Communication

Introduction

Inter-process communication is at the heart of all distributed systems

Based on low-level message passing offered by the underlying network

Protocols: rules for communicating processes structured in layers

Four widely-used models:

- Remote Procedure Call (RPC)
- Remote Method Invocation (RMI)
- Message-Oriented Middleware (MOM)
- Streams

Topics to be covered

PART 1
Layered Protocols
Remote Procedure Call (RPC)
Remote Method Invocation (RMI)

PART 2
Message-Oriented Middleware (MOM)
Streams

Layered Protocols

Low-Level
Transport
Application
Middleware

Layered Protocols

General Structure

Based on low-level message passing

A wants to communicate with *B*

A builds a message in its own address space

A executes a call to the OS to send the message

Need to agree on the meaning of the bits being sent

Layered Protocols

Processes define and adhere to rules (protocols) to communicate

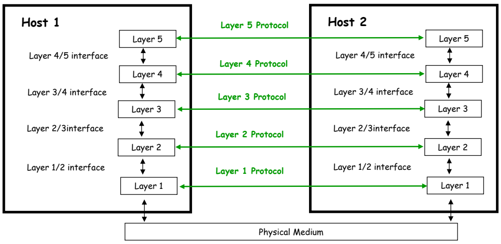
Protocols are structured into layers – each layer deals with a specific aspect of communication

Each layer uses the services of the layer below it – an interface specifies the services provided by the lower layer to the upper layers

The upper layer sees the lower layer as a black box (benefitd?)

Layered Protocols

Layer n on machine 1 talks with layer n on machine 1 based on the Layer n protocol



Protocol suite or protocol stack: collection of protocols used in a particular system

Each protocol adds a header

The OSI Model

The ISO OSI or the OSI model

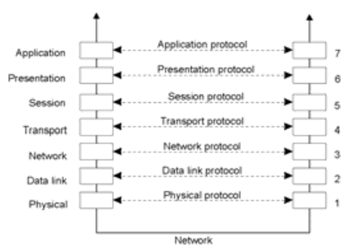
Designed to allow *open* systems to communicate

Two general type of protocols:

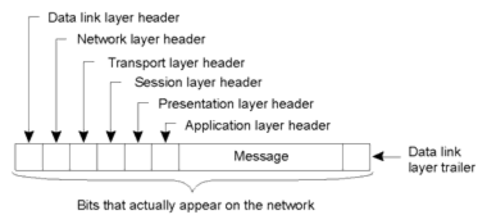
- Connection-oriented: before exchanging data, the sender and the receiver must establish a connection (e.g., telephone), possibly negotiate the protocols to be used, release the connection when done
- Connectionless: no setup in advance (e.g., sending an email)

The OSI Model

- Each layer provides an interface to the one above
- Message send (downwards) Message received (upwards) *example*
- Each layer adds a header



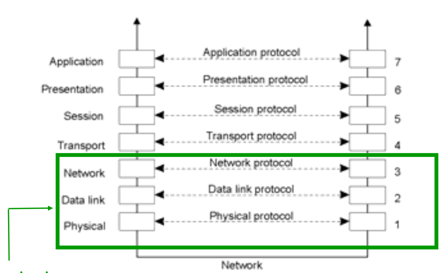
The OSI Model



- The information in the layer n header is used for the layer n protocol
- Independence among layers
- OSI protocols not so popular, instead Internet protocols (e.g., TCP and IP)
- reference model (not an actual implementation)

Low-level Layers

These layers implement the basic functions of a computer network



Lower-level

implemented by the routers (intermediate machines that forward the messages)

Low-level Layers: The Physical Layer

Physical layer:

Concerns with transmitting 0s and 1s
Standardizing the electrical, mechanical and signaling interfaces so that when A sends a 0 bit, it is received as a 0

Issues

- How many volts to use for 0 and 1
- How many bits per sec (data rates)
- Whether to transmit in both direction (duplex/simplex)

Example standard: RS-232-C for serial communication lines

the specification and implementation of bits, and their transmission between sender and receiver

Low-level Layers: The Data Link Layer

Data link layer:

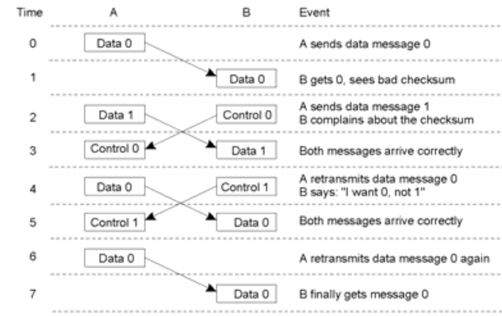
Group bits into frames and sees that each frame is correctly received

Puts a special bit pattern at the start and end of each frame (to mark them) as well as a checksum
If checksums differ, requests a *retransmission*

Frames are assigned sequence numbers

prescribes the transmission of a series of bits into a frame to allow for error and flow control

Low-level Layers: The Data Link Layer



Discussion between a receiver and a sender in the data link layer.
A tries to sends two messages, 0 and 1, to B

Low-level Layers: The Network Layer

Network layer:

Deals with the fact that communication might require multi-hops
At each hop, through which link to forward the packet

Routing: choose the best ("delay-wise") path

Example protocol at this layer: connectionless IP (part of the Internet protocol suite)

IP packets: each one is routed to its destination independent of all others. No internal path is selected or remembered

describes how packets in a network of computers are to be routed.

Low-level Layers

Physical Layer: specification and implementation of bits, transmission between sender and receiver

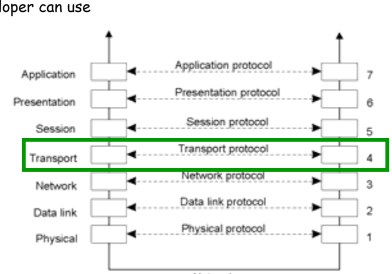
Data Link Layer: groups bits into frames, error and flow control

Network Layer: routes packets

NOTE
For many distributed systems, the lowest level interface is that of the network layer.

Transport Protocols

Turns the underlying network into something that an application developer can use



Transport Layer

Reliable connection

- The transport layer provides the actual communication facilities for most distributed systems.

- Breaks a *message* received by the application layer into *packets* and assigns each one of them a sequence number and send them all

- Header: which packets have been sent, received, there is room for, need to be retransmitted

- Reliable connection-oriented *transport* connections built on top of connection-oriented (all packets arrive in the correct sequence, if they arrive at all) or connectionless *network* services

Transport Layer

Standard (transport-layer) Internet protocols:

• Transmission Control Protocol (TCP): connection-oriented, reliable, stream-oriented communication (TCP/IP)

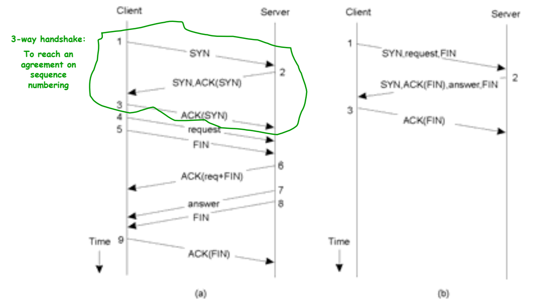
• Universal Datagram Protocol (UDP): connectionless, unreliable (best-effort) datagram communication (just IP with minor additions)

TCP vs UDP

Works reliably over any network
Considerable overhead

use UDP + additional error and flow control for a specific application

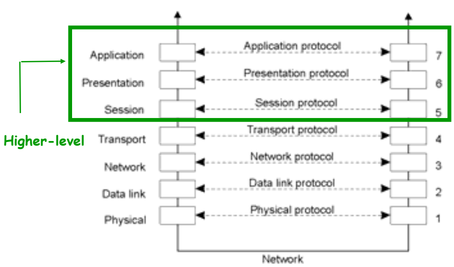
Transport Layer: Client-Server TCP



a) Normal operation of TCP.
b) Transactional TCP (T/TCP) enhancement

Higher-level Layers

In practice, only the application layer is used



Upper Layers

Session Layer

Maintain "logical" sessions using as many transport connections as necessary

Presentation Layer

Deals with non-uniform data representation (describing the messages in a platform-independent format and sending the descriptions along with data) and with compression and encryption

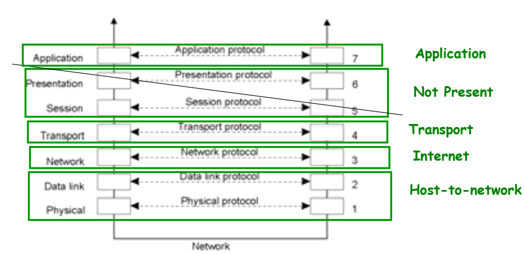
Application Layer

Intended to contain a collection of standard network applications, such as those for email, file transfer, etc

From the OSI reference model, all distributed systems just applications

Many application protocols are directly implemented on top of transport protocols, doing a lot of application-independent work.

