Imperial College London

Computer Networks and Distributed Systems

Interaction Primitives

Course 527 – Spring Term 2014-2015

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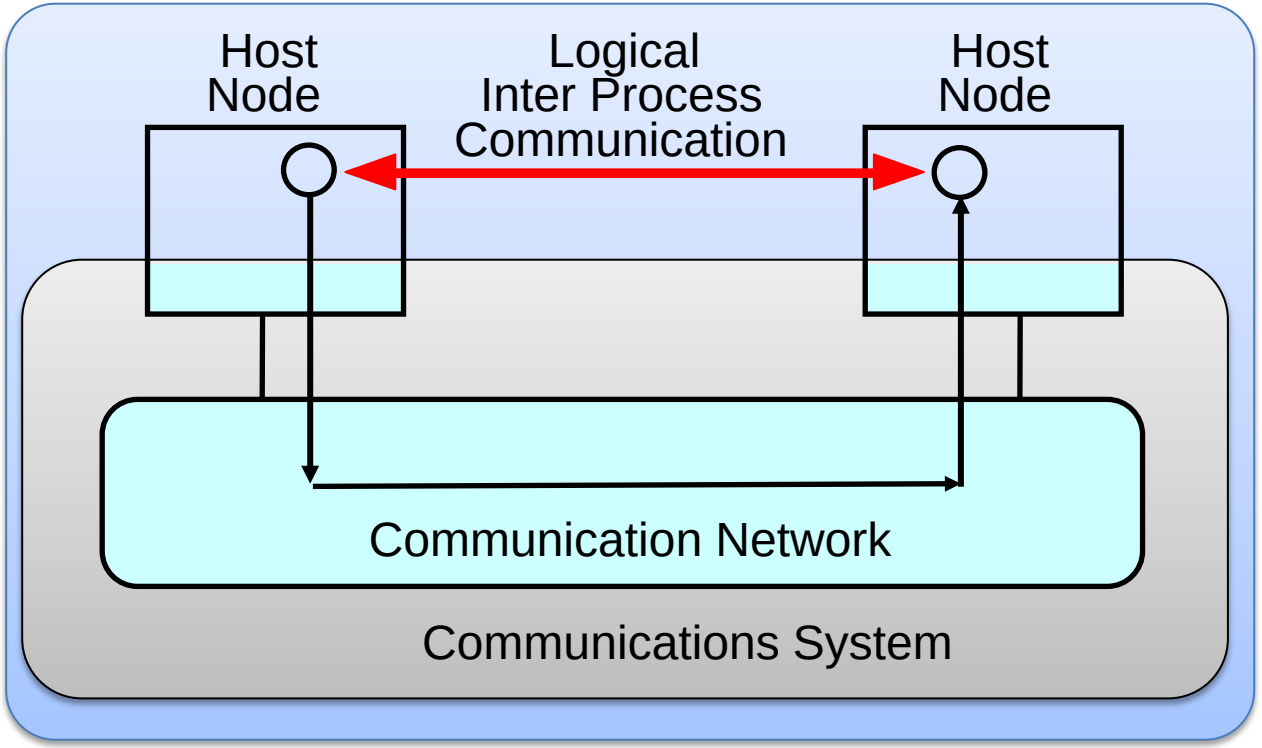
Interaction Primitives Contents

- Message passing
  - send & receive primitives
  - synchronisation
  - naming
- Remote procedure call
  - IDL
  - semantics
- Object invocation (in next lecture)

Introduction

- Components of a distributed system communicate in order to cooperate and synchronise their actions
- A distributed system makes use of message passing as a basic mechanism supported by the communication system as there is no shared memory
- OS primitives → low level + un-typed data
- Language primitives → higher level + typed data
- Shared memory abstractions (e.g., shared objects or Linda tuples) can be implemented using above message passing

Inter Process Communication (IPC)



Communication Service Characteristics

- Primitives available for inter-process communication can be based on connectionless or connection oriented communication

- Connectionless (Datagram)
  - "Send and pray" message could be lost, duplicated or delivered out-of-sequence. User not told
  - Potentially broadcast or multi-destination
  - Maintains no state information → cannot detect lost, duplicate or out-of-sequence messages
  - Each message contains full source & destination address
  - May discard messages which are corrupted or because of congestion → No error correction

Communication Service Characteristics

- Connection Service
  - Reliable, in-sequence delivery of messages
  - Performs error and flow control → errors reported to both ends
  - Overheads:
    - Time: establishment and termination of connection, error control protocol overheads
    - Space: state information maintained at both ends
      - unacknowledged messages
      - remote entity address
      - message sequence numbers flow control information

