A Paper-&-Pencil Strategy for Teaching Mitosis & Meiosis, Diagnosing Learning Problems & Predicting Examination Performance

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SCIENCE education literature is replete with documentation that students, at both the secondary school and collegiate levels, have difficulty mastering the basics of Mendelian genetics (Cho et al. 1985; Longden 1982; Stewart 1982, 1983; Walker et al. 1980). Likewise, teachers report that teaching these basic concepts can be a difficult assignment.

We also know that Mendel's contemporaries did not understand the implications of the genetics research he had done on garden peas when that research was presented and published in the mid-1860s. No doubt, the reasons they failed to understand his work are many, but one probably was their total lack of understanding of the chromosomal mechanics of the process of meiosis. Once that process had been described in the late 19th century, the parallels between chromosome behavior in meiosis and gene behavior, according to Mendelian explanations of inheritance, became apparent. A material basis for inheritance could be postulated if one assumed that genes are located on chromosomes. The concretes of chromosome behavior made the abstractions of gene transmission meaningful.

By the same token, if students are thoroughly grounded in their understanding of chromosome behavior in meiosis, they also should be in a better position to understand Mendelian inheritance. Science education literature supports this position (Mertens 1971, Smith 1991, Stewart 1982, Stewart et al. 1990). Too often student "success" in solving Mendelian genetics problems relies heavily on the memorization and rote application of an algorithm without sufficient understanding of the meiotic basis for the steps involved in the solution. If a variant problem is presented, the student may have no idea about how to solve it because it fails to conform to the algorithm.

Both the first author's personal experience and that of others (see, especially, Smith 1991) suggest that students need more than textbook reading assignments, lecture presentations, laboratory exercises and illustrative materials (diagrams, videos and photographs) to grasp the intricacies of the meiotic process. Involving students with some type of teaching strategy using concrete "chromosomes" with "genes" on them is useful in allowing students to move toward a more abstract understanding of meiosis. Manipulating pipe cleaner or pop-bead chromosomes is an approach that can facilitate learning, especially when one is working with small groups of students (Beison 1983). For larger groups, however, an alternative pencil-and-paper approach would be useful.

Some years ago, a secondary school biology teacher acquainted the first author with a meiosis teaching strategy developed by Professor Carl Bajema of Grand Valley State University in Michigan. This strategy (Bajema 1984) has been used in teaching genetics at Ball State University for several years and has been found to help students master the intricacies of meiosis and to relate chromosome transmission in meiosis to the Mendelian principles of gene segregation and independent assortment. Repeated use of the Bajema strategy led to the observation that students' scores on the graded strategy and their scores on each of the first two-hour examinations in the genetics course were correlated. The purpose of this paper is to (1) describe the Bajema strategy and how it is used in the general genetics course at Ball State University, and (2) discuss how it can be used as a means of identifying students who have misconceptions of the meiotic process that will interfere with their success in learning the basics of Mendelian inheritance. Not only can the Bajema strategy serve as a predictor of student success with future examinations of meiosis and Mendelian genetics, it can also

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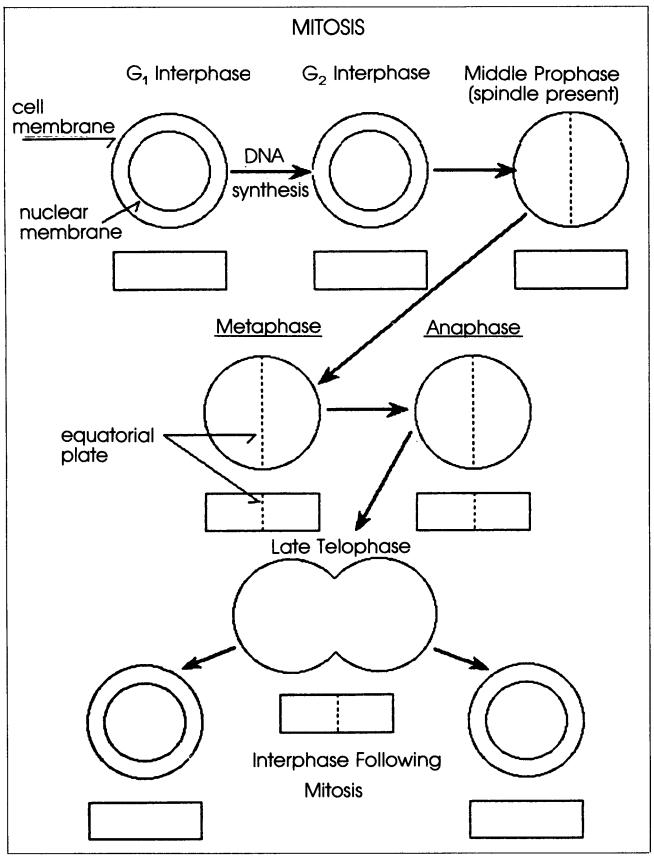

