Definition

In software engineering, a software **design pattern** is a general reusable solution to a commonly occurring problem within a given context in software **design**. It is not a finished **design** that can be transformed directly into source or machine code.

A pattern has four essential elements:

1. **Pattern Name**
2. **Problem**
3. **Solution**
4. **Consequence**

1. The **pattern name** is a handle we can use to describe a design problem, its solutions, and consequences in a word or two. Naming a pattern immediately increases our design vocabulary. It lets us design at a higher level of abstraction. Having a vocabulary for patterns lets us talk about them with our colleagues, in our documentation, and even to ourselves. It makes it easier to think about designs and to communicate them and their trade-offs to others. Finding good names has been one of the hardest parts of developing our catalog.
2. The **problem** describes when to apply the pattern. It explains the problem and its context. It might describe specific design problems such as how to represent algorithms as objects. It might describe class or object structures that are symptomatic of an inflexible design. Sometimes the problem will include a list of conditions that must be met before it makes sense to apply the pattern.
3. The **solution** describes the elements that make up the design, their relationships, responsibilities, and collaborations. The solution doesn't describe a particular concrete design or implementation, because a pattern is like a template that can be applied in many different situations. Instead, the pattern provides an abstract description of a design problem and how a general arrangement of elements (classes and objects in our case) solves it.
4. The **consequences** are the results and trade-offs of applying the pattern. Though consequences are often unvoiced when we describe design decisions, they are critical for evaluating design alternatives and for understanding the costs and benefits of applying the pattern. The consequences for software often concern space and time trade-offs. They may address language and implementation issues as well. Since reuse is often a factor in object-oriented design, the consequences of a pattern include its

impact on a system's flexibility, extensibility, or portability. Listing these consequences explicitly helps you understand and evaluate them.

The Catalog of Design Patterns

The catalog beginning on contains 23 design patterns. Their names and intents are listed

Abstract Factory

Provide an interface for creating families of related or dependent objects without specifying their concrete classes.

Adapter

Convert the interface of a class into another interface clients expect. Adapter lets classes work together that couldn't otherwise because of incompatible interfaces.

Bridge

Decouple an abstraction from its implementation so that the two can vary independently.

Builder

Separate the construction of a complex object from its representation so that the same construction process can create different representations.

Chain of Responsibility

Avoid coupling the sender of a request to its receiver by giving more than one object a chance to handle the request. Chain the receiving objects and pass the request along the chain until an object handles it.

Command

Encapsulate a request as an object, thereby letting you parameterize clients with different requests, queue or log requests, and support undoable operations.

Composite

Compose objects into tree structures to represent part-whole hierarchies. Composite lets clients treat individual objects and compositions of objects uniformly.

Decorator

Attach additional responsibilities to an object dynamically. Decorators provide a flexible alternative to sub classing for extending functionality.

Facade

Provide a unified interface to a set of interfaces in a subsystem. Facade defines a higher-level interface that makes the subsystem easier to use.

Factory Method

Define an interface for creating an object, but let subclasses decide which class to instantiate. Factory Method lets a class defer instantiation to subclasses.

Flyweight

Use sharing to support large numbers of fine-grained objects efficiently.

Interpreter

Given a language, define a representation for its grammar along with an interpreter that uses the representation to interpret sentences in the language.

Iterator

Provide a way to access the elements of an aggregate object sequentially without exposing its underlying representation.

Mediator

Define an object that encapsulates how a set of objects interact. Mediator promotes loose coupling by keeping objects from referring to each other explicitly, and it lets you vary their interaction independently.

Memento

Without violating encapsulation, capture and externalize an object's internal state so that the object can be restored to this state later.

Observer

Define a one-to-many dependency between objects so that when one object changes state, all its dependents are notified and updated automatically.

Prototype

Specify the kinds of objects to create using a prototypical instance, and create new objects by copying this prototype.

Proxy

Provide a surrogate or placeholder for another object to control access to it.

Singleton

Ensure a class only has one instance, and provide a global point of access to it.

State

Allow an object to alter its behaviour when its internal state changes. The object will appear to change its class.

Strategy

Define a family of algorithms, encapsulate each one, and make them interchangeable. Strategy lets the algorithm vary independently from clients that use it.

Template Method

Define the skeleton of an algorithm in an operation, deferring some steps to subclasses. Template Method lets subclasses redefine certain steps of an algorithm without changing the algorithm's structure.

Visitor

Represent an operation to be performed on the elements of an object structure. Visitor lets you define a new operation without changing the classes of the elements on which it operates.

Organizing the Catalog

Design patterns vary in their granularity and level of abstraction. Because there are many design patterns, we need a way to organize them. This section classifies design patterns so that we can refer to families of related patterns. The classification helps you learn the patterns in the catalog faster, and it can direct efforts to find new patterns as well.

We classify design patterns by two criteria. The first criterion, called purpose, reflects what a pattern does. Patterns can have creational, structural, or behavioural purpose. Creational patterns concern the process of object creation. Structural patterns deal with the composition of classes or objects. Behavioural patterns characterize the ways in which classes or objects interact and distribute responsibility.

		Purpose		
		Creational	**Structural**	**Behavioral**
Scope	**Class**	Factory Method	Adapter	Interpreter Template Method
	Object	Abstract Factory Builder Prototype Singleton	Adapter Bridge Composite Decorator Facade Proxy	Chain of Responsibility Command Iterator Mediator Memento Flyweight (195) Observer State Strategy Visitor

Organization of Design Pattern

The second criterion, called **scope**, specifies whether the pattern applies primarily to classes or to objects. Class patterns deal with relationships between classes and their subclasses. These relationships are established through inheritance, so they are static—fixed at compile-time. Object patterns deal with object relationships, which can be changed at run-time and are more dynamic. Almost all patterns use inheritance to some extent. So the only patterns labelled "class patterns" are those that focus on class relationships. Note that most patterns are in the Object scope.

Advantage of design pattern:

1. They are reusable in multiple projects.
2. They provide the solutions that help to define the system architecture.
3. They capture the software engineering experiences.
4. They provide transparency to the design of an application.
5. They are well-proved and testified solutions since they have been built upon the knowledge and experience of expert software developers.
6. Designs patterns donate guarantee an absolute solution to a problem. They provide clarity to the system architecture and the possibility of building a better system.

When should we use the design patterns?

We must use the design patterns **during the analysis and requirement phase of SDLC** (Software Development Life Cycle).

Design patterns ease the analysis and requirement phase of SDLC by providing information based on prior hands-on experiences.

What are different characteristics of design patterns?

A design pattern is a general repeatable solution to a commonly occurring problem in software design.

- It is a proven solution to problems that keep recurring.
- They are reusable solutions to common problems.
- Design patterns are not frameworks.
- Design patterns are more abstract than frameworks.
- Design pattern cannot be directly implemented.
- Design patterns are more primitive than a framework.
- A design pattern cannot incorporate a framework.
- Patterns may be documented using one of several alternative templates.
- Design patterns can speed up the development process by providing tested, proven development paradigms.
- Reusing design patterns helps to prevent subtle issues that can cause major problems and improves code readability for coders and architects familiar with the patterns.
- Patterns allow developers to communicate using well-known, well understood names for software interactions.

Describing Design Patterns

To reuse the design, we must also record the decisions, alternatives, and trade-offs that led to it. Concrete examples are important too, because they help you see the design in action. We describe design patterns using a consistent format. Each pattern is divided into sections according to the following template. The template lends a uniform structure to the information, making design patterns easier to learn, compare, and use.

Pattern Name and Classification

The pattern's name conveys the essence of the pattern succinctly. A good name is vital, because it will become part of your design vocabulary.

Intent

A short statement that answers the following questions: What does the design pattern do? What is its rationale and intent? What particular design issue or problem does it address?

Also Known As

Other well-known names for the pattern, if any.

Motivation

A scenario that illustrates a design problem and how the class and object structures in the pattern solve the problem. The scenario will help you understand the more abstract description of the pattern that follows.

Applicability

What are the situations in which the design pattern can be applied? What are examples of poor designs that the pattern can address? How can you recognize these situations?

Structure

A graphical representation of the classes in the pattern using a notation based on the Object Modelling Technique (OMT).We also use interaction diagrams to illustrate sequences of requests and collaborations between objects. Appendix B describes these notations in detail.

Participants

The classes and/or objects participating in the design pattern and their responsibilities.

Collaborations

How the participants collaborate to carry out their responsibilities.

Consequences

How does the pattern support its objectives? What are the trade-offs and results of using the pattern? What aspect of system structure does it let you vary independently?

Implementation

What pitfalls, hints, or techniques should you be aware of when implementing the pattern? Are there language-specific issues?

Sample Code

Code fragments that illustrate how you might implement the pattern in

Known Uses

Examples of the pattern found in real systems. We include at least two examples from different domains.

Related Patterns

What design patterns are closely related to this one? What are the important differences? With which other patterns should this one be used?

Solving Design Problems with Design Patterns

1. Finding Appropriate Objects
2. Determining object Granularity
3. Specifying object Interface
4. Designing for Change

1. Finding Appropriate Objects

Object-oriented programs are made up of objects. The hard part about object-oriented design is decomposing a system into objects. Design patterns can help in this process by identifying less obvious abstractions and the objects that capture them.

For example, objects that represent a process or algorithm don't occur in nature, but they can be crucial in a flexible design. The Strategy pattern describes how to implement families of algorithms to solve a particular problem. Those algorithms can be interchanged at run-time, since they are objects now and are subject to polymorphism for example.

2. Determining Object Granularity

Usually, objects vary in size and number. They can represent everything down to the hardware or all the way up to entire applications.

Design patterns can help to determine proper object granularity. For example, the Facade pattern describes how to represent complete subsystems as objects, and the Flyweight pattern describes how to support huge numbers of objects at the finest granularities.

A number of other patterns, such as Composite, describe how to decompose an object into smaller objects.

3. Specifying Object Interfaces

Design patterns help programmers to define interfaces by identifying their key elements and the kind of data that get sent across an interface. A design pattern can also tell what not to put in the interface.

For example, the Memento pattern describes how to encapsulate and save the internal state of an object so that the object can be restored to that state later. The pattern stipulates that Memento objects must define two interfaces:

- A restricted one that lets clients hold and copy mementos
- A privileged one that only the original objects can use to store and retrieve state in the memento.

5. Designing for Change

Designing a system that is robust to changes is a rather hard task to do. However, a design that doesn't take changes into account risks major redesigns in the future. Design patterns can ensure that a system can change in specific ways.

Each design pattern lets some aspect of the system structure vary independently of other aspects, thereby making a system more robust to a particular kind of change.

Let us look on some examples:

- Creating an object by specifying a class explicitly commits to a particular implementation instead of a particular interface. That means if we in the future want to change the object that we use we need also to implement the client code again. On the other hand using the design patterns, such as Abstract Factory pattern lets you avoid this problem.
- Dependence on hardware and software platform. Clients that know how an object is represented, stored, located, or implemented might need to be changed when the object changes. Hiding this information from clients keeps changes from cascading. An example is again Abstract Factory used to create different look-and-feel components across different operating systems.

How to Select a Design Pattern

Here are several different approaches to finding the design pattern that's right for your problem:

1. Consider how design patterns solve design problems.

2. Scan Intent sections

3. Study how patterns interrelate.

4. Study patterns of like purpose.

5. Examine a cause of redesign.

6. Consider what should be variable in your design.

Common causes of redesign of an existing system

- **Creating a class by specifying a class explicitly** : If need be use creational patterns instead
- **Dependence on specific methods** : If need be use Chain of Responsibility or Command pattern instead
- **Dependence on Hardware and/or software platforms** : Consider using Abstract Factory or Bridge pattern instead
- **Dependence on Object Representation or Implementation** : Must program to interface and not to implementation. Abstract Factory, Bridge, Memento, Proxy etc patterns can help.
- **Dependence on specific Algorithms** : Consider using Strategy or Visitor pattern
- **Extending functionality by subclassing** : Prefer composition over inheritance
- **Inability to alter classes conveniently** : esp. with third party libraries. Adapter, Decorator and Visitor can help.

Explain the concept of Software reusability used in design pattern

- Software Reliability is the probability of failure-free software operation for a specified period of time in a specified environment. Software Reliability is also an important factor affecting system reliability. It differs from hardware reliability in that it reflects the design perfection, rather than manufacturing perfection. The high complexity of software is the major contributing factor of Software Reliability problems.
- Software Reliability is not a function of time - although researchers have come up with models relating the two. The modeling technique for Software Reliability is reaching its prosperity, but before using the technique, we must carefully select the appropriate model that can best suit our case. Measurement in software is still in its infancy. No good quantitative methods have been developed to represent Software Reliability without excessive limitations. Various approaches can be used to improve the reliability of software, however, it is hard to balance development time and budget with software reliability.
- A good software reliability engineering program, introduced early in the development cycle, will mitigate these problems by: Preparing program management in advance for the testing effort and allowing them to plan both schedule and budget to cover the required testing.
- Continuous review of requirements throughout the life cycle, particularly for handling of exception conditions. If requirements are incomplete there will be no testing of the exception conditions.

