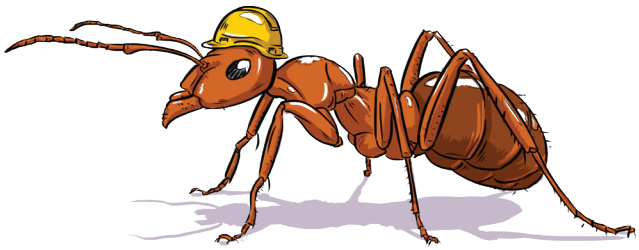
# AMAZING ANTS

## Simple Sidewalk Science



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# STUDENT'S PREFACE

As a boy I enjoyed playing outside, and I wanted to be a scientist. I read about inventors like Edison and Bell, and I dreamed of following in their footsteps. I collected butterflies. I kept tadpoles and watched them metamorphose into frogs. I borrowed a microscope and looked at the protozoa and other microscopic life forms that grew in my aquarium, the puddles in our driveway, and almost everywhere I looked. But I didn't know how to combine my interest in science with my love of nature. I wanted to be a scientist but didn't know how to start. And although I had certainly seen lots of ants, I hadn't really discovered them. I didn't realize how much I could learn about ants, and I didn't know how easy it is to study them. If you are reading this, I assume you too are interested in both science and nature. I hope this book will help you combine these interests and begin your development as a scientist.

Enjoy!

# STUDENT'S INTRODUCTION

Unless you live in Antarctica, Greenland, or Iceland (places where there aren't any) you have probably seen ants. But have you really looked at them? Have you ever looked for them? Have you thought of studying them? Do you know how fascinating ants are and how much you can learn about them? You can find out a lot about ants using just a few tools—things you can easily find around the house. You don't have to go far, and you don't need expensive or complicated equipment. Whether you live in the city, the suburbs, a village, or out in the country, you should be able to find ants near your home. If the weather is warm—late spring, summer, or early fall—then you can start your study of ants right now just by going outside. (Sometimes ants come inside, but when they do people seem to want to kill them rather than study them.)

How should you start? There is no one right way. The purpose of this book is to help you study ants scientifically in ways that are easy and inexpensive. Science isn't really hard. It's just a way of asking questions of nature and finding answers to these questions by doing experiments. So the real purpose of this book is to help you become a scientist, and working with ants can be an interesting and easy way to start. As you follow some of the suggestions in this book, you will be doing more than simply learning about the ants that live near you—and there may be more of these than you realized. You will also be learning a lot about how scientists work. How they design experiments. How they collect data. How they analyze data, and how they communicate their results and tell others what they have done and learned. It isn't hard, as you will see, but it does take work, and it is important to keep records.

This book is both an instruction book and a start on a research notebook. Chapter 1 gives some amazing ant facts. Chapter 2 lists the tools you need to get started. Chapter 3 describes some simple skills you can use to begin studying ants. Chapter 4 explains some of the ways scientists analyze and present data. Chapter 5 talks about what happens when the results of

your experiments surprise you. (Things don't always turn out the way you think they will in scientific research.) Chapter 6 describes several simple experiments. Each experiment is designed to answer a different kind of question. Following each sample experiment is a list of challenges related to that experiment. You can use the approaches from the sample experiment and others described in Chapter 3 to address the challenges. Chapter 7 explains how scientists tell other scientists about their results. Finally, Chapter 8 talks about what science is and how it works. This is really just a formal summary of what you will have learned working through the earlier chapters.

Throughout the book you will find pages where you can record your results in an organized way. Thus you have here both an instruction book and a "starter" research notebook.

The equipment required is mostly things anyone can find around the home. I have tried to keep the reading level reasonable for seventh or eighth grade students, but I hope parents can find ideas in this book to use with children of all ages, from preschool up. For 7th and 8th grade children, you should be able to read the book together.