OSI vs TCP/IP Model



OSI reference model

TCP/IP not an official reference model (many details regarding the interfaces left open to implementation) – but the de facto Internet communication protocol

Service Primitives

LISTEN: block waiting for an incoming connection

CONNECT: establish a connection with a waiting host

RECEIVE: block waiting for an incoming message

SEND: send a message to a host

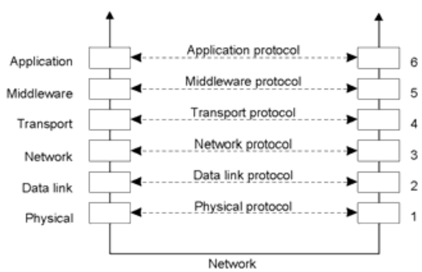
DISCONNECT: terminate a connection

Middleware Layer

Middleware is invented to provide common services and protocols that can be used by many rich set of communication protocols, but which allow *different* applications to communicate

- Marshaling and unmarshaling of data, necessary for integrated systems
- Naming protocols, so that different applications can easily share resources
- Security protocols, to allow different applications to communicate in a secure way
- Scaling mechanisms, such as support for replication and caching
- Authentication protocols, authorization
- Atomicity

Middleware Protocols



An adapted reference model for networked communication.

RPC

Basic RPC Model
Parameter Passing
Variations

Remote Procedure Call (RPC)

Basic idea:

Allow programs to call procedures located on other machines

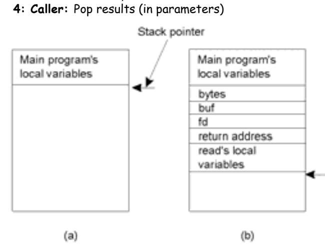
Some issues:

Calling and called procedures in different address spaces
Parameter passing
Crash of each machine

Conventional Procedure Call

Local procedure call: count = read(fd, buf, nbytes)

1: Caller: Push parameter values of the procedure on a stack + return address
2: Called procedure takes control
3: Called proc: Use stack for local variables, executes, pop local variables, save in cache return result, use return address
4: Caller: Pop results (in parameters)



Principle: "communication" with local procedure is handled by copying data **to/from the stack** (with a few exceptions)

Example: incr(i, i), (adds 1 to each parameter)

initially i = 0

Call-by-Value, i = 0

Call-by-Reference, (push the address of the variable), i = 2

Call-by-Copy/Restore

The value is copied in the stack as in call-by-value, and then copied back by the called procedure, i = 1

Client and Server Stubs

RPC supports location transparency (the calling procedure does not know that the called procedure is remote)

Client stub:

- local version of the called procedure
- called using the "stack" sequence
- it packs the parameters into a message and requests this message to be sent to the server (calls send)
- it calls receive and blocks till the reply comes back

When the message arrives, the server OS passes it to the server stub

Server Stub:

- typically waits on receive
- it transforms the request into a *local* procedure call
- after the call is completed, it packs the results, calls send
- it calls receive again and blocks

Client and Server Stubs

call to procedure *x* -> call *client stub* for procedure *x*

client stub calls send and blocks –

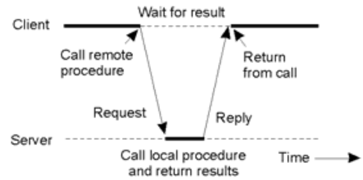
upon receipt, the server stub gets control –

the server stub calls the local procedure *x*

after procedure x ends, control returns to the server stub

server stub calls send, and then receive again and blocks

the client OS, passes it to the client stub, copies it to the caller and returns



Steps of a Remote Procedure Call

1. Client procedure calls client stub in normal way
2. Client stub builds message, calls local OS
3. Client's OS sends message to remote OS

