TDD25
Distributed Systems

Communication in Distributed Systems

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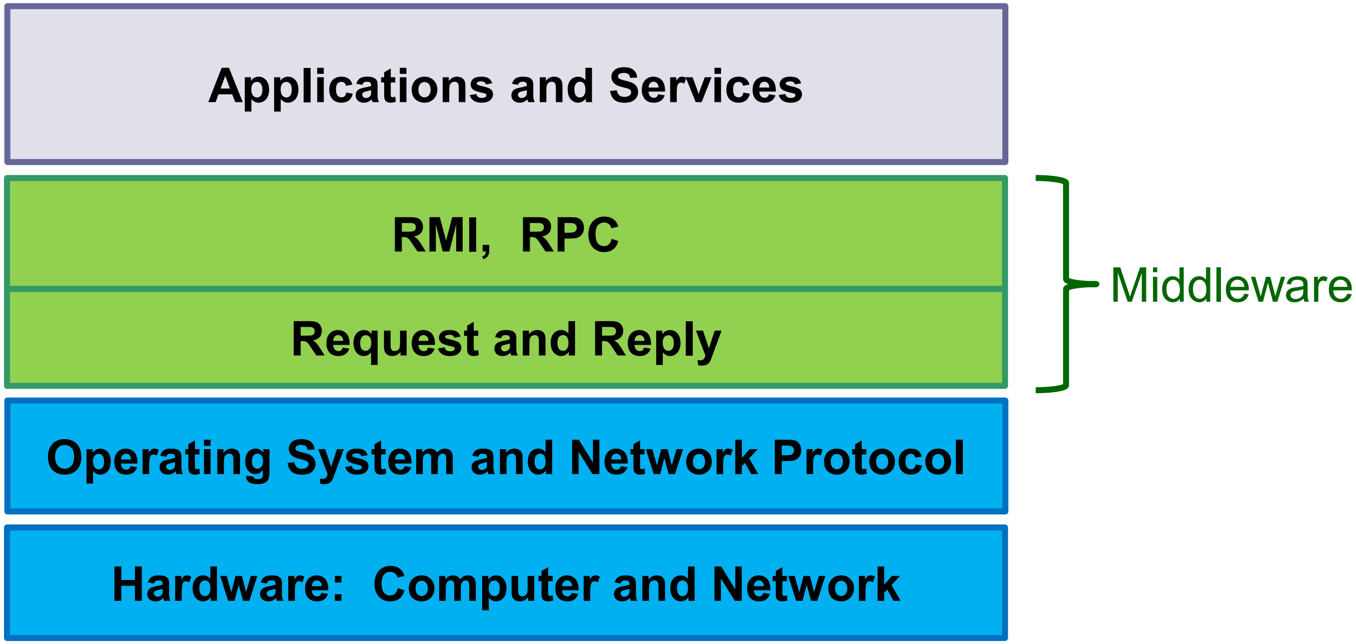
Agenda

COMMUNICATION IN DISTRIBUTED SYSTEMS

1. Communication System: Layered Implementation
2. Network Protocol
3. Request and Reply Primitives
4. RMI and RPC
5. RMI and RPC Semantics and Failures
6. Indirect Communication
7. Group Communication
8. Publish-Subscribe Systems

Communication Models and their Layered Implementation

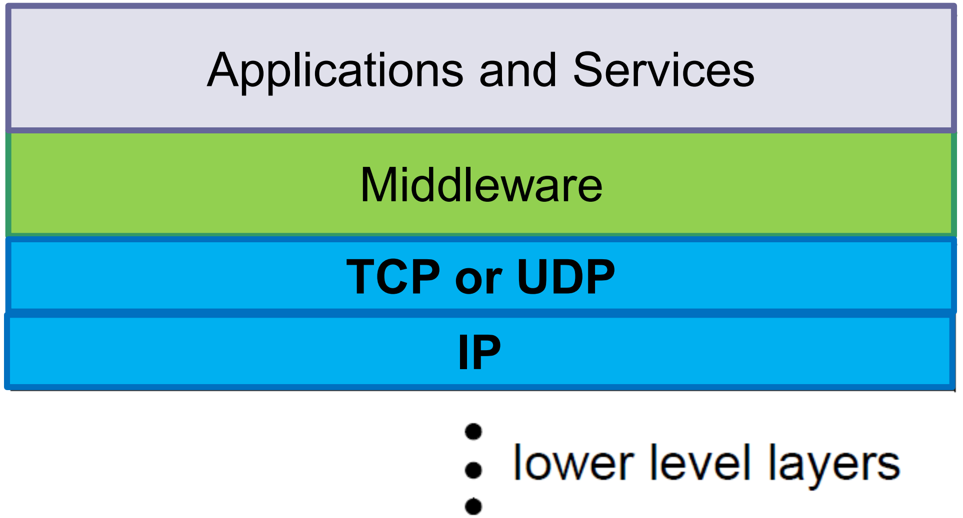


In this chapter:

- **Communication between distributed objects** by means of two models:
  - **Remote Method Invocation (RMI)**
  - **Remote Procedure Call (RPC)**
- RMI, as well as RPC, are implemented on top of **request and reply primitives**.
- Request and reply are implemented on top of the **network protocol** (e.g. TCP or UDP in case of the internet).

Network Protocol

- Middleware and distributed applications are implemented on top of a **network protocol**. Such a protocol is implemented as several layers.
  - In case of the Internet:



- **TCP** (**Transport Control Protocol**) and **UDP** (**User Datagram Protocol**) are both transport protocols implemented on top of the **Internet Protocol** (**IP**).

TCP Network Protocol

TCP is a **reliable** protocol.

- TCP **guarantees** the delivery to the receiving process of *all* data delivered by the sending process, in the *same* order.
- TCP implements **mechanisms** on top of IP **to meet reliability guarantees**.
  - **Sequencing**:
    - A *sequence number* is attached to each transmitted segment (packet). At the receiver side, packets are delivered in order of this number.
  - **Flow control**:
    - The sender takes care not to overwhelm the receiver. This is based on *periodic acknowledgements* received by the sender from the receiver.
  - **Retransmission and duplicate handling**:
    - If a segment is not acknowledged within a timeout, it is *retransmitted*. Using sequence number, the receiver detects and rejects duplicates.
  - **Buffering**:
    - Buffering balances the flow. If the receiving buffer is full, incoming segments are *dropped*. They will be retransmitted by the sender.
  - **Checksum**:
    - Each segment carries a *checksum*. If the received segment does not match the checksum, it is dropped (and will be retransmitted).