- SoHaR software reliability engineers are experienced in all the stages and tasks required in a comprehensive software reliability program. We can support or lead tasks such as:

  1) Reliability Allocation
  2) Defining and Analyzing Operational Profiles
  3) Test Preparation and Plan
  4) Software Reliability Models

- **Reliability Allocation**:-

  Reliability allocation is the task of defining the necessary reliability of a software item. The item may be part of an integrated hardware/software system, may be a relatively independent software application, or, more and more rarely, a standalone software program. In either of these cases our goal is to bring system reliability within either a strict constraint required by a customer or an internally perceived readiness level, or optimize reliability within schedule and cost constraints.
  SoHaR will assist your organization in the following tasks:
  Derive software reliability requirements from overall system reliability requirements.
  When possible, depending on lifecycle stage and historical data, estimate schedule and cost dependence on software reliability goals.
  Optimize reliability/schedule/cost based on your constraints and your customer's requirements,

- **Defining and Analyzing Operational Profiles**:-

  The reliability of software, much more so than the reliability of hardware, is strongly tied to the operational usage of an application. A software fault may lead to system failure only if that fault is encountered during operational usage. If a fault is not accessed in a specific operational mode, it will not cause failures at all. It will cause failure more often if it is located in code that is part of an often used "operation" (An operation is defined as a major logical task, usually repeated multiple times within an hour of application usage). Therefore in software reliability engineering we focus on the operational profile of the software which weighs the occurrence probabilities of each operation. Unless safety requirements indicate a modification of this approach we will prioritize our testing according to this profile.

SoHaR will work with your system and software engineers to complete the following tasks required to generate a useable operational profile:

Determine the operational modes (high traffic, low traffic, high maintenance, remote use, local use etc).

Determine operation initiators (components that initiate the operations in the system).

Determine and group "Operations" so that the list includes only operations that are significantly different from each other (and therefore may present different faults).

Determine occurrence rates for the different operations.

Construct the operational profile based on the individual operation probabilities of occurrence.

- **Test Preparation and Plan**:-

  Test preparation is a crucial step in the implementation of an effective software reliability program. A test plan that is based on the operational profile on the one hand, and subject to the reliability allocation constraints on the other, will be effective at bringing the program to its reliability goals in the least amount of time and cost.

  Software Reliability Engineering is concerned not only with feature and regression test, but also with load test and performance test. All these should be planned based on the activities outlined above.

  The reliability program will inform and often determine the following test preparation activities:

  Assessing the number of new test cases required for the current release.

  New test case allocation among the systems (if multi-system).

  New test case allocation for each system among its new operations.

  Specifying new test cases

  Adding the new test cases to the test cases from previous releases.

- **Software Reliability Models**:-

  Software reliability engineering is often identified with reliability models, in particular reliability growth models. These, when applied correctly, are successful at providing guidance to management decisions such as:

  Test schedule

  Test resource allocation

  Time to market

  Maintenance resource allocation

Chapter 2

A Case Study: Designing a Document Editor

This chapter presents a case study in the design of a "What-You-See-Is-What-You-Get" (or "WYSIWYG") document editor called **Lexi**.[1] We'll see how design patterns capture solutions to design problems in Lexi and applications like it. By the end of this chapter you will have gained experience with eight patterns, learning them by example.

Figure 2.1 depicts Lexi's user interface. A WYSIWYG representation of the document occupies the large rectangular area in the center. The document can mix text and graphics freely in a variety of formatting styles. Surrounding the document are the usual pull-down menus and scroll bars, plus a collection of page icons for jumping to a particular page in the document.

2.1 Design Problems

We will examine seven problems in Lexi's design:

1. *Document structure.* The choice of internal representation for the document affects nearly every aspect of Lexi's design. All editing, formatting, displaying, and textual analysis will require traversing the representation. The way we organize this information will impact the design of the rest of the application.

2. *Formatting.* How does Lexi actually arrange text and graphics into lines and columns? What objects are responsible for carrying out different formatting policies? How do these policies interact with the document's internal representation?

[1] Lexi's design is based on Doc, a text editing application developed by Calder [CL92].

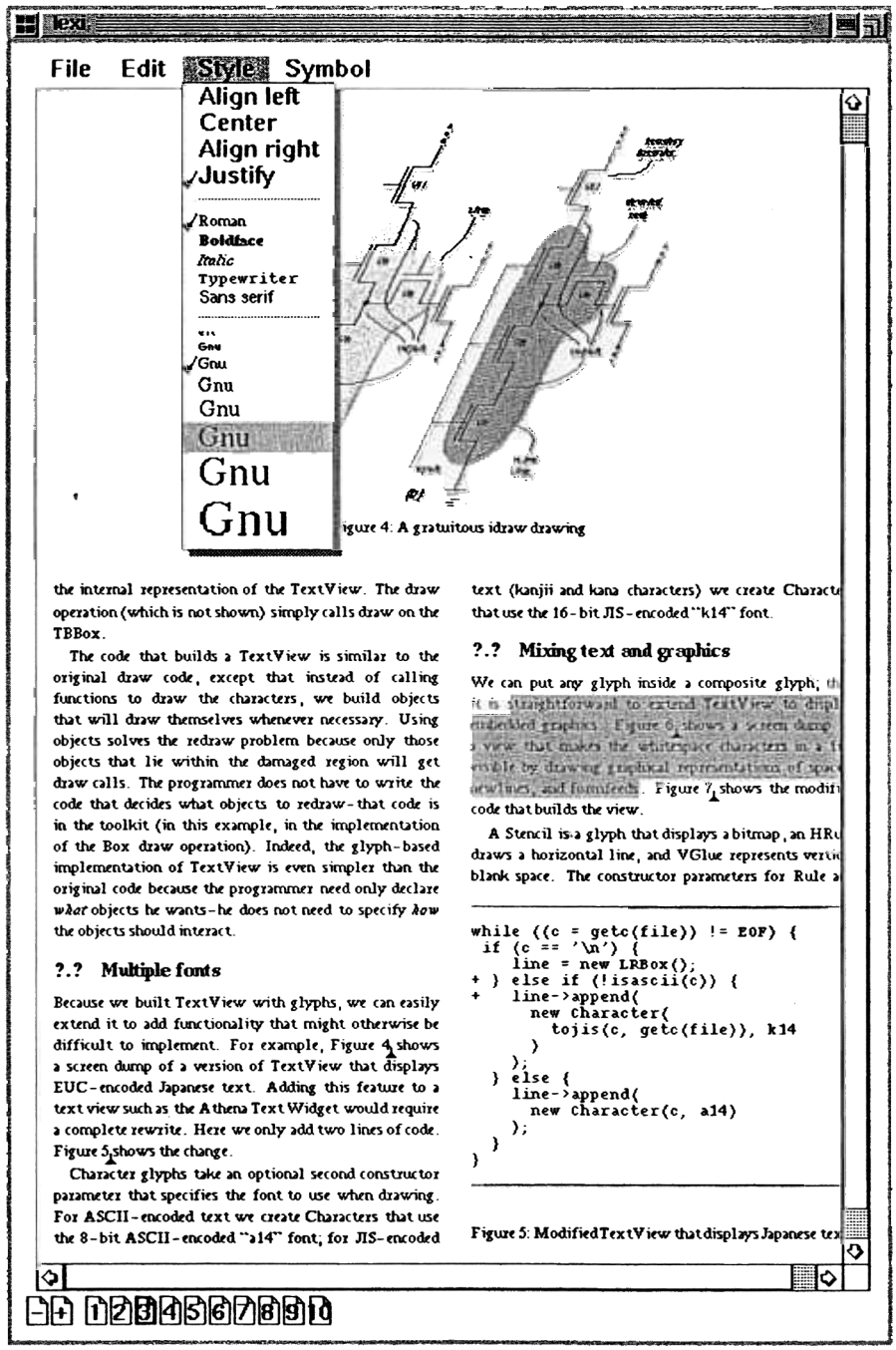


Figure 2.1: Lexi's user interface

3. *Embellishing the user interface.* Lexi's user interface includes scroll bars, borders, and drop shadows that embellish the WYSIWYG document interface. Such embellishments are likely to change as Lexi's user interface evolves. Hence it's important to be able to add and remove embellishments easily without affecting the rest of the application.

   Supporting multiple look-and-feel standards. Lexi should adapt easily to different look-and-feel standards such as Motif and Presentation Manager (PM) without major modification.

5. *Supporting multiple window systems.* Different look-and-feel standards are usually implemented on different window systems. Lexi's design should be as independent of the window system as possible.

6. *User operations.* Users control Lexi through various user interfaces, including buttons and pull-down menus. The functionality behind these interfaces is scattered throughout the objects in the application. The challenge here is to provide a uniform mechanism both for accessing this scattered functionality and for undoing its effects.

7. *Spelling checking and hyphenation.* How does Lexi support analytical operations such as checking for misspelled words and determining hyphenation points? How can we minimize the number of classes we have to modify to add a new analytical operation?

We discuss these design problems in the sections that follow. Each problem has an associated set of goals plus constraints on how we achieve those goals. We explain the goals and constraints in detail before proposing a specific solution. The problem and its solution will illustrate one or more design patterns. The discussion for each problem will culminate in a brief introduction to the relevant patterns.

2.2 Document Structure

A document is ultimately just an arrangement of basic graphical elements such as characters, lines, polygons, and other shapes. These elements capture the total information content of the document. Yet an author often views these elements not in graphical terms but in terms of the document's physical structure—lines, columns, figures, tables, and other substructures.[2] In turn, these substructures have substructures of their own, and so on.

Lexi's user interface should let users manipulate these substructures directly. For example, a user should be able to treat a diagram as a unit rather than as a collection of

[2] Authors often view the document in terms of its *logical* structure as well, that is, in terms of sentences, paragraphs, sections, subsections, and chapters. To keep this example simple, our internal representation won't store information about the logical structure explicitly. But the design solution we describe works equally well for representing such information.

individual graphical primitives. The user should be able to refer to a table as a whole, not as an unstructured mass of text and graphics. That helps make the interface simple and intuitive. To give Lexi's implementation similar qualities, we'll choose an internal representation that matches the document's physical structure.

In particular, the internal representation should support the following:

- Maintaining the document's physical structure, that is, the arrangement of text and graphics into lines, columns, tables, etc.
- Generating and presenting the document visually.
- Mapping positions on the display to elements in the internal representation. This lets Lexi determine what the user is referring to when he points to something in the visual representation.

In addition to these goals are some constraints. First, we should treat text and graphics uniformly. The application's interface lets the user embed text within graphics freely and vice versa. We should avoid treating graphics as a special case of text or text as a special case of graphics; otherwise we'll end up with redundant formatting and manipulation mechanisms. One set of mechanisms should suffice for both text and graphics.

Second, our implementation shouldn't have to distinguish between single elements and groups of elements in the internal representation. Lexi should be able to treat simple and complex elements uniformly, thereby allowing arbitrarily complex documents. The tenth element in line five of column two, for instance, could be a single character or an intricate diagram with many subelements. As long as we know this element can draw itself and specify its dimensions, its complexity has no bearing on how and where it should appear on the page.

Opposing the second constraint, however, is the need to analyze the text for such things as spelling errors and potential hyphenation points. Often we don't care whether the element of a line is a simple or complex object. But sometimes an analysis depends on the objects being analyzed. It makes little sense, for example, to check the spelling of a polygon or to hyphenate it. The internal representation's design should take this and other potentially conflicting constraints into account.

Recursive Composition

A common way to represent hierarchically structured information is through a technique called **recursive composition**, which entails building increasingly complex elements out of simpler ones. Recursive composition gives us a way to compose a document out of simple graphical elements. As a first step, we can tile a set of characters and graphics from left to right to form a line in the document. Then multiple lines can be arranged to form a column, multiple columns can form a page, and so on (see Figure 2.2).

