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Article

WormClassroom.org: An Inquiry-rich Educational Web Portal for Research Resources of *Caenorhabditis elegans*

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The utilization of biology research resources, coupled with a "learning by inquiry" approach, has great potential to aid students in gaining an understanding of fundamental biological principles. To help realize this potential, we have developed a Web portal for undergraduate biology education, WormClassroom.org, based on current research resources of a model research organism, *Caenorhabditis elegans*. This portal is intended to serve as a resource gateway for students to learn biological concepts using *C. elegans* research material. The driving forces behind the WormClassroom website were the strengths of *C. elegans* as a teaching organism, getting researchers and educators to work together to develop instructional materials, and the 3 P's (problem posing, problem solving, and peer persuasion) approach for inquiry learning. Iterative assessment is an important aspect of the WormClassroom site development because it not only ensures that content is up-to-date and accurate, but also verifies that it does, in fact, aid student learning. A primary assessment was performed to refine the WormClassroom website utilizing undergraduate biology students and nonstudent experts such as *C. elegans* researchers; results and comments were used for site improvement. We are actively encouraging continued resource contributions from the *C. elegans* research and education community for the further development of WormClassroom.

INTRODUCTION

Current education reform efforts have called for a balance of teaching and research in the university environment (Chalupa, 1999; Cech, 2003). These calls signify the recognition of the disproportionate emphasis on research over teaching at many major universities and the need to give a higher priority to undergraduate education. There have been several significant efforts to try to achieve a better balance between research and teaching in academia (Avila, 2003; Cech, 2003; Wood and Gentile, 2003). One of the most prominent is the funding of teacher-scholars by the Howard Hughes Medical Institute (HHMI) to develop new modes of science teaching (HHMI, 2002, 2006). The funding of HHMI teacher-scholars was a significant new venture for a research foundation best known for supporting excellence in research. One of the early innovations of this HHMI teacher-scholar effort is the "incubator" concept developed by Handelsman *et al.* (2004). In the article "scientific teaching," Handelsman *et al.* (2004) have urged universities to promote education reform by supporting the development of incubators ". . . where researchers incorporate research results into teaching materials with guidance from experts in pedagogy." This incubator concept highlights three important aspects of current reform efforts: 1) the need for researchers and educators to work together, 2) the utilization of research resources to promote student learning, and 3) the training of future faculty to develop teaching materials that take student learning into account. This approach is intriguing because education reform efforts need attention from both educators and science researchers. Bringing together researchers and educators has the key advantage that the compiled resources are accurate, up-to-date, and student-learning driven. Finally, there is the additional benefit that research data are generated from actual research lab problems and investigations that are of interest to students.

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We were excited by the incubator concept because, like many research groups, we had informally applied research resources from our own lab to biology education. Our utilization of research resources to education was driven by the recognition that students learn better by active engagement in the process of scientific inquiry (National Research Council [NRC], 2000). In particular, we were influenced by the 3 P's (problem posing, problem solving, and peer persuasion) approach developed by BioQUEST (2000) for learning biology, in which the 3 P's are used to engage students in authentic biological inquiry (Peterson and Jungck, 1988). Guided by the 3 P's approach for inquiry learning, we, a group of researchers and educators, began to develop instructional materials (IMs) that utilize resources of a model organism, *Caenorhabditis elegans* (*C. elegans*).

C. elegans (often referred to as "the worm"), although relatively primitive, shares many biological properties with more advanced organisms, including humans. It has proved to be a useful model research organism because of its genetic homology with higher organisms as well as similarities in morphological traits and development strategies. Research on *C. elegans* has shed light on many fundamental biological phenomena, such as cell fate determination and programmed cell death, that have important implications for human health.

Despite its popularity in research, the use of *C. elegans* and its research resources in the classroom are not widespread. One obstacle to its educational use may be that these research resources are primarily targeted for professionals in the research community, making it difficult for those outside the field to utilize them in undergraduate education. As a result, the use of *C. elegans* in the classroom is often limited to instructors who have *C. elegans* research backgrounds. Rectifying this lack of accessibility requires that researchers and educators work together in order to make the resources available for educational purposes.

Arising initially out of a desire within our laboratory to utilize research resources related to *C. elegans* cell division for educational purposes, we developed an education website, WormClassroom (http://www.WormClassroom.org). Through collaborations with other *C. elegans* labs, we came to realize the potential for a *C. elegans* community educational Web portal that could organize and link to research resources for inquiry-based learning.

In this article, we will describe the following: I. *C. elegans*—the organism and its professional community: 1) *C. elegans* as a valuable teaching organism and 2) educators and *C. elegans* professionals who have been involved in our efforts for making the WormClassroom site possible. II. The educational portal—the WormClassroom website: 1) current status of the WormClassroom website, 2) development of IMs utilizing the 3 P's approach, 3) example utilizations for inquiry learning, and 4) assessment of the WormClassroom site for its improvement and future *C. elegans* research resource applications to education.

C. elegans: THE ORGANISM AND ITS PROFESSIONAL COMMUNITY

C. elegans *as a Valuable Teaching Organism*

Caenorhabditis elegans (*Caeno*, recent; *rhabditis*, rod; *elegans*, nice) was first introduced by Sydney Brenner as a model organism for pursuing research in developmental biology and neurology in the 1960s. It is a free-living, nonparasitic soil nematode that can be safely used in the laboratory and is common around the world (Donald, 1997). It is small (~1 mm in length), transparent, and easily manipulated and observed; feeds on bacteria (such as *Escherichia coli*); and can be easily and cheaply cultivated in large numbers (10,000 worms per Petri dish) in the laboratory. It has a short life cycle: one generation takes ~3 d. Its life span is about 2–3 wk under suitable living conditions. What is unique to this organism is that wild-type individuals contain a constant 959 cells. The position of these cells is also constant. Because the worm is transparent, it is possible to track cells and follow cell lineages. The complete cell lineage of *C. elegans* was completed in the 1980s by John Sulston. Moreover, it was the first multicellular organism to have its genome completely sequenced (December 1998). This combination of attributes makes *C. elegans* an ideal tool for research.

