Software Architecture (06IS72)

PART - A

UNIT - 1

INTRODUCTION: The Architecture Business Cycle: Where do architectures come from? Software processes and the architecture business cycle; What makes a “good” architecture? What software architecture is and what it is not; Other points of view; Architectural patterns, reference models and reference architectures; Importance of software architecture; Architectural structures and views. **6 Hours**

UNIT - 2

ARCHITECTURAL STYLES AND CASE STUDIES: Architectural styles; Pipes and filters; Data abstraction and object-oriented organization; Event-based, implicit invocation; Layered systems; Repositories; Interpreters; Process control; Other familiar architectures; Heterogeneous architectures. Case Studies: Keyword in Context; Instrumentation software; Mobile robotics; Cruise control; Three vignettes in mixed style.

7 Hours

UNIT - 3

QUALITY: Functionality and architecture; Architecture and quality attributes; System quality attributes; Quality attribute scenarios in practice; Other system quality attributes; Business qualities; Architecture qualities.

Achieving Quality: Introducing tactics; Availability tactics; Modifiability tactics; Performance tactics; Security tactics; Testability tactics; Usability tactics; Relationship of tactics to architectural patterns; Architectural patterns and styles. **6 Hours**

UNIT - 4

ARCHITECTURAL PATTERNS – 1: Introduction; from mud to structure: Layers, Pipes and Filters, Blackboard. **7 Hours**

PART - B

UNIT - 5

ARCHITECTURAL PATTERNS – 2: Distributed Systems: Broker; Interactive Systems: MVC, Presentation-Abstraction-Control. **7 Hours**

UNIT - 6

ARCHITECTURAL PATTERNS – 3: Adaptable Systems: Microkernel; Reflection.

6 Hours

UNIT - 7

SOME DESIGN PATTERNS: Structural decomposition: Whole – Part; Organization of work: Master – Slave; Access Control: Proxy. **6 Hours**

UNIT - 8

DESIGNING AND DOCUMENTING SOFTWARE ARCHITECTURE: Architecture in the life cycle; designing the architecture; Forming the team structure; Creating a skeletal system. Uses of architectural documentation; Views; choosing the relevant views; Documenting a view; Documentation across views. **7 Hours**

TEXT BOOKS:

1. **Software Architecture in Practice** – Len Bass, Paul Clements, Rick Kazman, 2nd Edition, Pearson Education, 2003.
2. **Pattern-Oriented Software Architecture, A System of Patterns - Volume 1 –** Frank Buschmann, Regine Meunier, Hans Rohnert, Peter Sommerlad, Michael Stal, , John Wiley and Sons, 2006.
1. **Mary Shaw and David Garlan**: Software Architecture- Perspectives on an Emerging Discipline, Prentice-Hall of India, 2007.

REFERENCE BOOK:

1. **Design Patterns- Elements of Reusable Object-Oriented Software** – E. Gamma, R. Helm, R. Johnson, J. Vlissides:, Addison-Wesley, 1995. **Web site for Patterns:** http://www.hillside.net/patterns/

INDEX

SOFTWARE ARCHITECTURE NOTES

UNIT 1

Contents

Chapter 1: INTRODUCTION

The Architecture Business Cycle:

- Software designers build systems based exclusively on the technical requirements. Requirements beget design, which begets system. Modern software development methods recognize the naïveté of this model and provide all sorts of feedback loops from designer to analyst.

- Software architecture encompasses the structures of large software systems. The architectural view of a system is abstract, distilling away details of implementation, algorithm, and data representation and concentrating on the behavior and interaction of "black box" elements. A software architecture is developed as the first step toward designing a system that has a collection of desired properties.

- The software architecture of a program or computing system is the structure or structures of the system, which comprise software elements, the externally visible properties of those elements, and the relationships among them.

- Software architecture is a result of technical, business, and social influences. Its existence in turn affects the technical, business, and social environments that subsequently influence future architectures. We call this cycle of influences, from the environment to the architecture and back to the environment, the Architecture Business Cycle (ABC).

Where Do Architectures Come From? :

- Architecture is the result of a set of business and technical decisions. There are many influences at work in its design, and the realization of these influences will change depending on the environment in which the architecture is required to perform.

- An architect designing a system for which the real-time deadlines are believed to be tight will make one set of design choices; the same architect, designing a similar system in which the deadlines can be easily satisfied, will make different choices. And the same architect, designing a non-real-time system, is likely to make quite different choices still.

- Even with the same requirements, hardware, support software, and human resources available, an architect designing a system today is likely to design a different system than might have been designed five years ago.

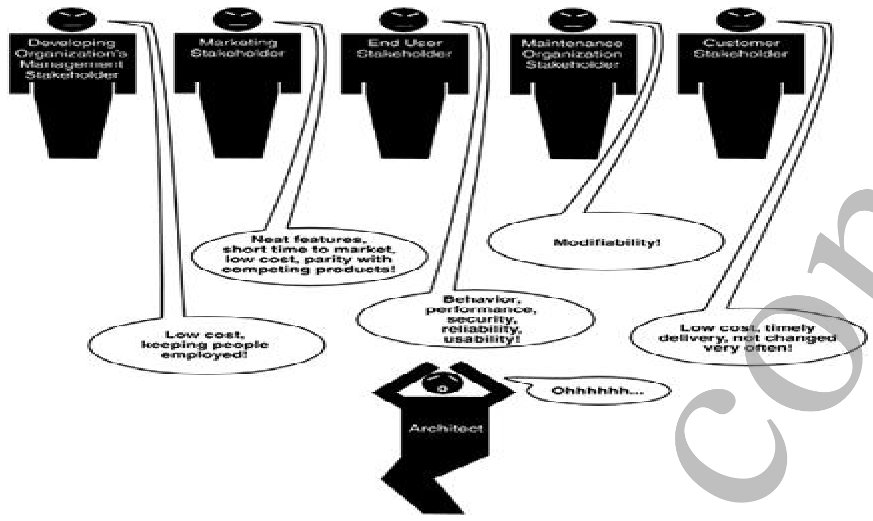
- In any development effort, the requirements make explicit some but only some of the desired properties of the final system. Not all requirements are concerned directly with those properties, a development process or the use of a particular tool may be mandated by them. Failure to satisfy other constraints may render the system just as problematic as if it functioned poorly.

ARCHITECTURES ARE INFLUENCED BY SYSTEM STAKEHOLDERS

Many people and organizations are interested in the construction of a software system. We call these stakeholders: The customer, the end users, the developers, the project manager, the maintainers, and even those who market the system are a few examples.

Stakeholders have different concerns that they wish the system to guarantee or optimize, including things as diverse as providing a certain behavior at runtime, performing well on a particular piece of hardware, being easy to customize, achieving short time to market or low cost of development, gainfully employing programmers who have a particular specialty, or providing a broad range of functions. Figure shows the architect receiving helpful stakeholder "suggestions."

Figure : Influence of stakeholders on the architect


Developing Organization's Management Stakeholder
Marketing Stakeholder
End User Stakeholder
Maintenance Organization Stakeholder
Customer Stakeholder
Neat features, short time to market, low cost, parity with competing products!
Modifiability!
Behavior, performance, security, reliability, usability!
Low cost, keeping people employed!
Low cost, timely delivery, not changed very often!
Ohhhhhh...
Architect

Having an acceptable system involves properties such as performance, reliability, availability, platform compatibility, memory utilization, network usage, security, modifiability, usability, and interoperability with other systems as well as behavior. These properties determine the overall design of the architecture. All of them, and others, affect how the delivered system is viewed by its eventual recipients, and so they find a voice in one or more of the system's stakeholders.

ARCHITECTURES ARE INFLUENCED BY THE DEVELOPING ORGANIZATION

In addition to the organizational goals expressed through requirements, an architecture is influenced by the structure or nature of the development organization. For example, if the organization has an abundance of idle programmers skilled in client-server communications, then a client-server architecture might be the approach supported by management. If not, it may well be rejected. Staff skills are one additional influence, but so are the development schedule and budget.

An organization may wish to make a long-term business investment in an infrastructure to pursue strategic goals and may view the proposed system as one means of financing and extending that infrastructure.

The organizational structure can shape the software architecture. The development of some of the subsystems was subcontracted because the subcontractors provided specialized expertise. This was made possible by a division of functionality in the architecture that allowed isolation of the specialities.

ARCHITECTURES ARE INFLUENCED BY THE BACKGROUND AND EXPERIENCE OF THE ARCHITECTS

If the architects for a system have had good results using a particular architectural approach, such as distributed objects or implicit invocation, chances are that they will try that same approach on a new development effort. Conversely, if their prior experience with this approach was disastrous, the architects may be reluctant to try it again. Architectural choices may also come from an architect's education and training, exposure to successful architectural patterns, or exposure to systems that have worked particularly poorly or particularly well. The architects may also wish to experiment with an architectural pattern or technique learned from a book or a course.

ARCHITECTURES ARE INFLUENCED BY THE TECHNICAL ENVIRONMENT

A special case of the architect's background and experience is reflected by the technical environment. The environment that is current when an architecture is designed will influence that architecture. It might include standard industry practices or software engineering techniques prevalent in the architect's professional community.

RAMIFICATIONS OF INFLUENCES ON AN ARCHITECTURE

- Influences on an architecture come from a wide variety of sources. Some are only implied, while others are explicitly in conflict.

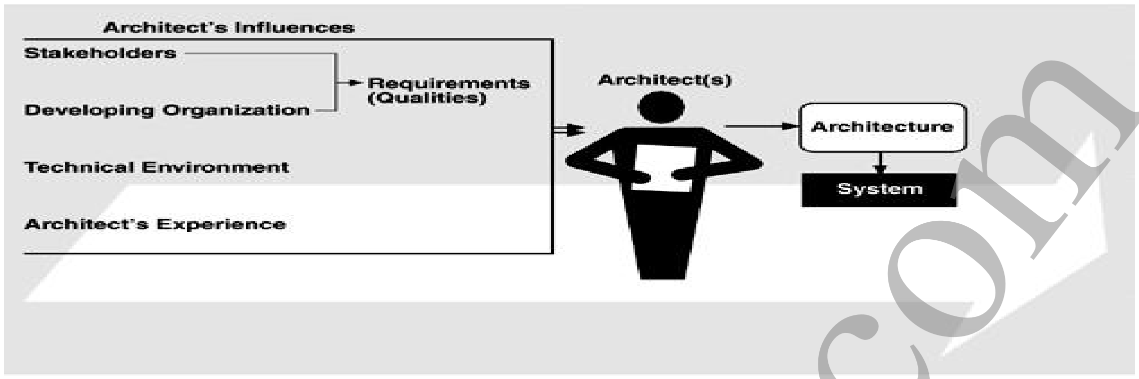
- Almost never are the properties required by the business and organizational goals consciously understood, let alone fully articulated. Customer requirements are seldom documented completely, which means that the inevitable conflict among different stakeholders' goals has not been resolved.

- Architects need to know and understand the nature, source, and priority of constraints on the project as early as possible. Therefore, they must identify and actively engage the stakeholders to solicit their needs and expectations. Without such engagement, the stakeholders will, at some point, demand that the architects explain why each proposed architecture is unacceptable, thus delaying the project and idling workers.

- Early engagement of stakeholders allows the architects to understand the constraints of the task, manage expectations, negotiate priorities, and make tradeoffs. Architecture reviews and iterative prototyping are two means for achieving it.

- The influences on the architect, and hence on the architecture, are shown in Figure 1.3. Architects are influenced by the requirements for the product as derived from its stakeholders, the structure and goals of the developing organization, the available technical environment, and their own background and experience.

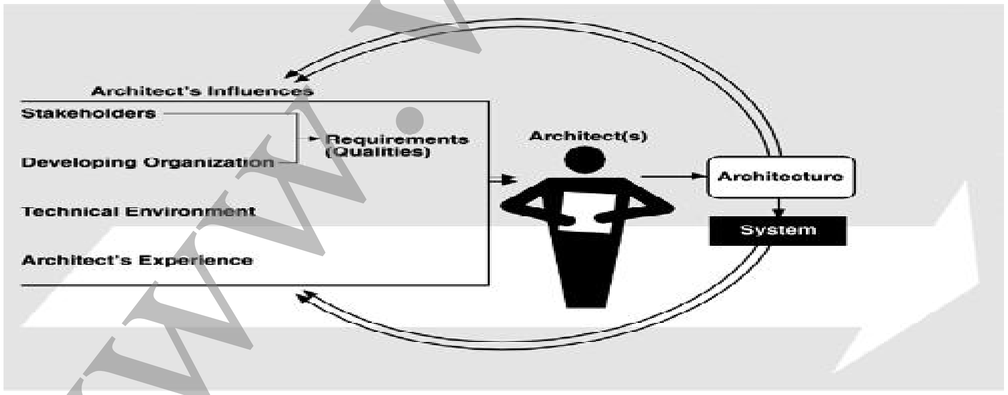
Figure 1.3 . Influences on the architecture



THE ARCHITECTURES AFFECT THE FACTORS THAT INFLUENCE THEM

The relationships among business goals, product requirements, architects' experience, architectures, and fielded systems form a cycle with feedback loops that a business can manage. A business manages this cycle to handle growth, to expand its enterprise area, and to take advantage of previous investments in architecture and system building. Figure 1.4 shows the feedback loops. Some of the feedback comes from the architecture itself, and some comes from the system built from it.

Figure 1.4. The Architecture Business Cycle



Here is how the cycle works:

- The architecture affects the structure of the developing organization. An architecture prescribes a structure for a system it particularly prescribes the units of software that must be implemented (or otherwise obtained) and integrated to form the system.

- These units are the basis for the development project's structure. Teams are formed for individual software units and the development, test, and integration activities all revolve around the units. Likewise, schedules and budgets allocate resources in chunks corresponding to the units.
    - If a company becomes adept at building families of similar systems, it will tend to invest in each team by nurturing each area of expertise. Teams become embedded in the organization's structure. This is feedback from the architecture to the developing organization.
    - In the software product line, separate groups were given responsibility for building and maintaining individual portions of the organization's architecture for a family of products. In any design undertaken by the organization at large, these groups have a strong voice in the system's decomposition, pressuring for the continued existence of the portions they control.
- The architecture can affect the goals of the developing organization. A successful system built from it can enable a company to establish a foothold in a particular market area. The architecture can provide opportunities for the efficient production and deployment of similar systems, and the organization may adjust its goals to take advantage of its newfound expertise to plumb the market. This is feedback from the system to the developing organization and the systems it builds.
- The architecture can affect customer requirements for the next system by giving the customer the opportunity to receive a system (based on the same architecture) in a more reliable, timely, and economical manner than if the subsequent system were to be built from scratch.
- The process of system building will affect the architect's experience with subsequent systems by adding to the corporate experience base. A system that was successfully built around a tool bus or .NET or encapsulated finite-state machines will engender similar systems built the same way in the future. On the other hand, architectures that fail are less likely to be chosen for future projects.

That architecture is a primary determinant of the properties of the developed system or systems. But the ABC is also based on a recognition that shrewd organizations can take advantage of the organizational and experiential effects of developing an architecture and can use those effects to position their business strategically for future projects.

<u>Software Processes and the Architecture Business Cycle</u> :

Software process is the term given to the organization, reutilization, and management of software development activities. These activities include the following:

- ❖ Creating the business case for the system
- ❖ Understanding the requirements
- ❖ Creating or selecting the architecture
- ❖ Documenting and communicating the architecture
- ❖ Analyzing or evaluating the architecture
- ❖ Implementing the system based on the architecture
- ❖ Ensuring that the implementation conforms to the architecture

ARCHITECTURE ACTIVITIES :

Architecture activities have comprehensive feedback relationships with each other.

Creating the Business Case for the System :

Creating a business case is broader than simply assessing the market need for a system. It is an important step in creating and constraining any future requirements. How much should the product cost? What is its targeted market? What is its targeted time to market? Will it need to interface with other systems? Are there system limitations that it must work within?

These are all questions that must involve the system's architects. They cannot be decided solely by an architect, but if an architect is not consulted in the creation of the business case, it may be impossible to achieve the business goals.

Understanding the Requirements :

There are a variety of techniques for eliciting requirements from the stakeholders. For example, object-oriented analysis uses scenarios, or "use cases" to embody requirements. Safety-critical systems use more rigorous approaches, such as finite-state-machine models or formal specification languages.

- One fundamental decision with respect to the system being built is the extent to which it is a variation on other systems that have been constructed. Since it is a rare system these days that is not similar to other systems, requirements elicitation techniques extensively involve understanding these prior systems' characteristics.

- Another technique that helps us understand requirements is the creation of prototypes. Prototypes may help to model desired behavior, design the user interface, or analyze resource utilization. This helps to make the system "real" in the eyes of its stakeholders and can quickly catalyze decisions on the system's design and the design of its user interface.

Creating or Selecting the Architecture :

Conceptual integrity is the key to sound system design and that conceptual integrity can only be had by a small number of minds coming together to design the system's architecture.

Communicating the Architecture :

For the architecture to be effective as the backbone of the project's design, it must be communicated clearly and unambiguously to all of the stakeholders. Developers must understand the work assignments it requires of them, testers must understand the task structure it imposes on them, management must understand the scheduling implications it suggests, and so forth. Toward this end, the architecture's documentation should be informative, unambiguous, and readable by many people with varied backgrounds.

Analyzing or Evaluating the Architecture :

In any design process there will be multiple candidate designs considered. Some will be rejected immediately. Others will contend for primacy. Choosing among these competing designs in a rational way is one of the architect's greatest challenges.

Evaluating an architecture for the qualities that it supports is essential to ensuring that the system constructed from that architecture satisfies its stakeholders' needs. Becoming more widespread are analysis techniques to evaluate the quality attributes that an architecture imparts to a system. Scenario-based techniques provide one of the most general and effective approaches for evaluating an architecture. The most mature methodological approach is found in the Architecture Tradeoff Analysis Method (ATAM)

Implementing Based on the Architecture :

This activity is concerned with keeping the developers faithful to the structures and interaction protocols constrained by the architecture. Having an explicit and well- communicated architecture is the first step toward ensuring architectural conformance. Having an environment or infrastructure that actively assists developers in creating and maintaining the architecture (as opposed to just the code) is better.

Ensuring Conformance to an Architecture :

Finally, when an architecture is created and used, it goes into a maintenance phase. Constant vigilance is required to ensure that the actual architecture and its representation remain faithful to each other during this phase.

What Makes a 'Good' Architecture? :

Given the same technical requirements for a system, two different architects in different organizations will produce different architectures, how can we determine if either one of them is the right one?

There is no such thing as an inherently good or bad architecture. Architectures are either more or less fit for some stated purpose. A distributed three-tier client-server architecture may be just the ticket for a large enterprise's financial management system but completely wrong for an avionics application. An architecture carefully crafted to achieve high modifiability does not make sense for a throw-away prototype.

We divide our observations into two clusters: process recommendations and product (or structural) recommendations. Our process recommendations are as follows:

- The architecture should be the product of a single architect or a small group of architects with an identified leader.
- The architect (or architecture team) should have the functional requirements for the system and an articulated, prioritized list of quality attributes (such as security or modifiability) that the architecture is expected to satisfy.
- The architecture should be well documented, with at least one static view and one dynamic view, using an agreed-on notation that all stakeholders can understand with a minimum of effort.
- The architecture should be circulated to the system's stakeholders, who should be actively involved in its review.
- The architecture should be analyzed for applicable quantitative measures (such as maximum throughput) and formally evaluated for quality attributes before it is too late to make changes to it.
- The architecture should lend itself to incremental implementation via the creation of a "skeletal" system in which the communication paths are exercised but which at first has minimal functionality. This skeletal system can then be used to "grow" the system incrementally, easing the integration and testing efforts

The architecture should result in a specific (and small) set of resource contention areas, the resolution of which is clearly specified, circulated, and maintained. For example, if network utilization is an area of concern, the architect should produce (and enforce) for each development team guidelines that will result in a minimum of network traffic. If performance is a concern, the architects should produce (and enforce) time budgets for the major threads.

The **structural rules** of thumb are as follows:

- The architecture should feature well-defined modules whose functional responsibilities are allocated on the principles of information hiding and separation of concerns. The information-hiding modules should include those that encapsulate idiosyncrasies of the computing infrastructure, thus insulating the bulk of the software from change should the infrastructure change.

- Each module should have a well-defined interface that encapsulates or "hides" changeable aspects (such as implementation strategies and data structure choices) from other software that uses its facilities. These interfaces should allow their respective development teams to work largely independently of each other.

- Quality attributes should be achieved using well-known architectural tactics specific to each attribute (Achieving Qualities).

- The architecture should never depend on a particular version of a commercial product or tool. If it depends upon a particular commercial product, it should be structured such that changing to a different product is straightforward and inexpensive.

- Modules that produce data should be separate from modules that consume data. This tends to increase modifiability because changes are often confined to either the production or the consumption side of data. If new data is added, both sides will have to change, but the separation allows for a staged (incremental) upgrade.

- For parallel-processing systems, the architecture should feature well-defined processes or tasks that do not necessarily mirror the module decomposition structure. That is, processes may thread through more than one module; a module may include procedures that are invoked as part of more than one process

- Every task or process should be written so that its assignment to a specific processor can be easily changed, perhaps even at runtime.

- The architecture should feature a small number of simple interaction patterns That is, the system should do the same things in the same way throughout. This will aid in understandability, reduce development time, increase reliability, and enhance modifiability. It will also show conceptual integrity in the architecture, which, while not measurable, leads to smooth development.

What Is Software Architecture?

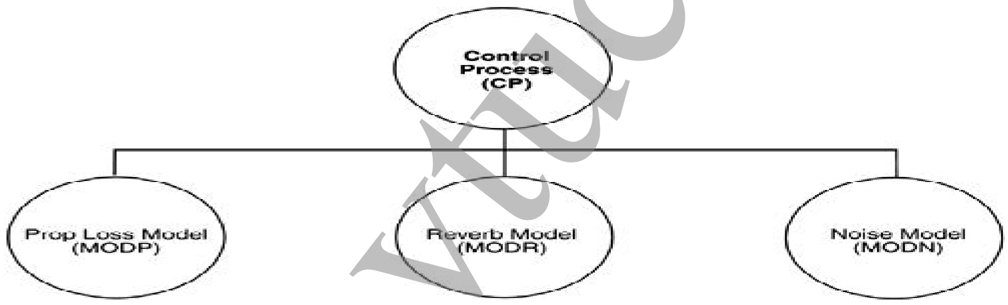
If a project has not achieved a system architecture, including its rationale, the project should not proceed to full-scale system development. Specifying the architecture as a deliverable enables its use throughout the development and maintenance process.

Architecture plays a pivotal role in allowing an organization to meet its business goals. Architecture commands a price (the cost of its careful development), but it pays for itself handsomely by enabling the organization to achieve its system goals and expand its software capabilities. Architecture is an asset that holds tangible value to the developing organization beyond the project for which it was created.

What Software Architecture Is and What It Isn't :

The following Figure gives a system description for an underwater acoustic simulation, purports to describe that system's "top-level architecture" and is precisely the kind of diagram most often displayed to help explain an architecture.

Figure 2.1. Typical, but uninformative, presentation of a software architecture



- The system consists of four elements.
- Three of the elements Prop Loss Model (MODP), Reverb Model (MODR), and Noise Model (MODN)?might have more in common with each other than with the fourth Control Process (CP)?because they are positioned next to each other.
- All of the elements apparently have some sort of relationship with each other, since the diagram is fully connected.

This is not a architecture since it fails to explain the following points :

- What is the nature of the elements? What is the significance of their separation? Do they run on separate processors? Do they run at separate times? Do the elements consist of processes, programs, or both? Do they represent ways in which the project

labor will be divided, or do they convey a sense of runtime separation? Are they objects, tasks, functions, processes, distributed programs, or something else?
- What are the responsibilities of the elements? What is it they do? What is their function in the system?
- What is the significance of the connections? Do the connections mean that the elements communicate with each other, control each other, send data to each other, use each other, invoke each other, synchronize with each other, share some information-hiding secret with each other, or some combination of these or other relations? What are the mechanisms for the communication? What information flows across the mechanisms, whatever they may be?
- What is the significance of the layout? Why is CP on a separate level? Does it call the other three elements, and are the others not allowed to call it? Does it contain the other three in an implementation unit sense? Or is there simply no room to put all four elements on the same row in the diagram?

This diagram does not show a software architecture. The most charitable thing we can say about such diagrams is that they represent a start.

The software architecture of a program or computing system is the structure or structures of the system, which comprise software elements, the externally visible properties of those elements, and the relationships among them.

There the primary building blocks were called "components," a term that has since become closely associated with the component-based software engineering movement, taking on a decidedly runtime flavor. "Element" was chosen here to convey something more general.

- First, architecture defines software elements. The architecture embodies information about how the elements relate to each other.
- Second, the definition makes clear that systems can and do comprise more than one structure and that no one structure can irrefutably claim to be the architecture. For example, all nontrivial projects are partitioned into implementation units; these units are given specific responsibilities and are frequently the basis of work assignments for programming teams.
- Third, the definition implies that every computing system with software has a software architecture because every system can be shown to comprise elements and the relations among them.
- Fourth, the behavior of each element is part of the architecture insofar as that behavior can be observed or discerned from the point of view of another element. Such behavior is what allows elements to interact with each other, which is clearly part of the architecture. This is another reason that the box-and-line drawings that are passed off as architectures are not architectures at all.
- Finally, the definition is indifferent as to whether the architecture for a system is a good one or a bad one, meaning that it will allow or prevent the system from meeting its

behavioral, performance, and life-cycle requirements.

Other Points of View :

The study of software architecture has evolved by observation of the design principles that designers follow and the actions that they take when working on real systems. It is an attempt to abstract the commonalities inherent in system design, and as such it must account for a wide range of activities, concepts, methods, approaches, and results.

- Architecture is high-level design.
- Architecture is the overall structure of the system.
- Architecture is the structure of the components of a program or system, their interrelationships, and the principles and guidelines governing their design and evolution over time.
- Architecture is components and connectors. Connectors imply a runtime mechanism for transferring control and data around a system.

