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Student-oriented learning: an inquiry-based developmental biology lecture course

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ABSTRACT In this junior-level undergraduate course, developmental life cycles exhibited by various organisms are reviewed, with special attention - where relevant - to the human embryo. Morphological features and processes are described and recent insights into the molecular biology of gene expression are discussed. Ways are studied in which model systems, including marine invertebrates, amphibia, fruit flies and other laboratory species are employed to elucidate general principles which apply to fertilization, cleavage, gastrulation and organogenesis. Special attention is given to insights into those topics which will soon be researched with data from the Human Genome Project. The learning experience is divided into three parts: Part I is a «tutorial» in which the Socratic (inquiry) method is employed by the instructor (GMM) to organize a review of classical developmental phenomena; Part II represents an «intellectual workshop» in which students study the details related to the surveys included in Part I as they have been reported in research journals; Part III focuses on a class project - the preparation of a spiral bound «book» on a topic of relevance to human developmental biology (e.g., Textbook of Embryonal Stem Cells). Student response to the use of the Socratic method increases as the course progresses and represents the most successful aspect of the course.

KEY WORDS: *Socratic method, inquiry-based learning, developmental biology lectures, developmental biology tutorial, cooperative learning*

Background Information

Scholarly Interests of the Author

The author's fields of interest, which underlie the *information content* and drive the *intellectual approach* to this course, include research in amphibian developmental genetics. A special concern focuses on attempts to introduce foreign genes into the axolotl, a laboratory model organism with general relevance to research projects in neurobiology and regenerative biology. That organism is maintained as a genetic stocks resource at the Indiana University Axolotl Colony. Several different pigment phenotypes and mutant genes which affect the development of one or another tissue or organ (e.g., eye, heart) are available. If marker genes such as green fluorescent protein or (β-galactosidase could be introduced into the genome of the axolotl, various experimental manipulations pioneered with this classical model organism could be extended to the molecular level.

Additional research interests encompass organogenesis during amphibian embryogenesis, especially mesoderm formation/differentiation and the mechanics of gastrulation/neurulation. The action of various growth factors which regulate tissue interactions in early amphibian embryogenesis are being interpreted—as an intellectual exercise—in terms of the classical morphogenesis models for mesoderm formation and primary embryonic induction. The extent to which the conceptual features of those models continue to serve as useful experimental paradigms for present-day developmental biology research is being assessed.

Representative Publications

This course, like most college-level courses, reflects the training and interests of its instructor(s). In this instance, GMM received his first developmental biology research training in the area of biochemistry. Then, he specialized in amphibian developmental genetics and early amphibian embryonic patterning. Most recently he has extended his undergraduate teaching into molecular biology. Thus, the citations listed below reflect his present interests in both amphibian embryology and molecular biology.

MALACINSKI, G.M. and ZELL, P.W. (1996). Learning molecular biology means more than memorizing the formula for tryptophan. *J. Coll. Sci. Teaching* 25: 198-202.

MALACINSKI, G.M., ARIIZUMI, T. and ASASHIMA, M. (2000). Work in progress: The renaissance in amphibian embryology. *Comp. Biochem. Physiol.* 126(B): 179-187.

MALACINSKI, G.M. (2002). *Essentials of Molecular Biology* (4th ed.). Jones and Bartlett, Boston.

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General Teaching Philosophy

The author devotes considerable time and energy to developing an *output* model for the undergraduate learning experience (e.g., Zell and Malacinski, 1994). Students are organized into collaborative learning groups and encouraged to explore the myriad aspects of both classical and contemporary developmental biology in ways (e.g., tutorials, group projects, report writing) which enhance their capacities for *independent learning*. It is expected that students who develop a high capacity for independent learning will be highly adaptable to the rigors of *information age* academic, research, and employment endeavors. Thus, various devices, including the Keirsey Temperament Sorter (mentioned below) are employed by the author to help individual students uncover their individual learning strengths and recognize areas for individual improvement. This model (output orientation) de-emphasizes the traditional (input) roles of the instructor as an *authority figure* for detailing course content and as a *transfer agent* for that content.

Instead, the instructor serves to guide learning experiences, and to structure those experiences so that students achieve maximal development of inquiry-based skills (e.g., analysis, deductive/inductive reasoning, conceptualization). Thus, this course provides a context and a focus for what is fashionably referred to as a *critical thinking* agenda.

