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Lesson

"Got Algae?" A Sorting Game for Introducing the Weird and Wonderful Diversity of Algae

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Abstract

Algae are a fascinating and diverse organismal group, with global ecological importance, a storied evolutionary history and deep connections to both contemporary and historical human societies. Yet non-experts who teach algal diversity face a lack of examples in many general biology textbooks and the difficulty of generalizing a group that includes many distantly-related lineages that don't share a single common ancestor. This lesson embraces the complexity of algae using a sorting game and tree-building activity. Students work in groups to decide which organisms from a provided set are eukaryotic algae. The class creates consensus statements about what exactly defines organisms as "algae" and self-discover that exceptions exist for every seemingly definitive algal trait. Students then build simple phylogenetic trees and map their organisms across the phylogenetic Tree of Eukaryotes in order to explore the complex evolutionary relationships between the major eukaryotic algal lineages. Student written responses recorded before and after the sorting game indicate students become more nuanced and expert-like in their descriptions of algae. This lesson is an engaging way to introduce students to algae and can be modified for a variety of courses including high school, non-majors biology courses and introductory biology courses.

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Learning Goals

Students will:

- know the general characteristics of algae and know that no defining characteristic is shared by all algae.
- understand why the evolutionary history of algae make them difficult to define as a monophyletic group.

Learning Objectives

Following this lesson, students will be able to:

- LO-1: Compare and contrast unknown organisms and decide if they are algae.
- LO-2: Summarize the general characteristics of algae and explain, with an example, how exceptions exist for each characteristic.
- LO-3: Construct and interpret a Eukaryotic Tree of Life in order to recognize the relationships among and independent evolutionary origins of eukaryotic algae.

INTRODUCTION

Have you ever thanked algae, perhaps for the air you breathe or the food you eat? Probably not, because most of us don't realize the significance of algae to our lives. Ecologically, they form the base of almost all aquatic food webs (1,2), produce much of the world's oxygen, are critical components to coral reefs (3), and are important ecosystem engineers, providing habitat for many other organisms (4,5). Evolutionarily, land plants are descended from green algae (6) and the oldest known evidence for sexual reproduction comes from red algae (7). Direct human connections are also numerous: algae are directly eaten by people all over the world (8,9) and algal-derived compounds like alginate, carrageenan and agar abound in grocery store and pharmacy products (10). Algae even played a role in the peopling of North and South America (11).

Despite their importance and ubiquity in nature, the diversity of algae can be challenging to teach and is not well-covered in general biology textbooks (12). General statements are difficult to make because the term "algae" encompasses many distantly-related types of organisms that don't share a single common ancestor (the subject of this lesson). The internet is replete with incorrect or incomplete definitions that make the topic even more fraught for a teacher who is not an algal expert (that said, the Wikipedia description of algae is quite good. In fact, the term "algae" is more appropriately thought of as a functional group than a label with taxonomic meaning (like "animal" or "fungi"). In a nutshell, the term "algae" refers to lineages of life that photosynthesize and are not land plants. The word "algae" is Latin in origin and initially referred to only seaweeds, a subset of algae as we know the term today. Seaweeds are marine algae, large enough to be seen with the naked eye and typically live attached to a substrate. Today, the term "algae" also includes many single-celled and colonial lineages such as the diatoms and dinoflagellates as well as the prokaryotic cyanobacteria commonly called "blue-green algae." The focus of this lesson is on eukaryotic algae.

The evolutionary history of eukaryotic algae is complicated, adding to a teacher's difficulty and the need for lessons such as the one described here. To illustrate, consider the five most familiar algal lineages: diatoms, dinoflagellates, brown algae (including kelps and other brown seaweeds), red algae (including red seaweeds) and green algae (including green seaweeds). Each of these lineages is monophyletic, i.e., all diatoms are descendants of a shared common ancestor, all dinoflagellates are descendants of a different shared common ancestor, and so on (13). Together, however, the five lineages do not form a monophyletic group. Red algae, green algae and land plants share a common ancestry and belong to a large monophyletic group within the eukaryotes known as Archaeplastida (14); this is why many algal experts refer to red and green seaweeds as "plants", but may recoil if you refer to a kelp as a plant. Diatoms and brown algae belong to a different monophyletic group known as Stramenopila, while dinoflagellates belong to yet another monophyletic group known as Alveolata, which also includes the malaria-causing organism *Plasmodium* (14). The organelle responsible for photosynthesis (the chloroplast or just "plastid" in most algae) evolved from a phenomenon known as endosymbiosis (13,15). Plastids have evolved independently via endosymbiosis numerous times in the history of the eukaryotes, hence why photosynthetic dinoflagellates are more closely-related to *Plasmodium* than they are to other algae. Evolution, like the algae, works in weird and wonderful ways.

