techniques. Because almost any design technique for real-time systems is preferable to no technique at all, a number of real-time design techniques are used in practice. But, there still is a long way to go before it will be possible to design real-time systems such as those described previously and be certain that, before the system has been implemented, every real-time constraint will be met and synchronization problems cannot arise.

Older real-time design techniques are extensions of non-real-time techniques to the real-time domain. For example, structured development for real-time systems (SDRTS) [Ward and Mellor, 1985] essentially is an extension of structured systems analysis (Section 12.3), data flow analysis (Section 14.3), and transaction analysis (Section 14.4) to real-time software. The development technique includes a component for real-time design. Newer techniques are described in [Liu, 2000] and [Gomaa, 2000].

As stated previously, it is unfortunate that the state of the art of real-time design is not as advanced as one would wish. Nevertheless, efforts are under way to improve the situation.

14.14 CASE Tools for Design

As stated in Section 14.10, a critical aspect of design is testing that the design artifacts accurately incorporate all aspects of the analysis. What is therefore needed is a CASE tool that can be used both for the analysis artifacts and the design artifacts, a so-called front-end or upperCASE tool (as opposed to a back-end or lowerCASE tool, which assists with the implementation artifacts).

A number of upperCASE tools are on the market. Some of the more popular ones include Analyst/Designer, Software through Pictures, and System Architect. UpperCASE tools generally are built around a data dictionary. The CASE tool can check that every field of every record in the dictionary is mentioned somewhere in the design or that every item in the design is reflected in the data flow diagram. In addition, many upperCASE tools incorporate a consistency checker that uses the data dictionary to determine that every item in the design has been declared in the specifications and conversely that every item in the specifications appears in the design.

Furthermore, many upperCASE tools incorporate screen and report generators. That is, the client can specify what items are to appear in a report or on an input screen and where and how each item is to appear. Because full details regarding every item are in the data dictionary, the CASE tool can easily generate the code for printing the report or displaying the input screen according to the client's wishes. Some upperCASE products also incorporate management tools for estimating and planning.

With regard to object-oriented design, Together, IBM Rational Rose, and Software through Pictures provide support for this workflow within the context of the complete object-oriented life cycle. Open-source CASE tools of this type include ArgoUML.

14.15 Metrics for Design

A variety of metrics can be used to describe aspects of the design. For example, the number of code artifacts (modules or classes) is a crude measure of the size of the target product. Cohesion and coupling are measures of the quality of the design, as are fault statistics. As with all other types of inspection, it is vital to keep a record of the number and type of design faults detected during a design inspection. This information is used during code inspections of the product and in design inspections of subsequent products.

The **cyclomatic complexity** M of a detailed design is the number of binary decisions (predicates) plus 1 [McCabe, 1976] or, equivalently, the number of branches in the code artifact. It has been suggested that cyclomatic complexity is a metric of design quality; the lower the value of M, the better. A strength of this metric is that it is easy to compute. However, it has an inherent problem. Cyclomatic complexity is purely a measure of the control complexity; the data complexity is ignored. That is, M does not measure the complexity of a code artifact that is data driven, such as by the values in a table. For example, suppose a designer is unaware of the C++ library function `toascii` and designs a code artifact from scratch that reads a character input by the user and returns the corresponding ASCII code (an integer between 0 and 127). One way of designing this is by means of a 128-way branch implemented by means of a **switch** statement. A second way is to have an array containing the 128 characters in ASCII code order and utilize a loop to compare the character input by the user with each element of the array of characters; the loop is exited when a match is obtained. The current value of the loop variable then is the corresponding ASCII code. The two designs are equivalent in functionality but have cyclomatic complexities of 128 and 1, respectively.

When the classical paradigm is used, a related class of metrics for the design phase is based on representing the architectural design as a directed graph with the modules represented by nodes and the flows between modules (procedure and function calls) represented by arcs. The **fan-in** of a module can be defined as the number of flows into the module plus the number of global data structures accessed by the module. The **fan-out** similarly is the number of flows out of the module plus the number of global data structures updated by the module. A measure of complexity of the module then is given by $length \times (fan\text{-}in \times fan\text{-}out)^2$ [Henry and Kafura, 1981], where **length** is a measure of the size of the module (Section 9.2.1). Because the definitions of *fan-in* and *fan-out* incorporate global data, this metric has a data-dependent component. Nevertheless, experiments have shown that this metric is no better a measure of complexity than simpler metrics, such as cyclomatic complexity [Kitchenham, Pickard, and Linkman, 1990; Shepperd, 1990].

