Second Edition

Mineralogy
and Optical Mineralogy

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Mineralogical Society of America

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Preface

Introduction

Welcome to the world of mineralogy! Mineralogy, while usually associated with geology, is really a stand-alone discipline that weaves itself into such diverse fields as chemistry, art, forensic science, wine production, and health-related issues, to name only a few. While this book is geared toward mineralogy as it applies to geology, it will also address mineralogy as a discipline in itself, and show you how it is related to the other sciences, arts, and everyday life. We developed the second edition of this textbook based on our now over 60 years of research and teaching in mineralogy, and many more years spent *thinking* about the best way to teach mineralogy in the 20th century.

This book is an outgrowth (possibly an *overgrowth* would be a better term!) of two CD-ROMs produced by Tasa Graphic Arts, Inc. The first, *The Study of Minerals*, was written by M.D.D. in conjunction with two of her former colleagues (Gil Wiswall and Rich Busch) at West Chester University (Dyar et al., 1997, 1998). Its purpose was to illustrate the major concepts needed to teach mineralogy in a graphical, interactive fashion. *Hands-On Mineral Identification*, a collaboration between M.D.D. and Dennis Tasa, soon followed, because we wanted to share the fun of mineralogy with the general public (Dyar, 1997). However, in writing these CD-ROMs, we became motivated to expand into a medium that would allow more background information and detailed explanations of our graphics, so the idea of this textbook was born.

From that point on, the book gradually became a reality through a combination of serendipitous circumstances: the genius and willingness of Dennis Tasa, who came up with the idea of animating every illustration in this book on an accompanying web tool; the chance meeting of Darby and Mickey in a van on a field trip at the NSF-sponsored Teaching Mineralogy Workshop in 1996, where they discovered their similar teaching philosophies; and our mutual desire to incorporate newer pedagogy into the teaching and learning of mineralogy.

As teachers, we were both excited by the prospect of seeing the material we teach in mineralogy come alive through colorful, 3-D animations. We can think of no other topic in the geosciences that is so inherently dependent on 3-D concepts. For years, we have both struggled with perspective drawings on a chalkboard that just don’t do this material justice.

Further motivation was supplied by funding from the National Science Foundation, whose support of this project made it possible for M.D.D. to spend a semester at the University of Idaho and share M.E.G.’s Mineralogy class. We were fortunate to have this time together to dissect this material and have endless discussions about the best way to teach this course. This text represents a merging of our approaches, and it has benefited greatly from the insights made possible by spending time together in the same classroom.

How This Book Differs from the Others

This book differs in several ways from a traditional mineralogy textbook: (1) it is supported by a set of animations available on the web; (2) a searchable mineral database has been created to avoid cumbersome tables; (3) we use modern pedagogy; (4) it is written so that the more advanced chapters build on information learned in the earlier chapters.

It is fairly commonplace now for textbooks to include animations. While these can often be useful as stand-alone items, integrating them with ones in the textbook will help you better learn the material that requires 3-D animations to understand.

The comprehensive mineral database, which is often included in beginning mineralogy textbooks, is contained in our mineral database app. This has several other advantages. First, the database is more easily searched than one in a standard paper text. Second, you can easily have it with you always, whether you are in the lab or the field, and no paper database has rotatable structures.

Very few science textbooks are taking advantage of advances in pedagogy that have occurred over the past 10 to 20 years. Instead, these textbooks tend to present the material in the same way it has been taught for the past 100 years. These methods worked in the past, and may still work well for some students. However, research has shown that newer pedagogies can result in better learning, which is why we have incorporated them into our text.

Who Cares About Mineralogy?

We hope that this book will help you appreciate the role of mineralogy as it applies to geology, the other sciences, and more broadly speaking, our everyday lives. As a geology student, your thoughts about minerals are probably like ours when we took mineralogy. First, we heard that the course was very hard, and we thought the only goal of the course would be to learn how to identify minerals. Admittedly the course and the course material can be difficult because of the need to visualize things in three dimensions for the first time in your academic career. At the same time, you have to recall (or learn for the first time) principles from other courses such as mathematics, physics, and chemistry. The many animations on the MSA website should help you deal with the first of these problems. To help overcome the need for background knowledge in chemistry, physics, and mathematics, we have utilized new pedagogical methods that use spiral learning, concept maps, and inquiry-based learning to present this material.

Probably the biggest problem with mineralogy is your expectation that the main thing you will learn is how to identify minerals. You probably think that mineralogy is really only useful to identify minerals and, in turn, rocks. This could not be further from the truth. One of the goals of this book will be to broaden not only your views, but the views of others on the importance of mineralogy outside the field of geology. We'll do that by providing you with many relevant, everyday, uses and applications of minerals.

Our Reasons for Writing this Book

Mineralogy is of fundamental importance to the geosciences (solid earth, planetary, soil, hydrological, environmental, and ocean sciences) because the composition, structure, and physical properties of minerals ultimately control natural chemical and mechanical processes. Mineralogy has traditionally been one of the cornerstones of the geoscience curriculum. We cannot hope to understand how the Earth or other planets work if we do not know what they are made of! Whether representing melting reactions near the Moho on a pressure-temperature diagram, or examining Eh-pH relations that control acid mine drainage while using minerals to immobilize hazardous waste, the relationships between minerals and their local environments have important implications for all geosciences and for society. Ignorance of mineralogy has cost our society dearly, as witnessed by the asbestos problem of the 1980s (Gunter, 1994) and, more recently, the ruling that quartz is a human carcinogen (Gunter, 1999). Mineralogy is also particularly needed by K-12 educators: the first questions asked by students about geology are usually based on pebbles picked up on the playground. Elementary school children are always asking their teachers "What is this?"