A hypothesis-driven research approach is emphasized as a context for enhancing critical thinking skills, despite the emergence of *data mining* as a contemporary research approach to gaining insight into the mechanisms which guide the expression and manifestation of complexity in embryological processes.

General Features of the Course

This course is taught to approximately 15 to 25 junior/senior-level undergraduate biology majors. Graduate students are not permitted to enroll (for credit), and thus the cohort group is relatively homogenous. Prerequisites for enrolling include courses in molecular biology and genetics. Often, students will have completed a course in cell biology and evolutionary biology as well. Chemistry courses expected of enrollees include general chemistry and organic chemistry. Occasionally, a few students will also have completed an undergraduate course in biochemistry. That sequence of courses reflects the arrangement of the undergraduate biology curriculum at Indiana University. Several years ago, it was decided to place molecular biology at the front end of the curriculum, rather than—as previously—toward the back end (senior level). Consequently, by the end of their second year, many biology students will have completed a year of general biology courses, a one-semester (15-week) course in molecular biology, and a one-semester course in genetics. The genetics course is partitioned between Mendelian inheritance (approx. 1/3) and molecular genetics (approx. 2/3).Students who then enroll in this developmental biology course are prepared for immersion in both descriptive and molecular analyses of developmental phenomena. This course is not required for the biology major, and enrollments, therefore, are relatively low, considering that at Indiana University approximately 600 students per year enroll in the molecular biology prerequisite course. This course (L317) is thus listed officially as an «elective» course.

As a one-semester course, it runs for a total of 15 weeks, with three 50-minute classroom (lecture) and one 50-minute collaborative learning sessions per week. The classroom sessions are conducted by GMM and usually take the form of a traditional lecture presentation, organized in a Socratic (inquiry) format, as described below. The collaborative learning sessions are separate from the lectures and are organized by a graduate student (teaching assistant). Usually, three (hour) exams and a final examination are given. The extent to which a student actively participates in collaborative learning sessions is factored into the course grade. Students are encouraged to cooperate rather than compete in all phases of the course. Final course grades are based upon an absolute standard set by the instructor, rather than on an individual student's performance relative to his/her peers' performance (so-called «curving»). A majority of the class earns grades of A or B (A-F scale).

Students are obligated to enroll in a separate laboratory-based developmental biology course (L318), which is organized by GMM and conducted with the full participation of a the graduate teaching assistant. Laboratory exercises are—whenever feasible—coordinated with lecture content. The emphasis in these exercises is on practical aspects of developmental biology (manipulation of a diverse collection of living embryos) and intellectual endeavors (generating and testing meaningful hypotheses). A brief description of the laboratory exercises is given below.

Socratic Teaching Method for Enhancing Student Critical Thinking Skills

For a lecture course with less than two dozen students, this method works especially well. It succeeds in making the classroom experience interactive. The instructor emphasizes «questions», rather than «answers,» and thereby steers students away from passive note taking and toward the use of inquiry and the scientific method for building knowledge (Birnbacher, 1999). With the instructor modeling thought processes in a very explicit fashion, students are presented with an opportunity for enhancing their analytical (critical) thinking skills.

During the first few weeks, students are often hesitant to participate in class discussion. Thus, the instructor needs to facilitate discussion by adopting some of the following roles: friendly interviewer, military drill instructor, or random selector. Next, as the instructor poses questions, those questions should be rephrased a few times so as to be interpretable by students with diverse learning skills. For example, the question «*Why is embryonic determination often viewed as a progressive phenomenon?*» can be rephrased as «*Does the state of determination of a group of embryonic cells change as development proceeds?*» or as «*Does the differentiation potential of a group of embryonic cells become fixed during the course of development?*»

As students offer answers, the instructor's role changes. Initially, the instructor needs to validate the answers in such a way as to encourage further student participation (and of course modify those answers, if necessary). Then, the instructor needs to narrow the focus of the answers, to foster the use of disciplined, linear thought processes. Here, the instructor has the ability to model thought processes and enhance the intellectual level by offering a set of distinctions or alternative meanings for the term *embryonic determination* or comments regarding *operational definitions.*

Once the culture of the classroom adapts to this teaching style, students become aware of its inherent strengths and express their appreciation by participating more frequently. Enhanced self-esteem results, as students become «risk takers» and succeed by offering ever more sophisticated contributions to class discussion.