## A WARNING

IF YOU ARE ALLERGIC TO BEE OR WASP STINGS, you should be careful when studying ants. Ants evolved from and are related to wasps. Not all ants sting, but some do. The fire ants of the southeast are particularly notorious for stinging. They can also rapidly swarm all over you if you accidentally step on or disturb a nest. So be careful. If you are allergic to bee stings, talk with your parents and/or your doctor before getting down on the ground with ants.

# CHAPTER 3
# The Skills You Need

The more you study ants, the more you will learn what works and what doesn't. (And remember, what works for someone else may not be what works for you.) With time you will develop your own methods for working with them and discover what techniques work best for the question you are trying to answer. So what follows are some suggestions to get you started. If, after you have tried these, you discover approaches that work better for you, use them.

## Finding Ants

There are three general approaches to finding ants. You can look for individual ants out foraging for food. You can search for the nests where ants live in colonies. You can also set out baits to attract ants, as described in the next section.

Most ants don't build anthills—at least not large ones. If you do know of some anthills in the area you are studying, you can start with those ants. But even if there are anthills near you, there are probably lots of other ants whose homes are less obvious. Some of the smallest live in places you might not suspect. So where and how should you look?

**Note:** How many ants you find will depend on several things, but one in particular might be a problem. If you are looking in an area that has been treated with pesticides, you may find fewer ants than you would in a similar area that is pesticide-free. (Many lawn service companies use such pesticides.) You might not even find any. There isn't much you can do about it except to find areas that have not been treated.

### Foraging Ants

Foraging ants may be found anywhere. Some will be easy to find, and others may take more time and patience to see. (Remember that patience is an important skill for all scientists. Thomas Edison said, "Genius is one percent inspiration and ninety-nine percent perspiration.")

- Look on the sidewalk. This is the easiest place to spot ants wandering around.
- Look on plants.
    - Look on tree trunks. At first you may not see any ants but wait and keep looking. After a while you may see more than one kind of ant walking up or down the trunk.
    - If you have big old trees with holes near the roots, look around these. Carpenter ants—large black ants—like to live in hollow tree trunks and often can be seen entering or leaving through holes near the base of the trunk.
    - Look on bushes and shrubs—especially deciduous ones. (Deciduous ones are those that lose their leaves in the winter.) You might find ants on evergreen shrubs, but probably not as many.

- Look on other plants, checking their stems and leaves as well as any buds or flowers. (If you have peonies in your garden, you will almost certainly find ants on peony buds before the flowers open.)

- Look on the ground.
  - A good way to start is to get down on your hands and knees and crawl slowly across your lawn. Keep your eyes on the ground and really look. It may help to stop once in a while and just focus on one area for a few minutes. Some of the smallest, slowest, or shyest ants won't be obvious at first, but you may see them if you are patient.
  - If you are looking in an area with litter (not trash, but the collection of leaves and grass and twigs that accumulates in wooded areas), try clearing a space that is two to three feet across and watching it for a few minutes. After a while, ants may start to come out to explore the newly cleared area.

## Ant Nests

Ants nest in many places, and most ants don't build large mounds. Therefore, if you want to find where ants have their homes, you need to look in a variety of habitats. (Some of these habitats may not exist where you are looking. For example, well-kept lawns probably have fewer places for ants to live than uncultivated fields, open spaces, and woodlands.)

**When looking for ant nests, please disturb things as little as possible. If you turn a rock or something else over to look under it, place it gently back when you are finished. The less you disturb the environment the better.**

