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Undergraduate Textbook Representations of Meiosis Neglect Essential Elements

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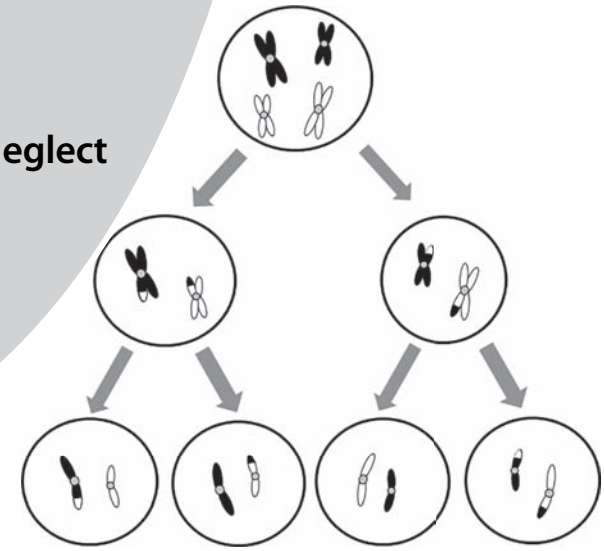
RESEARCH ON LEARNING

Undergraduate Textbook Representations of Meiosis Neglect Essential Elements



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ABSTRACT

The process of meiosis is an essential topic that secondary and postsecondary students struggle with. The important meiosis-related concepts of homology, ploidy, and segregation can be described using the DNA Triangle framework, which connects them to the multidimensional nature of DNA (chromosomal, molecular, and informational levels). We have previously established that undergraduate biology students typically fail to describe and/or link appropriate levels to their explanations of meiosis. We hypothesize that students' understanding mirrors the resources they are given – in other words, textbook figures often lack many of the important connections that experts include when talking about meiosis. Prior work showed that text in meiosis chapters typically fails to include many concepts that experts consider important, so we examined how textbook figures present meiosis concepts. We found that almost all textbook representations include the chromosomal level of DNA, but few include the other levels, even to illustrate concepts that are rooted in informational and/or molecular levels. In particular, the molecular level of DNA was absent from nearly all introductory textbook figures examined, and the informational level was seldom depicted in mid/upper-level textbook figures. The previously established deficits in text portions of textbooks are clearly not compensated by their accompanying illustrations.

Key Words: *DNA levels; genetics education; visual representations; expert-novice continuum.*

○ Introduction

The flow of genetic information is considered to be one of the five core, overarching concepts in undergraduate biology (AAAS, 2011). Meiosis is a topic that clearly falls within the category of information flow, as it explains how information encoded in DNA passes from one generation to the next. The process of meiosis is an important part of the curriculum, as it helps students understand major concepts in genetics and evolution. Much research on student understanding of meiosis has focused on identifying and describing the various misconceptions (or alternate conceptions) held by learners (Kindfield, 1994; Lewis et al., 2000; Wright & Newman, 2011; Newman et al., 2012; Ozcan et al., 2012; Smith & Knight, 2012; Kalas et al., 2013). While this research is extremely important for helping build awareness of the various difficulties that students will likely face when learning about meiosis, it does not help educators understand *why* these difficulties persist. To address this gap in the literature, much of our work has been devoted to investigating what aspects of conceptual understanding of meiosis are missing for students. We have previously established that learners and experts conceptualize aspects of meiosis very differently and that only experts bring a molecular level of understanding to their descriptions of the process (Newman et al., 2012; Wright et al., 2017).

We argue that one of the reasons for student difficulties in understanding meiosis is the incredible complexity of DNA itself. Genetic information is encoded in DNA in both concrete and abstract ways, making DNA a difficult molecule to conceptualize. Plus, DNA is a molecule that is incredibly small (the helix cannot be observed directly, even with a microscope) while also being incredibly large (containing thousands or millions of subunits). While genetic information is encoded in DNA, not all parts of a DNA molecule are used at the same time, by the same cell type, or even for the same purpose. All of this complexity is difficult for a novice to grasp and integrate into a cohesive mental model. The DNA Triangle framework integrates three different scales at which DNA can be considered: chromosomal (C), molecular (M), and informational (I) (Wright et al., 2017). The C level describes the structure of chromosomes (with and without sister chromatids), identification of chromosomes by banding pattern and centromere location, representations of chromatin packing, and counting chromosomes. The I level describes how DNA encodes genetic information, such as genes or alleles, protein-coding regions, or regulatory information. Finally, the M level describes the chemistry and nucleotide sequence of DNA. In previous work (Wright et al., 2017), the DNA Triangle framework was applied to meiosis and used to understand how experts described the concepts of ploidy (how many sets of genetic information are contained in the cell), homology, and the mechanism of homologous pairing (renamed "segregation" in

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this article). Biology experts explained the concept of homology by linking the I and M levels, the concept of ploidy using both the C and I levels, and how proper segregation was achieved with the C and M levels (Figure 1). Students, on the other hand, focused mainly on the C level and did not, for any of the topics, bring in M-level knowledge.