There is a myriad of interesting opportunities for including algae in biology curricula. For example, as photosynthetic organisms, algae make energy available to other organisms and so form the basis of aquatic food webs, useful in many ecology contexts. Species of green seaweeds, brown seaweeds and red seaweeds evolved independently of each other yet can look similar, live side by side at the seashore and perform the same ecological functions — great examples of convergent evolution (16). For experimental biology, several types of algae including *Volvox* (17), *Chlamydomonas* (18) and *Ectocarpus* (19) have been developed as model organisms. For a human connection, many examples exist of the cultural importance of algae around the world (20-22).

Published lessons use algae to varying degrees, with most including algae primarily as examples of processes like photosynthesis (23,24), biofuel production, or as an outgroup to a lesson about land plants (25). The goal of the present lesson is to feature algal diversity and to lean into the complexity of defining algae. Here students work in groups to review information cards for a collection of organisms and decide if each is an alga or not. Armed with their sorting results, the class is tasked with creating consensus statements about what exactly defines organisms as "algae." Students then build simple phylogenetic trees and map their organisms across the phylogenetic tree of eukaryotes in order to explore the complex evolutionary relationships between the major algal lineages. Several other card-based lessons and games about biodiversity exist (26)(25), with this lesson being the first to focus on algae.

Intended Audience

The lesson is designed for second-year biology students in an organismal lab course at a large, research university. The course content focuses on diversity within algae, fungi and bryophytes.

Required Learning Time

The lesson is designed for a 50-minute lecture class.

Prerequisite Student Knowledge

This lesson is intended as an introduction to the algae for undergraduate students that builds from students' prior and varied experiences with algae. Most students will have heard of algae, some will know the differences between algae and plants and name lots of examples, others may know only one or two vague ideas (e.g., "lives in water" or "feels slimy"). Any level of understanding is fine and no pre-class work or reading is necessary to bring students up to the same level. Students should have a middle or high-school introduction to photosynthesis in plants (e.g., know that photosynthesis is the process for generating chemical energy in plants and occurs in a special organelle called a chloroplast). To interpret the algae cards, it is helpful but not strictly necessary for students to already know the terms "flagella", "unicellular", "multicellular" and to interpret the relative size of the organisms using the provided scale bars (or hand) in each photo. For the second page of the worksheet (see Supporting File S2. Got Algae – student worksheet), students should be familiar with reading and interpreting phylogenetic trees. An excellent resource for background information is the Understanding Evolution website.

Prerequisite Teacher Knowledge

The instructor should be familiar with the general characteristics and evolutionary history of algae, in particular dinoflagellates, diatoms, brown algae, red algae and green algae. Several helpful background resources include:

- introduction to algae
- diatoms
- dinoflagellates
- red algae
- brown algae
- green algae

A general overview of the evolution of the plastid organelle is on Scitable — this content goes beyond the lesson, but may be helpful information for some teachers. For those who want to delve deeper, the Algae digital textbook (3rd Edition) is a relatively inexpensive textbook option.

The second page of the worksheet (see supporting File S2. Got Algae – student worksheet) has students constructing a phylogenetic tree using information from their organism cards. The instructor should be familiar with reading and interpreting phylogenetic trees; the Understanding Evolution website is a rich resource for background information about phylogenetics, including the "starburst" tree used in this lesson (). Another excellent resource for learning to read trees, including interactive review questions, is the Digital Atlas of Ancient Life. In particular, it is important to know the concepts of a "monophyletic group," a.k.a., a "clade" (group composed only of organisms who share a most recent common ancestor with each other) and a "polyphyletic group" (a group composed of organisms that does not include their shared common ancestor). Both of these concepts are covered in the Understanding Evolution site.

