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PA160: Net-Centric Computing II.

Distributed Systems

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Lecture overview

Distributed Systems

- Key characteristics
- Challenges and Issues
- Distributed System Architectures
- Inter-process Communication

Middleware

- Remote Procedure Calls (RPC)
- Remote Method Invocation (RMI)
- Common Object Request Broker Architecture (CORBA)

Service Oriented Architecture (SAO)

Web Services

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Lecture overview

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Distributed Systems – Definition

Distributed System by Coulouris, Dollimore, and Kindberg

A system in which hardware and software components located at networked computers communicate and coordinate their actions only by message passing.

Distributed System by Tanenbaum and Steen

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

- the independent/autonomous machines are interconnected by communication networks and equipped with software systems designed to produce an integrated and consistent computing environment

Core objective of a distributed system: resource sharing

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Distributed Systems – Key characteristics

- **Autonomicity** – there are several autonomous computational entities, each of which has its own local memory
- **Heterogeneity** – the entities may differ in many ways
  - computer HW (different data types' representation), network interconnection, operating systems (different APIs), programming languages (different data structures), implementations by different developers, etc.
- **Concurrency** – concurrent (distributed) program execution and resource access
- **No global clock** – programs (distributed components) coordinate their actions by exchanging messages
  - message communication can be affected by delays, can suffer from variety of failures, and is vulnerable to security attacks
- **Independent failures** – each component of the system can fail independently, leaving the others still running (and possibly not informed about the failure)
  - How to know/differ the states when a network has failed or became unusually slow?
  - How to know immediately if a remote server crashed?

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Distributed Systems – Challenges and Issues

What do we want from a Distributed System (DS)?

- *Resource Sharing*
- *Openness*
- *Concurrency*
- *Scalability*
- *Fault Tolerance*
- *Security*
- *Transparency*

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Distributed Systems – Challenges and Issues

Resource Sharing

- main motivating factor for constructing DSs
- is should be easy for the users (and applications) to access remote resources, and to share them in a *controlled and efficient way*
  - each resource must be managed by a software that provides interfaces which enable the resource to be manipulated by clients
  - *resource* = anything you can imagine (e.g., storage facilities, data, files, Web pages, etc.)

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Distributed Systems – Challenges and Issues

Openness

- whether the system can be extended and re-implemented in various ways and new resource-sharing services can be added and made available for use by a variety of client programs
  - specification and documentation of key software interfaces must be published
    - using an *Interface Definition Language (IDL)*
- involves HW extensibility as well
  - i.e., the ability to add hardware from different vendors

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Distributed Systems – Challenges and Issues

Concurrency

- every resource in a DS must be designed to be safe in a concurrent environment
  - applies not only to servers, but to objects in applications as well
- ensured by standard techniques, like *semaphores*

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Distributed Systems – Challenges and Issues

Scalability

- a DS is scalable if the cost of adding a user (or resource) is a constant amount in terms of resources that must be added
  - and is able to utilize the extra hardware/software *efficiently*
  - and remains manageable

Date	*Computers*	*Web servers*
1979, Dec.	188	0
1989, July	130,000	0
1999, July	56,218,000	5,560,866
2003, Jan	171,638,297	35,424,956

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Distributed Systems – Challenges and Issues

Fault Tolerance

- a characteristic where a distributed system provides an appropriately handling of errors that occurred in the system
  - the failures can be *detected* (sometimes hard or even impossible), *masked* (made hidden or less severe), or *tolerated*
- achieved by deploying two approaches: *hardware redundancy* and *software recovery*

Security

- involves *confidentiality*, *integrity*, *authentication*, and *availability*

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Distributed Systems – Challenges and Issues

Transparency

- certain aspects of the DS should be made invisible to the user / application programmer
  - i.e., the system is perceived as a whole rather than a collection of independent components
- several *forms of transparency*:
  - **Access transparency** – enables local and remote resources to be accessed using identical operations
  - **Location transparency** – enables resources to be accessed without knowledge of their location
  - **Concurrency transparency** – enables several processes to operate concurrently using shared resources without interference between them
  - **Replication transparency** – enables multiple instances of resources to be used to increase reliability and performance
    - without knowledge of the replicas by users / application programmers

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Distributed Systems – Challenges and Issues

Transparency II.

- *forms of transparency* cont'd.:
  - **Failure transparency** – enables the concealment of faults, allowing users and application programs to complete their tasks despite of a failure of HW/SW components
  - **Mobility/migration transparency** – allows the movement of resources and clients within a system without affecting the operation of users or programs
  - **Performance transparency** – allows the system to be reconfigured to improve performance as loads vary
  - **Scaling transparency** – allows the system and applications to expand in scale without changes to the system structure or application algorithms

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Distributed Systems – Architecture Models

- defines the way in which the components of systems interact with one another, and
- defines the way in which the components are mapped onto an underlying network of computers

- the overall goal is to ensure that the structure will meet present and possibly future demands
  - the major concerns are to make system *reliable, manageable, adaptable,* and *cost-effective*
- principal architecture models:
  - **client-server model** – most important and most widely used
    - a service may be further provided by *multiple servers*
    - the servers may in turn be clients for another servers
    - *proxy servers* (caches) may be employed to increase availability and performance
  - **peer processes** – all the processes play similar roles
    - based either on *structured* (Chord, CAN, etc.), *unstructured*, or *hybrid* architectures

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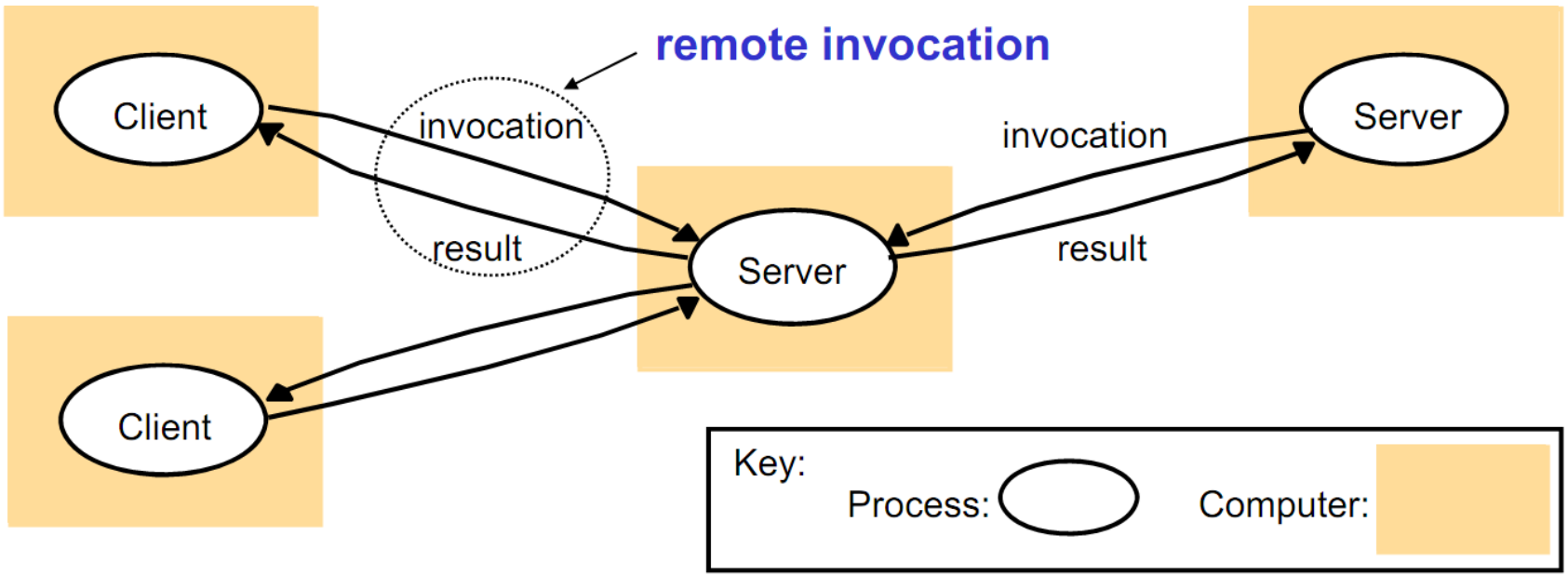
Distributed Systems – Architecture Models