- Look on the ground just as you did for individual ants. Look for small holes with ants entering and leaving. You may see some holes surrounded by small mounds of fine dirt. These may be entrances to ant homes even if ants aren't coming and going at the moment.
- Look under things.
  - Look under rocks or other objects—boards, branches, bark, pavers, etc.—that are lying on the ground. **CAUTION!** Especially if you are in an area that has snakes or scorpions or other small critters that might hurt you, be careful when turning over rocks and other objects lying on the ground. A good approach is to lift the rock or other object carefully from the far side—the side away from you. That way if something is living under the rock and darts out when you disturb it, it will be heading away from you rather than toward you. Whenever you are working outside, you should be aware of animals (snakes, scorpions, wasps, spiders, ticks, etc.) or plants (poison ivy, poison oak, etc.) living in that area that might be harmful to you. Know how to recognize and avoid them.
  - Look under dead bark on downed trees or branches.
- Follow foraging ants home.
  - If you see an ant carrying something, an insect part—a seed, or anything else that might be food—then following it should lead you to its home. (This might take

some time. You will be surprised at how far some ants wander away from their homes in search of food.)

- Give ants food to carry home and watch them. There is more information about baiting ants in the next section. However, if you put out cookie crumbs in various places where you have seen ants, they will probably find them and carry them back to their nests. If you use light-colored cookies, it should be easy to follow a crumb, and thus the ant carrying it back to its home.

- Look inside things.
  - Look in hollow twigs or dead plant stems. Some small ants live inside these.
  - Look in old acorns—ones that look as though they have been around not from the last fall but from the fall before that. There are tiny "acorn ants" that live inside acorns and similar sized plant seeds or growths.

## Foraging Ants

Ants on peonies (*Formica incerta*)

# CHAPTER 6
# Experiments and Challenges

Science is an ongoing process. It is never complete. Every answer raises another question. We saw that in the previous chapter. A simple experiment to ask what baits ants liked best led to the observation that some ants cover food laid out as baits.

It isn't possible to list all of the experiments you could do with ants. What scientists have learned about ants fills thousands of research papers and hundreds of books. You may or may not learn something that is completely new to science. You can, however, learn a lot that will be new to you. Most importantly, by experimenting with ants, you will learn how science works in a way that would be impossible by just reading about it.

What follows is not a complete list of experiments but some suggestions to get you started. As you work, you will get some answers but will discover far more questions. That is how science works, and if you have read this far, you are already well on your way to becoming a scientist.

## What Can Ants Taste?

With our tongue we can sense at least four different tastes: sweet, salty, sour, and bitter. There may be a fifth called umami. (Umami is an old idea but a relatively new taste term. It refers to a savory taste and is hard to define. You can read more about it from a variety of sources on the web.) Sweet, salty, sour, and bitter are already familiar to you. Table sugar—sucrose—has a sweet taste. Table salt—sodium chloride—has a salty taste. Vinegar—acetic acid—tastes sour. Coffee is an example of a bitter food. In nature, things with a bitter taste are often toxic, and our ability to taste bitter may help us avoid poisonous foods. (But you can't rely on it to keep you safe.)

You learned in Chapter 3 how to design taste tests. These can help you learn if ants can taste something whether they taste it and like it or taste it and don't like it. Thus you should be able to design experiments to address the taste challenges listed below. You will probably then think of other questions to ask.

### Sample Taste Experiment

What effect does the concentration of a solution of something like sugar have on the reaction of ants to the solution? Does it matter? If you think about it, concentration should matter. If you dilute a solution of sugar more and more, two things should happen. First, it will become so dilute that the sugar can't be tasted. Also, at some point it will become so dilute that even if the sugar can still be tasted, there is so little sugar in the solution that ants might use more energy carrying it back to the nest than they get from it. Based on both of these possibilities, you can make a **hypothesis:** a guess about how ants behave. The hypothesis would be that ants can tell something about how concentrated a sugar solution is and that concentration matters. The **prediction** from this hypothesis would be that if you present ants with several solutions of varying sugar concentrations, two things are likely. First, the more dilute the solution, the

smaller the number of ants that will be attracted to it. (They will prefer the more concentrated solution.) Second, at some point a solution will be so dilute that ants won't respond to it any differently than they respond to water, either because they can't taste it or because it is just too dilute to be worth the effort.