This lesson explores a specific and very important phylogenetic tree, the Eukaryotic Tree of Life (sometimes called the "eToL"). This phylogeny is complicated and in flux as new information and molecular sequencing methods change our understanding of the relationships of eukaryotes. The recent open-access scientific review paper by Burki et al (2020) provides perhaps the most accessible and up-to-date summary of the eToL (14). This review paper includes helpful background information and history for the large eukaryotic clades containing algae (this lesson uses Alveolata, Stramenopila and Archaeplastida) and the taxonomic term "supergroup" (a clade that is larger than a kingdom, smaller than a domain). It is important to remember the learning outcome associated with this part of the worksheet: that "algae" as a group is polyphyletic and scattered across the eToL. Students are only asked to remember the deep relationships between Alveolata, Stramenopila and Archaeplastida, the interpretation of which has not changed in recent years, so using a slightly out-of-date version of the eToL is ok (as is used in Supporting File S4. Got Algae – presentation slides with instructor notes).

SCIENTIFIC TEACHING THEMES

Active Learning

The lesson relies heavily on group work and a worksheet, two in-class active-learning techniques shown to improve learning gains at the undergraduate level (27). Whole class discussions, clicker questions and real-time drawing (instructor draws using document camera, students copy and annotate) are also used to encourage student participation. The worksheet is structured so that students work in groups on a prompt (e.g., a sorting task, drawing a phylogenetic tree), followed by a whole class discussion where groups report out their responses in order to create a consensus answer. During class discussions, the instructor encourages students to respond to each other's comments in order to include many voices in the conversation. During real-time drawing of the consensus phylogenetic tree by the instructor, students are encouraged to add or edit suggestions for how to sort the organisms into clades. The instructor draws the phylogenetic tree in the bracket style known for being easier for students to interpret correctly (28).

Assessment

The lesson uses a combination of formative feedback in-class and summative feedback on a midterm exam and final exam. In-class, students receive formative feedback from their peers both in their groups and as a whole class when they discuss how to sort the algae cards, craft their list of general algal characteristics and build their phylogenetic trees. During group work, the instructor and TAs circulate to provide additional formative feedback. Clicker questions also provide formative feedback during periods of whole-class discussion. Clicker questions are provided in Supporting File S4. Got Algae – presentation slides with instructor notes. Summative feedback is given during the course midterm and final exam in the form of fill-in-the-blank and short-answer questions, provided in Supporting File S5. Got Algae – assessment questions.

Inclusive Teaching

The lesson begins by inviting students to contribute their prior knowledge and experiences with algae, for which there is no "wrong" answer and all contributions are welcome. Throughout the lesson, students are asked to discuss, debate and build consensus with their peers in group work and whole-class discussion. Several different activity types are used, including sorting tasks, clicker questions and drawing, accommodating different learning preferences. Students are asked to work in groups, however, students who indicate they strongly prefer to work independently are allowed to do so. Overall, the lesson is intensely active, which has been shown to reduce the achievement gap for underrepresented students in STEM (29).

LESSON PLAN

Pre-Class Preparation

In the original version of the activity, there were 12 organism cards in total. A thirteenth card was added after the recent discovery of a non-algal close relative of red algae, *Rhodelphis*. (30) Instructions for both the 12 and 13-card sets are included here. Preparing the algae cards for the sorting game takes about one hour to make 20 sets. Print one set of cards, in colour, per student group (12 or 13 algae cards in total per set, depending on the version you choose; see Supporting File S1. Got Algae – organism cards). Standard printer paper quality is fine, i.e., no need for card-stock or other heavy-weight paper. Each finished card is roughly postcard-sized and will need to be cut after printing. I recommend printing each slide separately, as many copies as you need, to make it easier to cut out the cards in bulk. Once cut, sort the trimmed cards into sets. A plastic sandwich bag or paper-clip is handy for keeping each set organized. Print one worksheet per group of students, plus a few extra if needed (Supporting File S2. Got Algae – student worksheet). For the class discussions, have a tool for summarizing notes and drawing in front of the class (e.g., document camera, white board, chalkboard, computer with stylus, etc.). It is helpful to have at least one assistant to help with distributing materials and helping student groups. Optional: select a relevant video or image to project before class to generate interest. I recommend a video of a kelp forest playing with the audio muted. Examples include:

- biologist Liam Coleman
- California Underwater Imagery Archive
- BBC Inside Out South

In-Class Plan

The Start of Class (5 minutes)

This lesson is used in a 50-minute lecture class as a first introduction to the course theme of "algae." As such, the first five minutes is used to remind students of the new course theme, briefly introduce the plan for the day and specific learning outcomes of the "Got Algae?" activity (see Supporting File S3. Got Algae – lesson outline). I also make a statement at the start of class to the effect that today's class will introduce lots of technical terminology that I don't expect students to know — the goal is for them to make comparisons, even if they don't know what the words mean yet (but they will by the end of the month!).