The use of this small worm in educational settings has grown in recent years. At the 15th International *C. elegans* Meeting, held at the University of California at Los Angeles in 2005, 14 teaching posters were presented, as well as an education panel focusing on the use of *C. elegans* in higher education. *C. elegans* is used in various disciplines to convey fundamental biological concepts. For instance, it is a good organism for students to observe animal behavior and on which to perform phenotype analyses. In addition, the available research resources, such as the stock of mutants, the complete genome sequence, and various genetic research tools, make *C. elegans* a valuable tool in classrooms. *C. elegans* is a well-established model system with a wealth of research resources that can be utilized in teaching biology.

Educators and C. elegans *Professionals*

The WormClassroom site owes its development to many *C. elegans* experts and educators. To date, most of the contributions have originated from the University of Wisconsin (UW)-Madison *C. elegans* community. However, there have been several key contributions from researchers worldwide. A comprehensive list of current contributors is available at the WormClassroom website (http://www.wormclassroom.org/contacts.html).

THE EDUCATIONAL PORTAL: THE WormClassroom WEBSITE

Our goal for WormClassroom is to make *C. elegans* research resources accessible in a form that can be used to develop inquiry-oriented instruction. In developing a Web portal of research data, no matter whether the content is a database, such as WormBase.org, or collection of data, such as CellsAlive.org, the organization of the resources is the primary challenge. The resources need to be organized in a way that provides students an appreciation of *C. elegans* and associated scientific research while allowing them to inquire using these resources to gain an understanding of basic scientific concepts.

Current Status of the WormClassroom Website

Resource Organization of the WormClassroom Site. The *C. elegans* researchers often identify themselves as members of other research communities. As a result, in the WormClassroom site, we categorized the *C. elegans* resources into five groupings: Cell Biology, Developmental Biology, Genetics, Evolutionary Biology, and Neuroscience. Figure 1 shows the homepage of the WormClassroom. This main entry page serves to present the resources of *C. elegans*, as well as additional materials to aid in the use of these resources. These additional materials include information on the development of the site, news items, a search query, and a guide to assist in the effective use of WormClassroom.

For *C. elegans* resources, the site includes the following sections: 1) About *C. elegans*: background and why it is studied; 2) *C. elegans* research: research data organized by the five discipline groupings identified above; 3) *C. elegans* people: listing of *C. elegans* researchers with contact information; 4) *C. elegans* education: teaching protocols, materials, and learning modules; and 5) More resources: relevant external resources organized and made accessible for learning.

Resource Organization within the Associated Disciplines. For resources within each research field, we apply the "consensus practice" developed by Kitcher (1984, 1993) for further resource organization. Frequently, in a research field, scientists have their own ways of solving problems and their own languages to assist their communication during inquiry. Kitcher described this practice as a "consensus practice" among investigators in the same research community who share the following: 1) a common language, 2) a set of questions taken to be most appropriate, 3) defined patterns of reasoning, and 4) a set of experimental procedures and guidelines for investigation. The concept of "consensus practice" provides a good set of guidelines for us to organize resources within a given discipline. This resource organization is used to familiarize students with *C. elegans*–based inquiry within a particular research field and encourages students to think like researchers. As stated, resources of *C. elegans* are sorted into five major research disciplines. For the Web interface for each of these five disciplines, we have organized the materials and information in a similar manner to generate the same look and feel between each category. To explain further, we will use the Cell Biology category as an example (see Figure 2, the entry page for Cell Biology). To introduce students to Cell Biology inquiry that utilizes *C. elegans*, we provide a set of questions often pursued by researchers in the discipline (Cell Biology Research Questions). Examples of research are illustrated, providing students with an in-depth look at *C. elegans* research in the field of Cell Biology (Example Research). A variety of Cell Biology research using *C. elegans* is also identified and made accessible for students so that they might understand the breadth of *C. elegans* research in this field. Research tools and methodologies used in *C. elegans* research are identified and described in order to provide users with an overview of the process of conducting cell biology research utilizing *C. elegans* (Cell Biology Research: Tools, Procedures, and Methodologies). Associated teaching materials (IMs) are also available for each research category. Terminology used in the field of Cell Biology using *C. elegans* is identified and defined (Glossary).

The primary intent of WormClassroom is to serve as a gateway to *C. elegans* research data for inquiry-based learning. Resources in the site, including links to external resources such as WormBase.org, WormAtlas.org, and WormBook.org are made accessible in a format that can serve as the basis for classroom instruction development to allow student inquiry.

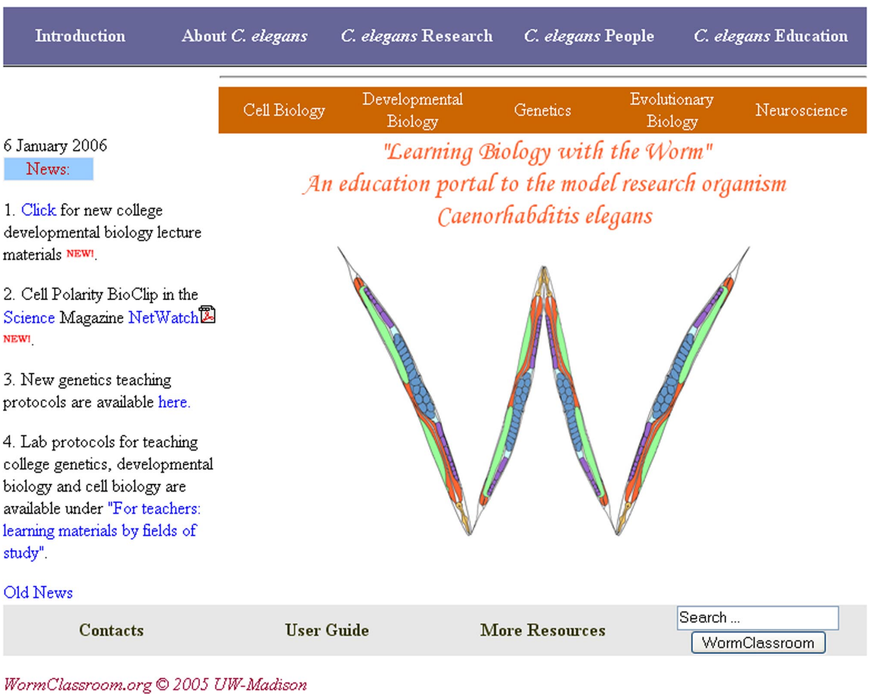

Figure 1. Home page of WormClassroom website.

