Keeping an Eye on Biology

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Genomic data sets offer opportunities for students to generate original findings without expensive laboratory equipment, extending the benefits of undergraduate research to the classroom (1–4). Yet, working with data sets online can frustrate biology students who may miss connections to fascinating biological questions. Integrating organismal and molecular biology with bioinformatics can enhance student learning. We have developed a program in genomics, adapted for a plant (Chamaecrista fasciculata) and an animal (Aiptasia pallida), designed to support student learning with a Web-based guide (http://serc.carleton.edu/exploring_genomics/index.html) (see the first chart).

Curriculum development began with a collaborative effort, “Teaching Big Science at Small Colleges,” to develop, assess, and share inquiry-based, integrated instructional units (I’Us) in genomics (http://serc.carleton.edu/genomics/index.html) (5). All I’Us are aligned with the evidence-based design principles described in America’s Lab Report (6). Incorporating our own genomics research on nonmodel organisms resulted in our learning module, Genomics Explorers (7). Students ask questions on several levels of biological organization, from genes to genomes to organisms and their environments (see the second chart).

Students initially worked with whole-transcriptome data from individuals with schizophrenia, shared by our collaborators at the National Center for Genome Resources. Despite the human interest factor, students frequently get stuck, and “Stop and Reflect” boxes that encourage both reflection and higher-order cognitive thinking. Reflecting on a lab learning experience has been shown to enhance student understanding of the nature of science (6).

Chamaecrista Genomics Explorer supports problem solving. The Explorer guides students to choose a starting point: a literature-based entry to the biology of Chamaecrista, a candidate gene approach, or variation among three known ecotypes (a SNP-based approach). Links to tools and data are available centrally and as students need them. We include concept guidance, “Puzzled?” boxes that link to hints where our study shows that students frequently get stuck, and “Stop and Reflect” boxes that encourage both reflection and higher-order cognitive thinking. Reflecting on a lab learning experience has been shown to enhance student understanding of the nature of science (6).

Genomics Explorers, an IBI prize–winning module, engages students with bioinformatics and molecular research.

Chamaecrista Genomics Data

Overview of Chamaecrista Genomics Research

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*IBI, Science Prize for Inquiry-Based Instruction; www.sciencemag.org/site/feature/data/prizes/inquiry/.
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briefly present their findings and next question to the entire lab, which encourages collaboration. We added visualization tools to support students in making comparisons among data sets, including mapping the transcriptome onto the soybean (*Glycine max*) genome.

In a third activity, students shift to a molecular lab experience, conducting expression analyses by isolating RNA and performing semiquantitative or quantitative polymerase chain reaction (PCR). Students have found nonsynonymous, single-nucleotide polymorphisms (SNPs) among ecotypes and then used restriction digests of their PCR products to determine whether the SNP was valid or an artifact of sequencing. Some chose to sequence their PCR products, providing additional information and validation for their work. If cost is a barrier, students can design functional genomics experiments without actually conducting them.

Groups present their experimental plans to the class for critique, and collaboration among groups is encouraged. Often, a whole class experiment emerges addressing a more comprehensive question. For example, several groups can collectively investigate the relative effects of different temperatures and photoperiods on the developmental expression of one or more genes of interest in two different ecotypes. The process is designed so students own their questions.

Students make their thinking visible with short presentations on their experimental questions and findings, lab notebook records, a final presentation and paper, and a model for the effects of genes and environment on flowering time (fig. S2). Each group produces a paper focused on their research question that includes an investigation seeking patterns at the level of the transcriptomes, not simply individual genes. Peer and instructor feedback is provided each week, and the final paper must address the points raised.

Genomic Explorers enables students to identify a research strategy and to use bioinformatics tools for investigation, without relying on the instructor for assistance. Off-loading the basic instruction to the Web site creates space for the in-depth conversation among students and the instructor on the nature of research and biology that typically arise during a traditional undergraduate research experience.

**References and Notes**


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**Supplementary Materials**

[www.sciencemag.org/cgi/content/full/339/6118/408/DC1](http://www.sciencemag.org/cgi/content/full/339/6118/408/DC1)

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