Communication Service Characteristics

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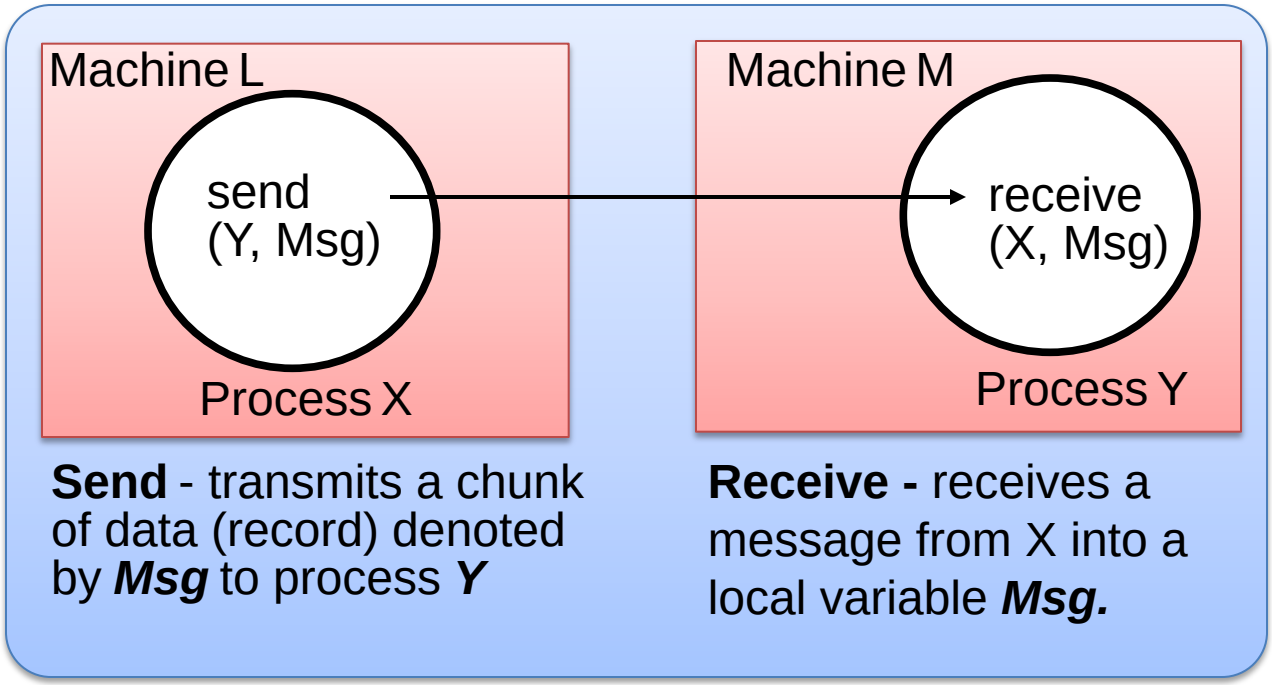
Message Passing



Which communication service does this map onto?

- Both sender and receiver directly name each other in their programs
  - What are the disadvantages?
  - What are the alternatives?