UDP Network Protocol

UDP is a protocol that does **not** guarantee reliable transmission.

- UDP offers no guarantee of delivery.
  - According to the IP, packets may be dropped because of congestion or network error.
    UDP adds no reliability mechanism to this.

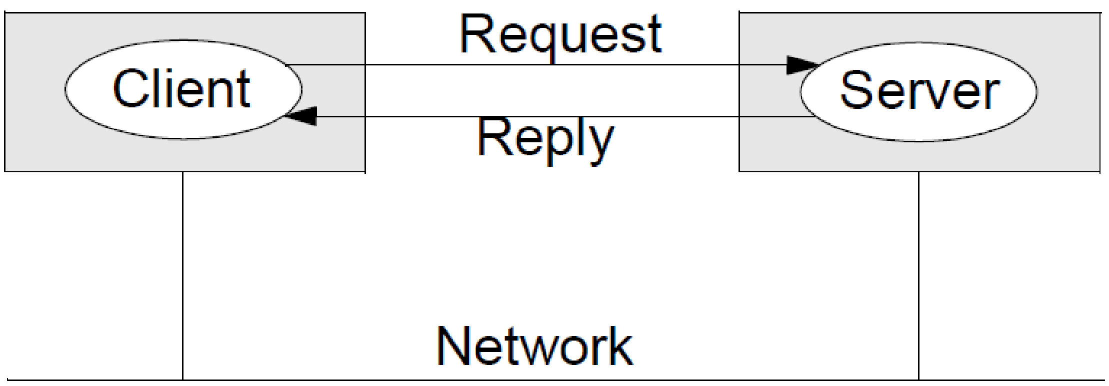
- UDP provides a means of transmitting messages with minimal additional costs or transmission delays above those due to IP transmission.
- Its use is restricted to applications and services that do not require reliable delivery of messages.
- If reliable delivery is requested with UDP, reliability mechanisms have to be implemented on top of the network protocol (in the middleware).

Request and Reply Primitives

- Communication between processes and objects in a distributed system is performed by **message passing**.
- In a typical scenario (e.g. client-server model), such a communication is through request and reply messages.

Request-Reply Primitives in the Client-Server Model

- The system is structured as a group of processes (objects), called **servers**, that deliver services to **clients**.



The client:

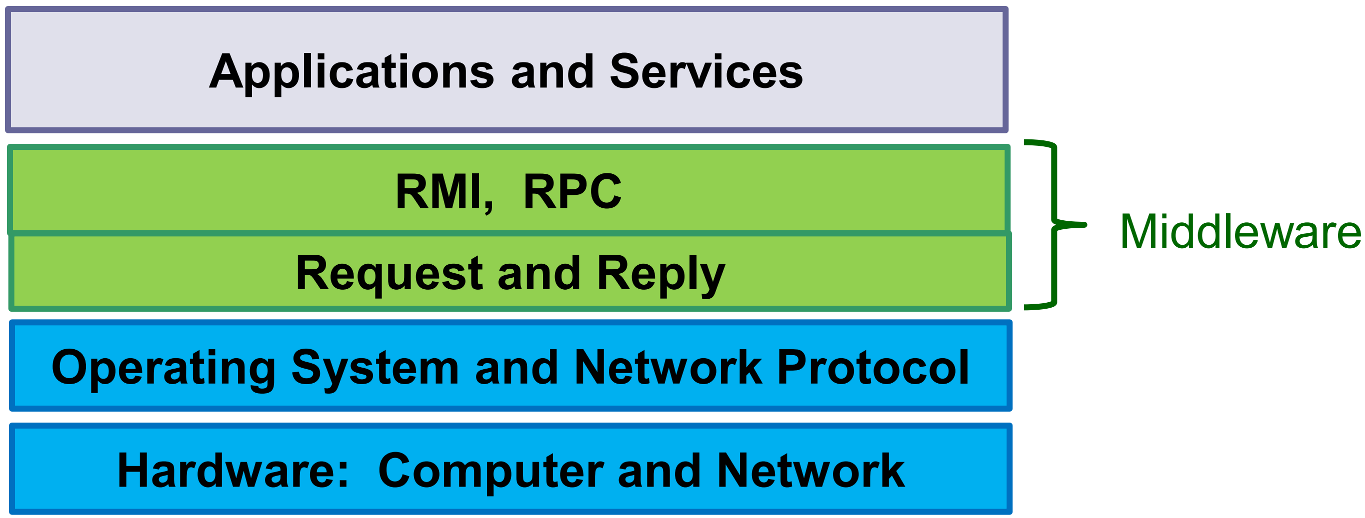
…
***send* (request)** to server_reference;

***receive* (reply);**
…

The server:

…
***receive* (request)** from client-reference;
execute requested operation
send (reply) to client_reference**;**
…

Remote Method Invocation (RMI) and Remote Procedure Call (RPC)

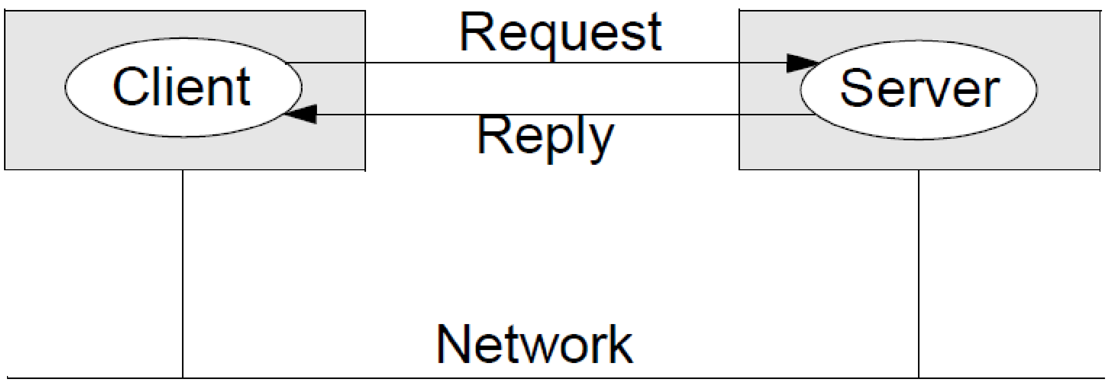


The goal: make, for the programmer, distributed computing look like centralized computing.