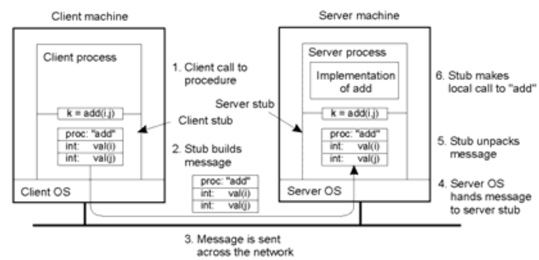
4. Remote OS gives message to server stub

5. Server stub unpacks parameters, calls server
6. Server does work, returns result to the stub
7. Server stub packs it in message, calls local OS
8. Server's OS sends message to client's OS

9. Client's OS gives message to client stub
10. Stub unpacks result, returns to client

Parameter Passing

Remote procedure add(i, j)



A server stub may handle more than one remote procedure

Two issues with parameter passing:

- Marshalling
- Reference Parameters

Parameter Passing

Parameter marshaling: There is more than just wrapping parameters into a message:

- Client and server *machines* may have different data *representations* (think of byte ordering)
- Wrapping a parameter means transforming a value into a sequence of bytes
- Client and server have to agree on the same encoding:
  - How are basic data values represented (integers, floats, characters)
  - How are complex data values represented (arrays, unions)
- Client and server need to properly interpret messages, transforming them into machine-dependent representations.

Passing Value Parameters

An integer (one 32-bit word), and a four-character string (one 32-bit word)

Example, integer 5 and string JILL

a) Original message on the Pentium (right-to-left)
b) The message after receipt on the SPARC (left-to-right)
c) The message after being inverted, ok with integers, problem with strings

The little numbers in boxes indicate the address of each byte

Passing Reference Parameters

Pointer refers to the address space of the process it is being used

Solutions:

- Forbid pointers and reference parameters in general

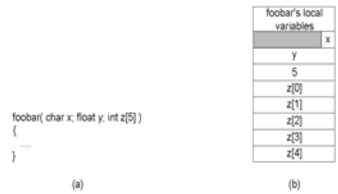
- Use **copy in/copy out** semantics: while procedure is executed, nothing can be assumed about parameter values (only Ada supports this model).

RPC assumes *all* data that is to be operated on is passed by parameters. Excludes passing **references** to (global) data.

One optimization, if the stubs know which are parameters are input and output parameters -> eliminate copying

What about pointers to complex (arbitrary) data structures?

Parameter Specification and Stub Generation



Need to agree on:

Encoding rules (message format, representation of simple data structures)

Actual exchange of messages (e.g., TCP/IP)

Implement the stubs!

Stubs for the same protocol and different procedures differ only in their interfaces to the applications

Interface Definition Language (IDL)

Extensions

- Calls to local procedures

- Asynchronous RPC

Doors

Try to use the RPC mechanism as the only mechanism for interprocess communication (IPC).

Doors are RPCs implemented for processes on the same machine

A single mechanism for communication: procedure calls (but with doors, it is not transparent)

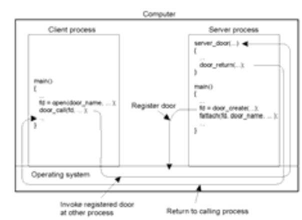
Server calls **door_create**: registers a door, an id is returned

fattach: associates a symbolic name with the id

Client invokes a door using **door_call**, the id and any parameters

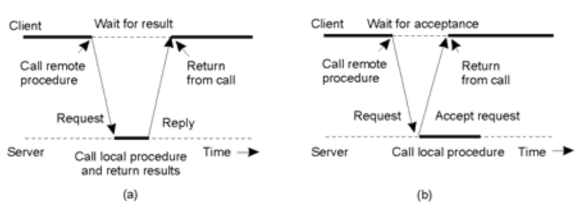
The OS does an upcall to the server

To return the result **door_return**



Asynchronous RPC

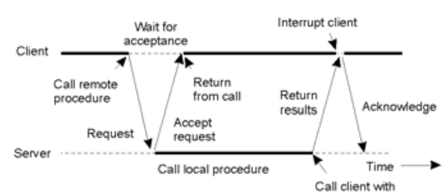
Try to get rid of the strict request-reply behavior, and let the client continue without waiting for ananswer from the server.