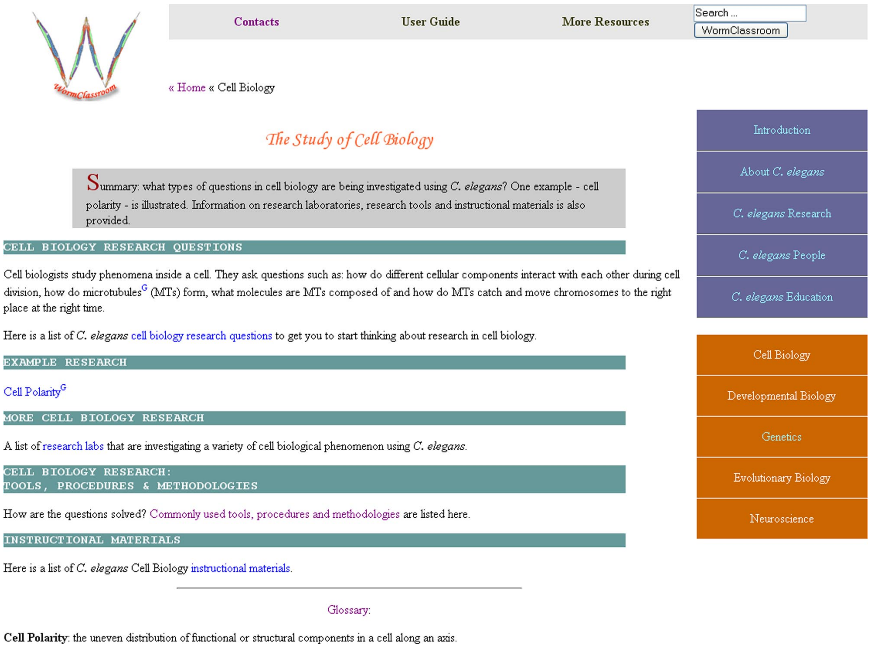

Figure 2. Entry page to the *C. elegans* research in cell biology.

IMs for the WormClassroom Website

We sought ways to develop IMs that combined input from both researchers and educators. Our work was primarily guided by the 3 P's approach (Peterson and Jungck, 1988). The concept of the 3 P's for learning biology was first proposed in the 1980s. To develop materials for inquiry learning, the 3 P's approach guided us in creating a question space to assist students in learning how to pose problems while simultaneously supplying resources and tools for student investigation.

Below, we describe the development of IMs that are available at the WormClassroom website. These materials include 1) raw research data such as movies of embryo development, 2) animations to illustrate key biological phenomena, and 3) learning modules with specific learning objectives identified.

Raw Research Data. The raw research data includes resources such as images, movies, sequence data of proteins, RNA transcripts, and genes. Because these data resources are traditionally targeted to researchers, a certain amount of background material is needed to help engage students in inquiry learning. To create a question space in which students may pose problems using these data, we provide as much background information as possible, without interpreting the data and the phenomenon shown. For instance, a movie (Figure 3, left image) that depicts a fertilized egg developing into a worm provides students the opportunity to inquire into many fundamental phenomena such as embryonic cleavage. Background resources accompanying this movie include information such as 1) the technical methods utilized for the movie acquisition, such as the type of microscopy used, and 2) data on key attributes of the embryo, such as its dimensions. Annotated images of the embryo are also provided with major components of the embryo labeled (see Figure 3, right image).

Animations. Animations are valuable educational tools because they depict phenomena that cannot be easily understood using still images (Stith, 2004). We utilized a type of

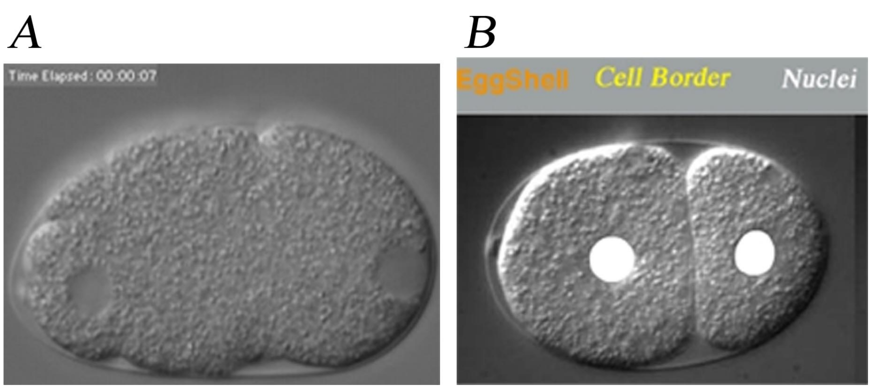

Figure 3. Raw research data and its accompanied background resource. (A) A differential interference contrast (DIC) movie of *C. elegans* embryo development (image courtesy of Ananth Badrinath, University of Southern California). (B) An annotated image of a two-cell embryo with nuclei labeled. The dimension of the embryo is 55 × 30 μm.

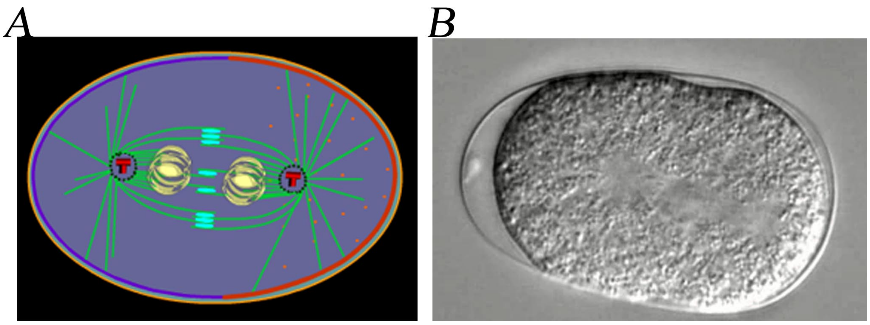

Figure 4. Movies of cell polarity animation with a matching real embryo development. (A) Animation of cell polarization in *C. elegans* early embryonic development. (B) DIC movie of a *C. elegans* embryonic development (image courtesy of Haining Zhang, University of Wisconsin-Madison).

animation called a "BioClip" (BioClips, 2004) that combines animations of a biological process with appropriate background materials. BioClips can be used to create a question space for student observation and for posing problems. For instance, we developed a cell polarity BioClip that illustrates cell polarization of a *C. elegans* embryo from a one- to four-cell stage (Lu *et al.*, 2007). For the development of the BioClip animation, we were guided by current research data of cell polarization in *C. elegans*. In the animation, we illustrate the phenomenon without imposing any current scientific interpretations to this animation, such as illustrating the interaction between microtubules and the membrane cortex without depicting the force between them. The animation is displayed next to a movie obtained with videomicroscopy (see Figure 4). Both movies are then made available online for student observation and problem posing. Examples of the types of problems students might pose are discussed in the section, "Utilization of WormClassroom Website for Inquiry Learning."

