Goals & Issues of Distributed Systems

Distributed Systems
Sistemi Distribuiti

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About these Slides

- the following slides borrow a great deal from the slides coming with the book adopted as the basic one for this course
  [Tanenbaum and van Steen, 2007]
- material from those slides (including pictures) has been re-used in the following, and integrated with new material according to the personal view of the professor
- every problem or mistake contained in these slides, however, should be attributed to the sole responsibility of this course's professor
- the goal for students, here, is to be exposed to the classical *general view* on distributed systems that the technical and scientific community has developed in the last decades

Next in Line. . .

Distributed System: Classic Definitions I

A distributed system can be defined as. . .

. . . a collection of *independent* computers that *appears* to its users as a *single coherent system* [Tanenbaum and van Steen, 2007]

User's view

- a possible definition, accounting for an *observational*, user-oriented view
- we may also call it the computer scientist definition of a distributed system
- from an engineering viewpoint, it is a sort of *a posteriori* definition

Distributed System: Classic Definitions II

A distributed system can be defined as...

... a collection of *autonomous* computational entities *conceived* as a *single coherent system* by its designer

Engineer's view

- another possible definition, accounting for a *constructive*, design-oriented view
- we may also call it the computer engineer definition of a distributed system
- from an engineering viewpoint, it is a sort of *a priori* definition

Distributed System: Classic Definitions III

Remarks

- a distributed system is made of a multiplicity of *components*
  - independent / autonomous computational entities (computers, microprocessors, . . .)
  - ! no definition focus specifically on either computational processes or computing devices, here
  - *no assumptions* on their individual nature, structure, behaviour, . . .
  - heterogeneity
- a distributed system can be seen as a single coherent system
  - according to either the user's view or the engineer's view—or both
  - need for *coherence* over multiplicity and heterogeneity

Distributed System: Another Definition

A distributed system can be defined as...

... one in which components located at *networked* computers *communicate* and *coordinate* their actions only by passing *messages*.

[Coulouris et al., 2012]

Remarks

This definition focusses on the following features of distributed systems:

- physical *distribution* of components
- the role of *interaction*—network-based communication and coordination
- uncoupling in terms of *control*

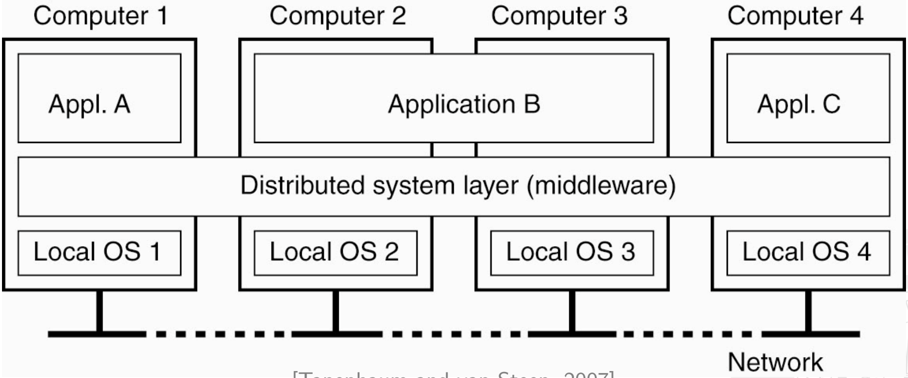
Distributed System: Working as One, Looking as One

Issues: coherence & uniformity

collaboration
: in order to achieve coherence, many *autonomous* entities should *collaborate*—that is, work altogether as a single (coherent) system

amalgamation
: in order to achieve uniformity, many *heterogeneous* entities should *amalgamate*—that is, look altogether as a single (uniform) system

An Architectural View of Distributed Systems: Middleware



[Tanenbaum and van Steen, 2007]

- a distributed system organised as middleware
- the *middleware layer* extends over multiple machines, and offers each application the *same interface*

An Architectural View of Distributed Systems: Old vs. New

Moving from a view of non-distributed computational systems. . .

