Drawing a Link Between Genetic Inheritance and Meiosis: A Set of Exercises for the Undergraduate Biology Classroom †

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Alleles are passed from parent to offspring through meiotic cell division and subsequent fusion of gametes. Despite this important link, general biology courses at the high school and college levels frequently discuss meiosis and genetic inheritance as two distinct content areas. As a consequence, students may leave biology courses with a working knowledge of both meiosis and genetic inheritance in isolation rather than understanding them as interconnected topics. In this paper, we describe and provide a series of classroom exercises that prompt students to explore the connection between meiosis and genetic inheritance. Specifically, students draw cells containing chromosomes with labeled alleles to illustrate key steps in the formation of gametes during meiosis and the subsequent fusion of gametes during fertilization. We believe that this approach is appropriate for either group or individual work, during or outside of class time, and we describe potential benefits for students and instructors.

INTRODUCTION

The inheritance of genetic information is a central topic in biology and is commonly taught in undergraduate introductory biology classes. Promoting student understanding of genetic inheritance addresses the core concepts of both Evolution and Information Flow as described in Vision and Change (1, 2). In addition to including a unit about genetic inheritance, undergraduate introductory biology classes also commonly teach about cell division, including meiosis. Meiosis and inheritance are closely intertwined, as parental germ cells undergo meiosis and produce gametes that carry specific alleles, and two gametes unite during fertilization to form an offspring. Despite this close interconnection between meiosis and genetic inheritance, undergraduate biology students often fail to connect their understanding about chromosome structure and behavior to genetic inheritance (3).

Recently, there have been calls for instructors to help enhance student understanding of close links between biological processes (including cell division and genetic inheritance) and chromosome structure by incorporating class activities (3). To investigate how the close relation-ship between meiosis and genetic inheritance is addressed by introductory biology textbooks, we conducted a broad survey of three commonly used textbooks (Raven 9th edition; Campbell 8th edition; Freeman 5th edition). In all three textbooks, the chapter on meiosis immediately preceded the chapter(s) on genetic inheritance. Within the chapter(s) on genetic inheritance, several figures depicted alleles and chromosomes in cells undergoing meiosis. However, the student practice questions at the end of the chapter included only at most one question that asked students to draw cells with chromosomes and alleles, or to apply simultaneously the concepts of meiosis and genetic inheritance. Instead, the majority of these questions were focused on generating Punnett squares and calculating genotypic and phenotypic ratios. While calculating these ratios is an important quantitative skill to develop, we argue that such a focus may preclude a deeper understanding of the underlying biological processes involved in gamete production and genetic inheritance. This lack of practice questions that span both meiosis and inheritance reveals a gap in opportunities for students to practice connections between these concepts more explicitly.

Here we describe an approach and a set of exercises for introductory biology instructors to use to strengthen student understanding of the link between meiosis and genetic inheritance and enhance student engagement in the learning process. Our approach involves guiding students in generating drawings of cells undergoing meiosis. Recently, Quillan and Thomas (4) have promoted the use of drawings in the biology curriculum, as drawings can provide a visual representation of structure, relationship, and process.

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Additionally, drawings can be used pedagogically for both formative and summative exercises (4), and it has recently been suggested that drawing concepts may improve a subject's memory of them (5).

Our approach makes use of the drawing-to-learn idea outlined by Quillan and Thomas (4). By having students draw germ cells and gametes containing chromosomes with labeled alleles, instructors can assess student understanding of the structure of chromosomes, the relationship between germ cell genotype and possible gamete genotypes, and the inheritance of alleles as chromosomes move during meiosis in ways that the more typical Punnett square exercises do not allow. Drawing exercises of this nature further engage students in structured active learning, which has been shown to improve student performance beyond that of more lecture-based approaches (6), and helps to narrow the achievement gap between disadvantaged and non-disadvantaged students (7). While various previously reported exercises may help students connect meiosis with specific facets of genetic inheritance (8), we describe here a comprehensive approach for teaching an entire genetics unit in either a high school or undergraduate biology course.