Learning Modules. We define a learning module as an interactive and self-contained learning environment complete with its own learning objectives that is accessible online. The raw research data and corresponding animations can be integrated into the learning module. Each learning module starts with biological phenomena to serve as a question space and induce student curiosity. Background resources and materials, as well as tools and additional resources, are made available to aid student investigation. For instance, the learning module Cell Lineage allows students to track a cell's development by tracing its predecessors and successors. Students can also investigate the spatial relationship (e.g., left/right) of cells during an embryo's development (http://www.wormclassroom.org/modules/celllineage/). This module opens with a flash animation illustrating the development from a zygote to a complete worm, with its cell types labeled. Along with the development, lines of different colors represent development of different cell types that ultimately form a functional worm. By observing this animation, students may wonder "what happens at branch points that generate daughter cells with different colors?" As shown in Figure 5, the developmental potential of cells in *C. elegans* is determined early in development (two-cell stage). The module also includes background information, questions to encourage and direct student thinking, and activities such as characterizing and analyzing the *C. elegans* developmental lineage. Inside each activity, movies of embryos are used for student inquiry into the lineage of cells and development of cells with different developmental potentials.

To effectively develop IMs using research resources for inquiry learning it is necessary to 1) organize research resources in a way that allows students to pose and solve questions and 2) provide additional resources that are sufficient for students to start and successfully follow through with their inquiry.

Utilization of WormClassroom Website for Inquiry Learning

Materials on the WormClassroom website are designed for curriculum development. Instructors play a major role in

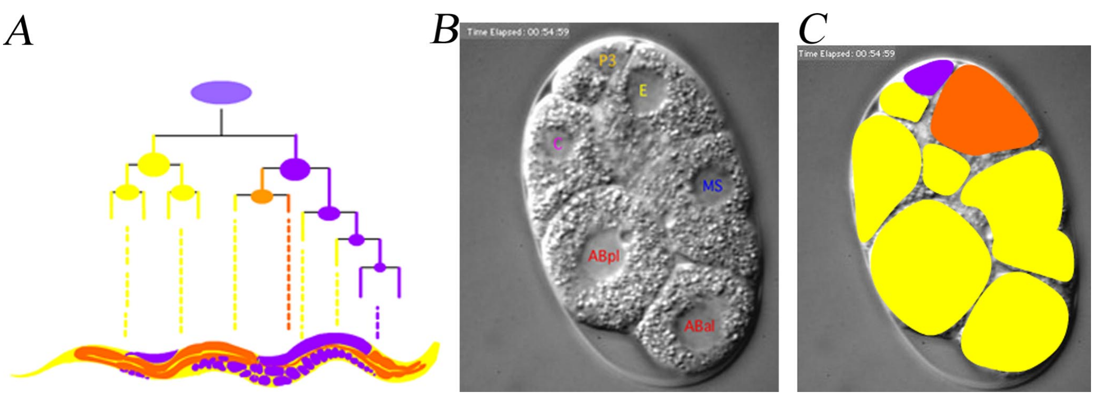

Figure 5. Cell lineage learning module. (A) The home page of the cell lineage module. (B) An annotated image of an embryo at eight-cell embryonic stage. (C) The image in the middle with cells in corresponding colors shown to the left.

Figure 6. Images of five *C. elegans* embryos after first embryonic division (two-cell stage). (A) Wild-type. (B) Mutant 1. (C) Mutant 2. (D) Mutant 3. (E) Mutant 4 (images courtesy of Kevin O'Connell, National Institute of Diabetes, Digestive and Kidney Diseases, National Institutes of Health).

specific materials selection to meet their instructional goals. Below we demonstrate the use of resources found in the WormClassroom website to engage students with research data. We will explore how movies of developing embryos, along with their accompanying resources, allow students to inquire into many fundamental biological concepts.

Phenomenon Observation and Background Information. Figure 6 shows images of five *C. elegans* embryos after the first embryonic division. (These images are available in the WormClassroom website as movies.) In the classroom, students can be directed to these online movies for observation.

To help students pose problems, background information is provided, such as that the movies are of early stage *C. elegans* embryos (see Figure 7).

Possible observations that would lead to question posing are listed in Table 1.

Problem Posing. At this stage, students will be posing questions regarding their observations. Table 2 presents a list of possible questions. As listed, the questions that might arise from observing the phenomena range from basic to advanced and span the disciplines of genetics, cell biology, and developmental biology.

Problem Solving. As discussed, the problems posed could range from basic, such as questions regarding the physical dimensions of the embryo, to advanced, such as genetic causes of the phenomenon shown in Figure 6. To help answer questions regarding the size of the embryo and daughter cells, the movie of the wild-type embryo can be used in conjunction with available measurement tools such as ImageJ (National Institutes of Health, 1999). Information on

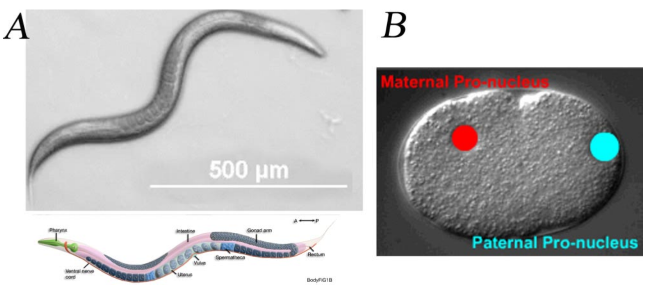

Figure 7. Background information about phenomena in observation. (A) Top, an adult *C. elegans* with scale; bottom, an illustration of *C. elegans* with its anatomy including embryos and oocytes (image courtesy of WormAtlas.org). (B) An annotated image showing a fertilized egg with its paternal and maternal pronuclei labeled.

the movie acquisition provides students the opportunity to understand that the development of an embryo is four-dimensional (4D = 3D + time) and that the embryo itself has dimensionality. A 4D dataset of wild-type embryo development is available for investigating questions regarding size.