Here is how you can do an experiment to find out if concentration matters. (The "Sample Research Reports" on page 64 in the appendix shows the results of experiments done to address the importance of concentration.)

1. Make a series of sugar solutions of various concentrations. (See "A Note About Solutions and Dilutions" under "Taste Tests" in Chapter 3 for more information about making solutions and dilutions and to remind yourself what is meant by a "v/v" solution.)

   a. 25% v/v — Dissolve ¼ cup sugar in water to a final volume of 1 cup. (This is a 25% v/v solution. That means that 25% of the solution, by volume, is sugar.)

   b. 12.5% v/v — Dilute the 25% solution from step "a" in half by mixing equal parts water and the 25% solution—for example, ¼ cup solution with ¼ cup water.

   c. 6.25% v/v — Dilute the 12.5% solution from step "b" in half by mixing equal parts water and the 12.5% solution—for example, ¼ cup solution with ¼ cup water.

   d. 0% — Use water alone.

2. Give ants a choice among these four solutions, as described above, and count how many ants are at each solution every two or three minutes for a half hour.

3. Graph the results just as we did for the baiting experiment. Put the number of ants at a solution on the Y axis, the vertical one. This is the dependent variable. Put the time in minutes on the X axis, the horizontal one. This is the controlled independent variable. Use four symbols and four lines, one for water and one for each of the sugar solutions, a-c. The sugar concentrations are the independent variable. For a different look at the results, you could also try graphing the average number of ants at each solution, a-c (on the Y axis) against the sugar concentration in each solution (on the X axis).

## Taste and Other Food Challenges

1. Can ants taste the same four or five things we can taste?

2. There are several artificial sweeteners in common use in the United States. These include saccharine (Sweet'nLow®), aspartame (Equal® and NutraSweet®) and sucralose (Splenda®). Their purpose is to give a sweet taste to foods but without adding as many calories as sugar does. Some people don't like the taste of artificial sweeteners.

   a. Can ants taste any of these?

   b. If so, do they like or dislike them?

c. Does it matter whether they are presented to ants alone or with real sugar?

3. Do ants respond to artificial flavors? How?
4. Do ants respond to the color of a food? How?
5. Do ants have food preferences?
   a. Consider carbohydrates, proteins and lipids.
   b. Consider solid and liquid foods.
   c. Consider food mixtures.
6. Do ants' food preferences vary by species?
7. Does the size of a solid food matter? (What happens if you vary the size of cookie crumbs, for example?)
8. If ants get all they want of one food, will they then shift their preference to a different one or a different nutrient type? (Do they try to get a balanced diet?)
9. Are there substances ants can "smell" from a short distance without actually having to "taste" them? Attractants? Repellants?
10. Do the answers to some of these questions depend on the type of ant, the time of day, or other non-food variables?

# Does Location Matter?

Different animals live in different habitats. Some prefer the woods, some like open fields, some live in marshes, and so on. The same is true of ants. Different ants live in different habitats. You have found ants by baiting, by looking for their homes, and by finding them out foraging and following them home. You have also started to be able to distinguish between some of the more common ants in your area. You may not know their scientific names, but you recognize them when you see them. You can now start to ask questions about where ants live.

## Sample Ant Location Experiment

One place to start is to find out how many different kinds of ants live in or visit some area near your home. Choose an area where you have seen at least a few ants. Be sure to pick an area small enough to study thoroughly—a flower garden perhaps or a small lawn.

Here is one way you can survey this area for ants. Note that it is just an expansion of the procedures described under "Baiting Ants" in Chapter 3.