Traditional RPC   Asynchronous RPC

Asynchronous RPC: the server immediately sends a reply back to the client the moment the RPC request is received, after which it calls the requested procedure

Differed Synchronous RPC



Deferred Synchronous RPC: two asynchronous RPCs combined

The client uses asynchronous RPC to call the server

The server uses asynchronous RPC to send the reply

One way RPC: the client does not wait at all (reliability?)

Performing an RPC

At-most-one semantics: no call is ever carried out more than once, even in the case of system crashes

Idempotent remote procedure: a call may be repeated multiple times

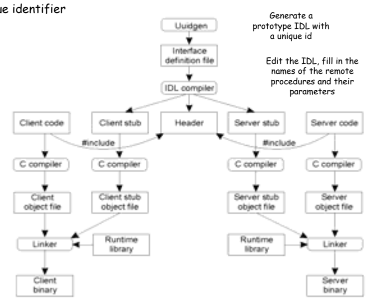
DCE RPC

Let the developer concentrate on only the client- and server-specific code; let the RPC system (generators and libraries) do the rest.

Writing a Client and a Server

IDL permits procedure declarations (similar to function prototypes in C).Type definitions, constant declarations, etc to provide information to correctly marshal/unmarshal paramters/results. Just the syntax (no semantics)

A globally unique identifier



The steps in writing a client and a server in DCE RPC.

Binding a Client to a Server

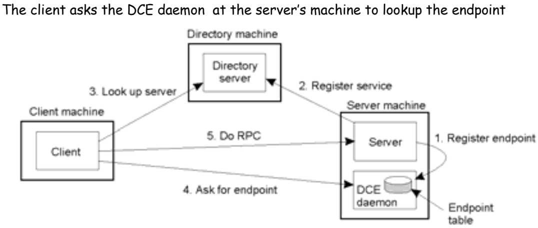
1. Locate the server machine

2. Locate the server on the machine: need to know an endpoint (port) on the server machine to which it can send messages

A table of (server, endpoints) is maintained on each server machine by a process called the DCE daemon

The server asks the OS for an endpoint and registers this endpoint with the DCE

The client asks the DCE daemon at the server's machine to lookup the endpoint



RPCgen

Check out the web page for an example

Programmer writes an example.x file

with the definitions of remote procedures (their prototype) and other variables

RPCgen generates:

- example.h (header file, function prototypes)
- exampel_svc.c (server stub)
- example_clnt.c (client stub)
- example_client.c (template, the programmer edits this file, procedure calls)
- example_server.c (template, the programmer edits this file)

Remote Object Invocation

Distributed Objects
Remote Object Invocation
Parameter Passing

Distributed Objects

Expand the idea of RPCs to invocations on remote objects

- Data (state) and operations on those data encapsulated into an object
- Operations are implemented as **methods** and are accessible through **interfaces**
- An object offers only its interface to clients.

  An object may implement many interfaces;

  Given an interface definition, there may be several objects that offer an implementation for it
- An interface and its implementation on *different* machines

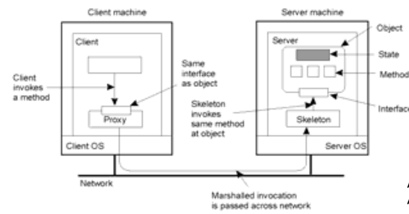
Distributed Objects

A client binds to a distributed object: an implementation of the object's *interface*, called a proxy, is loaded into the client's address space

Proxy (analog to a client stub):

Marshals method invocations into messages & Un-marshals reply messages

Actual object at a server machine: offers the same interface



Skeleton (analog to server stub)

Un-marshals requests to proper method invocations at the object's interface at the server

Note: the object itself is not distributed, aka remote object

Distributed Objects

Compile-time objects:

Related to language-level objects (e.g., Java, C++)

Objects defined as instances of a class
Compiling the class definition results in code that allows to instantiate Java objects
Language-level objects, from which proxy and skeletons are automatically generated.
Depends on the particular language

Runtime objects: Can be implemented in any language, but require use of an object adapter that makes the implementation *appear* as an object.

Adapter: objects defined based on their interfaces
Register an implementation at the adapter

Distributed Objects

Transient objects: live only by virtue of a server: if the server exits, so will the object.

Persistent objects: live independently from a server: if a server exits, the object's state and code remain (passively) on disk.