The challenge we face is to take advantage of this natural curiosity about minerals. However, the subject of mineralogy, when taught at the college level, has historically been less than inspiring to the majority of students. A large part of the problem, we feel, has been the lack of an adequate textbook. The issue is not that mineralogy is uninteresting, but rather that new methods and materials for teaching mineralogy are needed to demonstrate fundamental principles and to present this information in meaningful contexts to create a better learning environment. In this book, we attempt to face these challenges.

When we started teaching mineralogy, each of us taught the course the way we had learned it as students. The class is usually taught as a series of subjects (crystallography, crystal chemistry, classification, etc.) in a very linear fashion, starting with a set of supposedly-simple material and progressing in a straight line to complex material. For example, a mineralogy course traditionally starts with crystallography. While it is incredibly important for many untold reasons, crystallography is very difficult to learn without being placed in some context. There is a huge amount of vocabulary that goes with learning crystallography, and it is often the first time that students face college-level studies of abstract visualization in three dimensions. After several weeks of crystallography (often without even the mention of a mineral name), the class moves on to crystal chemistry. Again, a large amount of material is introduced, completely distinct from what has come before.

About half-way through the semester, the first mention of real minerals occurs, and the remaining studies of minerals and mineral classes typically march through the progression of systematic mineralogy beginning with elements, sulfides, oxides, and ending with silicates. Depending on the experiences of the instructor, these subjects may not be interrelated, but merely presented as a set of facts that together constitute the science of mineralogy. All too often, with time running short at the end of the semester, coverage of the silicates is limited.

After several years of teaching in exactly this sequence, *it became very apparent to us that this was not a good approach.* Clearly portions of the course were improperly balanced. The majority of the minerals we asked our students to learn do not occur commonly as rock-forming minerals; e.g., a small number of silicates make up over 90% of the Earth's crust. Why not start with the really important silicates (i.e., quartz, feldspars, micas, amphiboles, and pyroxenes) the first day? Why are we devoting so much time to crystallography and crystal chemistry without relating them to each other (or perhaps more importantly, to geologic processes, and to the types of minerals that will occur in various parageneses)? So we began to rethink our curriculum and teach this course differently. Eventually this led to the creation of this book.

Using this Book: Professors Take Note!

This book is designed to have great flexibility in its use, so that it can serve the needs of introductory or advanced level mineralogy courses. It is written at three "levels" with increasingly amounts of complexity (Table 0.1). *No one* will cover all the material in this book in a single semester course, but we hope that *everyone* will find specific chapters, which are written to be somewhat modular, that fit their curricula.

The text begins with an introduction to mineralogical concepts, which we call "Round One." This chapter contains everything a student really needs to know about mineralogy to succeed in life. It is our hope that ten years after taking this course, a student will still remember and understand the concepts presented there. This chapter usually takes us a week or two to cover in class.

The second section of the book, which we will refer to as "Round Two," includes all the basic material on minerals that a geologist needs to be exposed to. This section is divided into chapters on elements, important minerals, crystal systems, symmetry, and optics. This material usually requires about 6–8 weeks to cover in lecture form, and thus constitutes what might be needed to cover mineralogy in a course (like Rocks and Minerals) that also includes discussion of rocks.

The third section of the book represents the most advanced material coverage ("Round Three"), where we meet the course material for the third time! Here we use a more conventional approach to present this material. Where possible, concepts are derived from basic principles, and the interconnectedness of ideas is stressed. This section can be used as a standalone textbook all to itself for a junior- or senior-level mineralogy course. However, we use it as the basis for the last

Table 1. Organizational Structure of the Text, and Suggested Use in a One-semester Course

Round one (1 week) Chapter 1	*Round two (3-4 weeks) Chapters 2-6*	*Round three (8-10 weeks) Chapters 7-21*
Introduction	Ch.2. Hand Sample ID	
Big Ten Minerals	Ch.3. Crystal Chemistry	Ch.7. Chemistry of the Elements Ch.8. Bonding and Packing Ch.9. Chemical Analysis Ch.10. Mineral Formulas
Elements	Ch.4. Crystallography	Ch.11. 2-D Symmetry Ch.12. 3-D Symmetry Ch.13. Mathematical Crystallography Ch.14. Representation of Crystal Structures Ch.15. Diffraction
Crystal Systems	Ch.5. Optical Crystallography	Ch.16. Introduction to Optics Ch.17. Optical Crystallography Ch.18. Optical Crystal Chemistry Ch.19. Mineral Identification
Optical Systems	Ch.6. Systematic Mineralogy	Ch.20. Environments of Mineral Formation Ch.21. Nomenclature and Classification Ch.22. Silicate Minerals Ch.23. Non-Silicate Minerals Ch.24. Mineralogy Outside of Geology

half of our mineralogy classes, giving students a third, in-depth exposure to the material. We find that having the previous exposure (from Rounds One and Two) to the material at gradually increasing levels of complexity makes it easy for students to engage the most complicated concepts in mineralogy with relative ease.

So, you can use this book in one of three ways:

1. Use only the first two sections to cover mineralogy, as part of a Rocks and Minerals type course.
2. Use only the last section as part of an advanced course.
3. Mix and match chapters to suit your needs.

We encourage instructors to try the combined approach of using all three levels of the book to teach mineralogy. Modern pedagogy suggests that students learn best when curricula continually build upon previous learning experiences. A growing body of pedagogical research supports the idea that knowledge acquisition occurs in a non-linear, spiral fashion involving repeated exposure to concepts (e.g., Wals and van der Leij, 1997). This is called "spiral learning" (Figure 0.1) as described above.