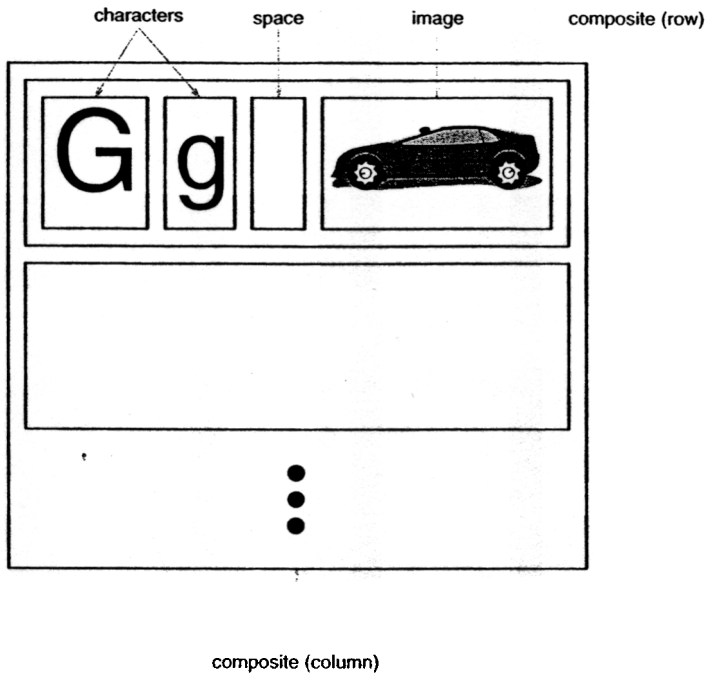


Figure 2.2: Recursive composition of text and graphics

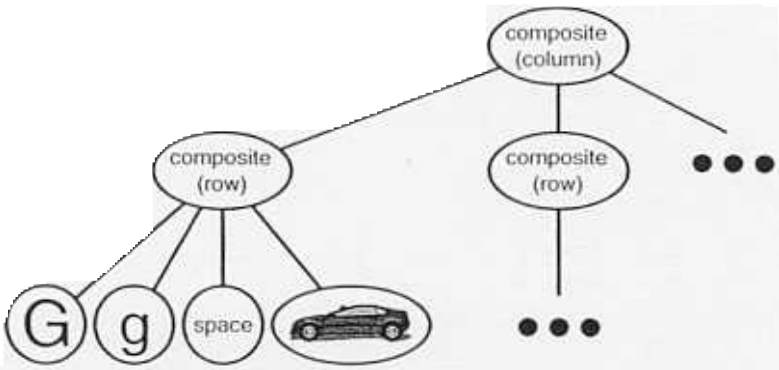


Figure 2.3: Object structure for recursive composition of text and graphics

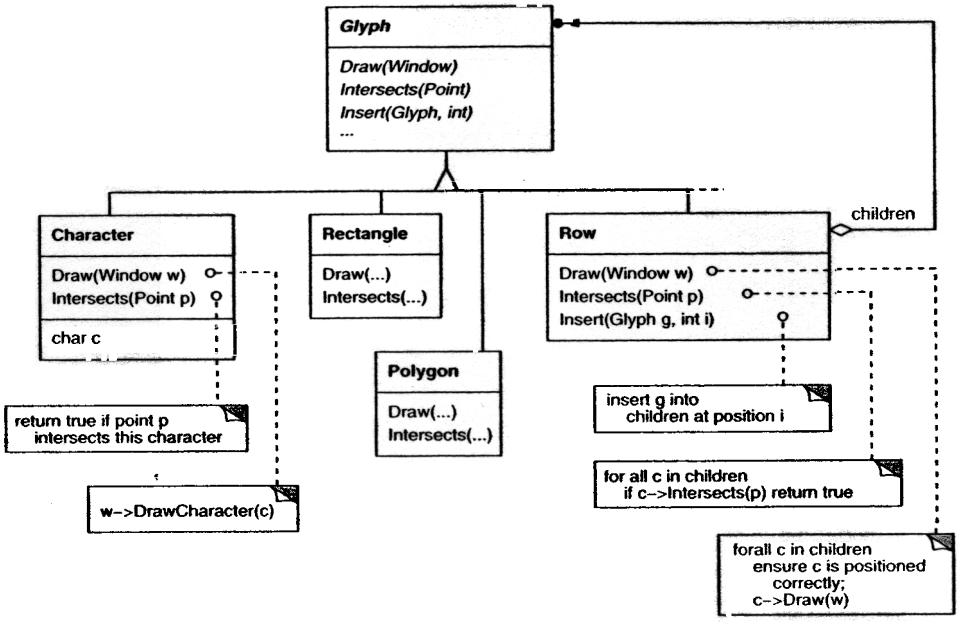


Figure 2.4: Partial Glyph class hierarchy

We can represent this physical structure by devoting an object to each important element. That includes not just the visible elements like the characters and graphics but the invisible, structural elements as well—the lines and the column. The result is the object structure shown in Figure 2.3.

By using an object for each character and graphical element in the document, we promote flexibility at the finest levels of Lexi's design. We can treat text and graphics uniformly with respect to how they are drawn, formatted, and embedded within each other. We can extend Lexi to support new character sets without disturbing other functionality. Lexi's object structure mimics the document's physical structure.

This approach has two important implications. The first is obvious: The objects need corresponding classes. The second implication, which may be less obvious, is that these classes must have compatible interfaces, because we want to treat the objects uniformly. The way to make interfaces compatible in a language like C++ is to relate the classes through inheritance.

Glyphs

We'll define a **Glyph** abstract class for all objects that can appear in a document structure.[3] Its subclasses define both primitive graphical elements (like characters and

[3] Calder was the first to use the term "glyph" in this context [CL90]. Most contemporary document editors don't use an object for every character, presumably for efficiency reasons. Calder demonstrated that this

Responsibility	Operations
appearance	`virtual void Draw(Window*)` `virtual void Bounds(Rect&)`
hit detection	`virtual bool Intersects(const Point&)`

structure	`virtual void Insert(Glyph*, int)`
	`virtual void Remove(Glyph*)`
	`virtual Glyph* Child(int)`
	`virtual Glyph* Parent()`

Table 2. Basic glyph interface

images) and structural elements (like rows and columns). Figure 2.4 depicts a representative part of the Glyph class hierarchy, and Table 2.1 presents the basic glyph interface in more detail using C++ notation.[4]

Glyphs have three basic responsibilities. They know (1) how to draw themselves, (2) what space they occupy, and (3) their children and parent.

Glyph subclasses redefine the `Draw` operation to render themselves onto a window. They are passed a reference to a `Window` object in the call to `Draw`. The **Window** class defines graphics operations for rendering text and basic shapes in a window on the screen. A **Rectangle** subclass of Glyph might redefine `Draw` as follows:

```
void Rectangle::Draw (Window* w) {
    w->DrawRect(_x0, _y0, _x1, _y1);
```

where `_x0`, `_y0`, `_x1`, and `_y1` are data members of `Rectangle` that define two opposing corners of the rectangle. `DrawRect` is the Window operation that makes the rectangle appear on the screen.

A parent glyph often needs to know how much space a child glyph occupies, for example, to arrange it and other glyphs in a line so that none overlaps (as shown in Figure 2.2). The `Bounds` operation returns the rectangular area that the glyph occupies. It returns the opposite corners of the smallest rectangle that contains the glyph. Glyph subclasses redefine this operation to return the rectangular area in which they draw.

The `Intersects` operation returns whether a specified point intersects the glyph. Whenever the user clicks somewhere in the document, Lexi calls this operation to determine which glyph or glyph structure is under the mouse. The Rectangle class redefines this operation to compute the intersection of the rectangle and the given point.

approach is feasible in his thesis [Cal93]. Our glyphs are less sophisticated than his in that we have restricted ours to strict hierarchies for simplicity. Calder's glyphs can be shared to reduce storage costs, thereby forming directed-acyclic graph structures. We can apply the Flyweight (195) pattern to get the same effect, but we'll leave that as an exercise for the reader.

[4] The interface we describe here is purposely minimal to keep the discussion simple. A complete interface would include operations for managing graphical attributes such as color, font, and coordinate transformations, plus operations for more sophisticated child management.

Because glyphs can have children, we need a common interface to add, remove, and access those children. For example, a Row's children are the glyphs it arranges into a row. The `Insert` operation inserts a glyph at a position specified by an integer index.[5] The `Remove` operation removes a specified glyph if it is indeed a child.

The `Child` operation returns the child (if any) at the given index. Glyphs like Row that can have children should use `Child` internally instead of accessing the child data structure directly. That way you won't have to modify operations like `Draw` that iterate through the children when you change the data structure from, say, an array to a linked list. Similarly, `Parent` provides a standard interface to the glyph's parent, if any. Glyphs in Lexi store a reference to their parent, and their `Parent` operation simply returns this reference.

Composite Pattern

Recursive composition is good for more than just documents. We can use it to represent any potentially complex, hierarchical structure. The Composite (163) pattern captures the essence of recursive composition in object-oriented terms. Now would be a good time to turn to that pattern and study it, referring back to this scenario as needed.

2.3 Formatting

We've settled on a way to *represent* the document's physical structure. Next, we need to figure out how to construct a *particular* physical structure, one that corresponds to a properly formatted document. Representation and formatting are distinct: The ability to capture the document's physical structure doesn't tell us how to arrive at a particular structure. This responsibility rests mostly on Lexi. It must break text into lines, lines into columns, and so on, taking into account the user's higher-level desires. For example, the user might want to vary margin widths, indentation, and tabulation; single or double space; and probably many other formatting constraints.[6] Lexi's formatting algorithm must take all of these into account.

By the way, we'll restrict "formatting" to mean breaking a collection of glyphs into lines. In fact, we'll use the terms "formatting" and "linebreaking" interchangeably. The techniques we'll discuss apply equally well to breaking lines into columns and to breaking columns into pages.

---

[5] An integer index is probably not the best way to specify a glyph's children, depending on the data structure the glyph uses. If it stores its children in a linked list, then a pointer into the list would be more efficient. We'll see a better solution to the indexing problem in Section 2.8, when we discuss document analysis.

[6] The user will have even more to say about the document's *logical* structure—the sentences, paragraphs, sections, chapters, and so forth. The *physical* structure is less interesting by comparison. Most people don't care where the linebreaks in a paragraph occur as long as the paragraph is formatted properly. The same is true for formatting columns and pages. Thus users end up specifying only high-level constraints on the physical structure, leaving Lexi to do the hard work of satisfying them.

Responsibility	Operations
what to format	`void SetComposition(Composition*)`
when to format	`virtual void Compose()`

Table 2.2: Basic compositor interface

Encapsulating the Formatting Algorithm

The formatting process, with all its constraints and details, isn't easy to automate. There are many approaches to the problem, and people have come up with a variety of formatting algorithms with different strengths and weaknesses. Because Lexi is a WYSIWYG editor, an important trade-off to consider is the balance between formatting quality and formatting speed. We want generally good response from the editor without sacrificing how good the document looks. This trade-off is subject to many factors, not all of which can be ascertained at compile-time. For example, the user might tolerate slightly slower response in exchange for better formatting. That trade-off might make an entirely different formatting algorithm more appropriate than the current one. Another, more implementation-driven trade-off balances formatting speed and storage requirements: It may be possible to decrease formatting time by caching more information.

Because formatting algorithms tend to be complex, it's also desirable to keep them well-contained or—better yet—completely independent of the document structure. Ideally we could add a new kind of Glyph subclass without regard to the formatting algorithm. Conversely, adding a new formatting algorithm shouldn't require modifying existing glyphs.

These characteristics suggest we should design Lexi so that it's easy to change the formatting algorithm at least at compile-time, if not at run-time as well. We can isolate the algorithm and make it easily replaceable at the same time by encapsulating it in an object. More specifically, we'll define a separate class hierarchy for objects that encapsulate formatting algorithms. The root of the hierarchy will define an interface that supports a wide range of formatting algorithms, and each subclass will implement the interface to carry out a particular algorithm. Then we can introduce a Glyph subclass that will structure its children automatically using a given algorithm object.

Compositor and Composition

We'll define a **Compositor** class for objects that can encapsulate a formatting algorithm. The interface (Table 2.2) lets the compositor know *what* glyphs to format and *when* to do the formatting. The glyphs it formats are the children of a special Glyph subclass called **Composition**. A composition gets an instance of a Compositor subclass (specialized for a particular linebreaking algorithm) when it is created, and it tells the compositor to `Compose` its glyphs when necessary, for example, when the user changes a document. Figure 2.5 depicts the relationships between the Composition and Compositor classes.

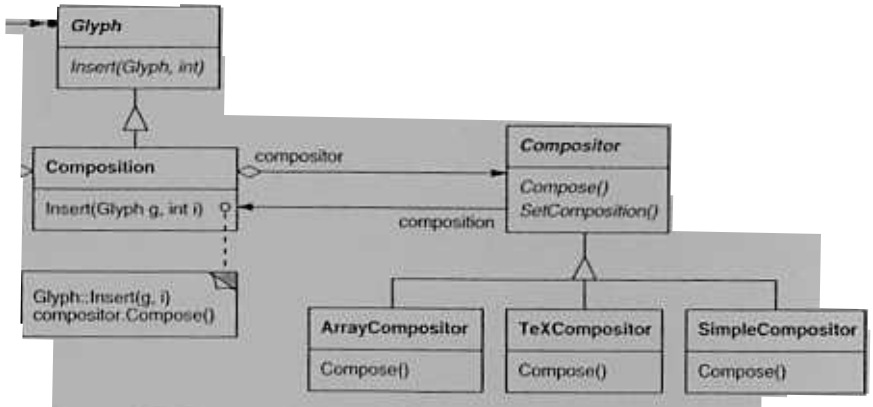


Figure 2.5: Composition and Compositor class relationships

An unformatted Composition object contains only the visible glyphs that make up the document's basic content. It doesn't contain glyphs that determine the document's physical structure, such as Row and Column. The composition is in this state just after it's created and initialized with the glyphs it should format. When the composition needs formatting, it calls its compositor's `Compose` operation. The compositor in turn iterates through the composition's children and inserts new Row and Column glyphs according to its linebreaking algorithm.[7] Figure 2.6 shows the resulting object structure. Glyphs that the compositor created and inserted into the object structure appear with gray backgrounds in the figure.

Each Compositor subclass can implement a different linebreaking algorithm. For example, a SimpleCompositor might do a quick pass without regard for such esoterica as the document's "color." Good color means having an even distribution of text and whitespace. A TeXCompositor would implement the full TEX algorithm [Knu84], which takes things like color into account in exchange for longer formatting times.

The Compositor-Composition class split ensures a strong separation between code that supports the document's physical structure and the code for different formatting algorithms. We can add new Compositor subclasses without touching the glyph classes, and vice versa. In fact, we can change the linebreaking algorithm at run-time by adding a single `SetCompositor` operation to Composition's basic glyph interface.

Strategy Pattern

Encapsulating an algorithm in an object is the intent of the Strategy (315) pattern. The key participants in the pattern are Strategy objects (which encapsulate different algorithms) and the context in which they operate. Compositors are strategies; they en-

[7] The compositor must get the character codes of Character glyphs in order to compute the linebreaks. In Section 2.8 we'll see how to get this information polymorphically without adding a character-specific operation to the Glyph interface.

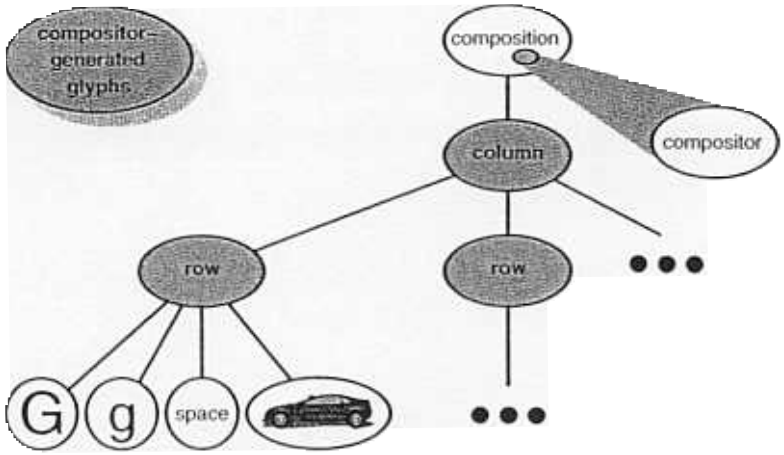


Figure 2.6: Object structure reflecting compositor-directed linebreaking

capsulate different formatting algorithms. A composition is the context for a compositor strategy.