Architectural Patterns, Reference Models, and Reference Architectures :

1. architectural pattern is a description of element and relation types together with a set of constraints on how they may be used. A pattern can be thought of as a set of constraints on an architecture. On the element types and their patterns of interaction and these constraints define a set or family of architectures that satisfy them. For example, client-server is a common architectural pattern.

    - Client and server are two element types, and their coordination is described in terms of the protocol that the server uses to communicate with each of its clients. Use of the term client-server implies only that multiple clients exist; the clients themselves are not identified, and there is no discussion of what functionality, other than implementation of the protocols, has been assigned to any of the clients or to the server.

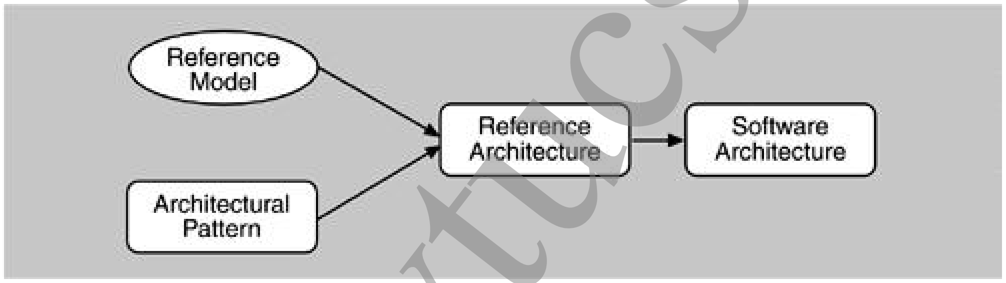
    - Countless architectures are of the client-server pattern under this (informal) definition, but they are different from each other. An architectural pattern is not an architecture, then, but it still conveys a useful image of the system, it imposes useful constraints on the architecture and, in turn, on the system.

    - One of the most useful aspects of patterns is that they exhibit known quality attributes. This is why the architect chooses a particular pattern and not one at random.

- Some patterns represent known solutions to performance problems, others lend themselves well to high-security systems, still others have been used successfully in high-availability systems. Choosing an architectural pattern is often the architect's first major design choice.

2. A reference model is a division of functionality together with data flow between the pieces. A reference model is a standard decomposition of a known problem into parts that cooperatively solve the problem. Arising from experience, reference models are a characteristic of mature domains.
3. A reference architecture is a reference model mapped onto software elements (that cooperatively implement the functionality defined in the reference model) and the data flows between them. Whereas a reference model divides the functionality, a reference architecture is the mapping of that functionality onto a system decomposition. The mapping may be, but by no means necessarily is, one to one. A software element may implement part of a function or several functions.

Figure 2.2. The relationships of reference models, architectural patterns, reference architectures, and software architectures.



Why Is Software Architecture Important? :

There are fundamentally three reasons for software architecture's importance.

1. Communication among stakeholders. Software architecture represents a common abstraction of a system that most if not all of the system's stakeholders can use as a basis for mutual understanding, negotiation, consensus, and communication.
2. Early design decisions. Software architecture manifests the earliest design decisions about a system, and these early bindings carry weight far out of proportion to their individual gravity with respect to the system's remaining development, its deployment, and its maintenance life. It is also the earliest point at which design decisions governing the system to be built can be analyzed.
3. Transferable abstraction of a system. Software architecture constitutes a relatively small, intellectually graspable model for how a system is structured and how its elements work together, and this model is transferable across systems. In particular, it can be applied to

other systems exhibiting similar quality attribute and functional requirements and can promote large-scale re-use.

ARCHITECTURE IS THE VEHICLE FOR STAKEHOLDER COMMUNICATION :

Each stakeholder of a software system-customer, user, project manager, coder, tester, and so on is concerned with different system characteristics that are affected by the architecture. For example, the user is concerned that the system is reliable and available when needed; the customer is concerned that the architecture can be implemented on schedule and to budget; the manager is worried (as well as about cost and schedule) that the architecture will allow teams to work largely independently, interacting in disciplined and controlled ways. The architect is worried about strategies to achieve all of those goals.

Architecture provides a common language in which different concerns can be expressed, negotiated, and resolved at a level that is intellectually manageable even for large, complex systems. Without such a language, it is difficult to understand large systems sufficiently to make the early decisions that influence both quality and usefulness.

ARCHITECTURE MANIFESTS THE EARLIEST SET OF DESIGN DECISIONS

Software architecture represents a system's earliest set of design decisions. These early decisions are the most difficult to get correct and the hardest to change later in the development process, and they have the most far-reaching effects.

The Architecture Defines Constraints on Implementation :

An implementation exhibits an architecture if it conforms to the structural design decisions described by the architecture. This means that the implementation must be divided into the prescribed elements, the elements must interact with each other in the prescribed fashion, and each element must fulfill its responsibility to the others as dictated by the architecture.

Resource allocation decisions also constrain implementations. These decisions m ay be invisible to implementors working on individual elements. The constraints permit a separation of concerns that allows management decisions to make the best use of personnel and computational capacity. Element builders must be fluent in the specification of their individual elements but not in architectural tradeoffs. Conversely, architects need not be experts in all aspects of algorithm design or the intricacies of the programming language, but they are the ones responsible for the architectural tradeoffs.

The Architecture Dictates Organizational Structure :

- Not only does architecture prescribe the structure of the system being developed, but that structure becomes engraved in the structure of the development project. The normal method for dividing up the labor in a large system is to assign different groups different portions of the system to construct. This is called the work breakdown structure of a system.

- A side effect of establishing the work breakdown structure is to freeze some aspects of the software architecture. A group that is responsible for one of the subsystems will resist having its responsibilities distributed across other groups. If these responsibilities have been formalized in a contractual relationship, changing them can become expensive. Tracking progress on a collection of tasks being distributed also becomes much more difficult.

- Once the architecture has been agreed on, then, it becomes almost impossible, for managerial and business reasons, to modify it. This is one argument (among many) for carrying out a comprehensive evaluation before freezing the software architecture for a large system.

The Architecture Inhibits or Enables a System's Quality Attributes :

Whether a system will be able to exhibit its desired (or required) quality attributes is substantially determined by its architecture.

The strategies for these and other quality attributes are supremely architectural. It is important to understand, however, that architecture alone cannot guarantee functionality

or quality. Poor downstream design or implementation decisions can always undermine an adequate architectural design. Decisions at all stages of the life cycle from high-level design to coding and implementation affect system quality. Therefore, quality is not completely a function of architectural design. To ensure quality, a good architecture is necessary, but not sufficient.

Predicting System Qualities by Studying the Architecture :

Is it possible to tell that the appropriate architectural decisions have been made (i.e., if the system will exhibit its required quality attributes) without waiting until the system is developed and deployed. If the answer were no, choosing an architecture would be a hopeless task random selection would perform as well as any other method. Fortunately, it is possible to make quality predictions about a system based solely on an evaluation of its architecture.

The Architecture Makes It Easier to Reason about and Manage Change

Every architecture partitions possible changes into three categories: local, non local, and architectural. A local change can be accomplished by modifying a single element. A non local change requires multiple element modifications but leaves the underlying architectural approach intact. An architectural change affects the fundamental ways in which the elements interact with each other. The pattern of the architecture and will probably require changes all over the system. Obviously, local changes are the most desirable, and so an effective architecture is one in which the most likely changes are also the easiest to make.

Deciding when changes are essential, determining which change paths have the least risk, assessing the consequences of proposed changes, and arbitrating sequences and priorities for requested changes all require broad insight into relationships, performance, and behaviors of system software elements. These are in the job description for an architect. Reasoning about the architecture can provide the insight necessary to make decisions about proposed changes.

The Architecture Helps in Evolutionary Prototyping :

Once an architecture has been defined, it can be analyzed and prototyped as a skeletal system. This aids the development process in two ways.

1. The system is executable early in the product's life cycle. Its fidelity increases as prototype parts are replaced by complete versions of the software. These prototype parts can be a lower-fidelity version of the final functionality, or they can be surrogates that consume and produce data at the appropriate rates.

2. A special case of having the system executable early is that potential performance problems can be identified early in the product's life cycle.

Each of these benefits reduces the risk in the project. If the architecture is part of a family of related systems, the cost of creating a framework for prototyping can be distributed over the development of many systems.

The Architecture Enables More Accurate Cost and Schedule Estimates :

Cost and schedule estimates are an important management tool to enable the manager to acquire the necessary resources and to understand whether a project is in trouble.

Cost estimations based on an understanding of the system pieces are, inherently, more accurate than those based on overall system knowledge. As we have said, the organizational structure of a project is based on its architecture.

Each team will be able to make more accurate estimates for its piece than a project manager will and will feel more ownership in making the estimates come true. Second, the initial definition of an architecture means that the requirements for a system have been reviewed and, in some sense, validated. The more knowledge about the scope of a system, the more accurate the estimates.

ARCHITECTURE AS A TRANSFERABLE, RE-USABLE MODEL :

The earlier in the life cycle re-use is applied, the greater the benefit that can be achieved. While code re-use is beneficial, re-use at the architectural level provides tremendous leverage for systems with similar requirements. Not only code can be re-used but so can the requirements that led to the architecture in the first place, as well as the experience of building the re-used architecture. When architectural decisions can be re-used across multiple systems, all of the early decision consequences are also transferred.

Software Product Lines Share a Common Architecture :

- A software product line or family is a set of software-intensive systems sharing a common, managed set of features that satisfy the specific needs of a particular market segment or mission and that are developed from a common set of core assets in a prescribed way.

- Chief among these core assets is the architecture that was designed to handle the needs of the entire family. Product line architects choose an architecture (or a family of closely related architectures) that will serve all envisioned members of the product line by making design decisions that apply across the family early and by making other decisions that apply only to individual members late.

- The architecture defines what is fixed for all members of the product line and what is variable. Software product lines represent a powerful approach to multi-system development that shows order-of- magnitude payoffs in time to market, cost, productivity, and product quality. The power of architecture lies at the heart of the paradigm. Similar to other capital investments, the architecture for a product line becomes a developing organization's core asset.

Systems Can Be Built Using Large, Externally Developed Elements :

- Whereas earlier software paradigms focused on programming as the prime activity, with progress measured in lines of code, architecture-based development often focuses on composing or assembling elements that are likely to have been developed separately,even independently, from each other.

- This composition is possible because the architecture defines the elements that can be incorporated into the system. It constrains possible replacements (or additions) according to how they interact with their environment, how they receive and relinquish control, what data they consume and produce, how they access data, and what protocols they use for communication and resource sharing.

- One key aspect of architecture is its organization of element structure, interfaces, and operating concepts. The most significant principle of this organization is interchangeability.

- Commercial off-the-shelf components, subsystems, and compatible communications interfaces all depend on the principle of interchangeability. However, there is much about software development through composition that remains unresolved.

- When the components that are candidates for importation and re-use are distinct subsystems that have been built with conflicting architectural assumptions, unanticipated complications can increase the effort required to integrate their functions.

An Architecture Permits Template-Based Development :

An architecture embodies design decisions about how elements interact that, while reflected in each element's implementation, can be localized and written just once. Templates can be used to capture in one place the inter-element interaction mechanisms. For instance, a template can encode the declarations for an element's public area where results will be left, or can encode the protocols that the element uses to engage with the system executive.

An Architecture Can Be the Basis for Training :

The architecture, including a description of how elements interact to carry out the required behavior, can serve as the introduction to the system for new project members. This reinforces our point that one of the important uses of software architecture is to support and encourage communication among the various stakeholders.

Architectural Structures and Views :

A view is a representation of a coherent set of architectural elements, as written by and read by system stakeholders. It consists of a representation of a set of elements and the relations among them. A structure is the set of elements itself, as they exist in software or hardware. For example, a module structure is the set of the system's modules and their organization. A module view is the representation of that structure, as documented by and used by some system stakeholders.

Architectural structures can by and large be divided into three groups, depending on the broad nature of the elements they show.

- Module structures. Here the elements are modules, which are units of implementation. Modules represent a code-based way of considering the system. They are assigned areas of functional responsibility. There is less emphasis on how the resulting software manifests itself at runtime. Module structures allow us to answer questions such as What is the primary functional responsibility assigned to each module?

What other software elements is a module allowed to use? What other software does it actually use? What modules are related to other modules by generalization or specialization (i.e., inheritance) relationships?

- Allocation structures. Allocation structures show the relationship between the software elements and the elements in one or more external environments in which the software is created and executed. They answer questions such as What processor does each software element execute on? In what files is each element stored during development, testing, and system building? What is the assignment of software elements to development teams?

These three structures correspond to the three broad types of decision that architectural design involves:

- How is the system to be structured as a set of code units (modules)?
- How is the system to be structured as a set of elements that have runtime behavior (components) and interactions (connectors)?
- How is the system to relate to nonsoftware structures in its environment (i.e., CPUs, file systems, networks, development teams, etc.)?

UNIT 2

Contents

UNIT: 2 ARCHITECTURAL STYLES AND CASE STUDIES

Architectural Styles:

The **software architecture** of a program or computing system is the structure or structures of the system, which comprise software components, the externally visible properties of those components, and the relationships between them. The term also refers to documentation of a system's software architecture. Documenting software architecture facilitates communication between stakeholders, documents early decisions about high- level design, and allows reuse of design components and patterns between projects.

An architectural style defines a family of systems in terms of a pattern of structural organization. This provides a vocabulary of components and connector types, and a set of constraints on how they can be combined. A semantic model may also exist which specify how to determine a system's overall properties from the properties of its parts.

Pipes and Filters :

- In a pipe and filter style each component has a set of inputs and a set of outputs. A component reads streams of data on its inputs and produces streams of data on its outputs, delivering a complete instance of the result in a standard order.

- This is usually accomplished by applying a local transformation to the input streams and computing incrementally so output begins before input is consumed. Hence components are termed "filters". The connectors of this style serve as conduits for the streams, transmitting outputs of one filter to inputs of another. Hence the connectors are termed "pipes". Among the important invariants of the style, filters must be independent entities: in particular, they should not share state with other filters.

- Another important invariant is that filters do not know the identity of their upstream and downstream filters. Their specifications might restrict what appears on the input pipes or make guarantees about what appears on the output pipes, but they may not identify the components at the ends of those pipes.

- Furthermore, the correctness of the output of a pipe and filter network should not depend on the order in which the filters perform their incremental processing—although fair scheduling can be assumed. Common specializations of this style include *pipelines*, which restrict the topologies to linear sequences of filters; bounded pipes, which restrict the amount of data that can reside on a pipe; and typed pipes, which require that the data passed between two filters have a well-defined type.

- A degenerate case of a pipeline architecture occurs when each filter processes all of its input data as a single entity. In this case the architecture becomes a "batch sequential" system. In these systems pipes no longer serve the function of providing a stream of data, and therefore are largely vestigial. Hence such systems are best treated as instances of a separate architectural style.

- The best known examples of pipe and filter architectures are programs written in the Unix shell. Unix supports this style by providing a notation for connecting components (represented as Unix processes) and by providing run time mechanisms for implementing pipes. As another well-known example, traditionally compilers have been viewed as a pipeline systems (though the phases are often not incremental).

- Third, systems can be easily maintained and enhanced: new filters can be added to existing systems and old filters can be replaced by improved ones. Fourth, they permit certain kinds of specialized analysis, such as throughput and deadlock analysis. Finally, they naturally support concurrent execution. Each filter can be implemented as a separate task and potentially executed in parallel with other filters.

Data Abstraction and Object-Oriented Organization :

- In this style data representations and their associated primitive operations are encapsulated in an abstract data type or object. The components of this style are the objects—or, if you will, instances of the abstract data types.

- Objects are examples of a sort of component we call a manager because it is responsible for preserving the integrity of a resource (here the representation). Objects interact through function and procedure invocations. Two important aspects of this style are (a) that an object is responsible for preserving the integrity of its representation (usually by maintaining some invariant over it), and (b) that the representation is hidden from other objects.

- The use of abstract data types, and increasingly the use of object-oriented systems, is, of course, widespread. There are many variations. For example, some systems allow "objects" to be concurrent tasks; others allow objects to have multiple interfaces.

- Object-oriented systems have many nice properties, most of which are well known. Because an object hides its representation from its clients, it is possible to change the implementation without affecting those clients. Additionally, the bundling of a set of accessing routines with the data they manipulate allows designers to decompose problems into collections of interacting agents. But object-oriented systems also have some disadvantages.

- The most significant is that in order for one object to interact with another (via procedure call) it must know the identity of that other object. This is in contrast, for example, to pipe and filter systems, where filters do need not know what other filters are in the system in order to interact with them.

- The significance of this is that whenever the identity of an object changes it is necessary to modify all other objects that explicitly invoke it. In a module oriented language this manifests itself as the need to change the "import" list of every module that uses the changed module. Further there can be side effect problems: if A uses object B and C also uses B, then C's effects on B look like unexpected side effects to A, and vice versa.

Event-based, Implicit Invocation :

- Traditionally, in a system in which the component interfaces provide a collection of procedures and functions, components interact with each other by explicitly invoking those routines. However, recently there has been considerable interest in an alternative integration technique, variously referred to as implicit invocation, reactive integration, and selective broadcast.

- This style has historical roots in systems based on actors, constraint satisfaction, daemons, and packet-switched networks. The idea behind implicit invocation is that instead of invoking a procedure directly, a component can announce (or broadcast) one or more events. Other components in the system can register an interest in an event by associating a procedure with the event.

- When the event is announced the system itself invokes all of the procedures that have been registered for the event. Thus an event announcement ``implicitly" causes the invocation of procedures in other modules. For example, in the Field system, tools such as editors and variable monitors register for a debugger's breakpoint events.

- When a debugger stops at a breakpoint, it announces an event that allows the system to automatically invoke methods in those registered tools. These methods might scroll an editor to the appropriate source line or redisplay the value of monitored variables. In this scheme, the debugger simply announces an event, but does not know what other tools (if any) are concerned with that event, or what they will do when that event is announced.

- One important benefit of implicit invocation is that it provides strong support for reuse. Any component can be introduced into a system simply by registering it for the events of that system. A second benefit is that implicit invocation eases system evolution. Components may be replaced by other components without affecting the interfaces of other components in the system.

- In contrast, in a system based on explicit invocation, whenever the identity of a that provides some system function is changed, all other modules that import that module must also be changed. The primary disadvantage of implicit invocation is that components relinquish control over the computation performed by the system.

- When a component announces an event, it has no idea what other components will respond to it. Worse, even if it does know what other components are interested in the events it announces, it cannot rely on the order in which they are invoked.

- Nor can it know when they are finished. Another problem concerns exchange of data. Sometimes data can be passed with the event. But in other situations event systems must rely on a shared repository for interaction. In these cases global performance and resource management can become a serious issue.

- Finally, reasoning about correctness can be problematic, since the meaning of a procedure that announces events will depend on the context of bindings in which it is invoked. This is in contrast to traditional reasoning about procedure calls, which need only consider a procedure's pre- and post- conditions when reasoning about an invocation of it.

Layered Systems :

- A layered system is organized hierarchically, each layer providing service to the layer above it and serving as a client to the layer below. In some layered systems inner layers are hidden from all except the adjacent outer layer, except for certain functions carefully selected for export. Thus in these systems the components implement a virtual machine at some layer in the hierarchy. The connectors are defined by the protocols that determine how the layers will interact. Topological constraints include limiting interactions to adjacent layers.

- The most widely known examples of this kind of architectural style are layered communication protocols. In this application area each layer provides a substrate for communication at some level of abstraction. Lower levels define lower levels of interaction, the lowest typically being defined by hardware connections. Other application areas for this style include database systems and operating systems.

- Layered systems have several desirable properties. First, they support design based on increasing levels of abstraction. This allows implementers to partition a complex problem into a sequence of incremental steps.

- Second, they support enhancement. Like pipelines, because each layer interacts with at most the layers below and above, changes to the function of one layer affect at most two other layers. Third, they support reuse. Like abstract data types, different implementations of the same layer can be used interchangeably, provided they support the same interfaces to their adjacent layers.

- This leads to the possibility of defining standard layer interfaces to which different implementers can build. (A good example is the OSI ISO model and some of the X Window System protocols.) But layered systems also have disadvantages. Not all systems are easily structured in a layered fashion. And even if a system *can* logically be structured as layers, considerations of performance may require closer coupling between logically high-level functions and their lower-level implementations.

- Additionally, it can be quite difficult to find the right levels of abstraction. This is particularly true for standardized layered models. One notes that the communications community has had some difficulty mapping existing protocols into the ISO framework: many of those protocols bridge several layers.

- In one sense this is similar to the benefits of implementation hiding found in abstract data types. However, here there are multiple levels of abstraction and implementation. They are also similar to pipelines, in that components communicate at most with one other component on either side. But instead of simple pipe read/write protocol of pipes, layered systems can provide much richer forms of interaction.

- This makes it difficult to define system independent layers (as with filters)—since a layer must support the specific protocols at its upper and lower boundaries. But it also allows much closer interaction between layers, and permits two- way transmission of information.

<u>Repositories :</u>

In a repository style there are two quite distinct kinds of components: a central data structure represents the current state, and a collection of independent components operate on the central data store. Interactions between the repository and its external components can vary significantly between systems.

The choice of control discipline leads to major subcategories. If the types of transactions in an input stream of transactions trigger selection of processes to execute, the repository can be a traditional database. If the current state of the central data structure is the main trigger of selecting processes to execute, the repository can be a blackboard. The blackboard model is usually presented with three major parts:

- **The knowledge sources:** separate, independent parcels of application dependent knowledge. Interaction among knowledge sources takes place solely through the blackboard.
- **The blackboard data structure:** problem-solving state data, organized into an application-dependent hierarchy. Knowledge sources make changes to the blackboard that lead incrementally to a solution to the problem.

- **Control:** driven entirely by state of blackboard. Knowledge sources respond opportunistically when changes in the blackboard make them applicable.

- Invocation of a knowledge source is triggered by the state of the blackboard. The actual locus of control, and hence its implementation, can be in the knowledge sources, the blackboard, a separate module, or some combination of these. Blackboard systems have traditionally been used for applications requiring complex interpretations of signal processing, such as speech and pattern recognition.

- They have also appeared in other kinds of systems that involve shared access to data with loosely coupled agents. There are, of course, many other examples of repository systems. Batch sequential systems with global databases are a special case. Programming environments are often organized as a collection of tools together with a shared repository of programs and program fragments.

- Even applications that have been traditionally viewed as pipeline architectures may be more accurately interpreted as repository systems. For example, while a compiler architecture has traditionally been presented as a pipeline, the "phases" of most modern compilers operate on a base of shared information (symbol tables, abstract syntax tree, etc.).

Interpreters :

In an interpreter organization a virtual machine is produced in software. An interpreter includes the pseudo-program being interpreted and the interpretation engine itself. The pseudo-program includes the program itself and the interpreter's analog of its execution state (activation record). The interpretation engine includes both the definition of the interpreter and the current state of *its* execution. Thus an interpreter generally has four components: an interpretation engine to do the work, a memory that contains the pseudo- code to be interpreted, a representation of the control state of the interpretation engine, and a representation of the current state of the program being simulated.

Interpreters are commonly used to build virtual machines that close the gap between the computing engine expected by the semantics of the program and the computing engine available in hardware.

Other Familiar Architectures :

There are numerous other architectural styles and patterns. Some are widespread and others are specific to particular domains.

• **Distributed processes:** Distributed systems have developed a number of common organizations for multi-process systems. Some can be characterized primarily by their topological features, such as ring and star organizations. Others are better characterized in terms of the kinds of inter-process protocols that are used for communication (e.g., heartbeat algorithms). One common form of distributed system architecture is a "client- server" organization . In these systems a server represents a process that provides services to other processes (the clients). Usually the server does not know in advance the identities or number of clients that will access it at run time. On the other hand, clients know the identity of a server (or can find it out through some other server) and access it by remote procedure call.
• **Main program/subroutine organizations:** The primary organization of many systems mirrors the programming language in which the system is written. For languages without support for

modularization this often results in a system organized around a main program and a set of subroutines. The main program acts as the driver for the subroutines, typically providing a control loop for sequencing through the subroutines in some order.

• **Domain-specific software architectures:** Recently there has been considerable interest in developing "reference" architectures for specific domains . These architectures provide an organizational structure tailored to a family of applications, such as avionics, command and control, or vehicle management systems. By specializing the architecture to the domain, it is possible to increase the descriptive power of structures. Indeed, in many cases the architecture is sufficiently constrained that an executable system can be generated automatically or semi-automatically from the architectural description itself.

• **State transition systems:** A common organization for many reactive systems is the state transition system . These systems are defined in terms a set of states and a set of named transitions that move a system from one state to another.

• **Process control systems:** Systems intended to provide dynamic control of a physical environment are often organized as process control systems . These systems are roughly characterized as a feedback loop in which inputs from sensors are used by the process control system to determine a set of outputs that will produce a new state of the environment.

Heterogeneous Architectures :

- Most systems typically involve some combination of several styles. There are different ways in which architectural styles can be combined. One way is through hierarchy. A component of a system organized in one architectural style may have an internal structure that is developed a completely different style.

- For example, in a Unix pipeline the individual components may be represented internally using virtually any style— including, of course, another pipe and filter, system. For example, a pipe connector may be implemented internally as a FIFO queue accessed by insert and remove operations.

- A second way for styles to be combined is to permit a single component to use a mixture of architectural connectors. For example, a component might access a repository through part of its interface, but interact through pipes with other components in a system, and accept control information through another part of its interface.

- Another example is an "active database". This is a repository which activates external components through implicit invocation. In this organization external components register interest in portions of the database. The database automatically invokes the appropriate tools based on this association. (Blackboards are often constructed this way; knowledge sources are associated with specific kinds of data, and are activated whenever that kind of data is modified.)

- A third way for styles to be combined is to completely elaborate one level of architectural description in a completely different architectural style.

Case Studies :

Following are the examples to illustrate how architectural principles can be used to increase our understanding of software systems. The first example shows how different architectural solutions to the same problem provide different benefits. The second case study summarizes experience in developing a domain-specific architectural style for a family of industrial products.