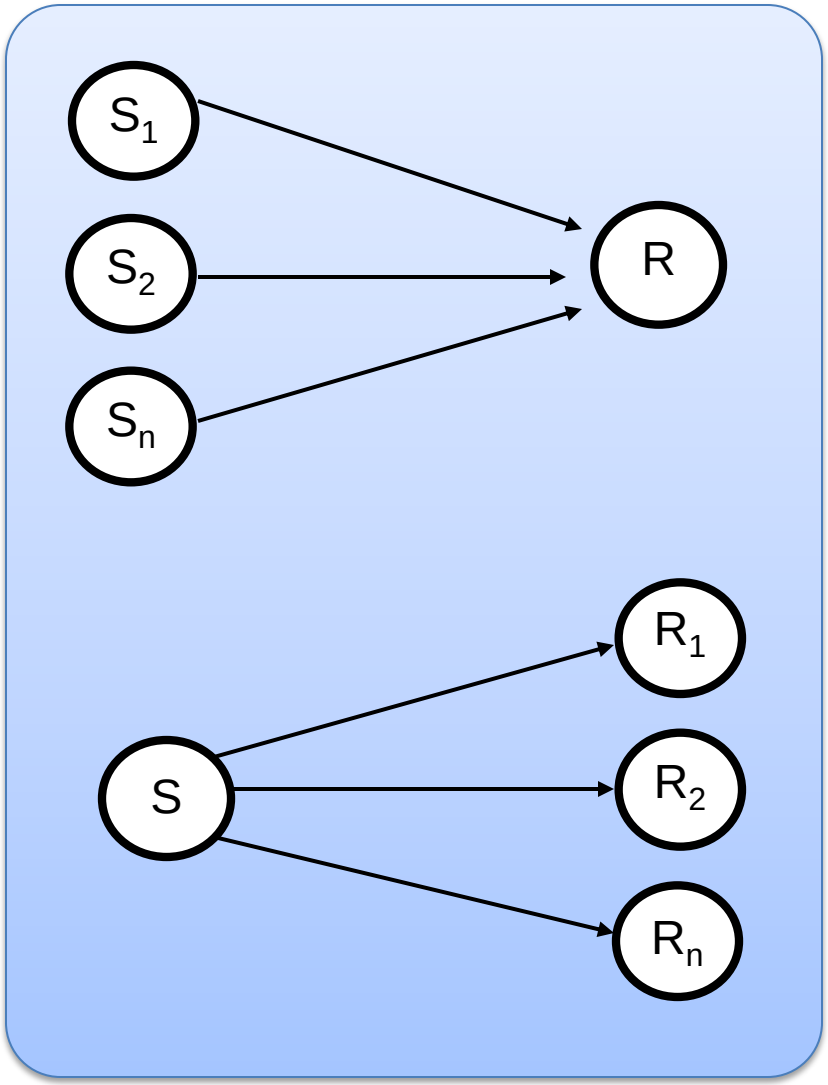
Communication Patterns

Many - to - One

- Many sender processes S_1, …, S_n may send to a single receiver. The receiver R receives the messages one at a time from a message queue
- Typical client-server

One - to - Many

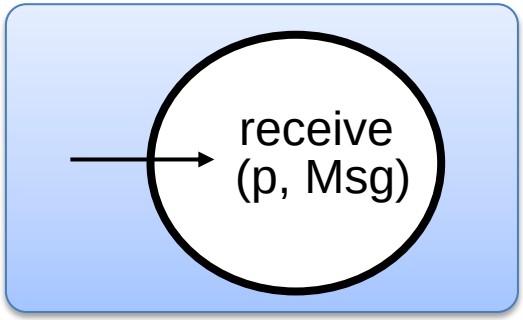
- Single sender S sends message to many receivers R_1, …, R_n
- LANs such as Ethernet provide hardware support for broadcast (all) and multicast (subset))



Blocked Receive Primitive

- **Blocked receive** - The destination process blocks if no message is available, and receives it into a target variable when it is available

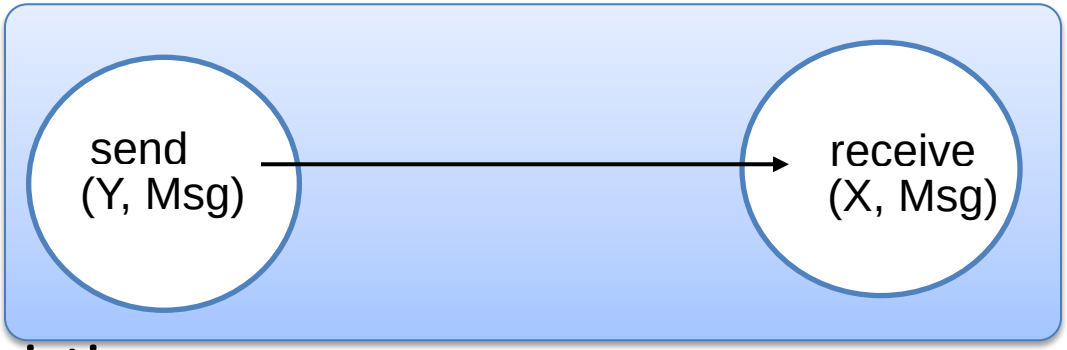
```
Ada   ACCEPT p ( mess: IN ....)
CSP   source?msg { direct naming }
Unix  size = recvfrom (socket, buffer,
                       from)
```



- Variations:
  - Timeout – specify a limit on the amount of time prepared to wait for a message, otherwise take an alternative action
  - Conditional receipt – the receiver returns an indication of whether a message was received (e.g. true or false) and the process continues. A non-blocking receive lets a process check if a message is waiting from different clients (cf. Polling)

Asynchronous Send

- Asynchronous send is an **unblocked send**, where the sender continues processing once the message has been copied out of its address space



- Characteristics:
  - Mostly used with blocking receive
  - Underlying system must provide buffering (usually at the receive end)
  - Loose coupling between sender and receiver(s)
  - Readily usable for multicast. Efficient implementation

Asynchronous Send

- Problems
  - Buffer exhaustion (no flow control). What should happen if the destination runs out of buffers?
  - Error reporting of lost messages is not sensible. Difficult for sender to match error report with affected message
  - Formal verification is more difficult, as need to account for the state of the buffers
- Maps closely onto connectionless communication service but can be implemented via a reliable connection service

How can 2 processes use async send and blocking-receive, synchronise to perform an action at the same time?