We encourage you to refer to the MSA website dedicated to this book. A conventional textbook with 2-D illustrations cannot present the critical material needed in a modern mineralogy course. We also encourage you to use the programs (i.e., CrystalViewer™, CrystalDiffract®, Single Crystal™—the latter two running in demo mode) and input files on the MSA website to "interact" with minerals. Of course, we also encourage you to supplement this textbook with a rich assortment of hands-on encounters with minerals using hand samples, thin sections, grain mounts and whatever other techniques you have around.

Course Goals

Before we leave this introduction, we would like to present a suggested pedagogical framework for a mineralogy course. These thoughts are the result of stepping back and questioning what we really want students to learn from our one semester mineralogy course. Together we have arrived at the course goals that are discussed below. We realize that learning comes from repetition of material moving from simple to complex, and from establishing connections between material as learning occurs. Thus we have incorporated several different teaching strategies into our courses, which are summarized here. We hope that this methodology will stimulate others to re-evaluate their own goals and methods for teaching this course.

Figure 0.1. *Spiral learning curve for a language. The curve builds from simple at the bottom to more complex at the top. The lower material must be mastered before the upper material can be learned.*

The first step in developing a course is to set forth its goals. Most professors instinctively model their courses on the ones they took as undergraduates. For a number of reasons, this is probably not the best approach: we are not clones of our professors, each class has its own level of student intellectual ability, and the material we are teaching is constantly changing. Accordingly, the following course objectives were developed. We believe this set should serve many, if not most, mineralogy courses currently being taught.

Introduce crystallography, crystal chemistry, and systematic mineralogy. Our goal is to help students attain a working knowledge of these basic concepts in mineralogy. What do these words mean? In this context, crystallography is simply the study of atomic arrangement. It is the science of how atoms arrange themselves to make crystals, and it has profound applications not just in mineralogy, but in chemistry, biology, physics, material science, and even mathematics. Crystal chemistry involves understanding the chemical make-up of those atomic arrangements. In other words, we want to know which kinds of atoms are where in the mineral, and why. Systematic mineralogy involves mineral classification and descriptions of minerals' physical properties.

Relate the physical properties of minerals to their crystal structures. Before students take mineralogy, they have probably thought about minerals from the perspective of hand samples; color, hardness, streak, and other properties are taught in middle, junior, and high school as well as in most introductory geology courses. Thus, most students enter the course focused on physical properties, which in this context include any observable or measurable characteristics. We can use these physical properties by relating them to characteristics of mineral structure or chemical composition. To understand minerals is to use these interrelationships to our advantage, to help not only in mineral identification, but also in relating mineralogy to geology.

Introduce analytical methods used in modern mineralogy, especially the polarizing light microscope. Ultimately in this course we must move away from hand sample diagnostic properties, which often yield incorrect mineral identifications, and into more unequivocal types of mineral characterizations. Analytical methods are an important part of mineralogy because they help identify and characterize minerals! If students have access to polarizing-light microscopes, they can learn one of the oldest and most useful tools in our field. It is also a useful skill to have when applying for jobs: for example, there are countless jobs outside the field of geology that require the use of light microscopy! Depending on the accessibility of other analytical equipment, students can also have the opportunity to learn how modern mineralogists work.

Learn how minerals are classified and named. As in biology, paleontology, and other fields where hierarchies are important, there is a formal classification system for minerals. It is based on the kind of anion or anionic complex in a mineral's structure, and, to a lesser extent, on crystal structure itself. Sadly, a large percentage of geologists do not understand the difference between a mineral species and a mineral group, leading to constant (and unnecessary!) confusion in petrologic studies and even raising important legal issues (e.g., Gunter et al., 2001). Mineral species names come from localities (where they are first found), appearance, chemical composition, and people's names. There are more than 4,300 officially-recognized mineral species names, and about 14,000 other mineral variety names that are in common usage. Through this course, we hope to give students familiarity with mineral nomenclature so they can use it correctly in their future lives as geoscientists, lawyers, medical professionals, etc.

Identify minerals in hand specimen and thin section, and with the aid of various analytical techniques. Mineral identification is a skill that is fundamental to many kinds of geology. By the end of this course, students should have the ability to identify many minerals with a hand lens on an outcrop, or in the lab with a thin section. The students' abilities to recognize minerals will progress as they gain experience and have access to different analytical facilities!

Appreciate the influence of crystal chemistry on mineral assemblages and mineral weathering. This is a course about minerals, so we try to avoid talking about rocks whenever possible (that's the province of petrology!). However, sometimes the process of mineral identification is aided by knowledge of where the sample comes from. So we'll look into the ways in which mineral chemistry affects rock-forming and rock-breakdown processes.

Develop the ability to research and learn mineralogical topics individually and in groups. When we teach this class, we encourage our students to explore this field through a series of individual and group learning projects. We hope that they will be inspired to look beyond classical mineralogy, and to do some research of their own on some aspect of mineralogy that they find interesting. We also explicitly recognize and do assessments based upon group and cooperative learning (e.g., Srogi and Baloche, 1997), and in doing so we remind our students that group learning is a necessary skill for employment in the 21st century. This approach incorporates the essential features of inquiry. Students are engaged by scientifically oriented questions. They give priority to evidence allowing them to develop and evaluate explanations that address these questions. Students must also evaluate their explanations in light of alternative explanations, and they must communicate and justify their explanations (National Research Council, 2000).

How to Accomplish the Goals

To accomplish the goals of learning mineralogy, we use four basic forms of pedagogy (i.e., learning methods and teaching styles) that should help students learn the material. These forms are: (1) spiral learning, (2) inquiry-based learning, (3) concept maps, and (4) interactive models and visualization. Each of these will be discussed in detail below, with pertinent mineralogical examples. We have selected these methods because research shows that they are some of the best strategies for learning.