The key to applying the Strategy pattern is designing interfaces for the strategy and its context that are general enough to support a range of algorithms. You shouldn't have to change the strategy or context interface to support a new algorithm. In our example, the basic Glyph interface's support for child access, insertion, and removal is general enough to let Compositor subclasses change the document's physical structure, regardless of the algorithm they use to do it. Likewise, the Compositor interface gives compositions whatever they need to initiate formatting.

2.4 Embellishing the User Interface

We consider two embellishments in Lexi's user interface. The first adds a border around the text editing area to demarcate the page of text. The second adds scroll bars that let the user view different parts of the page. To make it easy to add and remove these embellishments (especially at run-time), we shouldn't use inheritance to add them to the user interface. We achieve the most flexibility if other user interface objects don't even know the embellishments are there. That will let us add and remove the embellishments without changing other classes.

Transparent Enclosure

From a programming point of view, embellishing the user interface involves extending existing code. Using inheritance to do such extension precludes rearranging embellish-

ments at run-time, but an equally serious problem is the explosion of classes that can result from an inheritance-based approach.

We could add a border to Composition by subclassing it to yield a BorderedComposition class. Or we could add a scrolling interface in the same way to yield a ScrollableComposition. If we want both scroll bars and a border, we might produce a BorderedScrollableComposition, and so forth. In the extreme, we end up with a class for every possible combination of embellishments, a solution that quickly becomes unworkable as the variety of embellishments grows.

Object composition offers a potentially more workable and flexible extension mechanism. But what objects do we compose? Since we know we're embellishing an existing glyph, we could make the embellishment itself an object (say, an instance of class **Border**). That gives us two candidates for composition, the glyph and the border. The next step is to decide who composes whom. We could have the border contain the glyph, which makes sense given that the border will surround the glyph on the screen. Or we could do the opposite—put the border into the glyph—but then we must make modifications to the corresponding Glyph subclass to make it aware of the border. Our first choice, composing the glyph in the border, keeps the border-drawing code entirely in the Border class, leaving other classes alone.

What does the Border class look like? The fact that borders have an appearance suggests they should actually be glyphs; that is, Border should be a subclass of Glyph. But there's a more compelling reason for doing this: Clients shouldn't care whether glyphs have borders or not. They should treat glyphs uniformly. When clients tell a plain, unbordered glyph to draw itself, it should do so without embellishment. If that glyph is composed in a border, clients shouldn't have to treat the border containing the glyph any differently; they just tell it to draw itself as they told the plain glyph before. This implies that the Border interface matches the Glyph interface. We subclass Border from Glyph to guarantee this relationship.

All this leads us to the concept of **transparent enclosure**, which combines the notions of (1) single-child (or single-**component**) composition and (2) compatible interfaces. Clients generally can't tell whether they're dealing with the component or its **enclosure** (i.e., the child's parent), especially if the enclosure simply delegates all its operations to its component. But the enclosure can also *augment* the component's behavior by doing work of its own before and/or after delegating an operation. The enclosure can also effectively add state to the component. We'll see how next.

Monoglyph

We can apply the concept of transparent enclosure to all glyphs that embellish other glyphs. To make this concept concrete, we'll define a subclass of Glyph called **MonoGlyph** to serve as an abstract class for "embellishment glyphs," like Border (see Figure 2.7). MonoGlyph stores a reference to a component and forwards all requests to it.

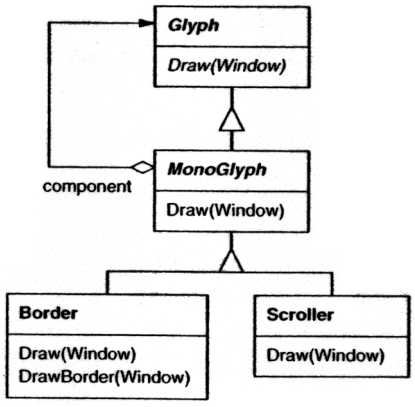


Figure 2.7: MonoGlyph class relationships

That makes MonoGlyph totally transparent to clients by default. For example, MonoGlyph implements the `Draw` operation like this:

```
void MonoGlyph::Draw (Window* w) {
    _component->Draw(w);
```

MonoGlyph subclasses reimplement at least one of these forwarding operations. `Border::Draw`, for instance, first invokes the parent class operation `MonoGlyph::Draw` on the component to let the component do its part—that is, draw everything but the border. Then `Border::Draw` draws the border by calling a private operation called `DrawBorder`, the details of which we'll omit:

```
void Border::Draw (Window* w)
    MonoGlyph::Draw(w);
    DrawBorder(w);
```

Notice how `Border::Draw` effectively *extends* the parent class operation to draw the border. This is in contrast to merely *replacing* the parent class operation, which would omit the call to the `MonoGlyph::Draw`.

Another MonoGlyph subclass appears in Figure 2.7. **Scroller** is a MonoGlyph that draws its component in different locations based on the positions of two scroll bars, which it adds as embellishments. When Scroller draws its component, it tells the graphics system to clip to its bounds. Clipping parts of the component that are scrolled out of view keeps them from appearing on the screen.

Now we have all the pieces we need to add a border and a scrolling interface to Lexi's text editing area. We compose the existing Composition instance in a Scroller instance to add the scrolling interface, and we compose that in a Border instance. The resulting object structure appears in Figure 2.8.

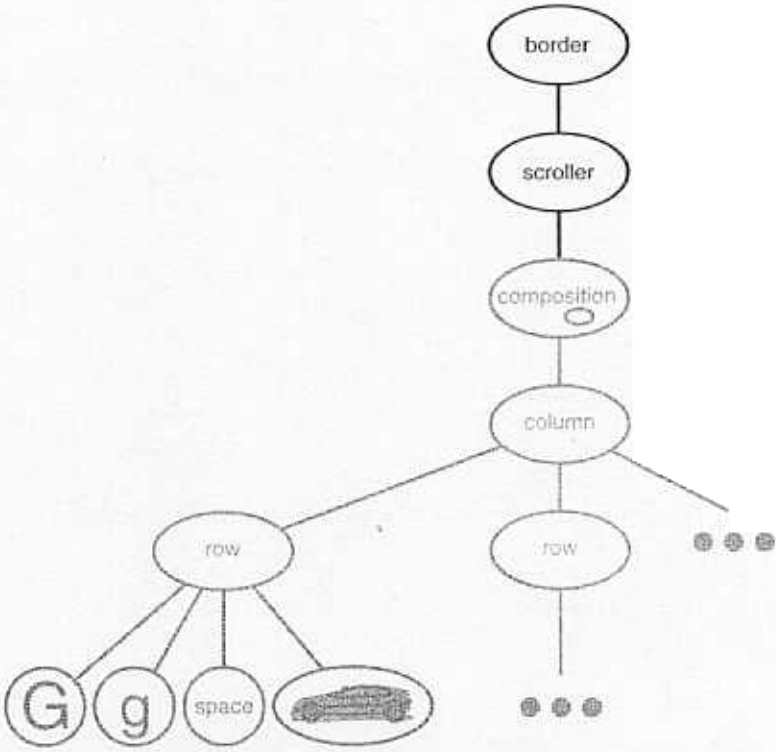


Figure 2.8: Embellished object structure

Note that we can reverse the order of composition, putting the bordered composition into the Scroller instance. In that case the border would be scrolled along with the text, which may or may not be desirable. The point is, transparent enclosure makes it easy to experiment with different alternatives, and it keeps clients free of embellishment code.

Note also how the border composes one glyph, not two or more. This is unlike compositions we've defined so far, in which parent objects were allowed to have arbitrarily many children. Here, putting a border around something implies that "something" is singular. We could assign a meaning to embellishing more than one object at a time, but then we'd have to mix many kinds of composition in with the notion of embellishment: row embellishment, column embellishment, and so forth. That won't help us, since we already have classes to do those kinds of compositions. So it's better to use existing classes for composition and add new classes to embellish the result. Keeping embellishment independent of other kinds of composition both simplifies the embellishment classes and reduces their number. It also keeps us from replicating existing composition functionality.

Decorator Pattern

The Decorator (175) pattern captures class and object relationships that support embellishment by transparent enclosure. The term "embellishment" actually has broader meaning than what we've considered here. In the Decorator pattern, embellishment refers to anything that adds responsibilities to an object. We can think for example of embellishing an abstract syntax tree with semantic actions, a finite state automaton with new transitions, or a network of persistent objects with attribute tags. Decorator generalizes the approach we've used in Lexi to make it more widely applicable.

2.5 Supporting Multiple Look-and-Feel Standards

Achieving portability across hardware and software platforms is a major problem in system design. Retargeting Lexi to a new platform shouldn't require a major overhaul, or it wouldn't be worth retargeting. We should make porting as easy as possible.

One obstacle to portability is the diversity of look-and-feel standards, which are intended to enforce uniformity between applications. These standards define guidelines for how applications appear and react to the user. While existing standards aren't that different from each other, people certainly won't confuse one for the other—Motif applications don't look and feel exactly like their counterparts on other platforms, and vice versa. An application that runs on more than one platform must conform to the user interface style guide on each platform.

Our design goals are to make Lexi conform to multiple existing look-and-feel standards and to make it easy to add support for new standards as they (invariably) emerge. We

also want our design to support the ultimate in flexibility: changing Lexi's look and feel at run-time.

Abstracting Object Creation

Everything we see and interact with in Lexi's user interface is a glyph composed in other, invisible glyphs like Row and Column. The invisible glyphs compose visible ones like Button and Character and lay them out properly. Style guides have much to say about the look and feel of so-called "widgets," another term for visible glyphs like buttons, scroll bars, and menus that act as controlling elements in a user interface. Widgets might use simpler glyphs such as characters, circles, rectangles, and polygons to present data.

We'll assume we have two sets of widget glyph classes with which to implement multiple look-and-feel standards:

1. A set of abstract Glyph subclasses for each category of widget glyph. For example, an abstract class ScrollBar will augment the basic glyph interface to add general scrolling operations; Button is an abstract class that adds button-oriented operations; and so on.

2. A set of concrete subclasses for each abstract subclass that implement different look-and-feel standards. For example, ScrollBar might have MotifScrollBar and PMScrollBar subclasses that implement Motif and Presentation Manager-style scroll bars, respectively.

Lexi must distinguish between widget glyphs for different look-and-feel styles. For example, when Lexi needs to put a button in its interface, it must instantiate a Glyph subclass for the right style of button (MotifButton, PMButton, MacButton, etc.).

It's clear that Lexi's implementation can't do this directly, say, using a constructor call in C++. That would hard-code the button of a particular style, making it impossible to select the style at run-time. We'd also have to track down and change every such constructor call to port Lexi to another platform. And buttons are only one of a variety of widgets in Lexi's user interface. Littering our code with constructor calls to specific look-and-feel classes yields a maintenance nightmare—miss just one, and you could end up with a Motif menu in the middle of your Mac application.

Lexi needs a way to determine the look-and-feel standard that's being targeted in order to create the appropriate widgets. Not only must we avoid making explicit constructor calls; we must also be able to replace an entire widget set easily. We can achieve both by *abstracting the process of object creation*. An example will illustrate what we mean.

Factories and Product Classes

Normally we might create an instance of a Motif scroll bar glyph with the following C++ code:

```
ScrollBar* sb = new MotifScrollBar
```

This is the kind of code to avoid if you want to minimize Lexi's look-and-feel dependencies. But suppose we initialize `sb` as follows:

```
ScrollBar* sb = guiFactory->CreateScrollBar();
```

where `guiFactory` is an instance of a **MotifFactory** class. `CreateScrollBar` returns a new instance of the proper ScrollBar subclass for the look and feel desired, Motif in this case. As far as clients are concerned, the effect is the same as calling the MotifScrollBar constructor directly. But there's a crucial difference: There's no longer anything in the code that mentions Motif by name. The `guiFactory` object abstracts the process of creating not just Motif scroll bars but scroll bars for *any* look-and-feel standard. And `guiFactory` isn't limited to producing scroll bars. It can manufacture a full range of widget glyphs, including scroll bars, buttons, entry fields, menus, and so forth.

All this is possible because MotifFactory is a subclass of **GUIFactory**, an abstract class that defines a general interface for creating widget glyphs. It includes operations like `CreateScrollBar` and `CreateButton` for instantiating different kinds of widget glyphs. Subclasses of GUIFactory implement these operations to return glyphs such as MotifScrollBar and PMButton that implement a particular look and feel. Figure 2.9 shows the resulting class hierarchy for `guiFactory` objects.

We say that factories create **product** objects. Moreover, the products that a factory produces are related to one another; in this case, the products are all widgets for the same look and feel. Figure 2.10 shows some of the product classes needed to make factories work for widget glyphs.

The last question we have to answer is, Where does `GUIFactory` instance come from? The answer is, Anywhere that's convenient. The variable `guiFactory` could be a global, a static member of a well-known class, or even a local variable if the entire user interface is created within one class or function. There's even a design pattern, Singleton (127), for managing well-known, one-of-a-kind objects like this. The important thing, though, is to initialize `guiFactory` at a point in the program *before* it's ever used to create widgets but *after* it's clear which look and feel is desired.