Figure 1. Template for student to use in showing the chromosomal events of mitosis. Note: Readers may enlarge Figures 1–4 on a photocopier and use them for instruction of their students.

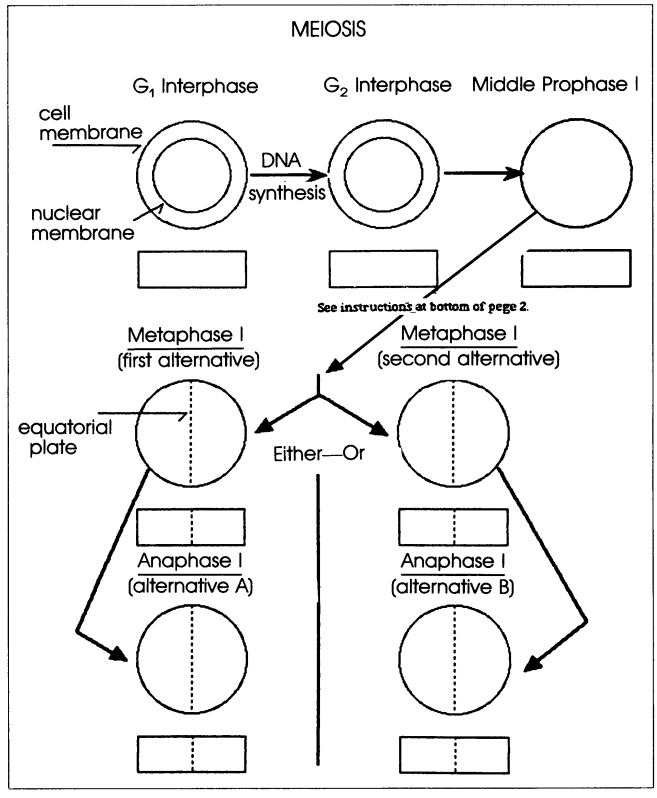

Figure 2. Template for showing the chromosomal events of prophase, metaphase and anaphase of meiosis I.

serve as a means of identifying the kinds of misconceptions of mitosis and meiosis that the student has formulated. Knowledge of these misconceptions can serve as the starting point for the introduction of clarifying instruction.

The Bajema Strategy

What is the Bajema strategy and what can be accomplished by having students use it? The essence of the strategy is four pages (Figures 1 through 4) of outline drawings of cells preceding through the stages of mitosis (Figure 1) and meiosis (Figures 2 through 4). Students are instructed to use colored pencils to draw two pairs of chromosomes, place genes on them and trace the sequence of events, first in mitosis and then in meiosis.

Starting with a cell in G_1 of the cell cycle (unreplicated DNA), the student is expected to show diagrammatically the effects of chromosome (DNA) replication on both the structure of the chromosomes and the genetic information in the nucleus. For example, if the student begins with a pair of long, red chromosomes, one of which bears gene *A* and the other *a*, and a second pair of short, green chromosomes, one bearing *B* and the other *b*, then, following DNA replication, each chromosome consists of two identical chromatids and the genetic information in the nucleus is *AAaaBBbb*. This nucleus is then traced through prophase, the end of metaphase (when the chromosomes are aligned on the equatorial plane), anaphase and telophase of mitosis. The student draws the spindle in appropriate cells, using a pencil of contrasting color. Genes (*A/a* and *B/b*) are shown on chromatids and daughter chromosomes. The cell's genetic information is summarized in a box beneath each cell (e.g. *AaBb* in the cell at G_1, but *AAaaBBbb* after DNA replication). When the mitotic process has been traced in this fashion, the student, having been actively involved in the drawing of concrete chromosomes and labeling of their genes, can see why daughter cells formed in mitosis are genetically identical to each other and to the cell from which they originated.