The issue of design metrics is complicated even more when the object-oriented paradigm is used. For example, the cyclomatic complexity of a class usually is low, because many classes typically include a large number of small, straightforward methods. Furthermore, as previously pointed out, cyclomatic complexity ignores data complexity. Because data and operations are equal partners within the object-oriented paradigm, cyclomatic complexity overlooks a major component that could contribute to the complexity of an object. Therefore, metrics for classes that incorporate cyclomatic complexity generally are of little use.

A number of object-oriented design metrics have been put forward, for example, in [Chidamber and Kemerer, 1994]. These and other metrics have been questioned on both theoretical and experimental grounds [Binkley and Schach, 1996; 1997; 1998].

14.16 Challenges of the Design Workflow

As pointed out in Sections 12.16 and 13.22, it is important not to do too much in the analysis workflow; that is, the analysis team must not prematurely start parts of the design workflow. In the design workflow, the design team can go wrong in two ways: by doing too much and by doing too little.

Consider the PDL (pseudocode) detailed design of Figure 14.7. The temptation is strong for a designer who enjoys programming to write the detailed design in C++ or Java, rather than PDL. That is, instead of sketching the detailed design in pseudocode, the designer may all but code the class. This takes longer to write than just outlining the class and longer to fix if a fault is detected in the design (see Figure 1.6). Like the analysis team, the members of the design team must firmly resist the urge to do more than what is required of them.

At the same time, the design team must be careful not to do too little. Consider the tabular detailed design of Figure 14.6. If the design team is in a hurry, it may decide to shrink the detailed design to just the narrative box. The team may even decide that the programmers should do the detailed design by themselves. Either of these decisions would be a mistake. A primary reason for the detailed design is to ensure that all interfaces are correct. The narrative box by itself is inadequate for this purpose; no detailed design at all clearly is even less helpful. Therefore, one challenge of the design workflow is for the designers to do just the correct amount of work.

In addition, there is a much more significant challenge. In "No Silver Bullet" (see Just in Case You Wanted to Know Box 3.4), Brooks [1986] decries the lack of what he terms *great designers*, that is, designers who are significantly more outstanding than the other members of the design team. In Brooks's opinion, the success of a software project depends critically on whether the design team is led by a great designer. Good design can be taught; great design is produced only by great designers, and they are "very rare."

The challenge, then, is to grow great designers. They should be identified as early as possible (the best designers are not necessarily the most experienced), assigned a mentor, provided a formal education as well as apprenticeships to great designers, and allowed to interact with other designers. A specific career path should be available for these designers, and the rewards they receive should be commensurate with the contribution that only a great designer can make to a software development project.

Chapter Review

The design workflow is introduced in Section 14.1. There are three basic approaches to design: operation-oriented design (Section 14.2), data-oriented design (Section 14.5), and object-oriented design (Section 14.6). Two instances of operation-oriented design are described, data flow analysis (Section 14.3) and transaction analysis (Section 14.4). Object-oriented design is applied to the elevator problem case study in Section 14.7 and to the MSG Foundation case study in Section 14.8. The design workflow is presented in Section 14.9. The design aspects of the test workflow are described in Section 14.10 and applied to the MSG Foundation case study in Section 14.11. Formal techniques for detailed design are discussed in Section 14.12. Real-time system design is described in Section 14.13. CASE tools and metrics for the design workflow are presented in Sections 14.14 and 14.15, respectively. The chapter concludes with a discussion of the challenges of the design workflow (Section 14.16).

An overview of the MSG Foundation case study for Chapter 14 appears in Figure 14.18, and for the elevator problem in Figure 14.19.

FIGURE 14.18 Overview of the MSG Foundation case study for Chapter 14.

Object-oriented design	Section 14.8
Overall class diagram	Figure 14.13
Part of overall class diagram with attribute formats added	Figure 14.14
Detailed design	Appendix G

FIGURE 14.19 Overview of the elevator problem case study for Chapter 14.

Object-oriented design	Section 14.7
Detailed class diagram	Figure 14.11

For Further Reading

Data flow analysis and transaction analysis are described in books such as [Gane and Sarsen, 1979] and [Yourdon and Constantine, 1979].

The March–April 2005 issue of *IEEE Software* contains a number of papers on design. Designing for recovery, that is, designing software to detect, react, and recover from exceptional conditions, is described in [Wirfs-Brock, 2006].

Briand, Bunse, and Daly [2001] discuss the maintainability of object-oriented designs. A comparison of both object-oriented and classical design techniques appears in [Fichman and Kemerer, 1992]. The redesign of an air traffic control system is described in [Jackson and Chapin, 2000]. Design techniques for high-performance, reliable systems are given in [Stolper, 1999]. A probabilistic approach to estimating the change proneness of an object-oriented design appears in [Tsantalis, Chatzigeorgiou, and Stephanides, 2005]. A discussion as to whether object-oriented design is intuitive appears in [Hadar and Leron, 2008].