The solution:
Asking for a service is solved by the client issuing a method invocation or procedure call; this is a **remote invocation** (**call**).

- RMI (RPC) is **transparent**: the calling object (procedure) is not aware that the called one is executing on a different machine, and vice versa.

Remote Method Invocation



The **client code** contains the call:

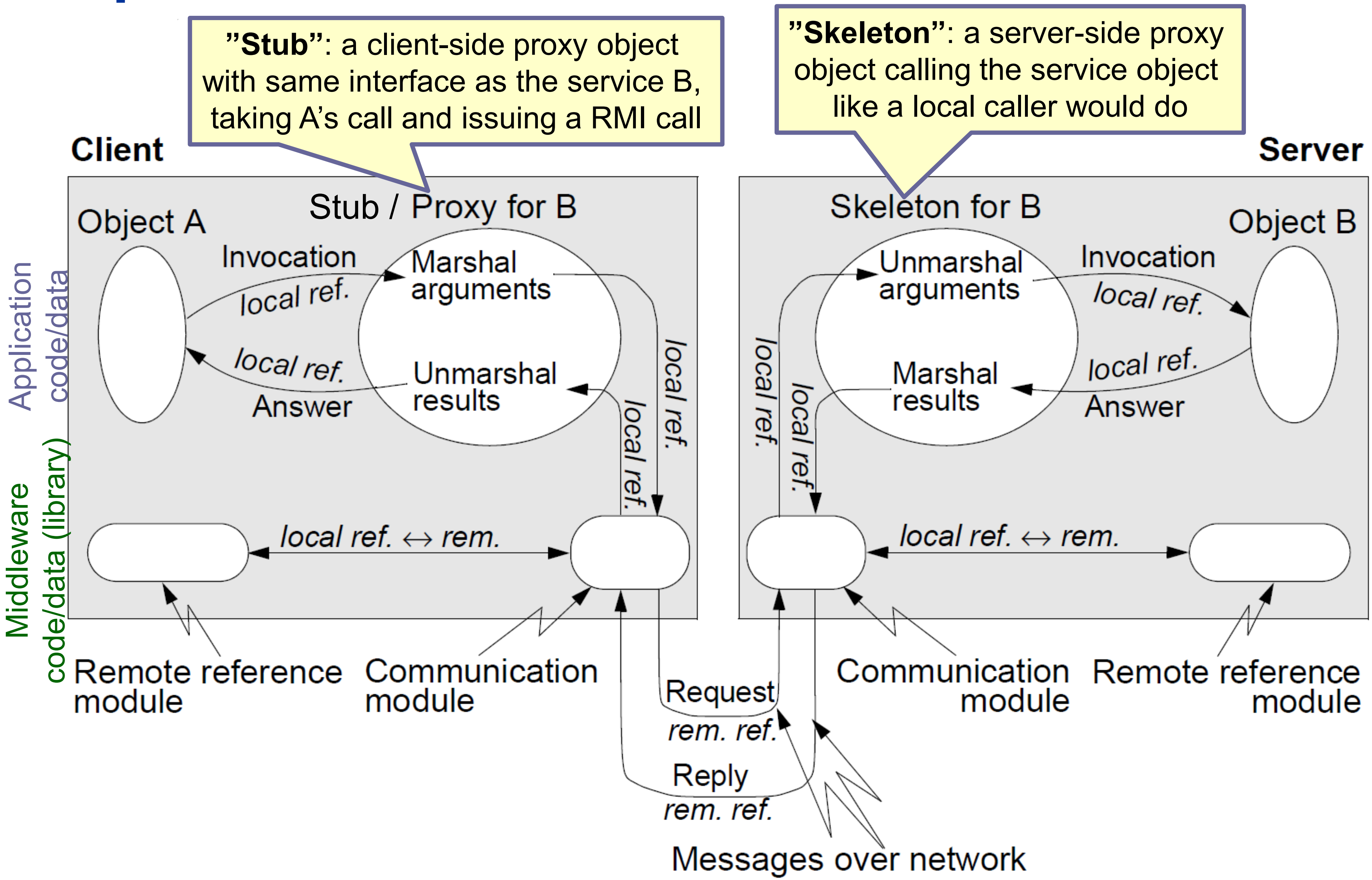
```
…
server_id.service ( arg_values_to_server,
                    locations_for_result_arguments );
…
```

The **server code** contains the method:

```
public service ( in type1 arg_from_client,
                 out type2 arg_to_client )
{ … };
```

The programmer is unaware of the request and reply messages which are sent over the network during execution of the RMI.

Implementation of RMI



Implementation of RMI

Question 1

- What if the two computers use different representations for data (integers, chars, floating point)?
  - The most elegant and flexible solution is to have a standard representation used for all values sent through the network.
  - The stub/proxy and skeleton convert to/from this representation during marshalling/unmarshalling.

Question 2

- Who generates the classes for stub/proxy and skeleton?
  - In advanced middleware systems (e.g. CORBA) the classes for proxies and skeletons can be generated automatically.
    - Given the **specification of the server interface** and the standard data representations, an **interface compiler** can generate the (source) code for stubs/proxies and skeletons.