Upon completing the mitosis diagram, the student is instructed to use a comparable procedure to trace the events of meiosis, again beginning with a cell having two pairs of chromosomes (one red pair and one green pair) and the genetic constitution *AaBb*. In meiosis the student is expected to show the effects of DNA replication and synapsis with the resulting two tetrads, but, for the sake of simplicity, crossing over is *not* introduced into the diagramming process.

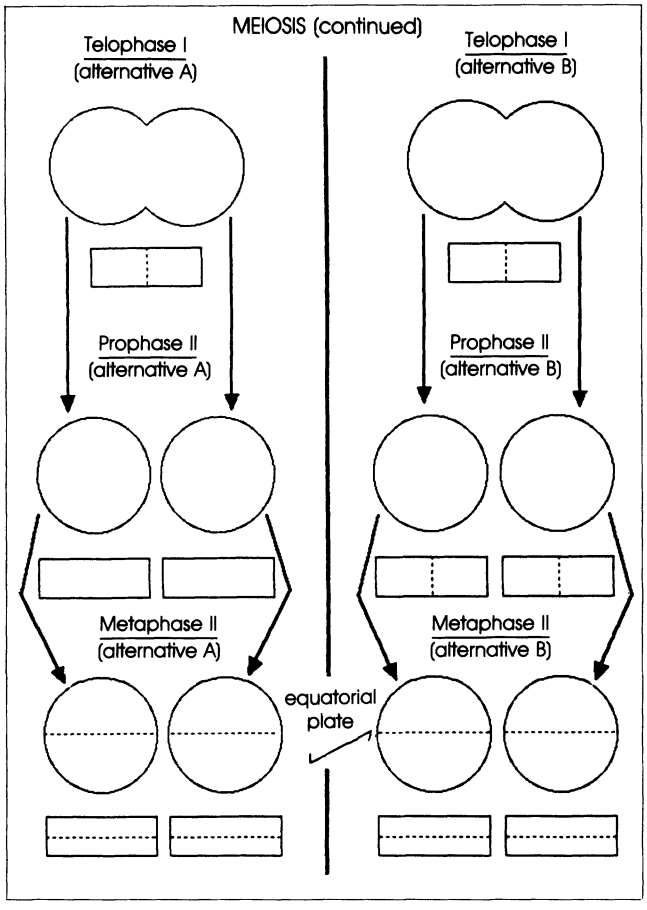

Figure 3. Template for showing the chromosomal events of telophase I and prophase and metaphase of meiosis II.