Synchronous Send

- Synchronous send is a **blocked send**, where the sender is held up until actual receipt of the message by the destination. It provides a synchronisation point for the sender and receiver (cf. handshaking)
  - CSP: `clock! start`

- Characteristics:
  - Tight coupling between sender and receiver (tends to restrict parallelism)
  - For looser coupling, use explicit buffer processes
  - Generally easier to reason about synchronous systems

Synchronous Send

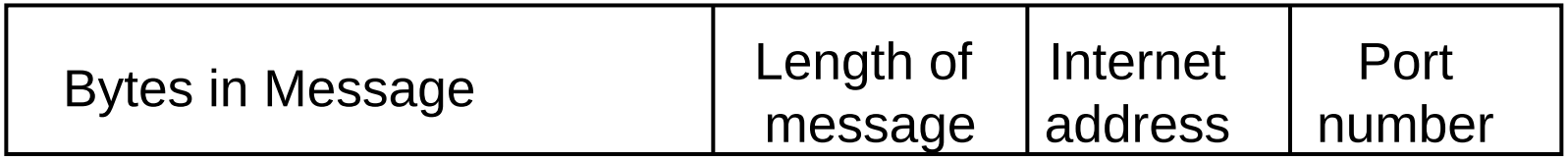
- Problems:
  - Failures and indefinite delays → indefinitely blocked ?
    - create a thread to delegate the send responsibility
  - No multi-destination
  - Implementation more complex (especially if timeout is included)
  - The underlying communication service is expected to be **reliable**

Unix Socket Interface

- Internet Addresses
  - Messages in the Internet (IP packets) are sent to addresses which consist of three components: (Netid, Hostid, Portid)
  - The network identifier and host identifier take up 32 bits divided up according to the class of the address (A,B,C). The port identifier is a 16 bit number significant only within a single host. (By convention port numbers 0..511 are reserved and are used for well known services e.g. telnet, http, smtp)
- Sockets
  - Sockets are the programming abstraction provided by Unix to give access to transport protocols or for local IPC. A socket provides a file descriptor at each end of the communication link

Java API for UDP Datagrams

- Two Java classes:
  - `DatagramPacket` provides a constructor to make a UDP packet from an array of bytes



  - Another constructor is used when receiving a message. Methods `getData, getPort, getAddress` can be used to retrieve fields of `DatagramPacket`
  - `DatagramSocket`
    - Methods `send` and `receive` for transmitting `datagramPacket. setSoTimeout` for a receiver to limit how long it blocks . If the timeout expires it throws an `interruptedIOException`

http://docs.oracle.com/javase/tutorial/networking/sockets/
http://docs.oracle.com/javase/tutorial/networking/datagrams

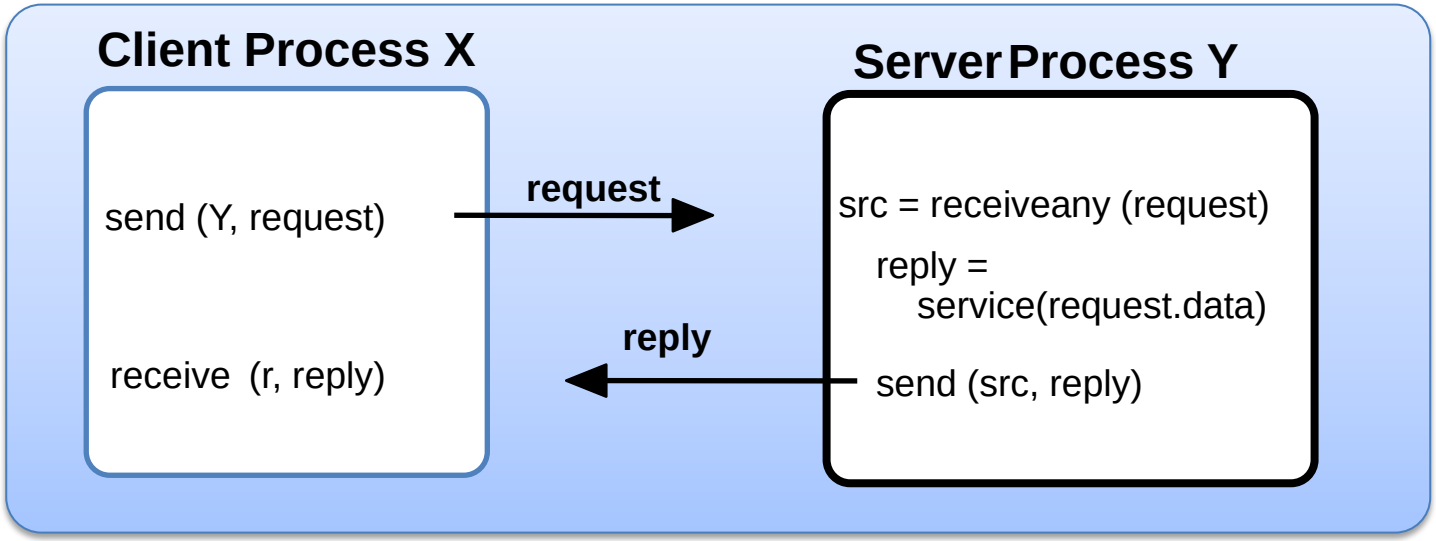
Java UDP Client

```
import java.io.*;
import java.net.*;

public class UDPClient {
  public static void main(String[] args)
    throws IOException {
    byte buf[] = System.console().readLine().getBytes();
    int serverPort = 6789;
    DatagramPacket pkt = new DatagramPacket(buf, buf.length,
      InetAddress.getByName(args[0]), serverPort);
    // create socket on any available port
    DatagramSocket socket = new DatagramSocket();
    socket.send(pkt);
    buf = new byte[256];
    pkt = new DatagramPacket(buf, buf.length);
    socket.receive(pkt);
    System.out.println(new String(pkt.getData()));
  }
}
```

