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Enhancing Graphical Literacy in Introductory Biology Students using the Decoding Disciplines Paradigm

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Abstract

In 2022, the Indiana University *Decoding Transitions to College Project* united high school and university instructors to identify bottlenecks in student learning that interfere with transitioning to university. I focused on a challenge experienced by many university students-interpreting graphs. Using Decoding, I developed a graphing checklist outlining steps to interpret graphs, including ***orientation*** (identifying variables), ***pattern recognition*** (describing function shape), and ***interpretation*** (explaining the biological context of graphs). The checklist was implemented in an introductory course in 2022 and 2023. Students were guided through its use during discussions of new graphs. Over 75 % of students found checklists useful for interpreting graphs in several potential contexts. Additionally, significant improvements were observed from pre- to post-semester assessments of graphing skills. This intervention highlights a practical application of Decoding to enhance graphical literacy, a critical competency for scientific success, and demonstrates the effectiveness of translating Decoding into actionable teaching strategies.

Keywords: Transition to university; biology; graphing literacy; Decoding the Disciplines; intervention

Verbesserung der Datenkompetenz von Biologiestudierenden im Grundstudium durch Decoding the Disciplines

Zusammenfassung

Im Jahr 2022 brachte das Projekt „Decoding the Transitions to College" an der Indiana University Lehrkräfte von High Schools und Universitäten zusammen, um Lernhürden zu identifizieren, die den Übergang zur Universität erschweren. Eine zentrale Lernhürde bei Studienanfängern war die Interpretation von Grafiken. Durch Dekodierungsinterviews entwickelte ich eine Checkliste, die in drei Schritte unterteilt ist: **Orientierung** (Identifikation unabhängiger und abhängiger Variablen), **Mustererkennung** (Beschreibung des Graphen) und **Interpretation** (Verknüpfung mit biologischen Konzepten). Diese Checkliste wurde 2022 und 2023 in einem Einführungskurs für Biologie eingesetzt. Studierende wurden angeleitet, neue Grafiken mit der Checkliste zu analysieren. Über 75 % der Studierenden berichteten, dass die Checkliste hilfreich war, um Grafiken zu verstehen und zu interpretieren. Zudem verbesserten sich die Datenkompetenzen in Evaluierungen vor und nach dem Semester

signifikant. Diese Studie zeigt eine erfolgreiche Intervention zur Förderung von Datenkompetenz, einer zentralen Fähigkeit für wissenschaftliches Arbeiten, und verdeutlicht die praktische Anwendung des Dekodierungsansatzes.

Schlüsselwörter: Studieneingangsphase; Biologie; Datenkompetenz; Decoding the Disciplines; Fachdidaktik

1 Introduction

Academically challenging transitions are an inevitable component of the first-year university student experience. As universities continue to recognize this challenge, in tandem with related social and emotional transitions, faculty and staff are becoming increasingly aware of the need to directly address the transition-related obstacles faced by our incoming students. As an instructor of a large-enrollment (60 to 300 students, depending on the section) introductory biology course at a large university in the United States, I have consistently encountered a number of foundational skills with which my students struggle, particularly those students that are new to collegiate-level academic expectations. Indiana University is a state school in Bloomington, Indiana, with a student body composed of over 69,000 undergraduate students and over 20,000 graduate students. The biology major boasts over 1000 undergraduates spanning first- to fourth-year students.

My introductory course for biology majors (Biology L111 Foundations of Biology: Diversity, Evolution, and Ecology; hereafter, "Biology L111") introduces these three sub-fields of organismal-level biology using a quantitative and analytical approach to course content. Incoming students are expected, but not required, to be well versed in at least algebra and have reached an intermediate level of graphical literacy. However, even prior to the COVID-19 pandemic, I was consistently confronted with the fact that my students were not equitably equipped with these skills. This variation in skill set is likely related to the lack of high school or university prerequisites for Biology L111. As long as the student has passed one general biology course in high school, they can enroll in Biology L111.

