Distributed Systems

(3rd Edition)

Chapter 02: Architectures

Version: February 25, 2017

Architectural styles

Basic idea

A style is formulated in terms of

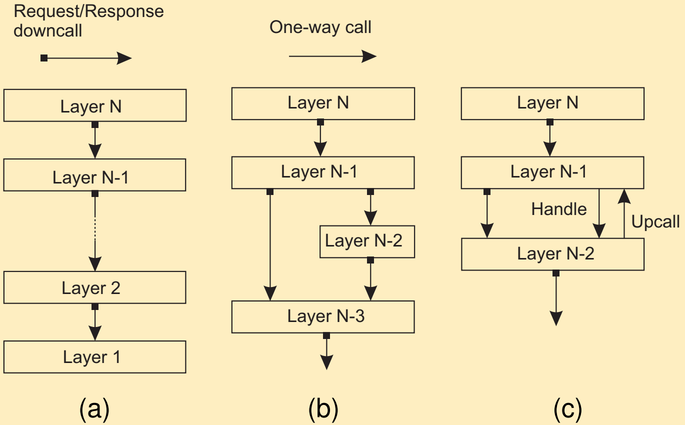
- (replaceable) components with well-defined interfaces
- the way that components are connected to each other
- the data exchanged between components
- how these components and connectors are jointly configured into a system.

Connector

A mechanism that mediates communication, coordination, or cooperation among components. Example: facilities for (remote) procedure call, messaging, or streaming.

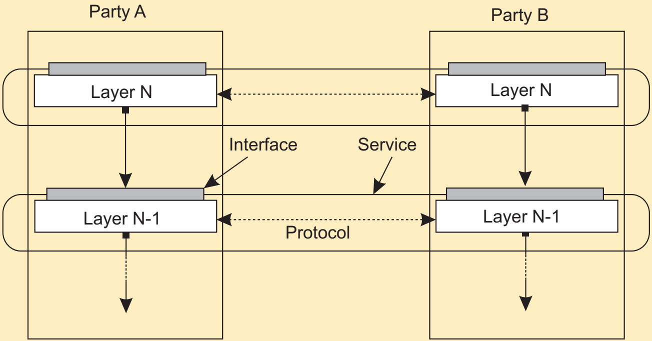
Layered architecture

Different layered organizations



Example: communication protocols

Protocol, service, interface



Two-party communication

Server

```
from socket import *
s = socket(AF_INET, SOCK_STREAM)
(conn, addr) = s.accept()  # returns new socket and addr. client
while True:                # forever
  data = conn.recv(1024)   # receive data from client
  if not data: break       # stop if client stopped
  conn.send(str(data)+"*") # return sent data plus an "*"
conn.close()               # close the connection
```

Client

```
from socket import *
s = socket(AF_INET, SOCK_STREAM)
s.connect((HOST, PORT)) # connect to server (block until accepted)
s.send('Hello, world')  # send some data
data = s.recv(1024)     # receive the response
print data              # print the result
s.close()               # close the connection
```

Application Layering

Traditional three-layered view

- Application-interface layer contains units for interfacing to users or external applications
- Processing layer contains the functions of an application, i.e., without specific data
- Data layer contains the data that a client wants to manipulate through the application components

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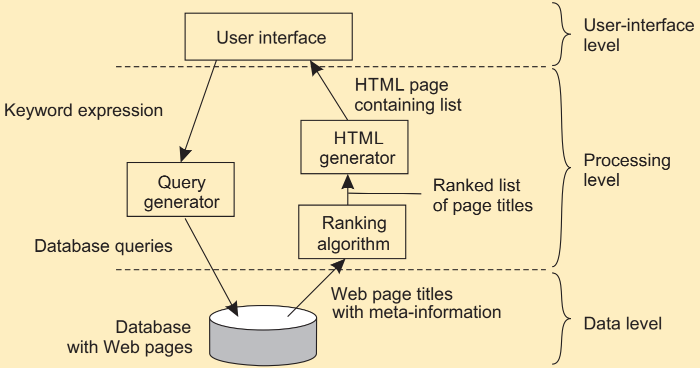
- Data layer contains the data that a client wants to manipulate through the application components

Observation

This layering is found in many distributed information systems, using traditional database technology and accompanying applications.

Application Layering

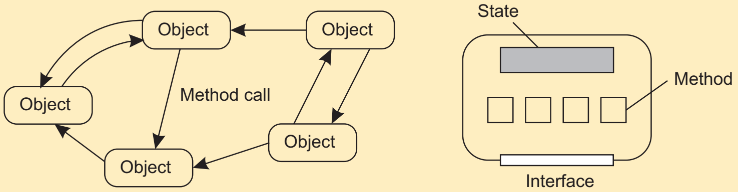
Example: a simple search engine



Object-based style

Essence

Components are objects, connected to each other through procedure calls. Objects may be placed on different machines; calls can thus execute across a network.



