BJARNE STROUSTRUP

Programming

Principles and Practice Using C++

A complete list of photo sources and credits appears on pages 1235–1236.

Stroustrup, Bjarne.
Programming principles and practice using C++ / Bjarne Stroustrup.
p. cm.
Includes bibliographical references and index.
ISBN 978-0-321-54372-1 (pbk. : alk. paper) 1. C++ (Computer program language) I. Title.

QA76.73.C153S82 2008
005.13'3—dc22
2008032595

ISBN-13: 978-0-321-54372-1
ISBN-10: 0-321-54372-6
Text printed in the United States on recycled paper at Courier in Kendallville, Indiana.
First printing, December 2008

Preface

> "Damn the torpedoes!
> Full speed ahead."
>
> **—Admiral Farragut**

Programming is the art of expressing solutions to problems so that a computer can execute those solutions. Much of the effort in programming is spent finding and refining solutions. Often, a problem is only fully understood through the process of programming a solution for it.

This book is for someone who has never programmed before but is willing to work hard to learn. It helps you understand the principles and acquire the practical skills of programming using the C++ programming language. My aim is for you to gain sufficient knowledge and experience to perform simple useful programming tasks using the best up-to-date techniques. How long will that take? As part of a first-year university course, you can work through this book in a semester (assuming that you have a workload of four courses of average difficulty). If you work by yourself, don't expect to spend less time than that (maybe 15 hours a week for 14 weeks).

Three months may seem a long time, but there's a lot to learn and you'll be writing your first simple programs after about an hour. Also, all learning is gradual: each chapter introduces new useful concepts and illustrates them with examples inspired by real-world uses. Your ability to express ideas in code – getting a computer to do what you want it to do – gradually and steadily increases as you go along. I never say, "Learn a month's worth of theory and then see if you can use it."

Why would you want to program? Our civilization runs on software. Without understanding software you are reduced to believing in "magic" and will be locked out of many of the most interesting, profitable, and socially useful technical fields of work. When I talk about programming, I think of the whole spectrum of computer programs from personal computer applications with GUIs (graphical user interfaces), through engineering calculations and embedded systems control applications (such as digital cameras, cars, and cell phones), to text manipulation applications as found in many humanities and business applications. Like mathematics, programming – when done well – is a valuable intellectual exercise that sharpens our ability to think. However, thanks to feedback from the computer, programming is more concrete than most forms of math, and therefore accessible to more people. It is a way to reach out and change the world – ideally for the better. Finally, programming can be great fun.

Why C++? You can't learn to program without a programming language, and C++ directly supports the key concepts and techniques used in real-world software. C++ is one of the most widely used programming languages, found in an unsurpassed range of application areas. You find C++ applications everywhere from the bottom of the oceans to the surface of Mars. C++ is precisely and comprehensively defined by a nonproprietary international standard. Quality and/or free implementations are available on every kind of computer. Most of the programming concepts that you will learn using C++ can be used directly in other languages, such as C, C#, Fortran, and Java. Finally, I simply like C++ as a language for writing elegant and efficient code.

This is not the easiest book on beginning programming; it is not meant to be. I just aim for it to be the easiest book from which you can learn the basics of real-world programming. That's quite an ambitious goal because much modern software relies on techniques considered advanced just a few years ago.

My fundamental assumption is that you want to write programs for the use of others, and to do so responsibly, providing a decent level of system quality; that is, I assume that you want to achieve a level of professionalism. Consequently, I chose the topics for this book to cover what is needed to get started with real-world programming, not just what is easy to teach and learn. If you need a technique to get basic work done right, I describe it, demonstrate concepts and language facilities needed to support the technique, provide exercises for it, and expect you to work on those exercises. If you just want to understand toy programs, you can get along with far less than I present. On the other hand, I won't waste your time with material of marginal practical importance. If an idea is explained here, it's because you'll almost certainly need it.

If your desire is to use the work of others without understanding how things are done and without adding significantly to the code yourself, this book is not for you. If so, please consider whether you would be better served by another book and another language. If that is approximately your view of programming, please also consider from where you got that view and whether it in fact is adequate for your needs. People often underestimate the complexity of programming as well as its value. I would hate for you to acquire a dislike for programming because of a mismatch between what you need and the part of the software reality I describe. There are many parts of the "information technology" world that do not require knowledge of programming. This book is aimed to serve those who do want to write or understand nontrivial programs.

Because of its structure and practical aims, this book can also be used as a second book on programming for someone who already knows a bit of C++ or for someone who programs in another language and wants to learn C++. If you fit into one of those categories, I refrain from guessing how long it will take you to read this book, but I do encourage you to do many of the exercises. This will help you to counteract the common problem of writing programs in older, familiar styles rather than adopting newer techniques where these are more appropriate. If you have learned C++ in one of the more traditional ways, you'll find something surprising and useful before you reach Chapter 7. Unless your name is Stroustrup, what I discuss here is not "your father's C++."

Programming is learned by writing programs. In this, programming is similar to other endeavors with a practical component. You cannot learn to swim, to play a musical instrument, or to drive a car just from reading a book – you must practice. Nor can you learn to program without reading and writing lots of code. This book focuses on code examples closely tied to explanatory text and diagrams. You need those to understand the ideals, concepts, and principles of programming and to master the language constructs used to express them. That's essential, but by itself, it will not give you the practical skills of programming. For that, you need to do the exercises and get used to the tools for writing, compiling, and running programs. You need to make your own mistakes and learn to correct them. There is no substitute for writing code. Besides, that's where the fun is!

On the other hand, there is more to programming – much more – than following a few rules and reading the manual. This book is emphatically not focused on "the syntax of C++." Understanding the fundamental ideals, principles, and techniques is the essence of a good programmer. Only well-designed code has a chance of becoming part of a correct, reliable, and maintainable system. Also, "the fundamentals" are what last: they will still be essential after today's languages and tools have evolved or been replaced.

What about computer science, software engineering, information technology, etc.? Is that all programming? Of course not! Programming is one of the fundamental topics that underlie everything in computer-related fields, and it has a natural place in a balanced course of computer science. I provide brief introductions to key concepts and techniques of algorithms, data structures, user interfaces, data processing, and software engineering. However, this book is not a substitute for a thorough and balanced study of those topics.

Code can be beautiful as well as useful. This book is written to help you see that, to understand what it means for code to be beautiful, and to help you to master the principles and acquire the practical skills to create such code. Good luck with programming!

A note to students

Of the 1000+ first-year students we have taught so far using drafts of this book at Texas A&M University, about 60% had programmed before and about 40% had never seen a line of code in their lives. Most succeeded, so you can do it, too.

You don't have to read this book as part of a course. I assume that the book will be widely used for self-study. However, whether you work your way through as part of a course or independently, try to work with others. Programming has an – unfair – reputation as a lonely activity. Most people work better and learn faster when they are part of a group with a common aim. Learning together and discussing problems with friends is not cheating! It is the most efficient – as well as most pleasant – way of making progress. If nothing else, working with friends forces you to articulate your ideas, which is just about the most efficient way of testing your understanding and making sure you remember. You don't actually have to personally discover the answer to every obscure language and programming environment problem. However, please don't cheat yourself by not doing the drills and a fair number of exercises (even if no teacher forces you to do them). Remember: programming is (among other things) a practical skill that you need to practice to master. If you don't write code (do several exercises for each chapter), reading this book will be a pointless theoretical exercise.

Most students – especially thoughtful good students – face times when they wonder whether their hard work is worthwhile. When (not if) this happens to you, take a break, reread the preface, and look at Chapter 1 ("Computers, People, and Programming") and Chapter 22 ("Ideals and History"). There, I try to articulate what I find exciting about programming and why I consider it a crucial tool for making a positive contribution to the world. If you wonder about my teaching philosophy and general approach, have a look at Chapter 0 ("Notes to the Reader").

You might find the weight of this book worrying, but it should reassure you that part of the reason for the heft is that I prefer to repeat an explanation or add an example rather than have you search for the one and only explanation. The other major part of the reason is that the second half of the book is reference material and "additional material" presented for you to explore only if you are interested in more information about a specific area of programming, such as embedded systems programming, text analysis, or numerical computation.

And please don't be too impatient. Learning any major new and valuable skill takes time and is worth it.

A note to teachers

No. This is not a traditional Computer Science 101 course. It is a book about how to construct working software. As such, it leaves out much of what a computer science student is traditionally exposed to (Turing completeness, state machines, discrete math, Chomsky grammars, etc.). Even hardware is ignored on the assumption that students have used computers in various ways since kindergarten. This book does not even try to mention most important CS topics. It is about programming (or more generally about how to develop software), and as such it goes into more detail about fewer topics than many traditional courses. It tries to do just one thing well, and computer science is not a one-course topic. If this book/course is used as part of a computer science, computer engineering, electrical engineering (many of our first students were EE majors), information science, or whatever program, I expect it to be taught alongside other courses as part of a well-rounded introduction.

Please read Chapter 0 ("Notes to the Reader") for an explanation of my teaching philosophy, general approach, etc. Please try to convey those ideas to your students along the way.

Support

The book's support website, **www.stroustrup.com/Programming**, contains a variety of materials supporting the teaching and learning of programming using this book. The material is likely to be improved with time, but for starters, you can find:

- Slides for lectures based on the book
- An instructor's guide
- Header files and implementations of libraries used in the book
- Code for examples in the book
- Solutions to selected exercises
- Potentially useful links
- Errata

Suggestions for improvements are always welcome.

Acknowledgments

I'd especially like to thank my late colleague and co-teacher Lawrence "Pete" Petersen for encouraging me to tackle the task of teaching beginners long before I'd otherwise have felt comfortable doing that, and for supplying the practical teaching experience to make the course succeed. Without him, the first version of the course would have been a failure. We worked together on the first versions of the course for which this book was designed and together taught it repeatedly, learning from our experiences, improving the course and the book. My use of "we" in this book initially meant "Pete and me."

Thanks to the students, teaching assistants, and peer teachers of ENGR 112 at Texas A&M University who directly and indirectly helped us construct this book, and to Walter Daugherity, who has also taught the course. Also thanks to Damian Dechev, Tracy Hammond, Arne Tolstrup Madsen, Gabriel Dos Reis, Nicholas Stroustrup, J. C. van Winkel, Greg Versoonder, Ronnie Ward, and Leor Zolman for constructive comments on drafts of this book. Thanks to Mogens Hansen for explaining about engine control software. Thanks to Al Aho, Stephen Edwards, Brian Kernighan, and Daisy Nguyen for helping me hide away from distractions to get writing done during the summers.

Thanks to the reviewers that Addison-Wesley found for me. Their comments, mostly based on teaching either C++ or Computer Science 101 at the college level, have been invaluable: Richard Enbody, David Gustafson, Ron McCarty, and K. Narayanaswamy. Also thanks to my editor, Peter Gordon, for many useful comments and (not least) for his patience. I'm very grateful to the production team assembled by Addison-Wesley; they added much to the quality of the book: Julie Grady (proofreader), Chris Keane (compositor), Rob Mauhar (illustrator), Julie Nahil (production editor), and Barbara Wood (copy editor).

In addition to my own unsystematic code checking, Bashar Anabtawi, Yinan Fan, and Yuriy Solodkyy checked all code fragments using Microsoft C++ 7.1 (2003) and 8.0 (2005) and GCC 3.4.4.

I would also like to thank Brian Kernighan and Doug McIlroy for setting a very high standard for writing about programming, and Dennis Ritchie and Kristen Nygaard for providing valuable lessons in practical language design.

Notes to the Reader

> "When the terrain disagrees with the map, trust the terrain."
>
> **—Swiss army proverb**

This chapter is a grab bag of information; it aims to give you an idea of what to expect from the rest of the book. Please skim through it and read what you find interesting. A teacher will find most parts immediately useful. If you are reading this book without the benefit of a good teacher, please don't try to read and understand everything in this chapter; just look at "The structure of this book" and the first part of the "A philosophy of teaching and learning" sections. You may want to return and reread this chapter once you feel comfortable writing and executing small programs.

0.1 The structure of this book

This book consists of four parts and a collection of appendices:

- *Part I, "The Basics,"* presents the fundamental concepts and techniques of programming together with the C++ language and library facilities needed to get started writing code. This includes the type system, arithmetic operations, control structures, error handling, and the design, implementation, and use of functions and user-defined types.
- *Part II, "Input and Output,"* describes how to get numeric and text data from the keyboard and from files, and how to produce corresponding output to the screen and to files. Then, it shows how to present numeric data, text, and geometric shapes as graphical output, and how to get input into a program from a graphical user interface (GUI).
- *Part III, "Data and Algorithms,"* focuses on the C++ standard library's containers and algorithms framework (the STL, standard template library). It shows how containers (such as **vector**, **list**, and **map**) are implemented (using pointers, arrays, dynamic memory, exceptions, and templates) and used. It also demonstrates the design and use of standard library algorithms (such as **sort**, **find**, and **inner_product**).
- *Part IV, "Broadening the View,"* offers a perspective on programming through a discussion of ideals and history, through examples (such as matrix computation, text manipulation, testing, and embedded systems programming), and through a brief description of the C language.
- *Appendices* provide useful information that doesn't fit into a tutorial presentation, such as surveys of C++ language and standard library facilities, and descriptions of how to get started with an integrated development environment (IDE) and a graphical user interface (GUI) library.

