Chapter 1. Introduction

Computer systems are undergoing a revolution. From 1945, when the modern computer era began, until about 1985, computers were large and expensive. Even minicomputers cost at least tens of thousands of dollars each. As a result, most organizations had only a handful of computers, and for lack of a way to connect them, these operated independently from one another.

Starting around the the mid-1980s, however, two advances in technology began to change that situation. The first was the development of powerful microprocessors. Initially, these were 8-bit machines, but soon 16-, 32-, and 64-bit CPUs became common. Many of these had the computing power of a mainframe (i.e., large) computer, but for a fraction of the price.

The amount of improvement that has occurred in computer technology in the past half century is truly staggering and totally unprecedented in other industries. From a machine that cost 10 million dollars and executed 1instruction per second, we have come to machines that cost 1000 dollars and are able to execute 1 billion instructions per second, a price/performance gain of 1013. If cars had improved at this rate in the same time period, a Rolls Royce would now cost 1 dollar and get a billion miles per gallon. (Unfortunately, it would probably also have a 200-page manual telling how to open the door.)

The second development was the invention of high-speed computer networks. Local-area networks or LANs allow hundreds of machines within a building to be connected in such a way that small amounts of information can be transferred between machines in a few microseconds or so. Larger amounts of data can be moved between machines at rates of 100 million to 10 billion bits/sec. Wide-area networks or WANs allow millions of machines all over the earth to be connected at speeds varying from 64 Kbps (kilobits per second) to gigabits per second.
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The result of these technologies is that it is now not only feasible, but easy, to put together computing systems composed of large numbers of computers connected by a high-speed network. They are usually called computer networks or distributed systems, in contrast to the previous centralized systems (or single-processor systems) consisting of a single computer, its peripherals, and perhaps some remote terminals.

1.1. Definition of a Distributed System

Various definitions of distributed systems have been given in the literature, none of them satisfactory, and none of them in agreement with any of the others. For our purposes it is sufficient to give a loose characterization:

A distributed system is a collection of independent computers that appears to its users as a single coherent system.

This definition has several important aspects. The first one is that a distributed system consists of components (i.e., computers) that are autonomous. A second aspect is that users (be they people or programs) think they are dealing with a single system. This means that one way or the other the autonomous components need to collaborate. How to establish this collaboration lies at the heart of developing distributed systems. Note that no assumptions are made concerning the type of computers. In principle, even within a single system, they could range from high-performance mainframe computers to small nodes in sensor networks. Likewise, no assumptions are made on the way that computers are interconnected. We will return to these aspects later in this chapter.

Instead of going further with definitions, it is perhaps more useful to concentrate on important characteristics of distributed systems. One important characteristic is that differences between the various computers and the ways in which they communicate are mostly hidden from users. The same holds for the internal organization of the distributed system. Another important characteristic is that users and applications can interact with a distributed system in a consistent and uniform way, regardless of where and when interaction takes place.

In principle, distributed systems should also be relatively easy to expand or scale. This characteristic is a direct consequence of having independent computers, but at the same time, hiding how these computers actually take part in the system as a whole. A distributed system will normally be continuously available, although perhaps some parts may be temporarily out of order. Users and applications should not notice that parts are being replaced or fixed, or that new parts are added to serve more users or applications.
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In order to support heterogeneous computers and networks while offering a single-system view, distributed systems are often organized by means of a layer of software–that is, logically placed between a higher-level layer consisting of users

and applications, and a layer underneath consisting of operating systems and basic communication facilities, as shown in Fig. 1-1 Accordingly, such a distributed system is sometimes called middleware.

Figure 1-1. A distributed system organized as middleware. The middleware layer extends over multiple machines, and offers each application the same interface.

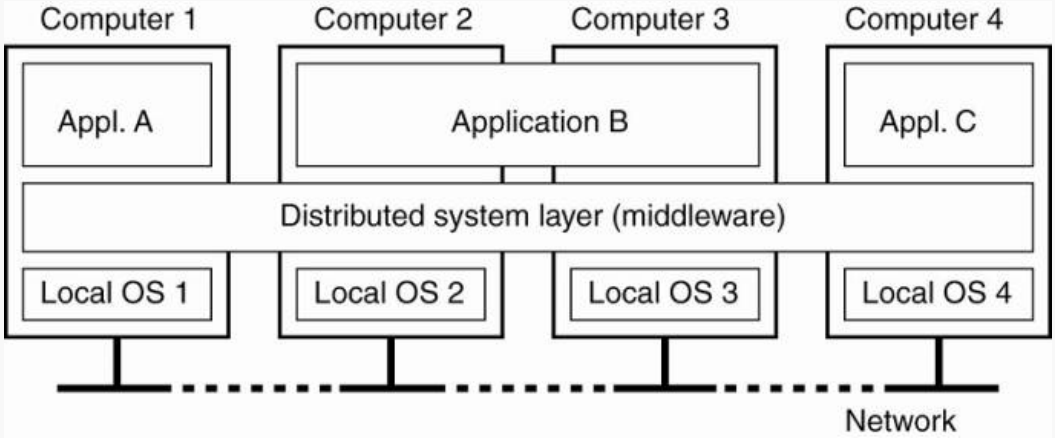

Fig. 1-1 shows four networked computers and three applications, of which application B is distributed across computers 2 and 3. Each application is offered the same interface. The distributed system provides the means for components of a single distributed application to communicate with each other, but also to let different applications communicate. At the same time, it hides, as best and reasonable as possible, the differences in hardware and operating systems from each application.

1.2. Goals

Just because it is possible to build distributed systems does not necessarily mean that it is a good idea. After all, with current technology it is also possible to put four floppy disk drives on a personal computer. It is just that doing so would be pointless. In this section we discuss four important goals that should be met to make building a distributed system worth the effort. A distributed system should make resources easily accessible; it should reasonably hide the fact that resources are distributed across a network; it should be open; and it should be scalable.

1.2.1. Making Resources Accessible

The main goal of a distributed system is to make it easy for the users (and applications) to access remote resources, and to share them in a controlled and efficient way. Resources can be just about anything, but typical examples include things like printers, computers, storage facilities, data, files, Web pages, and networks, to name just a few. There are many reasons for wanting to share resources. One obvious reason is that of economics. For example, it is cheaper to let a printer be shared by several users in a small office than having to buy and maintain a separate printer for each user. Likewise, it makes economic sense to share costly resources such as supercomputers, high-performance storage systems, imagesetters, and other expensive peripherals.
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Connecting users and resources also makes it easier to collaborate and exchange information, as is clearly illustrated by the success of the Internet with its simple protocols for exchanging files, mail, documents, audio, and video. The connectivity of the Internet is now leading to numerous virtual organizations in which geographically widely-dispersed groups of people work together by means of groupware, that is, software for collaborative editing, teleconferencing, and so on. Likewise, the Internet connectivity has enabled electronic commerce allowing us to buy and sell all kinds of goods without actually having to go to a store or even leave home.

However, as connectivity and sharing increase, security is becoming increasingly important. In current practice, systems provide little protection against eavesdropping or intrusion on communication. Passwords and other sensitive information are often sent as cleartext (i.e., unencrypted) through the network, or stored at servers that we can only hope are trustworthy. In this sense, there is much room for improvement. For example, it is currently possible to order goods by merely supplying a credit card number. Rarely is proof required that the customer owns the card. In the future, placing

orders this way may be possible only if you can actually prove that you physically possess the card by inserting it into a card reader.

Another security problem is that of tracking communication to build up a preference profile of a specific user (Wang et al., 1998). Such tracking explicitly violates privacy, especially if it is done without notifying the user. A related problem is that increased connectivity can also lead to unwanted communication, such as electronic junk mail, often called spam. In such cases, what we may need is to protect ourselves using special information filters that select incoming messages based on their content.

1.2.2. Distribution Transparency

An important goal of a distributed system is to hide the fact that its processes and resources are physically distributed across multiple computers. A distributed system that is able to present itself to users and applications as if it were only a single computer system is said to be transparent. Let us first take a look at what kinds of transparency exist in distributed systems. After that we will address the more general question whether transparency is always required.
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Types of Transparency

The concept of transparency can be applied to several aspects of a distributed system, the most important ones shown in Fig. 1-2.

Figure 1-2. Different forms of transparency in a distributed system (ISO, 1995).

Transparency	Description
Access	Hide differences in data representation and how a resource is accessed
Location	Hide where a resource is located
Migration	Hide that a resource may move to another location
Relocation	Hide that a resource may be moved to another location while in use
Replication	Hide that a resource is replicated
Concurrency	Hide that a resource may be shared by several competitive users
Failure	Hide the failure and recovery of a resource

Access transparency deals with hiding differences in data representation and the way that resources can be accessed by users. At a basic level, we wish to hide differences in machine architectures, but more important is that we reach agreement on how data is to be represented by different machines and operating systems. For example, a distributed system may have computer systems that run different operating systems, each having their own file-naming conventions. Differences in naming conventions, as well as how files can be manipulated, should all be hidden from users and applications.