If the look and feel is known at compile-time, then `guiFactory` can be initialized with a simple assignment of a new factory instance at the beginning of the program:

```
GUIFactory* guiFactory = new MotifFactory;
```

If the user can specify the look and feel with a string name at startup time, then the code to create the factory might be

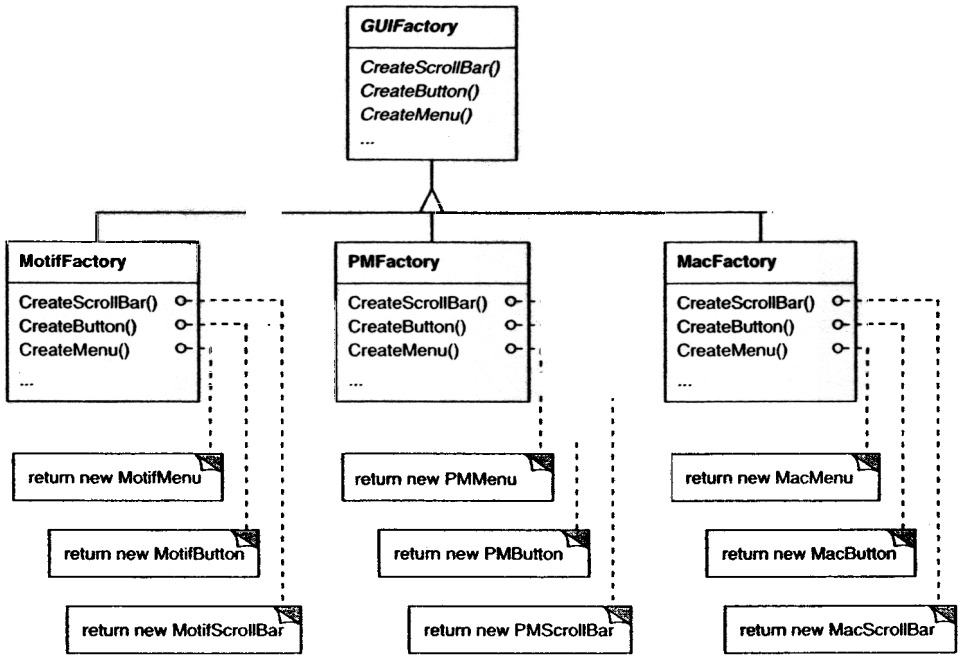


Figure 2.9: GUIFactory class hierarchy

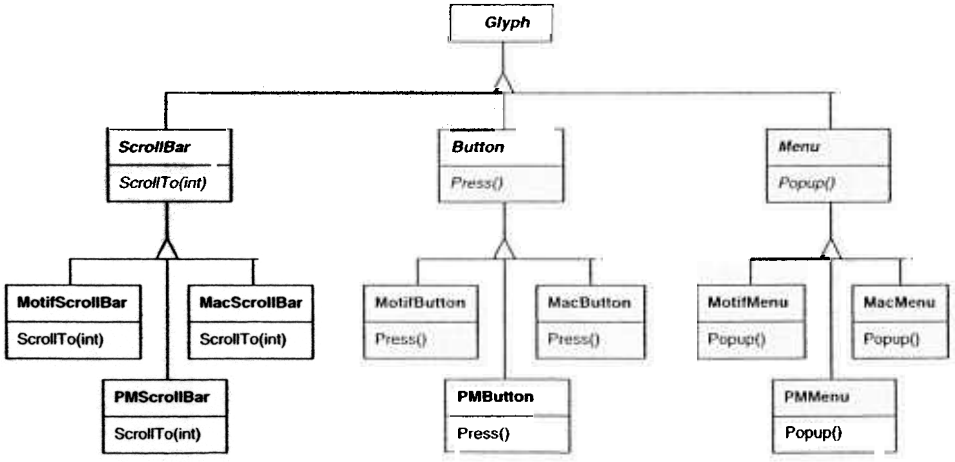


Figure 2.10: Abstract product classes and concrete subclasses

```
GUIFactory* guiFactory;
const char* styleName = getenv("LOOK_AND_FEEL");
    // user or environment supplies this at startup

if (strcmp(styleName, "Motif") == 0) {
    guiFactory = new MotifFactory;

} else if (strcmp(styleName, "Presentation_Manager"  == 0) {
    guiFactory = new PMFactory;

  else {
    guiFactory = new DefaultGUIFactory;
```

There are more sophisticated ways to select the factory at run-time. For example, you could maintain a registry that maps strings to factory objects. That lets you register instances of new factory subclasses without modifying existing code, as the preceding approach requires. And you don't have to link all platform-specific factories into the application. That's important, because it might not be possible to link a MotifFactory on a platform that doesn't support Motif.

But the point is that once we've configured the application with the right factory object, its look and feel is set from then on. If we change our minds, we can reinitialize `guiFactory` with a factory for a different look and feel and then reconstruct the interface. Regardless of how and when we decide to initialize `guiFactory`, we know that once we do, the application can create the appropriate look and feel without modification.

Abstract Factory Pattern

Factories and products are the key participants in the Abstract Factory (87) pattern. This pattern captures how to create families of related product objects without instantiating classes directly. It's most appropriate when the number and general kinds of product objects stay constant, and there are differences in specific product families. We choose between families by instantiating a particular concrete factory and using it consistently to create products thereafter. We can also swap entire families of products by replacing the concrete factory with an instance of a different one. The Abstract Factory pattern's emphasis on *families* of products distinguishes it from other creational patterns, which involve only one kind of product object.

2.6 Supporting Multiple Window Systems

Look and feel is just one of many portability issues. Another is the windowing environment in which Lexi runs. A platform's window system creates the illusion of multiple overlapping windows on a bitmapped display. It manages screen space for

windows and routes input to them from the keyboard and mouse. Several important and largely incompatible window systems exist today (e.g., Macintosh, Presentation Manager, Windows, X). We'd like Lexi to run on as many of them as possible for exactly the same reasons we support multiple look-and-feel standards.

Can We Use an Abstract Factory?

At first glance this may look like another opportunity to apply the Abstract Factory pattern. But the constraints for window system portability differ significantly from those for look-and-feel independence.

In applying the Abstract Factory pattern, we assumed we would define the concrete widget glyph classes for each look-and-feel standard. That meant we could derive each concrete product for a particular standard (e.g., MotifScrollBar and MacScrollBar) from an abstract product class (e.g., ScrollBar). But suppose we already have several class hierarchies from different vendors, one for each look-and-feel standard. Of course, it's highly unlikely these hierarchies are compatible in any way. Hence we won't have a common abstract product class for each kind of widget (ScrollBar, Button, Menu, etc.)—and the Abstract Factory pattern won't work without those crucial classes. We have to make the different widget hierarchies adhere to a common set of abstract product interfaces. Only then could we declare the `Create...` operations properly in our abstract factory's interface.

We solved this problem for widgets by developing our own abstract and concrete product classes. Now we're faced with a similar problem when we try to make Lexi work on existing window systems; namely, different window systems have incompatible programming interfaces. Things are a bit tougher this time, though, because we can't afford to implement our own nonstandard window system.

But there's a saving grace. Like look-and-feel standards, window system interfaces aren't radically different from one another, because all window systems do generally the same thing. We need a uniform set of windowing abstractions that lets us take different window system implementations and slide any one of them under a common interface.

Encapsulating Implementation Dependencies

In Section 2.2 we introduced a Window class for displaying a glyph or glyph structure on the display. We didn't specify the window system that this object worked with, because the truth is that it doesn't come from any particular window system. The Window class encapsulates the things windows tend to do across window systems:

- They provide operations for drawing basic geometric shapes.
- They can iconify and de-iconify themselves.

Responsibility	Operations

window management	`virtual void Redraw()`
	`virtual void Raise()`
	`virtual void Lower()`
	`virtual void Iconify()`
	`virtual void Deiconify()`
	`...`

graphics	`virtual void DrawLine(...)`
	`virtual void DrawRect(...)`
	`virtual void DrawPolygon(...)`
	`virtual void DrawText(...)`
	`...`

Table 2.3: Window class interface

- They can resize themselves.
- They can (re)draw their contents on demand, for example, when they are deiconified or when an overlapped and obscured portion of their screen space is exposed.

The Window class must span the functionality of windows from different window systems. Let's consider two extreme philosophies:

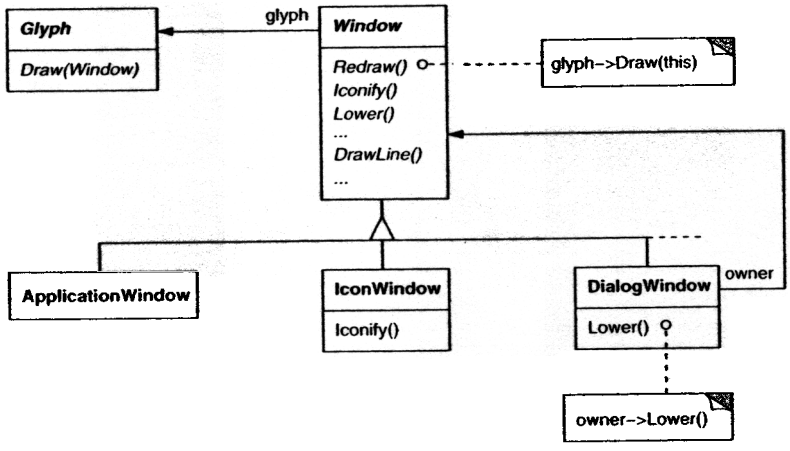
Intersection of functionality. The Window class interface provides only functionality that's common to *all* window systems. The problem with this approach is that our Window interface winds up being only as powerful as the least capable window system. We can't take advantage of more advanced features even if most (but not all) window systems support them.

2. *Union of functionality.* Create an interface that incorporates the capabilities of *all* existing systems. The trouble here is that the resulting interface may well be huge and incoherent. Besides, we'll have to change it (and Lexi, which depends on it) anytime a vendor revises its window system interface.

Neither extreme is a viable solution, so our design will fall somewhere between the two. The Window class will provide a convenient interface that supports the most popular windowing features. Because Lexi will deal with this class directly, the Window class must also support the things Lexi knows about, namely, glyphs. That means Window's interface must include a basic set of graphics operations that lets glyphs draw themselves in the window. Table 2.3 gives a sampling of the operations in the Window class interface.

Window is an abstract class. Concrete subclasses of Window support the different kinds of windows that users deal with. For example, application windows, icons, and warning dialogs are all windows, but they have somewhat different behaviors. So we can define subclasses like ApplicationWindow, IconWindow, and DialogWindow to capture these

differences. The resulting class hierarchy gives applications like Lexi a uniform and intuitive windowing abstraction, one that doesn't depend on any particular vendor's window system:



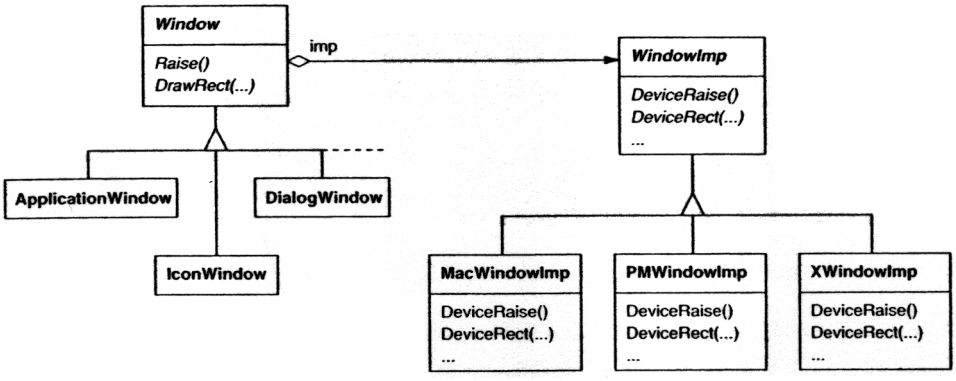
Now that we've defined a window interface for Lexi to work with, where does the real platform-specific window come in? If we're not implementing our own window system, then at some point our window abstraction must be implemented in terms of what the target window system provides. So where does that implementation live?

One approach is to implement multiple versions of the Window class and its subclasses, one version for each windowing platform. We'd have to choose the version to use when we build Lexi for a given platform. But imagine the maintenance headaches we'd have keeping track of multiple classes, all named "Window" but each implemented on a different window system. Alternatively, we could create implementation-specific subclasses of each class in the Window hierarchy—and end up with another subclass explosion problem like the one we had trying to add embellishments. Both of these alternatives have another drawback: Neither gives us the flexibility to change the window system we use after we've compiled the program. So we'll have to keep several different executables around as well.

Neither alternative is very appealing, but what else can we do? The same thing we did for formatting and embellishment, namely, *encapsulate the concept that varies*. What varies in this case is the window system implementation. If we encapsulate a window system's functionality in an object, then we can implement our Window class and subclasses in terms of that object's interface. Moreover, if that interface can serve all the window systems we're interested in, then we won't have to change Window or any of its subclasses to support different window systems. We can configure window objects to the window system we want simply by passing them the right window system-encapsulating object. We can even configure the window at run-time.

Window and WindowImp

We'll define a separate **WindowImp** class hierarchy in which to hide different window system implementations. WindowImp is an abstract class for objects that encapsulate window system-dependent code. To make Lexi work on a particular window system, we configure each window object with an instance of a WindowImp subclass for that system. The following diagram shows the relationship between the Window and WindowImp hierarchies:



By hiding the implementations in WindowImp classes, we avoid polluting the Window classes with window system dependencies, which keeps the Window class hierarchy comparatively small and stable. Meanwhile we can easily extend the implementation hierarchy to support new window systems.