We then used the framework to analyze text passages from college-level introductory and mid/upper-level textbooks to better understand where students' ideas about meiosis may originate or grow from (Wright et al., 2017). While not a perfect resource, textbooks are frequently used in college science courses because they contain extensive information about the particular subject and are one medium in which scientific knowledge is transferred into teachable knowledge. The results revealed that (1) many important concepts about meiosis were missing from college-level textbooks and (2) many of the concepts were not consistently presented to students at the appropriate level of DNA, according to the framework (Wright et al., 2017). For example, homologous chromosomes in introductory books were almost always described at the chromosomal level (e.g., chromosomes with the same size and shape) but not at the molecular level (e.g., containing nearly the same sequence of DNA nucleotides). Mid- and upper-level textbooks were more likely to use molecular-level language (i.e., sequence of nucleotides, sequence of bases, base-pairing based on complementary sequences) to describe concepts of homologous chromosomes and homologous pairing; introductory-level textbooks were nearly devoid of molecular-level language. This analysis partially answers the "why" and "where" questions related to students' difficulties with meiosis. Most college-level textbooks fail to describe important concepts consistently and do not help students "see" the molecular level when describing molecular-based concepts that are important for meiosis.

As experts are well aware, biology is not solely communicated through written or spoken words. Thus, an analysis of textbook passages alone does not give the complete picture of how meiosis is presented to learners. The discipline of biology is highly dependent on visual representations (graphs, illustrations, diagrams, etc.) that are used to communicate important ideas and processes. Visual representations are abundant in most college-level biology textbooks and, thus, should be investigated for the messages they are conveying to students. For example, a prior study showed that one commonly used introductory biology textbook contained 1214 figures (Wright et al., 2018). Many textbook figures are intended to help the learner visualize structures and processes that are not directly observable and are designed to help highlight important aspects about a process or phenomenon. Quillin and Thomas (2015) argue that teaching biology, which covers a vast expanse of time scales (chemical reactions to evolutionary change) and of size scales (atoms to ecosystems), would not be possible without the use of visual representations. Visual representations also provide learners a tool for developing scientific reasoning skills, because they give learners something to reason about (Anderson et al., 2013).

Since figures in biology textbooks are *meant to help teach students* (novices) biology content, we examined chapters from several commonly used textbooks for evidence that they provide the necessary information to complete the DNA Triangle for student learners. In other words, do textbook figures make up for the gaps in written descriptions of meiosis-related concepts? We analyzed meiosis-related diagrams and illustrations from 18 different textbooks (nine introductory-level and nine mid/upper-level), resulting in a total of 112 figures. Whereas our previous study (Wright et al., 2017) examined textbook passages for descriptions of ploidy, homology, and the mechanism of homologous pairing (segregation), in the present study we examined textbook figures for illustrations of the same concepts. First, we determined whether meiosis-related textbook figures made important concepts about ploidy, homology, and segregation explicit to learners. Then we used the DNA Triangle framework to determine the extent to which the figures presented information at the three levels (M, C, and/or I).

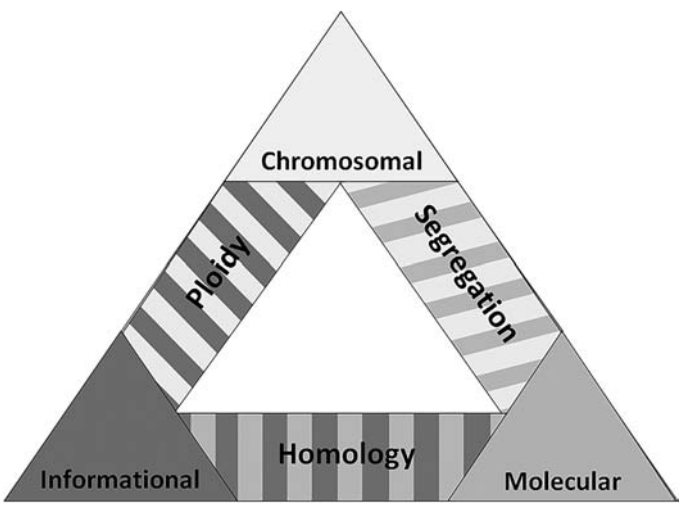

Figure 1. The DNA Triangle framework applied to meiosis. The concept of how proper Segregation is achieved links the Molecular and Chromosomal levels; the concept of Homology links the Informational and Molecular levels; and the concept of Ploidy links the Informational and Chromosomal levels. Figure modified from Wright et al. (2017).

○ Materials & Methods

Analysis of Textbooks: Overview

In order to understand how textbook illustrations convey information about meiosis to students, we examined meiosis-related figures from commonly used introductory biology textbooks as well as mid/upper-level textbooks focusing on cell biology, molecular biology, or genetics (all textbooks included in the study are listed in the Appendix). Three researchers (designated A, B, and C) coded the figures used in the study. Researchers A and B independently coded each figure for its *content* (which meiosis concepts were being illustrated by each of the figures). Then researchers A and C coded the same figures for *how* the DNA aspect was being illustrated for learners. A total of 112 figures (61 from introductory books, 51 from mid/upper-level books) were analyzed for both content and DNA Triangle levels. On average, introductory textbooks contained 6.8 figures related to meiosis (range: 2–12), while mid/upper-level books included 5.7 figures (range: 1–10). Multipart figures were counted as single figures in analyses.