- . . . by trying to extend the same old interpretation of systems
- good for preserving good habits
- bad when looking for new ideas and new problems

! *middleware* has obviously a role to play here

Middleware: A Principled Solution

Middleware for collaboration & amalgamation

Through *separation*, the middleware layer. . .

- . . . enables *meaningful interaction* between autonomous distributed components
  - communication issues like the language for messages and its semantic interpretation
- . . . hides differences in technology, structure, behaviour
  - providing both applications and components with a common shared interface—in the same way as operating systems

Next in Line. . .

What Made Computational Systems *Distributed*?

At the very beginning

- computers were huge & expensive machines
- computers were *islands*
  - computer science – at the time, as the art of computer programming – was born upon such machines

. . . then, drastic advances in Electronics and TLC occurred

- microprocessor technology made computational *devices* more and more powerful and cheap
- high-speed computer networks made *interconnection* of computational entities possible at a wide range of scales and speeds
  - the *scope* and *goal* of computer science changed dramatically

↓ from centralised (single-processor) systems

→ to decentralised (multi-processor), distributed systems

Why Should We Build a Distributed System?

A distributed system is *easy to build*

- hardware, software, and network components are easy to find & use
  - and to be *put together* somehow
- however, at a first sight, distribution apparently introduces *problems*, rather than solving them
  - ? why should we build a system as a distributed one?
  - ! in particularly, given that it is not easy to make a distributed system *actually work*

Making Distributed System Worth the Effort

Four goals for a distributed system...

- making (distributed, remote) *resources* available for use
- allowing *distribution* of resources to be hidden whenever unnecessary
- promoting openness
- promoting scalability

... plus, a fifth goal

- promoting situatedness

Making Resources Available

Resources are physically distributed

- a good reason to build a distributed system is to make them distributed resources *available* as they would belong to a single system

What is a resource?

Anything that ...

- ... could be in any way connected to a computational system
- ... anyone could legitimately use

E.g., printers, scanners, storage devices, distributed sensors, ...

By making interaction possible between users and resources, distributed systems are *enablers* of sharing, information exchange, collaboration, ...

Distribution Transparency

Physical distribution is not a feature, sometimes

- a(nother) good reason to build a distributed system is to make physical distribution *irrelevant* from the user's viewpoint

Transparency

- hiding non-relevant properties of the system's components and structure is called *transparency*
- there exists a number of different and useful sorts of transparency, according to the property hidden to the user's perception

By hiding non-relevant properties to users, distributed systems provide users with a *higher level of abstraction*

Types of Transparency in a Distributed System

- **access** hide differences in data *representation* and in the *access* to resources
- **location** hide the *location* of a resource
- **migration** hide the *change of location* of a resource
- **relocation** hide the *motion* of a resource
- **replication** hide that a resource is *replicated*
- **concurrency** hide the *sharing* of a resource by multiple users
- **failure** hide the *failure* and subsequent *recovery* of a resource

Access Transparency

Heterogeneity in representation and use

- different *data representation*
- different *component structure*
- different *resource* usage *interface* / *protocols*

All of them should be hidden from the user's view, whenever possible & non-relevant

Providing a homogeneous view over heterogeneity

- a distributed system should hide heterogeneity, by providing uniform/homogeneous access to data, components, resources

Location Transparency

Location of users and resources

- often, the physical location of a resource is not relevant for its use by the users—and, viceversa, the location of users is often irrelevant for the resource
    - e.g., the position of a storage facility, or of a single printer in a cluster of printers in a lab

Hiding physical distribution of users and resources

- distributed systems should hide physical distribution, whenever possible & non-relevant

Naming is essential

- there should exist a system of logical *identifiers*, not bound to physical location
    - e.g., URLs

Migration Transparency

Resources might be *mobile*

- locations change within a distributed system
- which has to maintain its coherence anyway

A distributed system should allow *migration* of resources

- without losing coherence
- without losing functionality

Also *users* might move

- some years ago this was a sort of secondary aspect
- nowadays, user's mobility is typically a core issue in the modelling and engineering of artificial systems