Figure 8 depicts a two-cell stage embryo that illustrates how the size of the two changes along the different sections in three dimensions. By making their own drawings and measurements, students may come to understand that a *C. elegans* embryo is oval, like a chicken egg, and has dimensionality. For example, the change in size of the nuclei is only evident in certain spatial dimensions and varies again over time. Elements or materials of a cell may not be seen either because they are not present or because they are not observable in the current section.

For investigating the cellular basis of the phenomenon, resources on microscopy provide students opportunities to understand the power and potential applications of microscopy techniques in *C. elegans* research and to further inquire

Table 1. Observation of the phenomenon

I. By observing the results of the five embryos' development
  1. The wild-type successfully developed into a worm.
  2. The four mutants failed in early development.
  3. Mutants 1 and 2 ended up as one cell with many nuclei sticking together.
  4. Mutants 3 and 4 stopped at three and four cells. Some of the cells had more than one nucleus.

II. By observing the development of the five embryos
  1. In all embryos, except mutant 2, there were two prominent pronuclei to begin with. These two pronuclei then moved to meet each other.
  2. These two pronuclei sometimes appear to be larger, sometimes smaller.
  3. After first division, wild type generated two daughter cells. Mutants 1 and 2 stayed as one cell. For mutants 3 and 4, one had three daughter cells and one had four daughter cells.
  4. In the wild-type embryo, each cell had no more than one nucleus. In mutants 1 and 2, the embryos ended up with many nuclei sticking together. In mutants 3 and 4, some cells had more than one nucleus.
  5. The wild-type embryo divided from 1 to 2, 3, 4, and many cells and then developed into a worm.
  6. In the wild-type embryo, the daughter cell was smaller than the mother cell.
  7. In the wild-type embryo, after first division, one daughter cell seemed to be larger than the other one.
  8. All the embryos seemed to stay the same size at all times.

Table 2. Questions that arose after observing the phenomenon

I. By observing the result of the five embryos' development
1. What features constitute a wild-type and mutant embryo? What is normal and abnormal in embryo development?
2. What happened to the mutant embryos?
3. How does the appearance between progeny and parents differ?
4. Are there any differences among predecessors of these embryos?
5. Were the movies of the five embryos collected under the same living conditions, such as temperature and food supply?
6. What may be the cause for the differences in these embryos' development?

II. By observing the development of the five embryos
1. From where do the two pronuclei originate?
2. Are the two pronuclei similar in size?
3. What happens when the two pronuclei meet?
4. What was happening from two pronuclei meeting, merging to one big nucleus, and then dividing into two cells with two nuclei again?
5. Does the size of the merging nucleus equal the sum of the two pronuclei?
6. Why were there many nuclei in mutant 1 and 2? Is it normal?
7. Can a cell possess more than one nucleus? What is a cell?
8. Why were there more than two daughter cells after first division in mutant 3 and 4? Is it normal?
9. Does a cell division always generate two daughter cells? If not, what may be the consequence?
10. Are daughter cells always smaller than mother cells? Do they grow before next division?
11. Does the embryo stay the same size during all of development? Do embryos without egg shells do the same?
12. Does cell number increase in the rate of $2 \times$ ($1 \rightarrow 2 \rightarrow 4 \rightarrow 8 \rightarrow 16 \ldots$)?

into the cause of the phenomenon at the cellular level (see Figure 9).

The WormClassroom website can serve as a gateway, allowing student inquiry that utilizes resources beyond the site. For instance, research resources, such as articles on the phenomenon shown, are available online and these articles include advanced research data, such as confocal images and protein sequences, for more advanced student learning. Movies from research on early embryo development, with detailed cellular components identified, such as the Goldstein *C. elegans* movie site (Goldstein, 2004), are also linked from the WormClassroom site, permitting students to inquire into the interaction among elements of cells.

For investigation of the genetic basis of a mutation, sequences of proteins and genes are made accessible online. Tools for sequence alignment are linked, giving students the opportunity to align different genomic sequences of these embryos in order to identify specific sites in the genes and protein that lead to the mutant defect. For instance, students could identify the specific genes of interest by taking these sequences and running a query using tools such as BLAST in the database WormBase.org.

Peer Persuasion. Peer persuasion can occur in various stages during student inquiry using the above-mentioned materials. It provides students the opportunity to share with their peers their observations, hypotheses, and conclusions. For example, many students believe that an embryo increases in volume during early development (our unpublished data). By observing the wild-type embryo development of *C. elegans*, students may be surprised to find that the embryo does not increase in volume. A student who observes just a single optical plane over time may come to the conclusion that the embryo does increase slightly in volume during early development, whereas a second student, who more carefully observe all optical sections over time, may come to the conclusion that there is no change in volume. During peer persuasion, other students may find that the first student's case is not persuasive, as the student did not do a thorough investigation of all sections over time. Through discussion, the group of students may conclude the embryo of *C. elegans* does stay constant in volume during early development due to egg shell confinement, or this discussion may initiate further inquiry into more precise measurements of the embryo volume. The peer-persuasion approach can be built into a curriculum in various ways, such as midcourse and final presentations, or by having students present their work in local conferences that are related to topics under their investigation. It provides students, as it does for scientists, the opportunity to reflect on their work as they defend their findings and further refine their work if needed.

In summary, we have illustrated the possible use of *C. elegans* research resources for students learning by inquiry. Other applications of these resources include classroom demonstration of a phenomenon or developing question sets for student investigation.