Content Analysis

We began by identifying the meiosis-related figures in the 18 textbooks listed in the Appendix. Each figure was then coded for content. All figures that included the concepts of homology, segregation, and/or ploidy were compared to 10 expert-approved concept statements about homology, ploidy, and segregation (Wright et al., 2017), to determine which aspects of meiosis were being conveyed to readers. The figures (and accompanying legends) from *Biological Science* (Freeman et al., 2016) were used as a training set, completed by coders A and B, independently. The researchers compared their results and refined coding criteria before continuing on with the rest of the analysis. Table 1 lists the concepts and gives examples of the criteria that were used to guide the analysis.

Comparison of the two coders revealed a Cohen's kappa coefficient for inter-rater agreement of 0.751, which represents a satisfactory inter-coder reliability (Cohen, 1960; Carletta, 1996). Resolution on disagreements was achieved after a brief discussion.

Representational Analysis

Researchers A and C reanalyzed the same figures using the DNA Triangle framework (Wright et al., 2017) to determine which level of DNA was being depicted in each figure. In other words, this was a representational analysis rather than a content analysis of the figures. Figures that illustrated the overall structure of a chromosome were coded as chromosomal (C). Figures that included allele letter designations (AA, Aa, aa), colored chromosomal bands showing the location of different alleles, gene names, or phenotypic information (e.g., red eyes vs. white eyes) were coded as informational (I). Figures that contained depictions of nucleotide bases, DNA sequence, or a close-up view of a DNA ladder in which nucleotide bases were evident were coded as molecular (M). Each figure could include one or more levels (e.g., C and I). After the researchers performed their coding independently, the kappa statistic, a measure of inter-rater reliability, was calculated to be 0.96. The few disagreements were discussed and resolution was achieved. It should be noted that seven of the 112 figures did not illustrate DNA at the C, I, or M level. All seven figures addressed the concept of ploidy but did not include a visual representation of DNA.

○ Results

Figure 2 illustrates the percentage of textbook figures that included the concepts of ploidy, segregation, and homology. Interestingly, the concept of ploidy was illustrated more often in introductory-

Table 1. Coding criteria used in the content analysis of undergraduate biology textbooks.

Category	Concept Statement	Criteria Used in Coding
Homology	Maternal and paternal chromosomes of the same kind are homologous.	Color is used to differentiate maternal and paternal chromosomes in a homologous pair and/or each chromosome in the pair is labeled "maternal" or "paternal."
	Homologous chromosomes are different from sister chromatids.	A figure contains a pair of replicated, homologous chromosomes (which are explicitly described as such) with sister chromatids clearly labeled.
	X and Y chromosomes behave as a homologous pair.	The X and Y chromosomes appear together as a homologous pair.
Ploidy	Chromosomes may contain one or two DNA molecules,[a] depending on whether or not DNA replication has taken place.	Condensed chromosomes appear as one-DNA molecules before DNA replication and as two-DNA molecules (sister chromatids) after replication. Figure legend or labels indicate that both forms are chromosomes.
	Chromosomes rather than chromatids determine ploidy.	Diploid cells are drawn with two sets of chromosomes (which is pointed out in figure labels and/or figure legend) while the haploid version has only one set of chromosomes, clearly indicated.
	Gametes are haploid.	A gamete is clearly labeled as haploid.
	A cell becomes haploid after meiosis I.	A cell is clearly labeled as haploid after meiosis I but before meiosis II.
Segregation	Physical linkage is essential for proper chromosome segregation.	Replicated homologous chromosomes are paired (and appear to be physically touching) before they are shown aligned at the metaphase plate.
	DNA sequence homology determines pairing.	Homologous chromosomes are drawn paired and the identical DNA sequence on both chromosomes is clearly shown.
	Crossing over requires DNA sequence homology.	A close-up look at a Holliday junction intermediate is shown, with identical DNA sequence on both strands clearly shown.

[a]Reworded from original statement, which said: "Chromosomes may contain one or two chromatids . . . ."

level books (54% of meiosis-related figures) than in mid/upper-level books (21.5%). Similarly, homology was illustrated more often in introductory books (70%) than in mid/upper-level books (47%). By contrast, the concept of how to achieve proper segregation was depicted more often in mid/upper-level figures (84%) than in introductory ones (49%).

While Figure 2 provides an overview of the broad pattern of content found in meiosis-related textbook figures, we also conducted a finer-grained content analysis to better understand what was being explicitly illustrated in each visual representation. Guided by previous work (Wright et al., 2017), each figure was analyzed for the presence or absence of each of the 10 concept statements deemed important for meiosis understanding (Table 2).

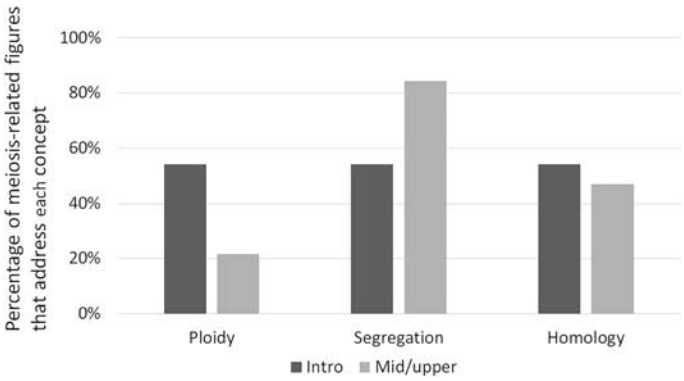

Figure 2. Introductory and mid/upper-level textbooks focus on different concepts in meiosis-related figures (n = 9 introductory books; n = 9 mid/upper-level books). Note that categories do not add up to 100% because some figures include more than one concept.