Case Study 1: Key Word in Context :

- In his paper of 1972, Parnas proposed the following problem :The KWIC [Key Word in Context] index system accepts an ordered set of lines, each line is an ordered set of words, and each word is an ordered set of characters. Any line may be ``circularly shifted" by repeatedly removing the first word and appending it at the end of the line.

- The KWIC index system outputs a listing of all circular shifts of all lines in alphabetical order. Parnas used the problem to contrast different criteria for decomposing a system into modules. He describes two solutions, one based on

- functional decomposition with shared access to data representations, and a second based on a decomposition that hides design decisions. Since its introduction, the problem has become well-known and is widely used as a teaching device in software engineering. Garlan, Kaiser, and Notkin also use the problem to illustrate modularization schemes based on implicit invocation .

- While KWIC can be implemented as a relatively small system it is not simply of pedagogical interest. Practical instances of it are widely used by computer scientists. For example, the “permuted” [sic] index for the Unix Man pages is essentially such a system.

- From the point of view of software architecture, the problem derives its appeal from the fact that it can be used to illustrate the effect of changes on software design. Parnas shows that different problem decompositions vary greatly in their ability to withstand design changes. Among the changes he considers are:

  Changes in processing algorithm: For example, line shifting can be performed on each line as it is read from the input device, on all the lines after they are read, or on demand when the alphabetization requires a new set of shifted lines.

  Changes in data representation: For example, lines can be stored in various ways.

Similarly, circular shifts can be stored explicitly or implicitly (as pairs of index and offset).Garlan, Kaiser, and Notkin, extend Parnas' analysis by considering:

Enhancement to system function: For example, modify the system so that shifted lines to eliminate circular shifts that start with certain noise words (such as "a", "an", "and", etc.). Change the system to be interactive, and allow the user to delete lines from the original lists.Performance: Both space and time.

• Reuse: To what extent can the components serve as reusable entities. We now outline four architectural designs for the KWIC system. All four are grounded in published solutions (including implementations). The first two are those considered in Parnas' original article. The third solution is based on the use of an implicit invocation style and represents a variant on the solution examined by Garlan, Kaiser, and Notkin. The fourth is a pipeline solution inspired by the Unix index utility. After presenting each solution and briefly summarizing its strengths and weakness, we contrast the different architectural decompositions in a table organized along the five design dimensions itemized above.

Solution : Main Program/Subroutine with Shared Data

The first solution decomposes the problem according to the four basic functions performed: input, shift, alphabetize, and output. These computational components are coordinated as subroutines by a main program that sequences through them in turn. Data is communicated between the components through shared storage ("core storage"). Communication between the computational components and the shared data is an unconstrained read write protocol. This is made possible by the fact that the coordinating program guarantees sequential access to the data.

Case Study 2: Instrumentation Software :

- This case study describes the industrial development of a software architecture at Tektronix, Inc. This work was carried out as a collaborative effort between several Tektronix product divisions and the Computer Research Laboratory over a three year period.

- The purpose of the project was to develop reusable system architecture for oscilloscopes. An oscilloscope is an instrumentation system that samples electrical signals and displays pictures (called traces) of them on a screen. Additionally, oscilloscopes perform measurements on the signals, and also display these on the screen.

- While oscilloscopes were once simple analogue devices involving little software, modern oscilloscopes rely primarily on digital technology and have quite complex software. It is not uncommon for a modern oscilloscope to perform dozens of measurements, supply megabytes of internal storage, interface to a network of workstations and other instruments, and provide sophisticated user interface including a touch panel screen with menus, built-in help facilities, and color displays.

- Like many companies that have had to rely increasingly on software to support their products, Tektronix was faced with number of problems. First, there was little reuse across different oscilloscope products. Instead, different oscilloscopes were built by different product divisions, each with their own development conventions, software organization, programming language,and development tools.

- Moreover, even within a single product division, each new oscilloscope typically required a redesign from scratch to accommodate changes in hardware capability and new requirements on the user interface. This problem was compounded by the fact that both hardware and interface requirements were changing increasingly rapidly.

- Furthermore, there was a perceived need to address "specialized markets". To do this it would have to be possible to tailor a general-purpose instrument, to a specific set of uses.

- Second, there were increasing performance problems because the software was not rapidly configurable within the instrument. This problem arises because an oscilloscope can be configured in many different modes, depending on the user's task. In old oscilloscopes reconfiguration was handled simply by loading different software to handle the new mode.

- But as the total size of software was increasing, this was leading to delays between a user's request for a new mode and a reconfigured instrument. The goal of the project was to develop an architectural framework for oscilloscopes that would address these problems. The result of that work was a domain-specific software architecture that formed the basis of the next generation of Tektronix oscilloscopes.

- Since then the framework has been extended and adapted to accommodate a broader class of system, while at the same time being better adapted to the specific needs of instrumentation software.

- This case study illustrates the issues involved in developing an architectural style for a real application domain. It underscores the fact that different architectural styles have different effects on the ability to solve a set of problems.

- It illustrates that architectural designs for industrial software must typically be adapted from pure forms to specialized styles that meet the needs of the specific domain. In this case, the final result depended greatly on the properties of pipe and filter architectures, but found ways to adapt that generic style so that it could also satisfy the performance needs of the product family.

UNIT 3

CONTENTS

Chapter 4: Quality

As we have seen in the Architecture Business Cycle, business considerations determine qualities that must be accommodated in a system's architecture. These qualities are over and above that of functionality, which is the basic statement of the system's capabilities, services, and behavior. Although functionality and other qualities are closely related, as you will see, functionality often takes not only the front seat in the development scheme but the only seat. This is short-sighted, however. Systems are frequently redesigned not because they are functionally deficient the replacements are often functionally identical. but because they are difficult to maintain, port, or scale, or are too slow, or have been compromised by network hackers. Architecture is the first stage in software creation in which quality requirements could be addressed. It is the mapping of a system's functionality onto software structures that determines the architecture's support for qualities.

Functionality and Architecture :

- Functionality and quality attributes are orthogonal. If functionality and quality attributes were not orthogonal, the choice of function would dictate the level of security or performance or availability or usability.

- Functionality is the ability of the system to do the work for which it was intended. A task requires that many or most of the system's elements work in a coordinated manner to complete the job, just as framers, electricians, plumbers, drywall hangers, painters, and finish carpenters all come together to cooperatively build a house.

- Therefore, if the elements have not been assigned the correct responsibilities or have not been endowed with the correct facilities for coordinating with other elements (so that, for instance, they know when it is time for them to begin their portion of the task), the system will be unable to offer the required functionality.

- Functionality may be achieved through the use of any of a number of possible structures. In fact, if functionality were the only requirement, the system could exist as a single monolithic module with no internal structure at all. Instead, it is decomposed into modules to make it understandable and to support a variety of other purposes.

- In this way, functionality is largely independent of structure. Software architecture constrains its allocation to structure when other quality attributes are important. For example, systems are frequently divided so that several people can cooperatively build them (which is, among other things, a time-to-market issue, though seldom stated this way). The interest of functionality is how it interacts with, and constrains, those other qualities.

Architecture and Quality Attributes :

Achieving quality attributes must be considered throughout design, implementation, and deployment. No quality attribute is entirely dependent on design, nor is it entirely dependent on implementation or deployment. Satisfactory results are a matter of getting the big picture (architecture) as well as the details (implementation) correct. For example:

- Usability involves both architectural and non architectural aspects. The non architectural aspects include making the user interface clear and easy to use. Should you provide a radio button or a check box? What screen layout is most intuitive?

What typeface is most clear? Although these details matter tremendously to the end user and influence usability, they are not architectural because they belong to the details of design. Whether a system provides the user with the ability to cancel operations, to undo operations, or to re-use data previously entered is architectural, however. These requirements involve the cooperation of multiple elements.

- Modifiability is determined by how functionality is divided (architectural) and by coding techniques within a module (non architectural). Thus, a system is modifiable if changes involve the fewest possible number of distinct elements. In spite of having the ideal architecture, however, it is always possible to make a system difficult to modify by writing obscure code.
- Performance involves both architectural and non architectural dependencies. It depends partially on how much communication is necessary among components (architectural), partially on what functionality has been allocated to each component (architectural), partially on how shared resources are allocated (architectural), partially on the choice of algorithms to implement selected functionality (non architectural), and partially on how these algorithms are coded (non architectural).

The message of this is twofold:

Architecture is critical to the realization of many qualities of interest in a system, and these qualities should be designed in and can be evaluated at the architectural level.

Architecture, by itself, is unable to achieve qualities. It provides the foundation for achieving quality, but this foundation will be to no avail if attention is not paid to the details.

- Within complex systems, quality attributes can never be achieved in isolation. The achievement of any one will have an effect, sometimes positive and sometimes negative, on the achievement of others. For example, security and reliability often exist in a state of mutual tension:

- The most secure system has the fewest points of failure typically a security kernel. The most reliable system has the most points of failure typically a set of redundant processes or processors where the failure of any one will not cause the system to fail. Another example of the tension between quality attributes is that almost every quality attribute negatively affects performance. Take portability. The main technique for achieving portable software is to isolate system dependencies, which introduces overhead into the system's execution, typically as process or procedure boundaries, and this hurts performance.

Following are the three classes:

1. Qualities of the system. We will focus on availability, modifiability, performance, security, testability, and usability.
2. Business qualities (such as time to market) that are affected by the architecture.
3. Qualities, such as conceptual integrity, that are about the architecture itself although they indirectly affect other qualities, such as modifiability

System Quality Attributes :

System quality attributes have been of interest to the software community at least since the 1970s. There are a variety of published taxonomies and definitions, and many of them have their own research and practitioner communities. From an architect's perspective, there are three problems with previous discussions of system quality attributes:

The definitions provided for an attribute are not operational. It is meaningless to say that a system will be modifiable. Every system is modifiable with respect to one set of changes and not modifiable with respect to another. The other attributes are similar.

A focus of discussion is often on which quality a particular aspect belongs to. Is a system failure an aspect of availability, an aspect of security, or an aspect of usability? All three attribute communities would claim ownership of a system failure.

Each attribute community has developed its own vocabulary. The performance community has "events" arriving at a system, the security community has "attacks" arriving at a system, the availability community has "failures" of a system, and the usability community has "user input." All of these may actually refer to the same occurrence, but are described using different terms.

A solution to the first two of these problems (non operational definitions and overlapping attribute concerns) is to use quality attribute scenarios as a means of characterizing quality attributes. A solution to the third problem is to provide a brief discussion of each attribute concentrating on its underlying concerns to illustrate the concepts that are fundamental to that attribute community.

QUALITY ATTRIBUTE SCENARIOS

A quality attribute scenario is a quality-attribute-specific requirement. It consists of six parts.

Source of stimulus. This is some entity (a human, a computer system, or any other actuator) that generated the stimulus.

Stimulus. The stimulus is a condition that needs to be considered when it arrives at a system.

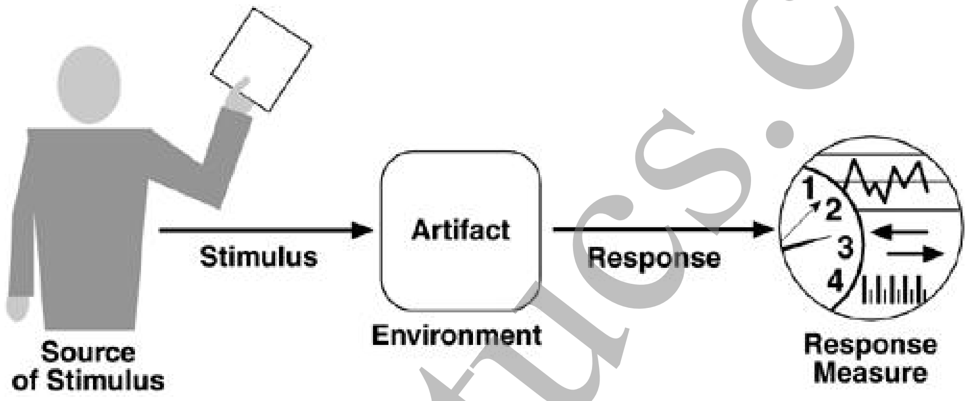
Environment. The stimulus occurs within certain conditions. The system may be in an overload condition or may be running when the stimulus occurs, or some other condition may be true.

Artifact. Some artifact is stimulated. This may be the whole system or some pieces of it.

Response. The response is the activity undertaken after the arrival of the stimulus.

Response measure. When the response occurs, it should be measurable in some fashion so that the requirement can be tested.

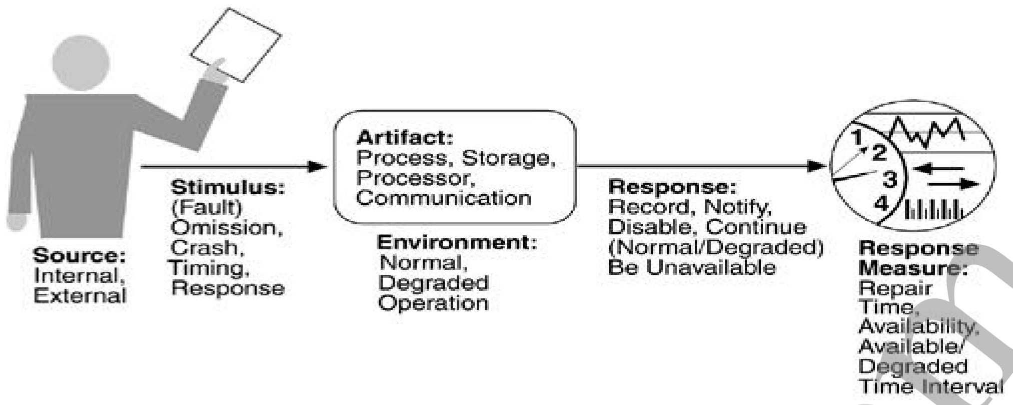
Figure 4.1 shows the parts of a quality attribute scenario.



Availability Scenario

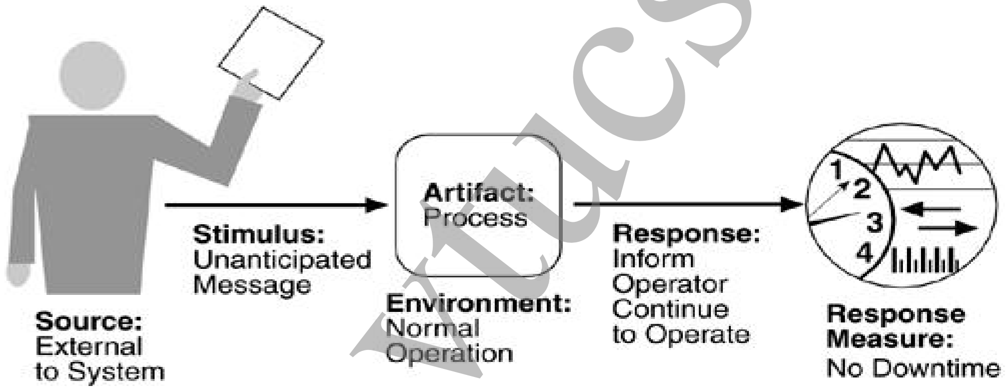
A general scenario for the quality attribute of availability, for example, is shown in Figure 4.2. Its six parts are shown, indicating the range of values they can take. From this we can derive concrete, system-specific, scenarios. Not every system-specific scenario has all of the six parts. The parts that are necessary are the result of the application of the scenario and the types of testing that will be performed to determine whether the scenario has been achieved.

figure 4.2. Availability general scenarios


Source:
Internal, External
Stimulus:
(Fault) Omission, Crash, Timing, Response
Artifact:
Process, Storage, Processor, Communication
Environment:
Normal, Degraded Operation
Response:
Record, Notify, Disable, Continue (Normal/Degraded) Be Unavailable
Response Measure:
Repair Time, Availability, Available/ Degraded Time Interval

An example availability scenario, derived from the general scenario of Figure 4.2 by instantiating each of the parts, is "An unanticipated external message is received by a process during normal operation. The process informs the operator of the receipt of the message and continues to operate with no downtime." Figure 4.3 shows the pieces of this derived scenario.

Figure 4.3. Sample availability scenario



- The source of the stimulus is important since differing responses may be required depending on what it is. For example, a request from a trusted source may be treated differently from a request from an untrusted source in a security scenario.

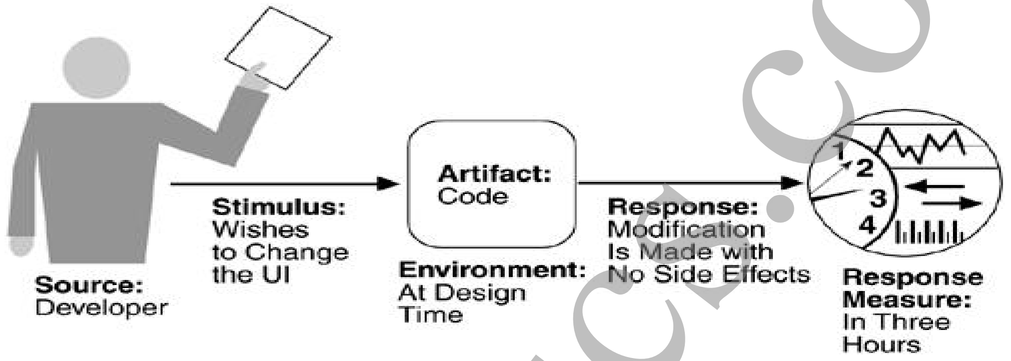
- The environment may also affect the response, in that an event arriving at a system may be treated differently if the system is already overloaded. The artifact that is stimulated is less important as a requirement. It is almost always the system, and we explicitly call it out for two reasons.

- First, many requirements make assumptions about the internals of the system (e.g., "a Web server within the system fails"). Second, when we utilize scenarios within an evaluation or design method, we refine the scenario artifact to be quite explicit about the portion of the system being stimulated. Finally, being explicit about the value of the response is important so that quality attribute requirements are made explicit. Thus, we include the response measure as a portion of the scenario.

Modifiability Scenario

A sample modifiability scenario is "A developer wishes to change the user interface to make a screen's background color blue. This change will be made to the code at design time. It will take less than three hours to make and test the change and no side effect changes will occur in the behavior." Figure 4.4 illustrates this sample scenario (omitting a few minor details for brevity).

Figure 4.4. Sample modifiability scenario


Source: Developer
Stimulus: Wishes to Change the UI
Artifact: Code
Environment: At Design Time
Response: Modification Is Made with No Side Effects
Response Measure: In Three Hours

A collection of concrete scenarios can be used as the quality attribute requirements for a system. Each scenario is concrete enough to be meaningful to the architect, and the details of the response are meaningful enough so that it is possible to test whether the system has achieved the response. When eliciting requirements, we typically organize our discussion of general scenarios by quality attributes; if the same scenario is generated by two different attributes, one can be eliminated.

<u>Quality Attribute Scenarios in Practice :</u>

- General scenarios provide a framework for generating a large number of generic, system-independent, quality-attribute-specific scenarios. Each is potentially but not necessarily relevant to the system you are concerned with. To make the general scenarios useful for a particular system, you must make them system specific.

- Making a general scenario system specific means translating it into concrete terms for the particular system. Thus, a general scenario is "A request arrives for a change in functionality, and the change must be made at a particular time within the development process within a specified period."

- A system-specific version might be "A request arrives to add support for a new browser to a Web-based system, and the change must be made within two weeks." Furthermore, a single general scenario may have many system- specific versions. The same system that has to support a new browser may also have to support a new media type.

- We now discuss the six most common and important system quality attributes, with the twin goals of identifying the concepts used by the attribute community and providing a way to generate general scenarios for that attribute.

AVAILABILITY

- Availability is concerned with system failure and its associated consequences. A system failure occurs when the system no longer delivers a service consistent with its specification. Such a failure is observable by the system's users either humans or other systems. An example of an availability general scenario appeared in Figure 4.3.

- Among the areas of concern are how system failure is detected, how frequently system failure may occur, what happens when a failure occurs, how long a system is allowed to be out of operation, when failures may occur safely, how failures can be prevented, and what kinds of notifications are required when a failure occurs.

- We need to differentiate between failures and faults. A fault may become a failure if not corrected or masked. That is, a failure is observable by the system's user and a fault is not. When a fault does become observable, it becomes a failure. For example, a fault can be choosing the wrong algorithm for a computation, resulting in a miscalculation that causes the system to fail.

- Once a system fails, an important related concept becomes the time it takes to repair it. Since a system failure is observable by users, the time to repair is the time until the failure is no longer observable. This may be a brief delay in the response time or it may be the time it takes someone to fly to a remote location in the mountains of Peru to repair a piece of mining machinery

The availability of a system is the probability that it will be operational when it is needed. This is typically defined as

$$\alpha = \frac{\text{mean time to failure}}{\text{mean time to failure} + \text{mean time to repair}}$$

From this come terms like 99.9% availability, or a 0.1% probability that the system will not be operational when needed.

Scheduled downtimes (i.e., out of service) are not usually considered when calculating availability, since the system is "not needed" by definition. This leads to situations where the system is down and users are waiting for it, but the downtime is scheduled and so is not counted against any availability requirements.

Availability General Scenarios

From these considerations we can see the portions of an availability scenario, shown in Figure 4.2.

Source of stimulus. We differentiate between internal and external indications of faults or failure since the desired system response may be different. In our example, the unexpected message arrives from outside the system.

Stimulus. A fault of one of the following classes occurs.

omission. A component fails to respond to an input.

crash. The component repeatedly suffers omission faults.

timing. A component responds but the response is early or late.

response. A component responds with an incorrect value.

In Figure 4.3, the stimulus is that an unanticipated message arrives. This is an example of a timing fault. The component that generated the message did so at a different time than expected.

Artifact. This specifies the resource that is required to be highly available, such as a processor, communication channel, process, or storage.

Environment. The state of the system when the fault or failure occurs may also affect the desired system response. For example, if the system has already seen some faults and is operating in other than normal mode, it may be desirable to shut it down totally. However, if this is the first fault observed, some degradation of response time or function may be preferred. In our example, the system is operating normally.

Response. There are a number of possible reactions to a system failure. These include logging the failure, notifying selected users or other systems, switching to a degraded mode with either less capacity or less function, shutting down external systems, or becoming unavailable during repair. In our example, the system should notify the operator of the unexpected message and continue to operate normally.

Response measure. The response measure can specify an availability percentage, or it can specify a time to repair, times during which the system must be available, or the duration for which the system must be available. In Figure 4.3, there is no downtime as a result of the unexpected message.

Table 4.1 presents the possible values for each portion of an availability scenario.

Table 4.1. Availability General Scenario Generation

Portion of Scenario	**Possible Values**
Source	Internal to the system; external to the system
Stimulus	Fault: omission, crash, timing, response
Artifact	System's processors, communication channels, persistent storage, processes
Environment	Normal operation; degraded mode (i.e., fewer features, a fall back solution)
Response	System should detect event and do one or more of the following: record notify appropriate parties, including the user and other systems disable sources of events that cause fault or failure according to defined rules be unavailable for a prespecified interval, where interval depends on criticality of system continue to operate in normal or degraded mode
Response Measure	Time interval when the system must be available

MODIFIABILITY

Modifiability is about the cost of change. It brings up two concerns.

What can change (the artifact)? A change can occur to any aspect of a system, most commonly the functions that the system computes, the platform the system exists on (the hardware, operating system, middleware, etc.), the environment within which the system operates (the systems with which it must interoperate, the protocols it uses to communicate with the rest of the world, etc.)

the qualities the system exhibits (its performance, its reliability, and even its future modifications), and its capacity (number of users supported, number of simultaneous operations, etc.). Some portions of the system, such as the user interface or the platform, are sufficiently distinguished and subject to change that we consider them separately. The category of platform changes is also called portability. Those changes may be to add, delete, or modify any one of these aspects.

When is the change made and who makes it (the environment)? Most commonly in the past, a change was made to source code. That is, a developer had to make the change, which was tested and then deployed in a new release. Now, however, the question of when a change is made is intertwined with the question of who makes it. An end user changing the screen saver is clearly making a change to one of the aspects of the system.

Equally clear, it is not in the same category as changing the system so that it can be used over the Web rather than on a single machine. Changes can be made to the implementation (by modifying the source code), during compile (using compile-time switches), during build (by choice of libraries), during configuration setup (by a range of techniques, including parameter setting) or during execution (by parameter setting). A change can also be made by a developer, an end user, or a system administrator.

Once a change has been specified, the new implementation must be designed, implemented, tested, and deployed. All of these actions take time and money, both of which can be measured.

Modifiability General Scenarios

From these considerations we can see the portions of the modifiability general scenarios. Figure 4.4 gives an example: "A developer wishes to change the user interface. This change will be made to the code at design time, it will take less than three hours to make and test the change, and no side-effect changes will occur in the behavior."

- **Source of stimulus**. This portion specifies who makes the changes? the developer, a system administrator, or an end user. Clearly, there must be machinery in place to allow the system administrator or end user to modify a system, but this is a common occurrence. In Figure 4.4, the modification is to be made by the developer.

- **Stimulus**. This portion specifies the changes to be made. A change can be the addition of a function, the modification of an existing function, or the deletion of a function. It can also be made to the qualities of the system making it more responsive, increasing its availability, and so forth. The capacity of the system may also change. Increasing the number of simultaneous users is a frequent requirement. In our example, the stimulus is a request to make a modification, which can be to the function, quality, or capacity.

  Variation is a concept associated with software product lines .When considering variation, a factor is the number of times a given variation must be specified. One that must be made frequently will impose a more stringent requirement on the response measures than one that is made only sporadically.

- **Artifact**. This portion specifies what is to be changed? the functionality of a system, its platform, its user interface, its environment, or another system with which it interoperates. In Figure 4.4, the modification is to the user interface.
- **Environment**. This portion specifies when the change can be made, design time, compile time, build time, initiation time, or runtime. In our example, the modification is to occur at design time.
- **Response**. Whoever makes the change must understand how to make it, and then make it, test it and deploy it. In our example, the modification is made with no side effects.
- **Response measure**. All of the possible responses take time and cost money, and so time and cost are the most desirable measures. Time is not always possible to predict, however, and so less ideal measures are frequently used, such as the extent of the change (number of modules affected). In our example, the time to perform the modification should be less than three hours.