Unfortunately, the world of programming doesn't really fall into four cleanly separated parts. Therefore, the "parts" of this book provide only a coarse classification of topics. We consider it a useful classification (obviously, or we wouldn't have used it), but reality has a way of escaping neat classifications. For example, we need to use input operations far sooner than we can give a thorough explanation of C++ standard I/O streams (input/output streams). Where the set of topics needed to present an idea conflicts with the overall classification, we explain the minimum needed for a good presentation, rather than just referring to the complete explanation elsewhere. Rigid classifications work much better for manuals than for tutorials.

The order of topics is determined by programming techniques, rather than programming language features; see §0.2. For a presentation organized around language features, see Appendix A.

To ease review and to help you if you miss a key point during a first reading where you have yet to discover which kind of information is crucial, we place three kinds of "alert markers" in the margin:

- Blue: concepts and techniques (this paragraph is an example of that)
- Green: advice
- Red: warning

0.1.1 General approach

In this book, we address you directly. That is simpler and clearer than the conventional "professional" indirect form of address, as found in most scientific papers. By "you" we mean "you, the reader," and by "we" we refer either to "ourselves, the author and teachers," or to you and us working together through a problem, as we might have done had we been in the same room.

This book is designed to be read chapter by chapter from the beginning to the end. Often, you'll want to go back to look at something a second or a third time. In fact, that's the only sensible approach, as you'll always dash past some details that you don't yet see the point in. In such cases, you'll eventually go back again. However, despite the index and the cross-references, this is not a book that you can open on any page and start reading with any expectation of success. Each section and each chapter assume understanding of what came before.

Each chapter is a reasonably self-contained unit, meant to be read in "one sitting" (logically, if not always feasible on a student's tight schedule). That's one major criterion for separating the text into chapters. Other criteria include that a chapter is a suitable unit for drills and exercises and that each chapter presents some specific concept, idea, or technique. This plurality of criteria has left a few chapters uncomfortably long, so please don't take "in one sitting" too literally. In particular, once you have thought about the review questions, done the drill, and worked on a few exercises, you'll often find that you have to go back to reread a few sections and that several days have gone by. We have clustered the chapters into "parts" focused on a major topic, such as input/output. These parts make good units of review.

Common praise for a textbook is "It answered all my questions just as I thought of them!" That's an ideal for minor technical questions, and early readers have observed the phenomenon with this book. However, that cannot be the whole ideal. We raise questions that a novice would probably not think of. We aim to ask and answer questions that you need to consider to write quality software for the use of others. Learning to ask the right (often hard) questions is an essential part of learning to think as a programmer. Asking only the easy and obvious questions would make you feel good, but it wouldn't help make you a programmer.

We try to respect your intelligence and to be considerate about your time. In our presentation, we aim for professionalism rather than cuteness, and we'd rather understate a point than hype it. We try not to exaggerate the importance of a programming technique or a language feature, but please don't underestimate a simple statement like "This is often useful." If we quietly emphasize that something is important, we mean that you'll sooner or later waste days if you don't master it. Our use of humor is more limited than we would have preferred, but experience shows that people's ideas of what is funny differ dramatically and that a failed attempt at humor can be confusing.

We do not pretend that our ideas or the tools offered are perfect. No tool, library, language, or technique is "the solution" to all of the many challenges facing a programmer. At best, it can help you to develop and express your solution. We try hard to avoid "white lies"; that is, we refrain from oversimplified explanations that are clear and easy to understand, but not true in the context of real languages and real problems. On the other hand, this book is not a reference; for more precise and complete descriptions of C++, see Bjarne Stroustrup, *The C++ Programming Language, Special Edition* (Addison-Wesley, 2000), and the ISO C++ standard.

0.1.2 Drills, exercises, etc.

Programming is not just an intellectual activity, so writing programs is necessary to master programming skills. We provide two levels of programming practice:

- *Drills:* A drill is a very simple exercise devised to develop practical, almost mechanical skills. A drill usually consists of a sequence of modifications of a single program. You should do every drill. A drill is not asking for deep understanding, cleverness, or initiative. We consider the drills part of the basic fabric of the book. If you haven't done the drills, you have not "done" the book.

- *Exercises:* Some exercises are trivial and others are very hard, but most are intended to leave some scope for initiative and imagination. If you are serious, you'll do quite a few exercises. At least do enough to know which are difficult for you. Then do a few more of those. That's how you'll learn the most. The exercises are meant to be manageable without exceptional cleverness, rather than to be tricky puzzles. However, we hope that we have provided exercises that are hard enough to challenge anybody and enough exercises to exhaust even the best student's available time. We do not expect you to do them all, but feel free to try.

In addition, we recommend that you (every student) take part in a small project (and more if time allows for it). A project is intended to produce a complete useful program. Ideally, a project is done by a small group of people (e.g., three people) working together for about a month while working through the chapters in Part III. Most people find the projects the most fun and what ties everything together.

Some people like to put the book aside and try some examples before reading to the end of a chapter; others prefer to read ahead to the end before trying to get code to run. To support readers with the former preference, we provide simple suggestions for practical work labeled **"Try this:**" at natural breaks in the text. A **Try this** is generally in the nature of a drill focused narrowly on the topic that precedes it. If you pass a **Try this** without trying – maybe because you are not near a computer or you find the text riveting – do return to it when you do the chapter drill; a **Try this** either complements the chapter drill or is a part of it.

At the end of each chapter you'll find a set of review questions. They are intended to point you to the key ideas explained in the chapter. One way to look at the review questions is as a complement to the exercises: the exercises focus on the practical aspects of programming, whereas the review questions try to help you articulate the ideas and concepts. In that, they resemble good interview questions.

The "Terms" section at the end of each chapter presents the basic vocabulary of programming and of C++. If you want to understand what people say about programming topics and to articulate your own ideas, you should know what each means.

Learning involves repetition. Our ideal is to make every important point at least twice and to reinforce it with exercises.

0.1.3 What comes after this book?

At the end of this book, will you be an expert at programming and at C++? Of course not! When done well, programming is a subtle, deep, and highly skilled art building on a variety of technical skills. You should no more expect to be an expert at programming in four months than you should expect to be an expert in biology, in math, in a natural language (such as Chinese, English, or Danish), or at playing the violin in four months – or in half a year, or a year. What you should hope for, and what you can expect if you approach this book seriously, is to have a really good start that allows you to write relatively simple useful programs, to be able to read more complex programs, and to have a good conceptual and practical background for further work.

The best follow-up to this initial course is to work on a real project developing code to be used by someone else. After that, or (even better) in parallel with a real project, read either a professional-level general textbook (such as Stroustrup, *The C++ Programming Language*), a more specialized book relating to the needs of your project (such as Qt for GUI, or ACE for distributed programming), or a textbook focusing on a particular aspect of C++ (such as Koenig and Moo, *Accelerated C++*; Sutter's *Exceptional C++*; or Gamma et al., *Design Patterns*). For complete references, see §0.6 or the Bibliography section at the back of the book.

Eventually, you should learn another programming language. We don't consider it possible to be a professional in the realm of software – even if you are not primarily a programmer – without knowing more than one language.

0.2 A philosophy of teaching and learning

What are we trying to help you learn? And how are we approaching the process of teaching? We try to present the minimal concepts, techniques, and tools for you to do effective practical programs, including

- Program organization
- Debugging and testing
- Class design
- Computation
- Function and algorithm design
- Graphics (two-dimensional only)
- Graphical user interfaces (GUIs)
- Text manipulation
- Regular expression matching
- Files and stream input and output (I/O)
- Memory management
- Scientific/numerical/engineering calculations
- Design and programming ideals
- The C++ standard library
- Software development strategies
- C-language programming techniques

Working our way through these topics, we cover the programming techniques called procedural programming (as with the C programming language), data abstraction, object-oriented programming, and generic programming. The main topic of this book is *programming*, that is, the ideals, techniques, and tools of expressing ideas in code. The C++ programming language is our main tool, so we describe many of C++'s facilities in some detail. But please remember that C++ is just a tool, rather than the main topic of this book. This is "programming using C++," not "C++ with a bit of programming theory."

Each topic we address serves at least two purposes: it presents a technique, concept, or principle and also a practical language or library feature. For example, we use the interface to a two-dimensional graphics system to illustrate the use of classes and inheritance. This allows us to be economical with space (and your time) and also to emphasize that programming is more than simply slinging code together to get a result as quickly as possible. The C++ standard library is a major source of such "double duty" examples – many even do triple duty. For example, we introduce the standard library **vector**, use it to illustrate widely useful design techniques, and show many of the programming techniques used to implement it. One of our aims is to show you how major library facilities are implemented and how they map to hardware. We insist that craftsmen must understand their tools, not just consider them "magical."

Some topics will be of greater interest to some programmers than to others. However, we encourage you not to prejudge your needs (how would you know what you'll need in the future?) and at least look at every chapter. If you read this book as part of a course, your teacher will guide your selection.

We characterize our approach as "depth-first." It is also "concrete-first" and "concept-based." First, we quickly (well, relatively quickly, Chapters 1–11) assemble a set of skills needed for writing small practical programs. In doing so, we present a lot of tools and techniques in minimal detail. We focus on simple concrete code examples because people grasp the concrete faster than the abstract. That's simply the way most humans learn. At this initial stage, you should not expect to understand every little detail. In particular, you'll find that trying something slightly different from what just worked can have "mysterious" effects. Do try, though! And please do the drills and exercises we provide. Just remember that early on you just don't have the concepts and skills to accurately estimate what's simple and what's complicated; expect surprises and learn from them.

We move fast in this initial phase – we want to get you to the point where you can write interesting programs as fast as possible. Someone will argue, "We must move slowly and carefully; we must walk before we can run!" But have you ever watched a baby learning to walk? Babies really do run by themselves before they learn the finer skills of slow, controlled walking. Similarly, you will dash ahead, occasionally stumbling, to get a feel of programming before slowing down to gain the necessary finer control and understanding. You must run before you can walk!

It is essential that you don't get stuck in an attempt to learn "everything" about some language detail or technique. For example, you could memorize all of C++'s built-in types and all the rules for their use. Of course you could, and doing so might make you feel knowledgeable. However, it would not make you a programmer. Skipping details will get you "burned" occasionally for lack of knowledge, but it is the fastest way to gain the perspective needed to write good programs. Note that our approach is essentially the one used by children learning their native language and also the most effective approach used to teach foreign languages. We encourage you to seek help from teachers, friends, colleagues, instructors, Mentors, etc. on the inevitable occasions when you are stuck. Be assured that nothing in these early chapters is fundamentally difficult. However, much will be unfamiliar and might therefore feel difficult at first.

Later, we build on the initial skills to broaden your base of knowledge and skills. We use examples and exercises to solidify your understanding, and to provide a conceptual base for programming.

We place a heavy emphasis on ideals and reasons. You need ideals to guide you when you look for practical solutions – to know when a solution is good and principled. You need to understand the reasons behind those ideals to understand why they should be your ideals, why aiming for them will help you and the users of your code. Nobody should be satisfied with "because that's the way it is" as an explanation. More importantly, an understanding of ideals and reasons allows you to generalize from what you know to new situations and to combine ideas and tools in novel ways to address new problems. Knowing "why" is an essential part of acquiring programming skills. Conversely, just memorizing lots of poorly understood rules and language facilities is limiting, a source of errors, and a massive waste of time. We consider your time precious and try not to waste it.

Many C++ language-technical details are banished to appendices and manuals, where you can look them up when needed. We assume that you have the initiative to search out information when needed. Use the index and the table of contents. Don't forget the online help facilities of your compiler, and the web. Remember, though, to consider every web resource highly suspect until you have reason to believe better of it. Many an authoritative-looking website is put up by a programming novice or someone with something to sell. Others are simply outdated. We provide a collection of links and information on our support website: **www.stroustrup.com/Programming**.

Please don't be too impatient for "realistic" examples. Our ideal example is the shortest and simplest code that directly illustrates a language facility, a concept, or a technique. Most real-world examples are far messier than ours, yet do not consist of more than a combination of what we demonstrate. Successful commercial programs with hundreds of thousands of lines of code are based on techniques that we illustrate in a dozen 50-line programs. The fastest way to understand real-world code is through a good understanding of the fundamentals.

