

COMP9243 — Week 2 (18s1)

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System Architecture

A distributed system is composed of a number of elements, the most important of which are software components, processing nodes and networks. Some of these elements can be specified as part of a distributed system's design, while others are given (i.e., they have to be accepted as they are). Typically when building a distributed system, the software is under the designer's control. Depending on the scale of the system, the hardware can be specified within the design as well, or already exists and has to be taken as-is. The key, however, is that the software components must be distributed over the hardware components in some way.

The software of distributed systems can become fairly complex—especially in large distributed systems—and its components can spread over many machines. It is important, therefore, to understand how to organise the system. We distinguish between the logical organisation of software components in such a system and their actual physical organisation. The *software architecture* of distributed systems deals with how software components are organised and how they work together, i.e., communicate with each other. Typical software architectures include the layered, object-oriented, data-centred, service-oriented and event-based architectures. Once the software components are instantiated and placed on real machines, we talk about an actual *system architecture*. A few such architectures are discussed in this section. These architectures are distinguished from each other by the roles that the communicating processes take on.

Choosing a good architecture for the design of a distributed system allows splitting of the functionality of the system, thus structuring the application and reducing its complexity. Note that there is no single best architecture—the best architecture for a particular system depends on the application's requirements and the environment.

Client-Server

The client-server architecture is the most common and widely used model for communication between processes. As Figure 1 shows, in this architecture one process takes on the role of a server, while all other processes take on the roles of clients. The server process provides a service (e.g., a time service, a database service, a banking service, etc.) and the clients are customers of that service. A client sends a request to a server, the request is processed at the server and a reply is returned to the client.

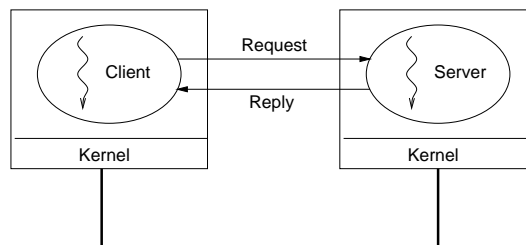


Figure 1: The client-server communication architecture.

A typical client-server application can be decomposed into three logical parts: the interface part, the application logic part, and the data part. Implementations of the client-server architecture vary with regards to how the parts are separated over the client and server roles. A thin

client implementation will provide a minimal user interface layer, and leave everything else to the server. A fat client implementation, on the other hand, will include all of the user interface and application logic in the client, and only rely on the server to store and provide access to data. Implementations in between will split up the interface or application logic parts over the clients and server in different ways.

Vertical Distribution (Multi-Tier)

An extension of the client-server architecture, the vertical distribution, or multi-tier, architecture (see Figure 2) distributes the traditional server functionality over multiple servers. A client request is sent to the first server. During processing of the request this server will request the services of the next server, who will do the same, until the final server is reached. In this way the various servers become clients of each other (see Figure 3). Each server is responsible for a different step (or tier) in the fulfilment of the original client request.

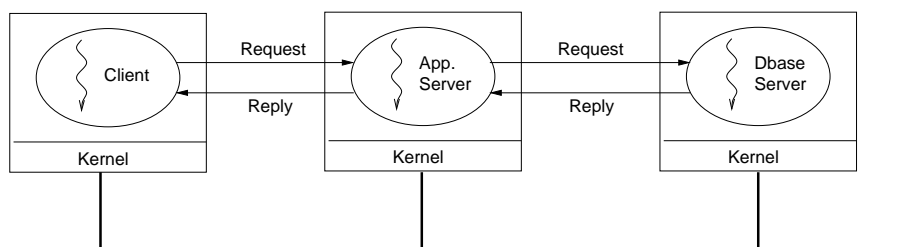


Figure 2: The vertical distribution (multi-tier) communication architecture.

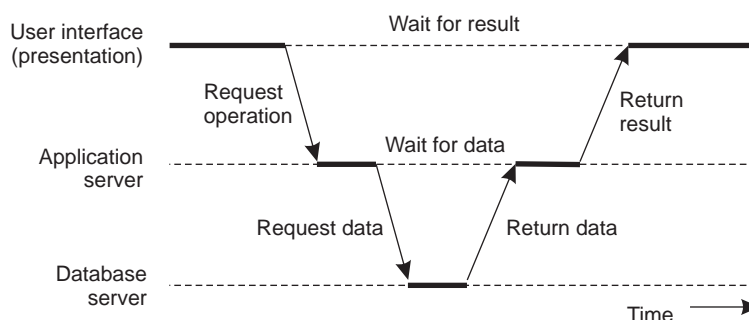


Figure 3: Communication in a multi-tier system.

Splitting up the server functionality in this way is beneficial to a system's scalability as well as its flexibility. Scalability is improved because the processing load on each individual server is reduced, and the whole system can therefore accommodate more users. With regards to flexibility this architecture allows the internal functionality of each server to be modified as long as the interfaces provided remain the same.