Table 4.2 presents the possible values for each portion of a modifiability scenario.

Table 4.2. Modifiability General Scenario Generation

Portion of Scenario	Possible Values
Source	End user, developer, system administrator
Stimulus	Wishes to add/delete/modify/vary functionality, quality attribute, capacity
Artifact	System user interface, platform, environment; system that interoperates with target system

Environment	At runtime, compile time, build time, design time
Response	Locates places in architecture to be modified; makes modification without affecting other functionality; tests modification; deploys modification
Response Measure	Cost in terms of number of elements affected, effort, money; extent to which this affects other functions or quality attributes

PERFORMANCE

- Performance is about timing. Events (interrupts, messages, requests from users, or the passage of time) occur, and the system must respond to them. There are a variety of characterizations of event arrival and the response but basically performance is concerned with how long it takes the system to respond when an event occurs.

- One of the things that make performance complicated is the number of event sources and arrival patterns. Events can arrive from user requests, from other systems, or from within the system. A Web-based financial services system gets events from its users (possibly numbering in the tens or hundreds of thousands). An engine control system gets its requests from the passage of time and must control both the firing of the ignition when a cylinder is in the correct position and the mixture of the fuel to maximize power and minimize pollution.

- For the Web-based financial system, the response might be the number of transactions that can be processed in a minute. For the engine control system, the response might be the variation in the firing time. In each case, the pattern of events arriving and the pattern of responses can be characterized, and this characterization forms the language with which to construct general performance scenarios.

- A performance scenario begins with a request for some service arriving at the system. Satisfying the request requires resources to be consumed. While this is happening the system may be simultaneously servicing other requests.

- An arrival pattern for events may be characterized as either periodic or stochastic. For example, a periodic event may arrive every 10 milliseconds. Periodic event arrival is most often seen in real-time systems. Stochastic arrival means that events arrive according to some probabilistic distribution. Events can also arrive sporadically, that is, according to a pattern not capturable by either periodic or stochastic characterizations.

- Multiple users or other loading factors can be modeled by varying the arrival pattern for events. In other words, from the point of view of system performance, it does not matter whether one user submits 20 requests in a period of time or whether two users each submit 10. What matters is the arrival pattern at the server and dependencies within the requests.

- The response of the system to a stimulus can be characterized by latency (the time between the arrival of the stimulus and the system's response to it), deadlines in processing (in the engine controller, for example, the fuel should ignite when the cylinder is in a particular position, thus introducing a processing deadline)

- the throughput of the system (e.g., the number of transactions the system can process in a second), the jitter of the response (the variation in latency), the number of events not processed because the system was too busy to respond, and

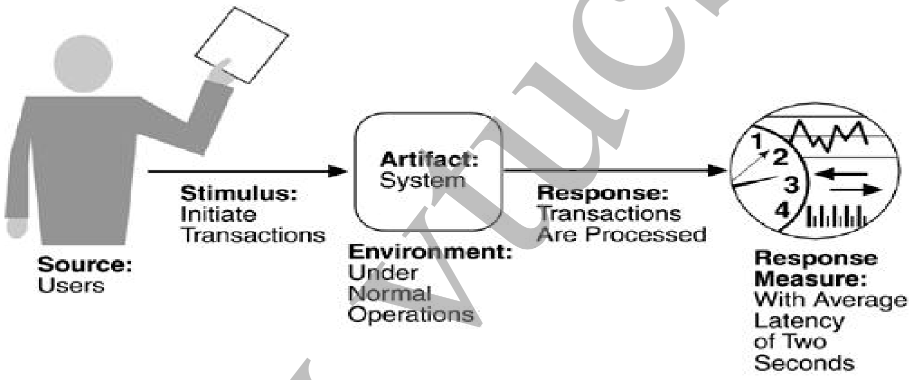
the data that was lost because the system was too busy.

Notice that this formulation does not consider whether the system is networked or standalone. Nor does it (yet) consider the configuration of the system or the consumption of resources.

Performance General Scenarios

From these considerations we can see the portions of the performance general scenario, an example of which is shown in Figure 4.5: "Users initiate 1,000 transactions per minute stochastically under normal operations, and these transactions are processed with an average latency of two seconds."

Figure 4.5. Sample performance scenario



Source of stimulus. The stimuli arrive either from external (possibly multiple) or internal sources. In our example, the source of the stimulus is a collection of users.

Stimulus. The stimuli are the event arrivals. The arrival pattern can be characterized as periodic, stochastic, or sporadic. In our example, the stimulus is the stochastic initiation of 1,000 transactions per minute.

Artifact. The artifact is always the system's services, as it is in our example. Environment.

The system can be in various operational modes, such as normal, emergency, or overload. In our example, the system is in normal mode.

Response. The system must process the arriving events. This may cause a change in the system environment (e.g., from normal to overload mode). In our example, the transactions are processed.

Response measure. The response measures are the time it takes to process the arriving events, the variation in this time (jitter), the number of events that can be processed within a particular time interval (throughput), or a characterization of the events that cannot be processed (miss rate, data loss). In our example, the transactions should be processed with an average latency of two seconds.

SECURITY

Security is a measure of the system's ability to resist unauthorized usage while still providing its services to legitimate users. An attempt to breach security is called an attack and can take a number of forms. It may be an unauthorized attempt to access data or services or to modify data, or it may be intended to deny services to legitimate users.

Some security experts use "threat" interchangeably with "attack."

Attacks, often occasions for wide media coverage, may range from theft of money by electronic transfer to modification of sensitive data, from theft of credit card numbers to destruction of files on computer systems, or to denial-of-service attacks carried out by worms or viruses. Still, the elements of a security general scenario are the same as the elements of our other general scenarios a stimulus and its source, an environment, the target under attack, the desired response of the system, and the measure of this response.

Security can be characterized as a system providing non repudiation, confidentiality, integrity, assurance, availability, and auditing. For each term, we provide a definition and an example.

- Non repudiation is the property that a transaction (access to or modification of data or services) cannot be denied by any of the parties to it. This means you cannot deny that you ordered that item over the Internet if, in fact, you did.
- Confidentiality is the property that data or services are protected from unauthorized access. This means that a hacker cannot access your income tax returns on a government computer.
- Integrity is the property that data or services are being delivered as intended. This means that your grade has not been changed since your instructor assigned it.
- Assurance is the property that the parties to a transaction are who they purport to be. This means that, when a customer sends a credit card number to an Internet merchant, the merchant is who the customer thinks they are. Availability is the property that the system will be available for legitimate use.
- Auditing is the property that the system tracks activities within it at levels

sufficient to reconstruct them. This means that, if you transfer money out of one account to another account, in Switzerland, the system will maintain a record of that transfer.

Each of these security categories gives rise to a collection of general scenarios.

Security General Scenarios

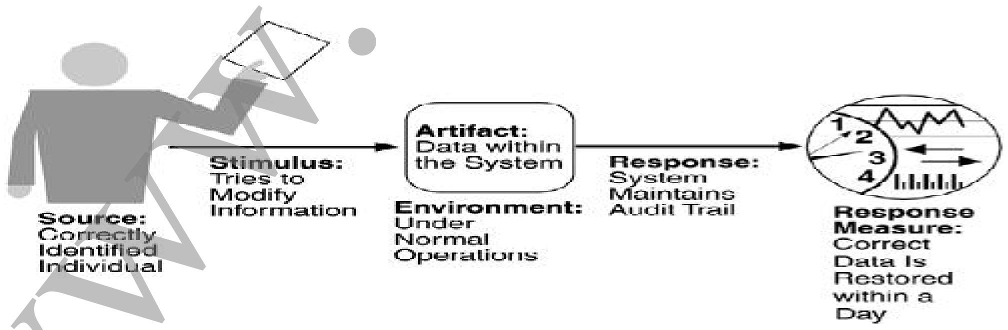
The portions of a security general scenario are given below. Figure 4.6 presents an example. A correctly identified individual tries to modify system data from an external site; system maintains an audit trail and the correct data is restored within one day.

Source of stimulus. The source of the attack may be either a human or another system. It may have been previously identified (either correctly or incorrectly) or may be currently unknown.

If the source of the attack is highly motivated (say politically motivated), then defensive measures such as "We know who you are and will prosecute you" are not likely to be effective; in such cases the motivation of the user may be important. If the source has access to vast resources (such as a government), then defensive measures are very difficult. The attack itself is unauthorized access, modification, or denial of service.

The difficulty with security is allowing access to legitimate users and determining legitimacy. If the only goal were to prevent access to a system, disallowing all access would be an effective defensive measure.

Figure 4.6. Sample security scenario


Source: Correctly Identified Individual
Stimulus: Tries to Modify Information
Artifact: Data within the System
Environment: Under Normal Operations
Response: System Maintains Audit Trail
Response Measure: Correct Data Is Restored within a Day
1
2
3
4

Stimulus. The stimulus is an attack or an attempt to break security. We characterize this as an unauthorized person or system trying to display information, change and/or delete information, access services of the system, or reduce availability of system services. In Figure 4.6, the stimulus is an attempt to modify data.

Artifact. The target of the attack can be either the services of the system or the data within it. In our example, the target is data within the system.

Environment. The attack can come when the system is either online or offline, either connected to or disconnected from a network, either behind a firewall or open to the network.

Response. Using services without authorization or preventing legitimate users from using services is a different goal from seeing sensitive data or modifying it. Thus, the system must authorize legitimate users and grant them access to data and services, at the same time rejecting unauthorized users, denying them access, and reporting unauthorized access.

Response measure. Measures of a system's response include the difficulty of mounting various attacks and the difficulty of recovering from and surviving attacks. In our example, the audit trail allows the accounts from which money was embezzled to be restored to their original state. Of course, the embezzler still has the money, and he must be tracked down and the money regained, but this is outside of the realm of the computer system.

Table 4.4 shows the security general scenario generation table.

Table 4.4. Security General Scenario Generation

Portion of Scenario	Possible Values
Source	Individual or system that is correctly identified, identified incorrectly, of unknown identity who is internal/external, authorized/not authorized with access to limited resources, vast resources
Stimulus	Tries to display data, change/delete data, access system services, reduce availability to system services
Artifact	System services; data within system
Environment	Either online or offline, connected or disconnected, firewalled or open
Response	Authenticates user; hides identity of the user; blocks access to data and/or services; allows access to data and/or services; grants or

Table 4.4. Security General Scenario Generation

Portion of Scenario

	Possible Values
Response Measure	withdraws permission to access data and/or services; records access/modifications or attempts to access/modify data/services by identity; stores data in an unreadable format; recognizes an unexplainable high demand for services, and informs a user or another system, and restricts availability of services
	Time/effort/resources required to circumvent security measures with probability of success; probability of detecting attack; probability of identifying individual responsible for attack or access/modification of data and/or services; percentage of services still available under denial-of-services attack; restore data/services; extent to which data/services damaged and/or legitimate access denied

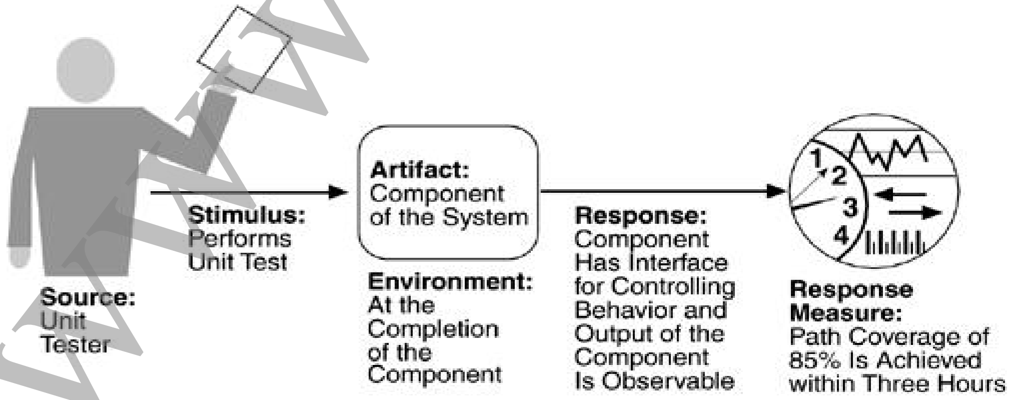
TESTABILITY

- Software testability refers to the ease with which software can be made to demonstrate its faults through (typically execution-based) testing. At least 40% of the cost of developing well-engineered systems is taken up by testing. If the software architect can reduce this cost, the payoff is large.
- In particular, testability refers to the probability, assuming that the software has at least one fault, that it will fail on its next test execution. Of course, calculating this probability is not easy and, when we get to response measures, other measures will be used.
- For a system to be properly testable, it must be possible to control each component's internal state and inputs and then to observe its outputs. Frequently this is done through use of a test harness, specialized software designed to exercise the software under test. This may be as simple as a playback capability for data recorded across various interfaces or as complicated as a testing chamber for an engine.
- Testing is done by various developers, testers, verifiers, or users and is the last step of various parts of the software life cycle. Portions of the code, the design, or the complete system may be tested. The response measures for testability deal with how effective the tests are in discovering faults and how long it takes to perform the tests to some desired level of coverage.

Testability General Scenarios

Figure 4.7 is an example of a testability scenario concerning the performance of a unit test: A unit tester performs a unit test on a completed system component that provides an interface for controlling its behavior and observing its output; 85% path coverage is achieved within three hours.

Figure 4.7. Sample testability scenario


Source: Unit Tester
Stimulus: Performs Unit Test
Artifact: Component of the System
Environment: At the Completion of the Component
Response: Component Has Interface for Controlling Behavior and Output of the Component Is Observable
1
2
3
4
Response Measure: Path Coverage of 85% Is Achieved within Three Hours

Source of stimulus. The testing is performed by unit testers, integration testers, system testers, or the client. A test of the design may be performed by other developers or by an external group. In our example, the testing is performed by a tester.

Stimulus. The stimulus for the testing is that a milestone in the development process is met. This might be the completion of an analysis or design increment, the completion of a coding increment such as a class, the completed integration of a subsystem, or the completion of the whole system. In our example, the testing is triggered by the completion of a unit of code.

Artifact. A design, a piece of code, or the whole system is the artifact being tested. In our example, a unit of code is to be tested.

Environment. The test can happen at design time, at development time, at compile time, or at deployment time. In Figure 4.7, the test occurs during development.

Response. Since testability is related to observability and controllability, the desired response is that the system can be controlled to perform the desired tests and that the response to each test can be observed. In our example, the unit can be controlled and its responses captured.

Response measure. Response measures are the percentage of statements that have been executed in some test, the length of the longest test chain (a measure of the difficulty of performing the tests), and estimates of the probability of finding additional faults. In Figure 4.7, the measurement is percentage coverage of executable statements.

Table 4.5 gives the testability general scenario generation table.

Table 4.5. Testability General Scenario Generation

Portion of Scenario	Possible Values

Source	Unit developer Increment integrator System verifier Client acceptance tester System user
Stimulus	Analysis, architecture, design, class, subsystem integration completed; system delivered
Artifact	Piece of design, piece of code, complete application
Environment	At design time, at development time, at compile time, at deployment time
Response	Provides access to state values; provides computed values; prepares test environment
Response Measure	Percent executable statements executed Probability of failure if fault exists,Time to perform tests, Length of longest dependency ,hain in a test, Length of time to prepare test environment

USABILITY

Usability is concerned with how easy it is for the user to accomplish a desired task and the kind of user support the system provides. It can be broken down into the following areas:

Learning system features. If the user is unfamiliar with a particular system or a particular aspect of it, what can the system do to make the task of learning easier?

Using a system efficiently. What can the system do to make the user more efficient in its operation?

Minimizing the impact of errors. What can the system do so that a user error has minimal impact?

Adapting the system to user needs. How can the user (or the system itself) adapt to make the user's task easier?

Increasing confidence and satisfaction. What does the system do to give the user confidence that the correct action is being taken?

In the last five years, our understanding of the relation between usability and software architecture has deepened (see the sidebar Usability Mea Culpa). The normal development process detects usability problems through building prototypes and user testing. The later a problem is discovered and the deeper into the architecture its repair must be made, the more the repair is threatened by time and budget pressures. In our scenarios we focus on aspects of usability that have a major impact on the architecture. Consequently, these scenarios must be correct prior to the architectural design so that they will not be discovered during user testing or prototyping.

Usability General Scenarios

Figure 4.8 gives an example of a usability scenario: A user, wanting to minimize the impact of an error, wishes to cancel a system operation at runtime; cancellation takes place in less than one second. The portions of the usability general scenarios are:

Source of stimulus. The end user is always the source of the stimulus.

Stimulus. The stimulus is that the end user wishes to use a system efficiently, learn to use the system, minimize the impact of errors, adapt the system, or feel comfortable with the system. In our example, the user wishes to cancel an operation, which is an example of minimizing the impact of errors.

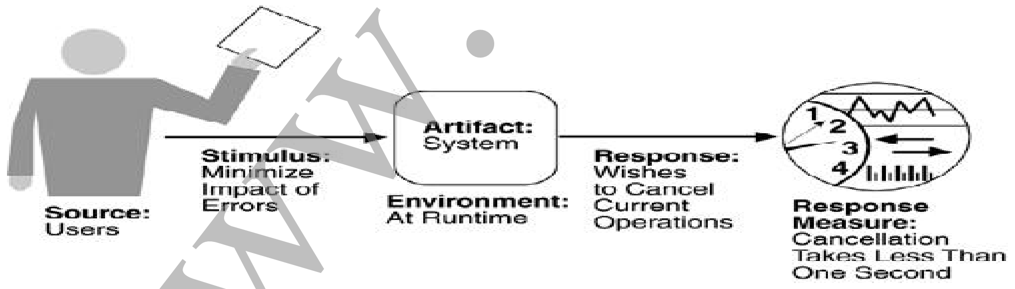
Artifact. The artifact is always the system.

Environment. The user actions with which usability is concerned always occur at runtime or at system configuration time. Any action that occurs before then is performed by developers and, although a user may also be the developer, we distinguish between these roles even if performed by the same person. In Figure 4.8, the cancellation occurs at runtime.

Response. The system should either provide the user with the features needed or anticipate the user's needs. In our example, the cancellation occurs as the user wishes and the system is restored to its prior state.

Response measure. The response is measured by task time, number of errors, number of problems solved, user satisfaction, gain of user knowledge, ratio of successful operations to total operations, or amount of time/data lost when an error occurs. In Figure 4.8, the cancellation should occur in less than one second.

Figure 4.8. Sample usability scenario



The usability general scenario generation table is given in Table 4.6.

Table 4.6. Usability General Scenario Generation

Portion of Scenario	Possible Values
Source	End user
Stimulus	At runtime or configure time System provides one or more of the following responses: to support "learn system features"
Response	Wants to learn system features; efficiently; minimize impact of errors; adapt system; feel comfortable
Artifact	System help system is sensitive to context; interface is familiar to user;interface is usable in an unfamiliar contextto support "use system efficiently

Table 4.7. Quality Attribute Stimuli

Quality Attribute	Stimulus
Availability	Unexpected event, nonoccurrence of expected event
Modifiability	Request to add/delete/change/vary functionality, platform, quality attribute, or capacity
Performance	Periodic, stochastic, or sporadic
Security	Tries to display, modify, change/delete information, access, or reduce availability to system services
Testability	Completion of phase of system development

Table 4.7 gives the stimuli possible for each of the attributes and shows a number of different concepts. Some stimuli occur during runtime and others occur before. The problem for the architect is to understand which of these stimuli represent the same occurrence, which are aggregates of other stimuli, and which are independent.

Once the relations are clear, the architect can communicate them to the various stakeholders using language that each comprehends. We cannot give the relations among stimuli in a general way because they depend partially on environment. A performance event may be atomic or may be an aggregate of other lower-level occurrences; a failure may be a single performance event or an aggregate.

For example, it may occur with an exchange of several messages between a client and a server (culminating in an unexpected message), each of which is an atomic event from a performance perspective.

Business Qualities :

In addition to the qualities that apply directly to a system, a number of business quality goals frequently shape a system's architecture. These goals center on cost, schedule, market, and marketing considerations. Each suffers from the same ambiguity that system qualities have, and they need to be made specific with scenarios in order to make them suitable for influencing the design process and to be made testable. Here, we present them as generalities, however, and leave the generation of scenarios as one of our discussion questions.

- **Time to market**. If there is competitive pressure or a short window of opportunity for a system or product, development time becomes important. This in turn leads to pressure to buy or otherwise re-use existing elements. Time to market is often reduced by using prebuilt elements such as commercial off-the- shelf (COTS) products or elements re-used from previous projects. The ability to insert or deploy a subset of the system depends on the decomposition of the system into elements.

- **Cost and benefit**. The development effort will naturally have a budget that must not be exceeded. Different architectures will yield different development costs. For instance, an architecture that relies on technology (or expertise with a technology) not resident in the developing organization will be more expensive to realize than one that takes advantage of assets already inhouse. An architecture that is highly flexible will typically be more costly to build than one that is rigid (although it will be less costly to maintain and modify).

- **Projected lifetime of the system**. If the system is intended to have a long lifetime, modifiability, scalability, and portability become important. But building
in the additional infrastructure (such as a layer to support portability) will usually compromise time to market. On the other hand, a modifiable, extensible product is more likely to survive longer in the marketplace, extending its lifetime.

- **Targeted market**. For general-purpose (mass-market) software, the platforms on which a system runs as well as its feature set will determine the size of the potential market. Thus, portability and functionality are key to market share. Other qualities, such as performance, reliability, and usability also play a role. To attack a large market with a collection of related products, a product line approach should be considered in which a core of the system is common (frequently including provisions for portability) and around which layers of software of increasing specificity are constructed.

- **Rollout schedule**. If a product is to be introduced as base functionality with many features released later, the flexibility and customizability of the architecture are important. Particularly, the system must be constructed with ease of expansion and contraction in mind.

- **Integration with legacy systems**. If the new system has to integrate with existing systems, care must be taken to define appropriate integration mechanisms. This property is clearly of marketing importance but has substantial architectural implications. For example, the ability to integrate a legacy system with an HTTP server to make it accessible from the Web has been a marketing goal in many corporations over the past decade. The architectural constraints implied by this integration must be analyzed.

Architecture Qualities :

- In addition to qualities of the system and qualities related to the business environment in which the system is being developed, there are also qualities directly related to the architecture itself that are important to achieve.

- Conceptual integrity is the underlying theme or vision that unifies the design of the system at all levels. The architecture should do similar things in similar ways. Fred Brooks writes emphatically that a system's conceptual integrity is of overriding importance, and that systems without it fail:

- Correctness and completeness are essential for the architecture to allow for all of the system's requirements and runtime resource constraints to be met

- Buildability allows the system to be completed by the available team in a timely manner and to be open to certain changes as development progresses. It refers to the ease of constructing a desired system and is achieved architecturally by paying careful attention to the decomposition into modules, judiciously assigning of those modules to development teams, and limiting the dependencies between the modules (and hence the teams). The goal is to maximize the parallelism that can occur in development.

- Because buildability is usually measured in terms of cost and time, there is a relationship between it and various cost models. However, buildability is more complex than what is usually covered in cost models. A system is created from certain materials, and these materials are created using a variety of tools.

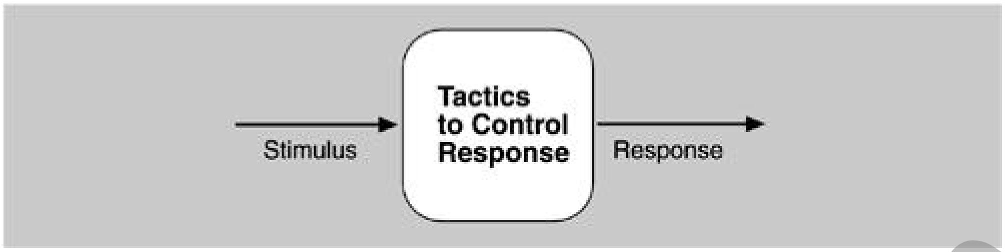
Chapter 5. Achieving Quality

Introducing Tactics :

What is it that imparts portability to one design, high performance to another, and integrability to a third? The achievement of these qualities relies on fundamental design decisions. We will examine these design decisions, which we call tactics. A tactic is a design decision that influences the control of a quality attribute response.

A system design consists of a collection of decisions. Some of these decisions help control the quality attribute responses; others ensure achievement of system functionality. In this section, we discuss the quality attribute decisions known as tactics. We represent this relationship in Figure 5.1. The tactics are those that architects have been using for years, and we isolate and describe them. We are not inventing tactics here, just capturing what architects do in practice.

Figure 5.1. Tactics are intended to control responses to stimuli.



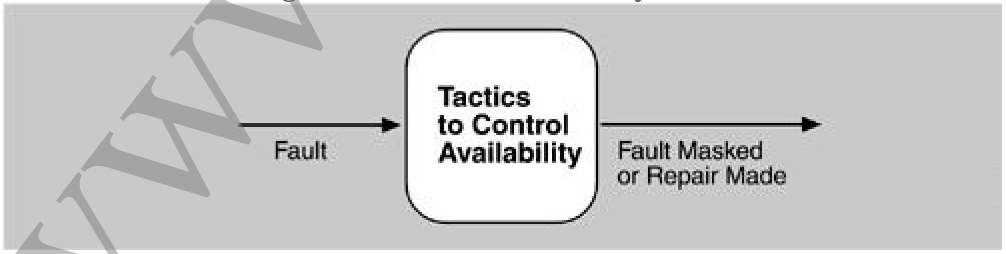
Each tactic is a design option for the architect. For example, one of the tactics introduces redundancy to increase the availability of a system. This is one option the architect has to increase availability, but not the only one. Usually achieving high availability through redundancy implies a concomitant need for synchronization (to ensure that the redundant copy can be used if the original fails). We see two immediate ramifications of this example.

1. **Tactics can refine other tactics**. We identified redundancy as a tactic. As such, it can be refined into redundancy of data (in a database system) or redundancy of computation (in an embedded control system). Both types are also tactics. There are further refinements that a designer can employ to make each type of redundancy more concrete. For each quality attribute that we discuss, we organize the tactics as a hierarchy.
2. **Patterns package tactics**. A pattern that supports availability will likely use both a redundancy tactic and a synchronization tactic. It will also likely use more concrete versions of these tactics. At the end of this section, we present an example of a pattern described in terms of its tactics.