An important group of transparency types has to do with the location of a resource. Location transparency refers to the fact that users cannot tell where a resource is physically located in the system. Naming plays an important role in achieving location transparency. In particular, location transparency can be achieved by assigning only logical names to resources, that is, names in which the location of a resource is not secretly encoded. An example of a such a name is the URL http://www.prenhall.com/index.html, which gives no clue about the location of Prentice Hall's main Web server. The URL also gives no clue as to whether index.html has always been at its current location or was recently moved there. Distributed systems in which resources can be moved without affecting how those resources can be accessed are said to provide migration transparency. Even stronger is the situation in which resources can be relocated while they are being accessed without the user or application noticing anything. In such cases, the system is said to support relocation transparency. An example of relocation transparency is when mobile users can continue to use their wireless laptops while moving from place to place without ever being (temporarily) disconnected.

As we shall see, replication plays a very important role in distributed systems. For example, resources may be replicated to increase availability or to improve performance by placing a copy close to the place where it is accessed. Replication transparency deals with hiding the fact that several copies of a resource exist. To hide replication from users, it is necessary that all replicas have the same name. Consequently, a system that supports replication transparency should generally support location transparency as well, because it would otherwise be impossible to refer to replicas at different locations.
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We already mentioned that an important goal of distributed systems is to allow sharing of resources. In many cases, sharing resources is done in a cooperative way, as in the case of communication. However, there are also many examples of

competitive sharing of resources. For example, two independent users may each have stored their files on the same file server or may be accessing the same tables in a shared database. In such cases, it is important that each user does not notice that the other is making use of the same resource. This phenomenon is called concurrency transparency. An important issue is that concurrent access to a shared resource leaves that resource in a consistent state. Consistency can be achieved through locking mechanisms, by which users are, in turn, given exclusive access to the desired resource. A more refined mechanism is to make use of transactions, but as we shall see in later chapters, transactions are quite difficult to implement in distributed systems.

A popular alternative definition of a distributed system, due to Leslie Lam-port, is "You know you have one when the crash of a computer you've never heard of stops you from getting any work done." This description puts the finger on another important issue of distributed systems design: dealing with failures. Making a distributed system failure transparent means that a user does not notice that a resource (he has possibly never heard of) fails to work properly, and that the system subsequently recovers from that failure. Masking failures is one of the hardest issues in distributed systems and is even impossible when certain apparently realistic assumptions are made, as we will discuss in Chap. 8. The main difficulty in masking failures lies in the inability to distinguish between a dead resource and a painfully slow resource. For example, when contacting a busy Web server, a browser will eventually time out and report that the Web page is unavailable. At that point, the user cannot conclude that the server is really down.
Degree of Transparency

Although distribution transparency is generally considered preferable for any distributed system, there are situations in which attempting to completely hide all distribution aspects from users is not a good idea. An example is requesting your electronic newspaper to appear in your mailbox before 7 A.M. local time, as usual, while you are currently at the other end of the world living in a different time zone. Your morning paper will not be the morning paper you are used to.

Likewise, a wide-area distributed system that connects a process in San Francisco to a process in Amsterdam cannot be expected to hide the fact that Mother Nature will not allow it to send a message from one process to the other in less than about 35 milliseconds. In practice it takes several hundreds of milliseconds using a computer network. Signal transmission is not only limited by the speed of light, but also by limited processing capacities of the intermediate switches.
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There is also a trade-off between a high degree of transparency and the performance of a system. For example, many Internet applications repeatedly try to contact a server before finally giving up. Consequently, attempting to mask a transient server failure before trying another one may slow down the system as a whole. In such a case, it may have been better to give up earlier, or at least let the user cancel the attempts to make contact.

Another example is where we need to guarantee that several replicas, located on different continents, need to be consistent all the time. In other words, if one copy is changed, that change should be propagated to all copies before allowing any other operation. It is clear that a single update operation may now even take seconds to complete, something that cannot be hidden from users.

Finally, there are situations in which it is not at all obvious that hiding distribution is a good idea. As distributed systems are expanding to devices that people carry around, and where the very notion of location and context awareness is becoming increasingly important, it may be best to actually expose distribution rather than trying to hide it. This distribution exposure will become more evident when we discuss embedded and ubiquitous distributed systems later in this chapter. As a simple example, consider an office worker who wants to print a file from her notebook computer. It is better to send the print job to a busy nearby printer, rather than to an idle one at corporate headquarters in a different country.

There are also other arguments against distribution transparency. Recognizing that full distribution transparency is simply impossible, we should ask ourselves whether it is even wise to pretend that we can achieve it. It may be much better to make distribution explicit so that the user and application developer are never tricked into believing that there is such a thing as transparency. The result will be that users will much better understand the (sometimes unexpected) behavior of a distributed system, and are thus much better prepared to deal with this behavior.

The conclusion is that aiming for distribution transparency may be a nice goal when designing and implementing distributed systems, but that it should be considered together with other issues such as performance and comprehensibility. The price for not being able to achieve full transparency may be surprisingly high.

1.2.3. Openness

Another important goal of distributed systems is openness. An open distributed system is a system that offers services according to standard rules that describe the syntax and semantics of those services. For example, in computer networks,

standard rules govern the format, contents, and meaning of messages sent and received. Such rules are formalized in protocols. In distributed systems, services are generally specified through interfaces, which are often described in an Interface Definition Language (IDL). Interface definitions written in an IDL nearly always capture only the syntax of services. In other words, they specify precisely the names of the functions that are available together with types of the parameters, return values, possible exceptions that can be raised, and so on. The hard part is specifying precisely what those services do, that is, the semantics of interfaces. In practice, such specifications are always given in an informal way by means of natural language.
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If properly specified, an interface definition allows an arbitrary process that needs a certain interface to talk to another process that provides that interface. It also allows two independent parties to build completely different implementations of those interfaces, leading to two separate distributed systems that operate in exactly the same way. Proper specifications are complete and neutral. Complete means that everything that is necessary to make an implementation has indeed been specified. However, many interface definitions are not at all complete, so that it is necessary for a developer to add implementation-specific details. Just as important is the fact that specifications do not prescribe what an implementation should look like; they should be neutral. Completeness and neutrality are important for interoperability and portability (Blair and Stefani, 1998). Interoperability characterizes the extent by which two implementations of systems or components from different manufacturers can co-exist and work together by merely relying on each other's services as specified by a common standard. Portability characterizes to what extent an application developed for a distributed system A can be executed, without modification, on a different distributed system B that implements the same interfaces as A.

Another important goal for an open distributed system is that it should be easy to configure the system out of different components (possibly from different developers). Also, it should be easy to add new components or replace existing ones without affecting those components that stay in place. In other words, an open distributed system should also be extensible. For example, in an extensible system, it should be relatively easy to add parts that run on a different operating system, or even to replace an entire file system. As many of us know from daily practice, attaining such flexibility is easier said than done.
Separating Policy from Mechanism

To achieve flexibility in open distributed systems, it is crucial that the system is organized as a collection of relatively small and easily replaceable or adaptable components. This implies that we should provide definitions not only for the highest-level interfaces, that is, those seen by users and applications, but also definitions for interfaces to internal parts of the system and describe how those parts interact. This approach is relatively new. Many older and even contemporary systems are constructed using a monolithic approach in which components are only logically separated but implemented as one, huge program. This approach makes it hard to replace or adapt a component without affecting the entire system. Monolithic systems thus tend to be closed instead of open.
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The need for changing a distributed system is often caused by a component that does not provide the optimal policy for a specific user or application. As an example, consider caching in the World Wide Web. Browsers generally allow users to adapt their caching policy by specifying the size of the cache, and whether a cached document should always be checked for consistency, or perhaps only once per session. However, the user cannot influence other caching parameters, such as how long a document may remain in the cache, or which document should be removed when the cache fills up. Also, it is impossible to make caching decisions based on the content of a document. For instance, a user may want to cache railroad timetables, knowing that these hardly change, but never information on current traffic conditions on the highways.

What we need is a separation between policy and mechanism. In the case of Web caching, for example, a browser should ideally provide facilities for only storing documents, and at the same time allow users to decide which documents are stored and for how long. In practice, this can be implemented by offering a rich set of parameters that the user can set (dynamically). Even better is that a user can implement his own policy in the form of a component that can be plugged into the browser. Of course, that component must have an interface that the browser can understand so that it can call procedures of that interface.

1.2.4. Scalability

Worldwide connectivity through the Internet is rapidly becoming as common as being able to send a postcard to anyone anywhere around the world. With this in mind, scalability is one of the most important design goals for developers of distributed systems.

Scalability of a system can be measured along at least three different dimensions (Neuman, 1994). First, a system can be scalable with respect to its size, meaning that we can easily add more users and resources to the system. Second, a geographically scalable system is one in which the users and resources may lie far apart. Third, a system can be administratively scalable, meaning that it can still be easy to manage even if it spans many independent administrative organizations. Unfortunately, a system that is scalable in one or more of these dimensions often exhibits some loss of performance as the system scales up.

