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Assessing Understanding of Biological Processes:
Elucidating Students' Models of Meiosis

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Central to secondary and college-level biology instruction is the development of student understanding of a number of subcellular processes. Yet one of the most crucial, meiosis, is consistently cited as one of the most difficult components of biology to learn (Johnstone & Mahmoud, 1980; Finley, Stewart, & Yarroch, 1982). A number of studies have documented a variety of meiosis misunderstandings among high school and college students following instruction on meiosis and Mendelian genetics (Brown, 1990; Hafner, 1991; Hildebrand, 1985, 1989; Kindfield, 1991a, 1991c; Slack & Stewart, 1990; Smith, 1991; Stewart & Dale, 1989; Stewart, Hafner, & Dale, 1990; Stewart & Van Kirk, 1990; Thomas, 1988 (cited in Brown, 1990)). Several of these have also documented both students' lacking any sense of connection between meiosis and Mendelian genetics and their ability to successfully solve Mendelian genetics problems without understanding meiosis. The facts that (a) many students harbor a variety of meiosis misunderstandings following instruction and (b) solutions to Mendelian genetics problems are not necessarily indicative of underlying meiosis knowledge suggest a need for better tools for analyzing student understanding of this important process.

For several years I have been utilizing a meiosis reasoning problem in both research (Hildebrand, 1989; Kindfield, 1991a, 1991c, in press) and teaching settings that provides direct access to individuals' current models of chromosomes and meiosis. As a research tool, I typically administer the problem in individual think-aloud/clinical interviews and have done so with practicing geneticists (N=5), intended or declared undergraduate genetics majors (N=31), and undergraduate other-than-genetics biology majors (N=13). In teaching settings, I have used the problem as a paper-and-pencil task in a genetics course for undergraduate non-science majors (four offerings each with ~20 students) and a genetics laboratory course for undergraduate genetics majors (three offerings each with ~48 students). In both cases, individuals' work on the problem has allowed me to derive their current chromosome and meiotic models and to identify what, if any, misunderstandings a particular individual might have about the process or its participating entities. In this paper, I will present the problem, elaborate on problem features, discuss implementation, and summarize solution evaluation using examples from my teaching and research.

THE MEIOSIS REASONING PROBLEM

The problem is quite simple in form and can easily be modified to accommodate varying levels of genetics instruction (i.e., varying cell descriptions, gamete sets, and/or symbol systems could be utilized–see below). It consists of a verbal description of a particular eukaryotic cell, sets of gametes that could result from this cell going through meiosis, and a question asking for the specific meiotic events that would lead to the formation of each gamete set. The specific problem that I have utilized in my research/teaching is as follows:

CELL DESCRIPTION

Suppose you have a diploid cell from a eukaryotic organism for which the haploid chromosome number is 2 (N=2). The organism is heterozygous for each of three different genes – a, b, and c. The a and b genes are genetically linked, while the c gene is located on a different chromosome.

QUESTION

Suppose that you can directly observe the genotypes of the four gametes that result when a **single diploid cell** undergoes meiosis. With respect to genes a, b, and c, what events would have to occur during the **specific** meiosis that gives rise to each of the sets of gametes on the following cards?

(NOTE: Each set of gametes is the result of a single diploid cell undergoing a **single** meiosis; 1's and 2's indicate the parental origin of each of the alleles.)

SAMPLE GAMETE SETS

(i)	$a_1b_1c_2$	$a_1b_1c_2$	$a_2b_2c_1$	$a_2b_2c_1$
(ii)	$a_1b_1c_1$	$a_1b_1c_2$	$a_2b_2c_1$	$a_2b_2c_2$
(iii)	$a_1b_1c_2$	$a_1b_2c_1$	$a_2b_1c_2$	$a_2b_2c_1$

PROBLEM FEATURES

The primary utility of this problem as an assessment or diagnostic tool is the equivalence between problem solutions and current chromosome/meiosis models. For example, a correct solution for gamete set (i) is as follows (see Figure 1 for a diagrammatic version of this solution): The chromosomes have already replicated prior to meiosis. During meiosis I the paired chromosomes align such that the a_1b_1 chromosome segregates with the c_2 chromosome and the a_2b_2 chromosome segregates with the c_1 chromosome at the first meiotic division. Replicated chromosomes align and sister chromatids separate during the second meiotic division to yield the four gametes in question.