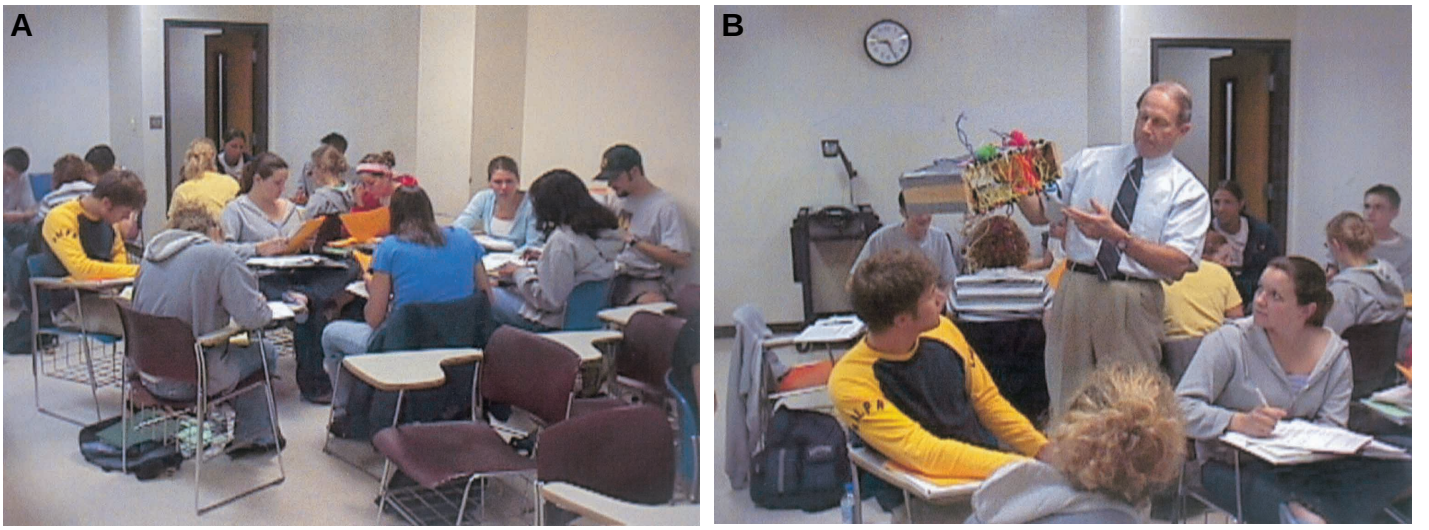

Fig. 1. Collaborative learning group meeting. (A) *Students cluster in circles of four to eight students to refine their (individual) answers to weekly worksheet questions. Students arrive at their learning group meeting with worksheets mostly completed. A graduate assistant occasionally joins the group to provide guidance, which includes clarification of jargon and explanations of related phenomena. Students are wholly responsible for generating satisfactory answers and upon leaving the meeting, turn in their worksheets for grading.* **(B)** *The author joins a group and explains the features of the cell membrane using a 3-D model.*

This aspect of the course represents its most successful feature! Because the course is limited to undergraduates, graduate students—who might inadvertently intimidate undergraduates with their advanced knowledge and more mature demeanors and thereby dampen class discussion—do not cast a shadow over classroom discussions.

A major disadvantage for the instructor includes learning how to exhibit patience when coping with silence among students. Other disadvantages include getting bogged down in an insignificant issue; sacrificing breadth of information content coverage; and needing to draw reluctant students into the discussion. Transferring some of the learning tasks to small groups does, however, provide opportunities for dealing with several of those shortcomings.

Collaborative (Small Group) Learning as a Special Feature

Literally hundreds of studies (e.g., Cohen, 1994) have concluded that collaborative learning sessions in which students engage in peer tutoring represents the most efficient and effective format for learning how to understand complex phenomena and to master problem-solving skills. With the aid of a generous grant from the Howard Hughes Medical Institute Undergraduate Initiative, consultants from the Indiana University School of Education were enlisted to provide assistance in the development of a step-by-step collaborative learning strategy for this course.

First, students are indexed according to their learning-style preferences with the Keirsey Temperament Sorter (http://www.advisorteam.com/user/ktsintro.asp). That scheme identifies various personality traits which govern learning-style preferences.