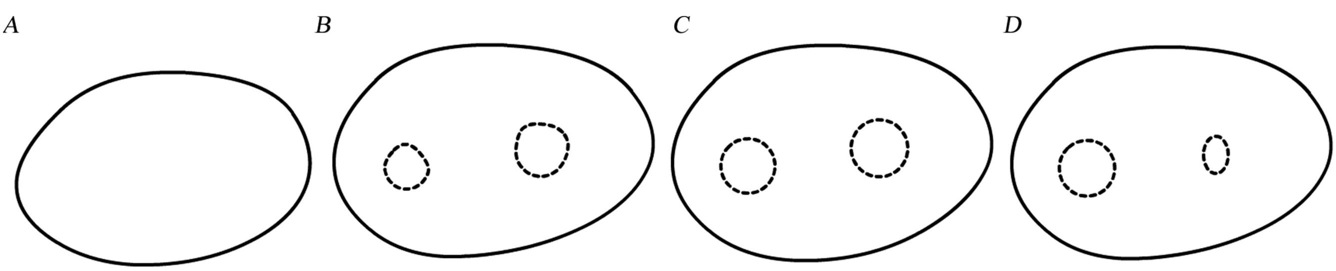

Figure 8. Outlines of the wild-type embryo in two-cell embryonic stage. (A) Section 2, neither of the nuclei are seen. (B) Section 4, nucleus on the right is larger than the one on the left. (C) Section 5, two nuclei seem to be the same size. (D) Section 7, nucleus on the right seems to be smaller than the left one.

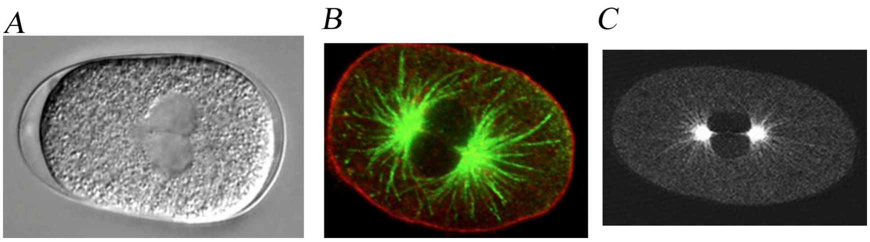

Figure 9. Images of different microscopy in the study of cell division in *C. elegans*. A *C. elegans* embryo at pronuclei meeting stage (before dividing into a two-cell embryo). (A) Differential interference contrast (DIC; Nomarski; image courtesy of Haining Zhang, University of Wisconsin-Madison). (B) Laser scanning confocal microscopy (LSCM; image courtesy of Maria Vidal Dinkelmann, University of Wisconsin-Madison). (C) Multiphoton fluorescence excitation microscopy (MPFE; image courtesy of Haining Zhang, University of Wisconsin-Madison).

For classroom use of WormClassroom site, instructors will drive the materials selection process and how to best incorporate it into their curriculum. Instructors may find it valuable to start with "About *C. elegans*." This orients instructors to *C. elegans* as a model organism, and provides examples of research. "*C. elegans* Education" includes teaching examples titled "a survey of currently used *C. elegans* curricula" by educators in the *C. elegans* field. It includes teaching examples ranging from introductory to advanced courses such as genetics and molecular biology in lab and lecture formats. Examples presented would inspire instructors in thinking about the use of *C. elegans* in the classroom to further develop their own *C. elegans* curricula. Contributed instructional materials are available right below the surveyed *C. elegans* curricula categorized into disciplines with different grade levels. These teaching materials include lab protocols, materials for lecture, and inquiry learning modules. For instructors interested in *C. elegans* for teaching a particular discipline, the links to individual disciplines will acquaint instructors with the use of *C. elegans* in a specific research field followed by links to the contributed instructional materials page mentioned. In addition to the designated instructional materials page, many *C. elegans* research datasets are available within the site that instructors may also find useful.

Assessment of the WormClassroom Website

Because there is no established set of assessment criteria for the application of research resources to inquiry learning, we developed our own criteria for assessing areas of the WormClassroom site that would benefit from evaluation. Since we aim to enhance student learning by using research resources of *C. elegans*, we have focused our primary assessment in three major areas: the assessment of 1) scientific content by experts, 2) website usability, and 3) student learning using resources from the WormClassroom. The assessment included the participation of students and professionals, such as biologists and website developers. Nonstudent participants are referred to as experts in our discussion below.

Assessment of Scientific Content by Experts. The major focus of the assessment included the following questions: 1) Is the information up-to-date and scientifically correct? 2) Does the scientific content introduce important concepts for further study? and 3) Is the content information adequate for the target audience? (see Table 3). We invited biologists and instructors teaching introductory biology to comment on the content of the WormClassroom website. With the collected feedback from all the experts, corrections were made to address inaccuracies.

Assessment of Website Usability. Nielsen (2003) argued that users leave a website if it is not easy to navigate. Because our resources are online, assessment of website usability is vital. By testing the website usability, we intended to understand 1) if the site effectively conveys its information to the user and 2) if the interface elements were usable.

For the Web usability study (see Table 4), a pilot testing was performed to try out the test procedure (Nielsen, 1993, 2000). We then recruited five undergraduate students ranging from freshmen to senior, with backgrounds in biology, for the study. To understand the usability of the site, students were encouraged to browse the website freely and

Table 3. Assessment of the scientific content by experts

Study questions	1. Is the information up-to-date and scientifically correct? 2. Does the scientific content introduce important concepts for further study? 3. Is the content information adequate for the target audience?
Participants	1. Scientific content experts, such as *C. elegans* researchers 2. Biology instructors
Methodology	1. Scientific content experts: went through every page to give feedback. 2. Other experts: provide comments after visiting the site.

Table 4. Assessment of website usability

Study questions	1. Is the website information effectively conveyed to the user (e.g., the meaning of images in the site)? 2. Are the Web interface elements usable (e.g., intuitive naming for links)?
Participants	1. Students 2. Experts, such as e-learning consultants and website developers
Methodology	1. Students: exploratory approach 2. Experts: provide feedback after visiting the site.

Table 5. Assessment of the student learning using resources in the WormClassroom

Study questions	1. Does the utilization of *C. elegans* resources enhance student learning and if so, how?
Participants	1. Undergraduate students
Methodology	1. Developed a lesson using resources in WormClassroom to study student learning. 2. Developed videotape recordings of students using the resources.

spend as much time as they wanted on what interested them. Students were asked to "think out loud" to express their thoughts, opinions, and feelings about the WormClassroom site as they explored it. The same facilitator was with the participants all the time to remind them to express their thoughts on what was visited. In addition, the facilitator helped solve any technology problems that arose. Student interaction was recorded using SnapZ X (Ambrosia, 2005) running on the same computer to record the vocal comments as well as the cursor movement through the entire sitting. Recording student interaction with the website provided insight into why students did what they did, what interested them, and what message was transferred to them. In addition to testing by students, we have also gathered comments from experts such as e-learning consultants, instructional technologists, Web developers, educators, and worm researchers for suggestions on Web usability improvement.