This activity can easily take longer than expected so it is important to stay on task and be quick with transitions. You can save time at the start by prompting students to form groups as they're arriving to class. I project the Lesson Outline using a document camera as students are arriving that shows both the learning outcomes and a large-font statement "Please get into groups of 3-4 for today's activity. You will stay with this group for the entire class." Students could also work in pairs, but the time needed to complete questions is more consistent if groups are of similar size (i.e., avoid having both pairs and groups of four for this activity). Distribute one worksheet to each group (Supporting File S2. Got Algae – student worksheet). Having an assistant to help distribute materials speeds this part up; alternatively, you can ask one member of each group to pick up their worksheet from the front of the room or distribute before class begins. Do not yet hand out the organism cards or students may become distracted by them.

Got Algae? Activity (45 minutes total)

Worksheet Prompt 1: Prior Knowledge of Algae (3 minutes)

Tell groups to answer the first worksheet prompt (*Define the word "algae"*), without using any text or internet resources. Give groups no longer than three minutes to answer this question. I quickly circulate the room and listen to a few discussions, gently reminding groups to summarize their thoughts on the worksheet. This question is tapping into their incoming ideas about algae, so whatever they write is acceptable. At this point, I would not make any corrections and only offer neutral comments like "That's interesting, can you expand on that more?" or prompts like "What immediately pops into your mind when I say the word 'algae'?" It's easy to go over time here and you want to leave sufficient time for the more substantial questions to come. I have a lesson timing breakdown (Table 1) printed for myself at the front of the room and use the timer on my mobile phone to keep on time.

Worksheet Prompt 2: Got Algae? Sorting Game (15 minutes)

While students work on the first worksheet question, quietly distribute the organism cards, one set per group. It takes about two minutes for three people (usually graduate student TAs) to distribute 25-30 card sets around a large lecture hall. Direct students to answer the second worksheet prompt: *Using the provided cards, assign each organism to either "algae" or "not algae" in the table below* (Figure 1). Give 10-12 minutes for this activity, with a warning to the whole class a few minutes before the end. Some groups finish sorting organisms with time to spare, others could debate for an hour. It's important to prompt the fast groups, who often haven't written much on their worksheet, to summarize their reasons in writing. Slower groups can be prompted to skip an organism or ignore a characteristic if they are stuck.

You and any assistants should circulate the room to provide guidance and prompts. I still avoid correcting student thinking at this point. I do want them to be able to explain their choices and reasoning so if necessary I might ask clarifying questions like "I see all of the organisms in your list are photosynthetic. Does this mean to be an 'alga', an organism must be photosynthetic?" Questions like this often prompt a discussion within the group. I will also remind individual groups to write their thoughts on the worksheet. Assistants may need to be instructed beforehand to provide similarly formative feedback to groups or they may feel obligated to provide the "right" answers. During the sorting, students usually ask about the more technical information on the cards, like membranes and pigments, which up to this point they haven't learned at all. Here I will stop the whole class to remind everyone they may notice unfamiliar information on the cards. I say it's ok if they don't know the function of "plastid membranes" or "carotenoids," we will learn all about these topics over the next month. Today, the important task is to make comparisons between organisms, such as presence or absence of characteristics, like flagella or membranes, and similarities between these characteristics. The timing for this activity is tight so it is wise to use a timer to keep on task and avoid being distracted by a lively group conversation.

Worksheet Prompt 3: Algae Consensus (12 minutes)

After the sort, it's time to discuss as a class which organisms are algae. Project the blank table labelled "Algae" and "Not Algae" (see Supporting File S4. Got Algae – presentation slides with instructor notes). I start by asking the class which organisms seemed easy to assign to "algae" or "not algae" and why. I take two or three responses and after each I ask the class if they agreed or not and why. I then do the same for organisms that were difficult to classify. I do not summarize student answers in writing because it takes too long, but this table could be projected on a document camera and annotated during the discussion if you have longer than 45 minutes.

Figure 1. Student groups working during the Got Algae? sorting game. Students make use of all available spaces including (A) the front of the lecture hall, (B) tiny fixed desks, and (C) the classroom floor.