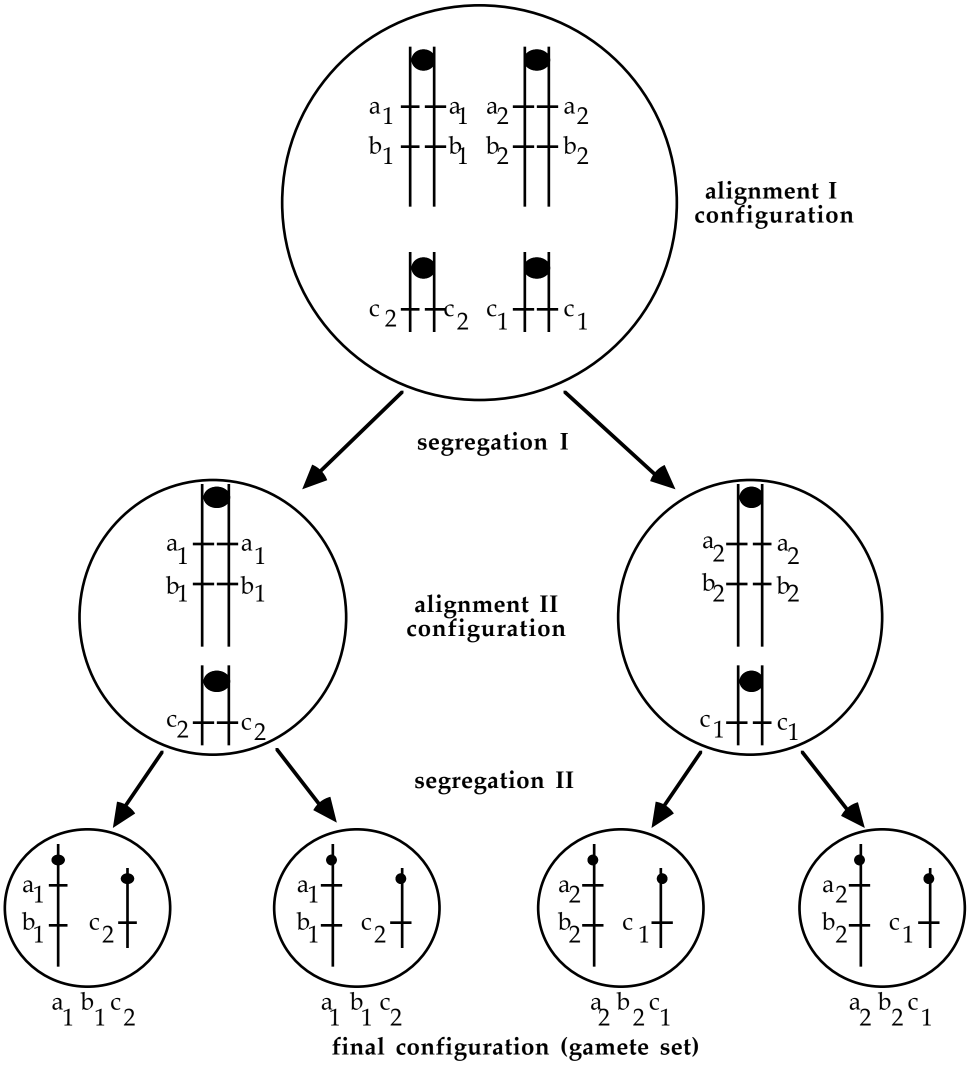

Figure 1. Simple solution for gamete set (i). Configuration refers to particular spatial arrangements of chromosomes at static points during meiosis. In the alignment I configuration, chromosomes are replicated (lines=chromatids and dots=centromeres), homologous chromosomes (i.e., chromosomes containing the same genes (e.g., a and b) though possibly different alleles (e.g., a_1 vs a_2) of those genes) are paired. In the alignment II configuration, individual chromosomes that separated as a result of segregation I are aligned in the center of each intermediate nucleus. In the final configuration, each final product nucleus contains one of each unreplicated chromosome as a result of segregation II.

A not uncommon alternate solution to this gamete set is as follows (see Figure 2 for a diagrammatic version of this solution): Chromosomes consisting of two chromatids pair and align during meiosis I. Any given chromosome at this stage contains one set of alleles from one parent and one set of alleles from the other parent. Paired chromosomes segregate such that each “cell” resulting from the first meiotic division contains one a_1b_1/a_2b_2 chromosome and one

c_1/c_2 chromosome. These chromosomes then align such that sister chromatids will segregate to yield the gamete set in question.