Relocation Transparency

Resources should be still accessible when moving

migration
: should not prevent users to access resources, *while they are changing their location*

relocation
: transparency is in some sense a specialised, *on line* version of migration transparency

A distributed system could be useful to *allow access* to *mobile resources* by *mobile users*, by hiding changes in location (migration transparency), even while changes are actually occurring (relocation transparency)

Replication Transparency I

Sometimes *replication* helps

Like, for instance,

- in providing a *local copy* of a *resource* to local agents/users—so as to
    - reduce bandwidth consumption
    - provide faster access
- in promoting *tolerance to failures*
    - through *redundancy*

Replication Transparency II

Whatever the motivation behind replication ...

... replication is not something a user should worry about

- all replicas should be accessible in the same, *transparent* way
- so they should have the *same name*
- and should be essentially in the *same state*, so to be *apparently one* and the same thing for each and every user

A distributed system could exploit *replication* techniques for many reasons, but should be able at the same time to make it *invisible* to the users

Concurrency Transparency I

Activity in a distributed systems involves *independent* entities

- users and resources are *distributed*, and work *autonomously*, in a *concurrent* way
- for instance, two users may try to exploit the same resource at the same time
- typically, no user need to be bothered with these facts—like, "another user is accessing the same database you are accessing just now", who cares?

Concurrency Transparency II

Concurrency in activities should be *hidden* to users

- while shared access to resources could be done cooperatively, it is often the case that users should access competitively to resources
- a distributed system could take care of this, by defining access policies governing concurrent sharing of resources
- possibly, transparently to the users

Concurrency & Consistency

The problem of *consistency*

- when many users access the same resource concurrently, *consistency* of its state is in jeopardy—but should be ensured anyway
- a distributed system should take care of ensuring resource safety even under concurrent accesses
- as usual, transparently to the users

A distributed system should take care of allowing transparent concurrent access to resources, while ensuring consistency of resources

Failure in Distributed Systems

Failure in a distributed system is any failure *anywhere* in the system

- "*You know you have [a distributed system] when the crash of a computer you've never heard of stops you from getting any work done.*" (L. Lamport)
- distribution might be either a source of problems or a blessing
- it means that a failure could occur anywhere, but also that a part of the system is likely keep on working
  - *distributed failure* is hard to control
  - *partial failure* is possible, and much better than *total failure* of centralised systems

Distribution should work as a *feature*

Failure Transparency

What does this mean?

- masking failures under realistic assumptions
- hiding failure of resources to users

Being failure transparent is a hard problem

- e.g., the problem of *latency*
  - how do we distinguish between a dead resource and a very slow one?
  - is “silence” from a resource originated by slowness, deliberate choice, resource failure, or network failure?

A distributed system should exploit distribution to *reduce* the impact of *partial failure* onto the overall system, *hiding failures* to *users* as much and often as possible.

Degree of Transparency in a Distributed System I

Hiding distribution is not always the best idea

- for instance, users may move and be subject to different time zones—this could lead to funny situations, if hidden, such as a download ending before it started
- also, you may appreciate to know where the file server is located (US, Japan, Europe?) when choosing from where you will download the new Ultra HD Pokémon movie from home
  - unless it is replicated in such a way that it does not matter

Degree of Transparency in a Distributed System II

Trade-off between transparency and information

- it typically concerns performance—yet, it is not limited to this
- location-awareness is often a feature
- every engineer should find out the precise *degree of transparency* its distributed system should feature, by taking into account other issues like performance, understandability, . . .

Next in Line. . .

Openness

What is openness?

- essentially, the property of a system to work with a number and sort of components that is not set once and for all at design time

$\leftarrow$ open systems are typically *designed to be open*

$\rightarrow$ open systems are fundamentally *unpredictable*

Designing over unpredictability requires predictable items

- something needs to be *a priori* shared between the system and the (potential) components
- like, e.g., standard rules for services syntax and semantics, message interchange, ...