1. Choose two or three foods to use as baits. You might choose a jelly, a meat—either canned or small pieces of lunch meat—and peanut butter. If you want to try four, add cookie crumbs.
2. Place small amounts of these baits on 3x5 cards or on little crackers. You might even want to use grids like the ones on page 82. Using grids will let you estimate the size of

the ants you see. Place the cards, crackers, or grids around the area you want to survey. If you put all of the baits on one card, cracker, or grid, then put a card at each location. If you put them on separate cards, crackers, or grids, then put a set of all of your baits at each location. Don't put the baits only in places where you think there might be ants. Space them out evenly. If the area is relatively large, then put them equal distances apart in a straight line. If the area is smaller, you might set them out in a grid. Again, space them equal distances apart.

3. Keep track of how many ants come to each bait at each location. You might check every five minutes for up to a half hour. In some locations you might need to wait even longer.

4. Describe the different ants as completely as possible. (See "Identifying Ants" in Chapter 3 for suggestions on how to do this.)

5. If you want to get a better look at the ants and compare them, then there are two things you might try.

    a. Pick up the card or cracker or grid with the ants on it, pop it into a zip-type bag and seal the bag so that the ants can't get away. Unfortunately some ants, particularly the more easily scared ones, will probably get away before you can get them in the bag.

    b. A second thing you might try is to put the bait on its card, cracker or grid in a bag to begin with and prop the bag open with a couple of toothpicks or small sticks. Then it should be easy to pick up the bag and zip it closed without losing the ants. I'll admit that I haven't tried this. I suspect it will take ants longer to find baits inside a bag, and it may be that they won't find it at all. But who knows, it might work. One of the things scientists have to do is develop new techniques and find new ways to do experiments. This is one you can at least try.

6. If you collected ants in zip-type bags, you now have two choices.

    a. Study them as thoroughly as you can in the bag. They will run around, but at least they can't escape, and you can get up close to look at them with a magnifying glass. When you are finished you can let them go near where you caught them.

    b. If you want to keep them permanently you can put the bag in the freezer overnight. This is a humane way to sacrifice them without physically damaging them. You can then keep them indefinitely. You might even learn how scientists identify them under a microscope. (See the appendix and websites mentioned there.)

7. Try to determine how many different types of ants came to your baits. This will probably be easier if you used grids rather than cards or cookies. It will be easier yet if you captured the ants, at least temporarily, in bags so that you can put them side by side and really study them under a magnifying glass or microscope.

## Location Challenges

1. If you can study different habitats, ask how many kinds of ants you can find in each of them.

   a. Do some habitats have more kinds of ants in a given area than others?

   b. Do some types of ants live in more than one kind of habitat?

2. How many types of ant "homes" can you find? Where, within a habitat like a field or woods or suburban lawn and garden, do ants live?

3. What effect, if any, does it have on the ant population if a lawn or garden has been treated with chemicals including fertilizers, herbicides, and pesticides?

4. How far from their nest do ants forage for food? Is this the same for all kinds of ants? Will they recruit other ants to travel farther for some foods than for others?

# What Happens When Ants Meet?

Ants can be very aggressive animals. You may have seen ants of different types coming to the same bait. How did they act toward each other? Did ants of different types act differently than ants of the same type? Were there battles or little skirmishes? Were there any consistent winners or losers in such contests?

Ant behavior is amazingly complex. The more you look and carefully observe, the more you will see and learn. A magnifying glass will help here. If, by any chance, you have access to a camera that will take videos close up that would be wonderful, but you can do a lot of work with just your eyes and a magnifying glass.

If you are studying ants on your own lawn and garden, it might help you to locate and mark as many ant nests—places where ant colonies live—as you can. See Chapter 3 to learn ways to locate ant nests. They can be marked with inexpensive flagging available at many home and garden stores. (See Chapter 2.)

## Sample Ant Behavior Experiment

You can start to observe ant behavior when they come to solid baits or to sugar solutions. You might proceed like this:

1. Choose a place where you have found ants before. This might be a place where you know there are several different kinds of ants.