After this I ask if the class wants to see how an expert in algae (a.k.a., a "phycologist"; *phykos* is Greek for *seaweed*;) would sort these organisms. I then show the slide in Supporting File S4 with the completed table. The class erupts into discussion when this slide is shown. Give them a minute to discuss and then ask what they notice. Someone will likely point out that something is missing (the *Plasmodium*). Show the next slide, which adds *Plasmodium* between the two categories with a "?". To capture whether they think *Plasmodium* is an "alga," I quickly poll students using the provided clicker question. The vast majority but not all think *Plasmodium* is not an alga. Here's where you can point out that humans like to categorize life in somewhat arbitrary or overly-simplistic ways. For *Plasmodium* it depends on how broadly you define "algae": most phycologists say no, some say yes. *Plasmodium* is descended from an ancestor that was an alga, but would itself not be considered to have an "algae lifestyle." If you include *Rhodelphis*, the same discussion for both *Plasmodium* and *Rhodelphis* can happen at the same time. The following linked articles are helpful introductions to

Plasmodium (The weird thing about the malaria parasite) and *Rhodelphis* (Spawn of the triffid? Tiny organisms give us glimpse into complex evolutionary tale).

Direct student groups to reflect on their sorting choices and the expert classifications in order to answer the third worksheet prompt: *Can you revise your definition of "algae" to include some general statements of what algae are and are not?* After three minutes, as a whole-class discussion, summarize in writing a short list of three or four general statements. Students usually say things like "algae are photosynthetic, mostly," "algae are usually aquatic," or "algae can be multicellular or unicellular." Be mindful of time, it is not critical to create a comprehensive list here. Rather, students should realize there are exceptions to every general characteristic of algae (even photosynthesis). You can end with this observation and say you'll review a complete list of general characteristics next class and point out some interesting exceptions (see Supporting Files S4. Got Algae – presentation slides with instructor notes and S6. Got Algae – next class presentation).

Worksheet Prompt 4: Algae and the Tree of Life (12 minutes)

Direct students to answer the last two worksheet prompts: *Draw a phylogenetic tree of relatedness for all of the given organisms (algae and non-algae)*, and *Do all algae share a single common ancestor and belong to a group that excludes all non-algae groups?* The last line on each organism card provides the necessary information (*Closest relative(s) of the organisms included in this activity*). Students will likely build several separate trees with only a few organisms (e.g., *Plasmodium*, *Stentor*, *Alexandrium*, and *Pfisteria*) because the cards don't provide enough information to create a single tree with all 12 organisms. This is ok! The current understanding of the evolutionary history of eukaryotes includes some very big gaps and we don't yet know in what order the largest eukaryotic clades diverged from each other (see Prerequisite Teacher Knowledge for background information on the Tree of Eukaryotes and phylogenetic trees). Some student groups may need to be redirected to use the *closest relative(s)* info and to not build their trees based on unicellularity vs. multicellularity. You can point out that the characteristics of "multicellularity" and "unicellularity" don't provide enough information to do more than sort organisms into two piles and don't help infer any other relationships between the organisms. Allow six minutes for this activity.

Bring the class together. Ask students to identify groups of organisms based on their cards. As they respond, draw their groupings using the document camera (see Supporting File S4. Got Algae – presentation slides with instructor notes for example drawing). Only draw correct groupings; if a student suggests an incorrect grouping, you can say "That doesn't sound quite right, can someone else add to or edit their interpretation?" Drawing the tree takes a while (budget about five minutes); practicing beforehand, having a prepared drawing beside you, abbreviating the organism names and leaving additional annotations for the post-class notes can save time. If time allows, follow the drawing with the provided clicker question to check if students understand the direction of time in a starburst phylogeny. To end the drawing, I point out or prompt students to notice that algal lineages are often most closely related to lineages that are not algae, and that the root of the tree as drawn is unknown. When the class consensus tree is done, I project the powerpoint slide showing a published tree of eukaryotes (example suggested in Supporting File S4. Got Algae – presentation slides). Point out that students have, on their own, recreated three of the major Eukaryotic lineages (Alveolates, Archaeplastids and Strameopiles) (14). An optional concluding point is to note that there is still much we don't know about the evolutionary history of eukaryotes, i.e., the base of the eukaryote family tree in still unresolved.