Interfaces for Open Systems

Interfaces to specify syntax for accessing services

- IDL (Interface Definition Languages) to define how *interfaces* are specified
- they capture syntax, rather than semantics—often, they do not specify the *protocol*, too

Issues for Open Systems

Interoperability

interoperability measures how easy / difficult is to make one component / system work with different ones based on some standard-based specifications

portability measures how much an application (or, a portion of it) can be moved to a different distributed system and keep working

extensibility measures how easy / difficult is to add new components and functionality to an existing distributed system

Separating Policies from Mechanisms I

Openness mandates for a clean architecture

- external interfaces are not enough
- components should be small and focussed enough to be easily modified / replaced
- internal specifications should be as neat as the external ones

Separating Policies from Mechanisms II

Components providing mechanisms should not impose policies

- mechanisms are the basic *operational bricks* made available to designers and developers
  - mechanisms should be *neutral*—which means they should not force any particular *choice*, letting systems open to different policy specifications
- policies exploit mechanisms to implement *choices* in a system, ruling admissible behaviour of components as well as their mutual interactions
  - policies should be either *encapsulated* into other components or *delegated* to users
  - (assuming the two things are really different)
- clear separation between mechanisms and policies should be enforced

Scalability

World-wide scale changes everything

- often, few realistic assumptions can be done on the actual "size" of a distributed system at design time
- there, *size* might mean actual size in number of components, but also in geographical distribution

Dimensions of scalability [Neuman, 1994]

- a system scales up when the *number* of users and resources grows
- a system scales up when the *geographical distribution* of users and resources extends
- a system scales up when it spans over a growing number of distinct *administrative domains*

Scalability is an issue whenever any dimension of a distributed system changes its order of magnitude

Scalability Problems: Scaling with Respect to Size

Examples of scalability limitations [Tanenbaum and van Steen, 2007]

centralised services a single server for all users

centralised data a single database for all distributed components

centralised algorithms complete information is assumed to be available in one single place

Centralisation

Making things centralised might be necessary

- even though a single server is a bottleneck, it could be a necessity in case of security problems, or, normative requirements
- even though a single collection of data is a bottleneck, it could still be needed if replication is insecure
- sometimes, the most efficient algorithm from a theoretical viewpoint might be a centralised one

However, *centralisation hinder scalability*, and should be avoided in general in distributed systems whenever possible

Decentralised vs. Centralised Algorithms I

The trouble with centralised algorithms [Raynal, 2013]

- data should flow from the whole network to and from the place where the centralised algorithm works
- the network would be overloaded
- any transmission problem would cause problems to the overall algorithm

→ only decentralised algorithms should be used in distributed systems

Decentralised vs. Centralised Algorithms II

Characteristics of decentralised algorithms [Kshemkalyani and Singhal, 2011]

- no machine has complete information about the system state
- machines make decisions based only on local information
- failure of one machine does not ruin the algorithm
- there is no implicit assumption that a global clock exists

Scalability Problems: Geographical Scalability I

The trouble with communication

- communication in LAN is typically synchronous—this does not scale up to WAN: e.g., how should timeouts be set up?
- communication in WAN is typically unreliable, and typically point-to-point—LAN broadcasting no longer an option: e.g., how could a service be located?

Shared troubles with size scalability

Centralisation is still a mess, since

- it requires computation and interaction capabilities to scale up with size
- it also leads to a *single point of failure*

Scalability Problems: Geographical Scalability II

Administration / organisation troubles

- e.g., within a single domain, users and components might be trusted: however, trust does not cross domain boundaries
- distributed systems typically extend over *multiple* administration / organisation *domains*
  - security measures are needed that may hinder scalability
  - policies may conflict

Techniques for Geographical Scalability

Three Basic Techniques [Neuman, 1994]

- hiding communication latency
  - asynchronous communication
- distribution
- replication

Scaling Techniques: Hiding Communication Latency I

The basic idea

Try to avoid wasting time waiting for remote responses to service requests whenever possible

Asynchronous communication

This basically means using *asynchronous communication* for requests whenever possible

- a request is sent by the application
- the application does not stop waiting for a response
- when a response come in, the application is interrupted and a handler is called to complete the request