Intended audience

The classroom exercises outlined in this paper are intended for undergraduate biology majors or nonmajors taking introductory biology courses. They may be extended or modified for use in other undergraduate courses focusing on genetics.

Learning time

We have designed the approach to be used during a unit on genetic inheritance. We recommend devoting at minimum the equivalent of approximately four 50-minute class sessions to this approach (one 50-minute class period per worksheet). However, the approach may be easily modified for use with class sessions of a different length. See the estimated time(s) in the "Faculty instructions" section.

Prerequisite student knowledge

Before students are introduced to this approach to learning genetics, we recommend that they develop a strong foundation in important related biological concepts. Below, we list this prerequisite knowledge and provide some specific suggestions for exercises that instructors could use with their students to more effectively engage them in our approach to learning genetics.

Students should be able to distinguish between a haploid and a diploid cell, and should be familiar with traditional representations of ploidy (n = x; 2n = y). When teaching this, we recommend having students draw cells that contain representations of chromosomes. They should clearly differentiate between different chromosomes by drawing distinct sizes of chromosomes (for example, a pair of homologous chromosomes in a diploid cell would be drawn as the same size; another pair of homologous chromosomes would be differently sized).

Students should be familiar with basic chromosome structure during the cell cycle, and chromosome movement/alignment during both mitosis and meiosis. When teaching this, we recommend having the students develop an ability to draw the chromosomes for a diploid cell with 2n = y (for various even-numbered values of y), at select stages of the cell cycle, including stages within mitosis and meiosis. In particular, we strongly recommend that students practice drawing cells with chromosomes at the following "key" stages: G1, G2, prophase (of mitosis or meiosis), metaphase(s) of mitosis/meiosis, and daughter cells. We have chosen these particular cell cycle stages because they provide good checkpoints to assess student understanding of chromosome structure (replicated vs. unreplicated) and movement (distribution and orientation at the midline of cell division). For instance, if students can correctly draw both metaphase II of meiosis and the resulting gamete cells, it can be assumed that they understood the chromosome movement that occurred during the intermediate anaphase II.

Students should be familiar with basic terminology involved in cell division and genetics. We recommend that students be able to define the following concepts: haploid, diploid, somatic cells, germ cells, gametes, zygote, fertilization, replicated chromosomes, unreplicated chromosomes, homologous chromosomes, sister chromatids, genes, alleles, genotype, and phenotype. We also recommend that students practice articulating *relationships* between these terms. (As one example: germ cells undergo meiosis to produce gametes, and gametes fuse during fertilization to form a zygote. As another example: alleles are different versions of genes, and an allele is found at a specific location along a chromosome.)

Students should be familiar with historical concepts of inheritance, including the importance of Mendel's work. While the approach we describe in this paper does not specifically address historical perspectives, we encourage instructors to engage students in learning important aspects of the history involved in our modern day understanding of genetic inheritance.

Learning objectives

After completing these exercises, students will be able to:

1. Draw, predict, and evaluate representations of chromosome structure and alleles in cells (including parental cells at various points of the cell cycle,

key stages within meiosis, resulting gametes, and a single offspring cell produced from the fusion of parental gametes)
2. Engage actively in class sessions by collaborating with classmates to draw, evaluate, and/or critique models of their work

PROCEDURE

Materials

Each student will require the following:

- Student practice worksheet for the class session (see Appendix 1)
- Pencil and/or colored pens
- Notebook or blank paper (for any additional notes or drawings)

Student instructions

See "Faculty instructions" section below, as faculty guide the students through each class session. If faculty would like to assign the worksheets to be completed outside of class, we recommend they model the process of filling out one worksheet with students during an initial class session. This will help students better understand the framework and expectations for subsequent worksheets.