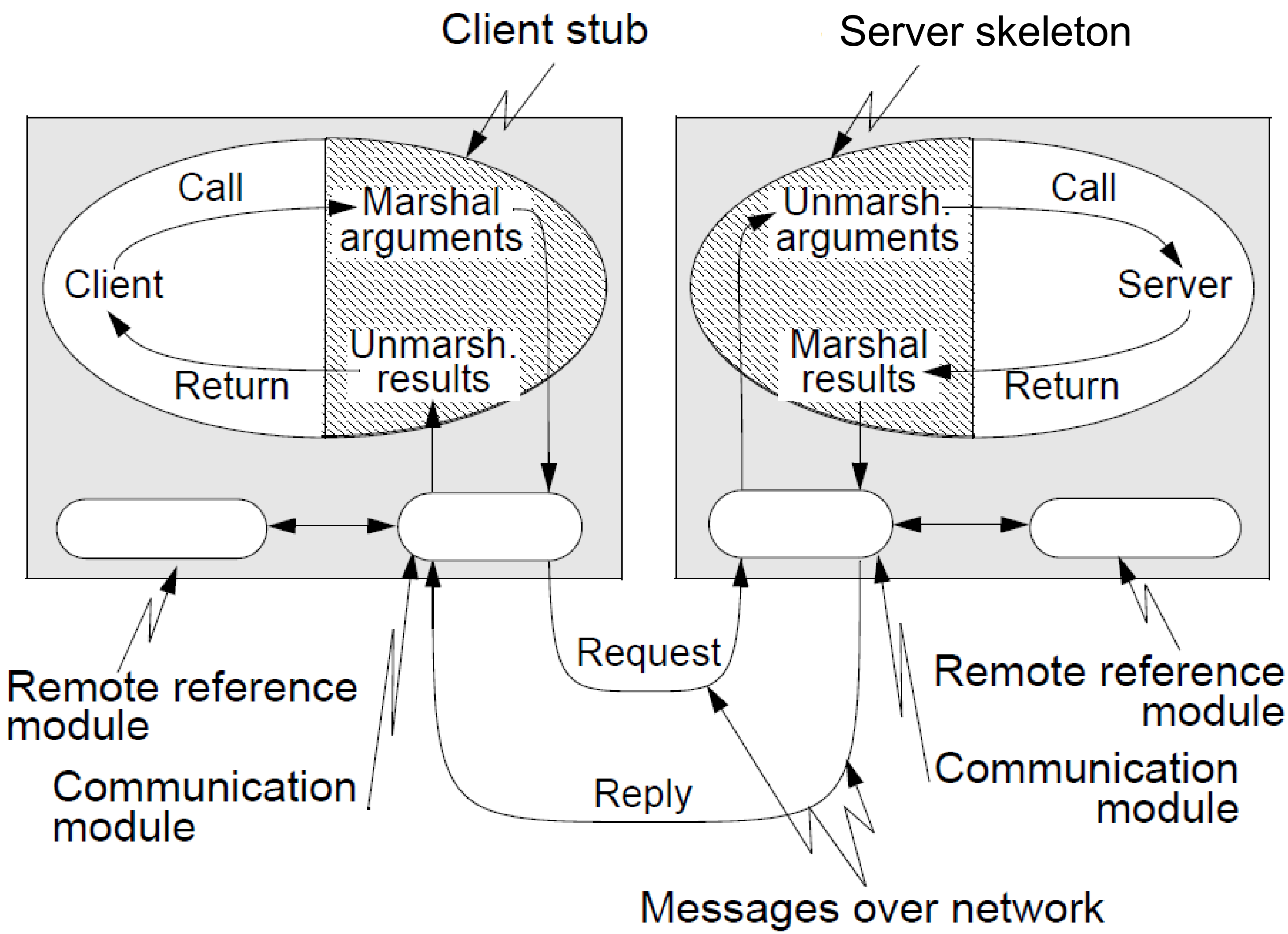
Implementation of RMI

- **Object A** and **Object B** belong to the *application*.
- **Remote reference module** and **communication module** belong to the *RMI middleware*.
- The **stub** (client-side proxy object for B) and the **skeleton** (server-side proxy object for remote callers to B) represent the so-called *RMI software*.
  - Glue code, specific to the function/method being called
  - Situated at the border between middleware and application
  - Generated automatically with help of available tools that are delivered together with the middleware software.
  - Transparent to the application core code
    - the call in A and the service B's code need *not* be modified to enable RMI

The life of a RMI communication

1. The calling sequence in the client object calls the method in the stub (client-side proxy) corresponding to the invoked method in B.
2. The method in the stub packs the arguments into a message (**marshalling**) and forwards it to the communication module.
3. Based on the remote reference obtained from the remote reference module, the communication module initiates the request/reply protocol over the network.
4. The communication module on the server’s machine receives the request. Based on the local reference received from the remote reference module, it calls the corresponding method in the skeleton for B.
5. The skeleton method extracts the arguments from the received message (**unmarshalling**) and calls the corresponding method in the server object B.
6. After receiving the results from B, the method in the skeleton packs them into the message to be sent back (**marshalling**) and forwards this message to the communication module.
7. The communication module sends the reply, through the network, to the client’s machine.
8. The communication module receives the reply and forwards it to the corresponding method in the stub.
9. The stub method extracts the results from the received message (**unmarshalling**) and forwards them to the client.

Remote Procedure Call



RMI Semantics and Failures

If everything works OK, RMI behaves exactly like a local invocation.

What if certain failures occur?

Classes of failures that have to be handled by an RMI protocol:

1. Lost request message
2. Lost reply message
3. Server crash
4. Client crash

We consider an **omission failure model**. This means:

- Messages are either lost or received correctly.
- Client or server processes either crash or execute correctly. After a crash, the server can possibly restart with or without loss of memory.

Lost Request Messages

- The communication module starts a **timer** when sending the request
- If the timer expires before a reply or acknowledgment comes back, the communication module sends the request message **again**.

Problem!

What if the request message was not truly lost (but, for example, the server is too slow) and the server receives it more than once?

- We must **avoid** that the server executes operations more than once.
- Messages have to be identified by an **identifier** and copies of the same message have to be filtered out:
  - If the duplicate arrives and the server has not yet sent the reply → simply send the reply.
  - If the duplicate arrives after the reply has been sent → the reply may have been lost or it did not arrive in time.

Lost Reply Message

The client can not distinguish the loss of a request from that of a reply; it simply resends the request because no answer has been received!

- If the reply really got lost → when the duplicate request arrives at the server, it already has executed the operation once!
- In order to resend the reply, the server may need to **re-execute** the operation in order to get the result.

Danger?!

- Some operations can be executed more than once without any problem; they are called **idempotent operations**
  → no danger with executing the duplicate request.
- There are operations which cannot be executed repeatedly without changing the effect (e.g. transferring an amount of money between two accounts)
  → **history** can be used to avoid re-execution.

History (log): stores a record of reply messages that have been transmitted, together with the message identifier and the client which it has been sent to.

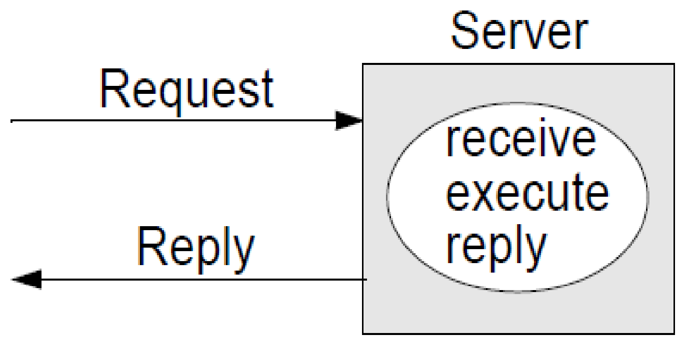
Conclusion with Lost Messages

- **Exactly-once semantics** can be implemented in the case of lost (request or reply) messages if both **duplicate filtering** and **history** are provided and the message is resent until an answer arrives:
  - Eventually a reply arrives at the client and the call has been executed correctly - exactly one time.