Horizontal Distribution

While vertical distribution focuses on splitting up a server's functionality over multiple computers, horizontal distribution involves replicating a server's functionality over multiple computers. A typical example, as shown in Figure 4, is a replicated Web server. In this case each server machine

contains a complete copy of all hosted Web pages and client requests are passed on to the servers in a round robin fashion. The horizontal distribution architecture is generally used to improve scalability (by reducing the load on individual servers) and reliability (by providing redundancy).

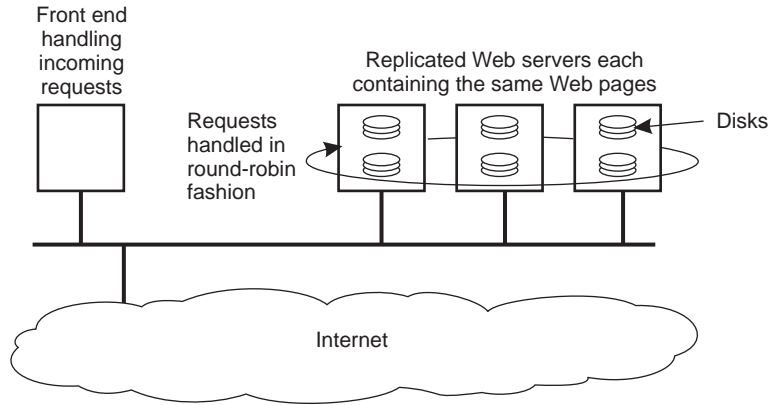


Figure 4: An example of a horizontally distributed Web server.

Note that it is also possible to combine the vertical and horizontal distribution models. For example, each of the servers in the vertical decomposition can be horizontally distributed. Another approach is for each of the replicas in the horizontal distribution model to themselves be vertically distributed.

Peer to Peer

Whereas the previous models have all assumed that different processes take on different roles in the communication architecture, the peer to peer (P2P) architecture takes the opposite approach and assumes that all processes play the same role, and are therefore peers of each other. In Figure 5 each process acts as both a client and a server, both sending out requests and processing incoming requests. Unlike in the vertical distribution architecture, where each server was also a client to another server, in the P2P model all processes provide the same logical services.

Well known examples of the P2P model are file-sharing applications. In these applications users start up a program that they use to search for and download files from other users. At the same time, however, the program also handles search and download requests from other users.

With the potentially huge number of participating nodes in a peer to peer network, it becomes practically impossible for a node to keep track of all other nodes in the system and the information they offer. To reduce the problem, the nodes form an *overlay network*, in which nodes form a virtual network among themselves and only have direct knowledge of a few other nodes. When a node wishes to send a message to an arbitrary other node it must first locate that node by propagating a request along the links in the overlay network. Once the destination node is found, the two nodes can typically communicate directly (although that depends on the underlying network of course).

There are two key types of overlay networks, the distinction being based on how they are built and maintained. In all cases a node in the network will maintain a list of neighbours (called its partial view of the network). In *unstructured* overlays the structure of the network often resembles a random graph. Membership management is typically random, which means that a nodes partial view consists of a random list of other nodes. In order to keep the network connected as nodes join and leave, all nodes periodically exchange their partial views with neighbours, creating a new

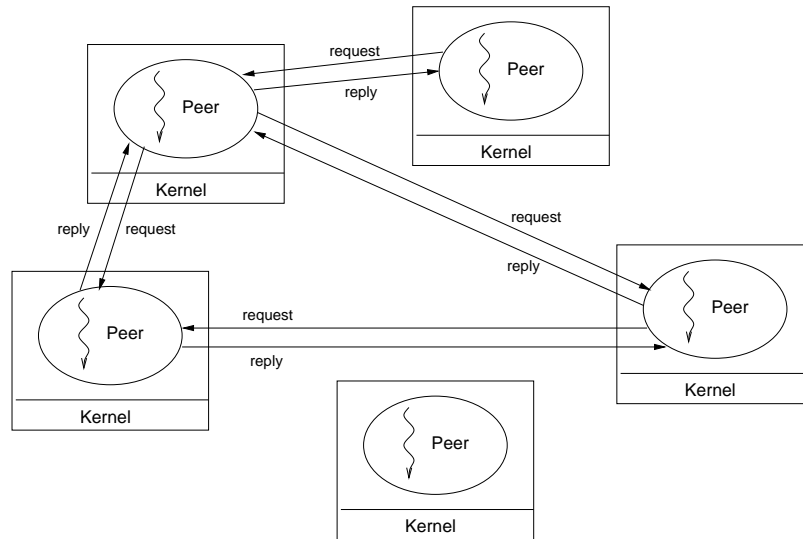


Figure 5: The peer to peer communication architecture.

neighbour list for themselves. As long as nodes both push and pull this information the network tends to stay well connected (i.e., it doesn't become partitioned).

In the case of *structured* overlays the choice of a node's neighbours is determined according to a specific structure. In a distributed hash table, for example, nodes work together to implement a hash table. Each node is responsible for storing the data associated with a range of identifiers. When joining a network, a node is assigned an identifier, locates the node responsible for the range containing that identifier, and takes over part of that identifier space. Each node keeps track of its neighbours in the identifier space. We will discuss specific structured overlays in more detail in a future lecture.