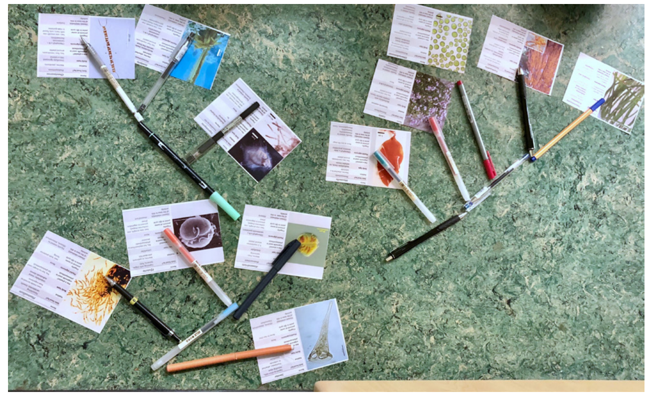

Figure 2. Phylogenetic trees built by students using information provided in their organism cards. The three separate trees are all monophyletic lineages from the Eukaryotic Tree of Life (Alveolata, Stramenopila, Archaeplastida) and contain both algae and non-algae examples to demonstrate the polyphyletic nature of algae.

Class Debrief (3 minutes)

While still showing the Tree of Eukaryotes, I point out that algae are hard to define with universal characteristics because they are so diverse in their evolutionary history (your students may be at a level to use the term polyphyletic). So why bother calling them all "algae"? Because despite their independent and unique origins, algae tend to perform the same functions wherever they are found; show slides provided in Supporting File S4. Got Algae – presentation slides, if time allows. I finish with a teaser for the next class, saying that even though these algae lineages independently evolved to become algae, their various origin stories share some very important things in common (much like many comic book superhero origin stories).

TEACHING DISCUSSION

This lesson has been run with two cohorts of students. The evidence of effectiveness includes formative evidence — a qualitative summary of student behaviour during the activity — for LO-1: Compare and contrast unknown organisms and decide if they are algae, and LO-2: Summarize the general characteristics of algae and explain, with an example, how exceptions exist for each characteristic. Summative evidence in the form of midterm exam question scores was used to assess LO-2 and LO-3: Construct and interpret a Eukaryotic Tree of Life in order to recognize the relationships among and independent evolutionary origins of eukaryotic algae.

Formative Evidence of Effectiveness for LO-1 and LO-2 from Worksheets and Discussion

During the lesson, students engage in lively debate as they work in their groups. Some organisms are easy for most groups to sort correctly (e.g., the seaweeds *Pyropia*, *Macrocystis*) while others are highly debated (e.g., those with no plastid but a photosynthetic ancestor like *Plasmodium*). Questions #2 on the student worksheet addresses LO-1 (see Supporting File S2. Got Algae – student worksheet). Most, but not all, groups sort *Plasmodium* into "not algae." Roughly half of the groups incorrectly sort *Trentapohlia* into "not algae"; about 20% do the same for *Pfisteria* and *Alexandrium*. The room erupts in discussion when the expert sorting results are projected, indicating that students are invested in the lesson.

Questions #1 and #3 (see Supporting File S2. Got Algae – student worksheet) are used as a low-stakes pre/post assessment of LO-2. Following the lesson, I informally compared student groups' descriptions of algae before and after the sorting activity. For Question #1, students typically listed single-words or short ubiquitous phrases about algae. Examples include "they photosynthesize," "are delicious," "sushi," "kelp," "seaweed," and "nori." Perhaps not surprisingly, no pre-activity definitions talked about the relatedness of algae to each other or other groups of eukaryotes. During the class discussion following the sorting game, and on Question #3 of the worksheet, students offered several general statements about algae that were more nuanced and closer to an expert's list of general characteristics (see Supporting File S4. Got Algae – presentation slides with instructor notes). Paraphrased class statements include 1) algae are mostly photosynthetic, 2) most algae live in water, can be ocean or freshwater, 3) algae can be unicellular or multicellular, 4) not all algae are closely-related to other algae. Qualifying words like "usually" and "most" are subtle but important evidence that students self-identified the exceptions to general characteristics of algae. Notably, two characteristics that are never given after the sorting game are those explicitly comparing algae to land plants ("lacking complex body structures such as roots, stems, leaves, xylem or phloem" and "lacking complex reproductive structures like seeds or flowers"). This is not surprising because no information about these characteristics is given on the organism cards. Omitting this information was a deliberate choice to avoid overwhelming students on the first day; comparisons between land algae and land plants develop as the course progresses toward the theme of bryophytes.

Summative Evidence of Effectiveness for LO-2 and LO-3 from Exam Questions

The lesson took place in two semesters of the course, however, only one semester included summative evaluation on a test. The course midterm exam occurred roughly four weeks after the lesson (see Supporting File S5. Got Algae – assessment questions). Assessment question #1 addressed LO-2: Summarize the general characteristics of algae and explain, with an example, how exceptions exist for each characteristic. The overall average on this question was lower than expected (69%, roughly 4 of 6 points earned). However, an informal review of 25 tests, roughly 1/4 of the class, revealed many students earned full points (3/3) for the first part "*List three of the general characteristics of algae*" and struggled with the second part "*From the list below, identify a type of algae that is an example of an exception to a common characteristic and explain how it is an exception.*" The most common error students made, which was not quantified, unfortunately, was to mismatch the example alga with the exception described.