Faculty instructions

In order to facilitate the adoption of this approach for instructors, we suggest below a general framework/approach to help structure each class session. There is a worksheet for each class session, and the worksheets follow a similar structure wherein students draw parental germ cells (containing chromosomes with labeled alleles) undergoing meiosis to produce gametes, and then layer the gamete drawings over a Punnett Square. The iterative nature of the drawings that students complete in each worksheet is intentional and a central feature of our approach. This is because the organization of information in a Punnett Square (gamete genotypes across the top and sides, genotype of fused gametes within) remains constant regardless of the type of genetic cross. By using a layered approach, students may more readily see the connection between the process/products of cell division and the genotypes of gametes that are represented in a Punnett Square.

In general throughout this unit, these worksheets guide students through drawing parental cross scenarios that increase in complexity. The worksheets are found in the supplemental materials (see Appendix 1 for the student worksheets and Appendix 2 for the worksheet answer keys). Using this approach typically takes at least four devoted class sessions, plus any desired additional time for feedback, discussion, and extensions.

The four class sessions can generally be divided as follows:

- Session 1: One gene, autosomal (Worksheet 1 in Appendix 1)
- Session 2: One gene, sex-linked (Worksheet 2 in Appendix 1)
- Session 3: Two autosomal genes carried on separate chromosomes (Worksheet 3 in Appendix 1)
- Session 4: Two autosomal genes carried on the same chromosome (linked genes; Worksheet 4 in Appendix 1)

Throughout this unit, we recommend keeping students actively engaged and providing frequent opportunities for feedback/discussion, as in our experience, many students initially find this to be a challenging activity. Instructors should feel free to use the exercises provided in the worksheets as either in-class activities or take-home activities for students to gain additional practice.

Here we provide a suggested framework/structure for each class session:

- **(5 min) Introduce students to the specific goals for that particular class session. We use the following goals for our students:**
  1. Apply an understanding of meiosis to patterns of inheritance (be able to draw and label cells that accurately depict genotypes of parents, the gametes produced from those parents, and possible offspring genotypes resulting from fertilization events).
  2. Given information about parental genotypes in a genetic cross, be able to set up an appropriate Punnett Square (including a drawn version depicting cells containing chromosomes with labeled alleles) and predict the expected genotypic outcome of the cross.
     - *Suggestion:* As this unit extends over multiple class sessions, we recommend that instructors use these same goals for each session, but be explicit about the type of cross that the students are learning during that particular session (for example, one gene that is sex-linked, two autosomal genes carried on separate chromosomes, etc.).

- **(5 min) Communicate expectations for student work and/or group work that day, and have students move accordingly in the classroom.**
  - *Suggestion:* Possibilities include students working independently and critiquing their own work, working independently and evaluating a partner's work, or working collaboratively (in pairs or small groups) and evaluating collaboratively. Instructors should feel free to vary how students work as desired.

- **(2 min) Distribute worksheet for that session (in Appendix 1), and orient students to the type of cross and the parental genotypes (both are listed at the top of each worksheet).**
  - In the worksheets, the genetic cross is presented in the form of parent 1 genotype × parent 2 genotype (e.g., Aa × aa).
  - *Suggestion:* Instructors may wish to assign a phenotype of their choice for the genetic alleles in the worksheet (e.g., A = round peas; a = wrinkled peas).
  - *Suggestion:* If assigning other similar practice questions, use letters that have easily distinguishable uppercase and lowercase designations (e.g., Bb × bb, rather than Ww × ww).

- **(15–30 min) Students complete the worksheet either individually or in groups. The worksheet guides them through drawing each parental germ cell at key stages of the cell cycle and meiotic division to illustrate the gametes produced; students then set up and interpret Punnett Squares using both typical genotypic designations and their drawn gametes.**
  - Please refer to the worksheets provided in Appendix 1.
  - *Suggestion:* As they draw, in scenarios where traits are carried on separate chromosomes, students should differentiate between chromosomes using different sizes for each type of chromosome; this makes it easy to distinguish haploid/diploid and to identify the location and identity of homologous chromosomes.