- However, the situation is different if we assume that the server can crash…

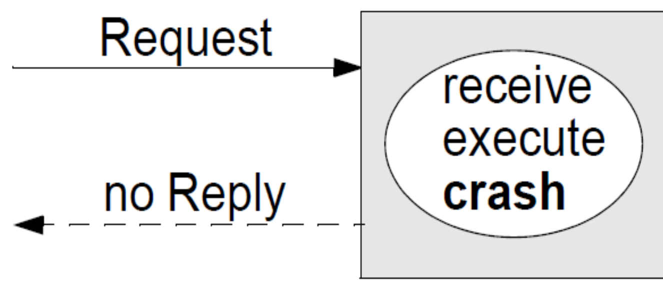
Server Crash

(a) The normal sequence:

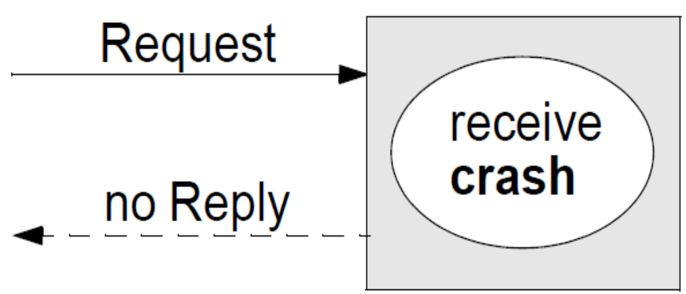


(b) The server crashes *after* executing the operation, but *before* sending the reply:

- As result of the crash, the server ***lost memory*** and does not remember that it has executed the operation.



(c) The server crashes *before* executing the operation:



Big problem!

The client cannot distinguish between these cases.

What to do if the client noticed that the server might be down? (it did not answer to repeated requests)?

Server Crash

Alternative 1: at-least-once semantics

- The client's communication module sends **repeated requests** and **waits** until the server reboots or it is rebound to a new machine; when it finally receives a reply, it forwards it to the client.

  - When the client got an answer, the RMI has been carried out at least one time, but possibly more.

Alternative 2: at-most-once semantics

- The client's communication module gives up and **immediately reports the failure to the client** (e.g., by raising an **exception**).

  - If the client got an answer, the RMI has been executed exactly once.
  - If the client got a failure message, the RMI has been carried out at most one time, but possibly not at all.

Alternative 3: exactly-once semantics

- This is what we would like to have (and what we could achieve for lost messages): the RMI has been carried out exactly one time.
- **However, this cannot be guaranteed, in general, for server crashes.**

Client Crash

The client sends a request to a server
and crashes *before* the server replies.

- The computation which is active in the server becomes an **orphan** - a computation nobody is waiting for.

Problems:

- waste of server CPU time
- locked resources (files, peripherals, etc.)
- if the client reboots and repeats the RMI, confusion can be created.

The solution is based on **identifying and killing the orphans**.

Summary - RMI Semantics and Failures

- If the problem of errors is ignored,
  maybe-semantics is achieved for RMI:
  - The client, in general, does not know if the remote method has been executed once, several times, or not at all.

- If server crashes can be excluded,
  exactly-once semantics is possible to achieve by resending requests, filtering out duplicates, and using history.

- If server crashes **with loss of memory** are considered,
  only **at-least-once** and **at-most-once semantics** are achievable in the best case.

Summary - RMI Semantics and Failures

In practical applications, **servers can survive crashes without loss of memory**.

- Transaction-based sophisticated **commitment protocols** are implemented in **distributed database systems** to achieve this goal.
  - In such systems, **history** can be used and duplicates can be filtered out after restart of the server:
    - The client repeats sending requests without being in danger operations to be executed more than once:
      - If no answer is received after a certain amount of tries, the client is notified, so it knows that the method has been executed at most once or not at all.
      - If an answer is received, it is forwarded to the client, which knows that the method has been executed exactly one time.

RMI implementation and error handling differs between systems. Sometimes **several** semantics are implemented, among which the user is allowed to select.

Direct vs. Indirect Communication

- The communication primitives studied so far are based on **direct coupling between sender and receiver**
  - the sender has a reference/pointer to the receiver and specifies it as an argument of the communication primitive.

- The sender writes something like:

  …

  send (request) to server_reference;

  …

→ Very Rigid!

Direct vs. Indirect Communication

An alternative: **Indirect communication**

- No direct coupling between sender and receiver(s).
- Communication is performed via an **intermediary**.

☺ **Space decoupling**:
sender does not know the identity of receiver(s).

☺ **Time decoupling**:
sender and receiver(s) have independent lifetimes:
they do not need to exist at the same time.

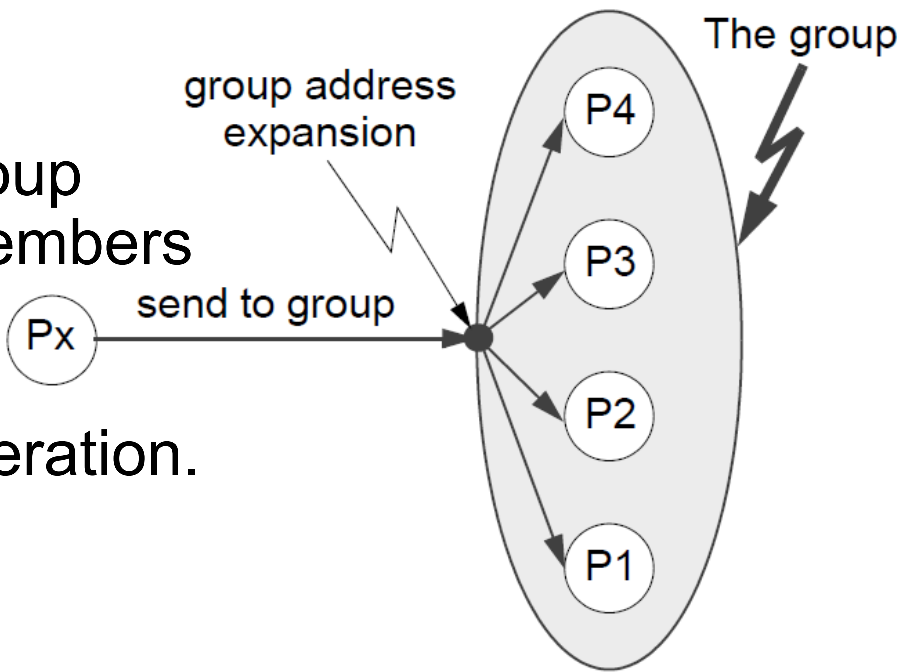
We look at **two examples**:

1. **Group communication**
2. **Publish-subscribe systems**

Group Communication

- The assumption with client-server communication and RMI (RPC) is that two parties are involved: the client and the server.
- Sometimes communication involves multiple processes, not only two.
  - A (simple) solution is to perform separate message passing operations or RMIs to each receiver.
- With **group communication**, a message can be sent to a group and then it is delivered to all members of the group

→ multiple receivers in one operation.



Group Communication

Why do we need it?

- **Special applications**: interest-groups, mail-lists, etc.
- **Fault tolerance based on replication**:
  - A request is sent to several servers which all execute the same operation (if one fails, the client still will be served).
- **Locating a service or object in a distributed system**:
  - The client sends a message to all machines, but only the one (or those) which holds the server/object responds.
- **Replicated data** (for reliability or performance):
  - whenever the data changes, the new value has to be sent to all processes managing replicas.

Group Communication

<u>Group membership management</u>:

- maintains the view of group membership, considering members joining, leaving, or failing.

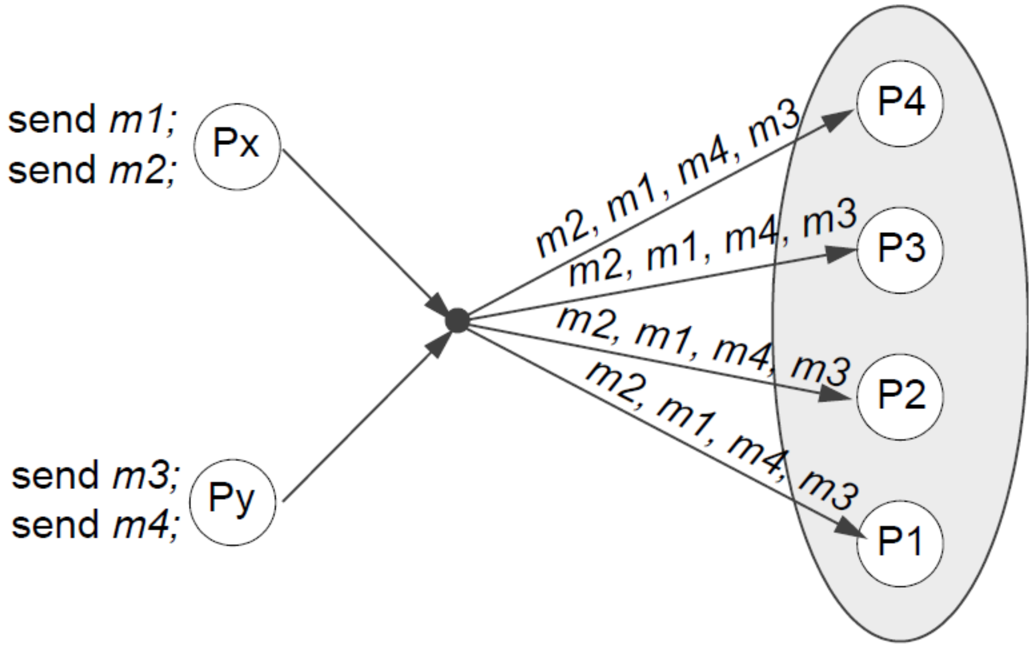
<u>Services provided</u> by group membership management:

- **Group membership changes**:
  - create/destroy process groups;
  - add/withdraw processes to/from group.
- **Failure detection**:
  - Detects processes that crash or become unavailable (due to e.g. communication failure);
  - Excludes processes from membership if crashed or unavailable.
- **Notification**:
  - Notifies members of events, e.g., processes joining/leaving group.
- **Group address expansion**:
  - Processes sending to a group specify the **group identifier**;
  - **address expansion** provides the actual addresses for the multicast operation delivering the message to each group members.

Group Communication

Essential features:

- **Atomicity** (all-or-nothing):
  - when a message is sent to a group, it will either arrive correctly at all members of the group or at none of them.
- **Ordering**
  - **FIFO-ordering**: Messages originating *from a given sender* are delivered in the order they have been sent, to all members of the group.
  - **Total-ordering**: When several messages, *from different senders*, are sent to a group, the messages reach *all* the members of the group in the *same* order.



Publish-Subscribe Systems

The general objective of **publish-subscribe systems** is to let information propagate from **publishers** to interested **subscribers**, in an **anonymous, decoupled** fashion.

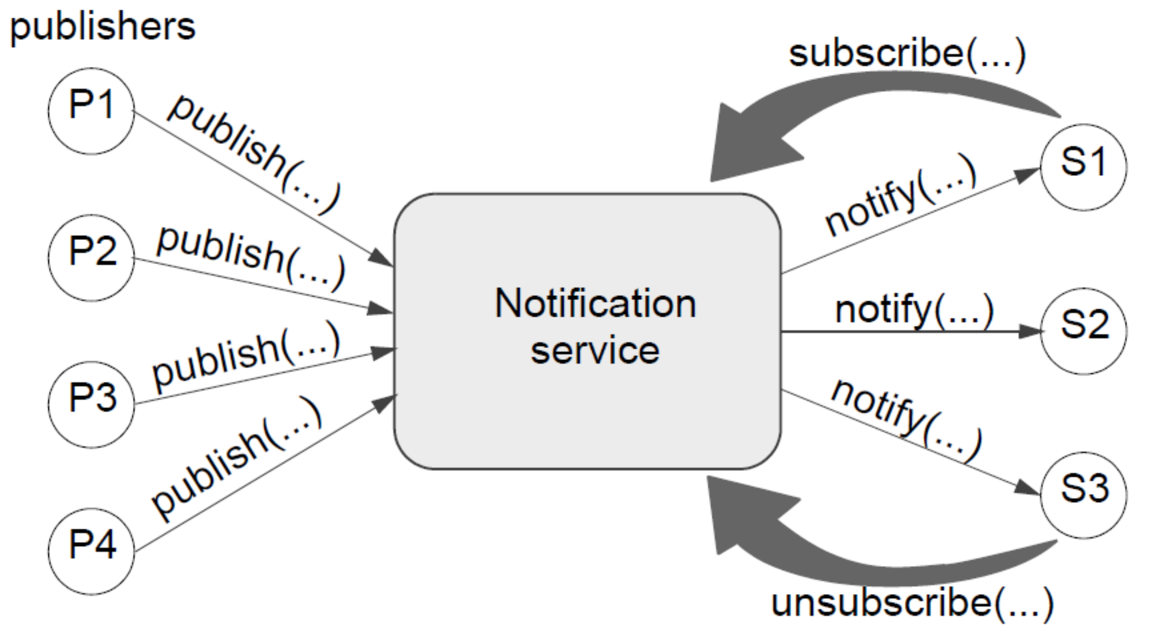
- **Publishers** publish events.
- **Subscribers** subscribe to and receive the events they are interested in.