Results are also presented in a chart (Figure 3) so that patterns can be clearly discerned. The chart shows that four mid/upper-level textbooks (M-1, M-2, M-3, and M-6) illustrate very few of the key concepts, and that two concepts (about the molecular basis of segregation) are missing from nearly every book. The majority of the introductory books explicitly illustrate maternal and paternal chromosomes of the same kind as homologous, point out visually that homologous chromosomes are different from sister chromatids, illustrate ploidy in terms of chromosomes, and show that chromosomes contain two sister chromatids after DNA replication has taken place. Only four of the nine introductory books, however, indicated in a figure that cells become haploid after meiosis I (an important distinction that is troublesome for many students). Only one textbook explicitly showed the X and Y chromosomes behaving as a homologous pair (most pointed out the differences between X and Y but not their sequence homology or their ability to pair), and none of the introductory books demonstrated two important points about segregation: that DNA base sequence homology determines pairing and that crossing over requires sequence homology.

Since textbooks are comprised of both text and visual representations, we combined the figure analysis with data used in an earlier publication (Wright et al., 2017) that focused on content analysis of text passages about meiosis from 12 textbooks that were analyzed in both studies. Figure 4 illustrates the presence (white: concept was explicitly stated in the text *and* clearly illustrated in at least one figure), partial presence (dots: concept was either explicitly stated in the text; *or* stripes: concept explicitly illustrated in at least one figure), or complete absence (black) of each of the 10 concept

Table 2. Percentage of textbooks that explicitly illustrate important meiosis-linked concepts in images and percentage of textbooks that explicitly illustrate and/or describe the concept within the text narrative.

Category	Concept Statement	Image Only		Image and/or Text	
		Intro (n = 9)	Mid/upper (n = 9)	Intro (n = 5)	Mid/upper (n = 7)
Homology	Maternal and paternal chromosomes of the same kind are homologous.	100%	56%	100%	43%
	Homologous chromosomes are different from sister chromatids.	100%	56%	100%	86%
	X and Y chromosomes behave as a homologous pair.	22%	22%	20%	29%
Ploidy	Chromosomes may contain one or two DNA molecules, depending on whether or not DNA replication has taken place.	78%	44%	100%	57%
	Chromosomes rather than chromatids determine ploidy.	78%	33%	100%	86%
	Gametes are haploid.	100%	67%	100%	86%
	A cell becomes haploid after meiosis I.	44%	0%	60%	14%
Segregation	Physical linkage is essential for proper chromosome segregation.	67%	78%	60%	86%
	DNA sequence homology determines pairing.	0%	0%	0%	43%
	Crossing over requires DNA sequence homology.	0%	22%	0%	57%

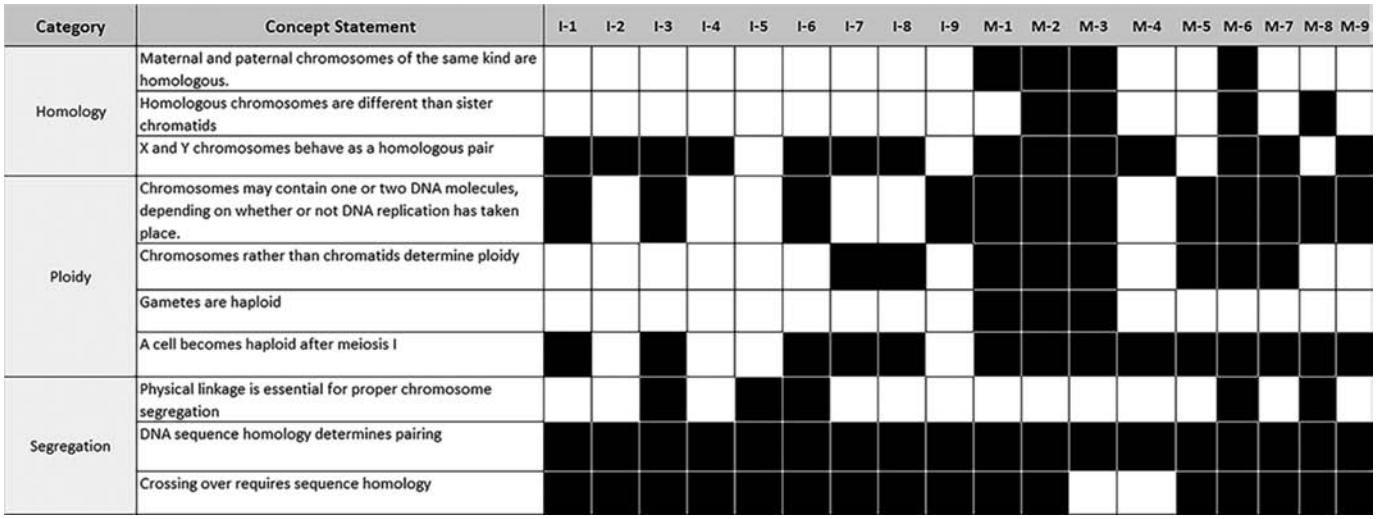

Figure 3. Appearance of the 10-concept statements in figures from 18 textbooks (I-1 to I-9 and M-1 to M-9). White indicates that the concept was illustrated by at least one figure in the meiosis-related chapter; black indicates that the concept was not illustrated by any figure in that particular textbook. Titles, authors, and other publication information of textbooks corresponding to each code are provided in the Appendix.