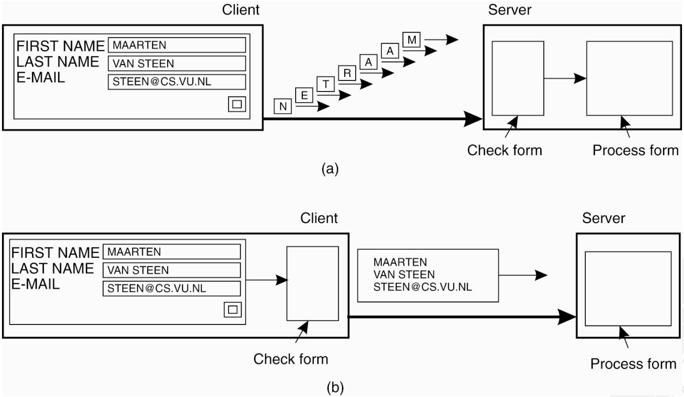
Scaling Techniques: Hiding Communication Latency II

Problem

Sometimes, asynchronous communication is not feasible

- like in Web application when a user is just waiting for the response
- alternative techniques like shipping code are needed—e.g., Javascript or Java Applets

Scaling Techniques: Code Shipping Example



The difference between letting (a) a server or (b) a client check forms as they are being filled [Tanenbaum and van Steen, 2007]

Scaling Techniques: Distribution

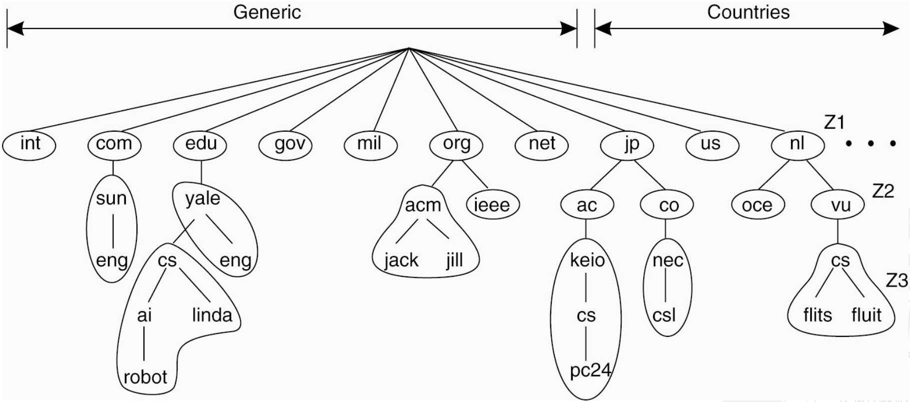
The basic idea

Taking a component, splitting it into parts, and spreading the parts across the system

Example: The Domain Name System (DNS)

- the DNS is hierarchically organised into a tree of *domains*
- domains are divided in non-overlapping *zones*
- the names in each zone are in charge of a single server
- e.g., `apice.unibo.it`
- the *naming service* is thus distributed across several machines, without centralisation

Scaling Techniques: Distribution Example



An example of dividing the DNS space into zones

[Tanenbaum and van Steen, 2007]

Scaling Techniques: Replication

The basic idea

- when degradation of performance occurs, *replicating* components across a distributed system may increase availability and solve problems of latency
- replication typically involves making a copy of a resource form the original location to a location in the proximity of the (potential) users

Caching

- is a special form of replication
- caching is making a copy of a resource, like replication
- however, caching is a decision by the client of a resource, replication by the owner of a resource

The Problem of Consistency

Duplicating a resource introduces *consistency* problems

- involving both caching and replication
- inconsistency is technically unavoidable, whenever copying a resource in a distributed setting
- the point is *how much inconsistency* could a system tolerate, and how it could be hidden from users and components of a distributed system

Scalability Problems: Administrative Scalability

The trouble with organisation

- maybe the most difficult problem: many non-technical problems to be solved, such as policy of organisation and human collaboration