Client-Server model



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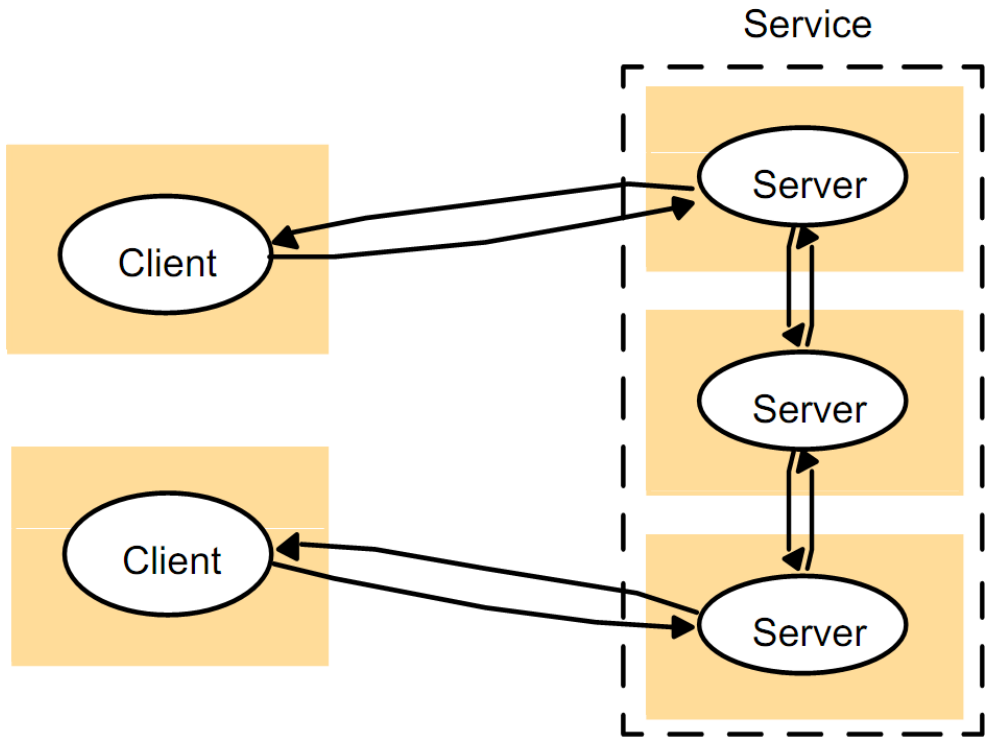
Distributed Systems – Architecture Models

Client-Server model – A Service provided by Multiple Servers



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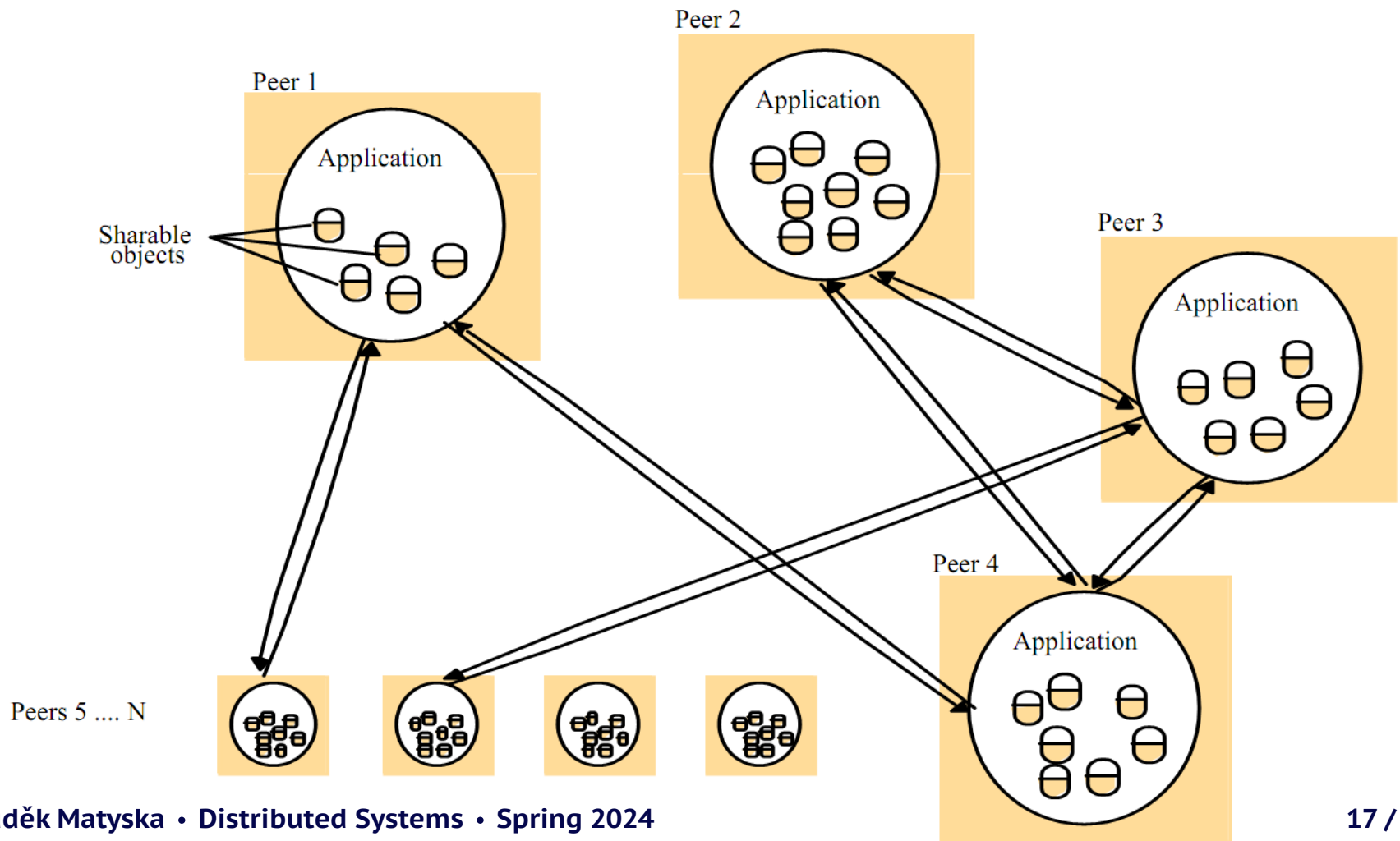
Distributed Systems – Architecture Models

Peer processes



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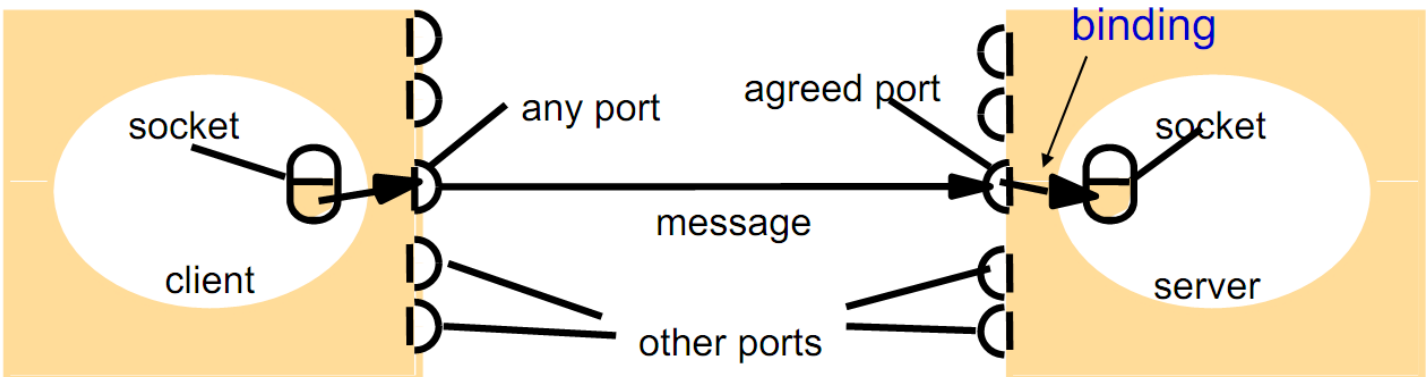
Distributed Systems – Inter-process Communication (IPC)

- the processes (components) need to communicate
- the communication may be:
  - *synchronous* – both send and receive are blocking operations
  - *asynchronous* – send is non-blocking and receive can have blocking (more common) and non-blocking variants
- the simplest forms of communication: **UDP** and **TCP sockets**



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Distributed Systems – Inter-process Communication

UDP and TCP sockets

UDP/TCP sockets

- provide unreliable/reliable communication services
- \+ the complete control over the communication lies in the hands of applications
- – too primitive to be used in developing a distributed system software
  - higher-level facilities (marshalling/unmarshalling data, error detection, error recovery, etc.) must be built from scratch by developers on top of the existing socket primitive facilities
  - force read/write mechanism instead of a *procedure call*
- – another problem arises when the software needs to be used in a platform different from where it was developed
  - the target platform may provide different socket implementation

$\Rightarrow$ *these issues are eliminated by the use of a* ***Middleware***

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Lecture overview

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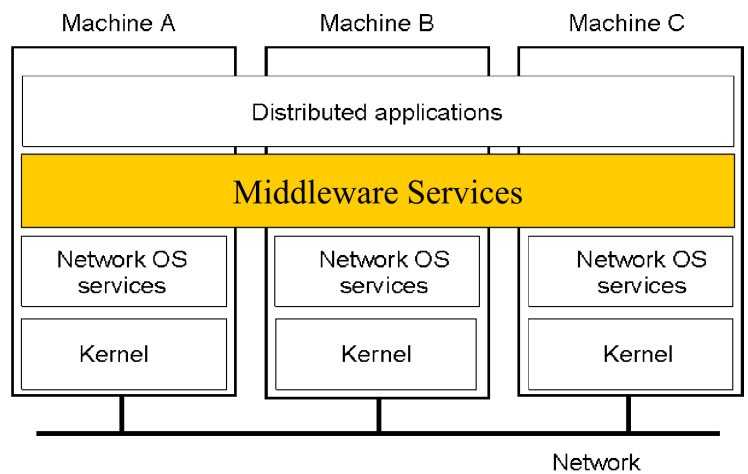
Middleware

- a software layer that provides a programming abstraction as well as masks the heterogeneity of the underlying networks, hardware, operating systems, and programming languages
  - ⇒ provides *transparency services*
  - represented by processes/objects that interact with each other to implement communication and resource sharing support
  - provides building blocks for the construction of SW components that can work with one another

- middleware examples:
  - Sun RPC (ONC RPC)
  - DCE RPC
  - MS COM/DCOM
  - Java RMI
  - CORBA
  - etc.