Subscribers are not directly targeted from publishers but *indirectly* via the **notification service** →

- Subscribers express their interest by issuing **subscriptions** for specific notifications, independently from the publishers that produces them;
- they are asynchronously notified for all **notifications**, submitted by any publisher, that **match** their subscription.

A generalization of the *Observer* design pattern in software architecture, where the event notifications are callbacks.

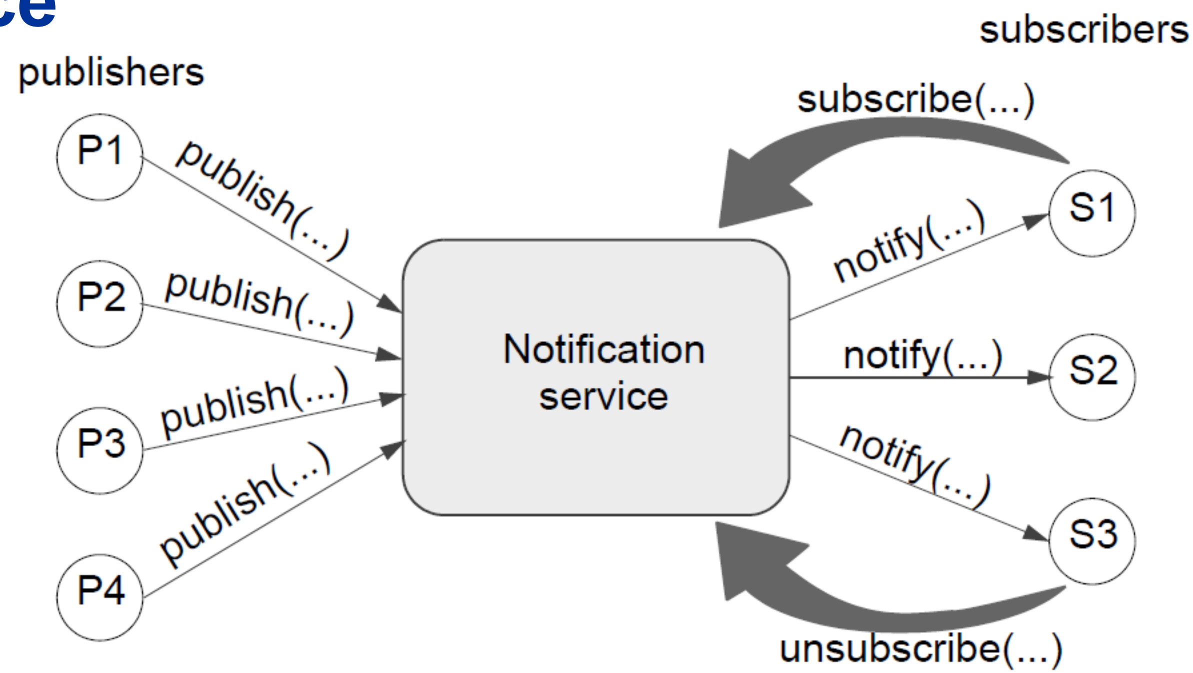
Publish-Subscribe Systems:
Notification Service



Notification Service: is a propagation mechanism that acts as a **logical intermediary** ("*broker*") between publishers and subscribers, to avoid each publisher to have to know all the subscriptions for each possible subscriber.

- Both publishers and subscribers communicate only with a single entity, the notification service, which
  - stores the **subscriptions** associated with each subscriber;
  - receives all the notifications from publishers;
  - **dispatches** the notifications to the correct subscribers.

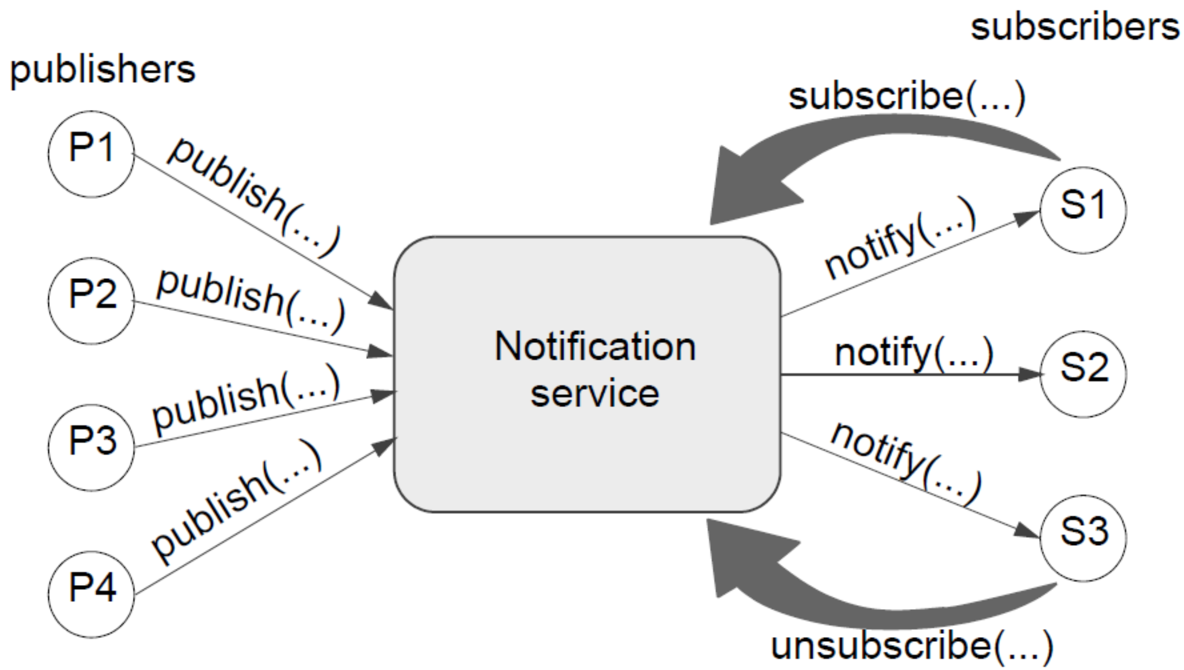
Publish-Subscribe Systems:
Notification Service