Scalability Problems

When a system needs to scale, very different types of problems need to be solved. Let us first consider scaling with respect to size. If more users or resources need to be supported, we are often confronted with the limitations of centralized services, data, and algorithms (see Fig. 1-3). For example, many services are centralized in the sense that they are implemented by means of only a single server running on a specific machine in the distributed system. The problem with this scheme is obvious: the server can become a bottleneck as the number of users and applications grows. Even if we have virtually unlimited processing and storage capacity, communication with that server will eventually prohibit further growth.

Figure 1-3. Examples of scalability limitations.

Concept	Example
Centralized services	A single server for all users
Centralized data	A single on-line telephone book
Centralized algorithms	Doing routing based on complete information

Unfortunately, using only a single server is sometimes unavoidable. Imagine that we have a service for managing highly confidential information such as medical records, bank accounts, and so on. In such cases, it may be best to implement that service by means of a single server in a highly secured separate room, and protected from other parts of the distributed system through special network components. Copying the server to several locations to enhance performance may be out of the question as it would make the service less secure.

Just as bad as centralized services are centralized data. How should we keep track of the telephone numbers and addresses of 50 million people? Suppose that each data record could be fit into 50 characters. A single 2.5-gigabyte disk partition would provide enough storage. But here again, having a single database would undoubtedly saturate all the communication lines into and out of it. Likewise, imagine how the Internet would work if its Domain Name System (DNS) was still implemented as a single table. DNS maintains information on millions of computers worldwide and forms an essential service for locating Web servers. If each request to resolve a URL had to be forwarded to that one and only DNS server, it is clear that no one would be using the Web (which, by the way, would solve the problem).

Finally, centralized algorithms are also a bad idea. In a large distributed system, an enormous number of messages have to be routed over many lines. From a theoretical point of view, the optimal way to do this is collect complete information about the load on all machines and lines, and then run an algorithm to compute all the optimal routes. This information can then be spread around the system to improve the routing.

The trouble is that collecting and transporting all the input and output information would again be a bad idea because these messages would overload part of the network. In fact, any algorithm that operates by collecting information from all the sites, sends it to a single machine for processing, and then distributes the results should generally be avoided. Only decentralized algorithms should be used. These algorithms generally have the following characteristics, which distinguish them from centralized algorithms:

1. No machine has complete information about the system state.
2. Machines make decisions based only on local information.
3. Failure of one machine does not ruin the algorithm.
4. There is no implicit assumption that a global clock exists.

The first three follow from what we have said so far. The last is perhaps less obvious but also important. Any algorithm that starts out with: "At precisely 12:00:00 all machines shall note the size of their output queue" will fail because it is impossible to get all the clocks exactly synchronized. Algorithms should take into account the lack of exact clock synchronization. The

larger the system, the larger the uncertainty. On a single LAN, with considerable effort it may be possible to get all clocks synchronized down to a few microseconds, but doing this nationally or internationally is tricky.

Geographical scalability has its own problems. One of the main reasons why it is currently hard to scale existing distributed systems that were designed for local-area networks is that they are based on synchronous communication. In this form of communication, a party requesting service, generally referred to as a client, blocks until a reply is sent back. This approach generally works fine in LANs where communication between two machines is generally at worst a few hundred microseconds. However, in a wide-area system, we need to take into account that interprocess communication may be hundreds of milliseconds, three orders of magnitude slower. Building interactive applications using synchronous communication in wide-area systems requires a great deal of care (and not a little patience).

Another problem that hinders geographical scalability is that communication in wide-area networks is inherently unreliable, and virtually always point-to-point. In contrast, local-area networks generally provide highly reliable communication facilities based on broadcasting, making it much easier to develop distributed systems. For example, consider the problem of locating a service. In a local-area system, a process can simply broadcast a message to every machine, asking if it is running the service it needs. Only those machines that have that service respond, each providing its network address in the reply message. Such a location scheme is unthinkable in a wide-area system: just imagine what would happen if we tried to locate a service this way in the Internet. Instead, special location services need to be designed, which may need to scale worldwide and be capable of servicing a billion users. We return to such services in Chap. 5.

Geographical scalability is strongly related to the problems of centralized solutions that hinder size scalability. If we have a system with many centralized components, it is clear that geographical scalability will be limited due to the performance and reliability problems resulting from wide-area communication. In addition, centralized components now lead to a waste of network resources. Imagine that a single mail server is used for an entire country. This would mean that sending an e-mail to your neighbor would first have to go to the central mail server, which may be hundreds of miles away. Clearly, this is not the way to go.

Finally, a difficult, and in many cases open question is how to scale a distributed system across multiple, independent administrative domains. A major problem that needs to be solved is that of conflicting policies with respect to resource usage (and payment), management, and security.

For example, many components of a distributed system that reside within a single domain can often be trusted by users that operate within that same domain. In such cases, system administration may have tested and certified applications, and may have taken special measures to ensure that such components cannot be tampered with. In essence, the users trust their system administrators. However, this trust does not expand naturally across domain boundaries.

If a distributed system expands into another domain, two types of security measures need to be taken. First of all, the distributed system has to protect itself against malicious attacks from the new domain. For example, users from the new domain may have only read access to the file system in its original domain. Likewise, facilities such as expensive image setters or high-performance computers may not be made available to foreign users. Second, the new domain has to protect itself against malicious attacks from the distributed system. A typical example is that of downloading programs such as applets in Web browsers. Basically, the new domain does not know behavior what to expect from such foreign code, and may therefore decide to severely limit the access rights for such code. The problem, as we shall see in Chap. 9, is how to enforce those limitations.

Scaling Techniques

Having discussed some of the scalability problems brings us to the question of how those problems can generally be solved. In most cases, scalability problems in distributed systems appear as performance problems caused by limited capacity of servers and network. There are now basically only three techniques for scaling: hiding communication latencies, distribution, and replication [see also Neuman (1994)].

Hiding communication latencies is important to achieve geographical scalability. The basic idea is simple: try to avoid waiting for responses to remote (and potentially distant) service requests as much as possible. For example, when a service has been requested at a remote machine, an alternative to waiting for a reply from the server is to do other useful work at the requester's side. Essentially, what this means is constructing the requesting application in such a way that it uses only asynchronous communication. When a reply comes in, the application is interrupted and a special handler is called to complete the previously-issued request. Asynchronous communication can often be used in batch-processing systems and parallel applications, in which more or less independent tasks can be scheduled for execution while another task is waiting

for communication to complete. Alternatively, a new thread of control can be started to perform the request. Although it blocks waiting for the reply, other threads in the process can continue.
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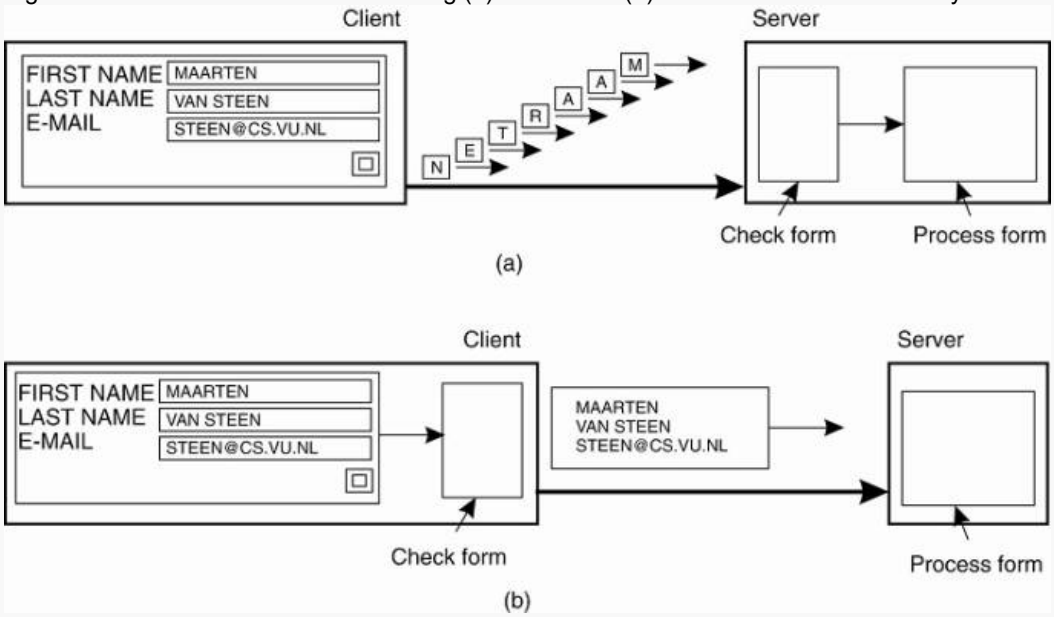
However, there are many applications that cannot make effective use of asynchronous communication. For example, in interactive applications when a user sends a request he will generally have nothing better to do than to wait for the answer. In such cases, a much better solution is to reduce the overall communication, for example, by moving part of the computation that is normally done at the server to the client process requesting the service. A typical case where this approach works is accessing databases using forms. Filling in forms can be done by sending a separate message for each field, and waiting for an acknowledgment from the server, as shown in Fig. 1-4(a). For example, the server may check for syntactic errors before accepting an entry. A much better solution is to ship the code for filling in the form, and possibly checking the entries, to the client, and have the client return a completed form, as shown in Fig. 1-4(b). This approach of shipping code is now widely supported by the Web in the form of Java applets and Javascript.