Hybrid

Many more architectures can be designed by combining the previously described architectures in different ways and result in what are called *hybrid architectures*. A few examples are:

Superpeer networks In this architecture a few *superpeers* form a peer to peer network, while the regular peers are clients to a superpeer. This hybrid architecture maintains some of the advantages of a peer to peer system, but simplifies the system by having only the superpeers managing the index of the regular peers, or acting as brokers (e.g., Skype).

Collaborative distributed systems In collaborative distributed systems, peers typically support each other to deliver content in a peer to peer like architecture, while they use a client server architecture for the initial setup of the network. In BitTorrent for example, nodes requesting to download a file from a server first contact the server to get the location of a *tracker*. The tracker then tells the nodes the locations of other nodes, from which chunks of the content can be downloaded concurrently. Nodes must then offer downloaded chunks to other nodes and are registered with the tracker, so that the other nodes can find them.

Edge-server networks In edge-server networks, as the name implies, servers are placed at the "edge" of the Internet, for example at internet service providers (ISPs) or close to enterprise networks. Client nodes (e.g., home users or an enterprise's employees) then access the nearby edge servers instead of the original server (which may be located far away). This architecture is typically well suited for large-scale content-distribution networks such as that provided by Akamai.

Processes and Server Architecture

A key property of all distributed systems is that they consist of separate processes that communicate in order to get work done. Before exploring the various ways that processes on separate computers can communicate, we will first review communication between processes on a single computer (i.e., a uniprocessor or multiprocessor).

Communication takes place between threads of control. There are two models for dealing with threads of control in an operating system. In the *process* model, each thread of control is associated with a single private address space. The threads of control in this model are called *processes*. In the *thread* model, multiple threads of control share a single address space. These threads of control are called *threads*. Sometimes threads are also referred to as lightweight processes because they take up less operating system resources than regular processes.

An important distinction between processes and threads is memory access. Threads share all of their memory, which means that threads can freely access and modify each other's memory. Processes, on the other hand, are prevented from accessing each other's memory. As an exception to this rule, in many systems it is possible for processes to explicitly share memory with other processes.

Some systems provide only a process model, while others provide only a thread model. More common are systems that provide both threads and processes. In this case each process can contain multiple threads, which means that the threads can only freely access the memory of other threads in the same process. In general, when we are not concerned about whether a thread of control is a process or thread, we will refer to it as a process.

A server process in a distributed system typically receives many requests for work from various clients, and it is important to provide quick responses to those clients. In particular, a server should not refuse to do work for one client because it blocked (e.g., because it invoked a blocking system call) while doing work for another client. This is a typical result of implementing a server as a single-threaded process. Alternatives to this are to implement the server using multiple threads, one of which acts as a dispatcher, and the others acting as workers. Another option is to design and build the server as a finite state machine that uses non-blocking system calls.

A key issue in the design of servers is whether they store information about clients or not. In the *stateful* model a server stores persistent information about a client (e.g., which files it has opened). While this leads to good performance since clients do not have to constantly remind servers what their state is, the flipside is that the server must keep track of all its clients (which leads to added work and storage on its part) and must ensure that the state can be recovered after a crash. In the *stateless* model, the server keeps no persistent information about its clients. In this way it does not need to use up resources to track clients, nor does it need to worry about restoring client state after a crash. On the other hand, it requires more communication since clients have to resend their state information with every request.

Often, as discussed above, the server in client-server is not a single machine, but a collection of machines that act as a *clustered server*. In many modern systems separate *virtual machines* are hosted on a single physical machine. This allows consolidation of many servers on a single machine, while providing isolation between them. Since virtual machines can be stopped, migrated, and restarted, virtualisation also provides a good basis for code mobility and load balancing.

Typically the machines (and processes) in such a cluster are assigned dedicated roles including, a logical switch, compute (or application logic) servers, and file or database servers. We have discussed the latter two previously, so now focus on the switch. The role of the switch is to receive client requests and route them to appropriate servers in the cluster. There are several ways to do this. At the lowest level, a transport-layer switch, reroutes TCP connections to other servers. The decision regarding which server to route the request to typically depends on system load. On a slightly higher level, an application switch analyses the incoming request and routes it according to application-specific logic. For example, HTTP requests for HTML files could be routed to one set of servers, while requests for images could be served by other servers. Finally, at an even higher level, A DNS server could act as a switch by returning different IP addresses for a single host name. Typically the server will store multiple addresses for a given name and cycle through

them in a round-robin fashion. The disadvantage of this approach is that the DNS server does not use any application or cluster specific knowledge to route requests.

A final issue with regards to processes is that of code mobility. In some cases it makes sense to change the location where a process is being executed. For example, a process may be moved to an unloaded server in a cluster to improve its performance, or to reduce the load on its current server. Processes that are required to process large amounts of data may be moved to a machine that has the data locally available to prevent the data from having to be sent over the network. We distinguish between two types of code mobility: *weak* mobility and *strong* mobility. In the first case, only code is transferred and the process is restarted from an initial state at its destination. In the second case, the code and an execution context are transferred, and the process resumes execution from where it left off before being moved.