Availability Tactics :

A failure occurs when the system no longer delivers a service that is consistent with its specification; this failure is observable by the system's users. A fault (or combination of faults) has the potential to cause a failure. Recall also that recovery or repair is an important aspect of availability. The tactics we discuss in this section will keep faults from becoming failures or at least bound the effects of the fault and make repair possible. We illustrate this in Figure 5.2.

Figure 5.2. Goal of availability tactics



Many of the tactics we discuss are available within standard execution environments such as operating systems, application servers, and database management systems. It is still important to understand the tactics used so that the effects of using a particular one can be considered during design and evaluation. All approaches to maintaining availability involve some type of redundancy, some type of health monitoring to detect a failure, and some type of recovery when a failure is detected. In some cases, the monitoring or recovery is automatic and in others it is manual.

FAULT DETECTION

Three widely used tactics for recognizing faults are ping/echo, heartbeat, and exceptions.

- **Ping/echo**. One component issues a ping and expects to receive back an echo, within a predefined time, from the component under scrutiny. This can be used within a group of components mutually responsible for one task. It can also used be used by clients to ensure that a server object and the communication path to the server are operating within the expected performance bounds. "Ping/echo" fault detectors can be organized in a hierarchy, in which a lowest-level detector pings the software processes with which it shares a processor, and the higher-level fault detectors ping lower-level ones. This uses less communications bandwidth than a remote fault detector that pings all processes.
- **Heartbeat (dead man timer).** In this case one component emits a heartbeat message periodically and another component listens for it. If the heartbeat fails, the originating component is assumed to have failed and a fault correction component is notified. The heartbeat can also carry data. For example, an automated teller machine can periodically send the log of the last transaction to a server. This message not only acts as a heartbeat but also carries data to be processed.

The ping/echo and heartbeat tactics operate among distinct processes, and the exception tactic operates within a single process. The exception handler will usually perform a semantic transformation of the fault into a form that can be processed.

FAULT RECOVERY

Fault recovery consists of preparing for recovery and making the system repair. Some preparation and repair tactics follow.

Voting. Processes running on redundant processors each take equivalent input and compute a simple output value that is sent to a voter. If the voter detects deviant behavior from a single processor, it fails it.

- The voting algorithm can be "majority rules" or "preferred component" or some other algorithm. This method is used to correct faulty operation of algorithms or failure of a processor and is often used in control systems. If all of the processors utilize the same algorithms, the redundancy detects only a processor fault and not an algorithm fault. Thus, if the consequence of a failure is extreme, such as potential loss of life, the redundant components can be diverse.

- One extreme of diversity is that the software for each redundant component is developed by different teams and executes on dissimilar platforms. Less extreme is to develop a single software component on dissimilar platforms.

- o Diversity is expensive to develop and maintain and is used only in exceptional circumstances, such as the control of surfaces on aircraft. It is usually used for control systems in which the outputs to the voter are straightforward and easy to classify as equivalent or deviant, the computations are cyclic, and all redundant components receive equivalent inputs from sensors.
- o Diversity has no downtime when a failure occurs since the voter continues to operate. Variations on this approach include the Simplex approach, which uses the results of a "preferred" component unless they deviate from those of a "trusted" component, to which it defers. Synchronization among the redundant components is automatic since they are all assumed to be computing on the same set of inputs in parallel.

Active redundancy (hot restart).

- All redundant components respond to events in parallel. Consequently, they are all in the same state. The response from only one component is used (usually the first to respond), and the rest are discarded. When a fault occurs, the downtime of systems using this tactic is usually milliseconds since the backup is current and the only time to recover is the switching time.

- Active redundancy is often used in a client/server configuration, such as database management systems, where quick responses are necessary even when a fault occurs. In a highly available distributed system, the redundancy may be in the communication paths. For example, it may be desirable to use a LAN with a number of parallel paths and place each redundant component in a separate path. In this case, a single bridge or path failure will not make all of the system's components unavailable.

- Synchronization is performed by ensuring that all messages to any redundant component are sent to all redundant components. If communication has a possibility of being lost (because of noisy or overloaded communication lines), a reliable transmission protocol can be used to recover. A reliable transmission protocol requires all recipients to acknowledge receipt together with some integrity indication such as a checksum.

- If the sender cannot verify that all recipients have received the message, it will resend the message to those components not acknowledging receipt. The resending of unreceived messages (possibly over different communication paths) continues until the sender marks the recipient as out of service.

Passive redundancy

- o One component (the primary) responds to events and informs the other components (the standbys) of state updates they must make. When a fault occurs, the system must first ensure that the backup state is sufficiently fresh before resuming services.

- This approach is also used in control systems, often when the inputs come over communication channels or from sensors and have to be switched from the primary to the backup on failure. This tactic depends on the standby components taking over reliably.

- Forcing switchovers periodically for example, once a day or once a week increases the availability of the system. Some database systems force a switch with storage of every new data item. The new data item is stored in a shadow page and the old page becomes a backup for recovery. In this case, the downtime can usually be limited to seconds.

- Synchronization is the responsibility of the primary component, which may use atomic broadcasts to the secondaries to guarantee synchronization.

Spare. A standby spare computing platform is configured to replace many different failed components. It must be rebooted to the appropriate software configuration and have its state initialized when a failure occurs.

Making a checkpoint of the system state to a persistent device periodically and logging all state changes to a persistent device allows for the spare to be set to the appropriate state. This is often used as the standby client workstation, where the user can move when a failure occurs. The downtime for this tactic is usually minutes.

There are tactics for repair that rely on component reintroduction. When a redundant component fails, it may be reintroduced after it has been corrected. Such tactics are shadow operation, state resynchronization, and rollback.

Shadow operation. A previously failed component may be run in "shadow mode" for a short time to make sure that it mimics the behavior of the working components before restoring it to service.

State resynchronization. The passive and active redundancy tactics require the component being restored to have its state upgraded before its return to service. The updating approach will depend on the downtime that can be sustained, the size of the update, and the number of messages required for the update. A single message containing the state is preferable, if possible. Incremental state upgrades, with periods of service between increments, lead to complicated software.

Checkpoint/rollback. A checkpoint is a recording of a consistent state created either periodically or in response to specific events. Sometimes a system fails in an unusual manner, with a detectably inconsistent state. In this case, the system should be restored using a previous checkpoint of a consistent state and a log of the transactions that occurred since the snapshot was taken.

FAULT PREVENTION

The following are some fault prevention tactics.

Removal from service. This tactic removes a component of the system from operation to undergo some activities to prevent anticipated failures. One example is rebooting a component to prevent memory leaks from causing a failure. If this removal from service is automatic, an architectural strategy can be designed to support it. If it is manual, the system must be designed to support it.

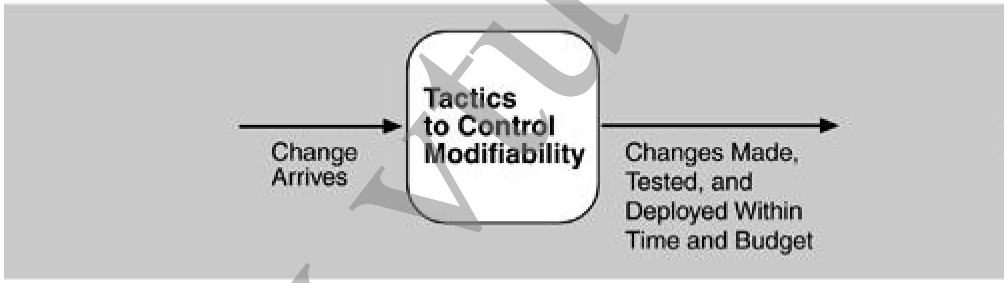
Transactions. A transaction is the bundling of several sequential steps such that the entire bundle can be undone at once. Transactions are used to prevent any data from being affected if one step in a process fails and also to prevent collisions among several simultaneous threads accessing the same data.

Process monitor. Once a fault in a process has been detected, a monitoring process can delete the nonperforming process and create a new instance of it, initialized to some appropriate state as in the spare tactic.

Modifiability Tactics :

Tactics to control modifiability have as their goal controlling the time and cost to implement, test, and deploy changes. Figure 5.4 shows this relationship.

Figure 5.4. Goal of modifiability tactics


Change Arrives
Tactics to Control Modifiability
Changes Made, Tested, and Deployed Within Time and Budget

We organize the tactics for modifiability in sets according to their goals. One set has as its goal reducing the number of modules that are directly affected by a change. We call this set "localize modifications." A second set has as its goal limiting modifications to the localized modules. We use this set of tactics to "prevent the ripple effect." Implicit in this distinction is that there are modules directly affected (those whose responsibilities are adjusted to accomplish the change) and modules indirectly affected by a change (those whose responsibilities remain unchanged but whose implementation must be changed to accommodate the directly affected modules). A third set of tactics has as its goal controlling deployment time and cost. We call this set "defer binding time."

LOCALIZE MODIFICATIONS

Although there is not necessarily a precise relationship between the number of modules affected by a set of changes and the cost of implementing those changes, restricting modifications to a small set of modules will generally reduce the cost. The goal of tactics in this set is to assign responsibilities to modules during design such that anticipated changes will be limited in scope. We identify five such tactics.

Maintain semantic coherence.

- Semantic coherence refers to the relationships among responsibilities in a module. The goal is to ensure that all of these responsibilities work together without excessive reliance on other modules. Achievement of this goal comes from choosing responsibilities that have semantic coherence.

- Coupling and cohesion metrics are an attempt to measure semantic coherence, but they are missing the context of a change. Instead, semantic coherence should be measured against a set of anticipated changes. One subtactic is to abstract common services. Providing common services through specialized modules is usually viewed as supporting re-use.

- This is correct, but abstracting common services also supports modifiability. If common services have been abstracted, modifications to them will need to be made only once rather than in each module where the services are used. Furthermore, modification to the modules using those services will not impact other users.

- This tactic, then, supports not only localizing modifications but also the prevention of ripple effects. Examples of abstracting common services are the use of application frameworks and the use of other middleware software.

- **Anticipate expected changes**.

  Considering the set of envisioned changes provides a way to evaluate a particular assignment of responsibilities. The basic question is "For each change, does the proposed decomposition limit the set of modules that need to be modified to accomplish it?"

  An associated question is "Do fundamentally different changes affect the same modules?" How is this different from semantic coherence? Assigning responsibilities based on semantic coherence assumes that expected changes will be semantically coherent.

  The tactic of anticipating expected changes does not concern itself with the coherence of a module's responsibilities but rather with minimizing the effects of the changes. In reality this tactic is difficult to use by itself since it is not possible to anticipate all changes. For that reason, it is usually used in conjunction with semantic coherence.

- **Generalize the module**. Making a module more general allows it to compute a broader range of functions based on input. The input can be thought of as defining a language for the module, which can be as simple as making constants input parameters or as complicated as implementing the module as an interpreter and making the input parameters be a program in the interpreter's language. The more general a module, the more likely that requested changes can be made by adjusting the input language rather than by modifying the module.

- **Limit possible options**. Modifications, especially within a product line may be far ranging and hence affect many modules. Restricting the possible options will reduce the effect of these modifications. For example, a variation point in a product line may be allowing for a change of processor. Restricting processor changes to members of the same family limits the possible options.

PREVENT RIPPLE EFFECTS

A ripple effect from a modification is the necessity of making changes to modules not directly affected by it. For instance, if module A is changed to accomplish a particular modification, then module B is changed only because of the change to module A. B has to be modified because it depends, in some sense, on A.

We begin our discussion of the ripple effect by discussing the various types of dependencies that one module can have on another. We identify eight types:

1. **Syntax of**

   - data. For B to compile (or execute) correctly, the type (or format) of the data that is produced by A and consumed by B must be consistent with the type (or format) of data assumed by B.

   - service. For B to compile and execute correctly, the signature of services provided by A and invoked by B must be consistent with the assumptions of B.

2. **Semantics of**

   - data. For B to execute correctly, the semantics of the data produced by A and consumed by B must be consistent with the assumptions of B.

   - service. For B to execute correctly, the semantics of the services produced by A and used by B must be consistent with the assumptions of B.

3. **Sequence of**

   - data. For B to execute correctly, it must receive the data produced by A in a fixed sequence. For example, a data packet's header must precede its body in order of reception (as opposed to protocols that have the sequence number built into the data).

   - control. For B to execute correctly, A must have executed previously within certain timing constraints. For example, A must have executed no longer than 5ms before B executes.

4. **Identity of an interface** of A. A may have multiple interfaces. For B to compile and execute correctly, the identity (name or handle) of the interface must be consistent with the assumptions of B.
5. **Location** of A (runtime). For B to execute correctly, the runtime location of A must be consistent with the assumptions of B. For example, B may assume that A is located in a different process on the same processor.
6. Quality of service/data provided by A. For B to execute correctly, some property involving the quality of the data or service provided by A must be consistent with B's assumptions. For example, data provided by a particular sensor must have a certain accuracy in order for the algorithms of B to work correctly.
7. Existence of A. For B to execute correctly, A must exist. For example, if B is requesting a service from an object A, and A does not exist and cannot be dynamically created, then B will not execute correctly.
8. Resource behavior of A. For B to execute correctly, the resource behavior of A must be consistent with B's assumptions. This can be either resource usage of A (A uses the same memory as B) or resource ownership (B reserves a resource that A believes it owns).

With this understanding of dependency types, we can now discuss tactics available to the architect for preventing the ripple effect for certain types.

- **Hide information**. Information hiding is the decomposition of the responsibilities for an entity (a system or some decomposition of a system) into smaller pieces and choosing which information to make private and which to make public. The public responsibilities are available through specified interfaces.

  The goal is to isolate changes within one module and prevent changes from propagating to others. This is the oldest technique for preventing changes from propagating. It is strongly related to "anticipate expected changes" because it uses those changes as the basis for decomposition.

- **Maintain existing interfaces**. If B depends on the name and signature of an interface of A, maintaining this interface and its syntax allows B to remain unchanged. Of course, this tactic will not necessarily work if B has a semantic dependency on A, since changes to the meaning of data and services are difficult to mask.

  Also, it is difficult to mask dependencies on quality of data or quality of service, resource usage, or resource ownership. Interface stability can also be achieved by separating the interface from the implementation. This allows the creation of abstract interfaces that mask variations. Variations can be embodied within the existing responsibilities, or they can be embodied by replacing one implementation of a module with another.

  Patterns that implement this tactic include

  - **adding interfaces**. Most programming languages allow multiple interfaces. Newly visible services or data can be made available through new interfaces, allowing existing interfaces to remain unchanged and provide the same signature.

- adding adapter. Add an adapter to A that wraps A and provides the signature of the original A.

- providing a stub A. If the modification calls for the deletion of A, then providing a stub for A will allow B to remain unchanged if B depends only on A's signature.

- **Restrict communication paths**. Restrict the modules with which a given module shares data. That is, reduce the number of modules that consume data produced by the given module and the number of modules that produce data consumed by it. This will reduce the ripple effect since data production/consumption introduces dependencies that cause ripples.

- **Use an intermediary**. If B has any type of dependency on A other than semantic, it is possible to insert an intermediary between B and A that manages activities associated with the dependency. All of these intermediaries go by different names, but we will discuss each in terms of the dependency types we have enumerated. As before, in the worst case, an intermediary cannot compensate for semantic changes. The intermediaries are

- data (syntax). Repositories (both blackboard and passive) act as intermediaries between the producer and consumer of data. The repositories can convert the syntax produced by A into that assumed by B. Some publish/subscribe patterns (those that have data flowing through a central component) can also convert the syntax into that assumed by B. The MVC and PAC patterns convert data in one formalism (input or output device) into another (that used by the model in MVC or the abstraction in PAC).

- service (syntax). The facade, bridge, mediator, strategy, proxy, and factory patterns all provide intermediaries that convert the syntax of a service from one form into another. Hence, they can all be used to prevent changes in A from propagating to B.

- identity of an interface of A. A broker pattern can be used to mask changes in the identity of an interface. If B depends on the identity of an interface of A and that identity changes, by adding that identity to the broker and having the broker make the connection to the new identity of A, B can remain unchanged.

- location of A (runtime). A name server enables the location of A to be changed without affecting B. A is responsible for registering its current location with the name server, and B retrieves that location from the name server.

- resource behavior of A or resource controlled by A. A resource manager is an intermediary that is responsible for resource allocation. Certain resource managers (e.g., those based on Rate Monotonic Analysis in real-time systems) can guarantee the satisfaction of all requests within certain constraints. A, of course, must give up control of the resource to the resource manager.

- existence of A. The factory pattern has the ability to create instances as needed, and thus the dependence of B on the existence of A is satisfied by actions of the factory.

DEFER BINDING TIME

The two tactic categories we have discussed thus far are designed to minimize the number of modules that require changing to implement modifications. Our modifiability scenarios include two elements that are not satisfied by reducing the number of modules to be changed time to deploy and allowing non developers to make changes. Deferring binding time supports both of those scenarios at the cost of requiring additional infrastructure to support the late binding.

Decisions can be bound into the executing system at various times. We discuss those that affect deployment time. The deployment of a system is dictated by some process. When a modification is made by the developer, there is usually a testing and distribution process that determines the time lag between the making of the change and the availability of that change to the end user.

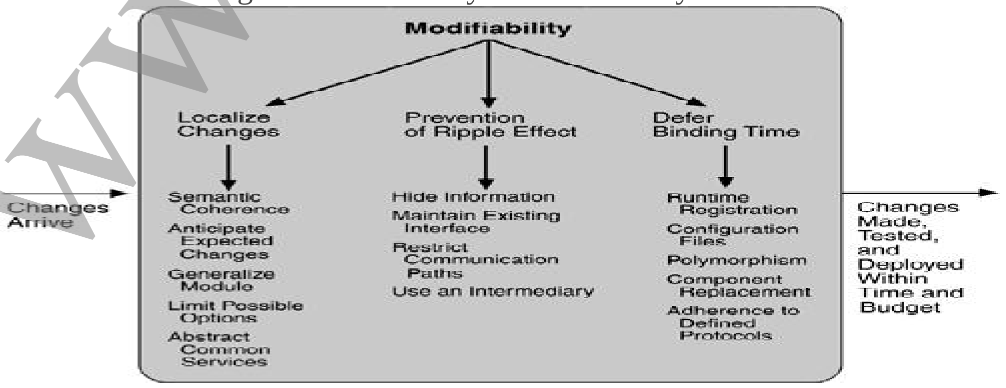
Binding at runtime means that the system has been prepared for that binding and all of the testing and distribution steps have been completed. Deferring binding time also supports allowing the end user or system administrator to make settings or provide input that affects behavior.

Many tactics are intended to have impact at load time or runtime, such as the following.

- Runtime registration supports plug-and-play operation at the cost of additional overhead to manage the registration. Publish/subscribe registration, for example, can be implemented at either runtime or load time.
- Configuration files are intended to set parameters at startup.
- Polymorphism allows late binding of method calls.
- Component replacement allows load time binding.
- Adherence to defined protocols allows runtime binding of independent processes.

The tactics for modifiability are summarized in Figure 5.5.

Figure 5.5. Summary of modifiability tactics

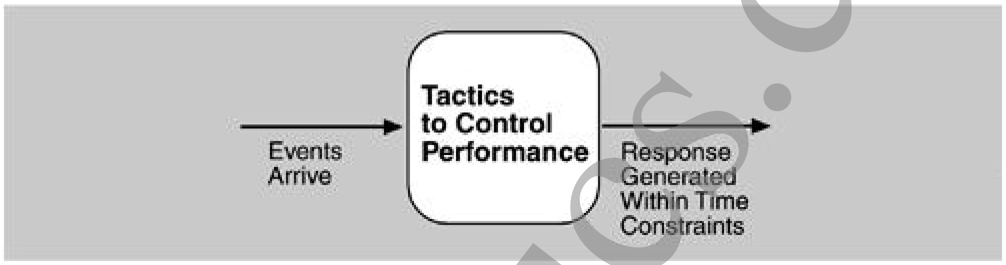


Performance Tactics :

The goal of performance tactics is to generate a response to an event arriving at the system within some time constraint. The event can be single or a stream and is the trigger for a request to perform computation. It can be the arrival of a message, the expiration of

a time interval, the detection of a significant change of state in the system's environment, and so forth. The system processes the events and generates a response. Performance tactics control the time within which a response is generated. This is shown in Figure 5.6.Latency is the time between the arrival of an event and the generation of a response to it.

Figure 5.6. Goal of performance tactics


Tactics to Control Performance
Events Arrive
Response Generated Within Time Constraints

After an event arrives, either the system is processing on that event or the processing is blocked for some reason. This leads to the two basic contributors to the response time: resource consumption and blocked time.

1. **Resource consumption**. Resources include CPU, data stores, network communication bandwidth, and memory, but it can also include entities defined by the particular system under design. For example, buffers must be managed and access to critical sections must be made sequential.

   Events can be of varying types (as just enumerated), and each type goes through a processing sequence. For example, a message is generated by one component, is placed on the network, and arrives at another component.

   It is then placed in a buffer; transformed in some fashion (marshalling is the term the Object Management Group uses for this transformation); processed according to some algorithm; transformed for output; placed in an output buffer; and sent onward to another component, another system, or the user. Each of these phases contributes to the overall latency of the processing of that event.

2. **Blocked time**. A computation can be blocked from using a resource because of contention for it, because the resource is unavailable, or because the computation depends on the result of other computations that are not yet available.

- **Contention for resources**. Figure 5.6 shows events arriving at the system. These events may be in a single stream or in multiple streams. Multiple streams vying for the same resource or different events in the same stream vying for the same resource contribute to latency. In general, the more contention for a resource, the more likelihood of latency being introduced. However, this depends on how the contention is arbitrated and how individual requests are treated by the arbitration mechanism.

- **Availability of resources**. Even in the absence of contention, computation cannot proceed if a resource is unavailable. Unavailability may be caused by the e resource being offline or by failure of the component or for some other reason. In any case, the architect must identify places where resource unavailability might cause a significant contribution to overall latency.

- **Dependency on other computation**. A computation may have to wait because it must synchronize with the results of another computation or because it is waiting for the results of a computation that it initiated. For example, it may be reading information from two different sources, if these two sources are read sequentially, the latency will be higher than if they are read in parallel.

With this background, we turn to our three tactic categories: resource demand, resource management, and resource arbitration.

RESOURCE DEMAND

Event streams are the source of resource demand. Two characteristics of demand are the time between events in a resource stream (how often a request is made in a stream) and how much of a resource is consumed by each request.

One tactic for reducing latency is to reduce the resources required for processing an event stream. Ways to do this include the following.

- **Increase computational efficiency**. One step in the processing of an event or a message is applying some algorithm. Improving the algorithms used in critical areas will decrease latency. Sometimes one resource can be traded for another. For example, intermediate data may be kept in a repository or it may be regenerated depending on time and space resource availability. This tactic is usually applied to the processor but is also effective when applied to other resources such as a disk.
- **Reduce computational overhead**. If there is no request for a resource, processing needs are reduced. The use of intermediaries (so important for modifiability) increases the resources consumed in processing an event stream, and so removing them improves latency. This is a classic modifiability/performance tradeoff.

Another tactic for reducing latency is to reduce the number of events processed. This can be done in one of two fashions.

- **Manage event rate**. If it is possible to reduce the sampling frequency at which environmental variables are monitored, demand can be reduced. Sometimes this is possible if the system was over engineered. Other times an unnecessarily high sampling rate is used to establish harmonic periods between multiple streams. That is, some stream or streams of events are over sampled so that they can be synchronized.
- **Control frequency of sampling**. If there is no control over the arrival of externally generated events, queued requests can be sampled at a lower frequency, possibly resulting in the loss of requests.

Other tactics for reducing or managing demand involve controlling the use of resources.

- **Bound execution times**. Place a limit on how much execution time is used to respond to an event. Sometimes this makes sense and sometimes it does not. For iterative, data-dependent algorithms, limiting the number of iterations is a method for bounding execution times.
- **Bound queue sizes**. This controls the maximum number of queued arrivals and consequently the resources used to process the arrivals.

RESOURCE MANAGEMENT

Even though the demand for resources may not be controllable, the management of these resources affects response times. Some resource management tactics are:

- **Introduce concurrency**. If requests can be processed in parallel, the blocked time can be reduced. Concurrency can be introduced by processing different streams of events on different threads or by creating additional threads to process different sets of activities. Once concurrency has been introduced, appropriately allocating the threads to resources (load balancing) is important in order to maximally exploit the concurrency.
- Maintain multiple copies of either data or computations. Clients in a client-server pattern are replicas of the computation. The purpose of replicas is to reduce the
  contention that would occur if all computations took place on a central server.
  Caching is a tactic in which data is replicated, either on different speed repositories or on separate repositories, to reduce contention. Since the data being cached is usually a copy of existing data, keeping the copies consistent and synchronized becomes a responsibility that the system must assume.
- Increase available resources. Faster processors, additional processors, additional memory, and faster networks all have the potential for reducing latency. Cost is usually a consideration in the choice of resources, but increasing the resources is definitely a tactic to reduce latency.

RESOURCE ARBITRATION

- Whenever there is contention for a resource, the resource must be scheduled. Processors are scheduled, buffers are scheduled, and networks are scheduled. The architect's goal is to understand the characteristics of each resource's use and choose the scheduling strategy that is compatible with it.

- A scheduling policy conceptually has two parts: a priority assignment and dispatching. All scheduling policies assign priorities. In some cases the assignment is as simple as first-in/first-out. In other cases, it can be tied to the deadline of the request or its semantic importance.

- Competing criteria for scheduling include optimal resource usage, request importance, minimizing the number of resources used, minimizing latency, maximizing throughput, preventing starvation to ensure fairness, and so forth. The architect needs to be aware of these possibly conflicting criteria and the effect that the chosen tactic has on meeting them.