2. Put out a bait—something you know ants have come to in the past—or a sugar solution.

3. Get comfortable down on the ground where you can watch. Ideally get close enough so that you can observe the bait with a magnifying glass. If you sit still, many ants won't be bothered by your presence and will come to the bait and behave normally. (This is one of the great things about studying ants. They generally ignore you.)

4. Watch carefully and keep track of what you see.

# TEACHER'S PREFACE

My interest in ants began in the summer of 1990 when I used them to introduce the process of science to students taking a non-majors college biology course. Starting with the observation that ants would come to various foods set out on the sidewalk, teams of students were able to design and carry out simple experiments to determine whether ants could taste the same four things—sweet, sour, salt, and bitter—that we could taste. Many students found working with ants on experiments of their own design more interesting than performing other experiments described in their laboratory manual, and it seemed to me that they learned more about science and the design of scientific experiments from this work than they did from a more traditional approach. I continued using ants when I taught the course in succeeding summers. The more I worked with ants, the more I wanted to learn about them. A few books helped, and before long I had colonies of ants living in plastic shoeboxes in my laboratory. I was using these colonies with the high school students who came to our spring "Science Festival." I also developed some two to three hour exercises using ants that I used as elective labs with our non-majors students and with a summer program we ran to recruit students for our Honors College.

I was hooked!

With retirement approaching, I began to see the study of ants not only as something I enjoyed, but as a field of research I could continue when I would no longer have a laboratory. I am a biochemist. Breast cancer had been my research focus, both at the Michigan Cancer Foundation, where I spent fourteen years, and then in the Department of Biology at Indiana University of Pennsylvania where I was a professor for twenty-two years. In the spring of 2000 I heard about the Ant Course. It is designed to introduce young scientists to the study, and particularly to the taxonomy (classification and naming), of ants. I applied twice and was rejected twice—after all, I was not a "young" scientist but an established professor, and I was a biochemist, not a field biologist. Nevertheless, I persisted, and on my third try was accepted. So in August 2003 I found myself at the Southwest Research Station near Portal, Arizona, in the beautiful Chiricahua mountains. There, for ten days, one of the twenty-seven students, eleven instructors, five visiting instructors, and one teaching assistant at "Ant Camp," I started to learn formally about ants and how to collect, identify, and prepare them in a proper collection.

I loved it!

The leaders of the Ant Course were Stefan Cover from the Museum of Comparative Zoology at Harvard University and Dr. Brian Fisher from the California Academy of Sciences. In 2007 Dr. Fisher, project leader of AntWeb, a website devoted to ants of the world, named me remote curator for Pennsylvania. (Ben Coulter has since been added as co-curator for Pennsylvania.) In the fall of 2008 I used a sabbatical leave to begin a survey of the ants of Pennsylvania that continues to this day. (The list of ninety species on the Pennsylvania page of AntWeb comes from collecting by me and others and from museum collections. You can find Pennsylvania on AntWeb [www.antweb.org] by clicking on "Georegions" then "Americas" then "Northern America" then "United States" and finally "Pennsylvania.") So I am now part of the community of myrmecologists—scientists who study ants.

I "discovered" ants when I began using them in my teaching. As I started looking, however, I couldn't find much evidence that these fascinating insects have been used in teaching biology at any level. This despite how fascinating people of all ages seem to find ants once they learn a bit about them, and how easy they are to work with and study. (As Stefan Cover once told me, their study is one of the places where a backyard biologist can still make a contribution.) So this book is intended to introduce the study of ants to those with an interest in nature and a desire to learn how science is done.

Because I live in Pennsylvania, the illustrations are of Pennsylvania ants, and the procedures described are ones I know work here. I am sure, however, that they will work throughout the continental United States and probably beyond. I hope the book will help aspiring young biologists learn a bit about how scientists work. But my greatest hope is that it will lead them to go beyond noticing ants to really starting to see them for the fascinating animals that they are. And who knows, perhaps one day an applicant to the Ant Course will state on her application that *Amazing Ants: Simple Sidewalk Science* was the book that got her started.