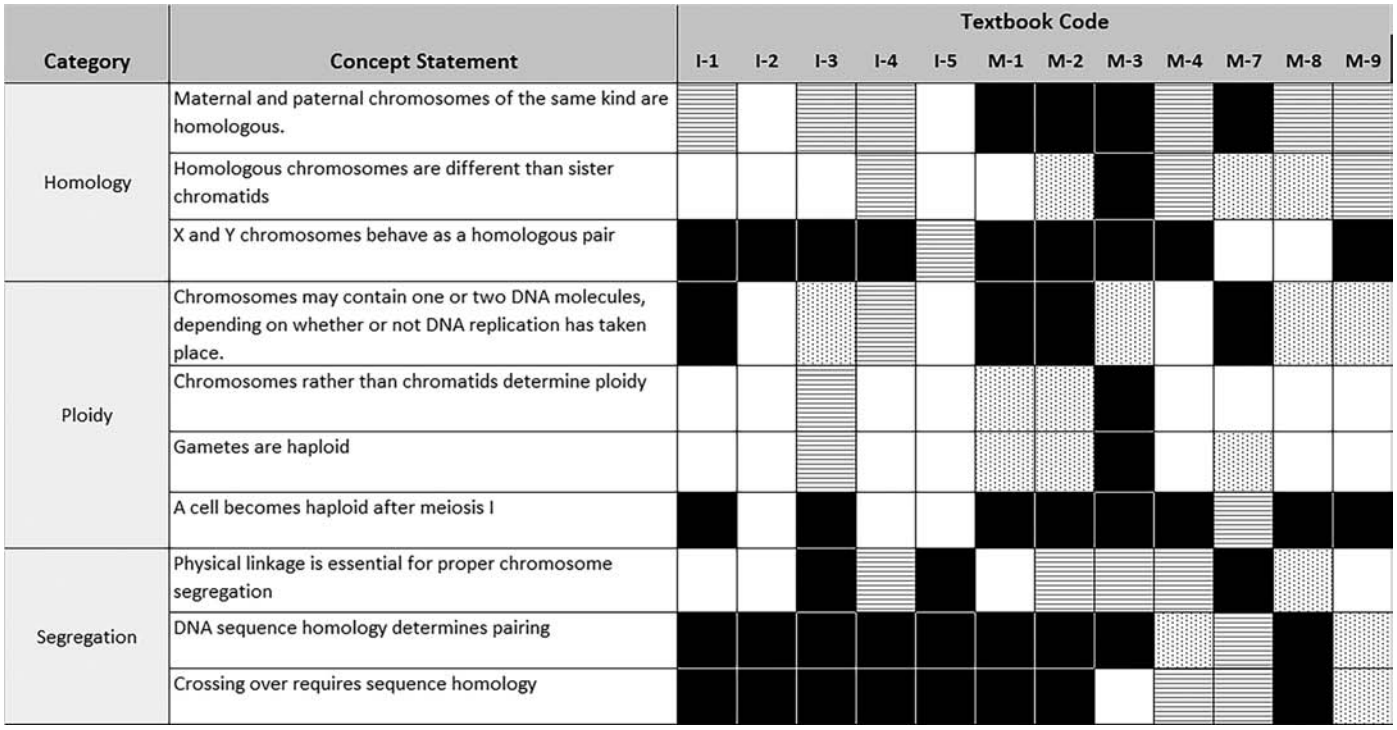

Figure 4. Inclusion of the 10-concept statements from 12 textbooks (I-1 to I-5, M-1 to M-4, and M-7 to M-9). White indicates that the concept was illustrated by at least one figure in the meiosis-related chapter *and* by a text passage in the same book (data from Wright et al., 2017). Stripes indicate that the concept appeared at least once in a figure but *not* in a textbook passage within the same book; dots indicate the reverse. Black indicates that the concept was *not* present in any of the figures or in the textbook passages. Titles, authors, and other publication information of textbooks corresponding to each code are provided in the Appendix.

statements. Regardless of level, most textbooks do not illustrate important concepts *both* as text and illustrations (only 35 of 120 boxes are white).