A **subscription** is respectively **installed** and **removed** on the notification service as result of subscriber processes executing:

- ***subscribe()***
- ***unsubscribe()***

Publish-Subscribe Systems



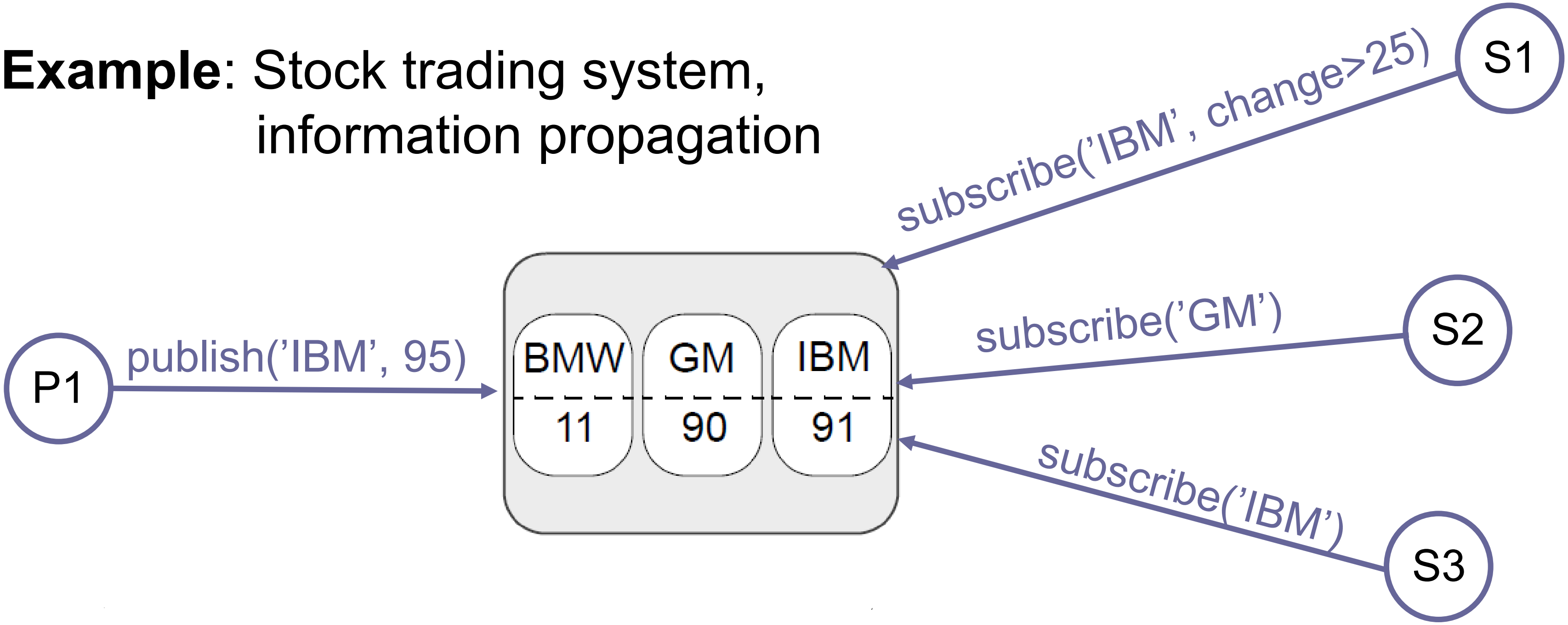
A publisher submits a piece of information by executing the ***publish*()** operation on the notification service.

The notification service *dispatches* a piece of information to a subscriber by executing the ***notify*()** on it.

- A publisher produces an event (publication), while the notification service issues the corresponding notification on interested subscribers.

Publish-Subscribe Systems

- **Example**: Stock trading system,
  information propagation



1. S1 has subscribed to 'IBM', with a filter indicating that it should be notified only if the stock increases by at least 25;

2. S2 and S3 have subscribed to 'GM' and 'IBM' respectively, without filter.

3. P1 is publishing the new value of 'IBM'. Who is notified?

4. S1 is not notified because its filter is not satisfied;
S2 is not notified because it's not interested in 'IBM';
S3 is notified.

Publish-Subscribe Systems

One of the main problems with publish-subscribe systems is to achieve **scalability of the notification service**.

- **Centralized implementations**:
  - are the simplest, however, scalability is limited by the processing power of the machine that hosts the service.
- **Distributed implementations**:
  - The notification service is realised as a network of distributed processes, called **brokers**;
    - the brokers interact among themselves with the common aim of dispatching notifications to all interested subscribers.
  - Such a solution is **scalable,** but more challenging to implement
    - it requires **complex** protocols for the coordination of the various brokers and the diffusion of the information.

Publish-Subscribe Systems

Example: MQTT (https://mqtt.org)

- MQTT is an OASIS standard messaging protocol for the Internet of Things (IoT)
- Designed as lightweight publish/subscribe messaging transport for connecting remote devices with a small code footprint and minimal network bandwidth.
- Client-server protocol (MQTT broker servers act as notification service)
- Runs over TCP/IP, or over other network protocols that provide ordered, *lossless*, bi-directional connections.
- Agnostic to the content of the payload
- Small transport overhead
- Protocol exchanges minimized to reduce network traffic
- Mechanism to notify interested parties when an abnormal disconnection occurs
- Three qualities of service for message delivery:
  - "At most once"
  - "At least once"
  - "Exactly once"
- Used in wide variety of industries: automotive, manufacturing, telecom, etc.
- Originally developed at IBM, specification opened. Current version 5.0 (2019)
- Open implementation e.g. in Eclipse Mosquitto https://mosquitto.org/

Acknowledgments

- Most of the slide contents is based on a previous version by Petru Eles, IDA, Linköping University.