On the other hand, we do not use "cute examples involving cuddly animals" to illustrate our points. We assume that you aim to write real programs to be used by real people, so every example that is not presented as language-technical is taken from a real-world use. Our basic tone is that of professionals addressing (future) professionals.

0.2.1 The order of topics

There are many ways to teach people how to program. Clearly, we don't subscribe to the popular "the way I learned to program is the best way to learn" theories. To ease learning, we early on present topics that would have been considered advanced only a few years ago. Our ideal is for the topics we present to be driven by problems you meet as you learn to program, to flow smoothly from topic to topic as you increase your understanding and practical skills. The major flow of this book is more like a story than a dictionary or a hierarchical order.

It is impossible to learn all the principles, techniques, and language facilities needed to write a program at once. Consequently, we have to choose a subset of principles, techniques, and features to start with. More generally, a textbook or a course must lead students through a series of subsets. We consider it our responsibility to select topics and to provide emphasis. We can't just present everything, so we must choose; what we leave out is at least as important as what we leave in – at each stage of the journey.

For contrast, it may be useful for you to see a list of (severely abbreviated) characterizations of approaches that we decided not to take:

- *"C first":* This approach to learning C++ is wasteful of students' time and leads to poor programming practices by forcing students to approach problems with fewer facilities, techniques, and libraries than necessary. C++ provides stronger type checking than C, a standard library with better support for novices, and exceptions for error handling.
- *Bottom-up:* This approach distracts from learning good and effective programming practices. By forcing students to solve problems with insufficient support from the language and libraries, it promotes poor and wasteful programming practices.
- *"If you present something, you must present it fully":* This approach implies a bottom-up approach (by drilling deeper and deeper into every topic touched). It bores novices with technical details they have no interest in and quite likely will not need for years to come. Once you can program, you can look up technical details in a manual. Manuals are good at that, whereas they are awful for initial learning of concepts.

- *Top-down:* This approach, working from first principles toward details, tends to distract readers from the practical aspects of programming and force them to concentrate on high-level concepts before they have any chance of appreciating their importance. For example, you simply can't appreciate proper software development principles before you have learned how easy it is to make a mistake in a program and how hard it can be to correct it.
- *"Abstract first":* Focusing on general principles and protecting the student from nasty real-world constraints can lead to a disdain for real-world problems, languages, tools, and hardware constraints. Often, this approach is supported by "teaching languages" that cannot be used later and (deliberately) insulate students from hardware and system concerns.
- *Software engineering principles first:* This approach and the abstract-first approach tend to share the problems of the top-down approach: without concrete examples and practical experience, you simply cannot appreciate the value of abstraction and proper software development practices.
- *"Object-oriented from day one":* Object-oriented programming is one of the best ways of organizing code and programming efforts, but it is not the only effective way. In particular, we feel that a grounding in the basics of types and algorithmic code is a prerequisite for appreciation of the design of classes and class hierarchies. We do use user-defined types (what some people would call "objects") from day one, but we don't show how to design a class until Chapter 6 and don't show a class hierarchy until Chapter 12.
- *"Just believe in magic":* This approach relies on demonstrations of powerful tools and techniques without introducing the novice to the underlying techniques and facilities. This leaves the student guessing – and usually guessing wrong – about why things are the way they are, what it costs to use them, and where they can be reasonably applied. This can lead to overrigid following of familiar patterns of work and become a barrier to further learning.

Naturally, we do not claim that these other approaches are never useful. In fact, we use several of these for specific subtopics where their strengths can be appreciated. However, as general approaches to learning programming aimed at real-world use, we reject them and apply our alternative: concrete-first and depth-first with an emphasis on concepts and techniques.

0.2.2 Programming and programming language

We teach programming first and treat our chosen programming language as secondary, as a tool. Our general approach can be used with any general-purpose programming language. Our primary aim is to help you learn general concepts, principles, and techniques. However, those cannot be appreciated in isolation. For example, details of syntax, the kinds of ideas that can be directly expressed, and tool support differ from programming language to programming language. However, many of the fundamental techniques for producing bug-free code, such as writing logically simple code (Chapters 5 and 6), establishing invariants (§9.4.3), and separating interfaces from implementation details (§9.7 and §14.1–2), vary little from programming language to programming language.

Programming and design techniques must be learned using a programming language. Design, code organization, and debugging are not skills you can acquire in the abstract. You need to write code in some programming language and gain practical experience with that. This implies that you must learn the basics of a programming language. We say "the basics" because the days when you could learn all of a major industrial language in a few weeks are gone for good. The parts of C++ we present were chosen as the subset that most directly supports the production of good code. Also, we present C++ features that you can't avoid encountering either because they are necessary for logical completeness or are common in the C++ community.

0.2.3 Portability

It is common to write C++ to run on a variety of machines. Major C++ applications run on machines we haven't ever heard of! We consider portability and the use of a variety of machine architectures and operating systems most important. Essentially every example in this book is not only ISO Standard C++, but also portable. Unless specifically stated, the code we present should work on every C++ implementation and has been tested on several machines and operating systems.

The details of how to compile, link, and run a C++ program differ from system to system. It would be tedious to mention the details of every system and every compiler each time we need to refer to an implementation issue. In Appendix E, we give the most basic information about getting started using Visual Studio and Microsoft C++ on a Windows machine.

If you have trouble with one of the popular, but rather elaborate, IDEs (integrated development environments), we suggest you try working from the command line; it's surprisingly simple. For example, here is the full set of commands needed to compile, link, and execute a simple program consisting of two source files, **my_file1.cpp** and **my_file2.cpp**, using the GNU C++ compiler, **g++**, on a Unix or Linux system:

```
g++ –o my_program my_file1.cpp my_file2.cpp
my_program
```

Yes, that really is all it takes.

0.3 Programming and computer science

Is programming all that there is to computer science? Of course not! The only reason we raise this question is that people have been known to be confused about this. We touch upon major topics from computer science, such as algorithms and data structures, but our aim is to teach programming: the design and implementation of programs. That is both more and less than most accepted notions of computer science:

- *More,* because programming involves many technical skills that are not usually considered part of any science
- *Less,* because we do not systematically present the foundation for the parts of computer science we use

The aim of this book is to be part of a course in computer science (if becoming a computer scientist is your aim), to be the foundation for the first of many courses in software construction and maintenance (if your aim is to become a programmer or a software engineer), and in general to be part of a greater whole.

We rely on computer science throughout and we emphasize principles, but we teach programming as a practical skill based on theory and experience, rather than as a science.

0.4 Creativity and problem solving

The primary aim of this book is to help you to express your ideas in code, not to teach you how to get those ideas. Along the way, we give many examples of how we can address a problem, usually through analysis of a problem followed by gradual refinement of a solution. We consider programming itself a form of problem solving: only through complete understanding of a problem and its solution can you express a correct program for it, and only through constructing and testing a program can you be certain that your understanding is complete. Thus, programming is inherently part of an effort to gain understanding. However, we aim to demonstrate this through examples, rather than through "preaching" or presentation of detailed prescriptions for problem solving.

0.5 Request for feedback

We don't think that the perfect textbook can exist; the needs of individuals differ too much for that. However, we'd like to make this book and its supporting materials as good as we can make them. For that, we need feedback; a good textbook cannot be written in isolation from its readers. Please send us reports on errors, typos, unclear text, missing explanations, etc. We'd also appreciate suggestions for better exercises, better examples, and topics to add, topics to delete, etc. Constructive comments will help future readers and we'll post errata on our support website: **www.stroustrup.com/Programming**.

0.6 References

Along with listing the publications mentioned in this chapter, this section also includes publications you might find helpful.

Austern, Matthew H. *Generic Programming and the STL: Using and Extending the C++ Standard Template Library*. Addison-Wesley, 1999. ISBN 0201309564.

Austern, Matthew H. (editor). "Technical Report on C++ Standard Library Extensions." ISO/IEC PDTR 19768.

Blanchette, Jasmin, and Mark Summerfield. *C++ GUI Programming with Qt 4*. Prentice Hall, 2006. ISBN 0131872493.

Gamma, Erich, Richard Helm, Ralph Johnson, and John M. Vlissides. *Design Patterns: Elements of Reusable Object-Oriented Software*. Addison-Wesley, 1994. ISBN 0201633612.

Goldthwaite, Lois (editor). "Technical Report on C++ Performance." ISO/IEC PDTR 18015.

Koenig, Andrew (editor). *The C++ Standard*. ISO/IEC 14882:2002. Wiley, 2003. ISBN 0470846747.

Koenig, Andrew, and Barbara Moo. *Accelerated C++: Practical Programming by Example*. Addison-Wesley, 2000. ISBN 020170353X.

Langer, Angelika, and Klaus Kreft. *Standard C++ IOStreams and Locales: Advanced Programmer's Guide and Reference*. Addison-Wesley, 2000. ISBN 0201183951.

Meyers, Scott. *Effective STL: 50 Specific Ways to Improve Your Use of the Standard Template Library*. Addison-Wesley, 2001. ISBN 0201749625.

Meyers, Scott. *Effective C++: 55 Specific Ways to Improve Your Programs and Designs (3rd Edition)*. Addison-Wesley, 2005. ISBN 0321334876.

Schmidt, Douglas C., and Stephen D. Huston. *C++ Network Programming, Volume 1: Mastering Complexity with ACE and Patterns*. Addison-Wesley, 2002. ISBN 0201604647.

Schmidt, Douglas C., and Stephen D. Huston. *C++ Network Programming, Volume 2: Systematic Reuse with ACE and Frameworks*. Addison-Wesley, 2003. ISBN 0201795256.

Stroustrup, Bjarne. *The Design and Evolution of C++*. Addison-Wesley, 1994. ISBN 0201543303.

Stroustrup, Bjarne. "Learning Standard C++ as a New Language." *C/C++ Users Journal,* May 1999.

Stroustrup, Bjarne. *The C++ Programming Language (Special Edition)*. Addison-Wesley, 2000. ISBN 0201700735.
Stroustrup, Bjarne. "C and C++: Siblings"; "C and C++: A Case for Compatibility"; and "C and C++: Case Studies in Compatibility." *C/C++ Users Journal,* July, Aug., Sept. 2002.
Sutter, Herb. *Exceptional C++: 47 Engineering Puzzles, Programming Problems, and Solutions*. Addison-Wesley, 2000. ISBN 0201615622.

A more comprehensive list of references can be found in the Bibliography section at the back of the book.

0.7 Biographies

You might reasonably ask, "Who are these guys who want to teach me how to program?" So here is some biographical information. I, Bjarne Stroustrup, wrote this book, and together with Lawrence "Pete" Petersen, I designed and taught the university-level beginner's (first-year) course that was developed concurrently with the book, using drafts of the book.

Bjarne Stroustrup

I'm the designer and original implementer of the C++ programming language. I have used the language, and many other programming languages, for a wide variety of programming tasks over the last 30 years or so. I just love elegant and efficient code used in challenging applications, such as robot control, graphics, games, text analysis, and networking. I have taught design, programming, and C++ to people of essentially all abilities and interests. I'm a founding member of the ISO standards committee for C++ where I serve as the chair of the working group for language evolution.

This is my first introductory book. My other books, such as *The C++ Programming Language* and *The Design and Evolution of C++*, were written for experienced programmers.

I was born into a blue-collar (working-class) family in Århus, Denmark, and got my master's degree in mathematics with computer science in my hometown university. My Ph.D. in computer science is from Cambridge University, England. I worked for AT&T for about 25 years, first in the famous Computer Science Research Center of Bell Labs – where Unix, C, C++, and so much else were invented – and later in AT&T Labs–Research.

I'm a member of the U.S. National Academy of Engineering, a Fellow of the ACM, an IEEE Fellow, a Bell Laboratories Fellow, and an AT&T Fellow. As the first computer scientist ever, I received the 2005 William Procter Prize for Scientific Achievement from Sigma Xi (the scientific research society).

I do have a life outside work. I'm married and have two children, one a medical doctor and one a Ph.D. student. I read a lot (including history, science fiction, crime, and current affairs) and like most kinds of music (including classical, rock, blues, and country). Good food with friends is an essential part of life, and I enjoy visiting interesting places and people, all over the world. To be able to enjoy the good food, I run.

For more information, see my home pages: www.research.att.com/~bs and www.cs.tamu.edu/people/faculty/bs. In particular, there you can find out how to pronounce my name.