Because the process of meiosis is ultimately linked with the flow/passage of genetic information, we were also interested in how DNA was being depicted in each of the meiosis-linked figures used in the first analysis. We conducted a representational analysis of each illustration through the lens of the DNA Triangle framework and recorded how DNA was depicted in each (chromosomal, informational, and/or molecular levels). We found that nearly all of

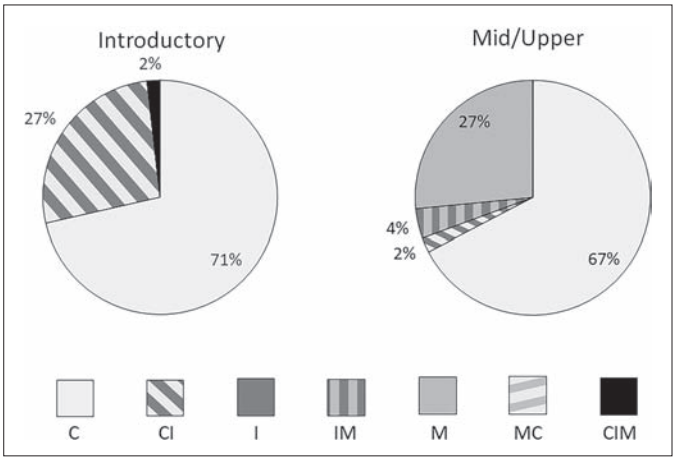

Figure 5. Percentage of figures that illustrate DNA at each of the various levels (M = Molecular, I = Informational, C = Chromosomal, and combinations of these) from introductory textbooks (56 figures in nine books) and mid/upper-level textbooks (49 figures in nine books). Categories use the same shading as in Figure 1.

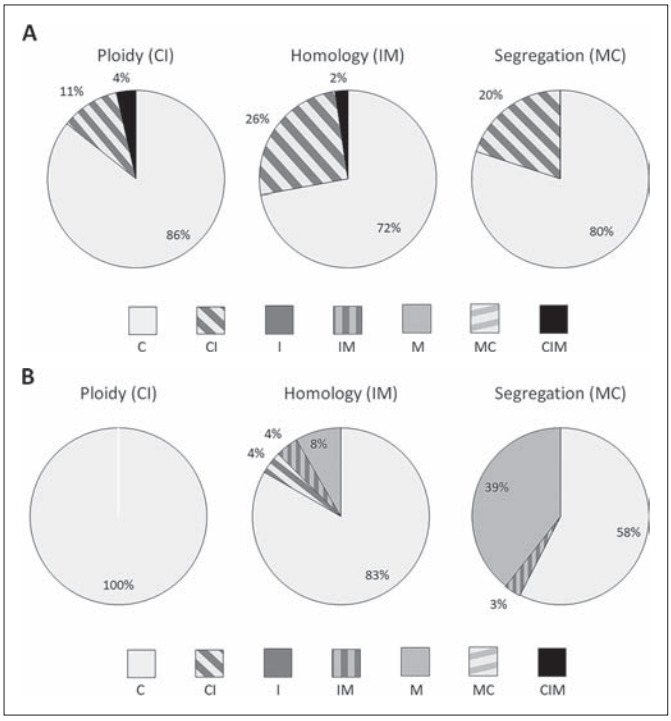

Figure 6. Concepts and level of DNA illustrated for each concept in (**A**) introductory textbooks (61 figures in nine books) and (**B**) mid/upper-level textbooks (51 figures in nine books). For reference, the levels predicted by the DNA Triangle for each conceptual category (M = Molecular, I = Informational, C = Chromosomal, and combinations of these) are indicated with the same shading as in Figure 1.

the meiosis-related figures contained representations of DNA (105 of the 112). The few figures that did not contain a depiction of DNA were life-cycle diagrams showing ploidy changing during the life cycle of an organism (such as humans or ferns) or within a single sex cell undergoing meiosis I and meiosis II. In other words, the overall depiction was at a cellular or organismal level; these figures were excluded from further analysis. Figure 5 illustrates two phenomena: (1) the majority of meiosis-related textbook figures showed only one distinct level of DNA, and (2) the majority of figures (71% of figures from introductory and 67% of figures from mid/upper-level books) focused only on the C level. The M level was almost completely absent in introductory-level textbook figures (only one of 56 figures examined included it), but 28% included I-level representation along with the chromosomes. By contrast, more mid/upper-level textbook figures (30%) illustrated DNA at the M level, while fewer (11%) included the I level.

A deeper analysis of the introductory figures emphasized the unidimensional nature of meiosis-related figures. Regardless of the concept (ploidy, segregation, or homology), DNA was overwhelmingly illustrated at the C level. Representations of DNA at more than one level in a particular figure was an infrequent occurrence. For example, only three of 24 ploidy-related figures illustrated DNA at both the C and I levels (Figure 6A). Representation of DNA at more than one level was also often inappropriate; for example, segregation should be described at the C and M levels (Wright et al., 2017), not the C and I levels.

An even higher percentage of figures from mid/upper-level textbooks illustrated DNA at only one level (Figure 6B). While 13 of 32 figures about segregation revealed the molecular level of DNA, only one segregation-related figure used a combination of levels (M and I). The concept of homology, which is best illustrated at the M and I levels, was illustrated mainly at the C level (20 of 24 figures).

○ Conclusions & Discussion

Evagorou et al. (2015) argued that visual representations are crucial for communication and teaching in science, technology, engineering, and mathematics (STEM) fields. Scientists communicate their experimental results in graphs and charts, create diagrams and models to help explain and ask new questions about natural phenomena, and modify existing diagrams and models to accommodate new information. The combination of strong foundational knowledge plus discipline-specific experiences allows STEM experts to communicate with each other, regardless of the representation utilized. Students, on the other hand, are learners who often lack the foundational knowledge and representational competence needed to decipher the complex visual language of science (e.g., Kozma & Russell, 1997; Trumbo, 1999; Wu & Shah, 2004; Ainsworth, 2006; Schonborn & Anderson, 2006; Wright et al., 2014, 2018).