- **(5–20 min) Instructor provides a way for the students to receive feedback on the accuracy of their drawings and worksheet answers.**
  - Please refer to the worksheet answer keys provided in Appendix 2.
  - *Suggestion:* As the instructor draws the answer, they should offer explanations, allow students time to jot down notes/corrections, and invite questions from students. Alternatively, the instructor may have students critique each other's drawings first, before providing the answers as a check. As another alternative, instructors may provide or post the answer key for students to refer to outside of class, as long as students have an opportunity to ask questions during a future class session.

- **(Time varies; at instructor discretion) Any other topics the instructor wishes to include or emphasize.**

For example, instructors may wish to discuss historical concepts of inheritance, phenotypic ratios, the importance of Mendel's work and approach, the work of other geneticists, pedigree analysis, genetic maps, the connections between genetics and society, and interesting examples/applications of genetics. This information could be discussed at any point during the class sessions, or the instructor may wish to devote particular full class sessions for this to allow more time for discussion and exploration.

Suggestions for determining student learning

As part of determining student learning, we recommend that instructors evaluate student drawings for common misconceptions. See Table 1 for a list of sample exercises, examples of incorrect student drawings, and a brief explanation of misconceptions that those drawings may illustrate.

To assess student learning, we recommend using or modifying questions from the worksheets or Table 1 for short quizzes, in-class student response questions (such as through the use of clickers), or on exams. We then recommend grading the students on the accuracy of their drawings, including proper labeling of alleles and depiction of chromosomes in any or all of the following cells: parental germ cells, germ cells undergoing various stages of meiosis, gametes produced, and a cell of an offspring produced from the fusion of two parental gametes.

Sample data

Students often struggle with these exercises due to misconceptions involving meiosis or chromosome structure and behavior during cell division. Therefore, mistakes that students make during the class activities are a very important source of information for both students and instructors. In Table 1, we provide sample questions, with the correct answer together with annotated drawings that depict common student mistakes and misconceptions and a brief explanation of the concept or principle the student fails to understand.
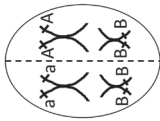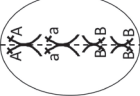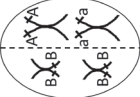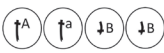
Safety issues

None.
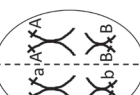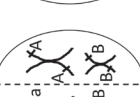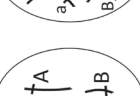
DISCUSSION

Field testing

We have used this approach for several semesters in Foundations of Biology, an introductory biology course for majors at a small liberal arts college. This course emphasizes the interconnections between genetics and evolution and includes units on cell division, genetics, molecular biology, and evolutionary processes. Our classes have ranged in

TABLE 1.
Sample questions for students, with correct answer, sample incorrect answers revealing misconceptions, and the principle that the student fails to understand as illustrated through the incorrect response.

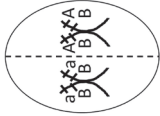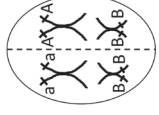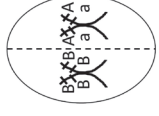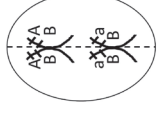| Sample Question and Correct Answer	Sample Incorrect Answers from Students, Revealing Misconceptions	Correct Concept/Principle that Student Fails To Understand as Illustrated through the Incorrect Response
Genes 'A' and 'B' are located on separate chromosomes. An individual has genotype AaBB. Draw a germ cell from this individual at metaphase of meiosis I. Draw this cell as it could be accurately pictured at this stage—you should show the chromosomes and clearly label the locations of all alleles. (Assume that crossing over has not occurred). **Correct answer:**		Chromosomes align differently in mitosis and meiosis.
		Homologous chromosomes are present in diploid cells.
		Homologous chromosomes line up across from each other in metaphase I.
		Alleles present match those in parental genotype.
		Alleles for a gene are located in the same location in sister chromatids.
		Chromosomes are replicated because the cell has already completed the "S" phase of the cell cycle.
Draw all of the gametes that would be produced from a single germ cell of an individual having genotype AaBB, where genes 'A' and 'B' are located on separate chromosomes. **Correct answer:**		Gametes are haploid.
		Gametes contain unreplicated chromosomes.
		Gametes contain one of each type of allele (Mendel's Principle of Segregation)
		Gametes contain one of each type of allele (Mendel's Principle of Segregation)
		Meiosis results in the production of four daughter cells.