Undergraduates often struggle to understand the graphs presented to them during course lectures (Bowen & Roth, 1998). Students can face several difficulties when interpreting a graph; these can involve issues related to the format of the graph or the level/type of prior knowledge of graph content (Shah & Hoefner, 2002) as well as becoming intimidated by the amount of information conveyed on the graph (Glazer, 2011).

Based on my own survey data, over 70 % of my introductory biology students are interested in graduate school or medical professions. Understanding, interpreting, and creating visual representations of data, information, or models (i. e., data literacy) are crucial skills necessary for every career in science, technology, engineering, and mathematics (STEM) as well as all medical professions.

To succeed in their chosen field, as a student and as a professional, one must immerse oneself in the relevant primary literature, most of which will contain graphical representations of experimental results. Every scientist will eventually need to interpret those graphs to better inform their own research, and they will certainly need to produce clear representations of their own data. Every physician will not only need to interpret graphs that present results of clinical trials, but they will also have to understand and explain graphs of test results to their patients. If a student takes Biology L111 in their first semester of university, the class represents the first step toward these careers, and if poor graphical literacy goes unchecked, students may struggle in upper-level biology, chemistry, and physics classes, all of which are requirements of the biology major at most universities; they may in turn exhibit poor performance on entrance exams; and in some cases, their intended career path may become unattainable.

Graphs can be encountered in other facets of our lives outside of academia or professions. Hence, everyone benefits from a basic understanding of orienting oneself to a graph. As consumers of media, we must be able to recognize when the scale or units of graphs have been modified to misrepresent information, perhaps to show a difference when one does not actually exist. A founda-

tional level of graphical literacy is an essential component of critical thinking and differentiating fact from fiction.

Based on the myriad of ways in which individuals encounter data, information, and graphs, researchers have begun to recognize the need for educational interventions to improve data literacy (e. g., Glazer, 2011; Gebre, 2018). Several such interventions have recently been put forth for use in the classroom (e. g., Gardner et al., 2024).

In my classroom, I observed that the gaps in my students' understanding of graphs were particularly wide in our discussions of ecological models. Students are typically quite surprised that ecology, the study of interactions among organisms, can be both quantitative and analytical, and they frequently have difficulty interpreting the relevant graphical representations of models of ecological processes (e. g., D'Avanzo, 2006). This struggle was most obvious when analyzing the results of summative assessments such as in-person, closed-note exams. Yet, similar results were also observed for online, open-note exams during and after the pandemic. In particular, I noted low performance on exam questions that involved analysis of graphically represented course concepts, particularly topics related to population growth models. Specifically, only 20 % and 40 % of students were able to correctly answer a relatively difficult question on paper and online exams, respectively. This question of interest was especially challenging because it required students to analyze the graph provided yet answer a question about a related graph that was not shown. The question was meant to assess whether students possessed a deep understanding of the population growth model represented in the graph. The low scores on these types of complex graphing questions may be related to the propensity of students to view graphs as simply a picture rather than an abstract representation of a scientific concept or phenomena (e. g., Hadjidemetriou & Williams, 2002).

All too often, students who encounter challenges early in a course will respond to their frustration by giving up and investing increasingly less effort into the course, the ultimate reasons for which can vary from individual identity triggers (Lund Dean & Jolly, 2012) to science anxiety (Rozgonjuk et al., 2024) to the culture fostered in the classroom by the instructor (Muenks et al., 2024). Ultimately, a fraction of students can be "lost," either from the class or even from the major. Such attrition is often measured using "DFW" rates, which account for all students who have received failing grades of "D" or "F" or who have withdrawn (W) from the course. During the spring semester of 2021 (prior to the work described herein), the DFW rate for my Biology L111 course was 22.3 %. Students who comprise this statistic inevitably feel a sense of failure and may even be placed on academic probation, which can affect scholarship eligibility. These consequences may further impede the pursuit of their career goals, both personally and economically, and can sometimes lead to leaving university altogether.