A high-priority event stream can be dispatched only if the resource to which it is being assigned is available. Sometimes this depends on pre-empting the current user of the resource. Possible preemption options are as follows: can occur anytime; can occur only at specific pre-emption points; and executing processes cannot be pre-empted. Some common scheduling policies are:

1. First-in/First-out. FIFO queues treat all requests for resources as equals and satisfy them in turn. One possibility with a FIFO queue is that one request will be stuck behind another one that takes a long time to generate a response. As long as all of the requests are truly equal, this is not a problem, but if some requests are of higher priority than others, it is problematic.

2. Fixed-priority scheduling. Fixed-priority scheduling assigns each source of resource requests a particular priority and assigns the resources in that priority order. This strategy insures better service for higher-priority requests but admits the possibility of a low-priority, but important, request taking an arbitrarily long time to be serviced because it is stuck behind a series of higher-priority requests. Three common prioritization strategies are

   - semantic importance. Each stream is assigned a priority statically according to some domain characteristic of the task that generates it. This type of scheduling is used in mainframe systems where the domain characteristic is the time of task initiation.

   - deadline monotonic. Deadline monotonic is a static priority assignment that assigns higher priority to streams with shorter deadlines. This scheduling policy is used when streams of different priorities with real-time deadlines are to be scheduled.

   - rate monotonic. Rate monotonic is a static priority assignment for periodic streams that assigns higher priority to streams with shorter periods. This scheduling policy is a special case of deadline monotonic but is better known and more likely to be supported by the operating system.

3. Dynamic priority scheduling:

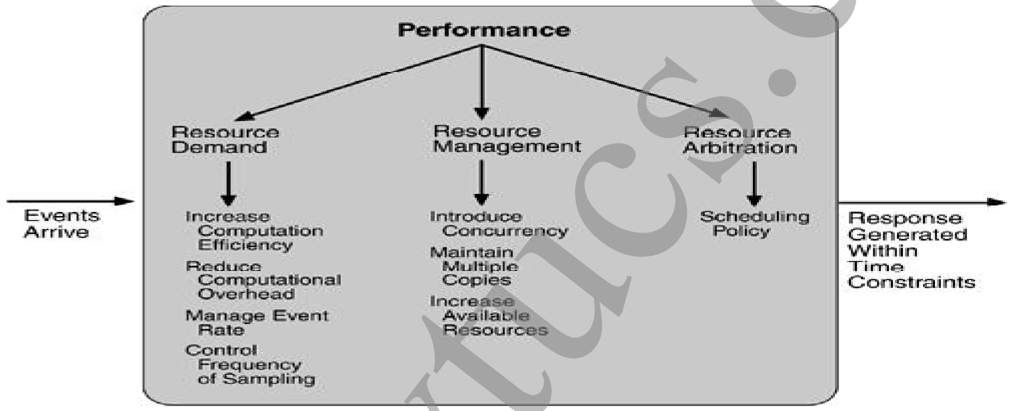
- round robin. Round robin is a scheduling strategy that orders the requests and then, at every assignment possibility, assigns the resource to the next request in that order. A special form of round robin is a cyclic executive where assignment possibilities are at fixed time intervals.

- earliest deadline first. Earliest deadline first assigns priorities based on the pending requests with the earliest deadline.

4. Static scheduling. A cyclic executive schedule is a scheduling strategy where the pre-emption points and the sequence of assignment to the resource are determined offline.

The tactics for performance are summarized in Figure 5.7.

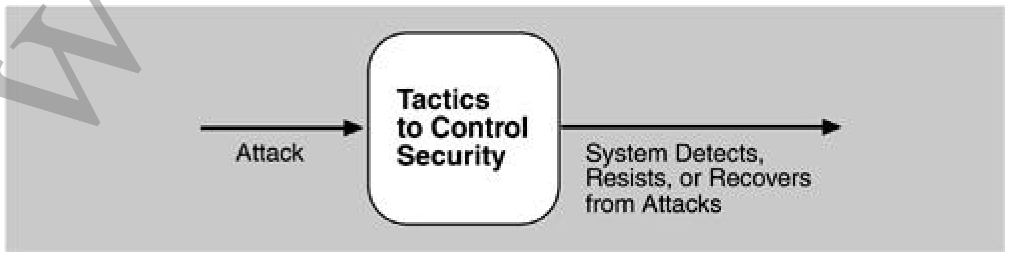
Figure 5.7. Summary of performance tactics


Performance
Resource Demand
Resource Management
Resource Arbitration
Events Arrive
Increase Computation Efficiency
Reduce Computational Overhead
Manage Event Rate
Control Frequency of Sampling
Introduce Concurrency
Maintain Multiple Copies
Increase Available Resources
Scheduling Policy
Response Generated Within Time Constraints

Security Tactics :

Tactics for achieving security can be divided into those concerned with resisting attacks, those concerned with detecting attacks, and those concerned with recovering from attacks. All three categories are important. Using a familiar analogy, putting a lock on your door is a form of resisting an attack, having a motion sensor inside of your house is a form of detecting an attack, and having insurance is a form of recovering from an attack. Figure 5.8 shows the goals of the security tactics.

Figure 5.8. Goal of security tactics


Attack
Tactics to Control Security
System Detects, Resists, or Recovers from Attacks

RESISTING ATTACKS

The following tactics can be used in combination to achieve these goals.

- Authenticate users. Authentication is ensuring that a user or remote computer is actually who it purports to be. Passwords, one-time passwords, digital certificates, and biometric identifications provide authentication.
- Authorize users. Authorization is ensuring that an authenticated user has the rights to access and modify either data or services. This is usually managed by providing some access control patterns within a system. Access control can be by user or by user class. Classes of users can be defined by user groups, by user roles, or by lists of individuals.
- Maintain data confidentiality. Data should be protected from unauthorized access. Confidentiality is usually achieved by applying some form of encryption to data and to communication links. Encryption provides extra protection to persistently maintained data beyond that available from authorization.

  Communication links, on the other hand, typically do not have authorization controls. Encryption is the only protection for passing data over publicly accessible communication links. The link can be implemented by a virtual private network (VPN) or by a Secure Sockets Layer (SSL) for a Web-based link. Encryption can be symmetric (both parties use the same key) or asymmetric (public and private keys).
- Maintain integrity. Data should be delivered as intended. It can have redundant information encoded in it, such as checksums or hash results, which can be encrypted either along with or independently from the original data.
- Limit exposure. Attacks typically depend on exploiting a single weakness to attack all data and services on a host. The architect can design the allocation of services to hosts so that limited services are available on each host.

DETECTING ATTACKS

The detection of an attack is usually through an intrusion detection system. Such systems work by comparing network traffic patterns to a database. In the case of misuse detection, the traffic pattern is compared to historic patterns of known attacks. In the case of anomaly detection, the traffic pattern is compared to a historical baseline of itself. Frequently, the packets must be filtered in order to make comparisons. Filtering can be on the basis of protocol, TCP flags, payload sizes, source or destination address, or port number.

Intrusion detectors must have some sort of sensor to detect attacks, managers to do sensor fusion, databases for storing events for later analysis, tools for offline reporting and analysis, and a control console so that the analyst can modify intrusion detection actions.

RECOVERING FROM ATTACKS

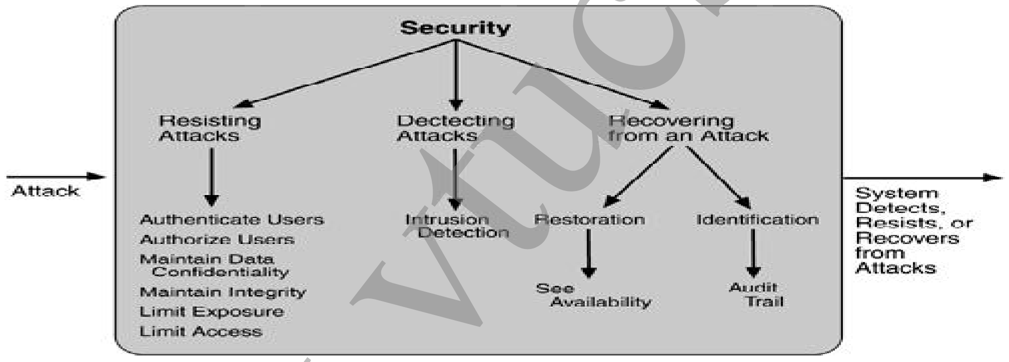
- Tactics involved in recovering from an attack can be divided into those concerned with restoring state and those concerned with attacker identification (for either preventive or punitive purposes).

- The tactics used in restoring the system or data to a correct state overlap with those used for availability since they are both concerned with recovering a consistent state from an inconsistent state. One difference is that special attention is paid to maintaining redundant copies of system administrative data such as passwords, access control lists, domain name services, and user profile data.

- The tactic for identifying an attacker is to maintain an audit trail. An audit trail is a copy of each transaction applied to the data in the system together with identifying information. Audit information can be used to trace the actions of an attacker, support non repudiation (it provides evidence that a particular request was made), and support system recovery. Audit trails are often attack targets themselves and therefore should be maintained in a trusted fashion.

Figure 5.9 provides a summary of the tactics for security.

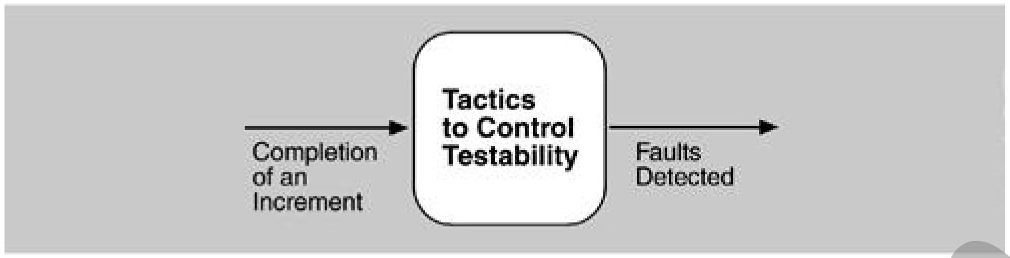
Figure 5.9. Summary of tactics for security



Testability Tactics :

- The goal of tactics for testability is to allow for easier testing when an increment of software development is completed. Figure 5.10 displays the use of tactics for testability. Architectural techniques for enhancing the software testability have not received as much attention as more mature fields such as modifiability, performance, and availability, since testing consumes such a high percentage of system development cost, anything the architect can do to reduce this cost will yield a significant benefit.

Figure 5.10. Goal of testability tactics



- The goal of a testing regimen is to discover faults. This requires that input be provided to the software being tested and that the output be captured.

- Executing the test procedures requires some software to provide input to the software being tested and to capture the output. This is called a test harness. A question we do not consider here is the design and generation of the test harness. In some systems, this takes substantial time and expense.

- We discuss two categories of tactics for testing: providing input and capturing output, and internal monitoring.

INPUT/OUTPUT

There are three tactics for managing input and output for testing.

- Record/playback. Record/playback refers to both capturing information crossing an interface and using it as input into the test harness. The information crossing an interface during normal operation is saved in some repository and represents output from one component and input to another. Recording this information allows test input for one of the components to be generated and test output for later comparison to be saved.
- Separate interface from implementation. Separating the interface from the implementation allows substitution of implementations for various testing purposes. Stubbing implementations allows the remainder of the system to be tested in the absence of the component being stubbed. Substituting a specialized component allows the component being replaced to act as a test harness for the remainder of the system.

- Specialize access routes/interfaces. Having specialized testing interfaces allows the capturing or specification of variable values for a component through a test harness as well as independently from its normal execution.

  For example, metadata might be made available through a specialized interface that a test harness would use to drive its activities. Specialized access routes and interfaces should be kept separate from the access routes and interfaces for required functionality. Having a hierarchy of test interfaces in the architecture means that test cases can be applied at any level in the architecture and that the testing functionality is in place to observe the response.

INTERNAL MONITORING

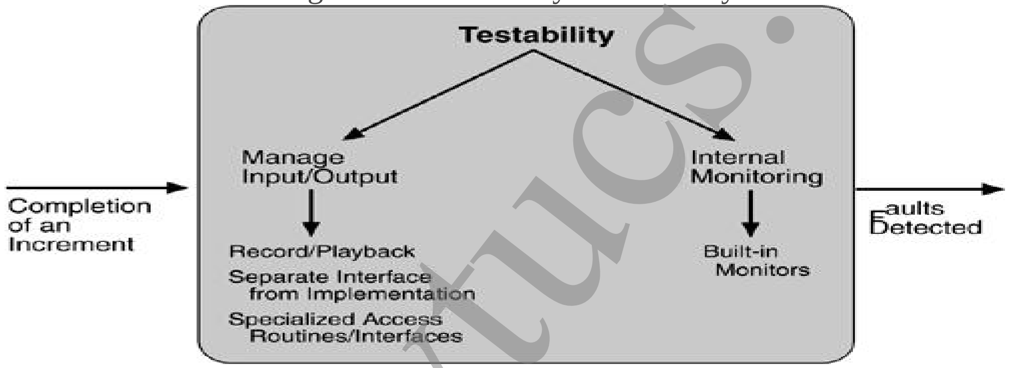
A component can implement tactics based on internal state to support the testing process.

- Built-in monitors. The component can maintain state, performance load, capacity, security, or other information accessible through an interface. This interface can be a permanent interface of the component or it can be introduced temporarily via an instrumentation technique such as aspect-oriented programming or preprocessor macros.

  A common technique is to record events when monitoring states have been activated. Monitoring states can actually increase the testing effort since tests may have to be repeated with the monitoring turned off. Increased visibility into the activities of the component usually more than outweigh the cost of the additional testing.

Figure 5.11 provides a summary of the tactics used for testability.

Figure 5.11. Summary of testability tactics

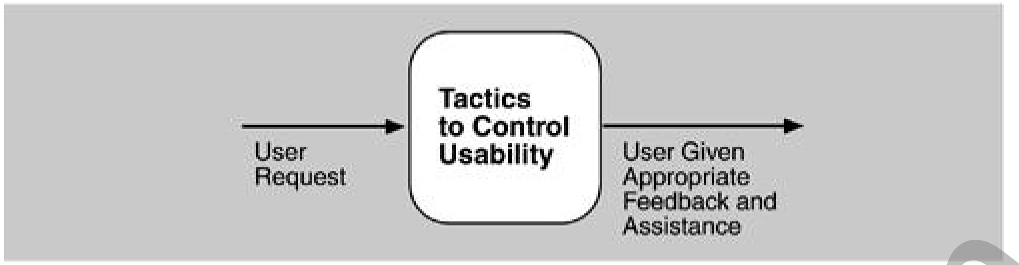

Testability
Manage Input/Output
Internal Monitoring
Completion of an Increment
Faults Detected
Record/Playback
Separate Interface from Implementation
Specialized Access Routines/Interfaces
Built-in Monitors

Usability Tactics :

Usability is concerned with how easy it is for the user to accomplish a desired task and the kind of support the system provides to the user. Two types of tactics support usability, each intended for two categories of "users." The first category, runtime, includes those that support the user during system execution. The second category is based on the iterative nature of user interface design and supports the interface developer at design time. It is strongly related to the modifiability tactics already presented.

Figure 5.12 shows the goal of the runtime tactics.

Figure 5.12. Goal of runtime usability tactics


User Request
Tactics to Control Usability
User Given Appropriate Feedback and Assistance

RUNTIME TACTICS

- Once a system is executing, usability is enhanced by giving the user feedback as to what the system is doing and by providing the user with the ability to issue usability-based commands. For example, cancel, undo, aggregate, and show multiple views support the user in either error correction or more efficient operations.

- Researchers in human computer interaction have used the terms "user initiative," "system initiative," and "mixed initiative" to describe which of the human computer pair takes the initiative in performing certain actions and how the interaction proceeds. Understanding Quality Attributes, combine initiatives from both perspectives.

- For example, when canceling a command the user issues a cancel "user initiative" and the system responds. During the cancel, however, the system may put up a progress indicator "system initiative." Thus, cancel demonstrates "mixed initiative." We use this distinction between user and system initiative to discuss the tactics that the architect uses to achieve the various scenarios.

- When the user takes the initiative, the architect designs a response as if for any other piece of functionality. The architect must enumerate the responsibilities of the system to respond to the user command. To use the cancel example again: When the user issues a cancel command, the system must be listening for it (thus, there is the responsibility to have a constant listener that is not blocked by the actions of whatever is being canceled); the command to cancel must be killed; any resources being used by the canceled command must be freed; and components that are collaborating with the canceled command must be informed so that they can also take appropriate action.

When the system takes the initiative, it must rely on some information, a model, about the user, the task being undertaken by the user, or the system state itself. Each model requires various types of input to accomplish its initiative. The system initiative tactics are those that identify the models the system uses to predict either its own behavior or the user's intention. Encapsulating this information will enable an architect to more easily tailor and modify those models. Tailoring and modification can be either dynamically based on past user behavior or offline during development.

- Maintain a model of the task. In this case, the model maintained is that of the task.
  The task model is used to determine context so the system can have some idea of what the user is attempting and provide various kinds of assistance. For example, knowing that

sentences usually start with capital letters would allow an application to correct a lower-case letter in that position.

- Maintain a model of the user. In this case, the model maintained is of the user. It determines the user's knowledge of the system, the user's behavior in terms of expected response time, and other aspects specific to a user or a class of users. For example, maintaining a user model allows the system to pace scrolling so that pages do not fly past faster than they can be read.
- Maintain a model of the system. In this case, the model maintained is that of the system. It determines the expected system behavior so that appropriate feedback
  can be given to the user. The system model predicts items such as the time needed to complete current activity.

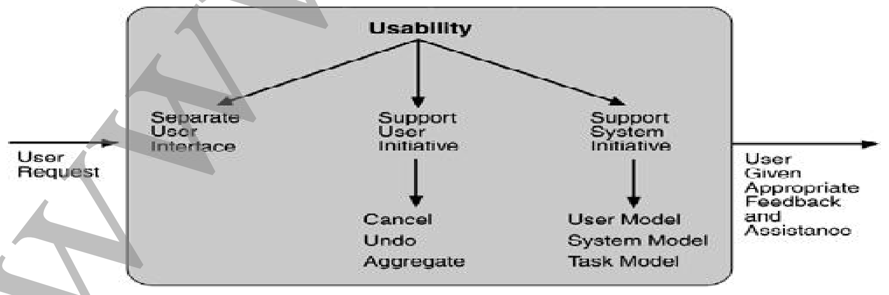
DESIGN-TIME TACTICS

User interfaces are typically revised frequently during the testing process. That is, the usability engineer will give the developers revisions to the current user interface design and the developers will implement them. This leads to a tactic that is a refinement of the modifiability tactic of semantic coherence:

- Separate the user interface from the rest of the application. Localizing expected changes is the rationale for semantic coherence. Since the user interface is expected to change frequently both during the development and after deployment, maintaining the user interface code separately will localize changes to it. The software architecture patterns developed to implement this tactic and to support the modification of the user interface are:
  - Model-View-Controller
  - Presentation-Abstraction-Control
  - Arch/Slinky

Figure 5.13 shows a summary of the runtime tactics to achieve usability.

Figure 5.13. Summary of runtime usability tactics



Relationship of Tactics to Architectural Patterns :

The Active Object design pattern decouples method execution from method invocation to enhance concurrency and simplify synchronized access to objects that reside in their own thread of

control.
The motivation for this pattern is to enhance concurrency, a performance goal. Thus, its main purpose is to implement the "introduce concurrency" performance tactic. Notice the other tactics this pattern involves, however.

- Information hiding (modifiability). Each element chooses the responsibilities it will achieve and hides their achievement behind an interface.

- Intermediary (modifiability). The proxy acts as an intermediary that will buffer changes to the method invocation.

- Binding time (modifiability). The active object pattern assumes that requests for the object arrive at the object at runtime. The binding of the client to the proxy, however, is left open in terms of binding time.

- Scheduling policy (performance). The scheduler implements some scheduling policy.

Any pattern implements several tactics, often concerned with different quality attributes, and any implementation of the pattern also makes choices about tactics. For example, an implementation could maintain a log of requests to the active object for supporting recovery, maintaining an audit trail, or supporting testability.

The analysis process for the architect involves understanding all of the tactics embedded in an implementation, and the design process involves making a judicious choice of what combination of tactics will achieve the system's desired goals.

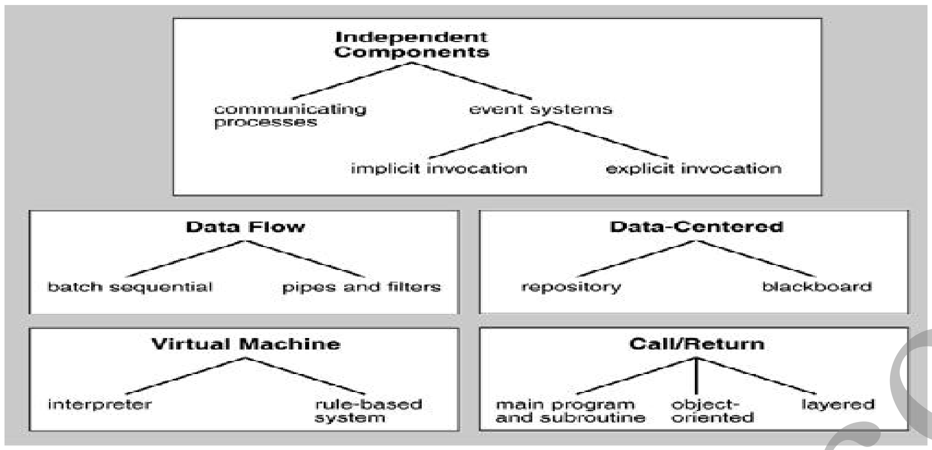
Architectural Patterns and Styles :

An architectural pattern in software, also known as an architectural style, is analogous to an architectural style in buildings, such as Gothic or Greek Revival or Queen Anne. It consists of a few key features and rules for combining them so that architectural integrity is preserved. An architectural pattern is determined by:

- A set of element types (such as a data repository or a component that computes a mathematical function).
- A topological layout of the elements indicating their interrelation-ships.
- A set of semantic constraints (e.g., filters in a pipe-and-filter style are pure data transducers. They incrementally transform their input stream into an output stream, but do not control either upstream or downstream elements).
- A set of interaction mechanisms (e.g., subroutine call, event-subscriber, blackboard) that determine how the elements coordinate through the allowed topology.

These patterns occur not only regularly in system designs but in ways that sometimes prevent us from recognizing them, because in different disciplines the same architectural pattern may be called different things. In response, a number of recurring architectural patterns, their properties, and their benefits have been cataloged. One such catalog is illustrated in Figure 5.14.

Figure 5.14. A small catalog of architectural patterns, organized by is-a lations



In this figure patterns are categorized into related groups in an inheritance hierarchy. For example, an event system is a sub style of independent elements. Event systems themselves have two sub patterns: implicit invocation and explicit invocation.

What is the relationship between architectural patterns and tactics? As shown earlier, we view a tactic as a foundational "building block" of design, from which architectural patterns and strategies are created.

Unit 4
Contents

Architectural Patterns – 1: Introduction

- From mud to structure
- Layers
- Pipes and Filters
- Blackboard

UNIT 4
Chapter 6: ARCHITECTURAL PATTERNS-1

Introduction :

"A **pattern for software architecture** describes a particular recurring design problem that arises in specific design contexts and presents a well-proven generic scheme for its solution. The solution scheme is specified by describing its constituent components, their responsibilities and relationships, and the ways in which they collaborate."

In general, patterns have the following characteristics :

- A pattern describes a solution to a recurring problem that arises in specific design situations.
- Patterns are not invented; they are distilled from practical experience.
- Patterns describe a group of components (e.g., classes or objects), how the components interact, and the responsibilities of each component. That is, they are higher level abstractions than classes or objects.
- Patterns provide a vocabulary for communication among designers. The choice of a name for a pattern is very important.
- Patterns help document the architectural vision of a design. If the vision is clearly understood, it will less likely be violated when the system is modified.
- Patterns provide a conceptual skeleton for a solution to a design problem and, hence, encourage the construction of software with well-defined properties

Typically a pattern will be described with a schema that includes at least the following three parts :

1. Context
2. Problem
3. Solution

Context

The Context section describes the situation in which the design problem arises.

Problem

The Problem section describes the problem that arises repeatedly in the context.In particular, the description describes the set of **forces** repeatedly arising in the context. A force is some aspect of the problem that must be considered when attempting a solution. Example types of forces include:

- requirements the solution must satisfy (e.g., efficiency)
- constraints that must be considered (e.g., use of a certain algorithm or protocol)
- desirable properties of a solution (e.g., easy to modify)

Forces may complementary (i.e., can be achieved simultaneously) or contradictory (i.e., can only be balanced).

Solution

The Solution section describes a proven solution to the problem.

The solution specifies a configuration of elements to balance the forces associated with the problem.

- A pattern describes the static structure of the configuration, identifying the components and the connectors (i.e., the relationships among the components).
- A pattern also describes the dynamic runtime behavior of the configuration, identifying the control structure of the components and connectors.

Categories of Patterns

Patterns can be grouped into three categories according to their level of abstraction:

Architectural patterns
Design patterns
Idioms

Architectural patterns

"An **architectural pattern** expresses a fundamental structural organization schema for software systems. It provides a set of predefined subsystems, specifies their responsibilities, and includes rules and guidelines for organizing the relationships between them."

An architectural pattern is a high-level abstraction. The choice of the architectural pattern to be used is a fundamental design decision in the development of a software system. It determines the system-wide structure and constrains the design choices available for the various subsystems. It is, in general, independent of the implementation language to be used.

An example of an architectural pattern is the Pipes and Filters pattern. In Unix for instance, a filter is a program that reads a stream of bytes from its standard input and writes a transformed stream to its standard output. These programs can be chained together with the output of one filter becoming the input of the next filter in the sequence via the pipe mechanism.

Design patterns

"A **design pattern** provides a scheme for refining the subsystems or components of a software system, or the relationships between them. It describes a commonly- recurring structure of communicating components that solves a general design problem within a particular context."

A design pattern is a mid-level abstraction. The choice of a design pattern does not affect the fundamental structure of the software system, but it does affect the structure of a subsystem. Like the architectural pattern, the design pattern tends to be independent of the implementation language to be used.

