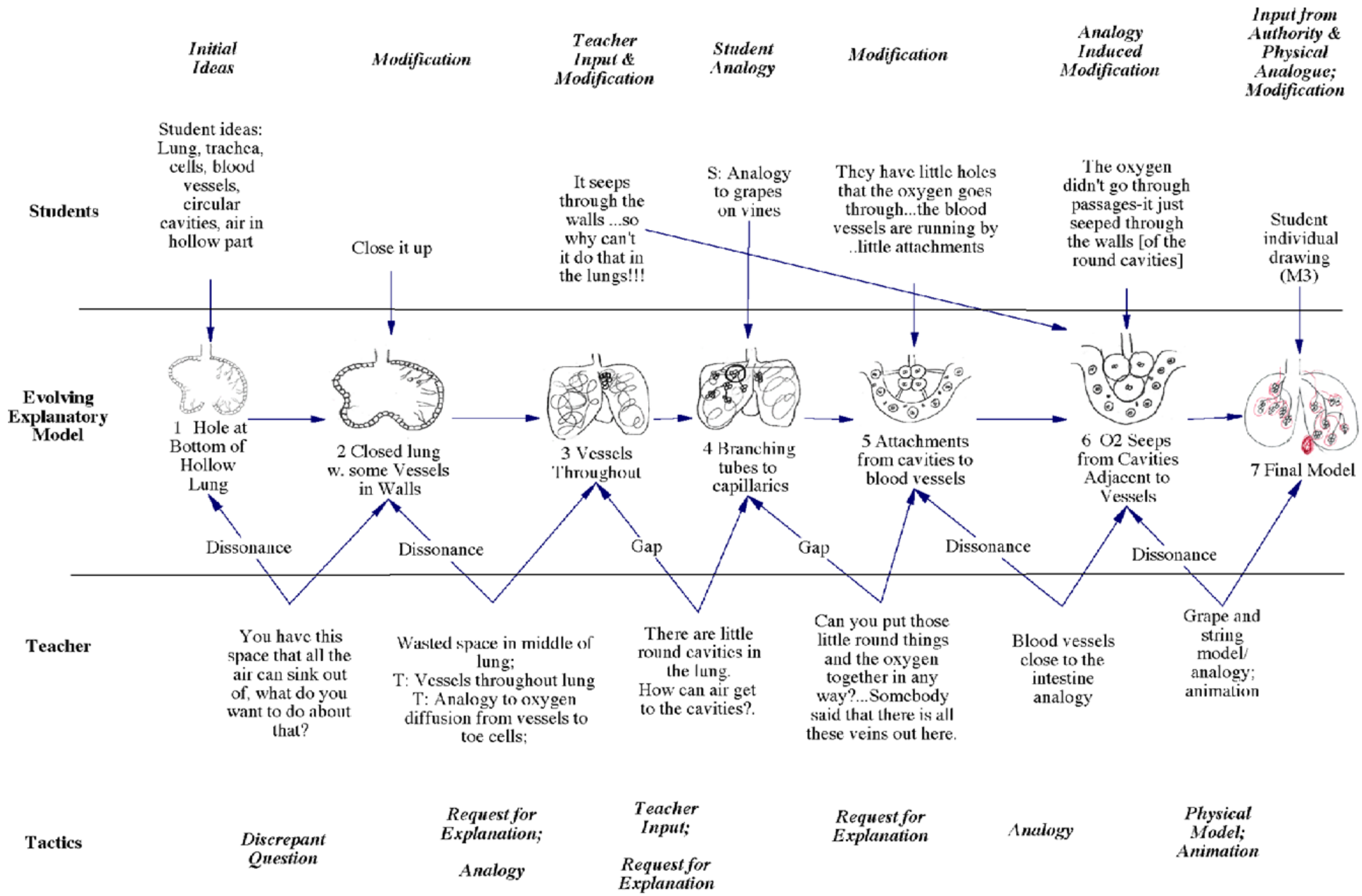
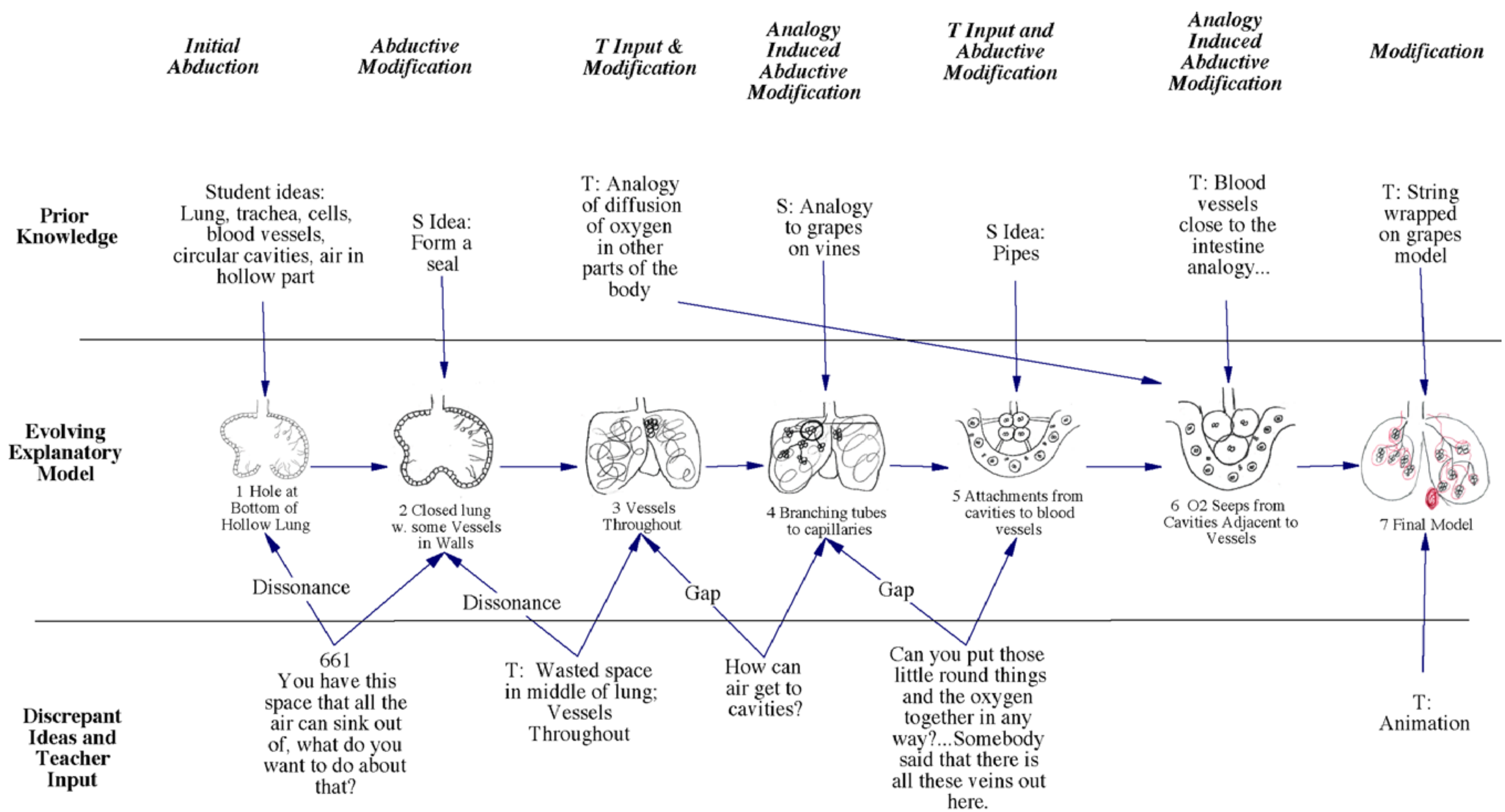
Figure 1



Co-Construction and Model Evolution
Figure 2



Abduction and Analogy in Model Evolution
Figure 3