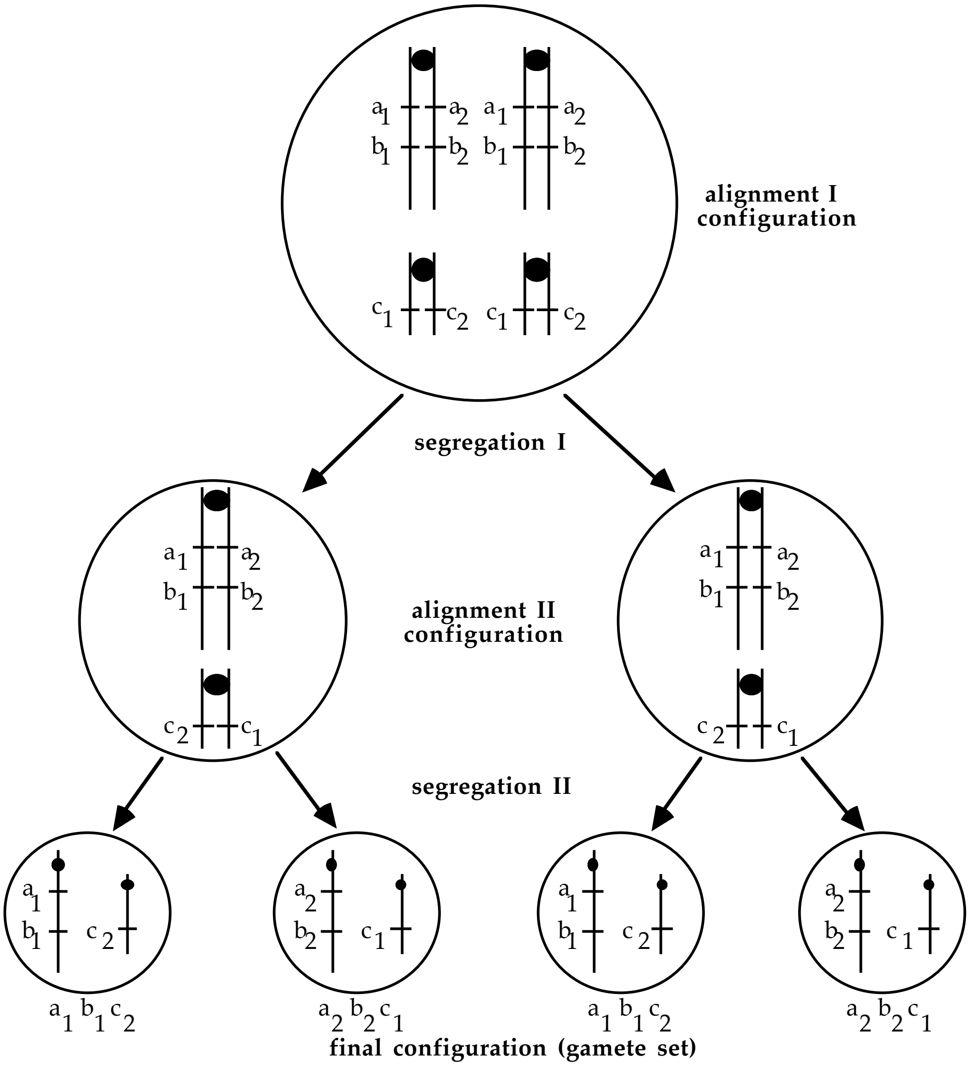

Figure 2. Alternate solution for gamete set (i). Same diagrammatic conventions as in Figure 1 (lines=chromatids and dots=centromeres).

Notice that the chromosomes behave similarly in both solutions but the genetic constitution of the chromosomes in the alternate solution is inconsistent with the accepted view of chromosomes as replicated and therefore containing identical sister chromatids at the beginning of meiosis. This solution, or any other containing chromosomes of this alternate type (prior to crossing over), displays the existence of some type of misunderstanding about chromosomes. Though other possibilities exist, this particular conceptualization of two-chromatid-plus-centromere chromosomes is often the result of a misunderstanding about the origin of chromosomes having this structure. Specifically, students often think that instead of originating via replication, chromosomes having this structure originate from the joining of the homologous chromosomes contributed by each gamete upon fertilization (Kindfield, 1991a). Thus, seeing this alternate solution makes explicit that existence of a flawed chromosome model, and also points to the misunderstanding that might be underlying this model.