Lawrence "Pete" Petersen

In late 2006, Pete introduced himself as follows: "I am a teacher. For almost 20 years, I have taught programming languages at Texas A&M. I have been selected by students for Teaching Excellence Awards five times and in 1996 received the Distinguished Teaching Award from the Alumni Association for the College of Engineering. I am a Fellow of the Wakonse Program for Teaching Excellence and a Fellow of the Academy for Educator Development.

As the son of an army officer, I was raised on the move. After completing a degree in philosophy at the University of Washington, I served in the army for 22 years as a Field Artillery Officer and as a Research Analyst for Operational Testing. I taught at the Field Artillery Officer's Advanced Course at Fort Sill, Oklahoma, from 1971 to 1973. In 1979 I helped organize a Test Officer's Training Course and taught it as lead instructor at nine different locations across the United States from 1978 to 1981 and from 1985 to 1989.

In 1991 I formed a small software company that produced management software for university departments until 1999. My interests are in teaching, designing, and programming software that real people can use. I completed master's degrees in industrial engineering at Georgia Tech and in education curriculum and instruction at Texas A&M. I also completed a master's program in microcomputers from NTS. My Ph.D. is in information and operations management from Texas A&M.

My wife, Barbara, and I live in Bryan, Texas. We like to travel, garden, and entertain; and we spend as much time as we can with our sons and their families, and especially with our grandchildren, Angelina, Carlos, Tess, Avery, Nicholas, and Jordan."

Sadly, Pete died of lung cancer in 2007. Without him, the course would never have succeeded.

Postscript

Most chapters provide a short "postscript" trying to give some perspective on the information presented in the chapter. We do that in the realization that the information can be – and often is – daunting and will only be fully comprehended after doing exercises, reading further chapters (which apply the ideas of the chapter), and a later review. Don't panic. Relax; this is natural and expected. You won't become an expert in a day, but you can become a reasonably competent programmer as you work your way through the book. On the way, you'll encounter much information, many examples, and many techniques that lots of programmers have found stimulating and fun.

A Display Model

> "The world was black and white then.
> [It] didn't turn color
> until sometime in the 1930s."
>
> —Calvin's dad

This chapter presents a display model (the output part of GUI), giving examples of use and fundamental notions such as screen coordinates, lines, and color. **Line**, **Lines**, **Polygon**s, **Axis**, and **Text** are examples of **Shape**s. A **Shape** is an object in memory that we can display and manipulate on a screen. The next two chapters will explore these classes further, with Chapter 13 focusing on their implementation and Chapter 14 on design issues.

12.1 Why graphics?

Why do we spend four chapters on graphics and one on GUIs (graphical user interfaces)? After all, this is a book about programming, not a graphics book. There is a huge number of interesting software topics that we don't discuss, and we can at best scratch the surface on the topic of graphics. So, "Why graphics?" Basically, graphics is a subject that allows us to explore several important areas of software design, programming, and programming language facilities:

- *Graphics are useful.* There is much more to programming than graphics and much more to software than code manipulated through a GUI. However, in many areas good graphics are either essential or very important. For example, we wouldn't dream of studying scientific computing, data analysis, or just about any quantitative subject without the ability to graph data. Chapter 15 gives simple (but general) facilities for graphing data.
- *Graphics are fun.* There are few areas of computing where the effect of a piece of code is as immediately obvious and – when finally free of bugs – as pleasing. We'd be tempted to play with graphics even if it wasn't useful!
- *Graphics provide lots of interesting code to read.* Part of learning to program is to read lots of code to get a feel for what good code is like. Similarly, the way to become a good writer of English involves reading a lot of books, articles, and quality newspapers. Because of the direct correspondence between what we see on the screen and what we write in our programs, simple graphics code is more readable than most kinds of code of similar complexity. This chapter will prove that you can read graphics code after a few minutes of introduction; Chapter 13 will demonstrate how you can write it after another couple of hours.

- *Graphics are a fertile source of design examples*. It is actually hard to design and implement a good graphics and GUI library. Graphics are a very rich source of concrete and practical examples of design decisions and design techniques. Some of the most useful techniques for designing classes, designing functions, separating software into layers (of abstraction), and constructing libraries can be illustrated with a relatively small amount of graphics and GUI code.
- *Graphics provide a good introduction to what is commonly called object-oriented programming and the language features that support it*. Despite rumors to the contrary, object-oriented programming wasn't invented to be able to do graphics (see Chapter 22), but it was soon applied to that, and graphics provide some of the most accessible examples of object-oriented designs.
- *Some of the key graphics concepts are nontrivial*. So they are worth teaching, rather than leaving it to your own initiative (and patience) to seek out information. If we did not show how graphics and GUI were done, you might consider them "magic," thus violating one of the fundamental aims of this book.

12.2 A display model

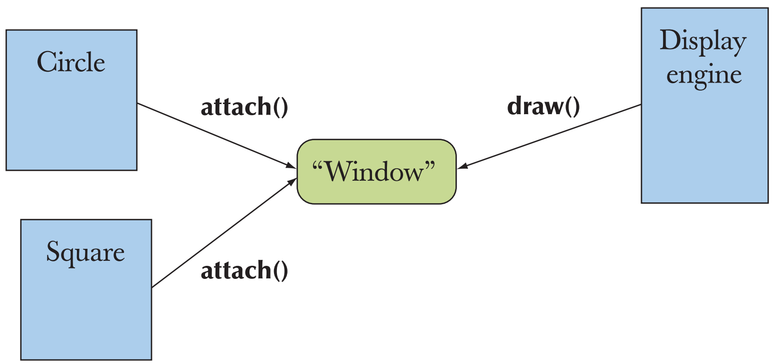
The iostream library is oriented toward reading and writing streams of characters as they might appear in a list of numeric values or a book. The only direct supports for the notion of graphical position are the newline and tab characters. You can embed notions of color and two-dimensional positions, etc., in a one-dimensional stream of characters. That's what layout (typesetting, "markup") languages such as Troff, Tex, Word, HTTP, and XML (and their associated graphical packages) do. For example:

```
<hr>
<h2>
Organization
</h2>
This list is organized in three parts:
<ul>
    <li><b>Proposals</b>, numbered EPddd, . . .</li>
    <li><b>Issues</b>, numbered EIddd, . . .</li>
    <li><b>Suggestions</b>, numbered ESddd, . . .</li>
</ul>
<p>We try to . . .
<p>
```

This is a piece of HTML specifying a header (**<h2> . . . </h2>**) a list (** . . . **) with list items (**<il> . . . </il>**) and a paragraph (**<p>**). We left out most of the actual text because it is irrelevant here. The point is that you can express layout notions in plain text, but the connection between the characters written and what appears on the screen is indirect, governed by a program that interprets those "markup" commands. Such techniques are fundamentally simple and immensely useful (just about everything you read has been produced using them), but they also have their limitations.

In this chapter and the next four, we present an alternative: a notion of graphics and of graphical user interfaces that is directly aimed at a computer screen. The fundamental concepts are inherently graphical (and two-dimensional, adapted to the rectangular area of a computer screen), such as coordinates, lines, rectangles, and circles. The aim from a programming point of view is a direct correspondence between the objects in memory and the images on the screen.

The basic model is as follows: We compose objects with basic objects provided by a graphics system, such as lines. We "attach" these graphics objects to a window object, representing our physical screen. A program that we can think of as the display itself, as "a display engine," as "our graphics library," as "the GUI library," or even (humorously) as "the small gnome writing on the back of the screen" then takes the objects we have added to our window and draws them on the screen:



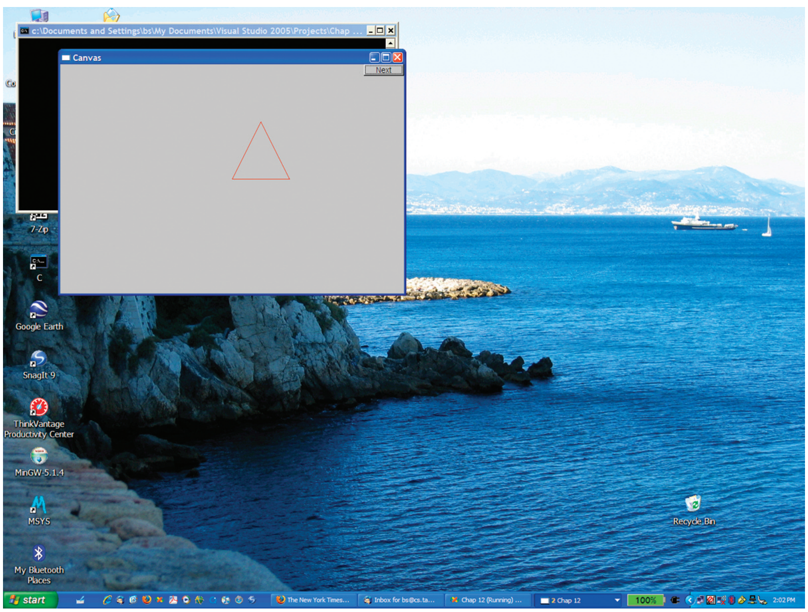
The "display engine" draws lines on the screen, places strings of text on the screen, colors areas of the screen, etc. For simplicity, we'll use the phrase "our GUI library" or even "the system" for the display engine even though our GUI library does much more than just drawing the objects. In the same way that our code lets the GUI library do most of the work for us, the GUI library delegates much of its work to the operating system.

12.3 A first example

Our job is to define classes from which we can make objects that we want to see on the screen. For example, we might want to draw a graph as a series of connected lines. Here is a small program presenting a very simple version of that:

```
#include "Simple_window.h"    // get access to our window library
#include "Graph.h"            // get access to our graphics library facilities

int main()
{
    using namespace Graph_lib;   // our graphics facilities are in Graph_lib

    Point tl(100,100);           // to become top left corner of window

    Simple_window win(tl,600,400,"Canvas");    // make a simple window

    Polygon poly;                // make a shape (a polygon)

    poly.add(Point(300,200));    // add a point
    poly.add(Point(350,100));    // add another point
    poly.add(Point(400,200));    // add a third point

    poly.set_color(Color::red);  // adjust properties of poly

    win.attach (poly);           // connect poly to the window

    win.wait_for_button();       // give control to the display engine
}
```

When we run this program, the screen looks something like this:



Let's go through the program line by line to see what was done. First we include the headers for our graphics interface libraries:

```
#include "Simple_window.h"     // get access to our window library
#include "Graph.h"             // get access to our graphics library facilities
```

Then, in **main()**, we start by telling the compiler that our graphics facilities are to be found in **Graph_lib**:

```
using namespace Graph_lib;     // our graphics facilities are in Graph_lib
```

Then, we define a point that we will use as the top left corner of our window:

```
Point tl(100,100);    // to become top left corner of window
```

Next, we create a window on the screen:

```
Simple_window win(tl,600,400,"Canvas");    // make a simple window
```

We use a class representing a window in our **Graph_lib** interface library called **Simple_window**. The name of this particular **Simple_window** is **win**; that is, **win** is a variable of class **Simple_window**. The initializer list for **win** starts with the point to be used as the top left corner, **tl**, followed by **600** and **400**. Those are the width and height, respectively, of the window, as displayed on the screen, measured in pixels. We'll explain in more detail later, but the main point here is that we specify a rectangle by giving its width and height. The string **Canvas** is used to label the window. If you look, you can see the word **Canvas** in the top left corner of the window's frame.

On our screen, the window appeared in a position chosen by the GUI library. In §13.7.2, we'll show how to choose a particular position, but for now, we'll just take what our library picks; that's often just right anyway.

Next, we put an object in the window:

```
Polygon poly;                  // make a shape (a polygon)

poly.add(Point(300,200));      // add a point
poly.add(Point(350,100));      // add another point
poly.add(Point(400,200));      // add a third point
```

We define a polygon, **poly**, and then add points to it. In our graphics library, a **Polygon** starts empty and we can add as many points to it as we like. Since we added three points, we get a triangle. A point is simply a pair of values giving the *x* and *y* (horizontal and vertical) coordinates within a window.