Figure 1-4. The difference between letting (a) a server or (b) a client check forms as they are being filled.



Another important scaling technique is distribution. Distribution involves taking a component, splitting it into smaller parts, and subsequently spreading those parts across the system. An excellent example of distribution is the Internet Domain Name System (DNS). The DNS name space is hierarchically organized into a tree of domains, which are divided into nonoverlapping zones, as shown in Fig. 1-5. The names in each zone are handled by a single name server. Without going into too many details, one can think of each path name being the name of a host in the Internet, and thus associated with a network address of that host. Basically, resolving a name means returning the network address of the associated host. Consider, for example, the name nl.vu.cs.flits. To resolve this name, it is first passed to the server of zone Z1 (see Fig. 1-5) which returns the address of the server for zone Z2, to which the rest of name, vu.cs.flits, can be handed. The server for Z2 will return the address of the server for zone Z3, which is capable of handling the last part of the name and will return the address of the associated host.
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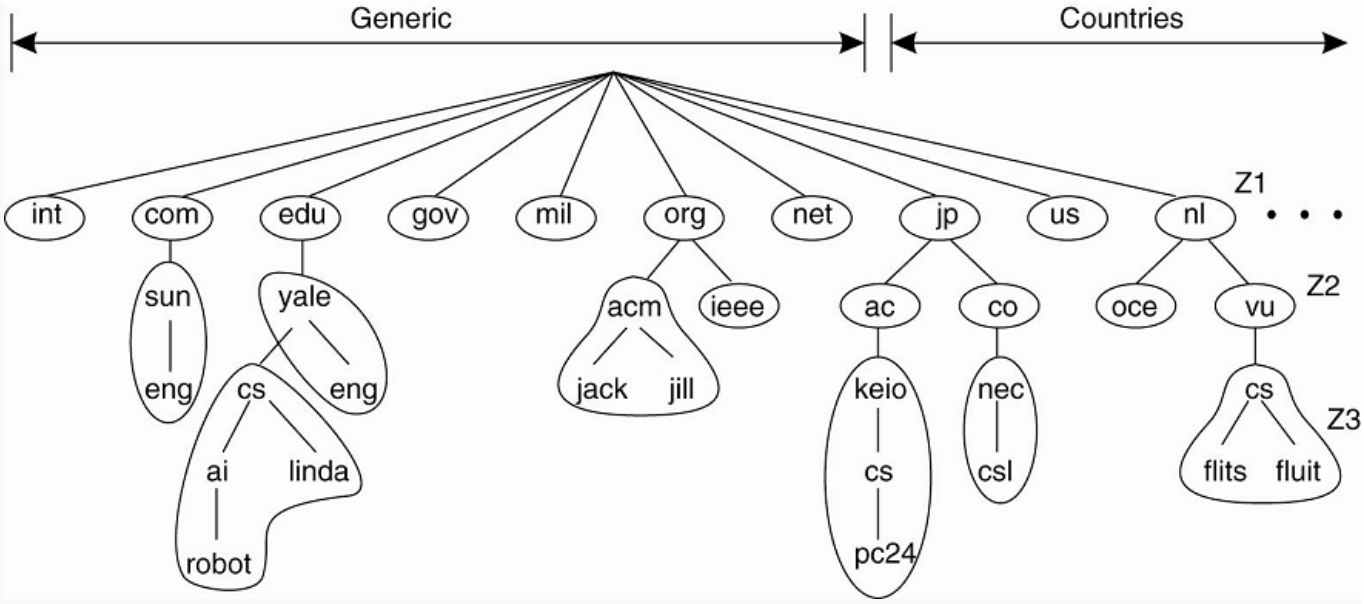
Figure 1-5. An example of dividing the DNS name space into zones.



This example illustrates how the naming service, as provided by DNS, is distributed across several machines, thus avoiding that a single server has to deal with all requests for name resolution.

As another example, consider the World Wide Web. To most users, the Web appears to be an enormous document-based information system in which each document has its own unique name in the form of a URL. Conceptually, it may even appear as if there is only a single server. However, the Web is physically distributed across a large number of servers, each handling a number of Web documents. The name of the server handling a document is encoded into that document's URL. It is only because of this distribution of documents that the Web has been capable of scaling to its current size.

Considering that scalability problems often appear in the form of performance degradation, it is generally a good idea to actually replicate components across a distributed system. Replication not only increases availability, but also helps to balance the load between components leading to better performance. Also, in geographically widely-dispersed systems, having a copy nearby can hide much of the communication latency problems mentioned before.
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Caching is a special form of replication, although the distinction between the two is often hard to make or even artificial. As in the case of replication, caching results in making a copy of a resource, generally in the proximity of the client accessing that resource. However, in contrast to replication, caching is a decision made by the client of a resource, and not by the owner of a resource. Also, caching happens on demand whereas replication is often planned in advance.

There is one serious drawback to caching and replication that may adversely affect scalability. Because we now have multiple copies of a resource, modifying one copy makes that copy different from the others. Consequently, caching and replication leads to consistency problems.

To what extent inconsistencies can be tolerated depends highly on the usage of a resource. For example, many Web users find it acceptable that their browser returns a cached document of which the validity has not been checked for the last few minutes. However, there are also many cases in which strong consistency guarantees need to be met, such as in the case of electronic stock exchanges and auctions. The problem with strong consistency is that an update must be immediately propagated to all other copies. Moreover, if two updates happen concurrently, it is often also required that each copy is updated in the same order. Situations such as these generally require some global synchronization mechanism. Unfortunately, such mechanisms are extremely hard or even impossible to implement in a scalable way, as she insists that photons and electrical signals obey a speed limit of 187 miles/msec (the speed of light). Consequently, scaling by replication may introduce other, inherently nonscalable solutions. We return to replication and consistency in Chap. 7.

When considering these scaling techniques, one could argue that size scalability is the least problematic from a technical point of view. In many cases, simply increasing the capacity of a machine will the save the day (at least temporarily and perhaps at significant costs). Geographical scalability is a much tougher problem as Mother Nature is getting in our way. Nevertheless, practice shows that combining distribution, replication, and caching techniques with different forms of consistency will often prove sufficient in many cases. Finally, administrative scalability seems to be the most difficult one, partly also because we need to solve nontechnical problems (e.g., politics of organizations and human collaboration). Nevertheless, progress has been made in this area, by simply ignoring administrative domains. The introduction and now widespread use of peer-to-peer technology demonstrates what can be achieved if end users simply take over control (Aberer and Hauswirth, 2005; Lua et al., 2005; and Oram, 2001). However, let it be clear that peer-to-peer technology can at best be only a partial solution to solving administrative scalability. Eventually, it will have to be dealt with.

1.2.5. Pitfalls

It should be clear by now that developing distributed systems can be a formidable task. As we will see many times throughout this book, there are so many issues to consider at the same time that it seems that only complexity can be the result. Nevertheless, by following a number of design principles, distributed systems can be developed that strongly adhere to the goals we set out in this chapter. Many principles follow the basic rules of decent software engineering and will not be repeated here.

However, distributed systems differ from traditional software because components are dispersed across a network. Not taking this dispersion into account during design time is what makes so many systems needlessly complex and results in mistakes that need to be patched later on. Peter Deutsch, then at Sun Microsystems, formulated these mistakes as the following false assumptions that everyone makes when developing a distributed application for the first time:

1. The network is reliable.
2. The network is secure.
3. The network is homogeneous.
4. The topology does not change.
5. Latency is zero.
6. Bandwidth is infinite.
7. Transport cost is zero.
8. There is one administrator.

Note how these assumptions relate to properties that are unique to distributed systems: reliability, security, heterogeneity, and topology of the network; latency and bandwidth; transport costs; and finally administrative domains. When developing nondistributed applications, many of these issues will most likely not show up.

Most of the principles we discuss in this book relate immediately to these assumptions. In all cases, we will be discussing solutions to problems that are caused by the fact that one or more assumptions are false. For example, reliable networks simply do not exist, leading to the impossibility of achieving failure transparency. We devote an entire chapter to deal with the fact that networked communication is inherently insecure. We have already argued that distributed systems need to take heterogeneity into account. In a similar vein, when discussing replication for solving scalability problems, we are essentially tackling latency and bandwidth problems. We will also touch upon management issues at various points throughout this book, dealing with the false assumptions of zero-cost transportation and a single administrative domain.