size from 24 to 55 students, but we believe this approach can be easily used for a range of class sizes, from a small seminar-style course to a large-enrollment course at a public university.

We find that many of our students enter the Foundations of Biology course with experience completing traditional Punnett Square analysis of genetic inheritance. However, while our students could often easily set up a Punnett Square, they were unable to describe or draw the chromosomes and alleles contained by any gamete along the top or side of the Punnett Square. We feel this illustrates that students are missing the link between gametic genetic content (as determined by meiosis) and the setup of a Punnett Square. To address this gap, we developed these exercises (described above) to provide students with repeated practice in drawing the genetic content of cells

TABLE 1.
Continued.

Sample Question and Correct Answer	Sample Incorrect Answers from Students, Revealing Misconceptions	Correct Concept/Principle that Student Fails To Understand as Illustrated through the Incorrect Response
Genes 'A' and 'B' are linked. An individual has genotype AaBB. Draw a germ cell from this individual at metaphase of meiosis I. Draw this cell as it could be accurately pictured at this stage—you should accurately show the chromosomes and clearly label the locations of <u>all</u> alleles. (Assume that crossing over has not occurred). **Correct answer:** 		Linked genes are located along the same chromosome.
		Homologous chromosomes have the same genes but may have different alleles for those genes.
		Homologous chromosomes line up across from each other in metaphase I.
Fill in the blanks with the most appropriate answer. Select your answers from the following list: parent genotypes, parent phenotypes, offspring genotypes, offspring phenotypes, gamete genotypes, gamete phenotypes. For ALL genetic crosses, when creating a Punnett Square, _____ are listed along the top and sides, and _____ are listed in the interior of the square. **Correct answer:** **Gamete genotypes;** **offspring genotypes**	**Parent genotype; gamete genotypes**	During sexual reproduction, gametes from parents fuse to form offspring.
	Parent genotype; offspring genotypes	During sexual reproduction, gametes from parents fuse to form offspring.

and gametes (chromosomes with the associated alleles), and layering these drawings on a traditional Punnett square.

Evidence of student learning

We measured evidence of the effectiveness of our approach in relation to each of our stated learning objectives (above) using data collected from two sections of our Foundations of Biology course (one taught by KB, one taught by SS) both in the fall semester of 2013. We obtained approval to report all data below from these courses (HSRC# 2013.08.002, The College of Wooster). For the purposes of this paper, we combined the data collected across the two sections and report the pooled data below.

We measured students' ability to draw, predict, and evaluate representations of chromosome structure and alleles in cells (including parental cells undergoing meiosis, resulting gametes, and a single offspring cell produced from the fusion of parental gametes) (Learning Objective 1) using two questions from the Genetics Concept Assessment

Tool (9) on our course comprehensive final exam. The questions we included required students to link information about genotypes with drawings of chromosomes (with alleles) present in cells. While we did not conduct a pretest assessment of these specific concepts among our students, nearly 80% of the students in our course answered the two concept inventory questions correctly on our final exam. These pass rates are similar to the percentage of students answering questions correctly when the Genetics Concept Assessment Tool was tested and validated (9). We note that students completed this final exam approximately two months after the cell division and genetics units in which we used the approach described in this paper, suggesting longer-term retention of the concepts.