Java UDP Server

```
import java.io.*;
import java.net.*;

public class UDPServer {
  public static void main(String[] args) throws IOException {
    DatagramSocket sock = new DatagramSocket(6789); // Same Port
      while (true) {
      byte buf[] = new byte[256];
      DatagramPacket pkt = new DatagramPacket(buf, buf.length);
      sock.receive(pkt);
      String s = new String(pkt.getData(), 0, pkt.getLength());
      System.out.println(s);
      buf = System.console().readLine().getBytes();
      InetAddress clientAddress = pkt.getAddress();
      int clientPort = pkt.getPort();
      pkt = new DatagramPacket(buf, buf.length, clientAddress,
        clientPort);
      sock.send(pkt); }
  }
}
```

Client Server Interactions



- Request-reply is used to implement client - server communication

- Process Y address must be known to all client processes. This is usually achieved by publishing it in a nameserver

Message Passing Recap

- OS level message interaction primitives e.g., sockets are considered as the assembly language level of distributed systems. They are too low-level an abstraction to be productively used by programmers
  - Message passing systems do not deal with the problems of marshalling a set of data values into a single contiguous chunk of memory which can be sent as a message
  - Data types are represented in memory in different ways by different machines and by different compilers. Message passing does not address this heterogeneity
  - Programming paradigms such as client-server is cumbersome
  - Component interface is not explicit – many different types of messages may be received by a process into a single message variable

Message Passing Recap

- However,
  - Asynchronous message passing permits parallelism
  - Message passing is the fundamental means of interacting in distributed systems and can be used to implement higher level primitives such as Remote Procedure Call or Object invocation

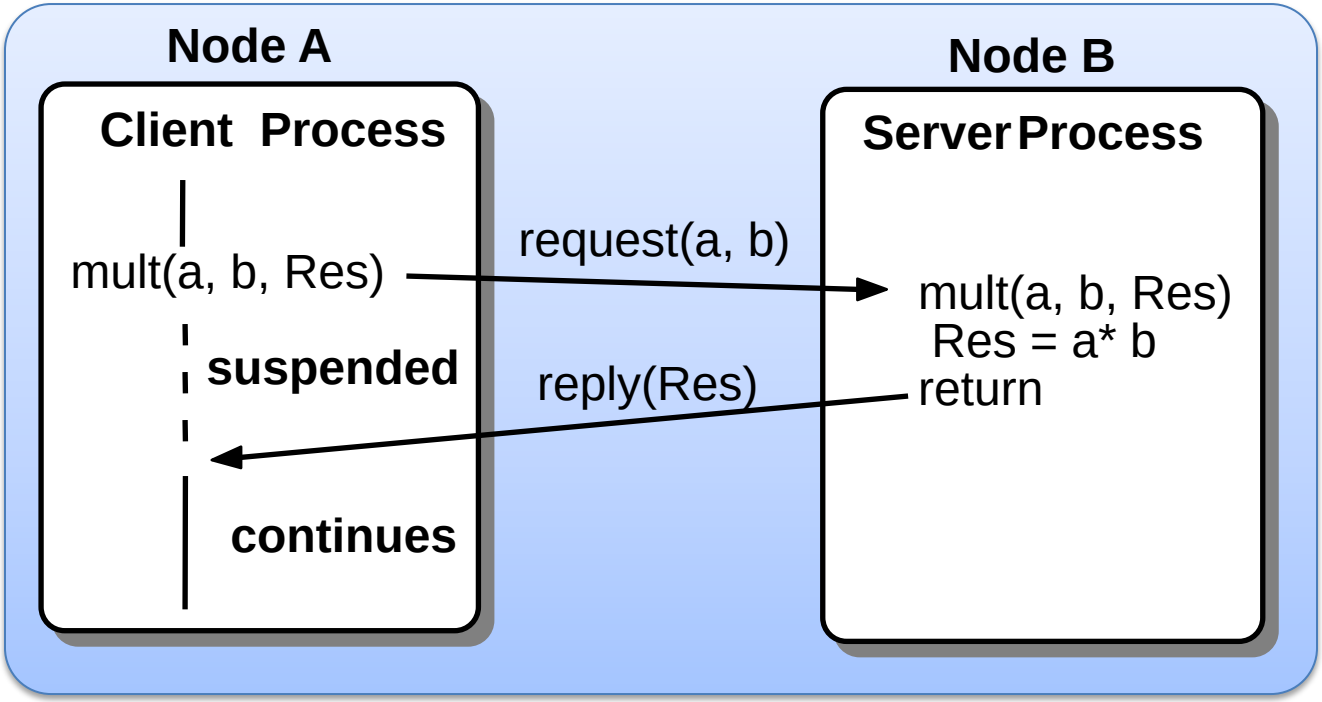
Remote Procedure Call (RPC)