1.3. Types of Distributed Systems

Before starting to discuss the principles of distributed systems, let us first take a closer look at the various types of distributed systems. In the following we make a distinction between distributed computing systems, distributed information systems, and distributed embedded systems.

1.3.1. Distributed Computing Systems

An important class of distributed systems is the one used for high-performance computing tasks. Roughly speaking, one can make a distinction between two subgroups. In cluster computing the underlying hardware consists of a collection of similar workstations or PCs, closely connected by means of a high-speed local-area network. In addition, each node runs the same operating system.

The situation becomes quite different in the case of grid computing. This subgroup consists of distributed systems that are often constructed as a federation of computer systems, where each system may fall under a different administrative domain, and may be very different when it comes to hardware, software, and deployed network technology.

Cluster Computing Systems

Cluster computing systems became popular when the price/performance ratio of personal computers and workstations improved. At a certain point, it became financially and technically attractive to build a supercomputer using off-the-shelf technology by simply hooking up a collection of relatively simple computers in a high-speed network. In virtually all cases, cluster computing is used for parallel programming in which a single (compute intensive) program is run in parallel on multiple machines.

[Page 18]

One well-known example of a cluster computer is formed by Linux-based Beowulf clusters, of which the general configuration is shown in Fig. 1-6. Each cluster consists of a collection of compute nodes that are controlled and accessed by means of a single master node. The master typically handles the allocation of nodes to a particular parallel program, maintains a batch queue of submitted jobs, and provides an interface for the users of the system. As such, the master actually runs the middleware needed for the execution of programs and management of the cluster, while the compute nodes often need nothing else but a standard operating system.

Figure 1-6. An example of a cluster computing system.
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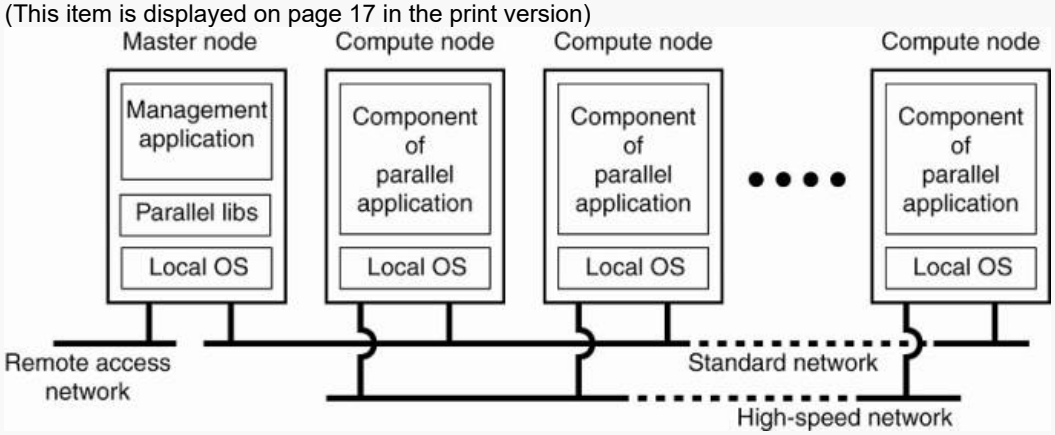


An important part of this middleware is formed by the libraries for executing parallel programs. As we will discuss in Chap. 4, many of these libraries effectively provide only advanced message-based communication facilities, but are not capable of handling faulty processes, security, etc.

As an alternative to this hierarchical organization, a symmetric approach is followed in the MOSIX system (Amar et al., 2004). MOSIX attempts to provide a single-system image of a cluster, meaning that to a process a cluster computer offers the ultimate distribution transparency by appearing to be a single computer. As we mentioned, providing such an image under all circumstances is impossible. In the case of MOSIX, the high degree of transparency is provided by allowing processes to dynamically and preemptively migrate between the nodes that make up the cluster. Process migration allows a user to start an application on any node (referred to as the home node), after which it can transparently move to other nodes, for example, to make efficient use of resources. We will return to process migration in Chap. 3.

Grid Computing Systems

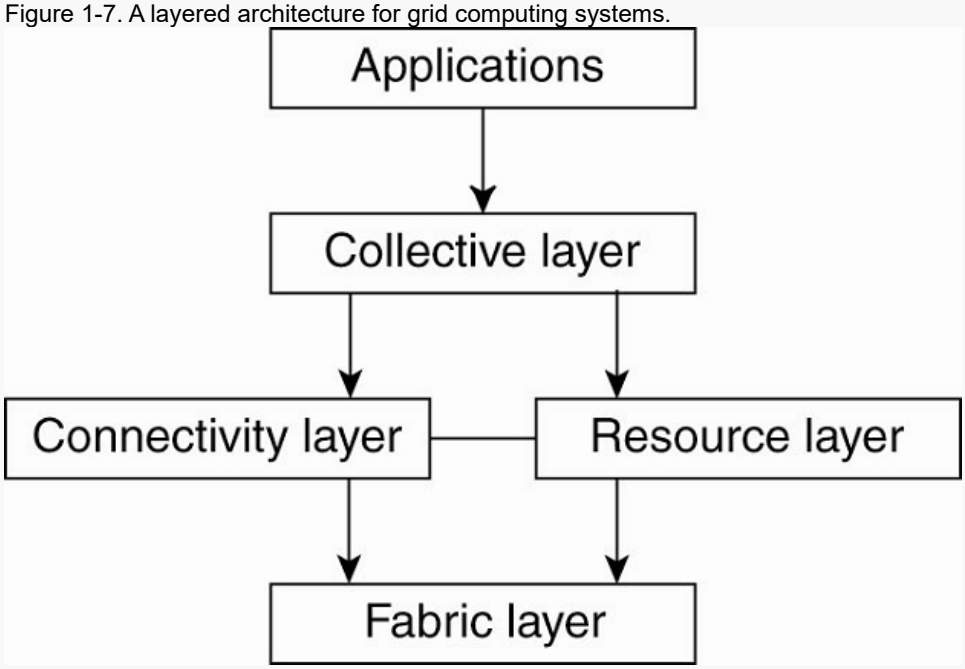
A characteristic feature of cluster computing is its homogeneity. In most cases, the computers in a cluster are largely the same, they all have the same operating system, and are all connected through the same network. In contrast, grid

computing systems have a high degree of heterogeneity: no assumptions are made concerning hardware, operating systems, networks, administrative domains, security policies, etc.

A key issue in a grid computing system is that resources from different organizations are brought together to allow the collaboration of a group of people or institutions. Such a collaboration is realized in the form of a virtual organization. The people belonging to the same virtual organization have access rights to the resources that are provided to that organization. Typically, resources consist of compute servers (including supercomputers, possibly implemented as cluster computers), storage facilities, and databases. In addition, special networked devices such as telescopes, sensors, etc., can be provided as well.

Given its nature, much of the software for realizing grid computing evolves around providing access to resources from different administrative domains, and to only those users and applications that belong to a specific virtual organization. For this reason, focus is often on architectural issues. An architecture proposed by Foster et al. (2001). is shown in Fig. 1-7 [Page 19]

Figure 1-7. A layered architecture for grid computing systems.



The architecture consists of four layers. The lowest fabric layer provides interfaces to local resources at a specific site. Note that these interfaces are tailored to allow sharing of resources within a virtual organization. Typically, they will provide functions for querying the state and capabilities of a resource, along with functions for actual resource management (e.g., locking resources).

The connectivity layer consists of communication protocols for supporting grid transactions that span the usage of multiple resources. For example, protocols are needed to transfer data between resources, or to simply access a resource from a remote location. In addition, the connectivity layer will contain security protocols to authenticate users and resources. Note that in many cases human users are not authenticated; instead, programs acting on behalf of the users are authenticated. In this sense, delegating rights from a user to programs is an important function that needs to be supported in the connectivity layer. We return extensively to delegation when discussing security in distributed systems.

The resource layer is responsible for managing a single resource. It uses the functions provided by the connectivity layer and calls directly the interfaces made available by the fabric layer. For example, this layer will offer functions for obtaining configuration information on a specific resource, or, in general, to perform specific operations such as creating a process or reading data. The resource layer is thus seen to be responsible for access control, and hence will rely on the authentication performed as part of the connectivity layer.

The next layer in the hierarchy is the collective layer. It deals with handling access to multiple resources and typically consists of services for resource discovery, allocation and scheduling of tasks onto multiple resources, data replication, and so on. Unlike the connectivity and resource layer, which consist of a relatively small, standard collection of protocols, the collective layer may consist of many different protocols for many different purposes, reflecting the broad spectrum of services it may offer to a virtual organization.
[Page 20]

Finally, the application layer consists of the applications that operate within a virtual organization and which make use of the grid computing environment.