It was with four years' worth of frustrating assessment results that I began to work with the Decoding the Disciplines community at my university. I was invited to participate in the *Decoding Transitions to College Project* during the summer of 2022. As a Fellow in this workshop, I worked with university colleagues in biology and Spanish as well as high school teachers in both disciplines to apply the Decoding the Disciplines paradigm to bottlenecks (i. e., obstacles) in student learning that we jointly identified as being most common to our respective groups of students. This paradigm was developed by a group of faculty beginning in the 1990s as they collectively realized that their current methods were not adequately teaching students the skills they needed to succeed in their respective fields of study (Pace & Middendorf, 2004; Middendorf & Shopkow, 2017; Pace, 2017; Pace, 2021). Since its development, the paradigm has been introduced to higher educational universities and facilities around the world. By the 2020s, when the above-mentioned issues involving the transition from high school to college were gaining attention within higher education circles, one of the original developers of the paradigm, along with the principal of the online Indiana University High School, began to explore the applicability of Decoding the Disciplines within K-12 (primary and secondary education) classrooms. These initial explorations highlighted how well middle and high school teachers responded to applications of Decoding in their classrooms, and hence a faculty member and

administrator launched the first *Decoding Transitions to College Project (*Itow et al. *2025)* to bring together high school and university instructors to strategically and collaboratively address bottlenecks in student learning that were impeding a smooth transition from high school to college.

2 Methods

2.1 The Decoding Experience

As a participant in the *Decoding Transitions to College Project*, I engaged in the first several steps of the Decoding process, namely identifying a bottleneck in student learning, elucidating the steps necessary to get past the bottleneck, and creating ways to model these steps for my students. I focused on the bottleneck of successfully answering the population growth assessment question described above. While this was a very specific bottleneck, it served as a proxy for an advanced level of graphical literacy. Therefore, any pedagogical strategies resulting from the Decoding process would target general graphing skills of university students and not one specific assessment question. In Decoding, the steps required to overcome a bottleneck are often revealed through an intensive hour-long interview by two colleagues. During my decoding interview, I was truly shocked by how many steps would be required to correctly answer the assessment question. In the moment, I realized that I was not providing nearly enough preparation or structure for my students to successful interact with graphs. The post-interview process involved reflecting on the interview transcript to pinpoint the specific steps I had discussed to get through the bottleneck. I ultimately identified at least 11 steps necessary to correctly answer the assessment question.

2.2 The Graphing Checklist

Mirroring the steps identified during my interview, I developed a "graphing checklist" that would provide a generalizable and stepwise strategy for interacting with a new graph and its relevant biological context. I was able to categorize these steps into three fundamental skills needed to successfully interact with a graph: ***orientation*** (e. g., identifying independent and dependent variables), ***pattern recognition*** (e. g., describing the shape of the function), and ***interpretation*** (articulating *why* the function was changing in this way and connecting that information to the relevant biological concepts; Table 1). Notably, Pelnar and Cameron (2021), who examined the mental processes used by undergraduate psychology students when interpreting graphs, independently identified the same three categories of processes (orientation, pattern recognition, and interpretation) accomplished by students when encountering a graphical representation of data.

Table 1: Graphing checklist questions, categorized as orientation, pattern recognition, and interpretation. Questions were modified slightly for each checklist to address the relevant components of each graph.

Category	Question
Orientation	What is the independent variable?
	What is the dependent variable(s)?
	What are scale and units on the axes?
Pattern Recognition	What is the shape of the graph(s)?
	If there is more than one graph, what variable does each one represent?
	How is the graph of the dependent variable(s) (y-axis) changing as you increase along the x-axis?
	Write out this relationship.
Interpretation	Why are the graphs changing in this way?
	Are there any important points to note and how do they relate to the course concepts?
	Have we discussed any graphs related to this one?

2.3 Pre-Course Surveys of Biology L111 Students

2.3.1 Assessing Prior Course Experience

During the first week of the semester and prior to introducing the graphing checklist, I surveyed my students to determine the extent of their mathematics and biology background. The surveys were administered via the Canvas Learning Management System. The students were asked to indicate the highest level of biology completed prior to enrolling in Biology L111. Their options included both secondary school courses (Advanced Placement [AP] or dual-credit Biology, General Biology, Honors Biology, or Honors Biology in 8^{th} grade), university courses (Biology L112 Foundations of Biology: Biological Mechanisms or 200-level Biology or higher), or "other." In addition, the students were asked to indicate their highest level of mathematics prior to enrolling in Biology L111; the options included both secondary school courses (Algebra II, Pre-calculus, Finite Math, Calculus I, Calculus II, AP Calculus AB, AP Calculus BC), university courses (College-level Calculus I, College-level Calculus II, or a more advanced course than university Calculus II), or "other."