# TEACHER'S INTRODUCTION

As noted in the preface, my interest in ants began when I started using them in teaching a general biology course for non-majors in my first years in the Department of Biology at Indiana University of Pennsylvania (IUP). In the summer, when I had a lot of freedom in the laboratory part of the course, I began taking students outside to perform simple taste tests using the ants—I don't know what kind or kinds—that were easily found crawling on the sidewalks on campus. They would come quickly to simple baits like sugar water, and students soon learned how to work with them. Later I started colonies in my laboratory housed in test tubes half filled with water and plugged with cotton balls. These were kept in plastic shoeboxes. I dusted the inside walls of the shoeboxes with talcum powder to keep the ants from crawling out. All these techniques I learned from reading *Journey to the Ants: A Story of Scientific Exploration* by Bert Hölldobler and Edward O. Wilson. This delightful book is a great introduction to ants and its appendix has all the information you need to start keeping colonies of ants in the laboratory or classroom. (I've outlined a simple approach in the appendix.) With captive colonies—or parts of colonies, I didn't always manage to catch a queen—I was able to use ants with the groups of high school students who visited each spring when our college held its Science Festival aimed at recruiting science majors to IUP.

The simplest way to start using ants in teaching is to go outside and work with them where you find them. Unless your school grounds are regularly treated with insecticides, ants should be easy to find. Where you find a few of them wandering on the sidewalk, you will probably be able to attract more to baits and begin your observations and studies. It has been my experience that I can usually identify locations where ants can be found most days and this makes getting started quicker and more reliable.

Establishing colonies for use inside is possible but a bit more complicated. I tried to have a colony for each four students. Since all of our teaching laboratories were set up with six tables

of four students this meant I had to maintain a minimum of six colonies. I say a minimum because on a given day at a given time ants in some colonies just didn't come out to forage but stayed in their test tube "homes." Not feeding them for a couple of days before I was planning to use them helped but didn't always completely solve the problem. Of course having colonies in the classroom has great advantages. They are available when working outside is impossible because of time, weather, or other constraints. They are easier to observe than ants outside are. You can see the eggs and larvae in the test tubes and even put the whole shoebox under a stereo microscope or the video setups that are increasingly common in classrooms. Such a video setup allows an entire class to observe one colony and watch an experiment unfold together. (This could be particularly important when you don't have enough colonies or enough active ones to let each group work with one. If you have several classes in one day, it would be challenging to have enough active colonies to go around.)

I can picture science teachers finding ideas in this book to use with students of all ages, from preschool and up. I can even imagine teachers passing this book out to interested students in the spring and urging them to use it over the summer and come back in the fall with a project, either underway or completed, for a school or regional science fair. The equipment required is mostly things anyone can find around the home. I have tried to keep the reading level reasonable for 7th-8th grade students.

On April 9, 2013 the Next Generation Science Standards (NGSS) were released. They are based on the Framework for K–12 Science Education developed by the National Research Council. What follows is taken from appendix F of the NGSS, "Science and Engineering Practices in the NGSS."

The eight practices of science and engineering that the Framework for K-12 Science Education identifies as essential for all students to learn and describes in detail are listed below:

- asking questions (for science) and defining problems (for engineering)
- developing and using models
- planning and carrying out investigations
- analyzing and interpreting data
- using mathematics and computational thinking
- constructing explanations (for science) and designing solutions (for engineering)
- engaging in argument from evidence
- obtaining, evaluating, and communicating information

The approach taken in this book fits these standards. It is focused on showing that science is a method of studying the world rather than a collection of facts about it, and it tries to engage students in doing science with minimum restraints on what experiments they conduct or what questions they ask.

The appendix contains outlines of three approaches that I used with students of various sorts in a variety of settings. They vary in length and would need to be modified for different uses, but they give you an idea of what can be done. A list of required materials is included with each outline.