These are the methods that most of us actually use to learn in other contexts, and they are well documented as learning strategies. For example, spiral learning involves beginning with a new concept and continuously reinforcing it as new, more advanced concepts are introduced. Consider a non-mineralogical example: when we first learned to cook, we learned the ingredients before we learned the recipes, but in making the recipes we relearn the characteristics of the ingredients. The same is true for mineralogy, where we first learn the ingredients (i.e., elements) and next learn how those ingredients are "mixed" together to make things (i.e., minerals). One step further in this analogy would take the different dishes (i.e., minerals) and combine them to make a meal (i.e., rocks), all the while considering the elements and minerals that make up the rocks. Continuing with the cooking analogy, inquiry-based learning involves questioning what might happen when we do something (substituting baking soda for baking powder in a recipe, for example), and then doing it to see the outcome (flat cookies!). For concept maps, the cooking analogy would show linkages between different types of foods, and interactive multimedia might be used to show the interrelationships in three dimensions. Incorporating these new methods into a mineralogy course becomes intuitive (and quite liberating!) once we dismiss our preconceptions (and previous experiences) based on our own backgrounds, and think about how we all learn!

Spiral learning. The idea of spiral curriculum was first developed by Bruner (who was in turn inspired by Piaget) as part of what is called "constructivist theory" starting in the 1960s (e.g., Bruner, 1960, 1966, 1973, 1990), and it has been widely adapted in K-12 curricula around the world (Texley and Wild, 1996). It is based on the idea that learning is an active process in which students always construct new ideas and concepts based upon their current and previous knowledge. Its underlying tenet is that basic scientific concepts can be introduced to children in a form that is easily comprehensible to them at early stages of their education. The same concepts can then be revisited repeatedly at successively higher levels, enhancing and deepening students' understanding of the concepts, so that students are continually building upon what they have already learned. A spiral curriculum is a very powerful educational tool, as it enables educators to carefully stage their teaching of often quite complex concepts in a way that makes it intelligible and interesting to their students (see Tobin, 1993 for examples). However, constructive approaches are rarely used in college-level science courses, which are typically linear in the way they present material.

Figure 0.1 shows an example of spiral learning in language. There are a series of words along the spiral. These words start with the simplest components of speech at the bottom, and end with the more complex at the top. The first thing we must learn before we can learn any language is its alphabet. Once this is mastered, we start to make words from these letters, and then form sentences from these words. There are rules we use to make words (spelling), and there are also rules we use to build sentences (grammar). When we begin to compose sentences, we are using words, and in using words we must know the alphabet. Thus each concept reintroduces and builds on the one below it. Finally, we put sentences together to form paragraphs. At each level, we are using the material from the level below, so we are reinforcing our knowledge of it.

We learn mathematics in a similar way (in fact, did you ever notice how your algebra skills improved during calculus?) (Figure 0.2). The first things we learn in mathematics are numbers; this is of course the "alphabet" of mathematics. The next whirl of the spiral is counting, which reinforces acquaintance with numbers, and the next logical step is addition. Once we can add, then we can subtract, but we cannot learn subtraction until we know addition. This process continues up the spiral. In fact, we often joke that when learning mathematics you never actually learn the last mathematics course you took because you only learn the previous course while taking the current one!

Figure 0.3 shows a spiral learning curve for crystal chemistry and Figure 0.4 shows a spiral learning curve for crystallography. A similar theme can be seen in these two figures when compared to the previous figures on language and mathematics. In all cases we start with something very simple and build to more complex knowledge. However, in crystal chemistry and crystallography these two spirals are also linked to each other; we must understand both of them and their integration to understand either of them. This linkage of material is formalized in education theory based on a concept maps (see following section).

In our own courses, we also envision the interrelationships among concepts with a learning spiral (Figure 0.5). Students continually reinforce the concepts learned previously, and they master simple subsets of material (e.g., ten minerals and six crystal systems) before moving on to more involved material (e.g., >150 minerals and 32 crystal classes). In fact this is the method we use when we need to learn new material (i.e., obtain several publications on the subject and read each one in increasing detail).

Concept maps. Concept maps show how material can be linked in a nonlinear fashion. Concept maps, like spiral learning, have become very popular in modern learning theory, and have been applied to everything from foreign languages to law, and even the sciences. Novak (1991, 1995) provides a recent overview of concept maps.

Figure 0.6 shows a concept map of geology and mineralogy. Within the boxes on a concept map there are usually given some objects, and a relationship is shown between these objects by using lines to connect them to other boxes. Geology is the central theme of this concept map. Geology is broken into six separate disciplines in this concept map, though of course many more could be included. One of these disciplines is mineralogy. Mineralogy is in turn broken into two separate subdisciplines: descriptive mineralogy and crystallography. Then the concept map shows how crystallography uses various techniques such as X-rays and microscopes, and in turn how other disciplines such as chemistry, physics, and art use the same instruments. Thus, links are established between art and geology. This map is of course not all-inclusive, because it could also show links between other subdisciplines in the field of geology to other disciplines outside the field of geology.

Another concept map (Figure 0.7), shows how we link the goals of our mineralogy course. In this concept map, minerals are the central theme. The upper four boxes show how minerals relate to other things we see in the world. First, minerals make up rocks; this is important for geology and is one of the main reasons students take mineralogy! Minerals also weather to form soils, though this is more the domain of agriculture rather than geology. The other two boxes show that minerals make up bones and teeth, and minerals are also used in many important industrial applications. The lower portion of the concept map shown in Figure 0.7 hopefully clearly defines the goals for our course. It shows how minerals are classified, named, and identified.