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Middleware – Basic Services

- *Directory services* – services required to locate application services and resources, and route messages
  - ≈ service discovery
- *Data encoding services* – uniform data representation services for dealing with incompatibility problems on remote systems
  - e.g., Sun XDR, ISO's ASN.1, CORBA's CDR, XML, etc.
  - data marshalling/unmarshalling
- *Security services* – provide inter-application client-server security mechanisms
- *Time services* – provide a universal format for representing time on different platforms (possibly located in various time zones) in order to keep synchronisation among application processes
- *Transaction services* – provide transaction semantics to support commit, rollback, and recovery mechanisms

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Middleware

Basic Services – A Need for Data Encoding Services

Data encoding services are required, because remote machines may have:

- different byte ordering
- different sizes of integers and other types
- different floating point representations
- different character sets
- alignment requirements

```
main() {
    unsigned int n;
    char *a = (char *)&n;

    n = 0x11223344;
    printf("%02x, %02x, %02x, %02x\n",
            a[0], a[1], a[2], a[3]);
}
```

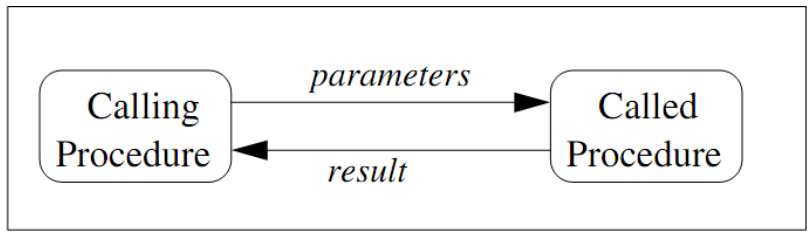
Output on a Pentium:
`44, 33, 22, 11`

Output on a G4:
`11, 22, 33, 44`

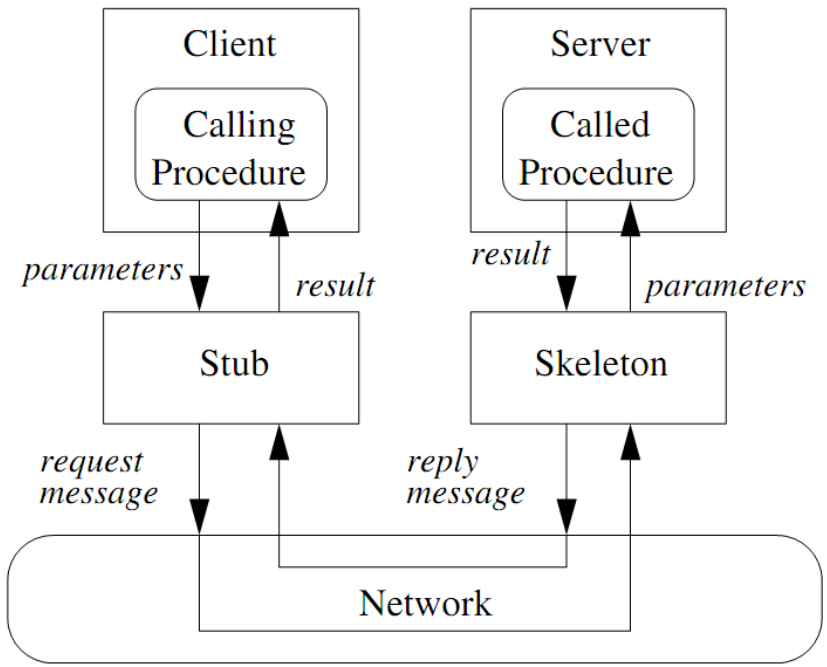
Remote Procedure Calls (RPC)

- very simple idea similar to a well-known procedure call mechanism
  - a client sends a request and blocks until a remote server sends a response
- the goal is to allow distributed programs to be written in the same style as conventional programs for centralised computer systems
  - while being *transparent* – the programmer need not be aware that the called procedure is executing on a local or a remote computer
- the idea:
  - the remote procedure is represented as a **stub** *on the client side*
    - behaves like a local procedure, but rather than placing the parameters into registers, it packs them into a message, issues a send primitive, and blocks itself waiting for a reply
  - the server passes the arrived message to a **server stub** (known as **skeleton** as well)
    - the skeleton unpacks the parameters and calls the procedure in a conventional manner
    - the results are returned to the skeleton, which packs them into a message directed to the client stub

Remote Procedure Calls (RPC)



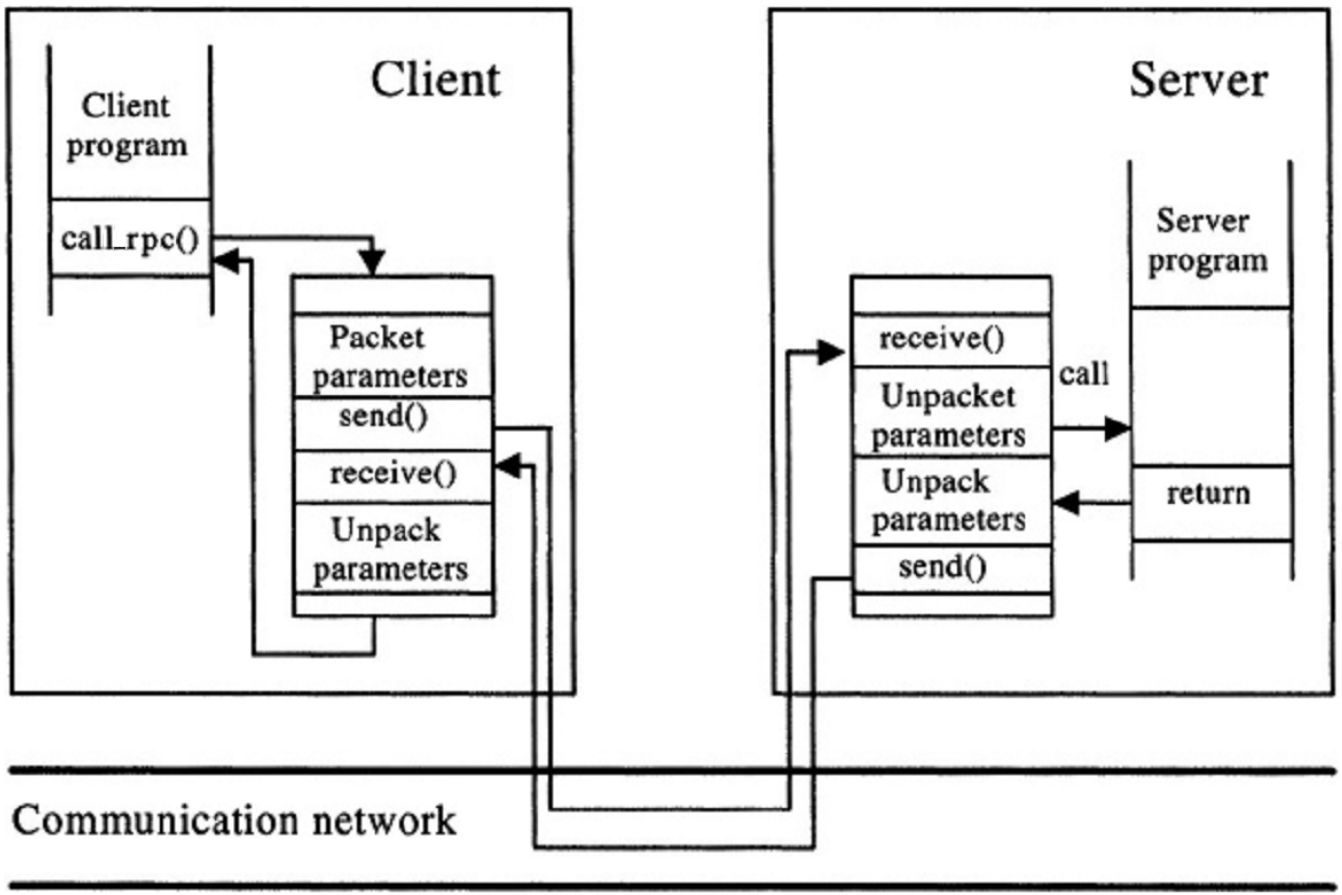
Local Procedure Call



Remote Procedure Call

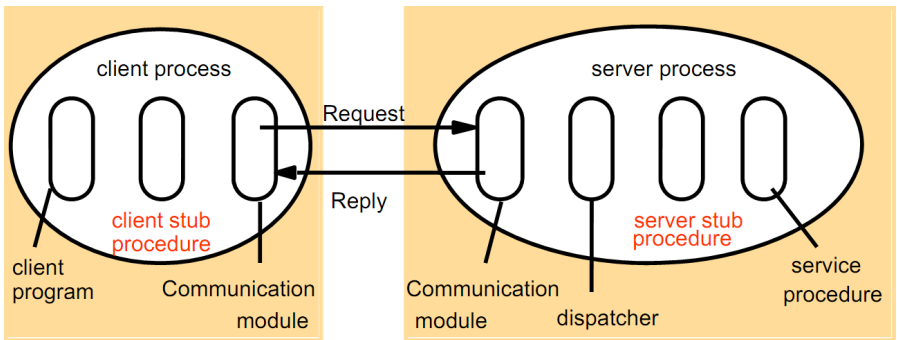
Remote Procedure Calls (RPC)