Communication

In order for processes to cooperate (e.g., work on a single task together), they must communicate. There are two reasons for this communication: synchronisation and sharing of data. Processes synchronise in order to coordinate their activities. This includes finding out whether another process is alive, determining how much of a task a process has executed, acquiring exclusive access to a resource, requesting another process to perform a certain task, etc. Processes share data about tasks that they are cooperatively working on. This may include sending data as part of a request (e.g., data to perform calculations on), returning the results of a calculation, requesting particular data, etc.

There are two ways that processes can communicate: through shared memory or through message passing. In the first case processes must have access to some form of shared memory (i.e., they must be threads, they must be processes that can share memory, or they must have access to a shared resource, such as a file). Communicating using shared memory requires processes to agree on specific regions of the shared memory that will be used to pass synchronisation information and data.

The other option (and the only option for processes that do not have access to shared memory), is for processes to communicate by sending each other messages. This generally makes use of inter-process communication (IPC) mechanisms made available by the underlying operating system. Examples of these mechanisms include pipes and sockets.

Communication in a Distributed System

While the discussion of communication between processes has, so far, explicitly assumed a uniprocessor (or multiprocessor) environment, the situation for a distributed system (i.e., a multicomputer environment) remains similar. The main difference is that in a distributed system, processes running on separate computers cannot directly access each other's memory. Nevertheless, processes in a distributed system can still communicate through either shared memory or message passing.

Message Passing

Message passing in a distributed system is similar to communication using messages in a non-distributed system. The main difference being that the only mechanism available for the passing of messages is network communication.

At its core, message passing involves two operations `send()` and `receive()`. Although these are very simple operations, there are many variations on the basic model. For example, the communication can be connectionless or connection oriented. Connection oriented communication requires that the sender and receiver first create a connection before `send()` and `receive()` can be used.

There are a number of important issues to consider when dealing with processes that communicate using message passing, which are described in the next section. Besides these variations in

the message passing model, there are also issues involved with communicating between processes on heterogeneous computers. This brings up issues such as data representation and dealing with pointers, which will be discussed in more detail later.

Communication Modes

There are a number of alternative ways, or modes, in which communication can take place. It is important to know and understand these different modes, because they are used to describe the different services that a communication subsystem offers to higher layers.

A first distinction is between the two modes *data-oriented communication* and *control-oriented communication*. In the first mode, communication serves solely to exchange data between processes. Although the data might trigger an action at the receiver, there is no explicit transfer of control implied in this mode. The second mode, control-oriented communication, explicitly associates a transfer of control with every data transfer. Data-oriented communication is clearly the type of communication used in communication via shared address space and shared memory, as well as message passing. Control-oriented communication is the mode used by abstractions such as remote procedure call, remote method invocation, active messages, etc. (communication abstractions are described in the next section).

Next, communication operations can be synchronous or asynchronous. In *synchronous communication* the sender of a message blocks until the message has been received by the intended recipient. Synchronous communication is usually even stronger than this in that the sender often blocks until the receiver has processed the message and the sender has received a reply. In *asynchronous communication*, on the other hand, the sender continues execution immediately after sending a message (possibly without having received an answer).

Another possible alternative involves the buffering of communication. In the buffered case, a message will be stored if the receiver is not able to pick it up right away. In the unbuffered case the message will be lost.

Communication can also be transient and persistent. In *transient communication* a message will only be delivered if a receiver is active. If there is no active receiver process (i.e., no one interested in or able to receive messages) then an undeliverable message will simply be dropped. In *persistent communication*, however, a message will be stored in the system until it can be delivered to the intended recipient. As Figure 6 shows, all combinations of synchronous/asynchronous and transient/persistent are possible.

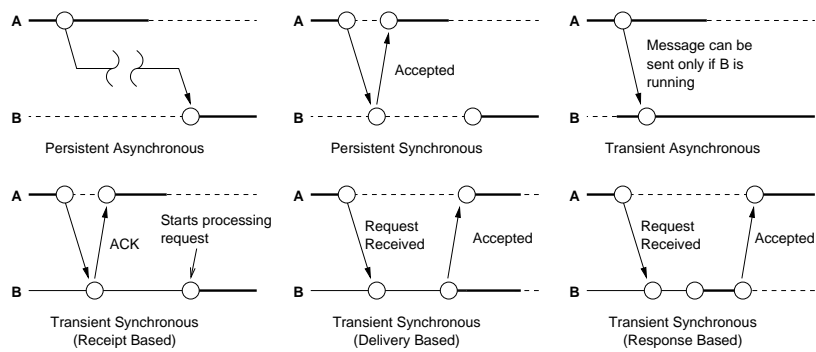


Figure 6: Possible combinations of synchronous/asynchronous and transient/persistent communication.

There are also varying degrees of reliability of the communication. With *reliable communication* errors are discovered and fixed transparently. This means that the processes can assume that a message that is sent will actually arrive at the destination (as long as the destination process is there to receive it). With *unreliable communication* messages may get lost and processes have to deal with it.