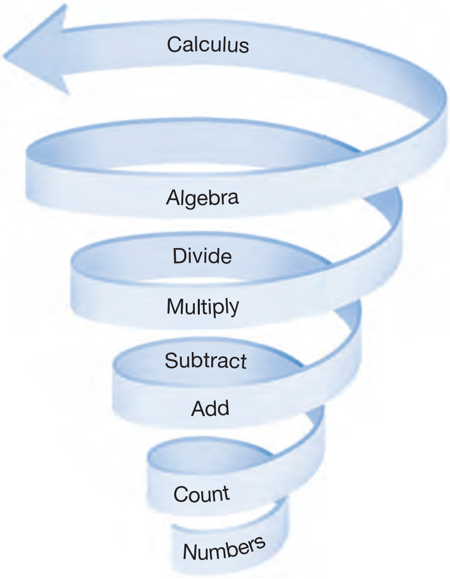

Figure 0.2. *Spiral learning curve for mathematics. The simple mathematical concepts are on the bottom, the more complex on the top. Each spiral will reinforce the material below.*

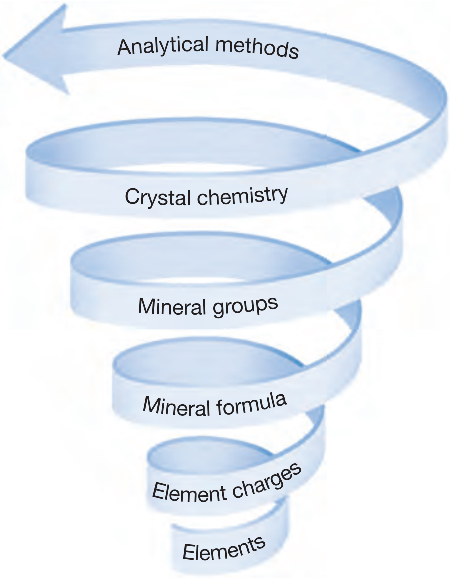

Figure 0.3. *Spiral learning curve for crystal chemistry.*

Inquiry-based learning. The inquiry-based approach (Fuller, 1980; Renner et al., 1985; Lawson et al., 1989; Wheeler, 2000; Bybee, 2000) is the centerpiece of the National Science Education Standards (National Research Council, 1996): "Inquiry into authentic questions generated from student experiences is the central strategy for teaching science" (p. 31). This approach is being increasingly used in the social science and education literature (Cangelosi, 1982 is an early example). The need for this approach is nicely summarized by Alberts (2000) as follows, in a paragraph where the word "Mineralogy" could easily be substituted for "Biology":

> "Where in a typical Biology 1 college course is the "science as inquiry" that is recommended for K–12 science classes in the National Science Education Standards (National Research Council, 1996)? These courses generally attempt to cover all of biology in a single year, a task that becomes evermore impossible with every passing year, as the amount of new knowledge explodes. Yet old habits die hard, and most Biology 1 courses are

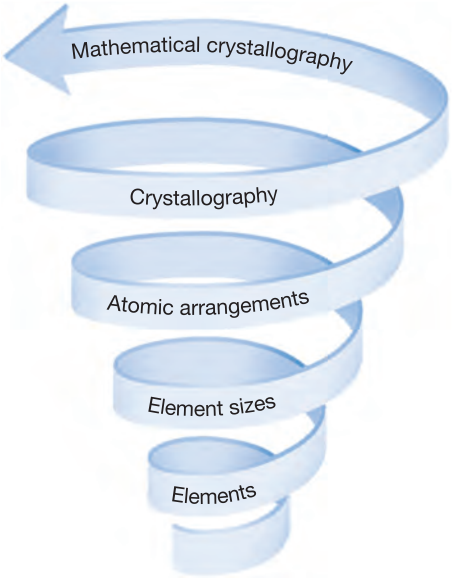

Figure 0.4. *Spiral learning curve for crystallography.*

> still given as a fact-laden rush of lectures. These lectures leave no time for inquiry: they fail to provide students with any sense of what science is, or why science as a way of knowledge has been so successful in improving our understanding of the natural world…" (Alberts, 2000, p. 9–10).

Alberts (2000) goes on to say that inquiry-based learning is by far more efficient for long-term knowledge than the more traditional ways of simply being told how something works. In inquiry-based learning, students must be asking questions why and, in turn, trying to figure out the answers for themselves. Eventually students may be told the answers in class or read them in books, but if they have already figured them out, or at least thought about them, they will remember them much longer, and it will make more sense to them than if someone simply told them.

To be honest, we ourselves have not yet become comfortable enough with this concept to structure the entire course around it, but we use a combination of presentations of material that can be learned by experience, and material that can be learned through traditional methods. This accommodates students with different learning styles, as clearly stated by Welch et al. (1981, p. 46):

> "Our stance is that all students should not be expected to attain competence in all inquiry-related outcomes, which science educators (including ourselves) have advocated in the past. For some students and in some school environments it may not be appropriate to expect any inquiry-related outcomes at all."