Formal design techniques are described in [Hoare, 1987]. The vital role played by the architect is described in [McBride, 2007]. Analogously to pair programming, pair design and its effectiveness are described in [Lui, Chan, and Nosek, 2008].

With regard to reviews during the design process, the original paper on design inspections is [Fagan, 1976]; detailed information can be obtained from that paper. Later advances in review techniques are described in [Fagan, 1986]. Architecture reviews are discussed in [Maranzano et al., 2005].

With regard to real-time design, specific techniques are to be found in [Liu, 2000] and [Gomaa, 2000]. A comparison of four real-time design techniques is found in [Kelly and Sherif, 1992]. A documentation-driven approach to the design of complex real-time systems is described in [Luqi, Zhang, Berzins, and Qiao, 2004]. The design of concurrent systems is described in [Magee and Kramer, 1999].

Metrics for design are described in [Henry and Kafura, 1981] and [Zage and Zage, 1993]. Metrics for object-oriented design are discussed in [Chidamber and Kemerer, 1994] and in [Binkley and Schach, 1996]. A model for object-oriented quality is presented in [Bansiya and Davis, 2002].

The proceedings of the International Workshops on Software Specification and Design are a comprehensive source for information on design techniques.

Key Terms

abstract data type design *476*
accessor *482*
architect *486*
architectural design *466*
class diagram *476*
cyclomatic complexity *491*
data flow analysis (DFA) *467*
data-oriented design *465*
design workflow *483*
detailed design *466*
fan-in *491*
fan-out *491*
general design *466*
high-level design *466*
length *491*
logical design *466*
low-level design *466*
modular design *466*
mutator *482*
object-oriented design (OOD) *476*
operation-oriented design *465*
package *486*
physical design *466*

Problems

14.1 Starting with your DFD for Problem 12.9, use data flow analysis to design a product for determining whether a bank statement is correct.

14.2 Use transaction analysis to design the software to control an ATM (Problem 8.9). At this stage omit error-handling capabilities.

14.3 Now take your design for Problem 14.2 and add modules to perform error handling. Carefully examine the resulting design and determine the cohesion and coupling of the modules. Be on the lookout for situations such as that depicted in Figure 14.10.

14.4 Two different techniques for depicting a detailed design are presented in Section 14.3.1 (Figures 14.6 and 14.7). Compare and contrast the two techniques.

14.5 Starting with your data flow diagram for the automated library circulation system (Problem 12.11), design the circulation system using data flow analysis.

14.6 Repeat Problem 14.5 using transaction analysis. Which of the two techniques did you find to be more appropriate?

14.7 Complete the detailed class diagram for the elevator problem case study (Figure 14.11) by listing the methods of the form Send message to **C Class** . . . that need to be included in the **Elevator Subcontroller Class**.

14.8 Complete the detailed class diagram for the elevator problem case study (Figure 14.11) by listing the methods of the form Send message to **C Class** . . . that need to be included in the **Floor Subcontroller Class**.

14.9 Complete the detailed class diagram for the elevator problem case study (Figure 14.11) by listing the methods of the form Send message to **C Class** . . . that need to be included in the **Sensor Class**.

14.10 Complete the detailed class diagram for the elevator problem case study (Figure 14.11) by listing the methods of the form Send message to **C Class** . . . that need to be included in the **Floor Button Class**.

14.11 Complete the detailed class diagram for the elevator problem case study (Figure 14.11) by listing the methods of the form Send message to **C Class** . . . that need to be included in the **Elevator Button Class**.

14.12 Complete the detailed class diagram for the elevator problem case study (Figure 14.11) by listing the methods of the form Send message to **C Class** . . . that need to be included in the **Scheduler Class**.

14.13 (Analysis and Design Project) Starting with your object-oriented analysis for the automated library circulation system (Problem 13.19), design the library system using object-oriented design.

14.14 (Analysis and Design Project) Starting with your object-oriented analysis for the product for determining whether a bank statement is correct (Problem 13.20), design the software using object-oriented design.

14.15 (Analysis and Design Project) Starting with your object-oriented analysis for the ATM software (Problem 13.21), design the ATM software using object-oriented design.

14.16 (Term Project) Starting with your specifications of Problem 12.20 or 13.22, design the Chocoholics Anonymous product (Appendix A). Use the design technique specified by your instructor.

14.17 (Case Study) Redesign the MSG Foundation product using data flow analysis.

14.18 (Case Study) Redesign the MSG Foundation product using transaction analysis.

14.19 (Case Study) The detailed design of Figures 14.16 and 14.17 is represented in PDL form. Represent the design using a tabular format. Which representation is superior? Give reasons for your answer.

14.20 (Readings in Software Engineering) Your instructor will distribute copies of [Hadar and Leron, 2008]. To what extent do you think that object-oriented design is intuitive?

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