Representational competence describes the difference between experts and novices in their ability to correctly decipher and use discipline-specific visual representations, such as a diagram of meiosis. While few biology instructors would expect their beginning (or even intermediate) undergraduate students to be able to independently (and correctly) interpret all the figures from a scientific publication, they probably would expect their students to be able to correctly interpret textbook figures. Textbooks, after all, are meant to support student learning and to help students scaffold their knowledge to make productive connections and conclusions. But college biology

textbooks are written and reviewed by biology experts – individuals who already have deep understanding about their discipline and may not realize what students do or do not "see" when looking at textbook diagrams and illustrations. Biologists aim to understand and to articulate how complex and dynamic interactions between and within systems, organisms, tissues, cells, and molecules help explain the natural world. The field of biology spans incredible scales and encompasses a wide range of entities, from those that are small and fast-moving (molecules) to those that are large and slow-moving (ecosystems) (Brownell et al., 2014). It is little wonder, then, that biology learners have difficulties interpreting the visual language of experts.

In this study, we explored the representational landscape of meiosis-related figures in undergraduate biology textbooks to answer the following two research questions: (1) Are important concepts about ploidy, segregation, and homology explicitly illustrated for learners? (2) What levels (C, I, and/or M) are used to represent DNA in meiosis-related figures? Our analysis of more than 100 figures from 18 different college biology textbooks reveals interesting patterns of what content is incorporated into textbook figures and how that content is illustrated for learners. Our findings lead us to conclude that textbook figures may be contributing factors to the persistent confusion that students seem to have about ploidy, homology, and segregation of chromosomes in the context of meiosis.

Depictions of important meiosis-related concepts often neglect to include all the elements outlined by experts as necessary to understanding the process. For example, none of the mid/upper-level textbooks and fewer than half of the introductory textbooks that we examined incorporated figures that explicitly illustrated the important concept that cells become haploid after the first meiotic division. Many figures only labeled cells as haploid after the second meiotic division. Numerous studies have revealed the struggles that typical biology students have when trying to understand the concept of ploidy (Kindfield, 1991; Dikmenli, 2010; Kalas et al., 2013; Newman & Wright, 2017; Wright et al., 2017). For example, students often conflate the structure of chromosomes (one-DNA vs. two-DNA chromosomes) with ploidy (Kindfield, 1991; Smith et al., 2008; Kalas et al., 2013), assuming that one-DNA chromosomes indicate a haploid cell while two-DNA chromosomes indicate a diploid cell. Experts understand that haploid does not simply signify half of the DNA; haploid indicates one complete set of genetic information, while diploid indicates two complete sets of genetic information. Textbook figures do not always point out that chromosomes may contain one or two DNA molecules, leaving students to make the connection on their own. By omitting these (and other) crucial concepts from visual representations of meiosis, textbooks may fail to provide adequate support for student learning.

In addition to examining figures for content, we also analyzed how DNA was represented in the visuals. The DNA Triangle framework was developed to capture how expert biologists describe the concepts of ploidy, homology, and chromosome segregation and for use as a resource in teaching meiosis-related concepts. For example, ploidy is a concept that needs to be examined and explained at the C and I levels of DNA, while the concept of homology incorporates the M and I levels of DNA. The nature of the framework mandates that integration of knowledge at *two levels* of DNA is needed to understand each of the three major concepts of meiosis. A striking finding from this study is how often textbooks use a unidimensional representation of DNA (usually C) to illustrate meiosis concepts. Few figures incorporate multiple levels of representation of DNA, which would presumably clarify important concepts for students. For example, segregation of chromosomes, which depends on proper alignment of homologous pairs of chromosomes through sequence-homology-directed crossing over, is best explained using both the M and C levels. Incredibly, none of the introductory-level textbook figures about segregation illustrated DNA at the M level (nucleotides or nitrogenous base sequences). The mid/upper-level textbooks did incorporate the M level in about 40% of segregation-associated figures; however, they never used both M and C at the same time. This finding is especially problematic because previous work has demonstrated that students have little understanding of chromosome behavior because they fail to incorporate molecular-level reasoning into their mental model of homology (Newman et al., 2012; Wright et al., 2017).

We conclude that students are often left with fundamental gaps in their understanding of meiosis due, in part, to how textbooks fail to support their learning through visual representations. Not only do textbooks typically neglect to point out several essential concepts about meiosis, they also fail to illustrate the complexity of DNA and how it is related to concepts of ploidy, segregation, and homology. Thus, current teaching resources fail to help instructors implement important national recommendations for biology education. For example, *Vision and Change* identifies five core concepts for biological literacy, including "Information Flow, Exchange, and Storage," which clearly encompasses meiosis as a mechanism for transmission of genetic information through generations, and "Structure and Function," defined as the concept that "a structure's physical and chemical characteristics influence its interactions with other structures and therefore its function" (AAAS, 2011; Brownell et al., 2014).