As an example, the lecture on hand sample identification may begin by passing around a set of hand samples of different minerals. We then ask the students to think about a classification scheme that would allow them to organize the minerals

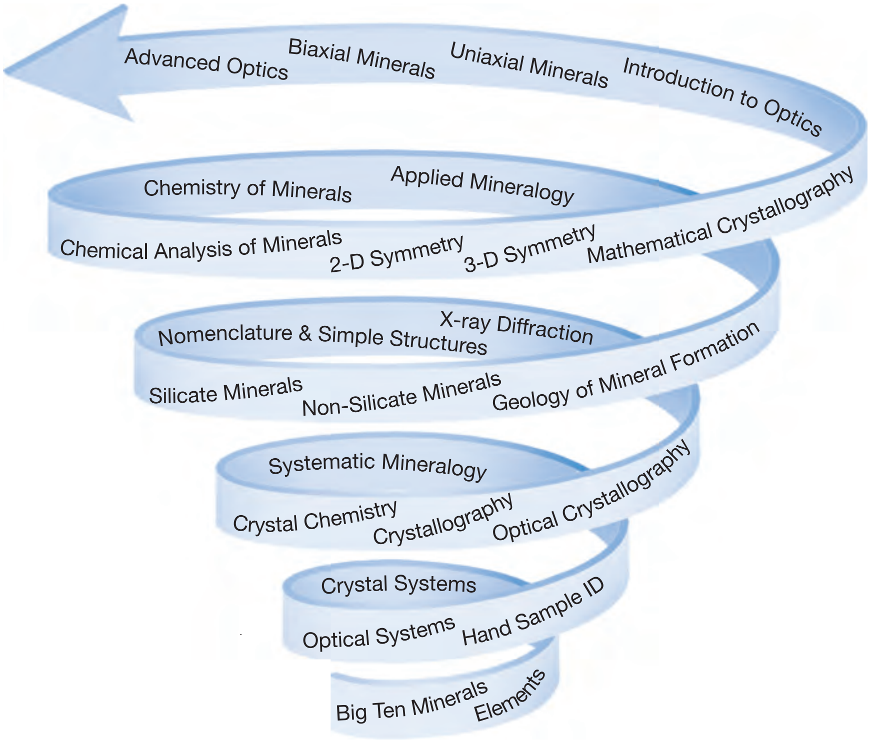

Figure 0.5. *Spiral learning curve for a one semester mineralogy course.*

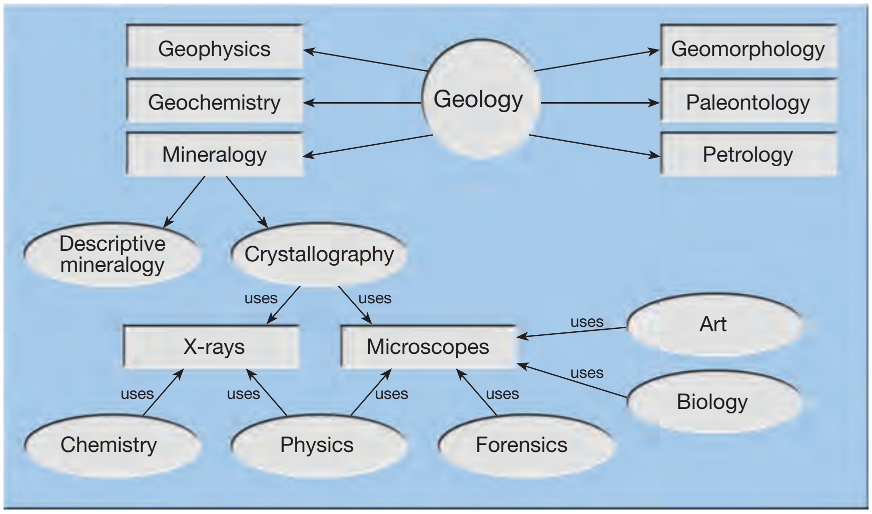

Figure 0.6. *Example of a concept map for geology and mineralogy. The map shows the different subdisciplines of geology and how mineralogy relates to other disciplines.*

into logical groups. Most students will instinctively group minerals by color and, to a lesser degree, morphology. A list of descriptive criteria for organizing the minerals is developed, and possible distinctions are discussed. Next, the chemical formulas for the minerals are written on the board, and students are asked to search for clues in the formulas to explain the differences in color (almost always caused by the presence of iron in silicate minerals). They are then given the opportunity to reconsider their putative classification scheme in light of the new chemical information. Ultimately they usually come up with a rational scheme that is not too far from the conventional one. Eventually, we present the "recognized" ways of identifying and classifying minerals, and end by summarizing the appropriate terminology in this area (which is often not far from the descriptive terminology used by students). So, we start off by asking students to conceive of their own schemes, and conclude with the "official" scheme, making the transition from inductive to traditional learning. This is a very different approach from what we normally use in formal lecturing. It takes a lot of time and patience, and it is very different from the way the material was taught to us. It also requires that the professor have a thorough understanding of the material being covered, because it is sometimes necessary to defend the rationale behind whatever it is that you are teaching. We love rising to this challenge!

Interactive models and visualization. One of the biggest problems in teaching mineralogy is the need to work with inherently three-dimensional course material, especially in a classroom with a two-dimensional blackboard. Most of us already rely extensively on visual aids including ball and stick models, coordination polyhedra, and optical indicatrices. However, unless the students interact with these materials, they are essentially static, and their teaching value is greatly diminished. The ideal is to pursue engagement with these materials, involving "student thought and interaction that goes beyond simple manipulation or movement via computer prompts" (Libarkin and Brick, 2002).

In many existing mineralogy classes, interactive tools are already used for many activities. Several of these are described in the *Journal of Geoscience Education* (e.g., Beaudoin, 1999) and in the MSA workbook on this topic (Brady et al., 1997). The infamous wooden blocks used to teach symmetry provide a good example of an exercise that helps students understand complex processes through direct manipulation. Many instructors employ styrofoam balls and wooden sticks to teach lessons about coordination polyhedra. Short of having students assemble their own crystal structure models (Gunter and Downs, 1991), visualizing and interacting with mineral structure models is more difficult. For these and many other abstract or inherently three-dimensional concepts in mineralogy, computer animations may provide a means for directly interacting with course material.