- Basic message passing leaves a lot of work for the programmer when implementing client-server interactions e.g. constructing messages, transforming data types

- Remote Procedure Calls aim to make a call to a remote service look the same as a call to a local procedure
  - The parameters to the call are carried in a request message and the results returned in a reply message
  - Of course since calls to procedures implemented remotely can fail in different ways to procedures implemented locally, the semantics of an RPC are different from those of a local procedure

- Birrel A.D. and Nelson B.J. (1984). Implementing remote procedure calls. ACM Transactions on Computer Systems, vol. 2, pp. 39-59.

RPC Interactions



- Client is suspended until the call completes
- Parameters must be passed **by value** since Client and Server processes do not share memory and consequently Client pointers have no meaning in Server address space

Stub Procedures

- Client has a local stub for every remote procedure it can call
- Server has local stub (skeleton) for every procedure which can be called by a remote client
- Stub procedures perform:
  - Parameter marshalling (packing) - assemble parameters in communication system messages
  - Unpacking received messages and assigning values to parameters
  - Transform data representations if necessary
  - Access communication primitives to send/receive messages
- Stubs can be generated automatically from an interface specification

Interface Definition Language (IDL)

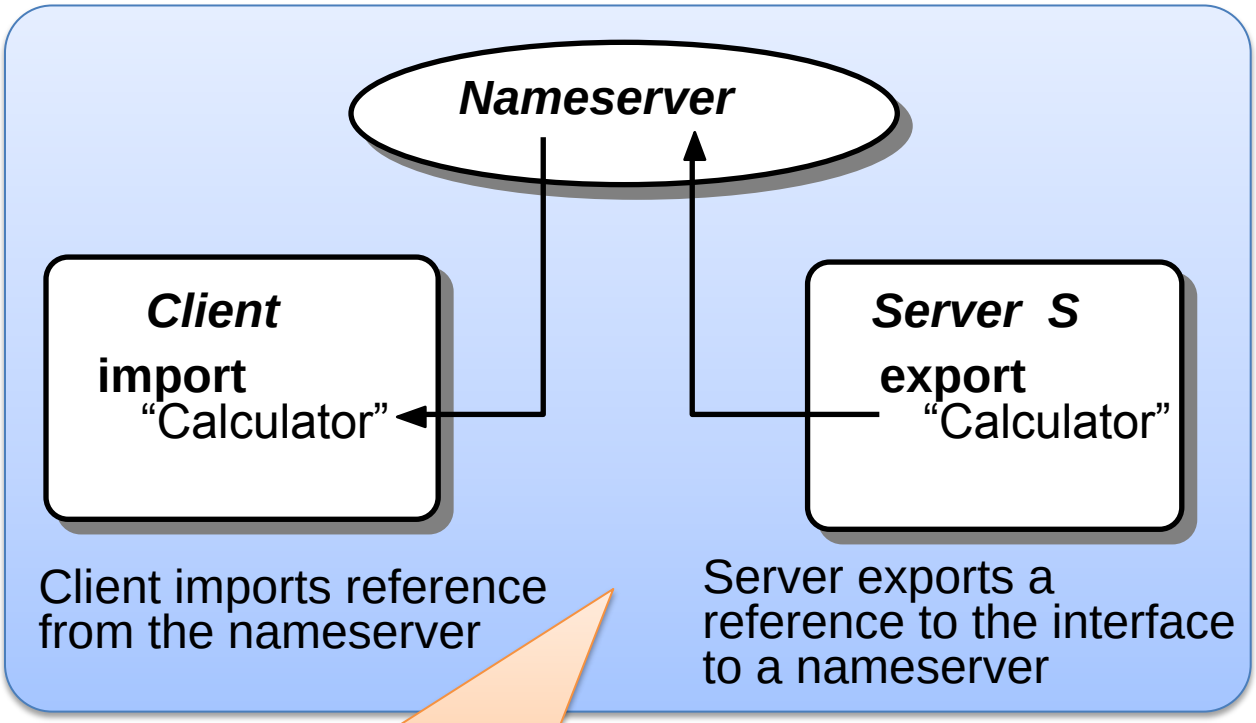
- IDL is a data typing language used to specify the interface operations and their parameters
  - Pseudo code example

```
interface calc  {
        void mult ( [in]  float a, [in]  float b, [out] float Res );
        void square ( [in]  float a, [out] float Res );
}
```