The remote procedure call in detail



Remote Procedure Calls (RPC)

Components



- client program, client stub
- *communication modules*
- server stub, service procedure
- *dispatcher* – selects one of the server stub procedures according to the procedure identifier in the request message

Sun RPC: the procedures are identified by:

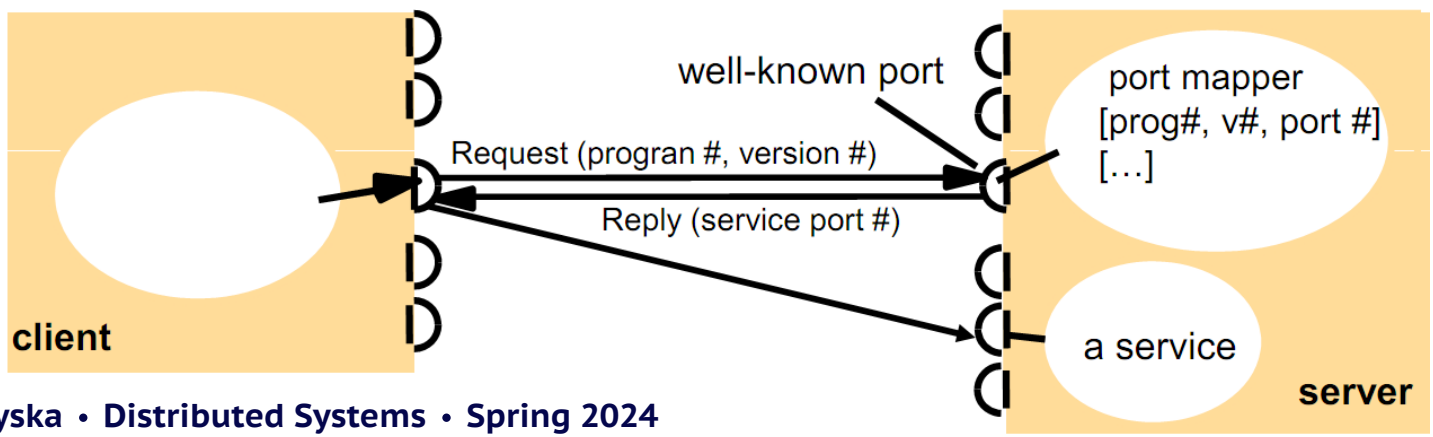
- *program number* – can be obtained from a central authority to allow every program to have its own unique number
- *procedure number* – the identifier of the particular procedure within the program
- *version number* – changes when a procedure signature changes

Remote Procedure Calls (RPC)

Location Services – Portmapper

Clients need to know the port number of a service provided by the server ⇒ **Portmapper**

- a server registers its *program#*, *version#*, and *port#* to the local portmapper
- a client finds out the *port#* by sending a request
  - the portmapper listens on a *well-known port* (111)
  - the particular procedure required is identified in the subsequent procedure call



Remote Procedure Calls (RPC)

Parameters passing

How to pass parameters to remote procedures?

- **pass by value** – easy: just copy data to the network message
- **pass by reference** – makes no sense without shared memory

Pass by reference: the steps

1. copy referenced items (marshalled) to a message buffer
2. ship them over, unmarshal data at server
3. pass local pointer to server stub function
4. send new values back

- *to support complex structures:*
  - copy the structure into pointerless representation
  - transmit
  - reconstruct the structure with local pointers on the server

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Remote Procedure Calls (RPC)

Parameters passing – eXternal Data Representation (XDR)

Sun RPC: to avoid compatibility problems, the **eXternal Data Representation (XDR)** is used

- XDR primitive functions examples:
  - `xdr_int()`, `xdr_char()`, `xdr_u_short()`, `xdr_bool()`, `xdr_long()`, `xdr_u_int()`, `xdr_wrapstring()`, `xdr_short()`, `xdr_enum()`, `xdr_void()`
- XDR aggregation functions:
  - `xdr_array()`, `xdr_string()`, `xdr_union()`, `xdr_vector()`, `xdr_opaque()`
- *only a single input parameter is allowed in a procedure call*
  - $\Rightarrow$ procedures requiring multiple parameters must include them as components of a single structure

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Remote Procedure Calls (RPC)

When Things Go Wrong I.

- local procedure calls do not fail
  - if they core dump, entire process dies
- there are more opportunities for errors with RPC
  - server could generate an error
  - problems in network (lost/delayed requests/replies)
  - server crash
  - client might crash while server is still executing code for it
- transparency breaks here
  - applications should be prepared to deal with RPC failures

Semantics of local procedure calls: **exactly once**

- difficult to achieve with RPC

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Remote Procedure Calls (RPC)

When Things Go Wrong II.

Four remote calls semantics available in RPC:

- **at-least-once semantic**
  - client keeps trying sending the message until a reply has been received
    - failure is assumed after n re-sends
  - guarantees that the call has been made “at least once”, but possibly multiple times
  - ideal for *idempotent operations*
- **at-most-once semantic**
  - client gives up immediately and reports back a failure
  - guarantees that the call has been made “at most once”, but possibly none at all
- **exactly-once semantic**
  - the most desirable, but the most difficult to implement
- **maybe semantic**
  - no message delivery guarantees are provided at all
  - (easy to implement)

Remote Procedure Calls (RPC)

When Things Go Wrong III.

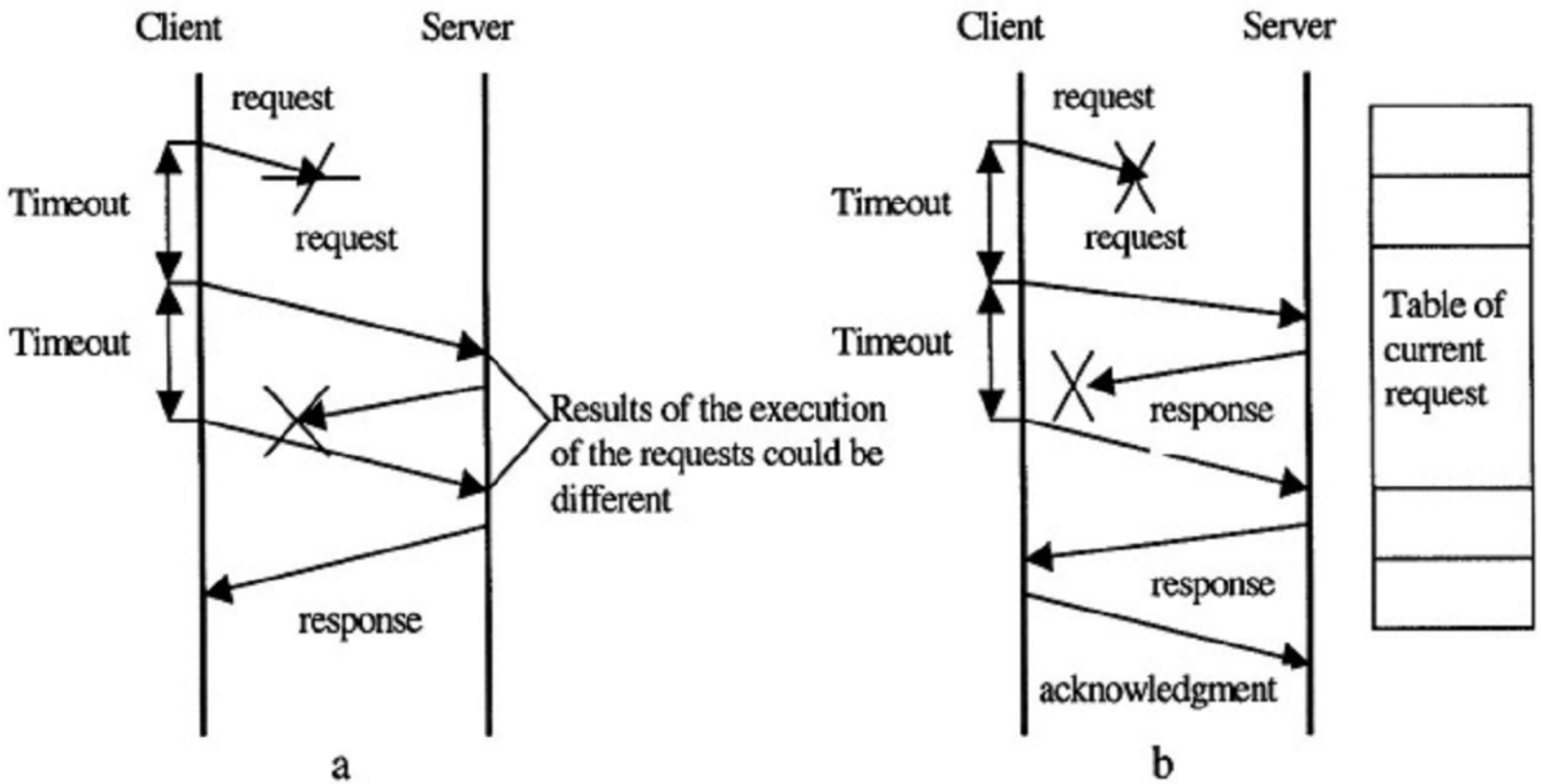
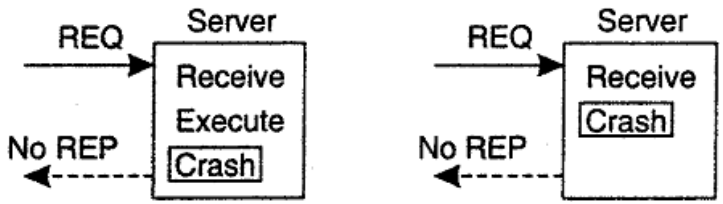


Figure: Message-passing semantics. (a) at-least-once; (b) exactly-once.