Use of interactive video- and computer-based learning programs has clear advantages for students. Research shows that the use of 3-D models will allow students to discern patterns more quickly and to detect relationships between patterns or structures that are not obvious in 2-D (e.g., Brodie et al., 1992; Kaufmann and Smarr, 1993). As noted in Bransford et al. (1999), "the ability of the human mind to quickly process and remember visual information suggests that concrete graphics and other visual representations of information can help people learn (Gordin and

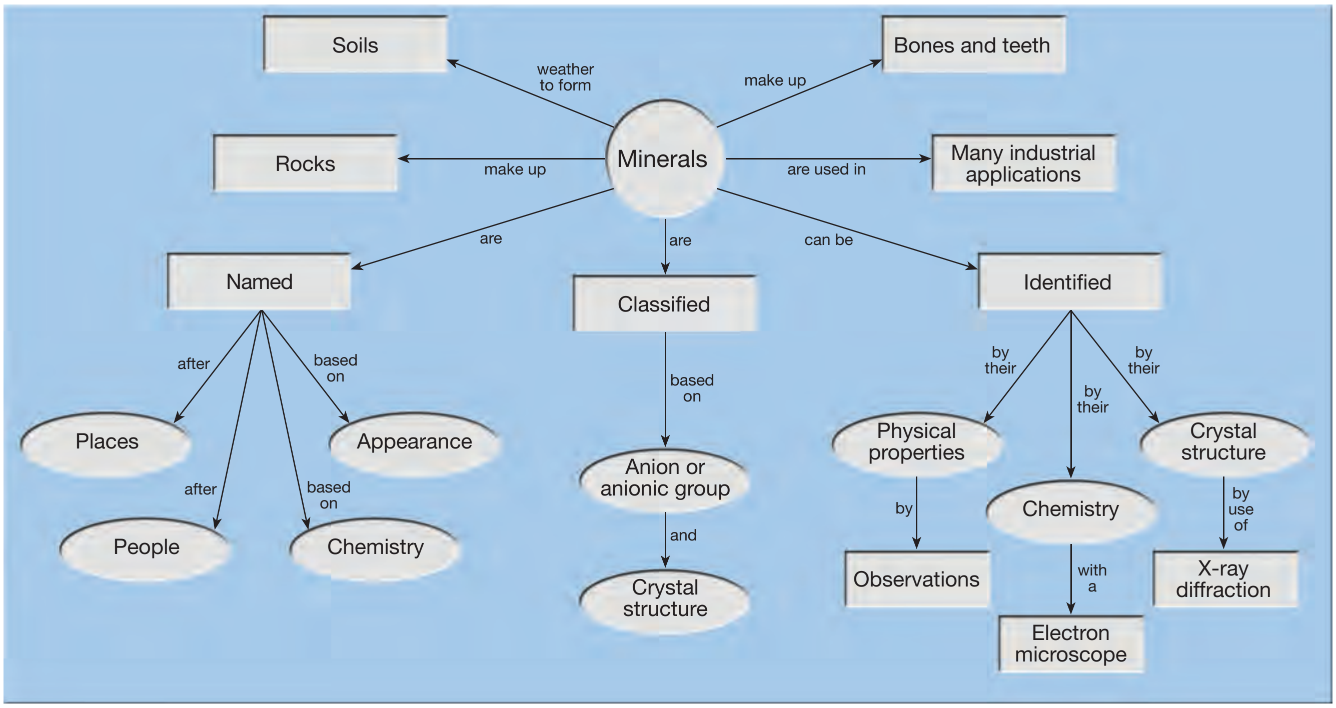

Figure 0.7. *Concept map graphically showing the goals of our mineralogy course.*

Pea, 1995), as well as help scientists in their work (Miller, 1986)." Interactive exercises have the potential to act as "tutors" to give students feedback on their understanding of the material. For example, the XTALDRAW program (Bartelmehs, 2002) or CrystalMaker (Palmer, 2002) begins with a simple listing of symmetry and atomic coordinates and from these, displays animated drawings of mineral structures. If used in lectures, these animations are basically an extension of static images with the advantage of better illustration (Libarkin and Brick, 2002). A more engaging student activity is to let the students build or manipulate the input files themselves, so they can understand the effects of varying crystal class or atomic locations. Of course, the MSA website should serve as a vehicle for in-depth interactions with the course content.

Finally…

Both Darby and Mickey (Figure 0.8) were fortunate to learn mineralogy the first time around from some wonderful instructors, despite the fact that traditional approaches were employed. However, the mineralogy courses of the 1960s and 1970s are still being regurgitated nearly verbatim in geology departments around the world, and this is, to us, a sad state of affairs. Writing this book is our response to the situation! As both research mineralogists and teaching faculty, we feel obligated to do what we can to teach our mineralogy courses in the most effective way possible. We believe that awareness of ongoing research into the effectiveness of new pedagogies, as well as use of this textbook, will convince instructors who teach mineralogy to consider making some changes for the betterment of the discipline.

We hope you enjoy this textbook, and that it helps make the study of minerals the most enjoyable class you've ever taken. We both feel that minerals are the most interesting, intriguing, and *important* aspect of geology: as Prof. Howie once said "If you take away the minerals, the rocks will fall down!" (Howie, 1999). We believe that rocks without minerals are just air. We firmly believe that *mineralogy can be fun*, and we hope you agree with us by the end of this book!

Acknowledgments

Production of this textbook was supported by NSF grants DUE-9952377 and DUE-0127191. We would like to thank all those mineralogists, as well as all the students and colleagues, from whom we have had the pleasure to learn.