  - The IDL compiler uses this interface definition to generate the code for both client and server stubs in calc.idl
  - The above assumes multiple in and out parameters but Sun RPC is more primitive and allows only a single input parameter and a single result although these may be complex data structures

Binding

- Binding maps an RPC interface used by a client to the implementation of that interface provided by a server



Calculator Client Code

```
#include "calc.idl"

void main()  {
  status = import (calc c, "calculator", nameserverAddress);

  c.mult(1.2, 5.6, Res);

  print (Res);
}
```

Lookup calculator in nameserver and bind to c

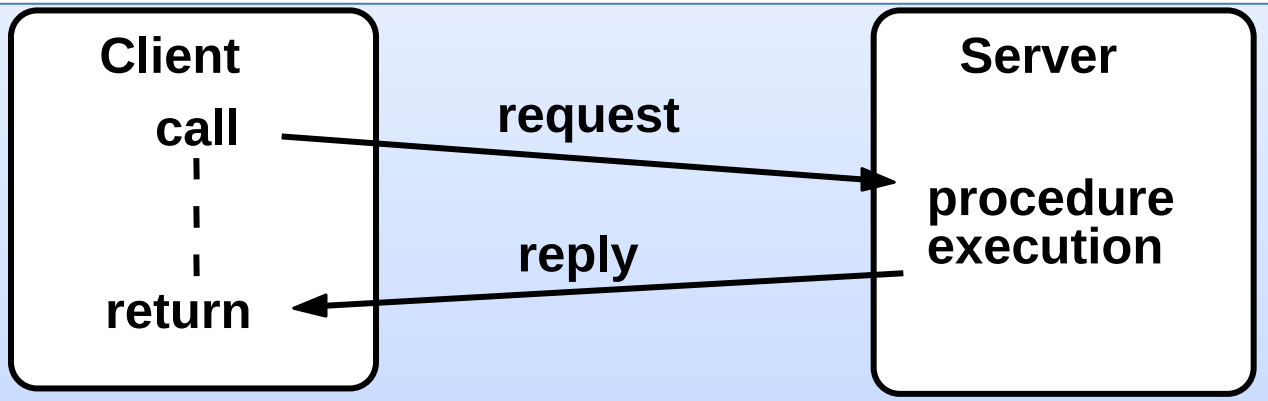
Use remote procedure reference c to invoke mult operation

Calculator Server Code

```
#include "calc.idl"

void main() {
   status = Export  (calc, "calculator", nameserverAddress);
   status = RpcServerListen ();
   //tells runtime system that server is ready to receive
   calls.
}

// implementation for interface procedures
void  mult (float a, float b, float  Res) {
   Res = a * b;
}

void square (float a, float Res) {
   Res = a * a;
}
```

RPC Failures

- Remote procedure calls differ from local procedure calls in the ways that they can fail



Client machine may crash during call

Duplicates or messages may be lost as a result of comms failure or corruption

Server machine may crash before request is received or during execution before reply is sent

Name server failure - cannot locate server

RPC Failures

- A server may also fail and quickly recover in-between client calls without the client knowing, but this may result in loss of state information pertaining to the client interaction - so the client needs to know about server epochs

- Orphan executions – result from a client crashing while the server is executing the procedure. For long running procedures, to avoid wasting resources, the server may wish to be informed of client crashes so that it can abort orphan executions

- A number of different **call semantics** are possible depending on the fault-tolerance measures taken to overcome these failures

Maybe (Best-Efforts) Call Semantics

```
bool call (request, reply) {
    send(request);
    return receive(reply, T) // return false if timeout;
}
```

- **No fault tolerance measures!!** If the call fails after timeout, the caller cannot tell whether the procedure was executed, whether request/reply were lost or the server crashed

What applications can this be used for?