WindowImp Subclasses

Subclasses of WindowImp convert requests into window system-specific operations. Consider the example we used in Section 2.2. We defined the `Rectangle::Draw` in terms of the `DrawRect` operation on the Window instance:

```
void Rectangle::Draw (Window* w) {
    w->DrawRect(_x0, _y0, _x1, _y1);
```

The default implementation of `DrawRect` uses the abstract operation for drawing rectangles declared by WindowImp:

```
void Window: DrawRect (
    Coord x0  Coord y0, Coord x1, Coord y1

     imp->DeviceRect(x0  y0, x1  y1)
```

where _imp is a member variable of Window that stores the WindowImp with which the Window is configured. The window implementation is defined by the instance of the WindowImp subclass that _imp points to. For an XWindowImp (that is, a WindowImp subclass for the X Window System), the DeviceRect's implementation might look like

```
void XWindowImp::DeviceRect (
    Coord x0, Coord y0, Coord x1, Coord y1

    int x = round(min(x0, x1));
    int y = round(min(y0, y1));
    int w = round(abs(x0 - x1));
    int h = round(abs(y0 - y1));
    XDrawRectangle(_dpy, _winid, _gc, x, y, w, h);
```

DeviceRect is defined like this because XDrawRectangle (the X interface for drawing a rectangle) defines a rectangle in terms of its lower left corner, its width, and its height. DeviceRect must compute these values from those supplied. First it ascertains the lower left corner (since (x0, y0) might be any one of the rectangle's four corners) and then calculates the width and height.

PMWindowImp (a subclass of WindowImp for Presentation Manager) would define DeviceRect differently:

```
void PMWindowImp::DeviceRect (
    Coord x0, Coord y0, Coord x1, Coord y1
) {
    Coord left = min(x0, x1);
    Coord right = max(x0, x1)
    Coord bottom = min(y0, y1
    Coord top = max(y0, y1);

    PPOINTL point[4];

    point[(   t = left;    point[0].y = top;
    point[1   t = right;   point[1].y = top;
    point[2   t = right;   point[2].y = bottom;
    point[3   t = left;    point[3].y = bottom;


        (GpiBeginPath(_hps, 1L) == false) ||
        (GpiSetCurrentPosition(_hps, &point[3]) == false)
        (GpiPolyLine(_hps, 4L, point) == GPI_ERROR)  ||
        (GpiEndPath(_hps) == false)

         / report error

    ) else {
        GpiStrokePath(_hps, 1L, 0L)
```

Why is this so different from the X version? Well, PM doesn't have an operation for drawing rectangles explicitly as X does. Instead, PM has a more general interface for specifying vertices of multisegment shapes (called a **path**) and for outlining or filling the area they enclose.

PM's implementation of `DeviceRect` is obviously quite different from X's, but that doesn't matter. WindowImp hides variations in window system interfaces behind a potentially large but stable interface. That lets Window subclass writers focus on the window abstraction and not on window system details. It also lets us add support for new window systems without disturbing the Window classes.

Configuring Windows with WindowImps

A key issue we haven't addressed is how a window gets configured with the proper WindowImp subclass in the first place. Stated another way, when does `_imp` get initialized, and who knows what window system (and consequently which WindowImp subclass) is in use? The window will need some kind of WindowImp before it can do anything interesting.

There are several possibilities, but we'll focus on one that uses the Abstract Factory (87) pattern. We can define an abstract factory class WindowSystemFactory that provides an interface for creating different kinds of window system-dependent implementation objects:

```
class WindowSystemFactory {
public:
    virtual WindowImp* CreateWindowImp() = 0;
    virtual ColorImp* CreateColorImp() = 0;
    virtual FontImp* CreateFontImp() = 0;

        a "Create   " operation for all window system resources
```

Now we can define a concrete factory for each window system:

```
class PMWindowSystemFactory : public WindowSystemFactory
    virtual WindowImp* CreateWindowImp()
        { return new PMWindowImp; }


class XWindowSystemFactory : public WindowSystemFactory
    virtual WindowImp* CreateWindowImp()
        { return new XWindowImp; }
    //
```

The Window base class constructor can use the `WindowSystemFactory` interface to initialize the `_imp` member with the WindowImp that's right for the window system:

```
Window::Window () {
    _imp = windowSystemFactory->CreateWindowImp();
```

The `windowSystemFactory` variable is a well-known instance of a WindowSystemFactory subclass, akin to the well-known `guiFactory` variable defining the look and feel. The `windowSystemFactory` variable can be initialized in the same way.

Bridge Pattern

The WindowImp class defines an interface to common window system facilities, but its design is driven by different constraints than Window's interface. Application programmers won't deal with WindowImp's interface directly; they only deal with Window objects. So WindowImp's interface needn't match the application programmer's view of the world, as was our concern in the design of the Window class hierarchy and interface. WindowImp's interface can more closely reflect what window systems actually provide, warts and all. It can be biased toward either an intersection or a union of functionality approach, whichever suits the target window systems best.

The important thing to realize is that Window's interface caters to the applications programmer, while WindowImp caters to window systems. Separating windowing functionality into Window and WindowImp hierarchies lets us implement and specialize these interfaces independently. Objects from these hierarchies cooperate to let Lexi work without modification on multiple window systems.

The relationship between Window and WindowImp is an example of the Bridge (151) pattern. The intent behind Bridge is to allow separate class hierarchies to work together even as they evolve independently. Our design criteria led us to create two separate class hierarchies, one that supports the logical notion of windows, and another for capturing different implementations of windows. The Bridge pattern lets us maintain and enhance our logical windowing abstractions without touching window system-dependent code, and vice versa.

2.7 User Operations

Some of Lexi's functionality is available through the document's WYSIWYG representation. You enter and delete text, move the insertion point, and select ranges of text by pointing, clicking, and typing directly in the document. Other functionality is accessed indirectly through user operations in Lexi's pull-down menus, buttons, and keyboard accelerators. The functionality includes operations for

- creating a new document,
- opening, saving, and printing an existing document,

- cutting selected text out of the document and pasting it back in,
- changing the font and style of selected text,
- changing the formatting of text, such as its alignment and justification,
- quitting the application,
- and on and on.

Lexi provides different user interfaces for these operations. But we don't want to associate a particular user operation with a particular user interface, because we may want multiple user interfaces to the same operation (you can turn the page using either a page button or a menu operation, for example). We may also want to change the interface in the future.

Furthermore, these operations are implemented in many different classes. We as implementors want to access their functionality without creating a lot of dependencies between implementation and user interface classes. Otherwise we'll end up with a tightly coupled implementation, which will be harder to understand, extend, and maintain.

To further complicate matters, we want Lexi to support undo and redo[8] of most *but not all* its functionality. Specifically, we want to be able to undo document-modifying operations like delete, with which a user can destroy lots of data inadvertently. But we shouldn't try to undo an operation like saving a drawing or quitting the application. These operations should have no affect on the undo process. We also don't want an arbitrary limit on the number of levels of undo and redo.

It's clear that support for user operations permeates the application. The challenge is to come up with a simple and extensible mechanism that satisfies all of these needs.

Encapsulating a Request

From our perspective as designers, a pull-down menu is just another kind of glyph that contains other glyphs. What distinguishes pull-down menus from other glyphs that have children is that most glyphs in menus do some work in response to an up-click.

Let's assume that these work-performing glyphs are instances of a Glyph subclass called **MenuItem** and that they do their work in response to a request from a client.[9] Carrying out the request might involve an operation on one object, or many operations on many objects, or something in between.

We could define a subclass of MenuItem for every user operation and then hard-code each subclass to carry out the request. But that's not really right; we don't need a subclass of MenuItem for each request any more than we need a subclass for each text

[8] That is, redoing an operation that was just undone.

[9] Conceptually, the client is Lexi's user, but in reality it's another object (such as an event dispatcher) that manages inputs from the user.

string in a pull-down menu. Moreover, this approach couples the request to a particular user interface, making it hard to fulfill the request through a different user interface.

To illustrate, suppose you could advance to the last page in the document both through a MenuItem in a pull-down menu *and* by pressing a page icon at the bottom of Lexi's interface (which might be more convenient for short documents). If we associate the request with a MenuItem through inheritance, then we must do the same for the page icon and any other kind of widget that might issue such a request. That can give rise to a number of classes approaching the product of the number of widget types and the number of requests.

What's missing is a mechanism that lets us parameterize menu items by the request they should fulfill. That way we avoid a proliferation of subclasses and allow for greater flexibility at run-time. We could parameterize MenuItem with a function to call, but that's not a complete solution for at least three reasons:

1. It doesn't address the undo/redo problem.
2. It's hard to associate state with a function. For example, a function that changes the font needs to know *which* font.
3. Functions are hard to extend, and it's hard to reuse parts of them.

These reasons suggest that we should parameterize MenuItems with an *object*, not a function. Then we can use inheritance to extend and reuse the request's implementation. We also have a place to store state and implement undo/redo functionality. Here we have another example of encapsulating the concept that varies, in this case a request. We'll encapsulate each request in a **command** object.

Command Class and Subclasses

First we define a **Command** abstract class to provide an interface for issuing a request. The basic interface consists of a single abstract operation called "Execute." Subclasses of Command implement Execute in different ways to fulfill different requests. Some subclasses may delegate part or all of the work to other objects. Other subclasses may be in a position to fulfill the request entirely on their own (see Figure 2.11). To the requester, however, a Command object is a Command object—they are treated uniformly.

Now MenuItem can store a Command object that encapsulates a request (Figure 2.12). We give each menu item object an instance of the Command subclass that's suitable for that menu item, just as we specify the text to appear in the menu item. When a user chooses a particular menu item, the MenuItem simply calls Execute on its Command object to carry out the request. Note that buttons and other widgets can use commands in the same way menu items do.

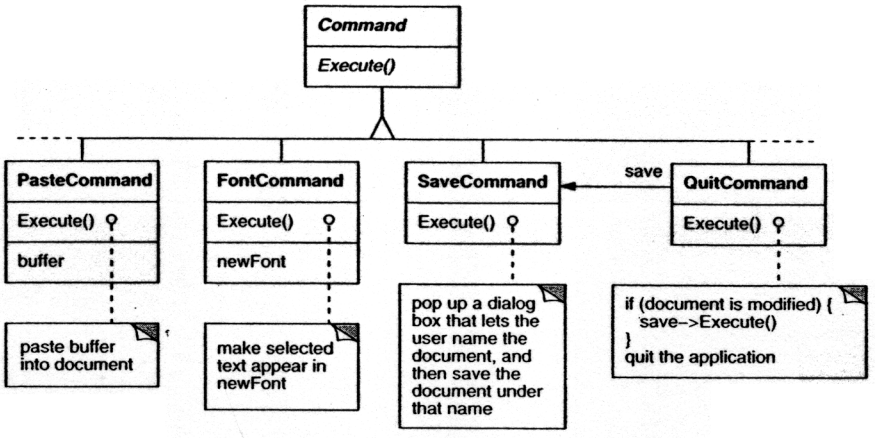


Figure 2.11: Partial Command class hierarchy

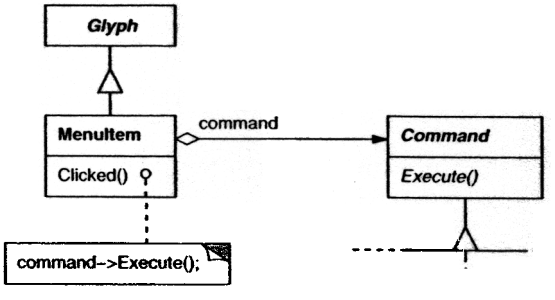


Figure 2.12: MenuItem-Command relationship

Undoability

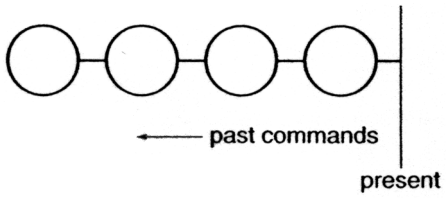
Undo/redo is an important capability in interactive applications. To undo and redo commands, we add an Unexecute operation to Command's interface. Unexecute reverses the effects of a preceding Execute operation using whatever undo information Execute stored. In the case of a FontCommand, for example, the Execute operation would store the range of text affected by the font change along with the original font(s). FontCommand's Unexecute operation would restore the range of text to its original font(s).

Sometimes undoability must be determined at run-time. A request to change the font of a selection does nothing if the text already appears in that font. Suppose the user selects some text, and requests a spurious font change. What should be the result of a subsequent undo request? Should a meaningless change cause the undo request to do something equally meaningless? Probably not. If the user repeats the spurious font change several times, he shouldn't have to perform exactly the same number of undo operations to get back to the last meaningful operation. If the net effect of executing a command was nothing, then there's no need for a corresponding undo request.

So to determine if a command is undoable, we add an abstract Reversible operation to the Command interface. Reversible returns a Boolean value. Subclasses can redefine this operation to return true or false based on run-time criteria.

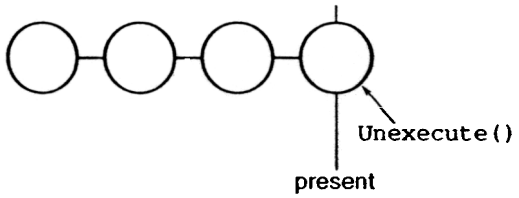
Command History

The final step in supporting arbitrary-level undo and redo is to define a **command history**, or list of commands that have been executed (or unexecuted, if some commands have been undone). Conceptually, the command history looks like this:

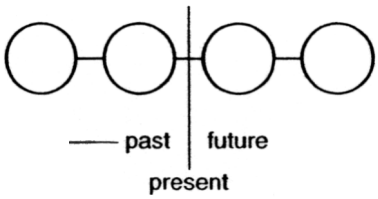


Each circle represents a Command object. In this case the user has issued four commands. The leftmost command was issued first, followed by the second-leftmost, and so on until the most recently issued command, which is rightmost. The line marked "present" keeps track of the most recently executed (and unexecuted) command.