2.3.2 Assessing Incoming Graphing Skills

Another key step in the Decoding the Disciplines paradigm is to assess the effectiveness of the intervention. Thus, I evaluated the effectiveness of the graphing checklists using identical pre- and post-semester assessments of students' abilities to successfully answer questions related to graphical orientation, pattern recognition, and interpretation. Scores for orientation, pattern recognition, and interpretation skills were averages of five, six, and five questions, respectively. The questions on these assessments were nearly identical to those in Table 1.

The graphing pre- and post-assessments also asked students to rate their ability to read and interpret graphs at the beginning and end of the semester on a scale of 1 to 5 (ranging from very weak to very strong). Such self-confidence ratings have been shown to be correlated with actual performance, permitting such ratings to serve as a proxy for student metacognition (Kleitman & Stankov, 2007).

2.4 Application of the Checklist

The graphing checklist was implemented during the fall semesters of 2022 and 2023 in Biology L111. In 2022, I taught two sections of L111, with 130 and 220 students, while in 2023, I taught one section of 148 students. During both years, approximately 70 % of these students were in their very first semester of undergraduate education.

Throughout the semester, the graphing checklist was provided whenever a new graph was presented in class. These checklists were embedded in a "note template" that followed along with my slides, allowing students to fill in notes as we progressed through the lecture. A total of 19 checklists, each modified slightly to address the specific graph, were provided throughout the 16-week semester. These graphs provided visual representations of concepts involving population genetics, genetic drift, mutation-selection balance, population growth, and resource competition. They varied from simple to complex graphs, as defined by Glazer (2011). Simple graphs present only one or two variables along two axes (x and y). Graphs of medium complexity may include more than two variables (e. g., the graph of the Hardy-Weinberg principle), and complex graphs can involve interactions between these variables (e. g., reaction norms) (Glazer, 2011).

During class, students were guided through the checklist by following my slides and lecture to ensure that everyone present would have a written record of the correct interpretation of the graph and its relevance to course content. For the first several checklists, I was careful to model in my slides the level of detail required for each question. As the semester progressed, I gradually began to solicit student input during lecture, prompting them to volunteer their interpretations of the graph. This approach allowed me to informally assess whether students were learning to detect and articulate the connection between the patterns depicted in the graph and the biological concept at hand. The students kept their checklists; I did not assess the checklists themselves, as they were meant to be a resource for the students to possess and use in whichever ways they found helpful.

2.5 Mid-Semester Assessments of Perceived Effectiveness of Graphing Checklists

In both years, students were surveyed via an optional Canvas survey (worth 1 point of extra credit) about their perceived usefulness of the checklists. In 2022, the survey was administered during the sixth week of the 16-week semester, while in 2023, the survey was administered during the tenth week of the semester. In both years, students were provided with eight ways in which the checklist could be helpful:

- orienting to only the most challenging graphs in the class
- interpreting and understanding only the most challenging graphs in the class
- orienting to all of the graphs in the class
- interpreting and understanding all of the graphs in the class
- completing homework problem sets
- completing quiz questions
- interpreting graphs in other classes
- interpreting graphs in scientific papers
- I did not find them helpful at all

Students were prompted to check all options that applied to their experience.