Assessment of the Student Learning Using Resources in the WormClassroom. The purpose of this assessment is to understand student learning using *C. elegans* resources (see Table 5). We developed a lesson using materials from the WormClassroom website. We worked closely with students, collected their written work, and videotaped their learning using the materials. The details of this study will not be described here because it requires lengthy discussion (Lu, Eliceiri, White, and Stewart, unpublished data).

Sharing Results and Planning for Action. We completed the assessment and revision of scientific content before the website usability testing. This way, the usability assessment could be more focused on questions we intended to answer and avoided the distraction of incorrect scientific information. The scientific content assessment is often easier than the other areas to revise because it usually reveals specific items that need to be corrected. The other two types of assessment may be more difficult to analyze because they can yield input that is more general in nature, such as trying to make the interface more "user friendly." The scientific content assessment was undertaken by a curriculum developer with Web skills, working closely with biologists going page-by-page through the whole site for content accuracy. With the assessment questions in mind, the correction of the content can be updated immediately. Any uncertainty was brought to other experts for later correction or clarification. With scientific discoveries being made daily, the content will be updated followed by a regular content assessment. When adding future resources, we plan to invite *C. elegans* educators specialized in different disciplines as facilitators to ensure the quality of the resources.

For Web usability assessment, the collected data were QuickTime movies recording students' voices and cursor movements. The data were transcribed and analyzed to examine major themes and patterns in students' browsing the Web site. Some example findings are listed in Table 6. Insights were categorized into issues regarding the content, interface, and animations. For instance, in the "interface issues" category, we found that image links, although popular in current Web design, are confusing to students. Students are often drawn to images as opposed to simple text links. With prevalent use of image links in current Web design, students (with some Web experience) learned they can click on images to see either enlarged images or access pages about these images. However, not all images are links. This often caused frustration during Web browsing once students found they got nowhere by clicking on nonlink images. More importantly, image links with valuable information may be overlooked if the users did not mouse-over them.

We have also applied Nielsen's "Severity Ratings for Usability Problems" (Nielsen, 2005) to scale the issues we classified for future improvement. For instance, we have developed many animations to ease student understanding of topics such as microscopy. Because of its platform independency, free download, and easy upgrade for both PC and Mac computers, we chose to make most of our animations in flash movie format (.swf). However, unlike other media formats such as QuickTime, most flash movies on the World Wide Web (WWW) do not include progression control bars to play certain frames. Students were often frustrated when they could not play or replay a certain frame of a movie. The severity ranking provides us with a priority list for Web usability improvement. The lack of progression control bars in flash movies ranks high in severity; thus, that issue will soon be fixed by adding control bars to the animations.

Table 6. Example of findings from the website usability assessment

Usability problems	1. Content issues: Naming for links and titles need to be precise. 2. Interface issues: Image links are confusing. For text presentation, reserve colors and underline for links. 3. Animation issues: For animations, a progression control bar is needed to indicate movie playing and for moving to wherever the user wishes.
Resources that interest students	1. "Questions to get you thinking" section in the WormClassroom site is very helpful. Students commented they were more focused when browsing the site with the questions in mind. 2. "Summary" section on top of each page is useful so that users get a quick idea of the page. 3. Multimedia content attracts and retains students' attention.

We expected that site content and website usability would be major factors in attracting and retaining student interest. What came as some surprise to us was the impact of other attributes of *C. elegans* research in getting student attention. Examples of such attributes include anecdotes from the research community and research honors such as the 2002 Nobel Prize awarded to researchers studying *C. elegans*. Understanding what is of most interest to students can be used to incorporate more interesting resources for student learning that can serve to motivate them to use the materials.

CONCLUSION AND DISCUSSION

The goal of WormClassroom website development is to aid student learning using research resources of *C. elegans*. As stated in BIO2010 (NRC, 2003), the development of teaching materials such as WormClassroom is a significant undertaking that requires not just time but expertise both in the subject matter and pedagogical approach. Motivated from our desire to share *C. elegans* resources with the undergraduate biology education community, we utilized the 3 P's pedagogical approach in combination with the multidisciplinary nature of *C. elegans* research and the consensus practice among scientists in the same research community for our resources application to education. WormClassroom is a project that will evolve with feedback gathered from iterative assessment of both scientific content and student learning. Resources in the WormClassroom website are made accessible in a format designed to promote student learning by inquiry. Assessment was performed to make certain that the content is scientifically correct and that the Web interface is usable. Findings from the assessments were then used to guide us in improving WormClassroom. Student learning using materials in the WormClassroom website has been collected and is under analysis for insight on the effectiveness of *C. elegans* research resources in student learning.

Despite its primary target of undergraduate biology education, resources in the WormClassroom site are not limited to undergraduate use. We encourage and welcome materials sharing for various levels of education in the WormClassroom. We have attempted to provide as many resources as possible while still leaving instructors the freedom to determine learning objectives when using the resources. Although the resources were developed with inquiry learning in mind, they can also be used to demonstrate phenomena or to develop question sets. Feedback from instructors indicates that they preferred having specific lesson plans available in WormClasssroom in addition to the general IMs and resources. These lesson plans are geared toward a specific course level and have clear daily activities identified with corresponding learning objectives. The hope is that instructors can share lessons and fine tune the various lesson plans to fit the particular needs of their courses. As a result, in addition to a collection of research resources, specific lesson plans for inquiry may be another way to encourage instructors to incorporate research resources to aid student learning.

The major resources in the current version of the WormClassroom site are from our lab, other *C. elegans* educators and researchers interested in teaching, and online *C. elegans* research websites. We have also invited *C. elegans* researchers specializing in various fields of study to contribute resources. Although researchers were enthusiastic regarding our efforts, time constraints often limited participation. Ideally contributions by researchers would be counted as a positive factor toward one's academic career. The Boyer Commission on Educating Undergraduates in the Research Universities (Boyer, 1998) has called for the faculty reward structure to be reconsidered at research universities to specifically reward efforts made in improving teaching. Contributions to an online resource for education, such as WormClassroom, could be viewed as enhancing one's teaching contribution and hopefully be counted toward one's academic credits.