Examples of design patterns include the following:

Adapter (or Wrapper) pattern.

This pattern adapts the interface of one existing type of object to have the same interface as a different existing type of object.

Iterator pattern.

This pattern defines mechanisms for stepping through container data structures element by element.

Strategy (or Policy) pattern.

The goal of this pattern is to allow any one of a family of related algorithms to be easily substituted in a system.

Idioms

"An **idiom** is a low-level pattern specific to a programming language. An idiom describes how to implement particular aspects of components or the relationships between them using the features of the given language."

- An idiom is a low-level abstraction. It is usually a language-specific pattern that deals with some aspects of both design and implementation.

- In some sense, use of a consistent program coding and formatting style can be considered an idiom for the language being used. Such a style would provide guidelines for naming variables, laying out declarations, indenting control structures, ordering the features of a class, determining how values are returned, and so forth. A good style that is used consistently makes a program easier to understand than otherwise would be the case.
- Another example of an idiom is the use of the Counted Pointer (or Counted Body or Reference Counting) technique for storage management of shared objects in C++. In this idiom, we control access to a shared object through two classes, a *Body* (representation) class and a *Handle* (access) class.

- An object of the *Body* class holds the shared object and a count of the number of references to the object.

- An object of a *Handle* class holds a direct reference to a body object; all other parts of the program must access the body indirectly through handle class methods. The handle methods can increment the reference count when a new reference is created and decrement the count when a reference is freed. When a reference count goes to zero, the shared object and its body can be deleted.
- A variant of the Counted Pointer idiom can be used to implement a "copy on write" mechanism. That is, the body is shared as long as only "read" access is needed, but a copy is created whenever one of the holders makes a change to the state of the object.

Layers :

- Some design patterns, describe the implementation of micro-architectures. These design patterns are useful, for the most part, to describe small-scale object interactions.

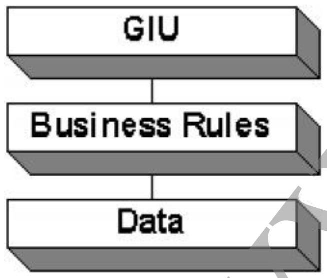
- Other design patterns are useful for abstracting large systems of objects. These are architectural design patterns. An architectural pattern is any pattern concerned with the construction context of a whole system, rather than just some part of a system.

- The distinction between micro-architectures and system architectures depends on your point of view and the scale of your system. If your system has 5 objects then the micro-architecture-style design patterns are architectural patterns because they consider the structure, relative communication, and design philosophy for the system. But more commonly, architectural design patterns are used to describe the structure of bigger systems where the number of objects is measured in hundreds or thousands.

Layers is an architectural design pattern that structures applications so they can be decomposed into groups of subtasks such that each group of subtasks is at a particular level of abstraction.

Some Examples

The traditional 3-tier client server model, which separates application functionality into three distinct abstractions, is an example of layered design.
.



Context

A large system requires decomposition. One way to decompose a system is to segment it into collaborating objects. In large systems a first-cut rough model might produce hundreds or thousands of potential objects. Additional refactoring typically leads to object groupings that provide related types of services. When these groups are properly segmented, and their interfaces consolidated, the result is a layered architecture.

Benefits

-Segmentation of high-level from low-level issues. Complex problems can be broken into smaller more manageable pieces.

-Since the specification of a layer says nothing about its implementation, the implementation details of a layer are hidden (abstracted) from other layers.

-Many upper layers can share the services of a lower layer. Thus layering allows us to reuse functionality.

-Development by teams is aided because of the logical segmentation.

-Easier exchange of parts at a later date.

A Layered model does not imply that each layer should be in a separate address space. Efficient implementations demand that layer-crossings be fast and cheap. Examples: User Interfaces may need efficient access to field validations.

Caching Layers

Layers are logical places to keep information caches. Requests that normally travel down through several layers can be cached to improve performance.

Intra- and inter-Application Communications

A systems programming interface is often implemented as a layer. Thus if two applications (or inter-application elements) need to communicate, placing the interface responsibilities into dedicated layers can greatly simplify the other applications layers and, as a bonus, make them more easily reusable.

The GUI Layer

The principle of separating the user interface from the application proper is old. It is rarely practiced, for all the talk we devote to it. The principle of separating the user interface from the application has the hardest consequences and is hardest to follow consistently.

It is easier on the user if input errors are brought up directly upon entry. Having the UI outside the application separates input from error detection. First the UI will change, so isolate and make an interface to it. Then someone will remove the human from the picture entirely, with electronic interchange or another application driving the program.

Therefore, just making an interface to the UI component is not sufficient, it has to be an interface that does not care about the UI.

<u>Pipes and Filters :</u>

"The **Pipes and Filters** architectural pattern provides a structure for systems that process a stream of data. Each processing step is encapsulated in a filter component. Data [are] passed through pipes between adjacent filters. Recombining filters allows you to build families of related filters."

Context

The context consists of programs that must process streams of data.

Problem

Suppose we need to build a system to solve a problem:

that must be built by several developers

that decomposes naturally into several independent processing steps for

which the requirements are likely to change.

Structure

The **filters** are the processing units of the pipeline. A filter may enrich, refine, or transform its input data

- It may enrich the data by computing new information from the input data and adding it to the output data stream.
- It may refine the data by concentrating or extracting information from the input data stream and passing only that information to the output stream.

- It may transform the input data to a new form before passing it to the output stream.
- It may, of course, do some combination of enrichment, refinement, and transformation.

A filter may be active (the more common case) or passive.

An **active** filter runs as a separate process or thread; it actively **pulls** data from the input data stream and **pushes** the transformed data onto the output data stream.

A **passive** filter is activated by either being called:

as a function, a pull of the output from the filter

as a procedure, a push of output data into the filter

The **pipes** are the connectors--between a data source and the first filter, between filters, and between the last filter and a data sink. As needed, a pipe synchronizes the active elements that it connects together.

A **data source** is an entity (e.g., a file or input device) that provides the input data to the system. It may either actively push data down the pipeline or passively supply data when requested, depending upon the situation.

A **data sink** is an entity that gathers data at the end of a pipeline. It may either actively pull data from the last filter element or it may passively respond when requested by the last filter element.

Implementation

Implementation of the pipes-and-filters architecture is usually not difficult. It often includes the following steps:

1. **Divide the functionality of the problem into a sequence of processing steps.**
Each step should only depend upon the outputs of the previous step in the sequence. The steps will become the filters in the system.

In dividing up the functionality, be sure to consider variations or later changes that might be needed--a reordering of the steps or substitution of one processing step for another.

2. **Define the type and format of the data to be passed along each pipe.**
For example, Unix pipes carry an unstructured sequence of bytes. However, many Unix filters read and write streams of ASCII characters that are structured into lines (with the newline character as the line terminator).

Another important formatting issue is how the end of the input is marked. A filter might rely upon a system end-of-input condition or it may need to implement their own "sentinel" data value to mark the end.

3. **Determine how to implement each pipe connection.**
For example, a pipe connecting active filters might be implemented with operating system or programming language runtime facility such as a message queue, a Unix-style pipe, or a synchronized-access bounded buffer.

A pipe connecting to a passive filter might be implemented as a direct call of the adjacent filter: a push connection as a call of the downstream filter as a procedure or a pull connection as a call of the upstream filter as a function.

4. **Design and implement the filters.**
The design of a filter is based on the nature of the task to be performed and the natures of the pipes to which it can be connected.

- An active filter needs to run with its own **thread of control**. It might run as as a "heavyweight" operating system process (i.e., having its own address space) or as a "lightweight" thread (i.e., sharing an address space with other threads).
- A passive filter does not require a separate thread of control (although it could be implemented with a separate thread).

The selection of the **size of the buffer** inside a pipe is an important performance tradeoff. Large buffers may use up much available memory but likely will involve less synchronization and context-switching overhead. Small buffers conserve memory at the cost of increased overhead.

To make filters flexible and, hence, increase their potential reusability, they often will need different **processing options** that can be set when they are initiated. For example, Unix filters often take command line parameters, access environment variables, or read initialization files.

5. **Design for robust handling of errors.**

Error handling is difficult in a pipes-and-filters system since there is no global state and often multiple asynchronous threads of execution. At the least, a pipes- and-filters system needs mechanisms for detecting and reporting errors. An error should not result in incorrect output or other damage to the data.

For example, a Unix program can use the stderr channel to report errors to its environment.

More sophisticated pipes-and-filters systems should seek to recover from errors. For example, the system might discard bad input and resynchronize at some well- defined point later in the input data. Alternatively, the system might back up the input to some well-defined point and restart the processing, perhaps using a different processing method for the bad data.

6. **Configure the pipes-and-filters system and initiate the processing.**

One approach is to use a standardized main program to create, connect, and initiate the needed pipe and filter elements of the pipeline.

Another approach is to use an end-user tool, such as a command shell or a visual pipeline editor, to create, connect, and initiate the needed pipe and filter elements of the pipeline.

Example

An example pipes-and-filter system might be a retargetable compiler for a programming language. The system might consist of a pipeline of processing elements similar to the following:

A **source** element reads the program text (i.e., source code) from a file (or perhaps a sequence of files) as a stream of characters.

A **lexical analyzer** converts the stream of characters into a stream of lexical tokens for the language--keywords, identifier symbols, operator symbols, etc.

A **parser** recognizes a sequence of tokens that conforms to the language grammar and translates the sequence to an abstract syntax tree.

A **"semantic" analyzer** reads the abstract syntax tree and writes an appropriately augmented abstract syntax tree.

A **global optimizer** (usually optionally invoked) reads an augmented syntax tree and outputs one that is equivalent but corresponds to program that is more efficient in space and time resource usage.

An **intermediate code generator** translates the augmented syntax tree to a sequence of instructions for a virtual machine.

A **local optimizer** converts the sequence of intermediate code (i.e., virtual machine) instructions into a more efficient sequence.

Note: A local optimizer may transform the program by removing unneeded loads and stores of data.

A **backend code generator** translates the sequence of virtual machine instructions into a sequence of instructions for some real machine platform (i.e., for some particular hardware processor augmented by operating system calls and a runtime library).

If the previous step generated symbolic assembly code, then an **assembler** is needed to translate the sequence of symbolic instructions into a relocatable binary module.

If the previous steps of the pipeline generated a sequence of separate binary modules, then a **linker** might be needed to bind the separate modules with library modules to form a single executable (i.e., object code) module.

A **sink** element outputs the resulting binary module into a file.

The pipeline can be reconfigured to support a number of different variations:

- If source code preprocessing is to be supported (e.g., as in C), then a **reprocessor** filter (or filters) can be inserted in front of the lexical analyzer.
- If the language is to be interpreted rather than translated into object code, then the backend code generator (and all components after it in the pipeline) can be replaced by an

interpreter that implements the virtual machine.

- If the compiler is to be retargeted to a different platform, then a backend code generator (and assembler and linker) for the new platform can be substituted for the old one.

- If the compiler is to be modified to support a different language with the same lexical structure, then only the parser, semantic analyzer, global optimizer, and intermediate code generator need to be replaced.

    - Note: If the parser is driven by tables that describe the grammar, then it may be possible to use the same parser with a different table.

If a load-and-go compiler is desired, the file-output sink can be replaced by a **loader** that loads the executable module into an address space in the computer's main memory and starts the module executing.

Blackboard :

- The **Blackboard** pattern is useful for problems for which no deterministic solution strategies are known. In Blackboard several specialized subsystems assemble their knowledge to build a possibly partial or approximate solution.

- This pattern is useful for problems for which no deterministic solution strategies are known. In Blackboard several specialised sub-systems assemble their knowledge to build a possibly partial or approximate solution.

- A **blackboard system** is an artificial intelligence application based on the blackboard architectural model, where a common knowledge base, the "blackboard", is iteratively updated by a diverse group of specialist knowledge sources, starting with a problem specification and ending with a solution.

- Each knowledge source updates the blackboard with a partial solution when its internal constraints match the blackboard state. In this way, the specialists work together to solve the problem. The blackboard model was originally designed as a way to handle complex, ill-defined problems, where the solution is the sum of its parts.

A blackboard-system application consists of three major components

- The software specialist modules, which are called knowledge sources (KSs). Like the human experts at a blackboard, each knowledge source provides specific expertise needed by the application. The ability to support interaction and cooperation among diverse KSs creates enormous flexibility in designing and maintaining applications. As the pace of technology has intensified, it becomes ever more important to be able to replace software modules as they become outmoded or obsolete.

- The blackboard, a shared repository of problems, partial solutions, suggestions, and contributed information. The blackboard can be thought of as a dynamic "library" of contributions to the current problem that have been recently "published" by other knowledge sources.

Unit 5

Contents

UNIT 5
Chapter 7: Architectural Patterns-2

Distributed Systems :

Distributed systems architecture has rapidly evolved by applying and combining different architecture patterns and styles. In recent years, decoupling interfaces and implementation, scalable hosting models, and service orientation were the prominent tenets of building distributed systems. Distributed systems have grown from independent enterprise applications to Internet-connected networks of managed services, hosted on- premise and/or clouds.

Creating successful distributed systems requires that you address how that system is designed, developed, maintained, supported, and governed. Microsoft's Service Oriented Architecture Maturity Model (SOAMM) assessment method helps customers assess maturity elements and prioritize the evolution of their enterprise architecture. Organizations are applying methods, patterns, and technologies to model systems and enable proper governance.

Building distributed systems involves three core capabilities, based on the following roles:
Implementation of applications/services.

Consumption of services from within and external to organizations.

Administration of services or composite services.

Broker :

The **Broker** pattern can be used to structure distributed software systems with decoupled components that interact by remote service invocations. A broker component is responsible for coordinating communication, such as forwarding requests, as well as for transmitting results and exceptions.

The Broker pattern has many of the benefits and liabilities of the Layered Application pattern.

Benefit
Broker provides the following benefits:
1) **Isolation**. Separating all the communication-related code into its own layer isolates it from the application. You can decide to run the application distributed or all on one computer without having to change any application code.

2) **Simplicity**. Encapsulating complex communication logic into a separate layer breaks down the problem space. The engineers coding the broker do not have to concern themselves with arcane user requirements and business logic, and the application developers do not have to concern themselves with multicast protocols and TCP/IP routing.

3) **Flexibility**.

- Encapsulating functions in a layer allows you to swap this layer with a different implementation. For example, you can switch from DCOM to .NET remoting to standard Web services without affecting the application code.

- Unfortunately, layers of abstraction can harm performance. The basic rule is that the more information you have, the better you can optimize. Using a separate broker layer may hide details about how the application uses the lower layer, which may in turn prevent the lower layer from performing specific optimizations.

- For example, when you use TCP/IP, the routing protocol has no idea what is being routed. Therefore, it is hard to decide that a packet containing a video stream, for instance, should have routing priority over a packet containing a junk e-mail.

- The Broker architectural pattern can be used to structure distributed software systems with decoupled components that interact by remote service invocations

Structure

There are six types of components in Broker architectural pattern:

- Clients, Servers, Brokers, Bridges, Client-side proxies and Server-side proxies

- A server implements objects that expose their functionality through interfaces that consist of operations and attributes

- These interfaces are either through Interface Definition Language (IDL), through a binary standard, or some kind of APIs.

- Interfaces are grouped by semantically-related functionality. So,we Would have

- Servers implementing specific functionality for a single application domain or task

- A broker is a messager that is responsible for the transmission of requests from clients to servers

It also takes care the transmission of responses and exceptions back to the client

- A broker will store control information for locating the receivers (servers) of the requests
- (it is normally down with some unique system identifier, IP address might not be enough)

- Broker also offer interface for clients and servers

- They are usually in the form of APIs with control operations such as registering servers and invoking server methods

- Broker keeps track of all the servers information it maintains locally. If a request comes in and it is for a server that is on the tracking list. It passes the request along directly

- If the server is currently inactive, the broker activates it (spawn a job, folk a process, create a thread, use a pre start job, etc)

- Then response are passed back to the client through the broker

- If the request is for a server hosted by another broker, the local broker finds a route to the remote broker and forwards the request using this route (So, a common way of communication among brokers is needed)

It hides the implementation detail such as:

Inter-process communication mechanism used for message transfer between clients and brokers

The creation and deletion of memory blocks (remember, we are dealing with multiple different languages to build a system, not just Java)

The marshaling of parameters and results

In most cases, client-side proxies translate the object model specified as part of the Broker architectural pattern to the object model of the programming language used to implement the client

Advantages

Location Transparency
Changeability and extensibility of components
Portability of a Broker system

Interoperability between different Broker systems
Reusability
Testing and Dubugging

MVC :

Model–View–Controller (**MVC**) is a software architecture currently considered an architectural pattern used in software engineering. The pattern isolates "domain logic" (the application logic for the user) from input and presentation (GUI), permitting independent development, testing and maintenance of each.

The **Model-View-Controller** pattern (MVC) divides an interactive application into three components. The model contains the core functionality and data. Views display information to the user. Controllers handle user input. Views and controllers together comprise the user interface. A change-propagation mechanism ensures consistency between the user interface and the model.

The **model** is used to manage information and notify observers when that information changes. The model is the domain-specific representation of the data upon which the application operates. Domain logic adds meaning to raw data (for example, calculating whether today is the user's birthday, or the totals, taxes, and shipping charges for shopping cart items). When a model changes its state, it notifies its associated views so they can be refreshed.

The **controller** receives input and initiates a response by making calls on model objects. A controller accepts input from the user and instructs the model and viewport to perform actions based on that input.

An MVC application may be a collection of model/view/controller triplets, each responsible for a different UI element.

MVC is often seen in web applications where the view is the HTML or XHTML generated by the app. The controller receives GET or POST input and decides what to do with it, handing over to domain objects (i.e. the model) that contain the business rules and know how to carry out specific tasks such as processing a new subscription.

Though MVC comes in different flavors, control flow is generally as follows:

The user interacts with the user interface in some way (for example, presses a mouse button).
The controller handles the input event from the user interface, often via a registered handler or callback and converts the event into appropriate user action, understandable for the model.
The controller notifies the model of the user action, possibly resulting in a change in the model's state. (For example, the controller updates the user's shopping cart.)

A view queries the model in order to generate an appropriate user interface (for example, the view lists the shopping cart's contents). The view gets its own data from the model. The controller may (in some implementations) issue a general instruction to the view to render itself. In others, the view is automatically notified by the model of changes in state (Observer) which require a screen update.
The user interface waits for further user interactions, which restarts the cycle.

Some implementations such as the W3C XForms also use the concept of a dependency graph to automate the updating of views when data in the model changes.

The goal of MVC is, by decoupling models and views, to reduce the complexity in architectural design and to increase flexibility and maintainability of code.

Presentation-Abstraction-Control :

Presentation-abstraction-control (PAC) is a software architectural pattern, somewhat similar to model-view-controller (MVC). PAC is used as a hierarchical structure of agents, each consisting of a triad of presentation, abstraction and control parts. The agents (or triads) communicate with each other only through the control part of each triad. It also differs from MVC in that within each triad, it completely insulates the presentation (view in MVC) and the abstraction (model in MVC), this provides the option to separately multithread the model and view which can give the user experience of very short program start times, as the user interface (presentation) can be shown before the abstraction has fully initialized.

The **Presentation-Abstraction-Control**

- pattern (PAC) defines a structure for interactive software systems in the form of a hierarchy of cooperating agents. Every agent is responsible for a specific aspect of the application's functionality and consists of three components: presentation, abstraction, and control. This subdivision separates the hum an- computer interaction aspects of the agent from its functional core and its communication with other agents.

- Presentation-abstraction-control (PAC) is a software architectural pattern that uses a structure for interactive software systems in the form of a hierarchy of cooperating agents. Each of the agent consist of a triad of presentation, abstraction and control components and is responsible for a specific aspect of the application's functionality.
- The agents in their triads communicate with one other through the control part of each triad insulating the presentation and abstraction. This insulation facilitates the

multithreading where the presentation as the user interface can be shown before the abstraction has fully initialized. This is unlike other software architecture known as Model-View-Controller (MVC) which is restricted to simple GUI's with one or more views on the same model.

- The Control in the PAC is similar to the Controller in the MVC architecture to some extent. The PAC architecture does not have the model as its core component. Like the MVC the Abstraction contains the data in the PAC.

Unit 6

Contents

Chapter 8: Architectural Patterns-3

Adaptive systems :

Cause and Effect

- For many years scientists saw the universe as a linear place. One where simple rules of cause and effect apply. They viewed the universe as big machine and thought that if they took the machine apart and understood the parts, then they would understand the whole.

- They also thought that the universe's components could be viewed as machines, believing that if we worked on the parts of these machines and made each part work better, then the whole would work better. Scientists believed the universe and everything in it could be predicted and controlled.

Complexity Theory

- Gradually as scientists of all disciplines explored these phenomena a new theory emerged complexity theory, A theory based on relationships, emergence, patterns and iterations. A theory that maintains that the universe is full of systems, weather systems, immune systems, social systems etc and that these systems are complex and constantly adapting to their environment. Hence complex adaptive systems.

- The agents in the system are all the components of that system. For example the air and water molecules in a weather system, and flora and fauna in an ecosystem. These agents interact and connect with each other in unpredictable and unplanned ways.

- But from this mass of interactions regularities emerge and start to form a pattern which feeds back on the system and informs the interactions of the agents. For example in an ecosystem if a virus starts to deplete one species this results in a greater or lesser food supply for others in the system which affects their behaviour and their numbers. A period of flux occurs in all the populations in the system until a new balance is established.

Properties

Complex adaptive systems have many properties and the most important are,

· Emergence: Rather than being planned or controlled the agents in the system interact in apparently random ways. From all these interactions patterns emerge which informs the behaviour of the agents within the system and the behaviour of the system itself. For example a termite hill is a wondrous piece of architecture with a maze of interconnecting passages, large caverns, ventilation tunnels and much more. Yet there is no grand plan, the hill just emerges as a result of the termites following a few simple local rules.

· Co-evolution: All systems exist within their own environment and they are also part of that environment. Therefore, as their environment changes they need to change to ensure best fit. But because they are part of their environment, when they change, they change their environment, and as it has changed they need to change again, and so it goes on as a constant process. (Perhaps it should have been Darwin's "Theory of Co-evolution".)

Some people draw a distinction between complex adaptive systems and complex evolving systems. Where the former continuously adapt to the changes around them but do not learn from the process. And where the latter learn and evolve from each change enabling them to influence their environment, better predict likely changes in the future..

· Requisite Variety: The greater the variety within the system the stronger it is. In fact ambiguity and paradox abound in complex adaptive systems which use contradictions to create new possibilities to co-evolve with their environment. Democracy is a good example in that its strength is derived from its tolerance and even insistence in a variety..

· Connectivity: The ways in which the agents in a system connect and relate to one another is critical to the survival of the system, because it is from these connections that the patterns are formed and the feedback disseminated. The relationships between the agents are generally more important than the agents themselves.

· Simple Rules: Complex adaptive systems are not complicated. The emerging patterns may have a rich variety, but like a kaleidoscope the rules governing the function of the system are quite simple. A classic example is that all the water systems in the world, all the streams, rivers, lakes, oceans, waterfalls etc with their infinite beauty, power and variety are governed by the simple principle that water finds its own level.

· Iteration: Small changes in the initial conditions of the system can have significant effects after they have passed through the emergence - feedback loop a few times (often referred to as the butterfly effect). A rolling snowball for example gains on each roll much more snow than it did on the previous roll and very soon a fist sized snowball .

· Self Organizing: There is no hierarchy of command and control in a complex adaptive system. There is no planning or managing, but there is a constant re-organizing to find the best fit with the environment. A classic example is that if one were to take any western town and add up all the food in the shops and divide by the number of people in the town there will be near enough two weeks supply of food, but there is no food plan, food manager or any other formal controlling process. The system is continually self organizing through the process of emergence and feedback.

· Edge of Chaos: Complexity theory is not the same as chaos theory, which is derived from mathematics. But chaos does have a place in complexity theory in that systems exist on a spectrum ranging from equilibrium to chaos. A system in equilibrium does not have the internal dynamics to enable it to respond to its environment and will slowly (or quickly) die. A system in chaos ceases to function as a system. The most productive state to be in is at the edge of chaos where there is maximum variety and creativity, leading to new possibilities.

Complex adaptive: systems are all around us. Most things we take for granted are complex adaptive systems, and the agents in every system exist and behave in total ignorance of the concept but that does not impede their contribution to the system. Complex Adaptive Systems are a model for thinking about the world around us not a model for predicting what will happen.

Microkernel :

The **Microkernel** pattern applies to software systems that must be able to adapt to changing system requirements. It separates a minimal functional core from extended functionality and customer-specific parts. The microkernel also serves as a socket for plugging in these extensions and coordinating their collaboration.

Context and Problem

The pattern may be applied in the context of complex software systems serving as a platform for other software applications. Such complex systems usually should be extensible and adaptable to emerging technologies, capable of coping with a range of standards and technologies. They also need to possess high performance and scalability qualities; as a result, low memory consumption and low processing demands are required. Taken together, the above requirements are difficult to achieve.

Solution, Consequences and Liabilities

- The most important core services of the system should be encapsulated in a microkernel component. The microkernel maintains the system resources and allows other components to interact with each other as well as to access the functionality of the microkernel. It encapsulates a significant part of system-specific dependencies, such as hardware-dependent aspects. The size of the microkernel should be kept to a minimum, therefore, only part of the core functionality can be included in it; the rest of the core functionality is deferred to separate internal servers.

- Internal servers extend the functionalities of the microkernel. Internal servers can for example handle graphics and storage media. Internal servers can have their own processes or they can be shared Dynamic Link Libraries (DLL) loaded inside the kernel. The external server provides a more complex functionality; they are built on top of the core services provided by the microkernel.

- Different external servers may be needed in the system in order to provide the functionality for specific application domains. These servers run in separate processes and employ the communication facilities provided by microkernel to receive requests from their clients and to return the results. The role of the adapter is to provide a transparent interface for clients to communicate with external servers. Adapter hides the system dependencies such as communication facilities from the client. Adapter thus improves the scalability and changeability of the system. The adapter enables the servers and clients to be distributed over a network.