Remote Procedure Calls (RPC)

When Things Go Wrong IV. – Complications

1. it is necessary to understand the application
   - *idempotent functions* – in the case of a failure, the message may be retransmitted and re-run without a harm
   - *non-idempotent functions* – has side-effects ⇒ the retransmission has to be controlled by the server
     - the duplicity request (retransmission) has to be detected
     - once detected, the server procedure is NOT re-run; just the results are resent (if available in a server cache)
2. in the case of a *server crash*, the order of execution vs. crash matters



3. in the case of a *client crash*, the procedure keeps running on the server
   - consumes resources (e.g., CPU time), possesess resources (e.g., locked files), etc.
   - may be overcome by employing *soft-state principles*
     - keep-alive messages

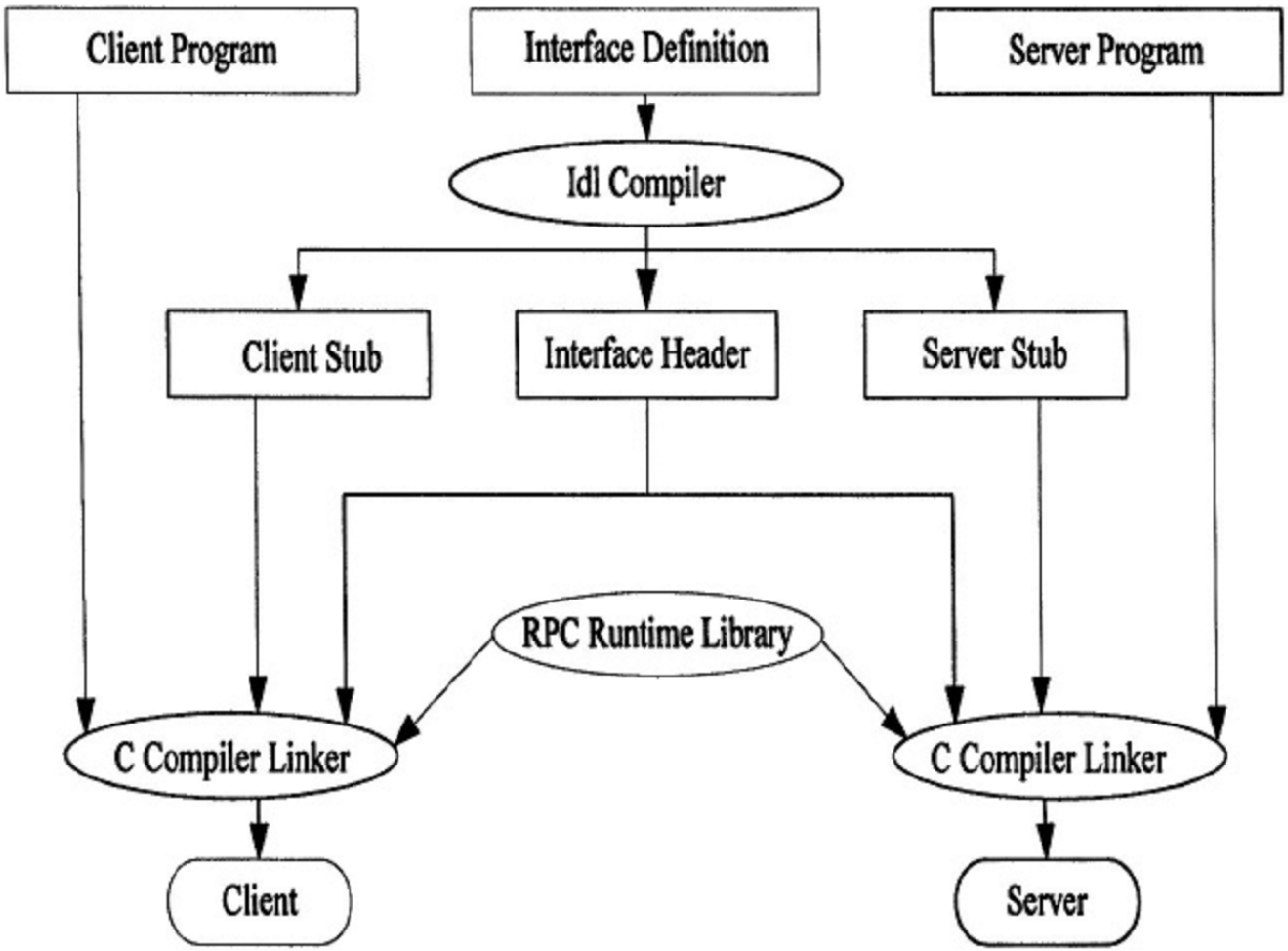
Remote Procedure Calls (RPC)

Code Generation I.

- RPC drawbacks:
  - complex API, not easy to debug
  - the use of XDR is difficult
- *but, it's often used in a similar way*
- $\Rightarrow$ the server/client code can be automatically generated
  - assumes well-defined interfaces (IDL)
  - the application programmer has to supply the following:
    - *interface definition file* – defines the interfaces (data structures, procedure names, and parameters) of the remote procedures that are offered by the server
    - *client program* – defines the user interfaces, the calls to the remote procedures of the server, and the client side processing functions
    - *server program* – implements the calls offered by the server
  - compilers:
    - `rpcgen` for C/C++, `jrpcgen` for Java

Remote Procedure Calls (RPC)

Code Generation II.



Remote Method Invocation (RMI)

- as the popularity of object technology increased, techniques were developed to allow calls to remote objects instead of remote procedures only

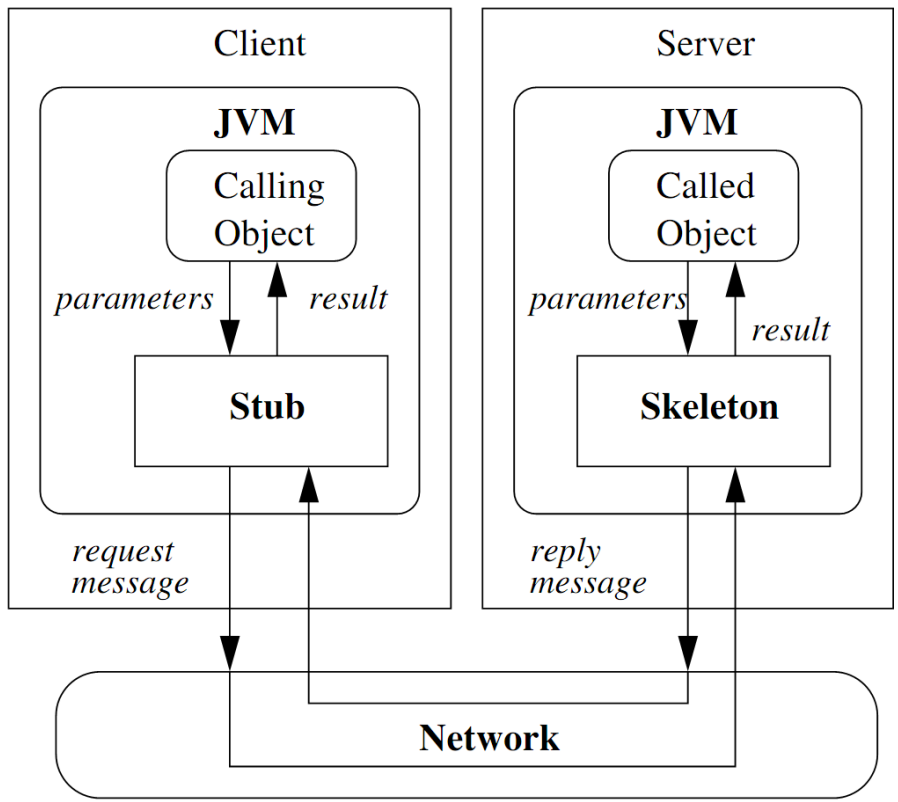
$\Rightarrow$ **Remote Method Invocation (RMI)**

- essentially the same as the RPC, except that it operates on objects instead of applications/procedures
  - the RMI model represents a *distributed object application*
    - it allows an object inside a JVM (a client) to invoke a method on an object running on a remote JVM (a server) and have the results returned to the client
  - the server application creates an object and makes it accesible remotely (i.e., registers it)
  - the client application receives a reference to the object on the server and invokes methods on it
    - the reference is obtained through looking up in the registry
  - ***important:*** *a method invocation on a remote object has the same syntax as a method invocation on a local object*

Remote Method Invocation (RMI)

Architecture I.