To undo the last command, we simply call Unexecute on the most recent command:

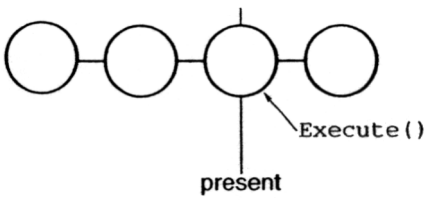


After unexecuting the command, we move the "present" line one command to the left. If the user chooses undo again, the next-most recently issued command will be undone in the same way, and we're left in the state depicted here:

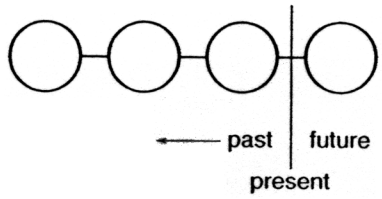


You can see that by simply repeating this procedure we get multiple levels of undo. The number of levels is limited only by the length of the command history.

To redo a command that's just been undone, we do the same thing in reverse. Commands to the right of the present line are commands that may be redone in the future. To redo the last undone command, we call Execute on the command to the right of the present line:



Then we advance the present line so that a subsequent redo will call redo on the following command in the future.



Of course, if the subsequent operation is not another redo but an undo, then the command to the left of the present line will be undone. Thus the user can effectively go back and forth in time as needed to recover from errors.

Command Pattern

Lexi's commands are an application of the Command (233) pattern, which describes how to encapsulate a request. The Command pattern prescribes a uniform interface for issuing requests that lets you configure clients to handle different requests. The interface shields clients from the request's implementation. A command may delegate all, part, or none of the request's implementation to other objects. This is perfect for applications like Lexi that must provide centralized access to functionality scattered throughout the application. The pattern also discusses undo and redo mechanisms built on the basic Command interface.

2.8 Spelling Checking and Hyphenation

The last design problem involves textual analysis, specifically checking for misspellings and introducing hyphenation points where needed for good formatting.

The constraints here are similar to those we had for the formatting design problem in Section 2.3. As was the case for linebreaking strategies, there's more than one way to check spelling and compute hyphenation points. So here too we want to support multiple algorithms. A diverse set of algorithms can provide a choice of space/time/quality trade-offs. We should make it easy to add new algorithms as well.

We also want to avoid wiring this functionality into the document structure. This goal is even more important here than it was in the formatting case, because spelling checking and hyphenation are just two of potentially many kinds of analyses we may want Lexi to support. Inevitably we'll want to expand Lexi's analytical abilities over time. We might add searching, word counting, a calculation facility for adding up tabular values, grammar checking, and so forth. But we don't want to change the Glyph class and all its subclasses every time we introduce new functionality of this sort.

There are actually two pieces to this puzzle: (1) accessing the information to be analyzed, which we have scattered over the glyphs in the document structure, and (2) doing the analysis. We'll look at these two pieces separately.

Accessing Scattered Information

Many kinds of analysis require examining the text character by character. The text we need to analyze is scattered throughout a hierarchical structure of glyph objects. To examine text in such a structure, we need an access mechanism that has knowledge about the data structures in which objects are stored. Some glyphs might store their children in linked lists, others might use arrays, and still others might use more esoteric data structures. Our access mechanism must be able to handle all of these possibilities.

An added complication is that different analyses access information in different ways. *Most* analyses will traverse the text from beginning to end. But some do the opposite—a reverse search, for example, needs to progress through the text backward rather than forward. Evaluating algebraic expressions could require an inorder traversal.

So our access mechanism must accommodate differing data structures, and we must support different kinds of traversals, such as preorder, postorder, and inorder.

Encapsulating Access and Traversal

Right now our glyph interface uses an integer index to let clients refer to children. Although that might be reasonable for glyph classes that store their children in an array, it may be inefficient for glyphs that use a linked list. An important role of the glyph abstraction is to hide the data structure in which children are stored. That way we can change the data structure a glyph class uses without affecting other classes.

Therefore only the glyph can know the data structure it uses. A corollary is that the glyph interface shouldn't be biased toward one data structure or another. It shouldn't be better suited to arrays than to linked lists, for example, as it is now.

We can solve this problem and support several different kinds of traversals at the same time. We can put multiple access and traversal capabilities directly in the glyph classes and provide a way to choose among them, perhaps by supplying an enumerated constant as a parameter. The classes pass this parameter around during a traversal to ensure they're all doing the same kind of traversal. They have to pass around any information they've accumulated during traversal.

We might add the following abstract operations to Glyph's interface to support this approach:

```
void First(Traversal kind)
void Next()
bool IsDone()
Glyph* GetCurrent()
void Insert(Glyph*)
```

Operations `First`, `Next`, and `IsDone` control the traversal. `First` initializes the traversal. It takes the kind of traversal as a parameter of type `Traversal`, an enumerated constant with values such as `CHILDREN` (to traverse the glyph's immediate children only), `PREORDER` (to traverse the entire structure in preorder), `POSTORDER`, and `INORDER`. `Next` advances to the next glyph in the traversal, and `IsDone` reports whether the traversal is over or not. `GetCurrent` replaces the `Child` operation; it accesses the current glyph in the traversal. `Insert` replaces the old operation; it inserts the given glyph at the current position.

An analysis would use the following C++ code to do a preorder traversal of a glyph structure rooted at `g`:

```
Glyph* g;

for (g->First(PREORDER); !g->IsDone()  g->Next
    Glyph* current = g->GetCurrent();

       do some analysis
```

Notice that we've banished the integer index from the glyph interface. There's no longer anything that biases the interface toward one kind of collection or another. We've also saved clients from having to implement common kinds of traversals themselves.

But this approach still has problems. For one thing, it can't support new traversals without either extending the set of enumerated values or adding new operations. Say we wanted to have a variation on preorder traversal that automatically skips nontextual glyphs. We'd have to change the `Traversal` enumeration to include something like `TEXTUAL_PREORDER`.

We'd like to avoid changing existing declarations. Putting the traversal mechanism entirely in the Glyph class hierarchy makes it hard to modify or extend without changing lots of classes. It's also difficult to reuse the mechanism to traverse other kinds of object structures. And we can't have more than one traversal in progress on a structure.

Once again, a better solution is to encapsulate the concept that varies, in this case the access and traversal mechanisms. We can introduce a class of objects called **iterators** whose sole purpose is to define different sets of these mechanisms. We can use inheritance to let us access different data structures uniformly and support new kinds of traversals as well. And we won't have to change glyph interfaces or disturb existing glyph implementations to do it.

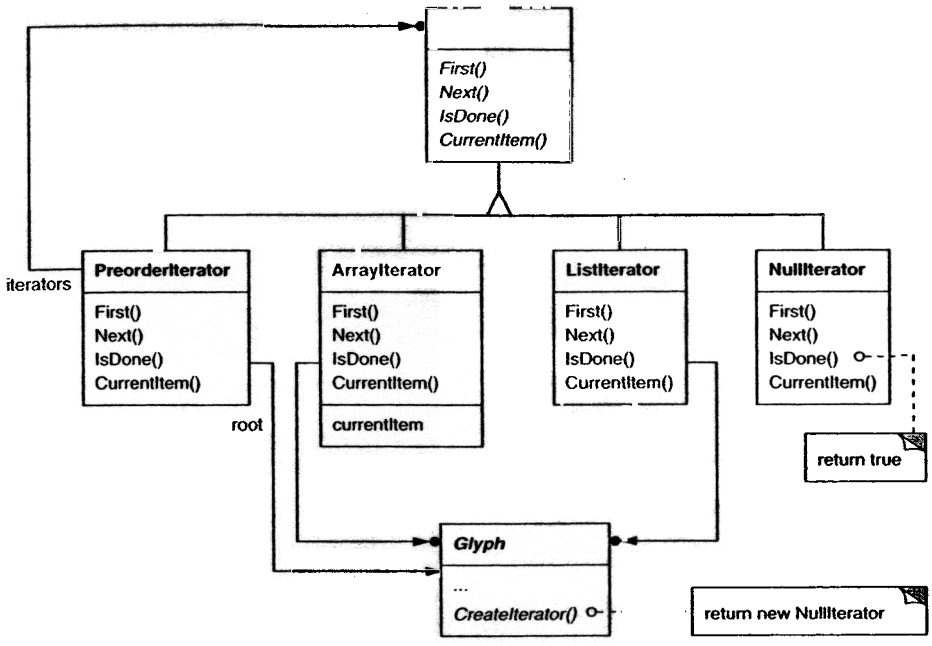


Figure 2.13: Iterator class and subclasses

Iterator Class and Subclasses

We'll use an abstract class called **Iterator** to define a general interface for access and traversal. Concrete subclasses like **ArrayIterator** and **ListIterator** implement the interface to provide access to arrays and lists, while **PreorderIterator, PostorderIterator,** and the like implement different traversals on specific structures. Each Iterator subclass has a reference to the structure it traverses. Subclass instances are initialized with this reference when they are created. Figure 2.13 illustrates the Iterator class along with several subclasses. Notice that we've added a CreateIterator abstract operation to the Glyph class interface to support iterators.

The Iterator interface provides operations First, Next, and IsDone for controlling the traversal. The ListIterator class implements First to point to the first element in the list, and Next advances the iterator to the next item in the list. IsDone returns whether or not the list pointer points beyond the last element in the list. CurrentItem dereferences the iterator to return the glyph it points to. An `ArrayIterator` class would do similar things but on an array of glyphs.

Now we can access the children of a glyph structure without knowing its representation:

```
Glyph* g;
Iterator<Glyph*>* i = g->CreateIterator();

for (i->First(); !i->IsDone(); i->Next()
    Glyph* child = i->CurrentItem();

        do something with current child
```

CreateIterator returns a NullIterator instance by default. A NullIterator is a degenerate iterator for glyphs that have no children, that is, leaf glyphs. NullIterator's IsDone operation always returns true.

A glyph subclass that has children will override CreateIterator to return an instance of a different Iterator subclass. *Which* subclass depends on the structure that stores the children. If the Row subclass of Glyph stores its children in a list `_children`, then its CreateIterator operation would look like this:

```
Iterator<Glyph*>* Row::CreateIterator () {
    return new ListIterator<Glyph*>(_children)
```

Iterators for preorder and inorder traversals implement their traversals in terms of glyph-specific iterators. The iterators for these traversals are supplied the root glyph in the structure they traverse. They call CreateIterator on the glyphs in the structure and use a stack to keep track of the resulting iterators.

For example, class `PreorderIterator` gets the iterator from the root glyph, initializes it to point to its first element, and then pushes it onto the stack:

```
void PreorderIterator::First () {
    Iterator<Glyph*>* i = _root->CreateIterator()

    if
        i->First();
        _iterators.RemoveAll()
        _iterators.Push(i);
```

`CurrentItem` would simply call `CurrentItem` on the iterator at the top of the stack:

```
Glyph* PreorderIterator CurrentItem () const
    Glyph* g = 0;

    if (_iterators.Size() > 0) {
        g = _iterators.Top()->CurrentItem()
    }
    return g;
```

The `Next` operation gets the top iterator on the stack and asks its current item to create an iterator, in an effort to descend the glyph structure as far as possible (this is a preorder traversal, after all). `Next` sets the new iterator to the first item in the traversal and pushes it on the stack. Then `Next` tests the latest iterator; if its `IsDone` operation returns true, then we've finished traversing the current subtree (or leaf) in the traversal. In that case, `Next` pops the top iterator off the stack and repeats this process until it finds the next incomplete traversal, if there is one; if not, then we have finished traversing the structure.

```
void PreorderIterator::Next () {
    Iterator<Glyph*>* i =
        _iterators.Top()->CurrentItem()->CreateIterator();
    i->First();

    while
         iterators.Size()   0 &&  iterators.Top(   IsDone

        delete _iterators.Pop();
        _iterators.Top()->Next()
```

Notice how the Iterator class hierarchy lets us add new kinds of traversals without modifying glyph classes—we simply subclass `Iterator` and add a new traversal as we have with `PreorderIterator`. Glyph subclasses use the same interface to give clients access to their children without revealing the underlying data structure they use to store them. Because iterators store their own copy of the state of a traversal, we can carry on multiple traversals simultaneously, even on the same structure. And though our traversals have been over glyph structures in this example, there's no reason we can't parameterize a class like `PreorderIterator` by the type of object in the structure. We'd use templates to do that in C++. Then we can reuse the machinery in `PreorderIterator` to traverse other structures.

Iterator Pattern

The Iterator (257) pattern captures these techniques for supporting access and traversal over object structures. It's applicable not only to composite structures but to collections

as well. It abstracts the traversal algorithm and shields clients from the internal structure of the objects they traverse. The Iterator pattern illustrates once more how encapsulating the concept that varies helps us gain flexibility and reusability. Even so, the problem of iteration has surprising depth, and the Iterator pattern covers many more nuances and trade-offs than we've considered here.

Traversal versus Traversal Actions

Now that we have a way of traversing the glyph structure, we need to check the spelling and do the hyphenation. Both analyses involve accumulating information during the traversal.

First we have to decide where to put the responsibility for analysis. We could put it in the Iterator classes, thereby making analysis an integral part of traversal. But we get more flexibility and potential for reuse if we distinguish between the traversal and the actions performed during traversal. That's because different analyses often require the same kind of traversal. Hence we can reuse the same set of iterators for different analyses. For example, preorder traversal is common to many analyses, including spelling checking, hyphenation, forward search, and word count.

So analysis and traversal should be separate. Where else can we put the responsibility for analysis? We know there are many kinds of analyses we might want to do. Each analysis will do different things at different points in the traversal. Some glyphs are more significant than others depending on the kind of analysis. If we're checking spelling or hyphenating, we want to consider character glyphs and not graphical ones like lines and bitmapped images. If we're making color separations, we'd want to consider visible glyphs and not invisible ones. Inevitably, different analyses will analyze different glyphs.