Second, students are grouped into sets of five or six, based upon their personality type. Each group is designed to have a mixture of introverts/extroverts, analyzers/valuers, detail-oriented/holistic viewers, and judgers/observers. That is, GMM and the graduate assistant collate the Keirsey indices and formulate the learning groups. Left to their own devices, students would likely organize themselves into homogenous social groups. Instead, groups organized on the basis of the Keirsey indices comprise diverse learning preferences and therefore achieve optimal effectiveness, for each issue/problem is automatically viewed from several different perspectives. Interestingly, many of the students exhibit learning preferences which are very different from GMM's own learning style. Thus, a mismatch—in principle—exists between the ways in which the instructor learns and understands complex phenomena (e.g., molecular mechanisms of sex determination in vertebrates) and the learning preferences of many of the students. That mismatch is amplified, of course, by the vast gap in learning experience of an accomplished instructor and a naive undergraduate. Such mismatches underpin the concept—well documented (e.g., Grow, 1991)—that peer tutoring (e.g., in collaborative learning situations of this type) represents for most students the best learning strategy. Consequently, it behooves the instructor to provide students with a menu of learning strategies which extends beyond the instructor's personal learning-style preferences to include the broad range of learning preferences described in the Keirsey Temperament Sorter. An example of such a menu (12 Ways to Learn Complex Phenomena) is in the Appendix.

Third, weekly problem sets (so-called *worksheets*) are provided to students several days in advance of their regularly scheduled learning-group meeting time. Students are expected to complete—to their fullest capacity—the worksheet and bring it to the learning group meeting. As they enter the meeting room, their worksheets are briefly reviewed by the graduate assistant for completeness. Individual groups organize in a circle and students discuss each problem and then expand/modify/complete their individual worksheets. During that time, the graduate assistant circulates through the room providing general assistance to each group. At the end of the meeting the completed worksheets are collected by the graduate assistant and then graded. Since worksheets are checked at the start of group meeting, underachievers are readily identified by the preparation and quality of the final, completed worksheet. Participation in group discussion is monitored by the graduate assistant (Fig. 1). Those

factors are included in the grading scheme employed to calculate a final course grade.

Fourth, worksheets are returned at the following group meeting, to be used during studying for examinations. The various examinations are based in part on questions of the type included in the worksheets. A sampling of worksheet questions is provided below. Students can often be observed to extend their collaborative learning meeting efforts to group studying for examinations, as well as to working on special projects such as oral presentations in the tutorial phase of the course.

A major advantage of the collaborative learning format is the high level of interaction which it fosters between students, who otherwise—at a university with 34,000 students—might not become acquainted with classmates. Incidentally, this same learning-group format is employed by GMM in a large (250-student) sophomore-level molecular biology course. In that course, a team composed of approximately 16 undergraduate teaching assistants and one graduate assistant guides the learning groups.

Several disadvantages, both technical and conceptual, are associated with this collaborative learning special feature (Zell and Malacinski, 1994). Technically, this teaching model is labor intensive. The instructor is required to prepare new worksheet problem sets each semester the course is taught. Furthermore, those problem sets need to be coordinated with the examination format, in order to motivate students to become actively involved in learning group activities. A graduate assistant needs to devote time to attending learning group meetings and grading weekly worksheets. Finally, record keeping (15 worksheets, various reports, examinations, etc.) is cumbersome.

Conceptually, the collaborative model for problem solving conflicts with the traditional competitive model associated with graduate-school training and research group activities. Although research collaborations are becoming more prevalent as consortia organize to solve large-scale research problems (e.g., genome sequencing), the «tournament model» for the advancement of individual scientific careers (Freeman *et al.*, 2001) represents a dominant characteristic of the developmental biology research enterprise. Thus, many teachers, themselves personally heavily invested in the tournament model, are reluctant to promote the collaborative model for learning among undergraduates.

Tutorials as a Special Feature

In order to foster independent learning, and to enhance verbal communication skills, special emphasis is placed on tutorials. These events consist primarily of brief (10 minute) oral reports presented during class by one or another student so as to «punctuate» the regular lectures presented by GMM. The topics are chosen by the instructor, and usually consist of issues or subject matter related to human development. For example, during a discussion of morphological cleavage patterns following fertilization, a report (including photographs from various textbooks) on cleavage of the mammalian (human) egg might be presented. Students are responsible for searching out information from diverse sources and organizing it into a brief presentation, complete with a brief outline for distribution to classmates.