Finally it is possible to provide guarantees about the ordering of messages. Thus, for example, a communication system may guarantee that all messages are received in the same order that they are sent, while another system may make no guarantees about the order of arrival of messages.

Communication Abstractions

In the previous discussion it was assumed that all processes explicitly send and receive messages (e.g., using `send()` and `receive()`). Although this style of programming is effective and works, it is not always easy to write correct programs using explicit message passing. In this section we will discuss a number of communication abstractions that make writing distributed applications easier. In the same way that higher level programming languages make programming easier by providing abstractions above assembly language, so do communication abstractions make programming in distributed systems easier.

Some of the abstractions discussed attempt to completely hide the fact that communication is taking place. While other abstractions do not attempt to hide communication, all abstractions have in common that they hide the details of the communication taking place. For example, the programmers using any of these abstractions do not have to know what the underlying communication protocol is, nor do they have to know how to use any particular operating system communication primitives.

The abstractions discussed in the coming sections are often used as core foundations of most middleware systems. Using these abstractions, therefore, generally involves using some sort of middleware framework. This brings with it a number of the benefits of middleware, in particular the various services associated with the middleware that tend to make a distributed application programmer's life easier.

Message-Oriented Communication

The *message-oriented communication* abstraction does not attempt to hide the fact that communication is taking place. Instead its goal is to make the use of flexible message passing easier.

Message-oriented communication is based around the model of processes sending messages to each other. Underlying message-oriented communication has two orthogonal properties. Communication can be synchronous or asynchronous, and it can be transient or persistent. Whereas RPC and RMI are generally synchronous and transient, message oriented communication systems make many other options available to programmers.

Message-oriented communication is provided by *message-oriented middleware* (MOM). Besides providing many variations of the `send()` and `receive()` primitives, MOM also provides infrastructure required to support persistent communication. The `send()` and `receive()` primitives offered by MOM also abstract from the underlying operating system or hardware primitives. As such, MOM allows programmers to use message passing without having to be aware of what platforms their software will run on, and what services those platforms provide. As part of this abstraction MOM also provides marshalling services. Furthermore, as with most middleware, MOM also provides other services that make building distributed applications easier.

MPI (Message Passing Interface) is an example of a MOM that is geared toward high-performance transient message passing. MPI is a message passing library that was designed for parallel computing. It makes use of available networking protocols, and provides a huge array of functions that basically perform synchronous and asynchronous `send()` and `receive()`.

Another example of MOM is MQ Series from IBM. This is an example of a *message queuing system*. Its main characteristic is that it provides persistent communication. In a message queuing system, messages are sent to other processes by placing them in queues. The queues hold messages until an intended receiver extracts them from the queue and processes them. Communication in a message queuing system is largely asynchronous.

The basic queue interface is very simple. There is a primitive to append a message onto the end of a specified queue, and a primitive to remove the message at the head of a specific queue.

These can be blocking or nonblocking. All messages contain the name or address of a destination queue.

Messages can only be added to and retrieved from local queues. Senders place messages in *source queues* (or *send queues*), while receivers retrieve messages from *destination queues* (or *receive queues*). The underlying system is responsible for transferring messages from source queues to destination queues. This can be done simply by fetching messages from source queues and directly sending them to machines responsible for the appropriate destination queues. Or it can be more complicated and involve relaying messages to their destination queues through an overlay network of routers. An example of such a system is shown in Figure 7. In the figure, an application on sender A sends a message to an application on receiver B. It places the message in its local source queue, from where it is forwarded through routers R1 and R2 into the receiver's destination queue.

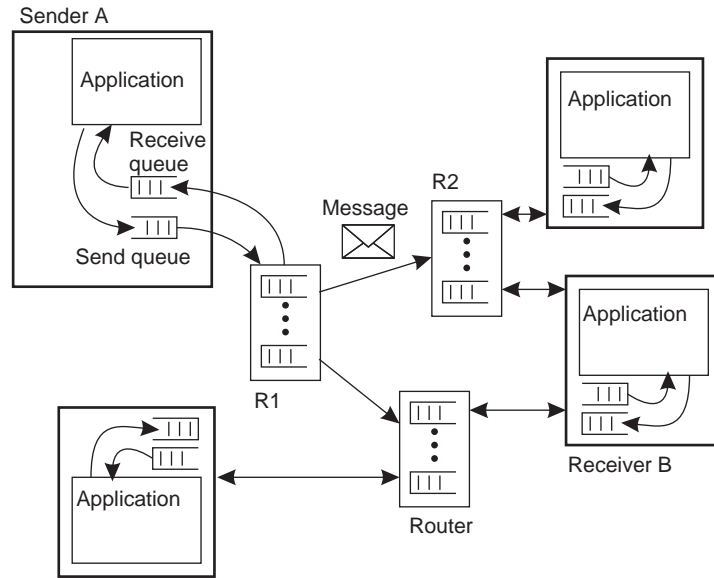


Figure 7: An example of a message queuing system.