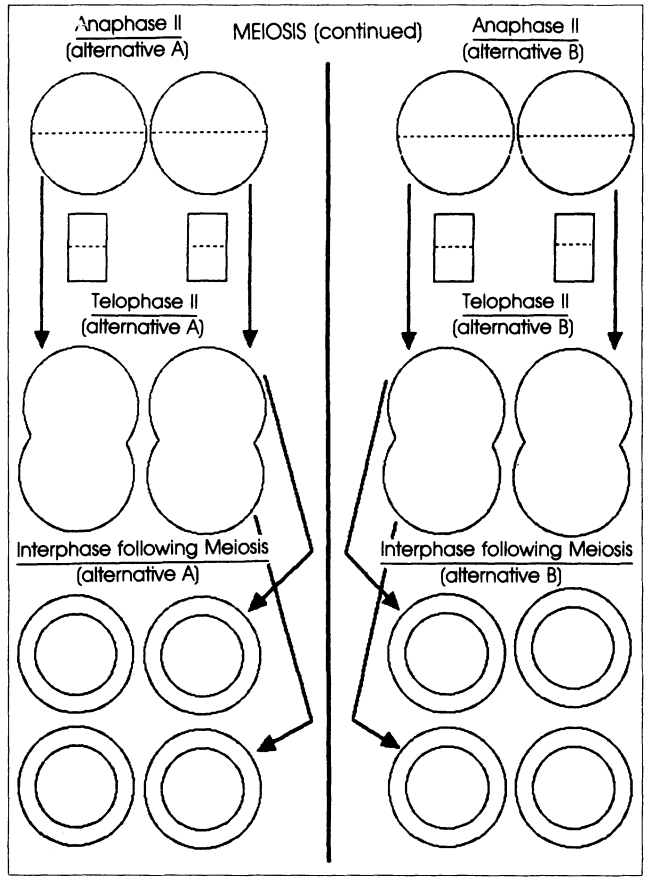

Figure 4. Template for showing the chromosomal events of anaphase II and telophase II along with the final products of the two cycles of meiosis.

Note that when crossing over does not occur, the chromosome consisting of two chromatids bearing the *A* alleles will always separate from the chromosome consisting of the two chromatids bearing the *a* alleles at anaphase I (first division segregation). However, if a crossover were to occur between the gene locus and the centromere of the chromosome, then second division segregation would result (i.e. the *A* and *a* alleles would not segregate until anaphase II). Introducing the complications of crossing over is better reserved for the time when students have mastered the basics of the meiotic process (Smith 1991).

At metaphase I (see Figure 2), students are confronted with what is often a major challenge to their thinking: Why are there two alternative ways to diagram metaphase I? The answer, of course, is that the chromosomes can align at the equator of the spindle at metaphase I in either one or the other of two unique combinations—*A*/*a*, *B*/*b* or *A*/a, *b*/*B*. These two equally probable alternative alignments necessitate following the two alternatives separately throughout the remainder of meiosis—anaphase I through telophase II. The two alternative alignments at metaphase I are the concrete basis for Mendel's principle of independent assortment, and they account for producing four kinds of gametes (*AB*, *Ab*, *aB* and *ab*) from the original cell having the genotype *AaBb*.

Personal experience and much of the educational research cited earlier suggest that many students solve genetics problems using an algorithm and having little or no understanding of the concrete biological basis for why the algorithm "works" as it does. The Bajema strategy causes students to come to grips with the biological concepts underlying the algorithm and thus provides the foundation for meaningful learning. Solving problems in Mendelian genetics becomes less an exercise in manipulating abstract symbols and more of a process having a concrete, biological basis.

How the Strategy Is Used

The Bajema Strategy is used as an applicational learning activity following the first two weeks of the introductory genetics course at Ball State University. Prior to having students complete the strategy, they are given a brief review of mitosis and a longer, more detailed presentation of meiosis. Transparencies of diagrams of mitosis and meiosis and, oftentimes,

projected kodachrome slides of the processes are used in the lectures. Students are provided with mimeographed lecture notes and copies of the transparencies used in the lecture presentations, and they are given a textbook reading assignment. In addition, students do two laboratory investigations—one of mitosis and one of meiosis. The former involves making slides of mitotic cells from onion root tips, including root tips treated with the mitotic poison colchicine. The meiosis investigation centers around preparing slides of meiotic cells in microsporogenesis using a species of *Tradescantia* (spiderwort) having six pairs of large chromosomes. All of this is done preceding the Bajema strategy; the strategy is done as a culminating homework assignment, turned in and evaluated on a 10-point scale.

What Can Be Learned from Using the Strategy?

Student Misconceptions

Although the Bajema tutorial was intended to be a learning activity for students, it has proved to be instructive for the course staff as well. Students' misconceptions of mitosis and meiosis are apparent by how they draw chromosomes, align them on spindles, and segregate and assort them during the two meiotic divisions. Misconceptions about meiosis are especially critical to learning basic genetics and included students' failure to:

1. Show centromeres uniting the two chromatids of a chromosome following replication.
2. Draw chromosomes in synapsis at prophase I so that chromosomes at metaphase I were aligned on the equator of the spindle as in mitosis rather than as homologues paired in tetrads.
3. Show alleles *A* and *a* on different chromosomes of the homologous pair, thus resulting in their being linked on the same chromosome.
4. Determine the two possible arrangements of chromosomes at metaphase I (i.e. failure to grasp the significance of independent assortment on chromosome and gene distribution).