The interface, through which the client and server interact, is (similarly to RPC) provided by **stubs** and **skeletons**:

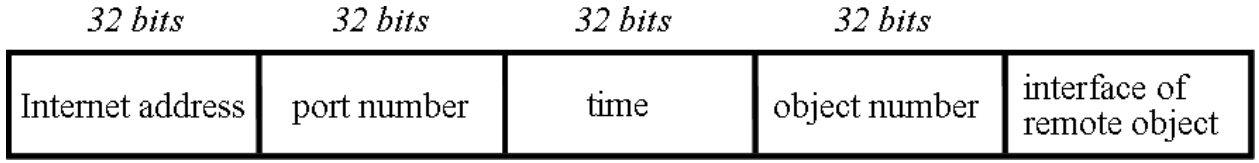


Remote Method Invocation (RMI)

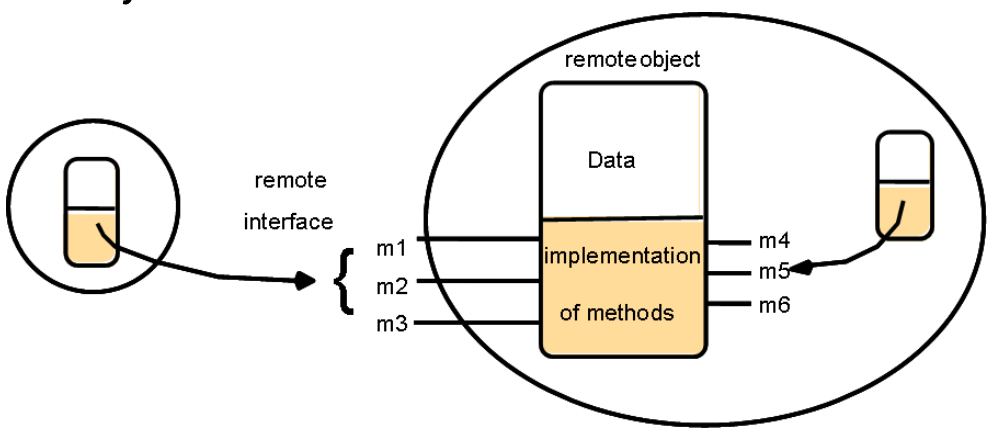
Architecture II.

Two fundamental concepts as the heart of distributed object model:

- *remote object reference* – an identifier that can be used throughout a distributed system to refer to a particular unique remote object
  - its construction must ensure its uniqueness



- *remote interface* – specifies, which methods of the particular object can be invoked remotely



Remote Method Invocation (RMI)

Architecture III.

- the remote objects can be accessed concurrently
  - the encapsulation allows objects to provide methods for protecting themselves against incorrect accesses
    - e.g., synchronization primitives (condition variables, semaphores, etc.)
- RMI transaction semantics similar to the RPC ones
  - *at-least-once*, *at-most-once*, *exactly-once*, and *maybe semantics*
- data encoding services:
  - stubs use *Object Serialization* to marshal the arguments
    - object arguments' values are rendered into a stream of bytes that can be transmitted over a network
    - $\Rightarrow$ the arguments must be primitive types or objects that implement `Serializable` interface
- parameters passing:
  - local objects passed *by value*
  - remote objects passed *by reference*

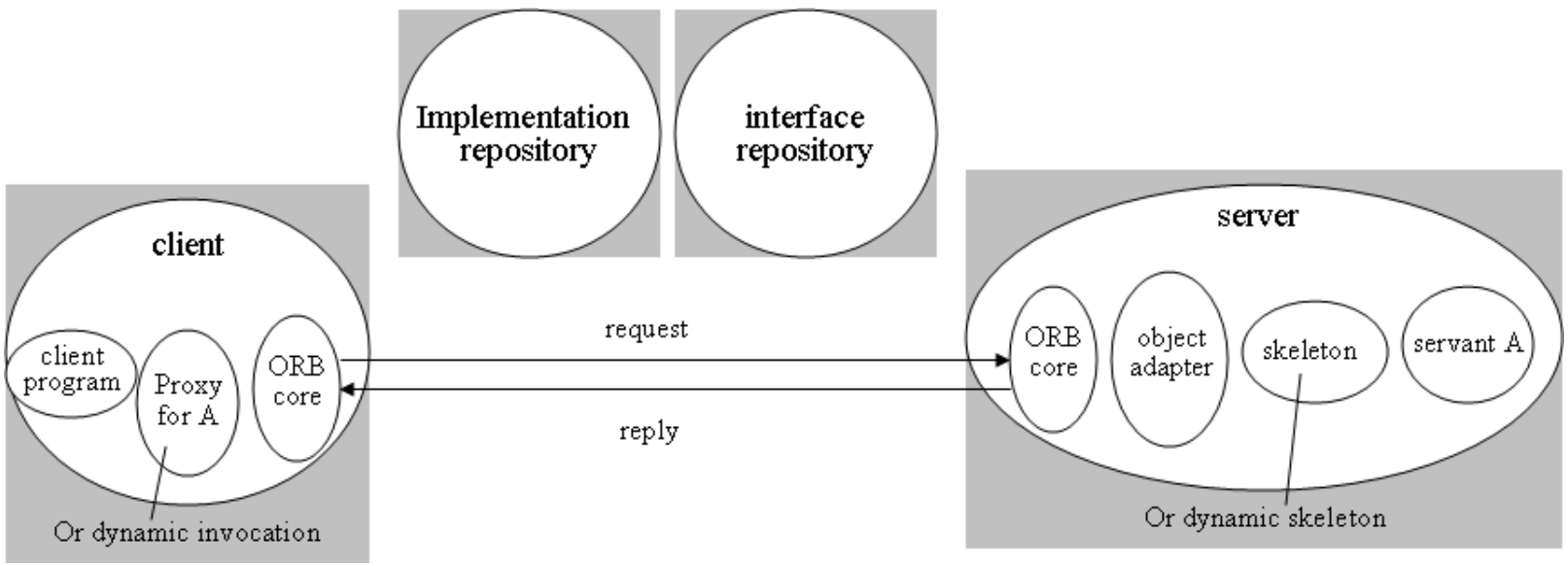
Common Object Request Broker Architecture (CORBA)

- an industry standard developed by the OMG (*Object Management Group* – a consortium of more than 700 companies) to aid in distributed objects programming
  - OMG was established in 1988
  - initial CORBA specification came out in 1992
    - but significant revisions have taken place from that time
- provides a **platform-independent** and **language-independent** architecture (framework) for writing distributed, object-oriented applications
  - i.e., application programs can communicate without restrictions to:
    - programming languages, hardware platforms, software platforms, networks they communicate over
  - but CORBA is just a *specification* for creating and using distributed objects; it is *not a piece of software or a programming language*
    - several implementations of the CORBA standard exist (e.g., IBM's SOM and DSOM architectures)

CORBA Components

CORBA is composed of five major components:

- *Object Request Broker (ORB)*
- *Interface Definition Language (IDL)*
- *Dynamic Invocation Interface (DII)*
- *Interface Repositories (IR)*
- *Object Adapters (OA)*



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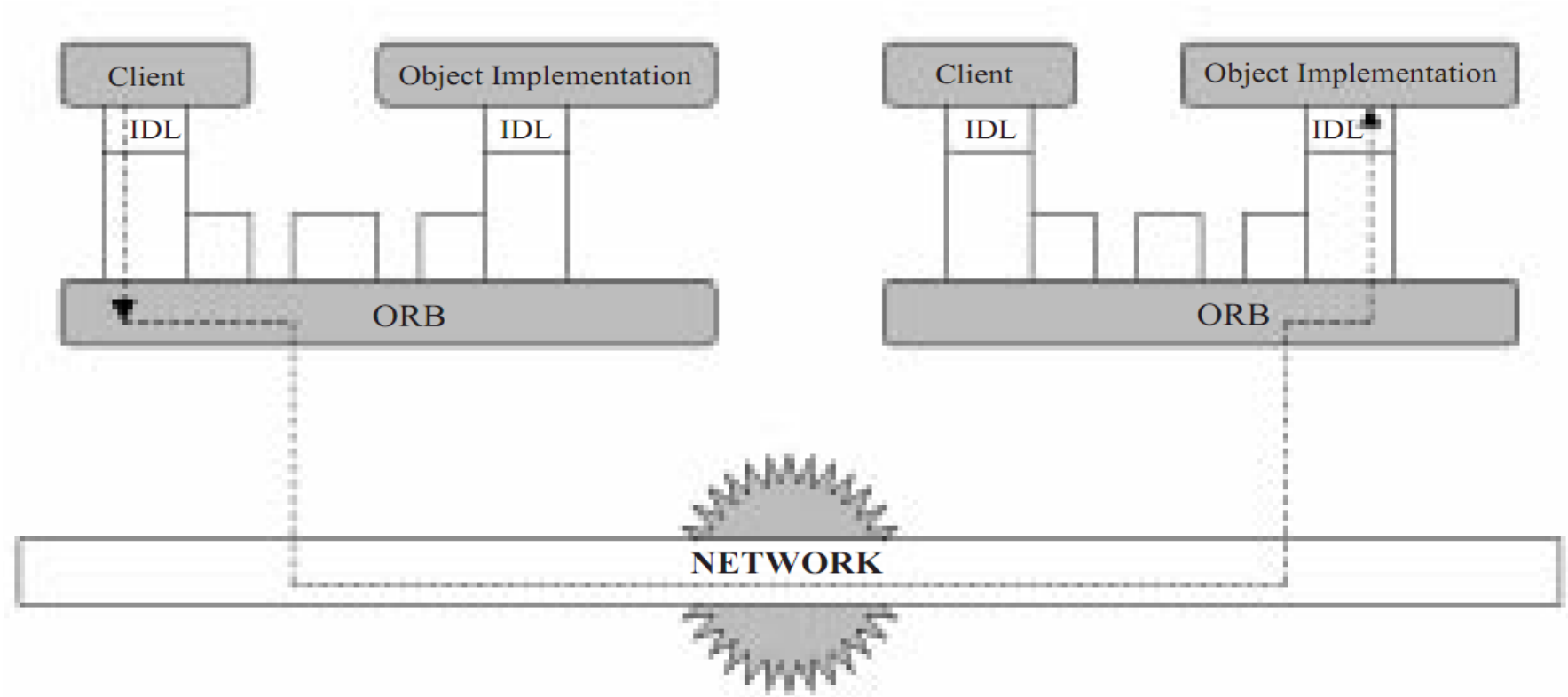
CORBA Components