A successful approach: Ignoring administrative domains

- users take over control: peer-to-peer technologies
- only a partial solution, nevertheless, something should be done

A recommendation for computer scientists & engineers

- not every organisation problem has a technical solution
- sometimes, personal interactions within an organisation are the only way to overcame a pseudo-technical problem

Situatedness I

What is situatedness? [Suchman, 1987]

- situatedness is in short the property of systems of being *immersed* in their environment
- that is, of being capable to (timely) *perceive* and *produce* environment change, by suitably dealing with environment events
- mobile, adaptive, and pervasive computing systems have emphasised the key role of situatedness for nowadays computational systems [Zambonelli et al., 2011]

Situatedness II

Situatedness & context-awareness

- computational systems are more and more affected by their *physical nature*
- this is not due to a lack of abstraction: indeed, we are suitably layering systems – including hardware and software layers –, where separation between the different layers is clear and well defined
- instead, this is mostly due to the increasingly *complex requirements* for computational systems, which mandate for an ever-increasing context-awareness [Baldauf et al., 2007]
- defining the notion of *context* is a complex matter [Omicini, 2002], with its boundaries typically blurred with the notion of *environment*—as clearly emerging from the field of *multi-agent systems* [Weyns et al., 2007]

Situatedness III

Context-awareness: space & time

- mobile computing scenarios have made clear that *situatedness* of computational systems nowadays requires at least *awareness of the spatio-temporal fabric*
- that is, any non-trivial system needs to know *where* it is working, and *when*, in order to effectively perform its function
- in its most general acceptation, then, any (working) environment for a computational systems is first of all made of space and time

! what we call *temporal* and *spatial context*

Situatedness IV

Context-awareness: environment

- more generally, situatedness of computational systems nowadays requires *awareness of the environment* where the systems are deployed and are expected to work
- that is, any non-trivial system needs to understand somehow its working environment, its *nature*, its *structure*, the *resources* it makes available for use, the possible *issues* that may harm the systems in any way

Situatedness V

Knowledge-Intensive Environments (KIE)

- special and nowadays particularly relevant sorts of working environments are the so-called knowledge-intensive environments
- there, *knowledge* available in large amounts, and *distributed* in the working environment, is important (if not essential) for the activities of the systems
- accessing, understanding, and possibly injecting knowledge while interacting (locally) within the working environment is essential for most computational systems to properly perform their activities and achieve their goals

Situatedness & Distributed Systems I

Why distributed systems for situatedness?

- physical distribution of computational systems is essential to cope with the *distributed nature* of many *working environments*
- ... as well as with the need for *situated computations*
- essentially, when the systems requirements mandate for situated computations within a distributed physical environment, situated distributed systems are the only way out
- e.g., disaster recovery scenarios, environmental monitoring, crowd steering, live events...

Situatedness & Distributed Systems II

Openness & scalability

- openness of distributed situated systems is essential to deal with the *unpredictability* of complex environments
- scalability allows distributed situated systems to cope with working environments of *growing complexity*

Pitfalls of Distributed Systems [Tanenbaum and van Steen, 2007]

False assumptions made by first time developer (by L. Peter Deutsch)

- the network is reliable
- the network is secure
- the network is homogeneous
- the topology does not change
- latency is zero
- bandwidth is infinite
- transport cost is zero
- there is one administrator

Such (false) assumptions typically produces all mistakes in the engineering of distributed systems

Pitfalls of Distributed Systems: Remarks

Such (false) assumptions...

... relate to properties that unique to distributed systems:

- reliability of the network
- security of the network
- heterogeneity of the network
- topology of the network
- latency
- bandwidth
- transport costs
- administrative domains

When engineering non-distributed systems, such problems are likely not to show up

Summing Up

- there are good reasons to build up distributed systems
  - several issues, and several opportunities, too
  - systems are inherently *complex*, nowadays, and distributed systems may help hiding some complexity and improving understanding and ease of use
- distributed systems introduces / reveals new dimensions of computational systems
  - when they are ignored, suddenly lead to severe issue
  - to account for them, a new discipline for system engineering is required

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