Other misconceptions are reflected in:

1. Placing genes *A/a* and *B/b* on the same pair of chromosomes rather than on two separate pairs.
2. Showing all four chromatids of a tetrad joined by one centromere rather than having a tetrad consist of two chromosomes, each composed of two chromatids joined by a common centromere.

Being aware of these misconceptions can help instructors anticipate student difficulties and design presentations so as to avoid reinforcing or perpetuating such misunderstandings. For the individual student who has acquired misconceptions of mitosis and meiosis, the Bajema strategy serves as a means of revealing the need for further instruction to eliminate the erroneous concepts and introduce the correct ones. Detecting and correcting misunderstandings early-on can prevent difficulties later in the course.

Table 1. Correlation coefficients relating scores on Bajema tutorial with scores on two examinations given in genetics course at Ball State University.

	Fall 1990		*Spring 1991*	
	Exam I	*Exam II*	*Exam I*	*Exam II*
r*	.63	.42	.62	.40
Class Size	44	44	43	41

r* = all correlation coefficients significant at $\alpha = .01$

Correlations

Casual observation suggested that student scores on the Bajema strategy correlated positively with scores on the first two examinations in the genetics course. Subsequent investigation confirmed this observation. Each student's Bajema strategy was graded on a scale of 0 to 10 and the students' scores on the strategy were correlated with their scores on the two examinations using the SPSS statistical package (SPSS, Inc. 1990).

Examination I (raw scores, 0 to 60) dealt with the topics of mitosis, meiosis, gametogenesis in animals, and micro- and megasporogenesis in angiosperms. Questions ranged from simple recall (e.g. matching diagrams or descriptions of events in the meiotic process with the name of the stage in which the event occurs) to various analysis and synthesis questions (e.g. "In the laboratory you counted six tetrads at diakinesis in a microspore mother cell of *Tradescantia*; how many chromosomes would you expect to find in a root tip cell of this plant?"). Examination II (raw scores, 0 to 46) involved various aspects of Mendelian genetics, including mono-, di-, tri- and polyhybrid crosses, Mendel's "laws" (segregation and independent assortment), and gene interaction or epistasis. Test questions included recognizing definitions by recalling the word defined, but emphasis was placed on problem solving and interpretation of quantitative data. Both examinations were regarded as "difficult" or "challenging" by most students and both resulted in a wide range of scores.

The correlation coefficients (r) calculated on data collected in Fall semester 1990 and Spring semester 1991 are reported in Table 1. Most introductory statistics textbooks will include a discussion of how to calculate and interpret correlation coefficients. All four correlation coefficients were found to be significantly different from zero using an alpha level of .01. The Bajema tutorial scores explained about 40 percent

(r^2) of the variation in Examination I scores and about 18 percent of the variation in Examination II scores each semester.

The question can now be asked, "For practical, pedagogical purposes, what is the meaning of the significant positive correlations between students' scores on the Bajema strategy and their performance on two examinations in the general genetics course at Ball State University?" The correlations are consistent with widely documented research that understanding the meiotic process provides a necessary foundation for meaningful learning of basic Mendelian genetics. At the very least, if a student did not do well with the Bajema tutorial it would seem to be a warning signal to both student and instructor that the student's future learning and test performance may be in jeopardy.

Summary

Although Bajema's mitosis and meiosis tutorial was developed as an instructional strategy for students, it also has proved to be useful in identifying students' misconceptions of these processes and in predicting their success on two examinations in the basic genetics course at Ball State University. We believe that instructors at both the secondary and collegiate levels will find the strategy useful as a diagnostic and predictive tool, while students will find it to be a means of concretizing the relationship between chromosome and gene transmission in the processes of mitosis and meiosis. With Dr. Bajema's kind approval, we offer it to the community of biology teachers as another tool in the repertoire of strategies designed to help teachers teach a difficult topic.

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