Just to show off, we then color the lines of our polygon red:

```
poly.set_color(Color::red);    // adjust properties of poly
```

Finally, we attach **poly** to our window, **win**:

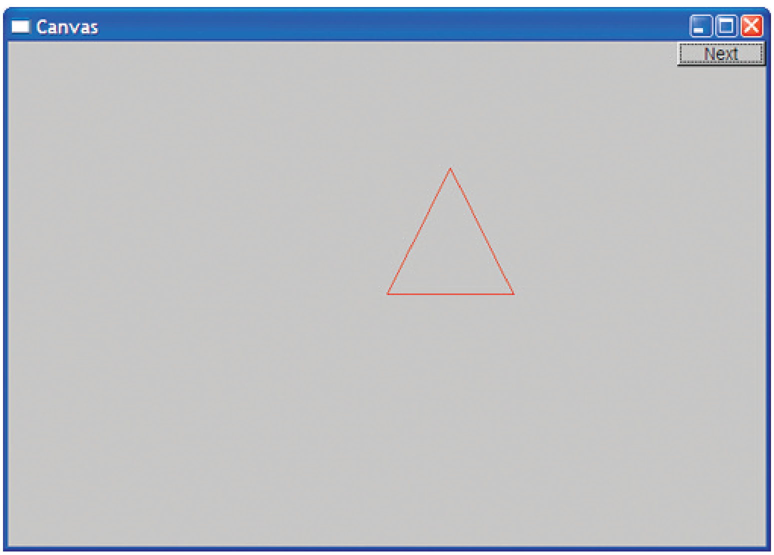
```
win.attach(poly);              // connect poly to the window
```

If the program wasn't so fast, you would notice that so far nothing had happened to the screen: nothing at all. We created a window (an object of class **Simple_window**, to be precise), created a polygon (called **poly**), painted that polygon red (**Color::red**), and attached it to the window (called **win**), but we have not yet asked for that window to be displayed on the screen. That's done by the final line of the program:

```
win.wait_for_button();         // give control to the display engine
```

To get a GUI system to display objects on the screen, you have to give control to "the system." Our **wait_for_button()** does that, and it also waits for you to "press" ("click") the "Next" button of our **Simple_window** before proceeding. This gives you a chance to look at the window before the program finishes and the window disappears. When you press the button, the program terminates, closing the window.

In isolation, our window looks like this:



You'll notice that we "cheated" a bit. Where did that button labeled "Next" come from? We built it into our **Simple_window** class. In Chapter 16, we'll move from

Simple_window to "plain" **Window**, which has no potentially spurious facilities built in, and show how we can write our own code to control interaction with a window.

For the next three chapters, we'll simply use that "Next" button to move from one "display" to the next when we want to display information in stages ("frame by frame").

You are so used to the operating system putting a frame around each window that you might not have noticed it specifically. However, the pictures in this and the following chapters were produced on a Microsoft Windows system, so you get the usual three buttons on the top right "for free." This can be useful: if your program gets in a real mess (as it surely will sometimes during debugging), you can kill it by hitting the × button. When you run your program on another system, a different frame will be added to fit that system's conventions. Our only contribution to the frame is the label (here, **Canvas**).

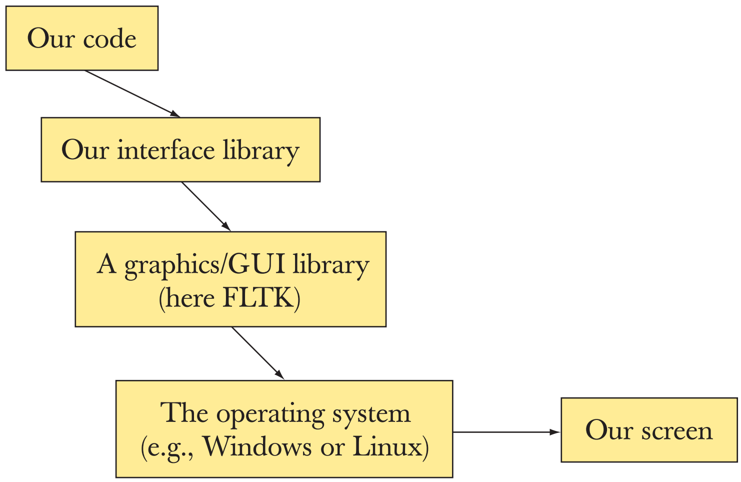
12.4 Using a GUI library

In this book, we will not use the operating system's graphical and GUI (graphical user interface) facilities directly. Doing so would limit our programs to run on a single operating system and would also force us to deal directly with a lot of messy details. As with text I/O, we'll use a library to smooth over operating system differences, I/O device variations, etc. and to simplify our code. Unfortunately, C++ does not provide a standard GUI library the way it provides the standard stream I/O library, so we use one of the many available C++ GUI libraries. So as not to tie you directly into one of those GUI libraries, and to save you from hitting the full complexity of a GUI library all at once, we use a set of simple interface classes that can be implemented in a couple of hundred lines of code for just about any GUI library.

The GUI toolkit that we are using (indirectly for now) is called FLTK (Fast Light Tool Kit, pronounced "full tick") from www.fltk.org. Our code is portable wherever FLTK is used (Windows, Unix, Mac, Linux, etc.). Our interface classes can also be re-implemented using other toolkits, so code using them is potentially even more portable.

The programming model presented by our interface classes is far simpler than what common toolkits offer. For example, our complete graphics and GUI interface library is about 600 lines of C++ code, whereas the extremely terse FLTK documentation is 370 pages. You can download that from www.fltk.org, but we don't recommend you do that just yet. You can do without that level of detail for a while. The general ideas presented in Chapters 12–16 can be used with any popular GUI toolkit. We will of course explain how our interface classes map to FLTK so that you will (eventually) see how you can use that (and similar toolkits) directly, if necessary.

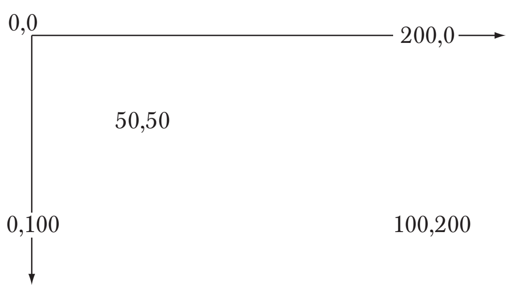
We can illustrate the parts of our "graphics world" like this:



Our interface classes provide a simple and user-extensible basic notion of two-dimensional shapes with limited support for the use of color. To drive that, we present a simple notion of GUI based on "callback" functions triggered by the use of user-defined buttons, etc. on the screen (Chapter 16).

12.5 Coordinates

A computer screen is a rectangular area composed of pixels. A pixel is a tiny spot that can be given some color. The most common way of modeling a screen in a program is as a rectangle of pixels. Each pixel is identified by an *x* (horizontal) coordinate and a *y* (vertical) coordinate. The *x* coordinates start with 0, indicating the leftmost pixel, and increase (toward the right) to the rightmost pixel. The *y* coordinates start with 0, indicating the topmost pixel, and increase (toward the bottom) to the lowest pixel:



Please note that *y* coordinates "grow downward." Mathematicians, in particular, find this odd, but screens (and windows) come in many sizes, and the top left point is about all that they have in common.

The number of pixels available depends on the screen: 1024-by-768, 1280-by-1024, 1450-by-1050, and 1600-by-1200 are common screen sizes.

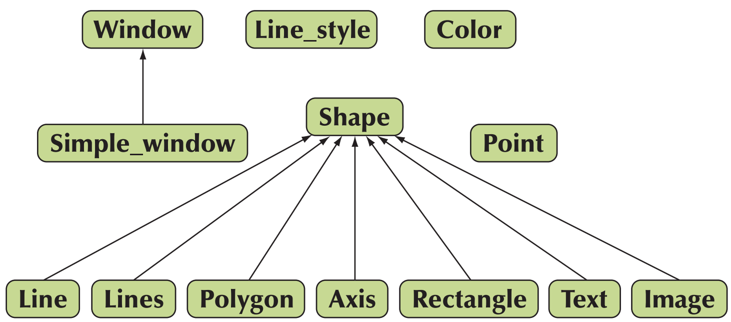
In the context of interacting with a computer using a screen, a window is a rectangular region of the screen devoted to some specific purpose and controlled by a program. A window is addressed exactly as a screen. Basically, we see a window as a small screen. For example, when we said

```
Simple_window win(tl,600,400,"Canvas");
```

we requested a rectangular area 600 pixels wide and 400 pixels high that we can address 0–599 (left to right) and 0–399 (top to bottom). The area of a window that you can draw on is commonly referred to as a *canvas*. The 600-by-400 area refers to "the inside" of the window, that is, the area inside the system-provided frame; it does not include the space the system uses for the title bar, quit button, etc.

12.6 Shapes

Our basic toolbox for drawing on the screen consists of about a dozen classes:



An arrow indicates that the class pointing can be used where the class pointed to is required. For example, a **Polygon** can be used where a **Shape** is required; that is, a **Polygon** is a kind of **Shape**.

We will start out presenting and using

- **Simple_window**, **Window**
- **Shape**, **Text**, **Polygon**, **Line**, **Lines**, **Rectangle**, **Function**, etc.
- **Color**, **Line_style**, **Point**
- **Axis**

Later (Chapter 16), we'll add GUI (user interaction) classes:

- **Button**, **In_box**, **Menu**, etc.

We could easily add many more classes (for some definition of "easy"), such as

- **Spline**, **Grid**, **Block_chart**, **Pie_chart**, etc.

However, defining or describing a complete GUI framework with all its facilities is beyond the scope of this book.

12.7 Using Shape primitives

In this section, we will walk you through some of the primitive facilities of our graphics library: **Simple_window**, **Window**, **Shape**, **Text**, **Polygon**, **Line**, **Lines**, **Rectangle**, **Color**, **Line_style**, **Point**, **Axis**. The aim is to give you a broad view of what you can do with those facilities, but not yet a detailed understanding of any of those classes. In the next chapters, we explore the design of each.

We will now walk through a simple program, explaining the code line by line and showing the effect of each on the screen. When you run the program you'll see how the image changes as we add shapes to the window and modify existing shapes. Basically, we are "animating" the progress through the code by looking at the program as it is executed.

12.7.1 Graphics headers and main

First, we include the header files defining our interface to the graphics and GUI facilities:

```
#include "Window.h"     // a plain window
#include "Graph.h"
```

or

```
#include "Simple_window.h"     // if we want that "Next" button
#include "Graph.h"
```

As you probably guessed, **Window.h** contains the facilities related to windows and **Graph.h** the facilities related to drawing shapes (including text) into windows. These facilities are defined in the **Graph_lib** namespace. To simplify notation we use a namespace directive to make the names from **Graph_lib** directly available in our program:

```
using namespace Graph_lib;
```

As usual, **main()** contains the code we want to execute (directly or indirectly) and deals with exceptions:

```
int main ()
try
{
	// . . . here is our code . . .

}
catch(exception& e) {
	// some error reporting
	return 1;
}
catch(...) {
	// some more error reporting
	return 2;
}
```

12.7.2 An almost blank window

We will not discuss error handling here (see Chapter 5, in particular, §5.6.3), but go straight to the graphics within **main()**:

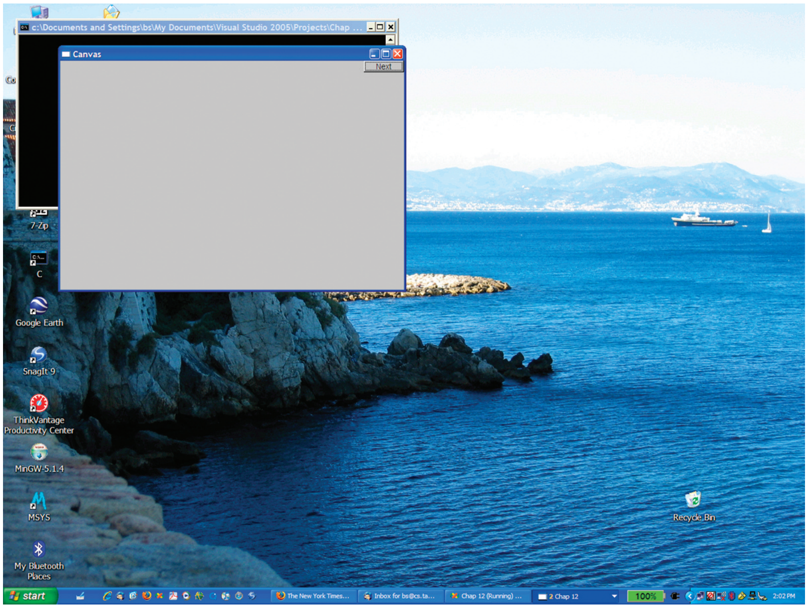
```
Point tl(100,100);     // top left corner of our window

Simple_window win(tl,600,400,"Canvas");
	// screen coordinate tl for top left corner
	// window size(600*400)
	// title: Canvas
win.wait_for_button();      // display!
```

This creates a **Simple_window**, that is, a window with a "Next" button, and displays it on the screen. Obviously, we need to have **#include**d the header **Simple_window.h** rather than **Window.h** to get **Simple_window**. Here we are specific about where on the screen the window should go: its top left corner goes at **Point(100,100)**. That's near, but not too near, the top left corner of the screen. Obviously, **Point** is a class with a constructor that takes a pair of integers and interprets them as an (x, y) coordinate pair. We could have written

```
Simple_window win(Point(100,100),600,400,"Canvas");
```

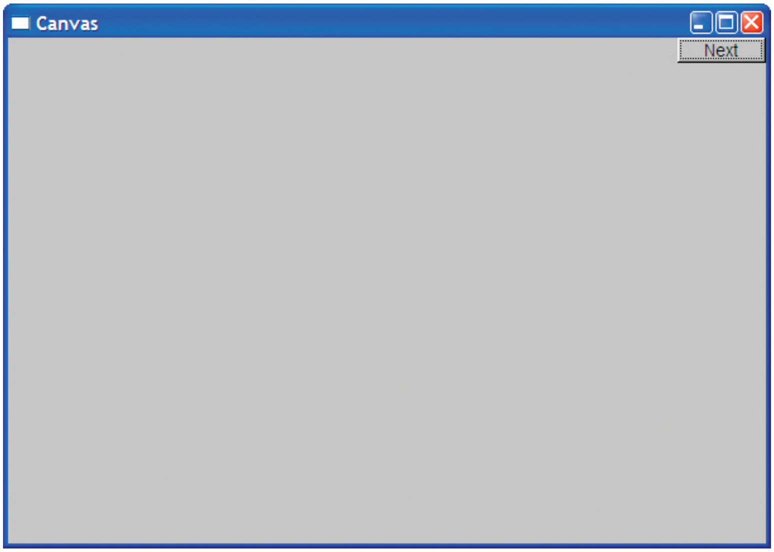
However, we want to use the point (100,100) several times so it is more convenient to give it a symbolic name. The 600 is the width and 400 is the height of the window, and **Canvas** is the label we want put on the frame of the window.