Encapsulation

Objects are said to encapsulate data and offer methods on that data without revealing the internal implementation.

RESTful architectures

Essence

View a distributed system as a collection of resources, individually managed by components. Resources may be added, removed, retrieved, and modified by (remote) applications.

1. Resources are identified through a single naming scheme
2. All services offer the same interface
3. Messages sent to or from a service are fully self-described
4. After executing an operation at a service, that component forgets everything about the caller

Basic operations

Operation	Description
`PUT`	Create a new resource
`GET`	Retrieve the state of a resource in some representation
`DELETE`	Delete a resource
`POST`	Modify a resource by transferring a new state

Example: Amazon's Simple Storage Service

Essence

Objects (i.e., files) are placed into buckets (i.e., directories). Buckets cannot be placed into buckets. Operations on `ObjectName` in bucket `BucketName` require the following identifier:

`http://BucketName.s3.amazonaws.com/ObjectName`

Typical operations

All operations are carried out by sending HTTP requests:

- Create a bucket/object: `PUT`, along with the URI
- Listing objects: `GET` on a bucket name
- Reading an object: `GET` on a full URI

On interfaces

Issue

Many people like RESTful approaches because the interface to a service is so simple. The catch is that much needs to be done in the parameter space.

Amazon S3 SOAP interface

Bucket operations	Object operations
ListAllMyBuckets	PutObjectInline
CreateBucket	PutObject
DeleteBucket	CopyObject
ListBucket	GetObject
GetBucketAccessControlPolicy	GetObjectExtended
SetBucketAccessControlPolicy	DeleteObject
GetBucketLoggingStatus	GetObjectAccessControlPolicy
SetBucketLoggingStatus	SetObjectAccessControlPolicy

On interfaces

Simplifications

Assume an interface `bucket` offering an operation `create`, requiring an input string such as `mybucket`, for creating a bucket “mybucket.”

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Conclusions

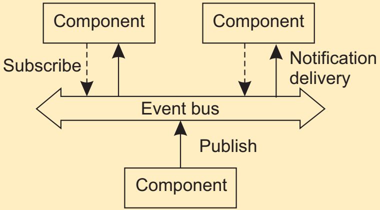
Are there any to draw?

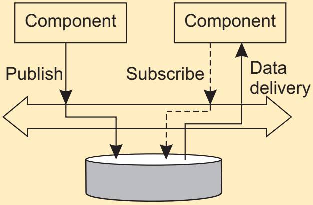
Coordination

Temporal and referential coupling

	Temporally coupled	**Temporally decoupled**
Referentially coupled	Direct	Mailbox
Referentially decoupled	Event-based	Shared data space

Event-based and Shared data space





Example: Linda tuple space

Three simple operations

- `in(t)`: remove a tuple matching template `t`
- `rd(t)`: obtain copy of a tuple matching template `t`
- `out(t)`: add tuple `t` to the tuple space

More details

- Calling `out(t)` twice in a row, leads to storing two copies of tuple `t` $\Rightarrow$ a tuple space is modeled as a multiset.
- Both `in` and `rd` are blocking operations: the caller will be blocked until a matching tuple is found, or has become available.

Example: Linda tuple space

Bob

```
blog = linda.universe._rd(("MicroBlog",linda.TupleSpace))[1]

blog._out(("bob","distsys","I am studying chap 2"))
blog._out(("bob","distsys","The linda example's pretty simple"))
blog._out(("bob","gtcn","Cool book!"))
```

Alice

```
blog = linda.universe._rd(("MicroBlog",linda.TupleSpace))[1]

blog._out(("alice","gtcn","This graph theory stuff is not easy"))
blog._out(("alice","distsys","I like systems more than graphs"))
```

Chuck

```
blog = linda.universe._rd(("MicroBlog",linda.TupleSpace))[1]

t1 = blog._rd(("bob","distsys",str))
t2 = blog._rd(("alice","gtcn",str))
t3 = blog._rd(("bob","gtcn",str))
```

Using legacy to build middleware

Problem

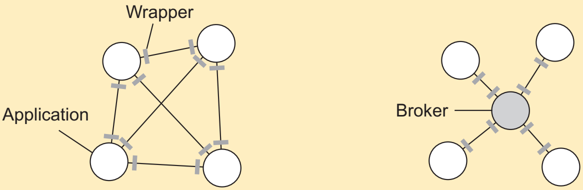
The interfaces offered by a legacy component are most likely not suitable for all applications.

Solution

A wrapper or adapter offers an interface acceptable to a client application. Its functions are transformed into those available at the component.