The benefits of the pattern can be mentioned like:

Good portability, since only microkernel need to be modified when porting the system to a new environment.

High flexibility and extensibility, as modifications or extensions can be done by modifying or extending internal servers.

Separation of low-level mechanisms (provided by microkernel and internal servers) and higher-level policies (provided by external servers) improves maintainability and changeability of the system.

There are some concerns about it as well.

1. The microkernel system requires much more inter-process communication inside one application execution because of the calls to internal and external servers.
2. The design and implementation of the microkernel -based system is far more complex than of a monolithic system

Reflection :

- The **Reflection** pattern provides a mechanism for changing structure and behavior of software systems dynamically. It supports the modification of fundamental aspects, such as type structures and function call mechanisms. In this pattern, an application is split into two parts. A meta level provides information about selected system properties and makes the software self-aware. A base level includes the application logic. Its implementation builds on the meta level. Changes to information kept in the meta level affect subsequent base-level behavior.

- The **Reflection** pattern provides a mechanism for changing structure and behavior of software systems dynamically. It supports the modification of fundamental aspects, such as type structures and function call mechanisms. In this pattern, an application is split into two parts. A meta level provides information about selected system properties and makes the software self-aware. A base level includes the application logic. Its implementation builds on the meta level. Changes to information kept in the meta level affect subsequent base-level behavior.

- The Reflective Blackboard architectural pattern is independent of programming languages and specific implementation frameworks, and its use can minimize the complexity caused by the presence of numerous system-level properties in MASs.

Structure

- The controller subsystem is composed of a meta-object protocol (MOP) component that together with a collection of meta-objects implement the multi-agent system control strategies. Meta-objects are composed of data (metadata) and are responsible for associating specific behavior (reactions) to operations performed over specific pieces of data.

These meta-objects can transparently modify the normal behavior of the blackboard, thus implementing the multi-agent system control strategies. Different agents can act over the blackboard by means of their sensors and effectuators, which can respectively sense and perform changes in the blackboard that can be considered their environment. The agents do not communicate directly; they only write and read data from the blackboard.

- Whenever an agent performs any operation over a specific piece of data stored at blackboard, the MOP component verifies if there is any meta-object associated to it. If positive it executes the reaction associated to the meta-object, i.e. its behavior.The meta-object execution can access the blackboard writing and deleting data.

- In this way, in a reflective blackboard architecture the semantics of a blackboard operation, in fact, is the result of the execution of the meta-objects associated to it. Meta-objects also may exist in the control subsystem without correspondent data in the blackboard. In this way the multi-agent system can associate reactions to data that is part of the multi-agent system vocabulary and probably will be written in the blackboard at runtime.

Reflection is used to intercept and modify the effects of operations of the blackboard.

From the point of view of application agents, computational reflection is transparent: an agent writes a piece of data on the blackboard, and has no knowledge this write operation has been intercepted and redirected to the meta-level. The following scenario illustrates the general behavior of the Reflective Blackboard architecture:

1. A knowledge source (or agent) performs an operation on the blackboard (write for example), supplying a piece of data and expecting some other piece of retrieved data;
2. This operation is intercepted by the meta-level's MOP, which will perform, if specified, control activities over the performed operation;
3. The MOP checks for the existence of meta-objects associated to the blackboard data and related to the performed operation. If the knowledge source has performed a write operation on the blackboard, the searched meta-objects will be those related to the written piece of data. On the other hand, if the knowledge source has performed read or delete operations, the searched meta-object will be related to the piece of data read from the blackboard;

UNIT-7

Contents

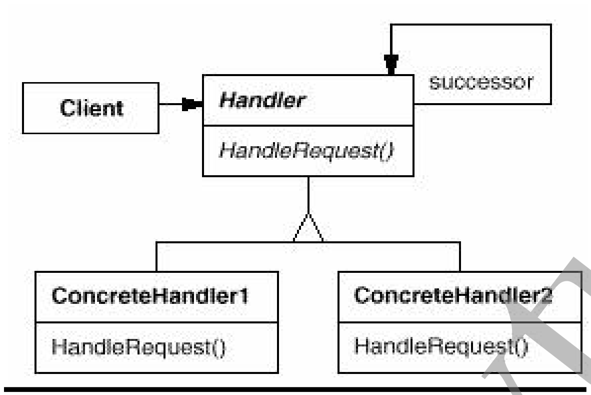
- **Some Design Patterns**
- Structural decomposition
- Whole – Part
- Organization of work: Master – Slave
- Access Control
- Proxy

UNIT-7
Chapter 9: SOME DESIGN PATTERNS

Structural Decomposition :

Design patterns systematically names, explains and evaluates an important and recurring design in object-oriented systems. Their main objective is to reuse successful designs and architectures of experienced and professional designers. Structural design patterns relate to class and object composition. They use inheritance to compose interfaces and define ways to compose objects to obtain new functionality.

The design patterns in this group further emphasize and clarify the fundamental differences between the UML and OPM design pattern models:



whole-Part :

In this there will be two parts. The structure of whole and part are shown below :

Class: Whole

Responsibility:

- Aggregates several smaller objects
- Provides services built on top of part objects
- Acts as a wrapper around its constituent parts

Collaborators: Part

Class: Part

Responsibility:
- Represents a particular object and its services

Collaborators: - Nil

- Whole object: It is an aggregation of smaller objects
- The smaller objects are called Parts

Whole object forms a semantic grouping of its Parts in that it coordinates and organizes their collaboration

The Whole uses the functionality of Parts objects for implementing services

Implementation

1. Design the public Interface of the Whole
2. Separate the Whole into Parts, or make it from existing ones (Use either bottom- up, top-down or both mixed)
3. Use existing Parts from component libraries or class libraries or package, specify their collaboration if you use bottom-up approach
4. Partition the Whole's services into smaller collaborating services and map these collaborating services to separate Parts if you follow a top-down approach
5. Specific the services of the Whole in terms of services of the Parts
6. Implement the Parts (Recursively if Parts are not leaf)
7. Implement the Whole by putting all the Parts together

Advantages

Changeability of Parts

Reusability

Defines class hierarchies consisting of primitive objects

Makes the client simple

Makes it easier to add new kinds of components

Disadvantages

1) Makes your design overly general
2) Lower efficiency through indirection
3) Complexity of decomposition into Parts might be an art

Organization of work : Master-Slave :

- The Master-Slave design pattern supports fault tolerance, parallel computation and computational accuracy. A master component distributes work to identical slave components and computes a final result from the results these slaves return.

- It is used when you have two or more processes that need to run simultaneously and continuously but at different rates. If these processes run in a single loop, severe timing issues can occur. These timing issues occur when one part of the loop takes longer to execute than expected. If this happens, the remaining sections in the loop get delayed.

- The Master/Slave pattern consists of multiple parallel loops. Each of the loops may execute tasks at different rates. Of these parallel loops, one loop acts as the master and the others act as slaves. The master loop controls all of the slave loops, and communicates with them using messaging architectures.

- It acquires a waveform from a transmission line and displays it on a graph every 100ms, and also provides a user interface that allows the user to change parameters for each acquisition. The Master/Slave design pattern is well suited for this application. In this application, the master loop will contain the user interface. The voltage acquisition and logging will happen in one slave loop, while the transmission line acquisition and graphing will.

- This situation can be avoided by applying the Master/Slave design pattern to the application. In this case, the user interface will be handled by the master loop, and every controllable section of the robotic arm will have its own slave loop. Using this method, each controllable section of the arm will have its own loop, and therefore, its own piece of processing time.

- The Master/Slave design pattern is very advantageous when creating multi-task applications. It gives you a more modular approach to application development because of its multi-loop functionality, but most importantly, it gives you more control of your application's time management.

The Master/Slave design pattern consists of multiple parallel loops. The loop that controls all the others is the master and the remaining loops are slaves. One master loop

always drives one or more slave loops. Since data communication directly between these loops breaks data flow, it must be done by writing and reading to messaging architectures

An access control model describes at a high level of abstraction a mechanism for governing access to shared resources.

UNIT 8

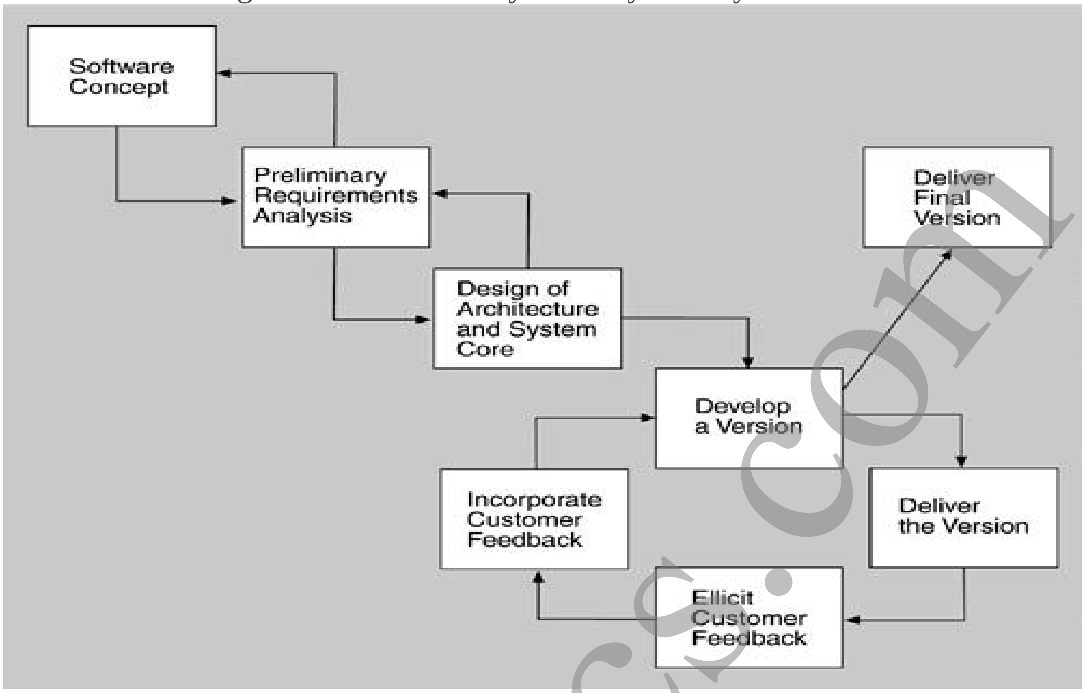
Contents

Chapter 10 : Designing and documenting software Architecture

Architecture in the Life Cycle :

Any organization that embraces architecture as a foundation for its software development processes needs to understand its place in the life cycle. Several life-cycle models exist in the literature, but one that puts architecture squarely in the middle of things is the Evolutionary Delivery Life Cycle model shown in Figure 7.1. The intent of this model is to get user and customer feedback and iterate through several releases before the final release. The model also allows the adding of functionality with each iteration and the delivery of a limited version once a sufficient set of features has been developed.

Figure 7.1. Evolutionary Delivery Life Cycle


Software Concept
Preliminary Requirements Analysis
Design of Architecture and System Core
Develop a Version
Deliver Final Version
Deliver the Version
Incorporate Customer Feedback
Ellicit Customer Feedback

The life-cycle model shows the design of the architecture as iterating with preliminary requirements analysis. Clearly, one cannot begin the design until he has some idea of the system requirements. On the other hand, it does not take many requirements in order for design to begin.

Once the architectural drivers are known, the architectural design can begin. The requirements analysis process will then be influenced by the questions generated during architectural design one of the reverse-direction arrows shown in Figure 7.1.

Designing the Architecture :

There is a method for designing an architecture to satisfy both quality requirements and functional requirements. This method is known as Attribute-Driven Design (ADD). ADD takes as input a set of quality attribute scenarios and employs knowledge about the relation between quality attribute achievement and architecture in order to design the architecture.

The ADD method can be viewed as an extension to most other development methods, such as the Rational Unified Process. The Rational Unified Process has several steps that result in the high-level design of an architecture but then proceeds to detailed design and implementation. Incorporating ADD into it involves modifying the steps dealing with the high-level design of the architecture and then following the process as described by Rational.

ATTRIBUTE-DRIVEN DESIGN

- ADD is an approach to defining a software architecture that bases the decomposition process on the quality attributes the software has to fulfill. It is a recursive decomposition process where, at each stage, tactics and architectural patterns are chosen to satisfy a set of quality scenarios and then functionality is allocated to instantiate the module types provided by the pattern. ADD is positioned in the life cycle after requirements analysis and, as we have said, can begin when the architectural drivers are known with some confidence.

- The output of ADD is the first several levels of a module decomposition view of an architecture and other views as appropriate. Not all details of the views result from an application of ADD; the system is described as a set of containers for functionality and the interactions among them. This is the first articulation of architecture during the design process and is therefore necessarily coarse grained.

- Nevertheless, it is critical for achieving the desired qualities, and it provides a framework for achieving the functionality. The difference between an architecture resulting from ADD and one ready for implementation rests in the more detailed design decisions that need to be made. These could be, for example, the decision to use specific object-oriented design patterns or a specific piece of middleware that brings with it many architectural constraints. The architecture designed by ADD may have intentionally deferred this decision to be more flexible.

ADD Steps

Following are the steps performed when designing an architecture using the ADD method.

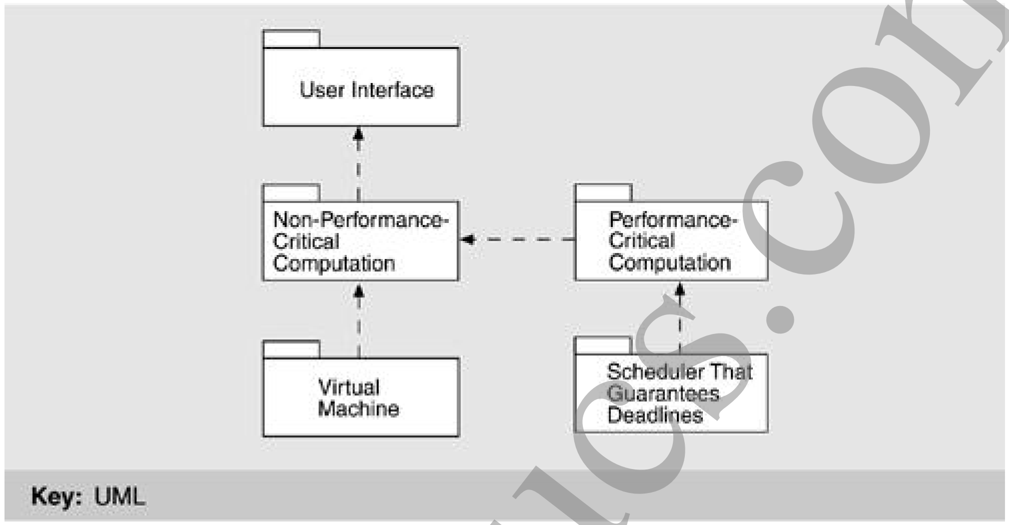
1. Choose the module to decompose. The module to start with is usually the whole system. All required inputs for this module should be available (constraints, functional requirements, quality requirements).
2. Refine the module according to these steps:
    a. Choose the architectural drivers from the set of concrete quality scenarios and functional requirements. This step determines what is important for this decomposition.
    b. Choose an architectural pattern that satisfies the architectural drivers. Create (or select) the pattern based on the tactics that can be used to achieve the drivers. Identify child modules required to implement the tactics.
    c. Instantiate modules and allocate functionality from the use cases and represent using multiple views.
    d. Define interfaces of the child modules. The decomposition provides modules and constraints on the types of module interactions. Document this information in

the interface document for each module.

e. Verify and refine use cases and quality scenarios and make them constraints for the child modules. This step verifies that nothing important was forgotten and prepares the child modules for further decomposition or implementation.

3. Repeat the steps above for every module that needs further decomposition.

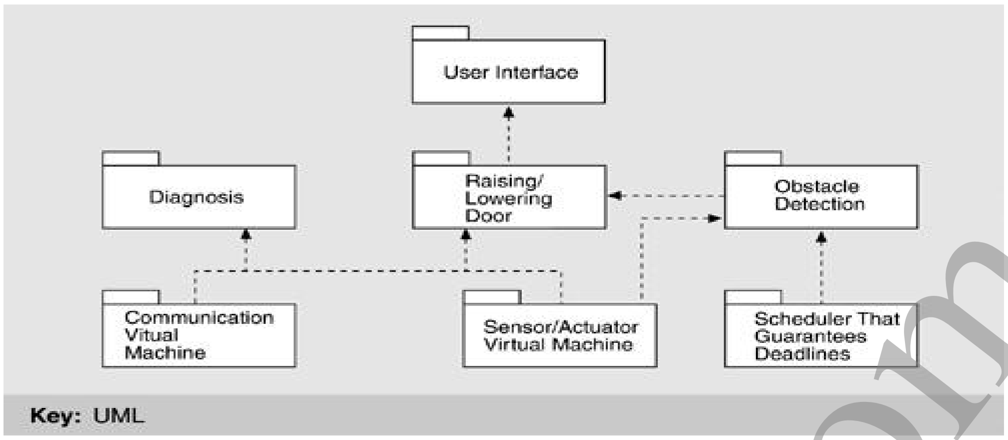
Figure 7.2. Architectural pattern that utilizes tactics to achieve garage door drivers


User Interface
Non-Performance-Critical Computation
Performance-Critical Computation
Virtual Machine
Scheduler That Guarantees Deadlines
Key: UML

Instantiate modules

In Figure 7.2, it identifies a non-performance-critical computation running on top of a virtual machine that manages communication and sensor interactions. The software running on top of the virtual machine is typically an application. In a concrete system we will normally have more than one module. There will be one for each "group" of functionality; these will be instances of the types shown in the pattern. Our criterion for allocating functionality is similar to that used in functionality-based design methods, such as most object-oriented design methods.

Figure 7.3. First-level decomposition of garage door opener


User Interface
Diagnosis
Raising/ Lowering Door
Obstacle Detection
Communication Vitual Machine
Sensor/Actuator Virtual Machine
Scheduler That Guarantees Deadlines
Key: UML

The result of this step is a plausible decomposition of a module. The next steps verify how well the decomposition achieves the required functionality.

Allocate functionality

- Applying use cases that pertain to the parent module helps the architect gain a more detailed understanding of the distribution of functionality. This also may lead to adding or removing child modules to fulfill all the functionality required. At the end, every use case of the parent module must be representable by a sequence of responsibilities within the child modules.

- Assigning responsibilities to the children in a decomposition also leads to the discovery of necessary information exchange. This creates a producer/consumer relationship between those modules, which needs to be recorded. At this point in the design, it is not important to define how the information is exchanged.

- Is the information pushed or pulled? Is it passed as a message or a call parameter? These are all questions that need to be answered later in the design process. At this point only the information itself and the producer and consumer roles are of interest. This is an example of the type of information left unresolved by ADD and resolved during detailed design.

- Some tactics introduce specific patterns of interaction between module types. A tactic using an intermediary of type publish-subscribe, for example, will introduce a pattern, "Publish" for one of the modules and a pattern "Subscribe" for the other. These patterns of interaction should be recorded since they translate into responsibilities for the affected modules.

These steps should be sufficient to gain confidence that the system can deliver the desired functionality. To check if the required qualities can be met, we need more than just the responsibilities so far allocated. Dynamic and runtime deployment information is also required to analyze the achievement of qualities such as performance, security, and reliability. Therefore, we examine additional views along with the module decomposition view.

Represent the architecture with views

- Module decomposition view-This shows how the module decomposition view provides containers for holding responsibilities as they are discovered. Major data flow relationships among the modules are also identified through this view.

- Concurrency view- In the concurrency view dynamic aspects of a system such as parallel activities and synchronization can be modeled. This modeling helps to identify resource contention problems, possible deadlock situations, data consistency issues, and so forth.

- Modeling the concurrency in a system likely leads to discovery of new responsibilities of the modules, which are recorded in the module view. It can also lead to discovery of new modules, such as a resource manager, in order to solve issues of concurrent access to a scarce resource and the like.

- The concurrency view is one of the component-and-connector views. The components are instances of the modules in the module decomposition view, and the connectors are the carriers of virtual threads. A "virtual thread" describes an execution path through the system or parts of it.

- This should not be confused with operating system threads (or processes), which implies other properties like memory/processor allocation. Those properties are not of interest on the level at which we are designing. Nevertheless, after the decisions on an operating system and on the deployment of modules to processing units are made, virtual threads have to be mapped onto operating system threads. This is done during detailed design.

- The connectors in a concurrency view are those that deal with threads such as "synchronizes with," "starts," "cancels," and "communicates with." A concurrency view shows instances of the modules in the module decomposition view as a means of understanding the mapping between those two views. It is important to know that a synchronization point is located in a specific module so that this responsibility can be assigned at the right place.

<u>Forming the Team Structure :</u>

Once the first few levels of the architecture's module decomposition structure are fairly stable, those modules can be allocated to development teams. This view will either allocate modules to existing development units or define new ones.

The close relationship between an architecture and the organization that produced it makes the point as follows:
Take any two nodes x and y of the system. Either they are joined by a branch or they are not. (That is, either they communicate with each other in some way meaningful to the

- operation of the system or they do not.) If there is a branch, then the two (not necessarily distinct) design groups X and Y which designed the two nodes must have negotiated and agreed upon an interface specification to permit communication between the two corresponding nodes of the design organization. If, on the other hand, there is no branch between x and y, then the subsystems do not communicate with each other, there was nothing for the two corresponding design groups to negotiate, and therefore there is no branch between X and Y.

- The impact of an architecture on the development of organizational structure is clear. Once an architecture for the system under construction has been agreed on, teams are allocated to work on the major modules and a work breakdown structure is created that reflects those teams. Each team then creates its own internal work practices (or a system-wide set of practices is adopted).

- For large systems, the teams may belong to different subcontractors. The work practices may include items such as bulletin boards and Web pages for communication, naming conventions for files, and the configuration control system. All of these may be different from group to group, again especially for large systems. Furthermore, quality assurance and testing procedures are set up for each group, and each group needs to establish liaisons and coordinate with the other groups.

- Thus, the teams within an organization work on modules. Within the team there needs to be high-bandwidth communications: Much information in the form of detailed design decisions is being constantly shared. Between teams, low-bandwidth communications are sufficient and in fact crucial.

- Highly complex systems result when these design criteria are not met. In fact, team structure and controlling team interactions often turn out to be important factors affecting a large project's success. If interactions between the teams need to be complex, either the interactions among the elements they are creating are needlessly complex or the requirements for those elements were not sufficiently "hardened" before development commenced. In this case, there is a need for high-bandwidth connections between teams, not just within teams, requiring substantial negotiations and often rework of elements and their interfaces. Like software systems, teams should strive for loose coupling and high cohesion.

- The module is a user interface layer of a system. The application programming interface that it presents to other modules is independent of the particular user interface devices (radio buttons, dials, dialog boxes, etc.) that it uses to present information to the human user, because those might change. The domain here is the repertoire of such devices.
- The module is a process scheduler that hides the number of available processors and the scheduling algorithm. The domain here is process scheduling and the list of appropriate algorithms.
- The module is the Physical Models Module of the A-7E architecture. It encapsulates the equations that compute values about the physical environment. The domain is numerical analysis (because the equations must be implemented to maintain sufficient accuracy in a digital computer) and avionics.

Recognizing modules as mini-domains immediately suggests that the most effective use of staff is to assign members to teams according to their expertise. Only the module structure permits this. As the sidebar Organizational and Architecural Structures discusses, organizations sometimes also add specialized groups that are independent of the architectural structures.

The impact of an organization on an architecture is more subtle but just as important as the impact of an architecture on the organization (of the group that builds the system described by the architecture).

Suppose you are a member of a group that builds database applications, assigned to work on a team designing an architecture for some application. inclination is probably to view the current problem as a database problem, to worry about what database system should be used or whether a home-grown one should be constructed, to assume that data retrievals are constructed as queries, and so on.

You therefore press for an architecture that has distinct subsystems for, say, data storage and management, and query formulation and implementation. A person from the telecommunications group, on the other hand, views the system in telecommunication terms, and for this person the database is a single subsystem.

Creating a Skeletal System :

- Once an architecture is sufficiently designed and teams are in place to begin building to it, a skeletal system can be constructed. The idea at this stage is to provide an underlying capability to implement a system's functionality in an order advantageous to the project

- Classical software engineering practice recommends "stubbing out" sections of code so that portions of the system can be added separately and tested independently. However, which portions should be stubbed? By using the architecture as a guide, a sequence of implementation becomes clear.

- First, implement the software that deals with the execution and interaction of architectural components. This may require producing a scheduler in a real-time system, implementing the rule engine (with a prototype set of rules) to control rule firing in a rule-based system, implementing process synchronization mechanisms in a multi-process system, or implementing client-server coordination in a client-server system.

- Often, the basic interaction mechanism is provided by third-party middleware, in which case the job becomes ones of installation instead of implementation. On top of this communication or interaction infrastructure, you may wish to install the simplest of functions, one that does little more than instigate some rote behavior. At this point, you will have a running system that essentially sits there and hums to itself, but a running system nevertheless. This is the foundation onto which useful functionality can be added.

- You can now choose which of the elements providing functionality should be added to the system. The choice may be based on lowering risk by addressing the most problematic areas first, or it may be based on the levels and type of staffing available, or it may be based on getting something useful to market as quickly as possible.

- Once the elements providing the next increment of functionality have been chosen, you can employ the uses structure to tell you what additional software should be running correctly in the system (as opposed to just being there in the form of a stub) to support that functionality.

- This process continues, growing larger and larger increments of the system, until it is all in place. At no point is the integration and testing task overwhelming; at every increment it is easy to find the source of newly introduced faults. Budgets and schedules are more predictable with smaller increments, which also provide management and marketing with more delivery options.

- Even the stubbed-out parts help pave the way for completion. These stubs adhere to the same interfaces that the final version of the system requires, so they can help with understanding and testing the interactions among components even in the absence of high-fidelity functionality.

- These stub components can exercise this interaction in two ways, either producing hard coded canned output or reading the output from a file. They can also generate a synthetic load on the system to approximate the amount of time the actual processing will take in the completed working version.

- This aids in early understanding of system performance requirements, including performance interactions and bottlenecks.

--- END---