In addition to allowing direct access to current student chromosome/meiosis models, the problem has several other features that aid in both diagnosis and student learning. First, because it is a reasoning problem, it requires the coordinated use of students' chromosome/meiosis knowledge. This is in opposition to the delineation of steps or phases in response to a request to describe meiosis which may simply require regurgitation of a memorized list of events rather than coordinated use of knowledge. It has been my experience that having students solve the problem brings up issues that they might not even address in a "description" of meiosis. For example, when asked at the end of research interviews to describe the cell in the **CELL DESCRIPTION** going through meiosis, most students leave out crossing over and its entailments altogether. Yet in their preceding work on the problem, crossing over and its effect on the outcomes of meiosis is invariably addressed. Even if crossing over is mentioned in a description, simply describing rarely requires that a student display his/her awareness of crucial yet subtle features of this event like the relevance of the relative positions of the centromere, gene(s), and crossover event(s) to the outcome of crossing over or the ramifications of crossing over for subsequent chromosome alignment. Regarding student learning outcomes, the coordinated application of what may exist, especially among introductory students, as rather isolated pieces of meiosis knowledge (Hildebrand, 1989; Kindfield, 1991c; Stewart & Dale, 1989; Stewart, Hafner, & Dale, 1990) to solving the meiosis reasoning problem may force problem solvers to confront discrepancies among discrete pieces of knowledge, possibly leading to the formation of a more robust understanding of meiosis (Hildebrand, 1989; Kindfield, 1991b and work in progress).

A second feature that makes this problem a useful assessment/learning tool is that gamete sets have multiple solutions. For example, while Gamete Set (ii) can be solved simply by having a single crossover occur between the c gene and the centromere of the c chromosomes, the gamete set could also result from (a) a single crossover occurring between the a and b genes and the centromere of the ab chromosomes if genes a and b are on the same side of the centromere or (b) a single crossover occurring between the a gene and the centromere of the ab chromosomes and a single crossover occurring between the b gene and the centromere of the ab chromosomes if genes a and b are on opposite sides of the centromere. (These three solutions are the simplest solutions in that they invoke the fewest number of crossover events for particular gene/centromere arrangements. Other solutions that invoke additional crossing over events are also possible.) In order to determine the most complete version possible of a student's current meiosis model, he/she can be asked at the outset to provide more than one solution for a given gamete set or asked if there are any other solutions after having solved for a given gamete set. In addition to completeness, requiring multiple solutions per set can also expose discrepancies or inconsistencies in student models if the student uses different models for different solutions. From the learning perspective, the existence of multiple solutions for any gamete set encourages flexible thinking and use of knowledge.

Yet another advantageous feature of this problem is that it provides opportunities for students to explicitly deal with the effects of a single cell versus a population of cells going through meiosis. In the absence of working on problems such as this one, students primarily deal with the effects of populations of cells going through meiosis since Mendelian genetics and Mendelian genetics problem solving are based on populations of cells going through meiosis followed by random fertilization. The familiar ratios of types of offspring derived from particular parental types result from the single occurrence of meiosis in many diploid parental cells that give rise to many gametes. However, a single occurrence of meiosis cannot give rise to a set of four gametes that reflects the population ratios. In my research (Hildebrand, 1989), experts as well as novices sometimes had difficulty separating the effects of a single occurrence of meiosis from the effects of a population of cells going through meiosis. Further, research on Mendelian genetics problem solving has demonstrated students' meiosis-specific difficulty in appropriately dealing with the ratios and probabilities associated with the outcomes of many meioses (Kinnear, 1983; Peard, 1983; Smith & Good, 1984). In addition to providing insights into current student meiosis models, work on this problem can also expose the existence of difficulties associated with thinking about single versus populations of cells going through meiosis. Again, regarding learning, it is possible that a more balanced treatment of single cells and populations of cells going through meiosis (i.e., having students reason about both single cell and population outcomes) might ameliorate at least some of the documented difficulties.