To actually get the window drawn on the screen, we have to give control to the GUI system. We do this by calling **win.wait_for_button()** and the result is:



In the background of our window, we see a laptop screen (somewhat cleaned up for the occasion). For people who are curious about irrelevant details, we can tell you that I took the photo standing near the Picasso library in Antibes looking across the bay to Nice. The black console window partially hidden behind is the one running our program. Having a console window is somewhat ugly and unnecessary, but it has the advantage of giving us an effective way of killing our window if a partially debugged program gets into an infinite loop and refuses to go away. If you look carefully, you'll notice that we have the Microsoft C++ compiler running, but you could just as well have used some other compiler (such as Borland or GNU).

For the rest of the presentation we will eliminate the distractions around our window and just show that window by itself:



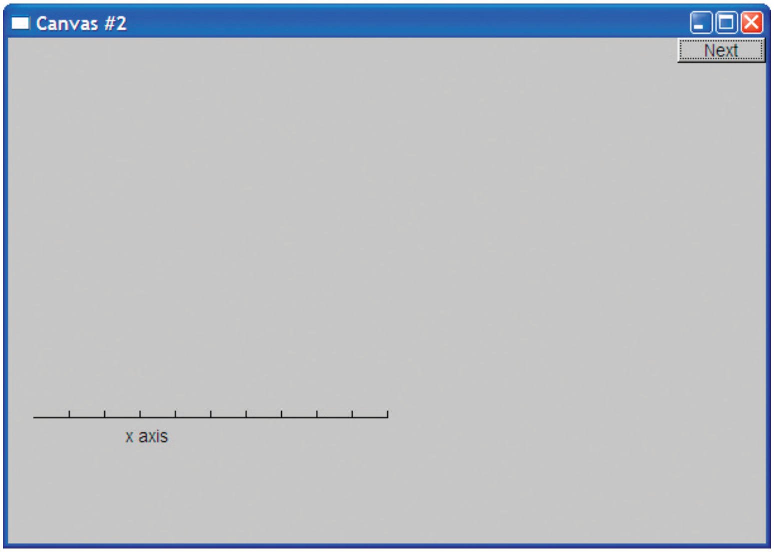
The actual size of the window (in inches) depends on the resolution of your screen. Some screens have bigger pixels than other screens.

12.7.3 Axis

An almost blank window isn't very interesting, so we'd better add some information. What would we like to display? Just to remind you that graphics is not all fun and games, we will start with something serious and somewhat complicated: an axis. A graph without axes is usually a disgrace. You just don't know what the data represents without axes. Maybe you explained it all in some accompanying text, but it is far safer to add axes; people often don't read the explanation and often a nice graphical representation gets separated from its original context. So, a graph needs axes:

```
Axis xa(Axis::x, Point(20,300), 280, 10, "x axis");      // make an Axis
                    // an Axis is a kind of Shape
                    // Axis::x means horizontal
                    // starting at (20,300)
                    // 280 pixels long
                    // 10 "notches"
                    // label the axis "x axis"
win.attach(xa);                    // attach xa to the window, win
win.set_label("Canvas #2");        // relabel the window
win.wait_for_button();             // display!
```

The sequence of actions is: make the axis object, add it to the window, and finally display it:



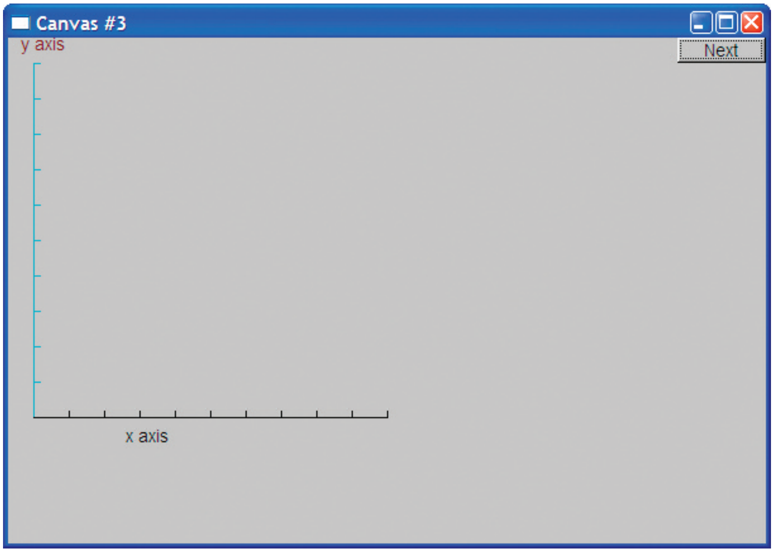
We can see that an **Axis::x** is a horizontal line. We see the required number of "notches" (10) and the label "x axis." Usually, the label will explain what the axis and the notches represent. Naturally, we chose to place the *x* axis somewhere near the bottom of the window. In real life, we'd represent the height and width by symbolic constants so that we could refer to "just above the bottom" as something like **y_max-bottom_margin** rather than by a "magic constant," such as **300** (§4.3.1, §15.6.2).

To help identify our output we relabeled the screen to **Canvas #2** using **Window**'s member function **set_label()**.

Now, let's add a *y* axis:

```
Axis ya(Axis::y, Point(20,300), 280, 10, "y axis");
ya.set_color(Color::cyan);                // choose a color
ya.label.set_color(Color::dark_red);      // choose a color for the text
win.attach(ya);
win.set_label("Canvas #3");
win.wait_for_button();      // display!
```

Just to show off some facilities, we colored our *y* axis cyan and our label dark red.



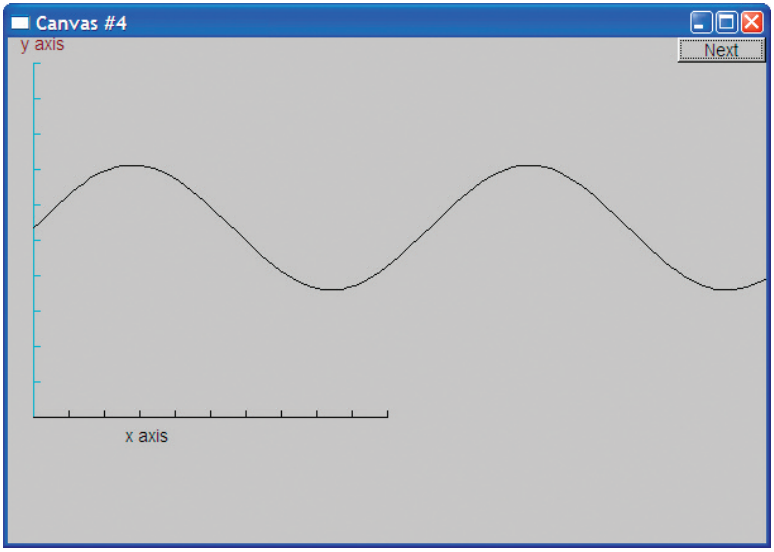
We don't actually think that it is a good idea to use different colors for *x* and *y* axes. We just wanted to show you how you can set the color of a shape and of individual elements of a shape. Using lots of color is not necessarily a good idea. In particular, novices tend to use color with more enthusiasm than taste.

12.7.4 Graphing a function

What next? We now have a window with axes, so it seems a good idea to graph a function. We make a shape representing a sine function and attach it:

```
Function sine(sin,0,100,Point(20,150),1000,50,50);    // sine curve
      // plot sin() in the range [0:100) with (0,0) at (20,150)
      // using 1000 points; scale x values *50, scale y values *50

win.attach(sine);
win.set_label("Canvas #4");
win.wait_for_button();
```

Here, the **Function** named **sine** will draw a sine curve using the standard library function **sin()** to generate values. We explain details about how to graph functions in §15.3. For now, just note that to graph a function we have to say where it starts (a **Point**) and for what set of input values we want to see it (a range), and we need to give some information about how to squeeze that information into our window (scaling):



Note how the curve simply stops when it hits the edge of the window. Points drawn outside our window rectangle are simply ignored by the GUI system and never seen.

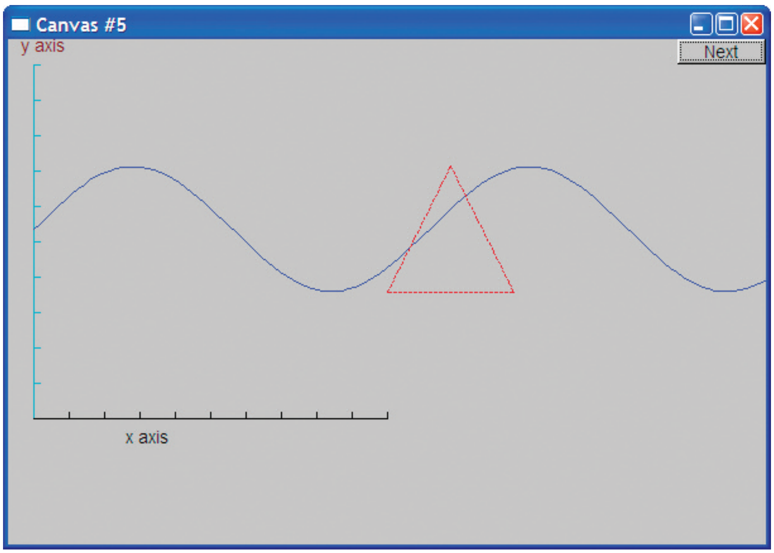
12.7.5 Polygons

A graphed function is an example of data presentation. We'll see much more of that in Chapter 15. However, we can also draw different kinds of objects in a window: geometric shapes. We use geometric shapes for graphical illustrations, to indicate user interaction elements (such as buttons), and generally to make our presentations more interesting. A **Polygon** is characterized by a sequence of points, which the **Polygon** class connects by lines. The first line connects the first point to the second, the second line connects the second point to the third, and the last line connects the last point to the first:

```
sine.set_color(Color::blue);        // we changed our mind about sine's color

Polygon poly;                       // a polygon; a Polygon is a kind of Shape
poly.add(Point(300,200));           // three points make a triangle
poly.add(Point(350,100));
poly.add(Point(400,200));

poly.set_color(Color::red);
```

```
poly.set_style(Line_style::dash);
win.attach(poly);
win.set_label("Canvas #5");
win.wait_for_button();
```

This time we change the color of the sine curve (**sine**) just to show how. Then, we add a triangle, just as in our first example from §12.3, as an example of a polygon. Again, we set a color, and finally, we set a style. The lines of a **Polygon** have a "style." By default that is solid, but we can also make those lines dashed, dotted, etc. as needed (see §13.5). We get



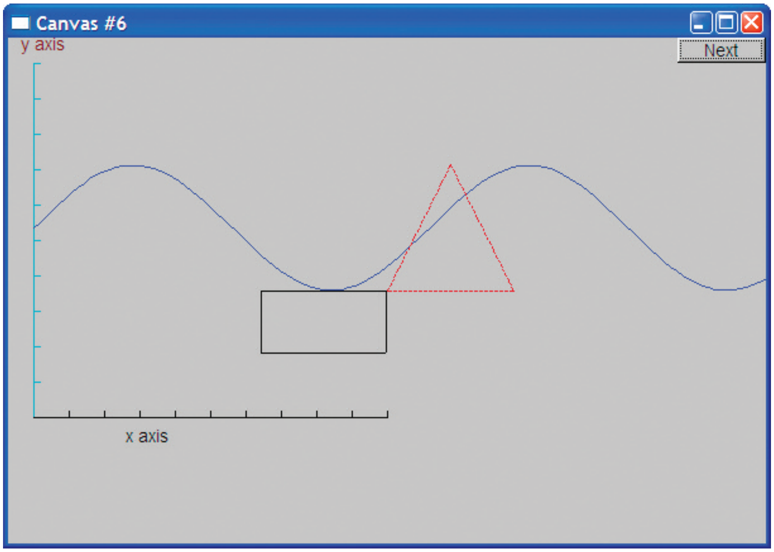
12.7.6 Rectangles

A screen is a rectangle, a window is a rectangle, and a piece of paper is a rectangle. In fact, an awful lot of the shapes in our modern world are rectangles (or at least rectangles with rounded corners). There is a reason for this: a rectangle is the simplest shape to deal with. For example, it's easy to describe (top left corner plus width plus height, or top left corner plus bottom right corner, or whatever), it's easy to tell whether a point is inside a rectangle or outside it, and it's easy to get hardware to draw a rectangle of pixels fast.