Binding a Client to an Object

Provide system-wide object references, freely passed between processes on different machines
Reference denotes the *server machine* plus an *endpoint for the object server*, an *id* of which object

When a process holds an object reference, it must first bind to the object

Bind: the local proxy (stub) is instantiated and initialized for specific object – implementing an interface for the object methods

Two ways of binding:
Implicit binding: Invoke methods directly on the referenced object (requires global references)

Explicit binding: Client must first explicitly bind to object before invoking it (generally returns a pointer to a proxy that then becomes locally available)

Binding a Client to an Object

```
Distr_object* obj_ref;        //Declare a systemwide object reference
obj_ref = …;                          // Initialize the reference to a distributed object
obj_ref-> do_something();             // Implicitly bind and invoke a method
                              (a)

Distr_object objPref;         //Declare a systemwide object reference
Local_object* obj_ptr;        //Declare a pointer to local objects
obj_ref = …;                          //Initialize the reference to a distributed object
obj_ptr = bind(obj_ref);              //Explicitly bind and obtain a pointer to the local proxy
obj_ptr -> do_something();            //Invoke a method on the local proxy
                              (b)
```

(a) Example with implicit binding using only global references
(b) Example with explicit binding using global and local references

Basic RMI

Assume client stub and server skeleton are in place

- Client invokes method at stub
- Stub marshals request and send it to server

- Server ensures referenced object is active
  - Created separate process to hold object
  - Load the object into server process
- Request is unmarshalled by object's skeleton, and referenced object is invoked
- *If request contained an object reference, invocation is applied recursively*
- Result is marshalled and passed back to client

- Client stub unmarshals reply and passes result to client application

Static vs Dynamic RMI

Remote Method Invocation (RMI)

Static invocation: the interfaces of an object are known when the client application is being developed

If interfaces change, the client application must be recompiled

Dynamic invocation: the application selects at runtime which method it will invoke at a remote object

invoke(object, method, input_parameters, output_parameters)

method is a parameter, **input_parameters**, **output_parameters** data structures

Static: **fobject.append(int)**

Dynamic: **invoke(fobject, id(append), int)**

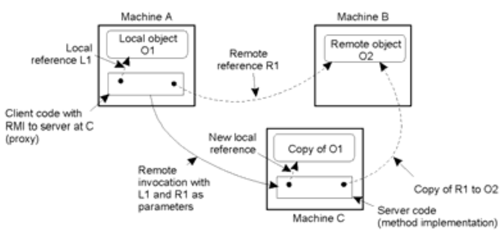
id(append) returns an id for the method append

Example uses: browsers, batch processing service to handle invocation requests

Object References as Parameters

When invoking a method with an object reference as a parameter, when it refers to *a remote object*, the reference is copied and passed as a value parameter (pass-by-reference)

When the reference refers to a *local object* (i.e., an object in the same address space as the client) the referred object is copied as a whole and passed along with the invocation (pass-by-value)



Java RMI

Distributed objects integrated into the language

- Remote objects (i.e., state on a single machine, interfaces available to many) the only form of distributed objects
- Interfaces implemented by proxies that appear as a local object
- Differences between remote and local objects (violating distribution transparency)
  - Cloning
  - Cloning a local object O results in a new object of the same type as O and with exactly the same state
  - Cloning of a remote object O executed only by the server – proxies of the actual object are not cloned (have to bind to the clone to access it)

Java RMI

- Differences between remote and local objects (continued)
  - Java allows objects to be constructed as a monitor by declaring a method to be synchronized (if two processes simultaneously call a synchronized method, only one will proceed while the other will be blocked)
    - Two ways:
      - Implement synchronization at the proxy level (block at the client - hard)
      - Implement synchronization at the server level (what if a client fails?)
  - Java allows concurrent access to synchronized methods from different proxies (need to use separate techniques)

Java RMI

Any serializable object type can be used as a parameter to an RMI

A type is serializable if it can be marshalled

Local objects are passed by value; whereas remote objects are passed by reference

A remote object is built from two different classes:

server class: implementation of the server-side code

client class: implementation of the proxy (needs the server's network address and endpoint)

Proxies are serializable, thus can be marshalled and passed as parameters

(sent over to other processes, which can unmarshall them and use them as references to remote objects)

Java RMI

Check out the web page for an implementation