A fourth important feature of this problem is that it is well suited to having students solve it by drawing diagrams of relevant chromosome configurations. In my experience, diagrams are virtually required for all but the simplest of gamete sets. With regard to assessment, diagrams often clarify components of the solution that when presented only verbally are ambiguous. For example, harkening back to the chromosome misunderstanding discussed earlier, a student might verbally express the alternate problem solution (see Figure 2) as follows: "The homologous chromosomes pair, line up, and separate during meiosis I. Then the sister chromatids split to give you the gamete set." This student's chromosome model is not at all evident in his/her verbal expression of the solution. However, accompanying diagrams of labeled chromosomes make the chromosome misunderstanding quite obvious. Regarding learning, Allen and Moll (1986), Smith (1989), and Thomson and Stewart (1985) have advocated incorporating student drawing into standard mitosis and meiosis instruction, and my own work (Hildebrand, 1989; Kindfield, in press) clearly indicates that diagrams and diagrammatic reasoning are crucial components of a meaningful understanding of meiosis. Thus providing opportunities, like this problem, for diagrammatic expression of meiosis knowledge is quite valuable.

Finally, the problem itself is inherently quite flexible. I noted earlier that the cell description and gamete sets can be changed to accommodate varying levels of sophistication with the subject matter. The problem can be presented as shown with no additional constraints or constraints such as considering all possible orders of gametes in a set can be included. In my research, I start with the unconstrained version of the problem and after a solution has been reached address the order issue as follows (using the solution in Figure 1 as an example): I look at the solution and say something like "In this solution, the gametes occur in the order $a_1b_1c_2$ $a_1b_1c_2$ $a_2b_2c_1$ $a_2b_2c_1$. How might that same gamete set be produced if the order of the gametes was $a_1b_1c_2$ $a_2b_2c_1$ $a_2b_2c_1$ $a_1b_1c_2$?" Depending on the response to this question, I might additionally comment that all orders are possible and further that a single model must account for all possible orders. When dealing with multiple gamete sets, I often make the same point that a single model must account for all biologically possible gamete sets. If when solving the problem the student has not considered the single model issue, discrepancies in his/her models are rather obvious. Making the single model issue explicit often leads to model changes and modified understanding of chromosomes/meiosis.

IMPLEMENTATION AND SOLUTION EVALUATION

As noted earlier, I have used the meiosis reasoning problem in individual interviews for research purposes and as a paper-and-pencil task in the classroom. In the research/interview setting, I provide the research participant with paper and pencil for his/her work and display each component of the problem (i.e., cell description, question, individual gamete sets) on a 4X6 index card. The participant initially works on one gamete set at a time typically without any interaction with the interviewer. During the initial problem-solving period, I diagnose the current state of the participant's chromosome and meiosis models from his/her work and use the results of this diagnosis to guide the remainder of the interview. Later, from more thorough analysis of the videotaped session and participant-generated diagrams, I flesh out the details of the participant's chromosome/meiosis models and any changes that occurred in these models during the course of the interview. The post-interview data analysis is quite painstaking and time consuming and is therefore not well suited to the classroom. However, the results of my own (Hildebrand, 1989; Kindfield, 1991c) and others' similar analyses (Brown, 1990; Smith, 1991; Stewart & Dale (1989), Stewart, Hafner, & Dale, 1990; Thomas, 1988 (cited in Brown, 1990)) concerning common misunderstandings of chromosomes and meiosis can be quite useful in more timely diagnosis in the classroom in that they provide both pointers to and possible interpretations for the components of student models that often vary from the scientifically accepted models of chromosome and meiosis.

In the classroom, I have presented the problem as a written assignment for individuals to complete with the following directions (where parts (a) and (b) are different gamete sets): Given a hypothetical cell like the one described below, please answer parts (a) and (b) that follow. As much as possible, SHOW YOUR WORK. If at any time you become uncertain about how to proceed, write down what you are thinking at that moment. For a given gamete set, students typically take about a page to provide a solution consisting of both verbal and pictorial components. Evaluating and commenting on an individual's work takes 2-5 minutes. While the individual written assignment format has served my purposes for using the problem in the past, I also envision alternate classroom implementations. One possibility is to bring the on-line diagnosis of the research interview into the classroom, having students work on the problem, individually or in groups, as the teacher periodically checks in on student progress. In addition, students could also report to the whole class as solutions are being formulated or once they are complete for peer evaluation.

SUMMARY

The meiosis problem described here provides instructors with a simple, flexible means for having students reason about individual occurrences of the entire process of meiosis. The results of student reasoning are useful in supplying instructors with critical information concerning the current state of students' chromosome and meiosis models that may not be revealed in a student's description of the process. Further, student reasoning about meiosis may also contribute significantly to students' building more complete and robust understandings of this important process. Given the central role played by meiosis in understanding genetics, the prevalence of student misunderstandings about his process and the described features of the meiosis reasoning problem, it could be a valuable addition to standard meiosis/genetics instruction.

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