So, most higher-level graphics libraries deal better with rectangles than with other closed shapes. Consequently, we provide **Rectangle** as a class separate from the **Polygon** class. A **Rectangle** is characterized by its top left corner plus a width and height:

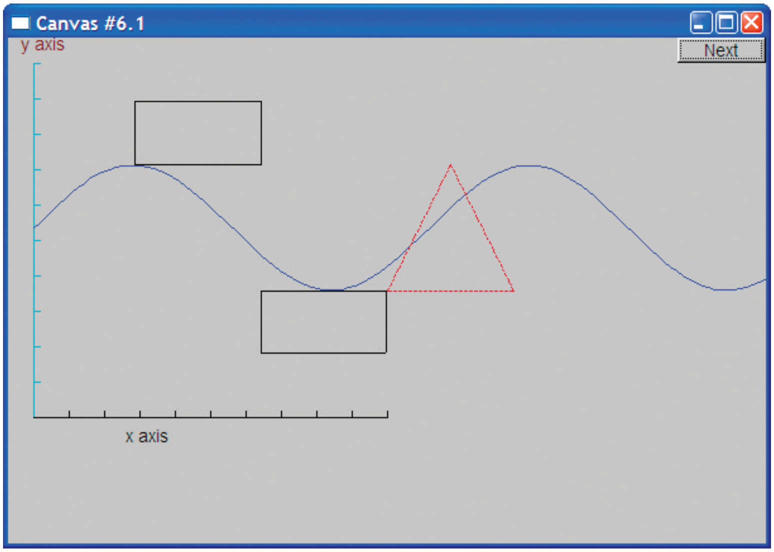
```
Rectangle r(Point(200,200), 100, 50);    // top left corner, width, height
win.attach(r);
win.set_label("Canvas #6");
win.wait_for_button();
```

From that, we get



Please note that making a polyline with four points in the right places is not enough to make a **Rectangle**. It is easy to make a **Closed_polyline** that looks like a **Rectangle** on the screen (you can even make an **Open_polyline** that looks just like a **Rectangle**); for example:

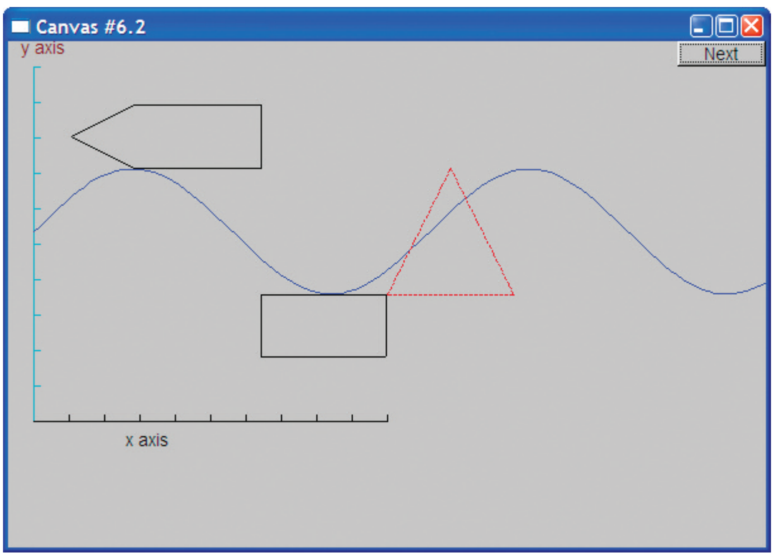
```
Closed_polyline poly_rect;
poly_rect.add(Point(100,50));
poly_rect.add(Point(100,50));
poly_rect.add(Point(200,100));
poly_rect.add(Point(100,100));
```



In fact, the *image* on the screen of such a **poly_rect** *is* a rectangle. However, the **poly_rect** object in memory is not a **Rectangle** and it does not "know" anything about rectangles. The simplest way to prove that is to add another point:

```
poly_rect.add(Point(50,75));
```

No rectangle has five points:



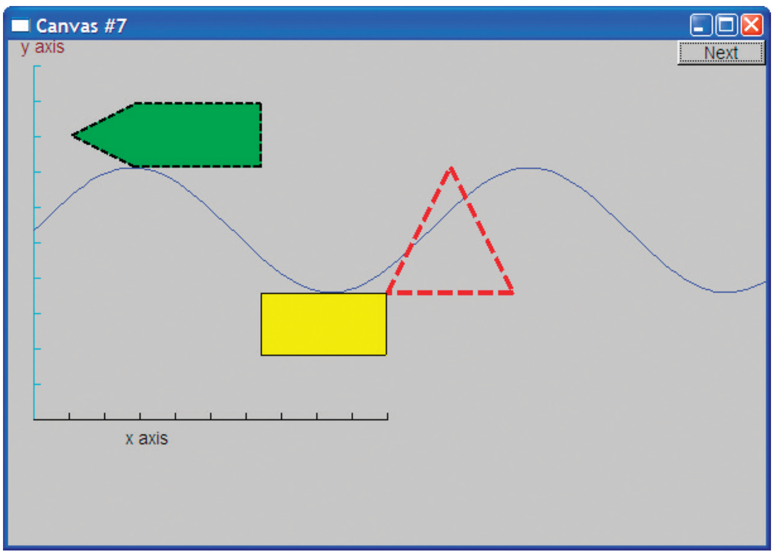
It is important for our reasoning about our code that a **Rectangle** doesn't just happen to look like a rectangle on the screen; it maintains the fundamental guarantees of a rectangle (as we know them from geometry). We write code that depends on a **Rectangle** really being a rectangle on the screen and staying that way.

12.7.7 Fill

We have been drawing our shapes as outlines. We can also "fill" a rectangle with color:

```
r.set_fill_color(Color::yellow);        // color the inside of the rectangle
poly.set_style(Line_style(Line_style::dash,4));
poly_rect.set_style(Line_style(Line_style::dash,2));
win.set_label("Canvas #7");
win.wait_for_button();
```

We also decided that we didn't like the line style of our triangle (**poly**), so we set its line style to "fat (thickness four times normal) dashed." Similarly, we changed the style of **poly_rect** (now no longer looking like a rectangle):



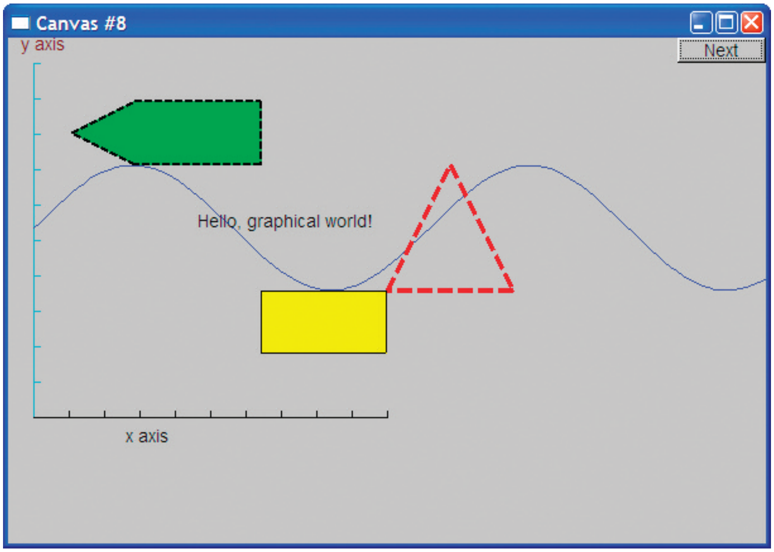
If you look carefully at **poly_rect**, you'll see that the outline is printed on top of the fill.

It is possible to fill any closed shape (see §13.9). Rectangles are just special in how easy (and fast) they are to fill.

12.7.8 Text

Finally, no system for drawing is complete without a simple way of writing text – drawing each character as a set of lines just doesn't cut it. We label the window itself, and axes can have labels, but we can also place text anywhere using a **Text** object:

```
Text t(Point(150,150), "Hello, graphical world! ");
win.attach(t);
win.set_label("Canvas #8");
win.wait_for_button();
```

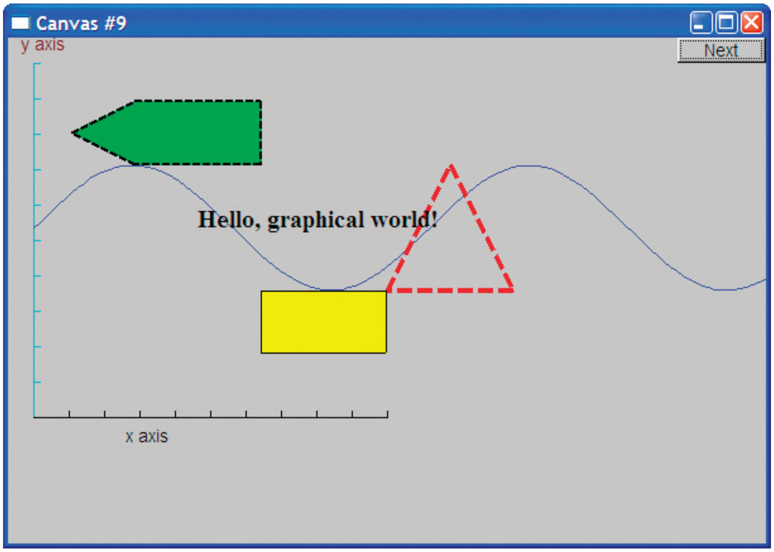


From the primitive graphics elements you see in this window, you can build displays of just about any complexity and subtlety. For now, just note a peculiarity of the code in this chapter: there are no loops, no selection statements, and all data was "hardwired" in. The output was just composed of primitives in the simplest possible way. Once we start composing these primitives using data and algorithms, things will start to get interesting.