Typically the collective, connectivity, and resource layer form the heart of what could be called a grid middleware layer. These layers jointly provide access to and management of resources that are potentially dispersed across multiple sites. An important observation from a middleware perspective is that with grid computing the notion of a site (or administrative unit) is common. This prevalence is emphasized by the gradual shift toward a service-oriented architecture in which sites offer access to the various layers through a collection of Web services (Joseph et al., 2004). This, by now, has led to the definition of an alternative architecture known as the Open Grid Services Architecture (OGSA). This architecture consists of various layers and many components, making it rather complex. Complexity seems to be the fate of any standardization process. Details on OGSA can be found in Foster et al. (2005).

1.3.2. Distributed Information Systems

Another important class of distributed systems is found in organizations that were confronted with a wealth of networked applications, but for which interoperability turned out to be a painful experience. Many of the existing middleware solutions are the result of working with an infrastructure in which it was easier to integrate applications into an enterprise-wide information system (Bernstein, 1996; and Alonso et al., 2004).

We can distinguish several levels at which integration took place. In many cases, a networked application simply consisted of a server running that application (often including a database) and making it available to remote programs, called clients. Such clients could send a request to the server for executing a specific operation, after which a response would be sent back. Integration at the lowest level would allow clients to wrap a number of requests, possibly for different servers, into a single larger request and have it executed as a distributed transaction. The key idea was that all, or none of the requests would be executed.

As applications became more sophisticated and were gradually separated into independent components (notably distinguishing database components from processing components), it became clear that integration should also take place by letting applications communicate directly with each other. This has now led to a huge industry that concentrates on enterprise application integration (EAI). In the following, we concentrate on these two forms of distributed systems.
Transaction Processing Systems

To clarify our discussion, let us concentrate on database applications. In practice, operations on a database are usually carried out in the form of transactions. Programming using transactions requires special primitives that must either be supplied by the underlying distributed system or by the language runtime system. Typical examples of transaction primitives are shown in Fig. 1-8. The exact list of primitives depends on what kinds of objects are being used in the transaction (Gray and Reuter, 1993). In a mail system, there might be primitives to send, receive, and forward mail. In an accounting system, they might be quite different. READ and WRITE are typical examples, however. Ordinary statements, procedure calls, and so on, are also allowed inside a transaction. In particular, we mention that remote procedure calls (RPCs), that is, procedure calls to remote servers, are often also encapsulated in a transaction, leading to what is known as a transactional RPC. We discuss RPCs extensively in Chap. 4.
[Page 21]

Figure 1-8. Example primitives for transactions.

Primitive	Description
BEGIN_TRANSACTION	Mark the start of a transaction
END_TRANSACTION	Terminate the transaction and try to commit
ABORT_TRANSACTION	Kill the transaction and restore the old values
READ	Read data from a file, a table, or otherwise
WRITE	Write data to a file, a table, or otherwise

BEGIN_TRANSACTION and END_TRANSACTION are used to delimit the scope of a transaction. The operations between them form the body of the transaction. The characteristic feature of a transaction is either all of these operations are executed or none are executed. These may be system calls, library procedures, or bracketing statements in a language, depending on the implementation.

This all-or-nothing property of transactions is one of the four characteristic properties that transactions have. More specifically, transactions are:

1. Atomic: To the outside world, the transaction happens indivisibly.
2. Consistent: The transaction does not violate system invariants.
3. Isolated: Concurrent transactions do not interfere with each other.
4. Durable: Once a transaction commits, the changes are permanent.

These properties are often referred to by their initial letters: ACID.

The first key property exhibited by all transactions is that they are atomic. This property ensures that each transaction either happens completely, or not at all, and if it happens, it happens in a single indivisible, instantaneous action. While a transaction is in progress, other processes (whether or not they are themselves involved in transactions) cannot see any of the intermediate states.

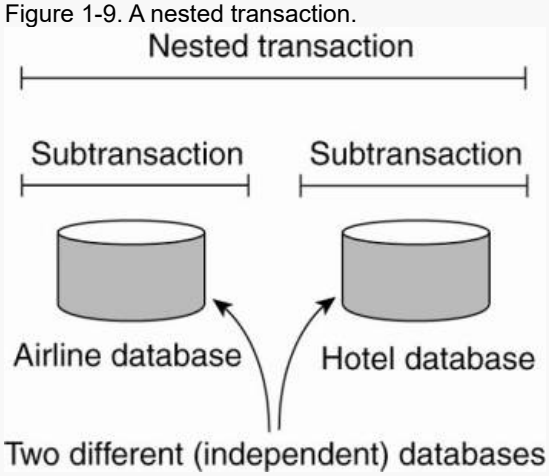
The second property says that they are consistent. What this means is that if the system has certain invariants that must always hold, if they held before the transaction, they will hold afterward too. For example, in a banking system, a key invariant is the law of conservation of money. After every internal transfer, the amount of money in the bank must be the same as it was before the transfer, but for a brief moment during the transaction, this invariant may be violated. The violation is not visible outside the transaction, however.
[Page 22]

The third property says that transactions are isolated or serializable. What it means is that if two or more transactions are running at the same time, to each of them and to other processes, the final result looks as though all transactions ran sequentially in some (system dependent) order.

The fourth property says that transactions are durable. It refers to the fact that once a transaction commits, no matter what happens, the transaction goes forward and the results become permanent. No failure after the commit can undo the results or cause them to be lost. (Durability is discussed extensively in Chap. 8.)

So far, transactions have been defined on a single database. A nested transaction is constructed from a number of subtransactions, as shown in Fig. 1-9. The top-level transaction may fork off children that run in parallel with one another, on different machines, to gain performance or simplify programming. Each of these children may also execute one or more subtransactions, or fork off its own children.

Figure 1-9. A nested transaction.



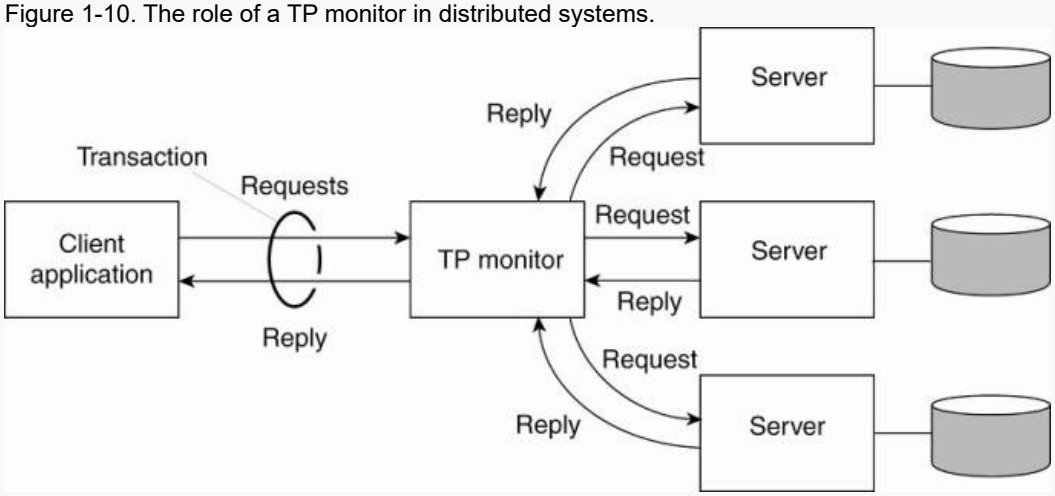
Subtransactions give rise to a subtle, but important, problem. Imagine that a transaction starts several subtransactions in parallel, and one of these commits, making its results visible to the parent transaction. After further computation, the parent aborts, restoring the entire system to the state it had before the top-level transaction started. Consequently, the results of the subtransaction that committed must nevertheless be undone. Thus the permanence referred to above applies only to top-level transactions.

Since transactions can be nested arbitrarily deeply, considerable administration is needed to get everything right. The semantics are clear, however. When any transaction or subtransaction starts, it is conceptually given a private copy of all data in the entire system for it to manipulate as it wishes. If it aborts, its private universe just vanishes, as if it had never existed. If it commits, its private universe replaces the parent's universe. Thus if a subtransaction commits and then later a new subtransaction is started, the second one sees the results produced by the first one. Likewise, if an enclosing (higher-level) transaction aborts, all its underlying subtransactions have to be aborted as well.
[Page 23]

Nested transactions are important in distributed systems, for they provide a natural way of distributing a transaction across multiple machines. They follow a logical division of the work of the original transaction. For example, a transaction for planning a trip by which three different flights need to be reserved can be logically split up into three subtransactions. Each of these subtransactions can be managed separately and independent of the other two.

In the early days of enterprise middleware systems, the component that handled distributed (or nested) transactions formed the core for integrating applications at the server or database level. This component was called a transaction processing monitor or TP monitor for short. Its main task was to allow an application to access multiple server/databases by offering it a transactional programming model, as shown in Fig. 1-10.