Remote Procedure Call (RPC)

The idea behind a *remote procedure call* (RPC) is to replace the explicit message passing model with the model of executing a procedure call on a remote node [BN84]. A programmer using RPC simply performs a procedure call, while behind the scenes messages are transferred between the client and server machines. In theory the programmer is unaware of any communication taking place.

Figure 8 shows the steps taken when an RPC is invoked. The numbers in the figure correspond to the following steps (steps seven to eleven are not shown in the figure):

1. client program calls client stub routine (normal procedure call)
2. client stub packs parameters into message data structure (marshalling)
3. client stub performs `send()` syscall and blocks
4. kernel transfers message to remote kernel

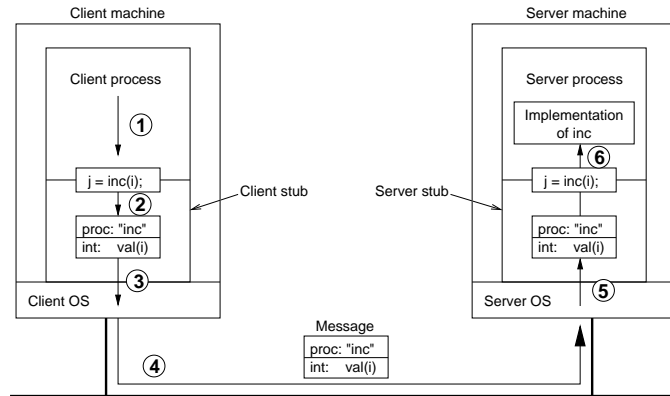


Figure 8: A remote procedure call.

5. remote kernel delivers to server stub procedure, blocked in `receive()`
6. server stub unpacks message, calls service procedure (normal procedure call)
7. service procedure returns to stub, which packs result into message
8. server stub performs `send()` syscall
9. kernel delivers to client stub
10. client stub unpacks result (unmarshalling)
11. client stub returns to client program (normal return from procedure)

A server that provides remote procedure call services defines the available procedures in a *service interface*. A service interface is generally defined in an *interface definition language* (IDL), which is a simplified programming language, sufficient for defining data types and procedure signatures but not for writing executable code. The IDL service interface definition is used to generate client and server stub code. The stub code is then compiled and linked in with the client program and service procedure implementations respectively.

The first widely used RPC framework was proposed by Sun Microsystems in Internet RFC1050 (currently defined in RFC1831). It is based on the XDR (External Data Representation) format defined in Internet RFC1014 (currently defined in RFC4506) and is still being heavily used as the basis for standard services originating from Sun such as NFS (Network File System) and NIS (Network Information Service). Another popular RPC framework is DCE (Distributed Computing Environment) RPC, which has been adopted in Microsoft's base system for distributed computing.

More modern RPC frameworks are based on XML as a data format and are defined to operate on top of widely used standard network protocols such as HTTP. This simplifies integration with Web servers and is useful when transparent operation through firewalls is desired. Examples of such frameworks are XML-RPC and the more powerful, but often unnecessarily complex SOAP.

As mentioned earlier there are issues involved with communicating between processes on heterogeneous architectures. These include different representations of data, different byte orderings, and problems with transferring pointers or pointer-based data structures. One of the tasks that RPC frameworks hide from programmers is the packing of data into messages (*marshalling*) and unpacking data from messages (*unmarshalling*). Marshalling and unmarshalling are performed in the stubs by code generated automatically from IDL compilers and stub generators.

An important part of marshalling is converting data into a format that can be understood by the receiver. Generally, differences in format can be handled by defining a standard *network format* into which all data is converted. However, this may be wasteful if two communicating machines use the same internal format, but that format differs from the network format. To avoid

this problem, an alternative is to indicate the format used in the transmitted message and rely on the receiver to apply conversion where required.

Because pointers cannot be shared between remote processes (i.e., addresses cannot be transferred verbatim since they are usually meaningless in another address space) it is necessary to flatten, or serialise, all pointer-based data structures when they are passed to the RPC client stub. At the server stub, these serialised data structures must be unpacked and recreated in the recipient's address space. Unfortunately this approach presents problems with aliasing and cyclic structures. Another approach to dealing with pointers involves the server sending a request for the referenced data to the client every time a pointer is encountered.

In general the RPC abstraction assumes synchronous, or blocking, communication. This means that clients invoking RPCs are blocked until the procedure has been executed remotely and a reply returned. Although this is often the desired behaviour, sometimes the waiting is not necessary. For example, if the procedure does not return any values, it is not necessary to wait for a reply. In this case it is better for the RPC to return as soon as the server acknowledges receipt of the message. This is called an *asynchronous RPC*.

It is also possible that a client does require a reply, but does not need it right away and does not want to block for it either. An example of this is a client that prefetches network addresses of hosts that it expects to contact later. The information is important to the client, but since it is not needed right away the client does not want to wait. In this case it is best if the server performs an asynchronous call to the client when the results are available. This is known as *deferred synchronous RPC*.