3 Results & Discussion

3.1 Prior Course Experience

The variation in preparedness was eye-opening; less than half the students (42 % in 2022 and 46 % in 2023) were adequately prepared for the course, which I consider as having at least taken Advanced Placement or dual-credit Biology in high school. The remainder of students had only taken a general or honors biology course anywhere from 2 to 4 years prior to starting college. Moreover, the first-year students in 2023 likely took their first biology class online, as biology is typically offered during the second year of high school. A higher proportion of students were prepared in terms of background in mathematics, with 82 % of students in both years having completed at least pre-calculus. The incoming biology skill set of Biology L111 was not well aligned with their post-undergraduate goals, with 70 % (2022) and 73 % (2023) of students indicating that they planned to attend either professional (medical, dental, veterinary, or nursing) school or graduate school. Based on my extensive experience working with Indiana high school biology instructors through our university's dual-credit program, such variation in collegiate preparedness is likely related to the socio-economic disparities that exist among high schools in our region. Private high schools and suburban high schools in economically wealthy areas tend to have more resources for teaching staff and are therefore able to offer more advanced science classes. More urban and rural high schools are under-resourced and may only have one course offering each of biology, chemistry, and physics. Such disparities in school funding are compounded by correlations with poverty levels within the community.

3.2 Pre- and Post-Semester Graphing Assessments

In 2022, students exhibited marginal improvements in the questions related to orientation (+3 %) and interpretation (+4 %); however, in 2023, improvements were substantially larger, with increases of 11 % and 12 %, respectively. In 2022, overall scores were significantly higher for the post-assessment (88.3 %) compared to the pre-assessment (85.7 %; paired t-test: $t = -3.57$, $df = 276$, $P < 0.001$), and the improvement was even larger in 2023 (91.5 % versus 83.3 %; $t = -8.47$, $df = 126$, $P < 0.0001$). Scores for questions related to pattern recognition only exhibited marginal changes, if any, between pre- and post-assignments in both years (0 % in 2022 and + 4 % in 2023). Overall, after 16 weeks of class, students exhibited substantial improvement, especially in 2023, in orienting themselves to the variables and axes of the graphs as well as interpreting *why* the data were changing as represented and how to interpret these patterns in terms of course concepts.

The larger improvements in 2023 compared to 2022 may be related to the substantially lower number of students I was teaching in the former ($n = 148$) versus the latter ($n = 350$). In 2023, my teaching efforts were not divided between two large lecture sections. Moreover, in 2023, I purposely reminded students on a regular basis *why* we were using the graphing checklists and how, even if they were doing well in the course, the checklists were helpful for others who might not be so fortunate. In fact, I presented the survey data related to biology background during class, to highlight the variation in preparedness. This effort at student "buy-in" was in response to a substantial proportion of university course evaluation comments in 2022 that indicated that the students found the checklists to be tedious. Many of these students implied that the graphing checklists were "busy work" that was below their skill level. Hence, in 2023, I chose to appeal to their altruism by pointing out the disparities among their peers in preparedness for the course.

The graphing pre- and post-assessment questions that asked students to rate their ability to read and interpret graphs at the beginning and end of the semester revealed several notable results. The students rated themselves on the post-assessment without access to their rating on the pre-assessment. In both years, students varied greatly in how they rated themselves before and after the course (Table 2). In both years, the percentage of students rating themselves as "very strong" increased by the end of the course (by 5 % in 2022 and by 14.1 % in 2023; Table 2). Moreover, 25.7 % of the 2022 students increased their overall rating by the end of the course, while 35.4 % of 2023 students increased their rating. Interestingly, in both years, over 50 % of students did not change their rating, which supports previously reported correlations between ratings and performance (Kleitman & Stankov, 2007).

Table 2: Percentages of students rating their "ability to read and intepret graphs" on a scale of 1 to 5 on the pre- and post-semester graphing assessment. Ratings were 1 (very weak), 2 (moderately weak), 3 (moderate), 4 (somewhat strong), 5 (very strong). Included are data for the number of students for whom I have scores for both assessments in each year as well as the percentage of students whose scores increased, decreased, or did not change from the pre-semester to the post-semester assessment.