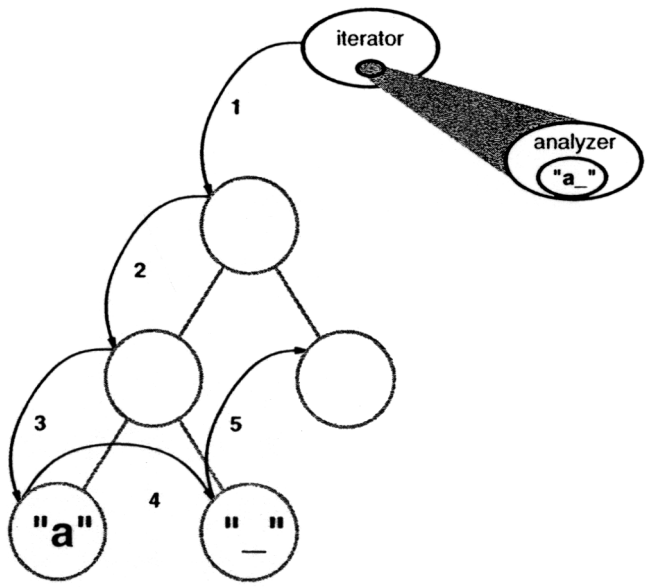
A given analysis must be able to distinguish different kinds of glyphs. An obvious way is to put the analytical capability into the glyph classes themselves. For each analysis we can add one or more abstract operations to the Glyph class and have subclasses implement them in accordance with the role they play in the analysis.

But the trouble with that approach is that we'll have to change every glyph class whenever we add a new kind of analysis. We can ease this problem in some cases: If only a few classes participate in the analysis, or if most classes do the analysis the same way, then we can supply a default implementation for the abstract operation in the Glyph class. The default operation would cover the common case. Thus we'd limit changes to the Glyph class and those subclasses that deviate from the norm.

Yet even if a default implementation reduces the number of changes, an insidious problem remains: Glyph's interface expands with every new analytical capability. Over time the analytical operations will start to obscure the basic Glyph interface. It becomes hard to see that a glyph's main purpose is to define and structure objects that have appearance and shape—that interface gets lost in the noise.

Encapsulating the Analysis

From all indications, we need to encapsulate the analysis in a separate object, much like we've done many times before. We could put the machinery for a given analysis into its own class. We could use an instance of this class in conjunction with an appropriate iterator. The iterator would "carry" the instance to each glyph in the structure. The analysis object could then perform a piece of the analysis at each point in the traversal. The analyzer accumulates information of interest (characters in this case) as the traversal proceeds:



The fundamental question with this approach is how the analysis object distinguishes different kinds of glyphs without resorting to type tests or downcasts. We don't want a `SpellingChecker` class to include (pseudo)code like

```
void SpellingChecker::Check (Glyph* glyph) {
    Character* c;
    Row* r;
    Image* i;

    if (c = dynamic_cast<Character*>(glyph))
        // analyze the character

    } else if (r = dynamic_cast<Row*>(glyph))
        // prepare to analyze r's children
```

```
    else if (i = dynamic_cast<Image*>(glyph)) {
      // do nothing
```

This code is pretty ugly. It relies on fairly esoteric capabilities like type-safe casts. It's hard to extend as well. We'll have to remember to change the body of this function whenever we change the Glyph class hierarchy. In fact, this is the kind of code that object-oriented languages were intended to eliminate.

We want to avoid such a brute-force approach, but how? Let's consider what happens when we add the following abstract operation to the Glyph class:

```
void CheckMe(SpellingChecker&)
```

We define `CheckMe` in every Glyph subclass as follows:

```
void GlyphSubclass::CheckMe (SpellingChecker& checker)
    checker.CheckGlyphSubclass(this);
```

where `GlyphSubclass` would be replaced by the name of the glyph subclass. Note that when `CheckMe` is called, the specific Glyph subclass is known—after all, we're in one of its operations. In turn, the `SpellingChecker` class interface includes an operation like `CheckGlyphSubclass` for every Glyph subclass[10]:

```
class SpellingChecker {
public:
    SpellingChecker

    virtual void CheckCharacter(Character*)
    virtual void CheckRow(Row*);
    virtual void CheckImage(Image*);

            and so forth

    List<char*>& GetMisspellings()

protected:
    virtual bool IsMisspelled(const char*

private:
    char _currentWord[MAX_WORD_SIZE]
    List<char*> _misspellings;
```

`SpellingChecker`'s checking operation for `Character` glyphs might look something like this:

[10] We could use function overloading to give each of these member functions the same name, since their parameters already differentiate them. We've given them different names here to emphasize their differences especially when they're called.

```
void SpellingChecker::CheckCharacter (Character* c) {
    const char ch = c->GetCharCode();

    if (isalpha(ch)) {
        // append alphabetic character to _currentWord

      else {
        // we hit a nonalphabetic character

        if (IsMisspelled(_currentWord)) {
            // add _currentWord to _misspellings
            _misspellings.Append(_currentWord);


         _currentWord[0] = '\0';
            // reset _currentWord to check next word
```

Notice we've defined a special `GetCharCode` operation on just the `Character` class. The visitor can deal with subclass-specific operations without resorting to type tests or casts—it lets us treat objects specially.

`CheckCharacter` accumulates alphabetic characters into the `_currentWord` buffer. When it encounters a nonalphabetic character, such as an underscore, it uses the `IsMisspelled` operation to check the spelling of the word in `_currentWord`.[11] If the word is misspelled, then `CheckCharacter` adds the word to the list of misspelled words. Then it must clear out the `_currentWord` buffer to ready it for the next word. When the traversal is over, you can retrieve the list of misspelled words with the `GetMisspellings` operation.

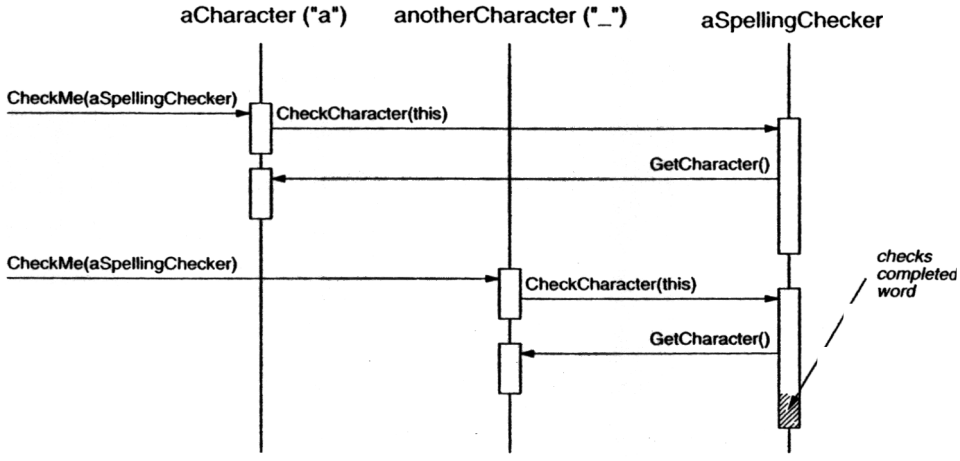
Now we can traverse the glyph structure, calling `CheckMe` on each glyph with the spelling checker as an argument. This effectively identifies each glyph to the SpellingChecker and prompts the checker to do the next increment in the spelling check.

```
SpellingChecker spellingChecker;
Composition* c;


Glyph* g;
PreorderIterator i(c);
```

[11] `IsMisspelled` implements the spelling algorithm, which we won't detail here because we've made it independent of Lexi's design. We can support different algorithms by subclassing `SpellingChecker`; alternatively, we can apply the Strategy (315) pattern (as we did for formatting in Section 2.3) to support different spelling checking algorithms.

```
for (i.First();   .IsDone()  i.Next()) {
    g = i.Curren  tem();
    g->CheckMe(s  llingChec  er)
```

The following interaction diagram illustrates how `Character` glyphs and the `SpellingChecker` object work together:



This approach works for finding spelling errors, but how does it help us support multiple kinds of analysis? It looks like we have to add an operation like `CheckMe(SpellingChecker&)` to Glyph and its subclasses whenever we add a new kind of analysis. That's true if we insist on an *independent* class for every analysis. But there's no reason why we can't give *all* analysis classes the same interface. Doing so lets us use them polymorphically. That means we can replace analysis-specific operations like `CheckMe(SpellingChecker&)` with an analysis-independent operation that takes a more general parameter.

Visitor Class and Subclasses

We'll use the term **visitor** to refer generally to classes of objects that "visit" other objects during a traversal and do something appropriate.[12] In this case we can define a `Visitor` class that defines an abstract interface for visiting glyphs in a structure.

[12] "Visit" is just a slightly more general term for "analyze." It foreshadows the terminology we use in the design pattern we're leading to.

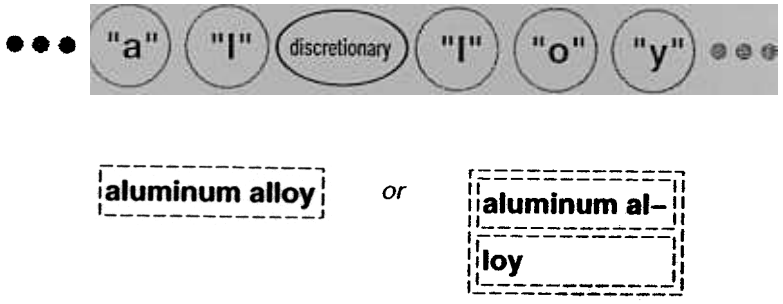
```
class Visitor {
public:
    virtual void VisitCharacter(Character*) {
    virtual void VisitRow(Row*) { }
    virtual void VisitImage(Image*) { }

    //      and so forth
}
```

Concrete subclasses of `Visitor` perform different analyses. For example, we could have a `SpellingCheckingVisitor` subclass for checking spelling, and a `HyphenationVisitor` subclass for hyphenation. `SpellingCheckingVisitor` would be implemented exactly as we implemented `SpellingChecker` above, except the operation names would reflect the more general `Visitor` interface. For example, `CheckCharacter` would be called `VisitCharacter`.

Since `CheckMe` isn't appropriate for visitors that don't check anything, we'll give it a more general name: `Accept`. Its argument must also change to take a `Visitor*`, reflecting the fact that it can accept any visitor. Now adding a new analysis requires just defining a new subclass of `Visitor`—we don't have to touch any of the glyph classes. We support all future analyses by adding this one operation to `Glyph` and its subclasses.

We've already seen how spelling checking works. We use a similar approach in `HyphenationVisitor` to accumulate text. But once `HyphenationVisitor`'s `VisitCharacter` operation has assembled an entire word, it works a little differently. Instead of checking the word for misspelling, it applies a hyphenation algorithm to determine the potential hyphenation points in the word, if any. Then at each hyphenation point, it inserts a **discretionary** glyph into the composition. Discretionary glyphs are instances of `Discretionary`, a subclass of `Glyph`.

A discretionary glyph has one of two possible appearances depending on whether or not it is the last character on a line. If it's the last character, then the discretionary looks like a hyphen; if it's not at the end of a line, then the discretionary has no appearance whatsoever. The discretionary checks its parent (a Row object) to see if it is the last child. The discretionary makes this check whenever it's called on to draw itself or calculate its boundaries. The formatting strategy treats discretionaries the same as whitespace, making them candidates for ending a line. The following diagram shows how an embedded discretionary can appear.



Visitor Pattern

What we've described here is an application of the Visitor (331) pattern. The Visitor class and its subclasses described earlier are the key participants in the pattern. The Visitor pattern captures the technique we've used to allow an open-ended number of analyses of glyph structures without having to change the glyph classes themselves. Another nice feature of visitors is that they can be applied not just to composites like our glyph structures but to *any* object structure. That includes sets, lists, even directed-acyclic graphs. Furthermore, the classes that a visitor can visit needn't be related to each other through a common parent class. That means visitors can work across class hierarchies.

An important question to ask yourself before applying the Visitor pattern is, Which class hierarchies change most often? The pattern is most suitable when you want to be able to do a variety of different things to objects that have a stable class structure. Adding a new kind of visitor requires no change to that class structure, which is especially important when the class structure is large. But whenever you add a subclass to the structure, you'll also have to update all your visitor interfaces to include a `Visit...` operation for that subclass. In our example that means adding a new `Glyph` subclass called `Foo` will require changing `Visitor` and all its subclasses to include a `VisitFoo` operation. But given our design constraints, we're much more likely to add a new kind of analysis to Lexi than a new kind of Glyph. So the Visitor pattern is well-suited to our needs.

2.9 Summary

We've applied eight different patterns to Lexi's design:

1. Composite (163) to represent the document's physical structure,
2. Strategy (315) to allow different formatting algorithms,

3. Decorator (175) for embellishing the user interface,
4. Abstract Factory (87) for supporting multiple look-and-feel standards,
5. Bridge (151) to allow multiple windowing platforms,
6. Command (233) for undoable user operations,
7. Iterator (257) for accessing and traversing object structures, and
8. Visitor (331) for allowing an open-ended number of analytical capabilities without complicating the document structure's implementation.

None of these design issues is limited to document editing applications like Lexi. Indeed, most nontrivial applications will have occasion to use many of these patterns, though perhaps to do different things. A financial analysis application might use Composite to define investment portfolios made up of subportfolios and accounts of different sorts. A compiler might use the Strategy pattern to allow different register allocation schemes for different target machines. Applications with a graphical user interface will probably apply at least Decorator and Command just as we have here.

While we've covered several major problems in Lexi's design, there are lots of others we haven't discussed. Then again, this book describes more than just the eight patterns we've used here. So as you study the remaining patterns, think about how you might use each one in Lexi. Or better yet, think about using them in your own designs!