Figure 1-10. The role of a TP monitor in distributed systems.

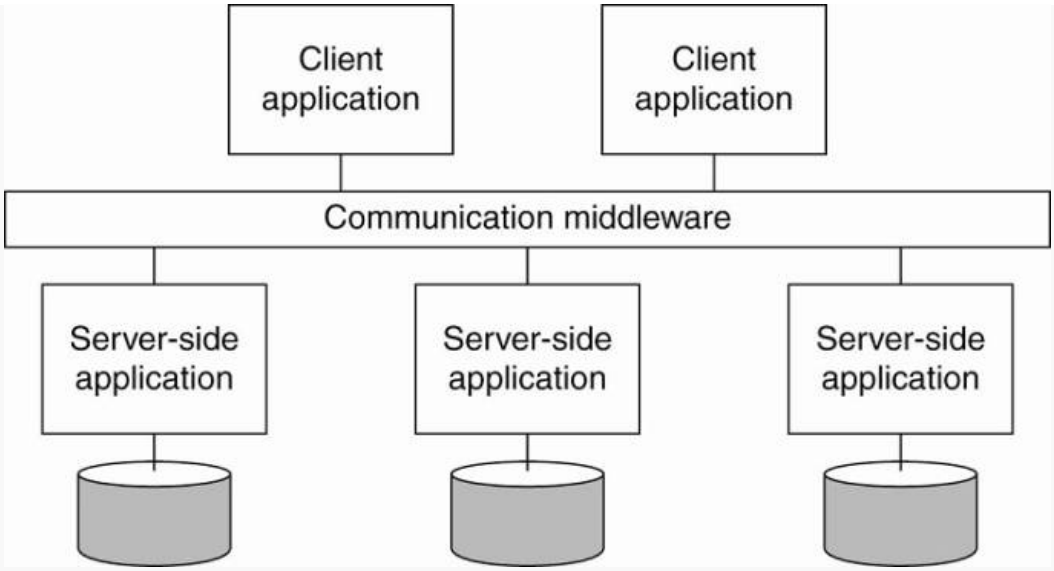


Enterprise Application Integration

As mentioned, the more applications became decoupled from the databases they were built upon, the more evident it became that facilities were needed to integrate applications independent from their databases. In particular, application components should be able to communicate directly with each other and not merely by means of the request/reply behavior that was supported by transaction processing systems.

This need for interapplication communication led to many different communication models, which we will discuss in detail in this book (and for which reason we shall keep it brief for now). The main idea was that existing applications could directly exchange information, as shown in Fig. 1-11.
[Page 24]

Figure 1-11. Middleware as a communication facilitator in enterprise application integration.



Several types of communication middleware exist. With remote procedure calls (RPC), an application component can effectively send a request to another application component by doing a local procedure call, which results in the request being packaged as a message and sent to the callee. Likewise, the result will be sent back and returned to the application as the result of the procedure call.

As the popularity of object technology increased, techniques were developed to allow calls to remote objects, leading to what is known as remote method invocations (RMI). An RMI is essentially the same as an RPC, except that it operates on objects instead of applications.

RPC and RMI have the disadvantage that the caller and callee both need to be up and running at the time of communication. In addition, they need to know exactly how to refer to each other. This tight coupling is often experienced as a serious drawback, and has led to what is known as message-oriented middleware, or simply MOM. In this case, applications simply send messages to logical contact points, often described by means of a subject. Likewise, applications can indicate their interest for a specific type of message, after which the communication middleware will take care that those messages are delivered to those applications. These so-called publish/subscribe systems form an important and expanding class of distributed systems. We will discuss them at length in Chap. 13.

1.3.3. Distributed Pervasive Systems

The distributed systems we have been discussing so far are largely characterized by their stability: nodes are fixed and have a more or less permanent and high-quality connection to a network. To a certain extent, this stability has been realized through the various techniques that are discussed in this book and which aim at achieving distribution transparency. For example, the wealth of techniques for masking failures and recovery will give the impression that only occasionally things may go wrong. Likewise, we have been able to hide aspects related to the actual network location of a node, effectively allowing users and applications to believe that nodes stay put.

However, matters have become very different with the introduction of mobile and embedded computing devices. We are now confronted with distributed systems in which instability is the default behavior. The devices in these, what we refer to as distributed pervasive systems, are often characterized by being small, battery-powered, mobile, and having only a wireless connection, although not all these characteristics apply to all devices. Moreover, these characteristics need not necessarily be interpreted as restrictive, as is illustrated by the possibilities of modern smart phones (Roussos et al., 2005).

As its name suggests, a distributed pervasive system is part of our surroundings (and as such, is generally inherently distributed). An important feature is the general lack of human administrative control. At best, devices can be configured by their owners, but otherwise they need to automatically discover their environment and "nestle in" as best as possible. This nestling in has been made more precise by Grimm et al. (2004) by formulating the following three requirements for pervasive applications:

- Embrace contextual changes.
- Encourage ad hoc composition.
- Recognize sharing as the default.

Embracing contextual changes means that a device must be continuously be aware of the fact that its environment may change all the time. One of the simplest changes is discovering that a network is no longer available, for example, because a user is moving between base stations. In such a case, the application should react, possibly by automatically connecting to another network, or taking other appropriate actions.

Encouraging ad hoc composition refers to the fact that many devices in pervasive systems will be used in very different ways by different users. As a result, it should be easy to configure the suite of applications running on a device, either by the user or through automated (but controlled) interposition.

One very important aspect of pervasive systems is that devices generally join the system in order to access (and possibly provide) information. This calls for means to easily read, store, manage, and share information. In light of the intermittent and changing connectivity of devices, the space where accessible information resides will most likely change all the time.

Mascolo et al. (2004) as well as Niemela and Latvakoski (2004) came to similar conclusions: in the presence of mobility, devices should support easy and application-dependent adaptation to their local environment. They should be able to efficiently discover services and react accordingly. It should be clear from these requirements that distribution transparency is not really in place in pervasive systems. In fact, distribution of data, processes, and control is inherent to these systems, for which reason it may be better just to simply expose it rather than trying to hide it. Let us now take a look at some concrete examples of pervasive systems.
[Page 26]
Home Systems

An increasingly popular type of pervasive system, but which may perhaps be the least constrained, are systems built around home networks. These systems generally consist of one or more personal computers, but more importantly integrate typical consumer electronics such as TVs, audio and video equipment, gaming devices, (smart) phones, PDAs, and other personal wearables into a single system. In addition, we can expect that all kinds of devices such as kitchen appliances, surveillance cameras, clocks, controllers for lighting, and so on, will all be hooked up into a single distributed system.

From a system's perspective there are several challenges that need to be addressed before pervasive home systems become reality. An important one is that such a system should be completely self-configuring and self-managing. It cannot be expected that end users are willing and able to keep a distributed home system up and running if its components are prone to errors (as is the case with many of today's devices.) Much has already been accomplished through the Universal Plug and Play (UPnP) standards by which devices automatically obtain IP addresses, can discover each other, etc. (UPnP Forum, 2003). However, more is needed. For example, it is unclear how software and firmware in devices can be easily updated without manual intervention, or when updates do take place, that compatibility with other devices is not violated.

Another pressing issue is managing what is known as a "personal space." Recognizing that a home system consists of many shared as well as personal devices, and that the data in a home system is also subject to sharing restrictions, much attention is paid to realizing such personal spaces. For example, part of Alice's personal space may consist of her agenda, family photo's, a diary, music and videos that she bought, etc. These personal assets should be stored in such a way that Alice has access to them whenever appropriate. Moreover, parts of this personal space should be (temporarily) accessible to others, for example, when she needs to make a business appointment.

Fortunately, things may become simpler. It has long been thought that the personal spaces related to home systems were inherently distributed across the various devices. Obviously, such a dispersion can easily lead to significant synchronization problems. However, problems may be alleviated due to the rapid increase in the capacity of hard disks, along with a decrease in their size. Configuring a multi-terabyte storage unit for a personal computer is not really a problem. At the same time, portable hard disks having a capacity of hundreds of gigabytes are being placed inside relatively small portable media players. With these continuously increasing capacities, we may see pervasive home systems adopt an architecture in which a single machine acts as a master (and is hidden away somewhere in the basement next to the central heating), and all other fixed devices simply provide a convenient interface for humans. Personal devices will then be crammed with daily needed information, but will never run out of storage.
[Page 27]

However, having enough storage does not solve the problem of managing personal spaces. Being able to store huge amounts of data shifts the problem to storing relevant data and being able to find it later. Increasingly we will see pervasive

systems, like home networks, equipped with what are called recommenders, programs that consult what other users have stored in order to identify similar taste, and from that subsequently derive which content to place in one's personal space. An interesting observation is that the amount of information that recommender programs need to do their work is often small enough to allow them to be run on PDAs (Miller et al., 2004).