- This is known as **maybe call semantics** because if the call fails the client cannot tell for sure whether the remote procedure has been called or not. If the call succeeds, the procedure will have been executed exactly once if using a communication service which does not generate duplicate messages

- Lightweight but leaves issues of state consistency of the server, with respect to the client, up to the application programmer

At-Least-Once Call Semantics

```
bool call (request, reply) {
      int retries = n;
      while(retries--) {
            send(request);
            if (receive(reply, T)) return true;    }
            return false; // return false if timeout;
}
```

- Retries up to n times – if the call succeeds then procedure has been executed one or more times as duplicate messages may have been generated

- If the call fails, a permanent communication failure (e.g., network partition) or server crash is a probability

At-Least-Once Call Semantics

- Useful for idempotent server operations i.e. they may be executed many times and have the same effect on server state as a single execution

- Sun RPC supports this semantic since it was originally designed for NFS in which the file operations are idempotent and servers record no client state. A call may thus succeed if the server has crashed and recovered within time n * T

At-Most-Once Call Semantics

- This guarantees that the remote procedure is either never executed or executed partially (due to a server crash) or once

- To do this, the server must keep track of request identifiers and discard retransmitted requests that have not completed execution. On the other hand, the server must buffer replies and retransmit until acknowledged by the client

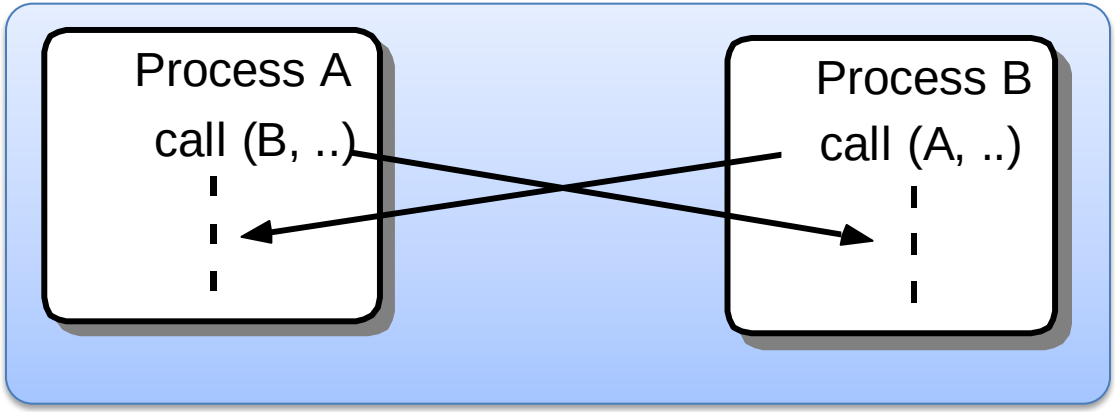
- Most RPC systems guarantee at-most-once semantics in the absence of server crashes

Transactional Call Semantics

- (Zero or Once)
- This guarantees that either the procedure is completely executed or it is not executed at all
- To ensure this, the server must implement an atomic transaction for each RPC i.e., either the state data in the server is updated permanently by an operation taking it from one consistent state to another or it is left in its original state, if the call is aborted or a failure occurs
- This requires **two phase commit** type of protocol

RPC Summary

- Interaction primitive similar to but not the same as well known procedure call
  - different local and remote primitives cannot move co-located components after compilation
- May result in deadlock



RPC Summary

- Often specific to a particular programming language or operating system
- RPC calls suspend client for network roundtrip delay + procedure execution time
- Not suitable for multimedia streams or bulk data transfer
- Not easy to use
- No reuse of interface specifications
- Servers are usually a heavyweight OS process

RPC Election Service

- Specify an RPC interface to an Election Service which allows a client to both query the current number of votes for a specified candidate and vote for one of the set of candidates. Each client has a voter number used for identification in requests and candidates are identified by a string name

```
interface election {
    void vote  ([in] int voterid, [in] string  candidate);
    void query ([in]  string candidate, [out] int votecount);
}
```

Election Service Implementation

- Give a pseudo-code implementation for the Election Service (server only) which would permit the interface to be invoked using an RPC mechanism. The RPC implementation supports **at-least-once** calling semantics but clients must only vote once

Election Server

```
#include  "election.idl"
void main ()  {
    status = export ( election, "electserver", docnameserver);
    status = RPCServerListen();
    voted:  array of booleans indexed by voterid of clients
    indicating whether they have voted  (could be a list);
    votes:  array of votes 'indexed' by candidate name

vote ( voterid, candidate) {
    if not (voted [voterid]) {
        voted [voterid] := true;
        votes [candidate]++
        } else do nothing as candidate has voted     }

query (candidates, votecount) {
    votecount := votes [candidate]; }
```