Object Request Broker (ORB)

- the heart of CORBA
  - introduced as a part of OMG's *Object Management Architecture (OMA)*, which the CORBA is based on
- a distributed service that implements all the requests to the remote object(s)
  - it **locates the remote object** on the network, **communicates the request** to the object, waits for the results and (when available) **communicates those results** back to the client
- implements *location transparency*
  - exactly the same request mechanism is used regardless of where the object is located
    - might be in the same process with the client or across the planet
- implements *programming language independence*
  - the client issuing a request can be written in a different programming language from the implementation of the CORBA object
- both the client and the object implementation are isolated from the ORB by an IDL interface
- *Internet Inter-ORB Protocol (IIOP)* – the standard communication protocol between ORBs

CORBA Components

Object Request Broker (ORB) II.



CORBA Components

Interface Definition Language (IDL)

- as with RMI, CORBA objects have to be specified with interfaces
  - interface $\approx$ a contract between the client (code using a object) and the server (code implementing the object)
    - indicates a set of operations the object supports and how they should be invoked (but NOT how they are implemented)
- defines modules, interfaces, types, attributes, exceptions, and method signatures
  - uses same lexical rules as C++
    - with additional keywords to support distribution (e.g. `interface`, `any`, `attribute`, `in`, `out`, `inout`, `readonly`, `raises`)
- defines language bindings for many different programming languages (e.g., C/C++, Java, etc.)
  - via language mappings, the IDL translates to different constructs in the different implementation languages
  - it allows an object implementor to choose the appropriate programming language for the object, and
  - it allows the developer of the client to choose the appropriate and possibly different programming language for the client

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CORBA Components

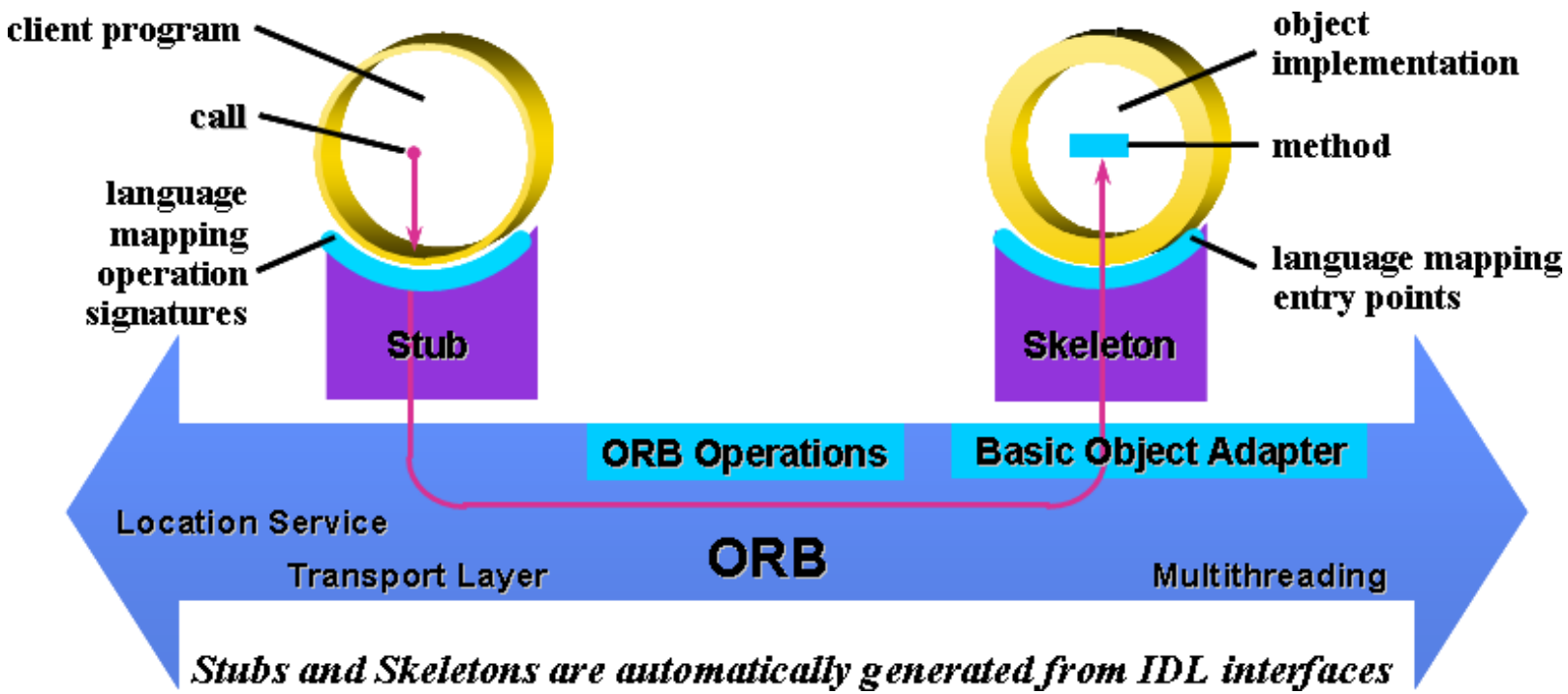
Interface Definition Language (IDL) example:

```
module StockObjects {
    struct Quote {
        string symbol;
        long at_time;
        double price;
        long volume;
    };
    exception Unknown{};
    interface Stock {
        // Returns the current stock quote.
        Quote get_quote() raises(Unknown);
        // Sets the current stock quote.
        void set_quote(in Quote stock_quote);
        // // Provides the stock description, e.g. company name.
        readonly attribute string description;
    };
    interface StockFactory {
        Stock create_stock(in string symbol, in string description);
    };
};
```