Therefore, it is important that instructors are mindful about all three levels of DNA and help students fill in the gaps by discussing the hidden molecular level explicitly. For example, instructors could create new diagrams that incorporate all levels (see Figure 7). This inclusion of multiple DNA levels may (1) help students recognize what makes homologous chromosomes homologous and (2) probe students to think about an underlying molecular process that could

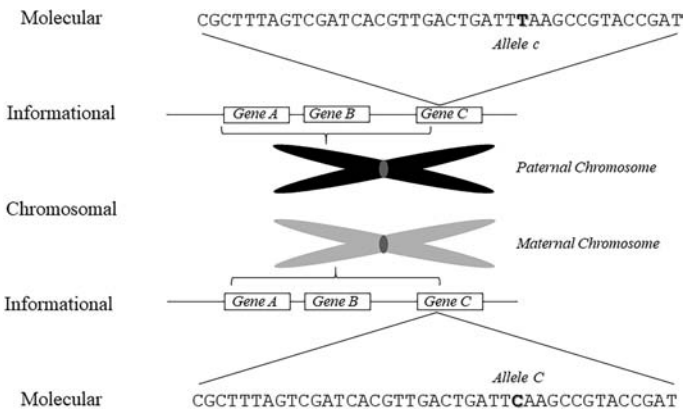

Figure 7. An example illustration of homologous chromosomes that incorporates the Molecular, Informational, and Chromosomal levels.

drive chromosome behavior (strand invasion and crossing over drives proper segregation). As argued by Anderson et al. (2013), to promote student reasoning, one must provide something (such as a figure or illustration) for students to reason with and about, and we argue that typical textbook images are falling short for learners. We have previously described a lesson for teaching meiosis that incorporates the molecular level (Newman & Wright, 2017) and have created an interactive video vignette (Wright et al., 2016) along the same lines for students to review on their own time ("Divide and Conquer," found at https://www.rit.edu/cos/interactive/MINT/ivv-list.php). These ideas are by no means exhaustive; we encourage instructors to be creative and find new ways of connecting the concepts for their students.

○ Acknowledgments

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Appendix: Textbooks Used in the Research Study

Level	Code	Title	Edition	Publisher	Year	Author(s)	Number of Figures
Intro	I-1	*The Living World*	7th	McGraw Hill	2012	George B. Johnson	10
	I-2	*Campbell Biology in Focus*	2nd	Pearson	2016	Lisa Urry, Michael Cain, Steven Wasserman, Peter Minorsky, Jane Reece	7
	I-3	*Principles of Life*	1st	W.H. Freeman	2013	David M. Hillis, David E. Sadava, Richard W. Hill, Mary V. Price	2
	I-4	*Biology*	2nd	McGraw-Hill Education	2010	Robert J. Brooker, Eric P. Widmaier, Linda E. Graham, Peter D. Stiling	5
	I-5	*Biological Science*	6th	Pearson	2016	Scott Freeman, Kim Quillin, Lizabeth Allison, Michael Black, Emily Taylor, Greg Podgorski, Jeff Carmichael	12
	I-6	*Life: The Science of Biology*	9th	W.H. Freeman	2009	David E. Sadava, David M. HIllis, H. Craig Heller, May Berenbaum	5
	I-7	*Biology: How Life Works*	2nd	W.H. Freeman	2016	James Morris, Daniel Hartl, Andrew Knoll, Robert Lue, Melissa Michael, Andrew Berry, Andrew Biewener, Brian Farrell, N. Michele Holbrook	7
	I-8	*Biology*	10th	Cengage Learning	2014	Eldra Solomon, Charles Martin, Diana W. Martin, Linda R. Berg	5
	I-9	*Biology for a Changing World*	1st	W.H. Freeman	2011	Michele Shuster, Janet Vigna, Gunjan Sinha, Matthew Tontonoz	8
Mid/ upper	M-1	*Molecular Biology of the Gene*	6th	Pearson	2007	James D. Watson, Tania A. Baker, Stephen P. Bell, Alexander Gann, Michael Levine, Richard Losick	2
	M-2	*Molecular Biology: Genes to Proteins*	4th	Jones & Bartlett	2011	Burton E. Tropp	1
	M-3	*Lewin's Essential Genes*	2nd	Jones & Bartlett	2010	Benjamin Lewin, Jocelyn E. Krebs	10
	M-4	*Molecular Biology*	2nd	Oxford University Press	2014	Nancy Craig, Rachel Green, Carol Greider, Gisela Storz, Cynthia Wolberger, Orna Cohen-Fix	8

Continued

Level	Code	Title	Edition	Publisher	Year	Author(s)	Number of Figures
	M-5	*Concepts of Genetics*	1st	McGraw-Hill Higher Education	2012	Robert J. Brooker	6
	M-6	*Introduction to Genetics: A Molecular Approach*	1st	Garland Science	2011	Terry A. Brown	8
	M-7	*Essentials of Genetics*	8th	Pearson	2012	William S. Klug, Michael R. Cummings, Charlotte A. Spencer, Michael A. Palladino	3
	M-8	*Human Molecular Genetics*	4th	Garland Science	2012	Tom Strachan, Andrew Read	4
	M-9	*Essential Cell Biology*	3rd	Garland Science	2009	Bruce Alberts, Dennis Bray, Karen Hopkin, Alexander D. Johnson, Julian Lewis, Martin Raff, Keith Roberts, Peter Walter	9