Assessment question #2 addressed LO-3: Construct and interpret a Eukaryotic Tree of Life in order to recognize the independent evolutionary origins of eukaryotic algae. The overall average on this question was 67% (4 of 6 points earned). An informal review of roughly 1/4 of student tests revealed the most common errors were to place the two major red algal lineages (Florideophyceae and Bangiophyceae — these terms are learned after the Got Algae? lesson) outside the Archaeplastida lineage or to mix them up with the green algal lineages Chlorophyta and Charophyceae. These errors suggest that more time could be spent during and after the lesson to clarify the relationships within the Archaeplastida. Almost all students correctly placed the Phaeophyceae (brown algae) and Bacillariophyceae (diatoms), which is encouraging because, anecdotally, many students enter the course assuming organisms as different as giant kelp and microscopic phytoplankton must be very distantly-related.

Modifications and Extensions to the Lesson

Future iterations of this lesson will include a short pre- and post-lesson quiz, delivered outside of class time via the course Learning Management System, to explicitly measure learning gains for all three learning objectives. For example, LO-3 could be easily addressed by presenting students with a phylogeny of major eukaryotic clades and asking students to identify the correct clade for representative algae. For instructors with more than 50 minutes to deliver this lesson, clicker-style questions could be used in class as an immediate pre/post assessment of student learning gains.

This lesson was designed for a class of approximately 100 students in a lecture-theatre setting. To date, it has been used in a room so crammed for space it initially seemed impossible to do group work, and a more typical stadium-seating lecture hall. In both situations, the lesson worked very well. Student ingenuity lead to spontaneous commandeering of floor and lectern space to spread out organism cards and build trees. I encourage students to work in similarly-sized groups (3 or 4) but always have a few who work in partners or on their own. Having a few groups of different sizes hasn't noticeably affected the timing or caused groups to be far out of sync with each other. Given these observations, I believe this lesson can be scaled for smaller or larger class sizes and readily adapted for groups of two to five.

The lesson as presented here requires careful time management to complete in 50 minutes. Student discussion is lively and productive, especially after the sorting game and during the class consensus of algal characteristics. Summarizing student comments in writing and clicker questions can also take more time than initially budgeted. To save time and allow for more active time in class, I will skip some slides of extra or extension material (see notes in Supporting File S4. Got Algae – presentation slides with instructor notes) and give all slides to students after class as a pdf file. Another possibility is to divide the lesson into two parts: Got Algae? game with discussion, and tree-building. The tree-building activity (page two of Supporting File S2. Got Algae – student worksheet) could become a separate activity for another class (just remember to keep the organism cards for it).

Modifying the lesson for high school students or for undergraduates who are not biology majors, could be achieved in several ways. The organism cards could be modified to present technical information as drawings (e.g., plastid membranes represented as simple drawings of ovals with two or more outlines, flagella shown as exaggerated tails on simple cell cartoons). Or some characteristics, like pigments, could be omitted completely. For younger audiences, scientific names could be replaced with common names or generic descriptors like "Organism 1." Because the purpose is for students to make comparisons between organisms, the amount and accuracy of the technical information can be reduced as necessary to achieve the learning objectives. If the tree-building activity is used, it will be important to keep the closest relatives' information on the cards. Conversely, this lesson could be made more complex and comprehensive with the inclusion of additional algal lineages such as cyanobacteria.

The lesson could be extended to allow students to find their own organisms prior to class to use as part of the sorting game. Student groups could be provided key criteria (e.g., organism has a plastid with two membranes) and tasked with finding a species and completing the rest of the organism card, including a photo. The instructor could choose to have the entire deck be student-generated or have a mix of student cards and cards provided here to create a full set. If student-generated cards were submitted as editable, digital files, the set could grow each year and students will almost certainly appreciate that the activity is developed by students, for students.

An additional extension would be to introduce more game-like elements to the sorting activity. For example, groups could be challenged to provide the most well-reasoned justification for including or not including organisms as algae and small prizes awarded. Or they could vote for particular sorting game organisms to become the focal subjects of future classes or even the class "algae mascot." Prompts that encourage reasoning and student ownership will help avoid motivating students to use the internet to find the "right" answer.