	2022		2023	
	Pre-assessment percentage	Post-assessment percentage	Pre-assessment percentage	Post-assessment percentage
Rating				
1	0.4	0.7	0	0
2	2.9	5.1	7.1	3.1
3	27.9	25	29.9	26.8
4	51.1	46.4	48	40.9
5	17.8	22.8	15	29.1
Changes in ratings				
Number of students		276		127
Increased (%)		25.7		35.4
Decreased (%)		23.2		13.4
Did not change (%)		51.1		51.2

Many students who rated themselves highly along this scale in the post-assessment cited the graphing checklists as having helped to improve their abilities to understand and interpret graphs. For example, in 2022, a student who increased their rating from 3 to 4 reported:

> "*After this class, I definitely feel more confident in reading graphs and being able to explain them to someone else. I think the graphing checklists helped me a ton and I really appreciate them.*"

Similarly, in 2023, a student who increased their rating from 4 to 5 stated:

> "*After using graphs throughout the entire semester in this class I feel it has really strengthened my ability to read and interpret graphs in a way I can correlate* [sic] *to my other classes. I think what helped me the most was the graphing checklists as it forced me to really think through what the graphs were saying and how to interpret them.*"

Interestingly, in 2022, a student who decreased their rating from 3 to 2 said this at the end of the course:

> *"I thought I was decent at interpreting graphs until I took this class. There's a lot that goes into interpreting graphs and histograms."*

3.3 Mid-Semester Assessments of the Effectiveness of Graphing Checklists

In 2022, 78.5 % of all students who completed the mid-semester survey (n = 297) found the checklists helpful for at least one of the eight possible ways listed in the "Methods." For example, 42 % of students found the checklists helpful in completing homework assignments, and 38 % found the checklist helpful in answering quiz questions. In 2023, this survey was administered later in the semester, and results indicated that 93.9 % of all students surveyed (n = 115) found the checklists helpful. This group of students found the checklist most helpful for completing for interpreting and understanding all graphs in the class (31 % of respondents), while 27 % found them helpful for interpreting and understanding only the most challenging graphs in class. Similar to the graphing assessment scores described above, the increase in overall perceived utility of the checklists in 2023 (93.9 % versus 78.5 %) may be due in part to the student "buy-in" effort and the fact that the 2023 students had an additional 4 weeks of checklists by the time they were surveyed compared to the 2022 students.

3.4 Other Indicators

As described earlier, universities often use DFW rates as a metric of student success in a given course. High rates are generally viewed as problematic in terms of instructor grading or a mismatch in the level (100, 200, 300, or 400) of the course and difficulty of course content. In 2022, my two sections of L111 exhibited a lower DFW rate (21.9 %) compared to 2021 (22.3 %). The DFW rate dropped even further for my section in 2023 (16.4 %).

In terms of the exam question that inspired the use of Decoding the Disciplines to dissect the steps required to answer the question correctly, student performance increased from 40 % in 2021 to 48 % in 2022. In 2023, the question was modified to be even more challenging (i. e., the question had more than one correct answer), yet 43 % of students were able to answer it correctly.

4 Conclusions

In his review of the literature on the interpretation of graphs, Glazer (2011) emphasizes the need for explicit instruction on interpreting graphs in introductory university science classes as well as research that monitors the effectiveness of specific interventions to improve graphing skills. The present study achieves both goals.

A substantial proportion of my Biology L111 students completed my class with enhanced abilities to read and interpret visual representations of course concepts. Needless to say, implementation of the graphing checklists was not the only variable that changed among years; thus, one can only point to a potential correlation (versus a causative relationship) between the use of the checklist and graphing assessment scores, student self-ratings, course DFW rates, and exam performance on graphing questions. That said, as long as students continue to self-report that the graphing checklists are directly related to their perceived improvements, I will consider the approach a success.

The present work provides a tangible and valuable example of the power of the Decoding the Disciplines paradigm. A direct line can be drawn from decoding the bottleneck of students' ability to interpret graphs to quantifiable improvements in student success in this introductory biology course. Student populations in both years were comprised of approximately 70 % first-year students who varied widely in their level of preparation for college-level biology. One can say with reasonable confidence that by the end of the course, those gaps had been at least marginally closed, thereby aiding in the transition of these students from high school to university. Individuals and groups using Decoding the Disciplines continue to successfully translate its power into concrete methods for enhancing students' higher-level learning.

Notes

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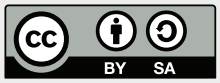

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