Compiling a Spiral-Bound Textbook as a Special Feature

Recognizing that subject-matter specialization and report writing represent substantial aspects of developmental biology research enterprises, students are provided with the opportunity to engage in a *bona fide* writing exercise. A topic which attracts a high level of interest in the developmental biology community is chosen by the instructor. For example, «embryonal stem cells» might be the topic of choice. The instructor compiles a list of chapter headings. Students choose their topic from the list and prepare the relevant chapter, in the format of a traditional review article. Once edited (by the instructor, GMM) and revised, the chapters are spiral-bound so as to represent the «product» of that semester's class.

One goal of this endeavor is to introduce students to the specialization aspect of developmental biology research, which is not readily appreciated from textbook readings. Another goal is to foster independent learning by providing journal research experience. Validation of their efforts is achieved when—at the end—students peruse the spiral-bound «product».

Information Content: Course Outline

This course does not attempt to represent a comprehensive survey of developmental phenomena. Rather, a sampling of traditional focal points from embryology are emphasized, along with a set of concepts or principles which usually apply to all developing systems. With the advent of the Internet, the student-learning experience in this course has been gradually guided away from textbook descriptions and toward information-age intellectual pursuit. Often, it is faster and more illuminating for students to plug key words into Internet search engines than to leaf through textbooks or journals on a library shelf. Worksheet questions occasionally are designed to require Internet searches, for example, «*Describe various mechanisms which generate one or another type of polarity in newly fertilized eggs.*» Notably absent from this course outline is a major emphasis on molecular biology studies. Translational control, transcriptional control, posttranslational modifications, etc., are mentioned, but not studied in detail. Recall, students enrolling in this course are heavily invested in the reductionist approach, having already completed a course in both molecular biology and genetics.

Several topics (e.g., appendage regeneration) are not covered in the lecture, since students concomitantly enroll in a developmental biology laboratory course in which those phenomena are studied in detail.

Abbreviated Course-Content Outline

I. Introduction
- A. How do we define developmental biology?
- B. Why is the Socratic method useful for this learning experience?
- C. Why should we be interested in studying this discipline?
- D. Brief overview: *epigenesis, germ layers, indirect development, pattern formation, reductionism, etc.*—how do they help us learn developmental biology?

II. Early developmental patterning
- A. Egg and sperm cells: Why do primordial germ cells migrate so far?
- B. What principles emerge from the study of gametogenesis?
  Concept: *Nothing in embryology makes sense outside the context of evolution*!
- C. Gamete maturation and fertilization: Why so complicated?
  Concept: *Phylogenetic history accounts for numerous examples of redundancy in developmental mechanisms*!

D. What early morphological features are common/variant?
Concept: *Reductionism often uses the distinction between «necessary», but «not sufficient»!*
E. What does early cleavage accomplish for the embryo?
F. What is the evidence that cytoplasmic components control early embryogenesis?
Concept: *Cytoplasmic organization systems play roles which thwart researchers' attempts to reduce developmental phenomena to gene expression circuits!*
G. When does the zygote nucleus first begin to direct patterning?
H. Genomic equivalence: How do mammalian cloning and genome sequencing impact on this notion?
I. Should the discipline of developmental biology be formatted in terms of *cell* behavior patterns?
Concept: *Five cell behavior patterns comprise embryogenesis: division, growth, movement, interaction, death!*

III. Cell movements, fates, and interactions during early embryogenesis
A. Experimental tracking of cells: How is a fate map established?
B. Gastrulation: What does it accomplish for the embryo?
Concept: *Neighboring cells influence each other's behavior patterns!*
C. Embryonic induction: How much of its molecular basis do we understand?
Concept: *Cells function in complex, counterintuitive ways, so developmental genetics studies (e.g., mutants) are often required for making discoveries!*
D. Axis formation: What mechanisms drive body plan morphogenesis?

IV. Intellectual distinctions guide data interpretation
A. In what way are the following terms—*fate, potency, determination, differentiation, totipotent, pluripotent*—useful for understanding mechanisms of development?
Concept: *Developmental phenomena have often been described in familiar, human terms (metaphors), which occasionally outlive their value!*
B. Operational definitions: why do they often change?
Concept: *The power of developmental biology can be harnessed by pharmaceutical companies for drug discovery!*

V. Learning about human development (mostly student presentations)
A. Descriptive analyses: How does human organogenesis compare to that of other vertebrates?
Concept: *Developmental processes constrain the evolution of patterning*
B. Analytical: Which features are amenable to molecular analyses?