This project would never have happened without the dedication and hard work of the staff at Tasa Graphic Arts, Inc.: Dennis Tasa and Karen

Tasa, Dan Pilkenton, Cindy Robison, and Holly Sievers. Work by David Palmer and the staff at CrystalMaker® Software (www.crystalmaker.com) made it possible to include viewer versions of their CrystalMaker®, CrystalDiffract®, and SingleCrystal™ software packages. We highly recommend that you purchase the full implementations from them.

We also acknowledge the support of our program directors at NSF, including Jill Singer, Jeffrey Ryan, and Keith Sverdrup. Special thanks go to Kylie Hanify and Don Halterman for proofreading the mineral database, and to Omar Davalos and Olivia Thomson for assistance with the second printing. We also thank our friends and colleagues at the Mineralogical Society of America, including Alex Speer and Rachel Russell, as well as the MSA subcommittee on this textbook, which was chaired by Peter Heaney. Paul Ribbe deserves special thanks for his early (and ongoing!) encouragement of this project.

In addition to those mentioned earlier, we also thank everyone on this list who contributed advice, photomicrographs, and reviews of this book.

Richard Abbott
Ross Angel
Bryan Bandli
David Barnett
Rachel Beane
Monte Boisen
John Brady
Kramer Campen
Ma Chi
Brian Cooper
Chuck Douthitt
Bob Downs
Drummond Earley
Eric Essene
Carl Francis
Greg Gerbi
Michael Glascock
Tim Glotch
Edward Grew
Bernard Grobéty
Steve Guggenheim
Bill Hames
Kylie Hanify
Rick Hervig
Kurt Hollocher
John Hughes
John Jaszczak
David Jenkins
Manfred Kampf
Dan Kile
Andrew Knudsen
Matt Kohn
André Lalonde
Pierre Le Roch
Donald Lindsley
Heather Lowers
Jerry Marchand
Hap McSween
David Mogk
Olaf Medenbach
Bill Metropolis
Stephen Nelson

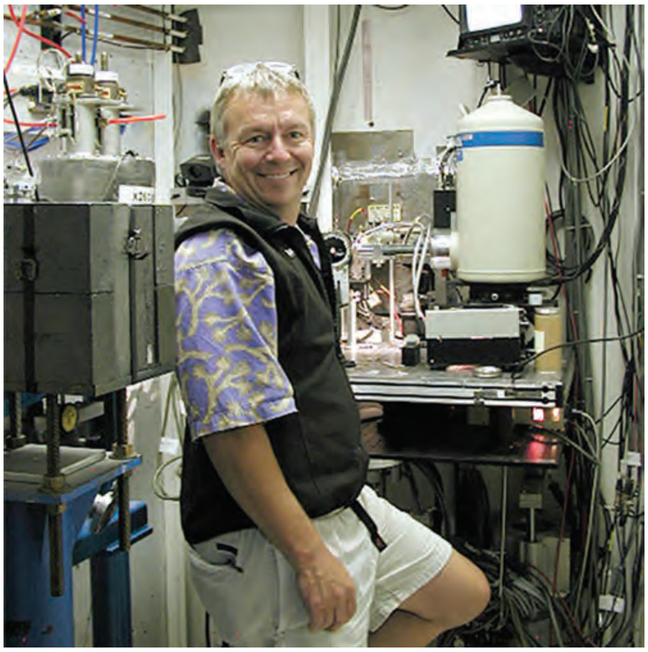

Figure 0.8. *Darby Dyar and Mickey Gunter.*

Jill Pasteris
Ron Peterson
Bob Reynolds
Michael Rhodes
Russell Rizzo
David Robertson
Matt Sanchez
Martha Schaefer
Sheila Seaman
Jane Selverstone
Eli Sklute
Michail Taran
Jenny Thomson
Bill Turner
David Von Bargen
Chris Voci
Kenneth Windom
Tom Williams
James Wittke
Thomas Witzke
Brigitte Wopenka
Bernhardt Wuensch
Andy Wulff

Finally, the photomicrographs of thin sections on the Mineral Database app (see the MSA website) are predominately the work of Peter Crowley of Amherst College. Peter also contributed ideas and acted as a sounding board for discussions of this text over many years. This project would not have been the same without his input.

In particular, M.D.D. also thanks those who inspired and encouraged her to pursue this very interesting field. Jim Besancon (Wellesley College) first tortured me with undergraduate mineralogy and then convinced me that I actually was good at it. Bernhardt Wuensch (M.I.T.) will always serve as my role model for brilliant teaching; thanks to him, I understand crystallography. My graduate advisor Roger Burns (M.I.T.) convinced me to switch from structural geology to mineralogy; he became a collaborator and the closest of friends. George Rossman (Caltech) took me in as a post-doc and has supported me in many ways ever since. I also had the good fortune to work closely with Charles Guidotti (University of Maine); from him I learned to understand the importance of thinking about minerals in petrologic contexts. Most importantly, I thank my children, Duncan and Lindy Crowley, and my ever-patient husband, Peter Crowley, for supporting me during this project.

M.E.G. would like to thank all those mineralogists who have encouraged him to complete this project and all those from who he has learned, especially his graduate professors at Virginia Tech—F.D. Bloss, G.V. Gibbs, and P.H. Ribbe: Bloss for writing several books that I learned from and for being my graduate advisor, mentor, and friend; Gibbs for all the lectures in mathematical crystallography; and Ribbe for all of those lectures in crystal chemistry. Most importantly, I thank my wife Suzanne Aaron, for all the support and proof-reading she's done over the years.

Finally, we would like to thank each other, because no co-authors could ever have been more patient, understanding, and helpful. We treasure the friendship that writing this book together has built.

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