A final issue that has been silently ignored so far is how a client stub knows where to send the RPC message. In a regular procedure call the address of the procedure is determined at compile time, and the call is then made directly. In RPC this information is acquired from a *binding service*; a service that allows registration and lookup of services. A binding service typically provides an interface similar to the following:

- `register(name, version, handle, UID)`
- `deregister(name, version, UID)`
- `lookup(name, version) → (handle, UID)`

Here `handle` is some physical address (IP address, process ID, etc.) and `UID` is used to distinguish between servers offering the same service. Moreover, it is important to include version information since the flexibility requirement for distributed system requires us to deal with different versions of the same software in a heterogeneous environment.

Remote Method Invocation (RMI)

When using RPC, programmers must explicitly specify the server on which they want to perform the call (possibly using information retrieved from a binding service). Furthermore, it is complicated for a server to keep track of the different state belonging to different clients and their invocations. These problems with RPC lead to the *remote method invocation* (RMI) abstraction. The transition from RPC to RMI is, at its core, a transition from the server metaphor to the object metaphor.

When using RMI, programmers invoke methods on remote objects. The object metaphor associates all operations with the data that they operate on, meaning that state is encapsulated in the remote object and much easier to keep track of. Furthermore, the concept of remote object, improves location transparency: once a client is bound to a remote object, it no longer has to worry about where that object is located. Also, objects are first-class citizens in an object-based model, meaning that they can be passed as arguments or received as results in RMI. This helps to relieve many of the problems associated with passing pointers in RPC.

Although, technically, RMI is a small evolutionary step from RPC, the model of remote and distributed objects is very powerful. As such, RMI and distributed objects form the base for a widely used distributed systems paradigm, and will be discussed in detail in a future lecture.

The Danger of Transparency

Unfortunately, the illusion of a procedure call is not perfect for RPCs and that of a method invocation is not perfect for RMI. The reason for this is that an RPC or RMI can fail in ways that a “real” procedure call or method invocation cannot. This is due to the problems such as not being able to locate a service (e.g., it may be down or have the wrong version), messages getting lost, servers crashing while executing a procedure, etc. As a result, the client code has to handle error cases that are specific to RPCs.

In addition to the new failure modes, the use of threads (to alleviate the problem of blocking) can lead to problems when accessing global program variables (like the POSIX `errno`). Moreover, some forms of arguments like varargs in C do not lend themselves well to the static generation of marshalling code. As mentioned earlier, pointer-based structures also require extra attention, and exceptions, such as user interrupts via keyboard, are more difficult to handle.

Furthermore, RPC and RMI involve many more software layers than local system calls and also incur network latencies. Both form potential performance bottlenecks. The code must, therefore, be carefully optimised and should use lightweight network protocols. Moreover, since copying often dominates the overhead, hardware support can help. This includes DMA directly to/from user buffers and scatter-gather network interfaces that can compose a message from data at different addresses on the fly. Finally, issues of concurrency control can show up in subtle ways that, again, break the illusion of executing a local operation. These problems are discussed in detail by Waldo et al. [WWWK94].

Group Communication

Group communication provides a departure from the point-to-point style of communication (i.e., where each process communicates with exactly one other process) assumed so far. In this model of communication a process can send a single message to a group of other processes. Group communication is often referred to as *broadcast* (when a single message is sent out to everyone) and *multicast* (when a single message is sent out to a predefined group of recipients).

Group communication can be applied in any of the previously discussed system architectures. It is often used to send requests to a group of replicas, or to send updates to a group of servers containing the same data. It is also used for service discovery (e.g., broadcast a request saying “who offers this service?”) as well as event notification (e.g., to tell everyone that the printer is on fire).

Issues involved with implementing and using group communication are similar to those involved with regular point-to-point communication. This includes reliability and ordering. The issues are made more complicated because now there are multiple recipients of a message and different combinations of problems may occur. For example, what if only one of the recipients does not receive a message, should it be multicast out to everyone again, or only to the process that did not receive it? Or, what if messages arrive in a different order on the different recipients and the order of messages is important?

A widely implemented (but not as widely used) example of group communication is IP multicast. The IP multicast specification has existed for a long time, but it has taken a while for implementations to make their way into the routers and gateways (which is necessary for it to become viable).

An increasingly important form of group communication is *gossip-based communication*, which is often used for data dissemination. This technique relies on epidemic behaviour like diseases spreading among people. One variant is *rumour spreading* (or simply *gossiping*), which resembles the way in which rumours spread in a group of people. In this form of communication, a node A that receives some new information will contact an arbitrary other node B in the system to push the data to that node. If node B did not have the data previously, nodes A and B will continue to contact other nodes and push the data to them. If, however, node B already had that data, then node A stops spreading the data with a certain probability. Gossiping cannot make any guarantees that all nodes will receive all data, but works quite well in practice to disseminate data quickly.

Event-Based Communication

The event-based abstraction decouples senders and receivers in communication. Senders produce events (which may carry data), without specifying a receiver for them. Receivers listen for events that they are interested in, without specifying specific senders. The underlying middleware is responsible for delivering appropriate events to appropriate receivers. A common category of event-based communication are *publish/subscribe* systems, where senders publish events, and receivers subscribe to events of interest. Subscriptions can be based on topic, content, or a more complex combination of event and context properties.