Visibility and maintenance of the WormClassroom are two additional pressing issues for building an education resource of *C. elegans* for inquiry learning. The two issues are interdependent. For WormClassroom to be successful, it must be current and accurate. The best way to ensure this is widespread use and participation. To increase its visibility, we have submitted the WormClassroom site to the major *C. elegans* research website lists such as WormBase, WormAtlas, the *C. elegans* WWW server, and the biology Wikipedia under *C. elegans* (Wikipedia, 2005). We have also submitted our work to leading education sites such as BioQUEST (2005) and MERLOT (2003). As for maintenance, often one may encounter dead links or out-of-date information while surfing online. It is a challenge to keep a website up-to-date without considerable effort. Another challenge includes finding ways to ease the process of material contributions to the site. It is important to streamline the submission process without a loss in quality of the contributed materials. Additional efforts need to be invested to automate as much of the site administration as possible and yet still include peer review as an important component.

Future Direction

Our intent is to develop a *C. elegans* education resource based on WormClassroom that may act as a counterpart to the *C. elegans* research resource WormBase (WormBase, 2000). To sustain our endeavor, more efforts need to be invested in different stages of the project including research resources, funding resources, and human resources. We are the initiator and the major contributor to the development of the WormClassroom website. However, for its further development, contributions are needed from diverse professionals. Funding is critical to sustain its development as well. The National Science Foundation does have funding for integration between research and education, such as the Arctic Research and Education Program (National Science Foundation, 2005). We hope our effort in applying resources of *C. elegans* to enhance student learning by inquiry, as well as similar efforts by other groups, will be recognized and supported by funding agencies to ensure their sustainability.

In summary, we developed WormClassroom for the utilization of *C. elegans* resources to aid student learning. We hope others will find it valuable and join our effort. Our ultimate goal is to form an education community of *C. elegans* based on WormClassroom to aid the current biology education reform effort.

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REFERENCES

Ambrosia (2005). Snapz Pro X. http://www.ambrosiasw.com/utilities/snapzprox/ (accessed 3 May 2006).

Avila, K.B.B. (2003). Integrating Research and Education. Biocomplexity Investigators Explore the Possibilities: Summary of a Workshop (Board of Life Science), Washington, DC: National Academies Press.

BioClips (2004). BioClips: Biology and Multimedia Home Page. http://www.bioclips.com (accessed 5 May 2004).

BioQUEST (2000). BioQUEST: Curriculum Consortium. http://www.bioquest.org (accessed 30 March 2000).

BioQUEST (2005). WormClassroom.org: a *C. elegans* education and learning community [electronic version]. BioQuest Notes *14*, 4. http://www.bioquest.org/bqnotes/BQ_Notes_Winter_2005.pdf (accessed 7 August 2006).

Boyer, E. L. (1998). The Boyer Commission on Educating Undergraduates in the Research University, Reinventing Undergraduate Education: A Blueprint for America's Research Universities, New York: Stony Brook.

Cech, T. R. (2003). Rebalancing teaching and research. Science *299*, 165.

Chalupa, L. M. (1999). Balancing research and teaching. Science *285*, 2073–2075.

Donald, D. L. (ed.) (1997). *C. elegans* II, New York, NY: Cold Spring Harbor Laboratory Press.

Goldstein, B. (2004). *C. elegans* Movies. http://www.bio.unc.edu/faculty/goldstein/lab/movies.html (accessed 3 May 2006).

Handelsman, J. *et al.* (2004). Scientific teaching. Science *304*, 521–522.

Howard Hughes Medical Institute (2002). Howard Hughes Medical Institute's Million-Dollar Professors. http://www.hhmi.org/news/091802.html (accessed 2 May 2006).

HHMI (2006). The 2006 HHMI Professors. http://www.hhmi.org/news/04052006_list.html (accessed 2 May 2006).

Kitcher, P. (1984). 1953 and all that: a tale of two sciences. Philosoph. Rev. *43*, 335–373.

Kitcher, P. (1993). The Advancement of Science: Science without Legend, Objectivity without Illusions, New York: Oxford University Press.

Lu, F., Eliceiri, W. K., and White, J. G. (2007). BioClips of symmetric and asymmetric cell division. Biol. Cell (*in press*).

MERLOT (2003). Multimedia educational resource for learning and online teaching. http://www.merlot.org (accessed 5 May 2003).

National Institutes of Health (1999). ImageJ—Image Processing and Analysis in Java. http://rsb.info.nih.gov/ij/ (accessed 3 May 2006).

National Research Council (2000). How People Learn: Brain, Mind, Experience, and School, Washington, DC: National Academy Press.

NRC (2003). BIO2010, Transforming Undergraduate Education for Future Research Biologists, Washington, DC: National Academy Press.

National Science Foundation (2005). Arctic Research and Education Program. http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=13448 (accessed 15 November 2005). Nielsen, J. (1993). Usability Engineering, San Francisco: Morgan Kaufmann Publishers.

Nielsen, J. (2000). Why You Only Need to Test with 5 Users. http://www.useit.com/alertbox/20000319.html (accessed 3 May 2005).

Nielsen, J. (2003). Usability 101, Introduction to Usability. http://www.useit.com/alertbox/20030825.html (accessed 26 August 2003).

Nielsen, J. (2005). Severity Ratings for Usability Problems. http://www.useit.com/papers/heuristic/severityrating.html (accessed 8 May 2005).

Peterson, N. S., and Jungck, J. R. (1988). Problem-posing, problem-solving, and persuasion in biology. Academic Comput. *2*, 14–17 and 48–50.

Stith, J. B. (2004). Use of animation in teaching cell biology. Cell Biol. Educ. *3*(3), 181–188.

Wikipedia (2005). *Caenorhabditis elegans.* http://en.wikipedia.org/wiki/C._elegans (accessed 1 May 2006).

Wood, W. B., and Gentile, J. M. (2003). Teaching in a research context. Science *302*, 1510.

WormBase (2000). WormBase: The Biology and Genome of *C. elegans.* http://www.wormbase.org/ (accessed 3 May 2006).