The next topic in this course is on algal origins and the evolution of the plastid by endosymbiosis. Having students complete the tree-building activity is an excellent set-up for this algal origins topic because they have discovered for themselves the polyphyletic history of algae. This lecture's slides and clicker questions are provided in Supporting File S6. Got Algae – next class presentation.

Conclusion

A sorting game is an effective and fun way to introduce students to the algae, a subject that can sometimes seem dry, confusing and crammed with disconnected facts and terminology. By interpreting and debating facts about real species, students discover on their own that algae are incredibly diverse in form and habit, and that no single character ubiquitously defines this group. Building simple phylogenetic trees using the organism cards introduces students to the Tree of Eukaryotes and primes them to explore further the complex evolutionary history of algae.

SUPPORTING MATERIALS

- S1. Got Algae – organism cards
- S2. Got Algae – student worksheet
- S3. Got Algae – lesson outline
- S4. Got Algae – presentation slides with instructor notes
- S5. Got Algae – assessment questions
- S6. Got Algae – next class presentation

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Table 1. Teaching Timeline for the Got Algae? Lesson.

Activity	Description	Estimated Time	Notes
Pre-Class Preparation			
Prepare Algae Cards and Worksheets	• Print one set of Algae Cards, in colour, per student group. • Cut ant trim printed cards to postcard-size. • Sort the trimmed cards into sets (one of each organism, 12 or 13 cards per set — there are two versions). A ziploc bag or paper-clip is handy for keeping each set organized. • Print one Worksheet per group of students, plus a few extra if needed. • Print one Lesson Outline. • Optional: Select a relevant video or image to project before class to generate interest.	1 hour to prepare 20 sets	• Algae Cards are provided in Supporting File S1, Worksheet in Supporting File S2, Lesson Outline in Supporting File S3. • Standard printer paper quality is fine. • Cards must be cut after printing. • Printing each slide separately, as many copies as you need, makes it easier to cut out the cards in bulk. • Using a large paper cutter to cut multiple sheets of the same two algae cards at once saves time, but be mindful that the sheets can slip or jam the cutter (4–6 sheets works well). • Make sure to tell students to return their algae cards intact and to not mark or write on the cards (so you can reuse them).
Gather other supplies			• Time-keeping device (such as mobile phone) • Something to write on in front of class (e.g., whiteboard markers if using whiteboard).
In-Class Lesson			
Start of class	• State objectives for activity and expectations for knowing activity terminology. • Arrange students into groups. • Distribute worksheets.	5 minutes	• Prompt students to form groups as they arrive to class to save time. • One worksheet per group. • Worksheet in Supporting File S2, Lesson Outline in Supporting File S3.
Prompt 1: Prior knowledge of algae	Students work in groups to capture their prior knowledge of algae.	3 minutes (45 total for activity)	• Lecture slides with notes are in Supporting File S4. • Quickly circulate to support, but not correct, students to answer this prompt. • TAs distribute Algae Cards (Supporting File S1) while students work on this first prompt.
Prompt 2: Sorting organisms	Students work in groups to sort organism cards into “algae” and “not algae” categories.	15 minutes (45 total for activity)	• Instructor and TAs circulate to support, but not correct, students. • Groups finished earlier can be encouraged to further explain their reasoning; slow groups can be guided to skip difficult characteristics or organisms. • May have to remind class they don’t need to know all the new terminology, can still make comparisons.
Prompt 3: Algae Consensus	Class discusses results of sorting activity and creates consensus list of general characteristics for algae.	12 minutes (45 total for activity)	• Slides for class discussion of sorting results in Supporting File S4. • May have time for only a few general characteristics of algae. Most important that students recognize that no character applies to all algae.
Prompt 4: Algae and the tree of life	Students work in groups to organize organisms by relatedness.	12 minutes (45 total for activity)	• Example of tree drawn on document camera and slide of published tree of eukaryotes in Supporting File S4. • Most important that students recognize that algal lineages are scattered across tree of eukaryotes, and algae are often most closely-related to non-algae.
Class debrief	Brief wrap-up of activity and connection to next lesson on origins of algae.	3 minutes	• Slides provided in Supporting File S4. • Slides from next class on endosymbiosis and origin of algae in Supporting File S6.
Post-Class Assessment			
Assessment questions	Exam-style short-answer and fill-in-the-blank questions.		Example questions provided in Supporting File S5.