Electronic Health Care Systems

Another important and upcoming class of pervasive systems are those related to (personal) electronic health care. With the increasing cost of medical treatment, new devices are being developed to monitor the well-being of individuals and to automatically contact physicians when needed. In many of these systems, a major goal is to prevent people from being hospitalized.

Personal health care systems are often equipped with various sensors organized in a (preferably wireless) body-area network (BAN). An important issue is that such a network should at worst only minimally hinder a person. To this end, the network should be able to operate while a person is moving, with no strings (i.e., wires) attached to immobile devices.

This requirement leads to two obvious organizations, as shown in Fig. 1-12. In the first one, a central hub is part of the BAN and collects data as needed. From time to time, this data is then offloaded to a larger storage device. The advantage of this scheme is that the hub can also manage the BAN. In the second scenario, the BAN is continuously hooked up to an external network, again through a wireless connection, to which it sends monitored data. Separate techniques will need to be deployed for managing the BAN. Of course, further connections to a physician or other people may exist as well.

Figure 1-12. Monitoring a person in a pervasive electronic health care system, using (a) a local hub or (b) a continuous wireless connection.

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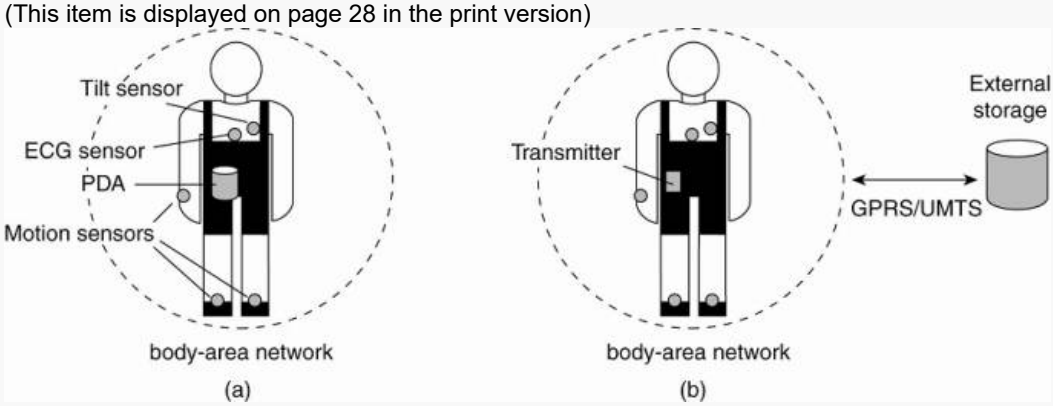


From a distributed system's perspective we are immediately confronted with questions such as:

1. Where and how should monitored data be stored?
2. How can we prevent loss of crucial data?
3. What infrastructure is needed to generate and propagate alerts?
   [Page 28]
4. How can physicians provide online feedback?
5. How can extreme robustness of the monitoring system be realized?
6. What are the security issues and how can the proper policies be enforced?

Unlike home systems, we cannot expect the architecture of pervasive health care systems to move toward single-server systems and have the monitoring devices operate with minimal functionality. On the contrary: for reasons of efficiency, devices and body-area networks will be required to support in-network data processing, meaning that monitoring data will, for example, have to be aggregated before permanently storing it or sending it to a physician. Unlike the case for distributed information systems, there is yet no clear answer to these questions.

Sensor Networks

Our last example of pervasive systems is sensor networks. These networks in many cases form part of the enabling technology for pervasiveness and we see that many solutions for sensor networks return in pervasive applications. What makes sensor networks interesting from a distributed system's perspective is that in virtually all cases they are used for processing information. In this sense, they do more than just provide communication services, which is what traditional

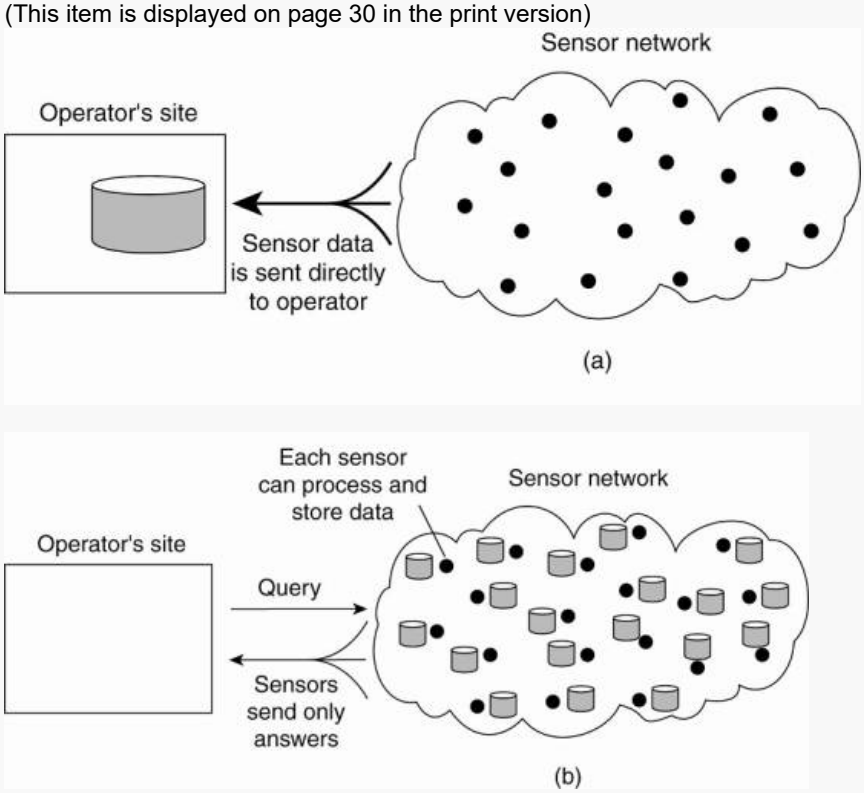
computer networks are all about. Akyildiz et al. (2002) provide an overview from a networking perspective. A more systems-oriented introduction to sensor networks is given by Zhao and Guibas (2004). Strongly related are mesh networks which essentially form a collection of (fixed) nodes that communicate through wireless links. These networks may form the basis for many medium-scale distributed systems. An overview is provided in Akyildiz et al. (2005).
[Page 29]

A sensor network typically consists of tens to hundreds or thousands of relatively small nodes, each equipped with a sensing device. Most sensor networks use wireless communication, and the nodes are often battery powered. Their limited resources, restricted communication capabilities, and constrained power consumption demand that efficiency be high on the list of design criteria.

The relation with distributed systems can be made clear by considering sensor networks as distributed databases. This view is quite common and easy to understand when realizing that many sensor networks are deployed for measurement and surveillance applications (Bonnet et al., 2002). In these cases, an operator would like to extract information from (a part of) the network by simply issuing queries such as "What is the northbound traffic load on Highway 1?" Such queries resemble those of traditional databases. In this case, the answer will probably need to be provided through collaboration of many sensors located around Highway 1, while leaving other sensors untouched.

To organize a sensor network as a distributed database, there are essentially two extremes, as shown in Fig. 1-13. First, sensors do not cooperate but simply send their data to a centralized database located at the operator's site. The other extreme is to forward queries to relevant sensors and to let each compute an answer, requiring the operator to sensibly aggregate the returned answers.

Figure 1-13. Organizing a sensor network database, while storing and processing data (a) only at the operator's site or (b) only at the sensors.
(This item is displayed on page 30 in the print version)



Neither of these solutions is very attractive. The first one requires that sensors send all their measured data through the network, which may waste network resources and energy. The second solution may also be wasteful as it discards the aggregation capabilities of sensors which would allow much less data to be returned to the operator. What is needed are facilities for in-network data processing, as we also encountered in pervasive health care systems.

In-network processing can be done in numerous ways. One obvious one is to forward a query to all sensor nodes along a tree encompassing all nodes and to subsequently aggregate the results as they are propagated back to the root, where the

initiator is located. Aggregation will take place where two or more branches of the tree come to together. As simple as this scheme may sound, it introduces difficult questions:

1. How do we (dynamically) set up an efficient tree in a sensor network?
2. How does aggregation of results take place? Can it be controlled?
3. What happens when network links fail?

These questions have been partly addressed in TinyDB, which implements a declarative (database) interface to wireless sensor networks. In essence, TinyDB can use any tree-based routing algorithm. An intermediate node will collect and aggregate the results from its children, along with its own findings, and send that toward the root. To make matters efficient, queries span a period of time allowing for careful scheduling of operations so that network resources and energy are optimally consumed. Details can be found in Madden et al. (2005).
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However, when queries can be initiated from different points in the network, using single-rooted trees such as in TinyDB may not be efficient enough. As an alternative, sensor networks may be equipped with special nodes where results are forwarded to, as well as the queries related to those results. To give a simple example, queries and results related temperature readings are collected at a different location than those related to humidity measurements. This approach corresponds directly to the notion of publish/subscribe systems, which we will discuss extensively in Chap. 13.