Distributed Shared Memory

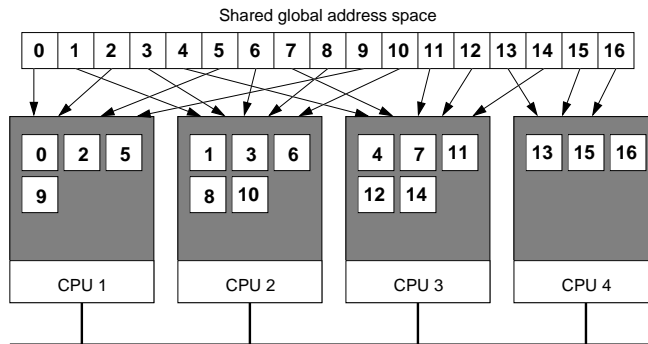


Figure 9: Distributed Shared Memory: pages in a global address space distributed over four independent computers.

Because distributed processes cannot access each other's memory directly, using shared memory in a distributed system requires special mechanisms that emulate the presence of directly accessible shared memory. This is called *distributed shared memory* (DSM). The idea behind DSM is that processes on separate computers all have access to the same virtual address space. The memory pages that make up this address space actually reside on separate computers. Whenever a process on one of the computers needs to access a particular page, it must find the computer that actually hosts that page and request the data from it. Figure 9 shows an example of how a virtual address space might be distributed over various computers.

There are many issues involved in the use and design of distributed shared memory. As such, a separate lecture will be dedicated to a detailed discussion of DSM.

Tuple Spaces

A *tuple space* is an abstraction of distributed shared memory into a generalised shared space. In this model of communication, processes place tuples containing data into the space, while others can search the space, and read and remove tuples from the space. The underlying middleware coordinates the placement and removal of the tuples, and ensures that properties such as ordering and consistency are maintained.

Streams

Whereas the previous communication abstractions dealt with discrete communication (that is they communicated chunks of data), the Stream abstraction deals with continuous communication, and in particular with the sending and receiving of *continuous media*. In continuous media, data is represented as a single stream of data rather than discrete chunks (for example, an email is a discrete chunk of data, a live radio program is not). The main characteristic of continuous media is that besides a spatial relationship (i.e., the ordering of the data), there is also a temporal

relationship between the data. Film is a good example of continuous media. Not only must the frames of a film be played in the right order, they must also be played at the right time, otherwise the result will be incorrect.

A stream is a communication channel that is meant for transferring continuous media. Streams can be set up between two communicating processes, or possibly directly between two devices (e.g., a camera and a TV). Streams of continuous media are examples of *isochronous communication*, that is communication that has minimum and maximum end-to-end time delay requirements.

When dealing with isochronous communication, *quality of service* is an important issue. In this case quality of service is related to the time dependent requirements of the communication. These requirements describe what is required of the underlying distributed system so that the temporal relationships in a stream can be preserved. This generally involves timeliness and reliability.

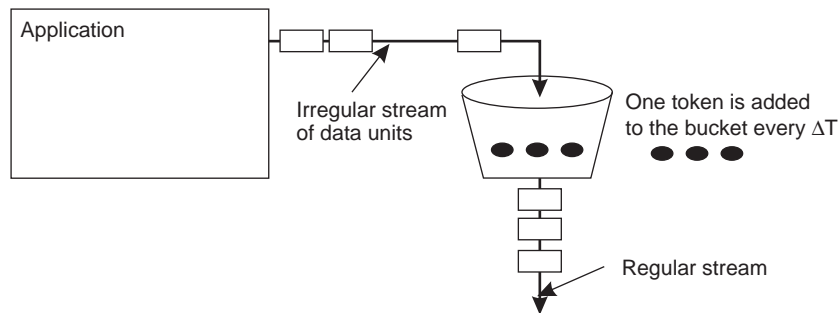


Figure 10: The token bucket model.

Quality of service requirements are often specified in terms of the parameters of a token bucket model (shown in Figure 10). In this model tokens (permission to send a fixed number of bytes) are regularly generated and stored in a bucket. An application wanting to send data removes the required amount of tokens from the bucket and then sends the data. If the bucket is empty the application must wait until more tokens are available. If the bucket is full newly generated tokens are discarded.

It is often necessary to synchronise two or more separate streams. For example, when sending stereo audio it is necessary to synchronise the left and right channels. Likewise when streaming video it is necessary to synchronise the audio with the video.

Formally, synchronisation involves maintaining temporal relationships between substreams. There are two basic approaches to synchronisation. The first is the client based approach, where it is up to the client receiving the substreams to synchronise them. The client uses a synchronisation profile that details how the streams should be synchronised. One possibility is to base the synchronisation on timestamps that are sent along with the stream. A problem with client side synchronisation is that, if the substreams come in as separate streams, the individual streams may encounter different communication delays. If the difference in delays is significant the client may be unable to synchronise the streams. The other approach is for the server to synchronise the streams. By multiplexing the substreams into a single data stream, the client simply has to demultiplex them and perform some rudimentary synchronisation.

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