We measured student active engagement in class sessions (Learning Objective 2) using instructor surveys completed immediately after class. In these surveys, we recorded the time that our students spent engaged in active learning during class sessions in which cell division and genetic inheritance were being discussed. We considered

active learning to be any class time in which students were drawing, working in groups, and asking questions. Our post-class survey data show that students spent 20 to 30 minutes of each 50-minute class period engaged in active learning during the units in which these drawing tools were used. Most of this time was spent with students engaging actively in drawing, comparing their work with classmates, and asking questions. From our perspective, a drawing approach to linking cell division and genetic inheritance transformed class sessions into a workshop-like situation and provided ample opportunities for active learning.

Summary and proposed benefits

We described here an approach involving drawing that biology instructors can use to engage students in linking meiosis with genetic inheritance. In this approach, students draw the genetic content (chromosomes and labeled alleles) in germ cells as they undergo key stages of the cell cycle and meiosis and then show the offspring that result from gamete fusion. They then connect their drawings to a traditional Punnett Square, describing the parental cross and resulting offspring. By using this drawing approach iteratively, involving increasingly complex genetic crosses, students gain repeated practice and confidence in drawing the genetic content of germ cells and gametes involved in genetic inheritance. After using this approach in our classes, we believe that it provides several potential benefits to both students and instructors (see Table 2 for a full list).

For instance, students engage actively in practicing their drawings and have opportunities for both self-assessment and instructor feedback. Meanwhile, instructors can challenge students to better understand the biological basis of a Punnett Square and can quickly and efficiently assess student learning as indicated through their drawings. Given these numerous potential benefits, we encourage biology instructors at the high school and undergraduate levels to adopt similar approaches or exercises in their classrooms. Doing so will help students develop a stronger understanding of the link between meiosis and genetic inheritance.

SUPPLEMENTAL MATERIALS

Appendix 1: Worksheets for students
Appendix 2: Answer keys for student worksheets

ACKNOWLEDGMENTS

TABLE 2.
Proposed benefits for both students and instructors derived from the drawing approach described in this paper. Specifically, in this approach, students draw the genetic content (chromosomes and labeled alleles) in germ cells as they undergo key stages of the cell cycle and meiosis, including the subsequent gametes produced.

Student benefits from engaging in this approach include:
- Having repeated practice opportunities to draw cells (including chromosomes with labeled alleles) at various stages of the cell cycle, in order to show the formation of gametes during meiosis and the subsequent fusion of gametes during fertilization.
- Engaging in active learning, which has been shown to enhance student learning (6) and can narrow the achievement gap between disadvantaged and non-disadvantaged students (7).
- Identifying their own questions and/or misconceptions before they take a quiz or exam.
- Receiving in-class feedback on their drawings (and any misconceptions they may have) from the instructor and/or teaching assistant.
- Quizzing themselves and each other by re-attempting the exercises in the worksheets or by designing modifications or extensions of those questions.

Instructor benefits from using this approach include:
- Engaging their students in structured exercises that help the students make a link between gametic genetic content (as determined by meiosis) and the setup of a Punnett Square.
- Facilitating better or more frequent interactions with students during class sessions.
- Modifying this approach in several ways to best fit their desired teaching approach, such as assigning the worksheets either during or outside of class time (as homework), and having the students engage in either individual practice or collaborative group work.
- Challenging their students to better understand the biological basis of a Punnett Square (few students have previously learned this conceptualization of genetic inheritance).
- Quickly visually assessing misconceptions (which are readily identifiable in the drawings) during class sessions while students are drawing; these misconceptions can then be addressed immediately. See Table 1.
- Quickly and efficiently grading quiz or exam questions that engage students in drawing cells (including chromosomes with labeled alleles) at various stages of the cell cycle.
- Extending this technique to related biological questions (such as the impacts of mutation on inheritance, the inheritance of two genes where one is autosomal and one is sex-linked, etc.).

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