Laboratory Exercises with Living Material Supplement Lecture Topics

Various living embryos which are available from research laboratories on campus are employed to gain an understanding of the morphological and genetic features of fertilization and tissue and organ formation. The actual exercises vary from semester to semester, depending upon availability of live embryos. A typical menu includes: Sea urchin fertilization and early development (including immunostaining of marker proteins); frog fertilization and early embryogenesis (including haploid development and extirpation/transplantation/parabiosis manipulations); *Drosophila* developmental genetics (including sample crosses); *C. elegans* patterning (including mutant phenotypes), and urodele limb regeneration (including effects of retinoic acid).

Sample Worksheet Questions

Design an experimental test of the following hypothesis: As a sperm penetrates the egg during the fertilization reaction, it leaves a residue of its outer membrane on the surface of the egg.

Present an experimental protocol for labeling *Drosophila* cells by somatic crossing over.

Sample Hour Exam Questions

Explain both the strengths and weaknesses of the *reductionist* approach to the study of developmental biology.

What role do imaginal discs play in insect embryogenesis? Explain the experimental designs (and data collected) which provide evidence to support the role you explained.

Textbooks for Assigned Readings

GILBERT, S.R. (2000) *Developmental Biology.* Sinauer, Sunderland, MA.

KALTHOFF, K. (1996) *Analysis of Biological Development.* McGraw-Hill, New York.

Visual Aids

FINK, R. (ed.) (1991). *A dozen eggs: Time-lapse microscopy of normal development*, Society for Developmental Biology (USA).

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Appendix

Menu of 12 Ways to Learn Complex Phenomena

Developing an understanding of complex phenomena in developmental biology often requires employing several different learning strategies. Armed with information about their learning preferences from the Keirsey Temperament Sorter described above, students are encouraged to develop learning methods which best suit their native preferences. The following list is provided to students at the beginning of the term, and during the course of the semester a sampling of learning tasks are keyed to the various entries on the list. The goal is to broaden the undergraduate student's repertoire of learning methods beyond the typical *read and memorize* strategy so often employed by college students.

1. Begin at the beginning: Learn what your Keirsey Temperament Sorter *learning style preference* is, and then develop strategies for specific tasks based on your learning *strengths.*
2. Collaborate: As undergraduates, *we learn best* when we learn together, with *study partners.* Get a group together.
3. Learn through metaphors: Review a problem or phenomenon in biology (e.g., neural crest cell migration) in terms which are familiar to you from daily life, in order to understand its intricacies.
4. Perform a context review: Understand a concept/theory/phenomenon (e.g., primary embryonic induction) by reviewing its history—what preceded it, what exists now, and what will it probably be like in the future?
5. Read alternative explanations: Since different authors often explain the same phenomenon (e.g., somatic cell crossing over) in different ways (use of symbolism/level of detail/illustrations/ etc.), reading more than one explanation often enhances understanding.
6. Surf the web: Your computer is a library! See what has been written about what you would like to learn.
7. Construct a «concept map»: Compile a list of key words, and then generate a flow sheet which cartoons the relationships between the terms (e.g., body axis/pattern formation).
8. Write it out: As Lee Iacocca (a prominent industrialist) once said:
   In conversation you can get away with all kinds of vagueness and nonsense, often without even realizing it. But there's something about putting your thoughts on paper that forces you to get down to specifics. That way, it's harder to deceive yourself—or anybody else.
9. Prepare a road map: Photocopy a set of illustrations, paste them on a large sheet of paper, and then draw arrows to connect key features, in a linear, progressive fashion.
10. Construct a 3-D model: By representing the phenomenon (e.g., molecular features of transcription factors), you are attempting to understand by using materials you can work with your hands, which leads to clearer images.
11. Step outside yourself: Disconnect yourself for a moment, and ask «what big picture am I dealing with,» and then try to assemble the facts (e.g., those known for muscle-cell differentiation) in a way which has meaning to you.
12. Work backwards: Begin with the final question, or answer to a problem (e.g., appendage regeneration requires innervated tissue), and work your way back, filling in knowledge gaps along the way.