CORBA Components

Interface Definition Language (IDL) III. – Stubs and Skeletons

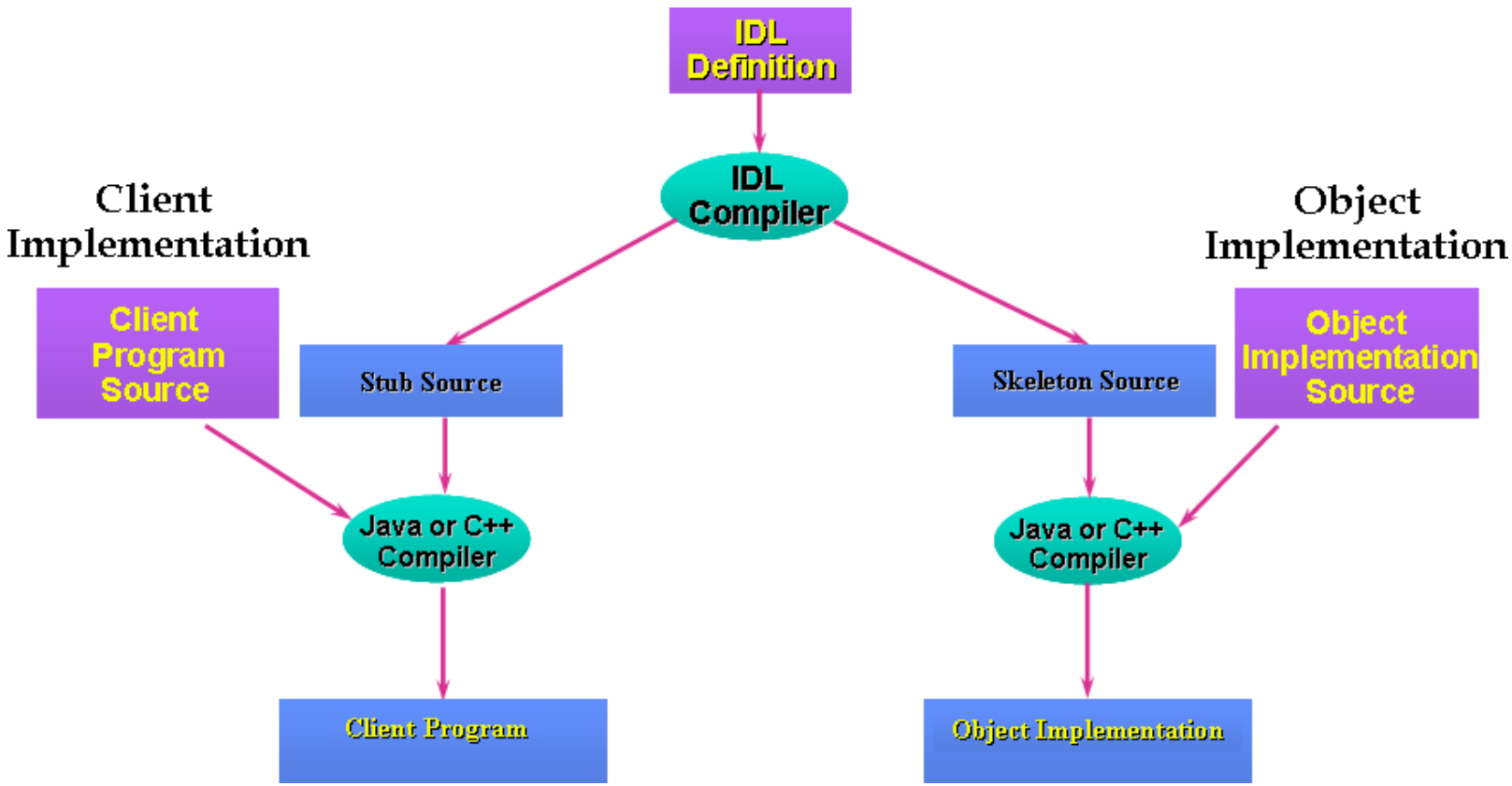
IDL compiler automatically compiles the IDL into **client stubs** and **object skeletons**:



CORBA Components

Interface Definition Language (IDL) IV. – Development Process

Using IDL



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CORBA Components

DII & DSI

Dynamic Invocation Interface (DII)

- CORBA supports both the *dynamic* and the *static invocation interfaces*
  - *static invocation interfaces* are determined at compile time
  - *dynamic interfaces* allow client applications to use server objects without knowing the type of those objects at compile time
- DII – an API which allows dynamic construction of CORBA object invocations

Dynamic Skeleton Interface (DSI)

- DSI is the server side's analogue to the client side's DII
  - allows an ORB to deliver requests to an object implementation that does not have compile-time knowledge of the type of the object it is implementing

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CORBA Components

Interface Repository (IR)

- a runtime component used to dynamically obtain information on IDL types (e.g. object interfaces)
  - using the IR, a client should be able to locate an object that is unknown at compile time, find information about its interface, and build a request to be forwarded through the ORB
  - this kind of information is necessary when a client wants to use the DII to construct requests dynamically

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CORBA Components

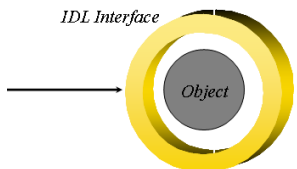
Object Adapters (OAs)

- the interface between the ORB and the server process
  - OAs listen for client connections/requests and map the inbound requests to the desired target object instance
- provide an API that object implementations use for:
  - generation and interpretation of object references
  - method invocation
  - security of interactions
  - object and implementation activation and deactivation
  - mapping object references to the corresponding object implementations
  - registration of implementations
- two basic kinds of OAs:
  - *basic object adapter (BOA)* – leaves many features unsupported, requiring proprietary extensions
  - *portable object adapter (POA)* – intended to support multiple ORB implementations (of different vendors), allow persistent objects, etc.

CORBA Object & Object Reference

CORBA Objects are fully encapsulated

- accessed through well-defined interfaces only
- interfaces & implementations are totally separate
  - for one interface, multiple implementations possible
  - one implementation may be supporting multiple interfaces



CORBA Object Reference is the distributed computing equivalent of a pointer

- CORBA defines the *Interoperable Object Reference (IOR)*
- an IOR contains a fixed object key, containing:
  - the object's fully qualified interface name (repository ID)
  - user-defined data for the instance identifier
  - can also contain transient information:
    - the host and port of its server, metadata about the server's ORB (for potential optimizations), etc.
- $\Rightarrow$ the IOR uniquely identifies one object instance

CORBA Services

CORBA Services (COS)

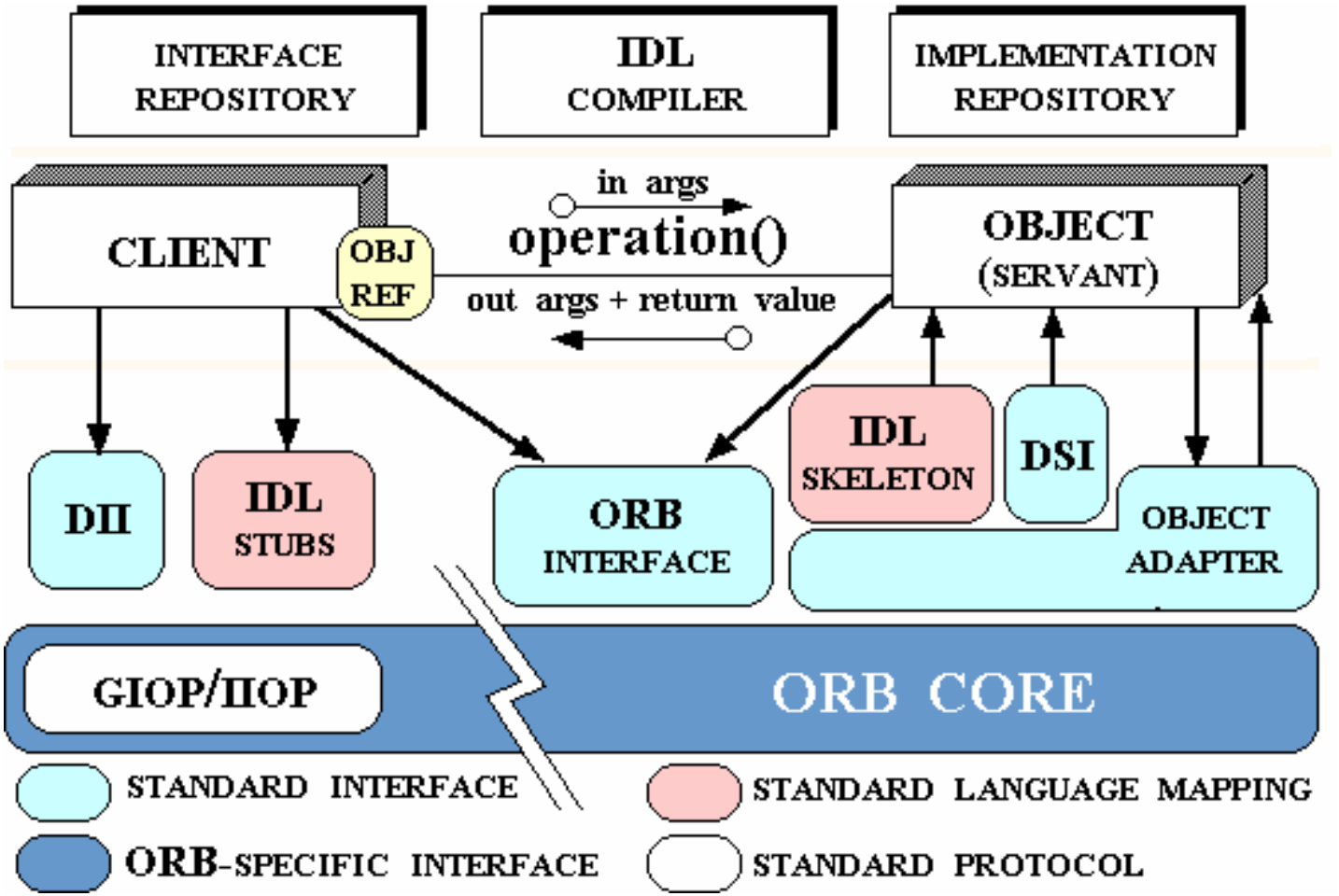
- the OMG has defined a *set of Common Object Services* to support the integration and interoperation of distributed objects
  - = frequently used components needed for building robust applications
  - typically supplied by vendors
  - OMG defines interfaces to services to ensure interoperability

CORBA Services

Popular Services Example

Service	*Description*
Object life cycle	Defines how CORBA objects are created, removed, moved, and copied
Naming	Defines how CORBA objects can have friendly symbolic names
Events	Decouples the communication between distributed objects
Relationships	Provides arbitrary typed n-ary relationships between CORBA objects
Externalization	Coordinates the transformation of CORBA objects to and from external media
Transactions	Coordinates atomic access to CORBA objects
Concurrency Control	Provides a locking service for CORBA objects in order to ensure serializable access
Property	Supports the association of name-value pairs with CORBA objects
Trader	Supports the finding of CORBA objects based on properties describing the service offered by the object
Query	Supports queries on objects

CORBA Architecture Summary



Lecture overview

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Lecture overview