We have seen how we can control the color of text: the label of an **Axis** (§12.7.3) is simply a **Text** object. In addition, we can choose a font and set the size of the characters:

```
t.set_font(Font::times_bold);
t.set_font_size(20);
win.set_label("Canvas #9");
win.wait_for_button();
```

We enlarged the characters of the **Text** string **Hello, graphical world!** to point size 20 and chose the Times font in bold:

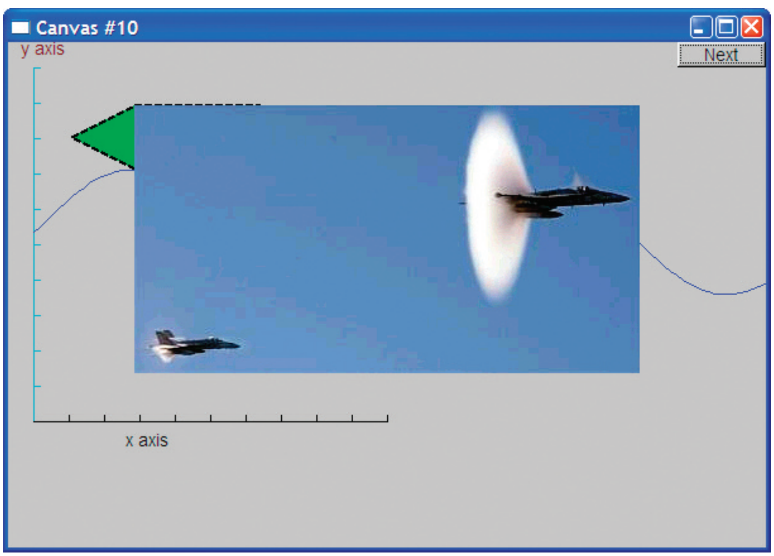


12.7.9 Images

We can also load images from files:

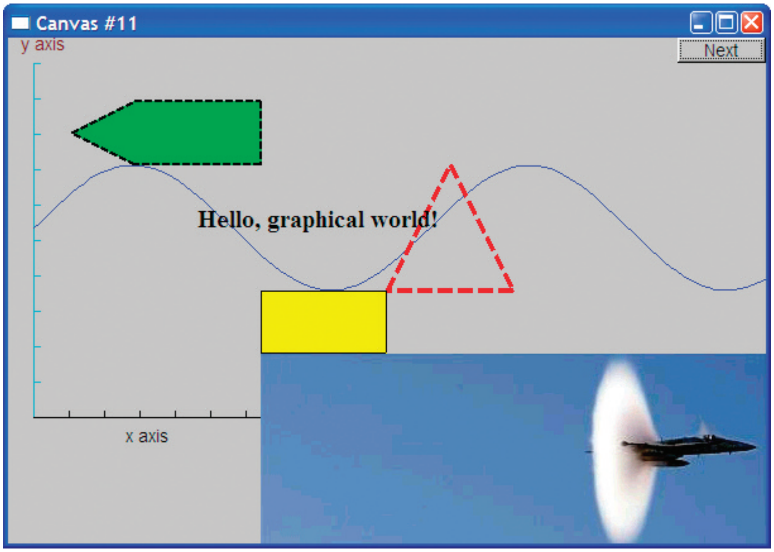
```
Image ii(Point(100,50),"image.jpg");        // 400*212-pixel jpg
win.attach(ii);
win.set_label("Canvas #10");
win.wait_for_button();
```

As it happens, the file called **image.jpg** is a photo of two planes breaking the sound barrier:



That photo is relatively large and we placed it right on top of our text and shapes. So, to clean up our window a bit, let us move it a bit out of the way:

```
ii.move(100,200);
win.set_label("Canvas #11");
win.wait_for_button();
```



Note how the parts of the photo that didn't fit in the window are simply not represented. What would have appeared outside the window is "clipped" away.

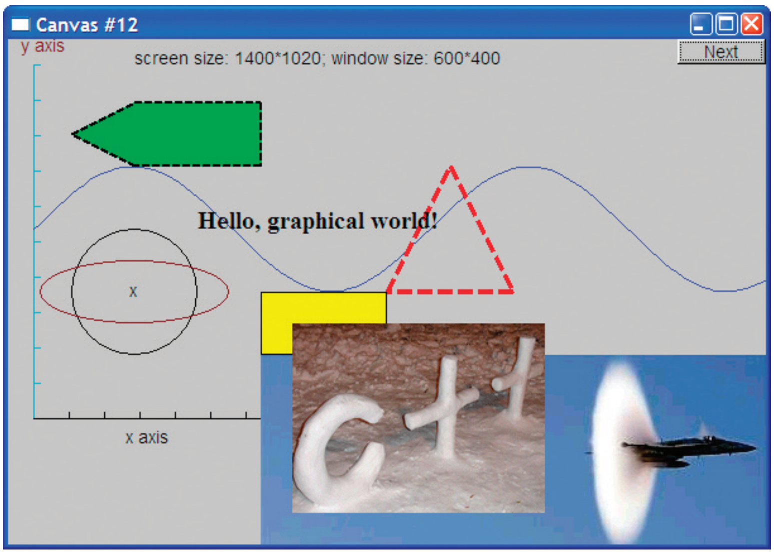
12.7.10 And much more

And here, without further comment, is some more code:

```
Circle c(Point(100,200),50);
Ellipse e(Point(100,200), 75,25);
e.set_color(Color::dark_red);
Mark m(Point(100,200),'x');

ostringstream oss;
oss << "screen size: " << x_max() << "*" << y_max()
        << "; window size: " << win.x_max() << "*" << win.y_max();
Text sizes(Point(100,20),oss.str());

Image cal(Point(225,225),"snow_cpp.gif");      // 320*240-pixel gif
cal.set_mask(Point(40,40),200,150);            // display center part of image
```

```
win.attach(c);
win.attach(m);
win.attach(e);

win.attach(sizes);
win.attach(cal);
win.set_label("Canvas #12");
win.wait_for_button();
```

Can you guess what this code does? Is it obvious?



The connection between the code and what appears on the screen is direct. If you don't yet see how that code caused that output, it soon will become clear. Note the way we used a **stringstream** (§11.4) to format the text object displaying sizes.

12.8 Getting this to run

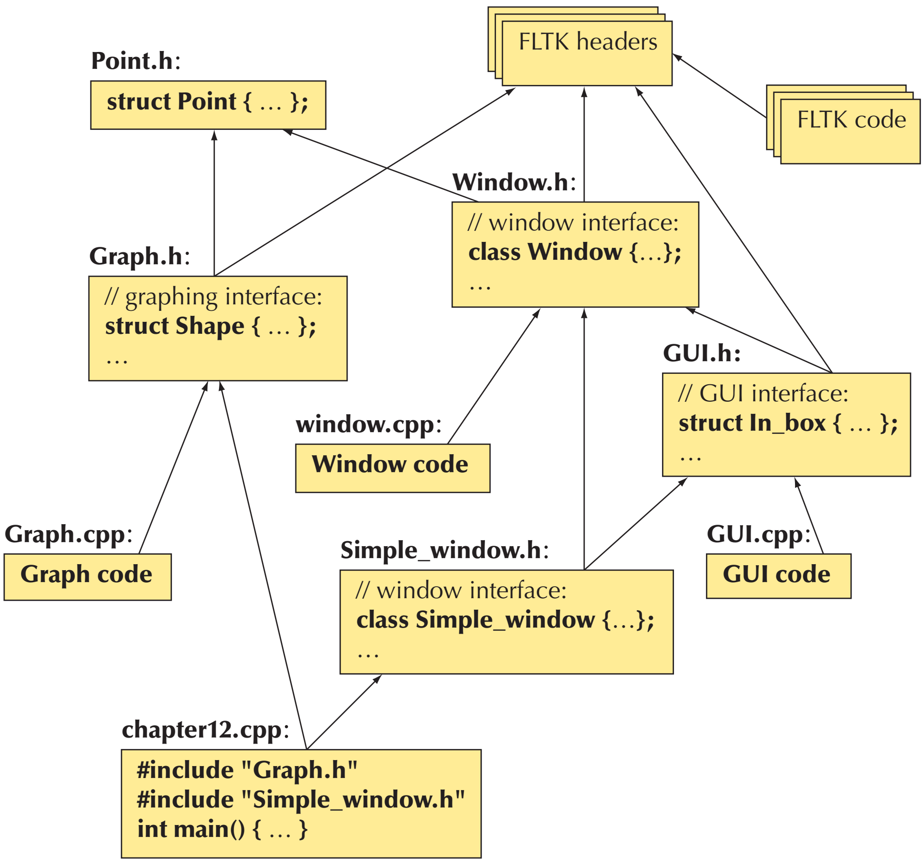
We have seen how to make a window and how to draw various shapes in it. In the following chapters, we'll see how those **Shape** classes are defined and show more ways of using them.

Getting this program to run requires more than the programs we have presented so far. In addition to our code in **main()**, we need to get the interface library code compiled and linked to our code, and finally, nothing will run unless the FLTK library (or whatever GUI system we use) is installed and correctly linked to ours.

One way of looking at the program is that it has four distinct parts:

- Our program code (**main()**, etc.)
- Our interface library (**Window**, **Shape**, **Polygon**, etc.)
- The FLTK library
- The C++ standard library

Indirectly, we also use the operating system. Leaving out the OS and the standard library, we can illustrate the organization of our graphics code like this:



Appendix D explains how to get all of this to work together.

12.8.1 Source files

Our graphics and GUI interface library consists of just five header files and three code files:

- Headers:
  - **Point.h**
  - **Window.h**
  - **Simple_window.h**
  - **Graph.h**
  - **GUI.h**
- Code files:
  - **Window.cpp**
  - **Graph.cpp**
  - **GUI.cpp**

Until Chapter 16, you can ignore the GUI files.

Drill

The drill is the graphical equivalent to the “Hello, World!” program. Its purpose is to get you acquainted with the simplest graphical output tools.

1. Get an empty **Simple_window** with the size 600 by 400 and a label **My window** compiled, linked, and run. Note that you have to link the FLTK library as described in Appendix D; **#include Graph.h**, **Window.h**, and **GUI.h** in your code; and include **Graph.cpp** and **Window.cpp** in your project.
2. Now add the examples from §12.7 one by one, testing between each added subsection example.
3. Go through and make one minor change (e.g., in color, in location, or in number of points) to each of the subsection examples.

Review

1. Why do we use graphics?
2. When do we try not to use graphics?
3. Why is graphics interesting for a programmer?
4. What is a window?
5. In which namespace do we keep our graphics interface classes (our graphics library)?
6. What header files do you need to do basic graphics using our graphics library?

7. What is the simplest window to use?
8. What is the minimal window?
9. What's a window label?
10. How do you label a window?
11. How do screen coordinates work? Window coordinates? Mathematical coordinates?
12. What are examples of simple "shapes" that we can display?
13. What command attaches a shape to a window?
14. Which basic shape would you use to draw a hexagon?
15. How do you write text somewhere in a window?
16. How would you put a photo of your best friend in a window (using a program you wrote yourself)?
17. You made a **Window** object, but nothing appears on your screen. What are some possible reasons for that?
18. You have made a shape, but it doesn't appear in the window. What are some possible reasons for that?

Terms

color	graphics	JPEG
coordinates	GUI	line style
display	GUI library	software layer
fill color	HTTP	window
FLTK	image	XML

Exercises

We recommend that you use **Simple_window** for these exercises.

1. Draw a rectangle as a **Rectangle** and as a **Polygon**. Make the lines of the **Polygon** red and the lines of the **Rectangle** blue.
2. Draw a 100-by-30 **Rectangle** and place the text "Howdy!" inside it.
3. Draw your initials 150 pixels high. Use a thick line. Draw each initial in a different color.
4. Draw a checkers board: 8-by-8 alternating white and red squares.
5. Draw a red ¼-inch frame around a rectangle that is three-quarters the height of your screen and two-thirds the width.
6. What happens when you draw a **Shape** that doesn't fit inside its window? What happens when you draw a **Window** that doesn't fit on your screen? Write two programs that illustrate these two phenomena.
7. Draw a two-dimensional house seen from the front, the way a child would: with a door, two windows, and a roof with a chimney. Feel free to add details; maybe have "smoke" come out of the chimney.

8. Draw the Olympic five rings. If you can't remember the colors, look them up.
9. Display an image on the screen, e.g., a photo of a friend. Label the image both with a title on the window and with a caption in the window.
10. Draw the file diagram from §12.8.
11. Draw a series of regular polygons, one inside the other. The innermost should be an equilateral triangle, enclosed by a square, enclosed by a pentagon, etc. For the mathematically adept only: let all the points of each **N**-polygon touch sides of the **(N+1)**-polygon.
12. A superellipse is a two-dimensional shape defined by the equation

$$\left|\frac{x}{a}\right|^m + \left|\frac{y}{b}\right|^n = 1; \qquad m,n > 0.$$

Look up *superellipse* on the web to get a better idea of what such shapes look like. Write a program that draws "starlike" patterns by connecting points on a superellipse. Take **a**, **b**, **m**, **n**, and **N** as arguments. Select **N** points on the superellipse defined by **a**, **b**, **m**, and **n**. Make the points equally spaced for some definition of "equal." Connect each of those **N** points to one or more other points (if you like you can make the number of points connect to another argument or just use **N–1**, i.e., all the other points).

13. Find a way to add color to the superellipse shapes from the previous exercise. Make some lines one color and other lines another color or other colors.

Postscript

The ideal for program design is to have our concepts directly represented as entities in our program. So, we often represent ideas by classes, real-world entities by objects of classes, and actions and computations by functions. Graphics is a domain where this idea has an obvious application. We have concepts, such as circles and polygons, and we represent them in our program as class **Circle** and class **Polygon**. Where graphics is unusual is that when writing a graphics program, we also have the opportunity to see objects of those classes on the screen; that is, the state of our program is directly represented for us to observe – in most applications we are not that lucky. This direct correspondence between ideas, code, and output is what makes graphics programming so attractive. Please do remember, though, that graphics are just illustrations of the general idea of using classes to directly represent concepts in code. That idea is far more general and useful: just about anything we can think of can be represented in code as a class, an object of a class, or a set of classes.

Index

A

B

C

E

F

G

H

I

M

N

Q

R

S

T

U

V

W

X

Z