Organizing wrappers

Two solutions: 1-on-1 or through a broker



Complexity with N applications

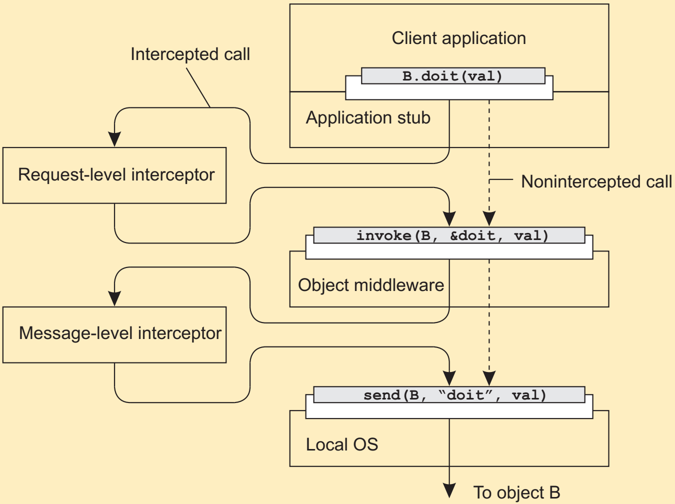
- 1-on-1: requires $N \times (N-1) = \mathscr{O}(N^2)$ wrappers
- broker: requires $2N = \mathscr{O}(N)$ wrappers

Developing adaptable middleware

Problem

Middleware contains solutions that are good for most applications ⇒ you may want to adapt its behavior for specific applications.

Intercept the usual flow of control

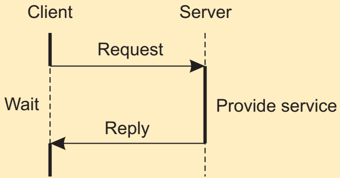


Centralized system architectures

Basic Client–Server Model

Characteristics:

- There are processes offering services (servers)
- There are processes that use services (clients)
- Clients and servers can be on different machines
- Clients follow request/reply model with respect to using services

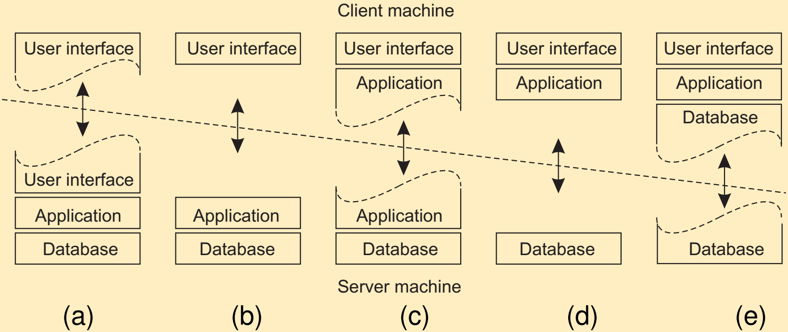


Multi-tiered centralized system architectures

Some traditional organizations

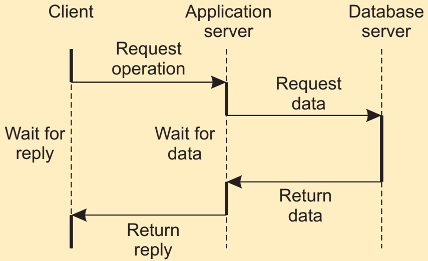
- Single-tiered: dumb terminal/mainframe configuration
- Two-tiered: client/single server configuration
- Three-tiered: each layer on separate machine

Traditional two-tiered configurations



Being client and server at the same time

Three-tiered architecture



Alternative organizations

Vertical distribution

Comes from dividing distributed applications into three logical layers, and running the components from each layer on a different server (machine).

Horizontal distribution

A client or server may be physically split up into logically equivalent parts, but each part is operating on its own share of the complete data set.

Peer-to-peer architectures

Processes are all equal: the functions that need to be carried out are represented by every process $\Rightarrow$ each process will act as a client and a server at the same time (i.e., acting as a servant).

Structured P2P

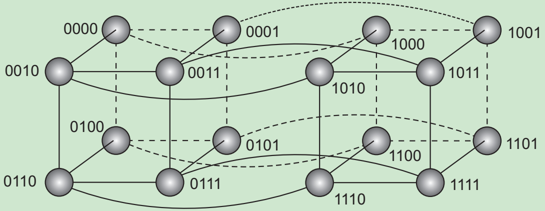
Essence

Make use of a semantic-free index: each data item is uniquely associated with a key, in turn used as an index. Common practice: use a hash function

$$key(data\ item) = hash(data\ item\text{'s}\ value).$$

P2P system now responsible for storing (*key*,*value*) pairs.

Simple example: hypercube



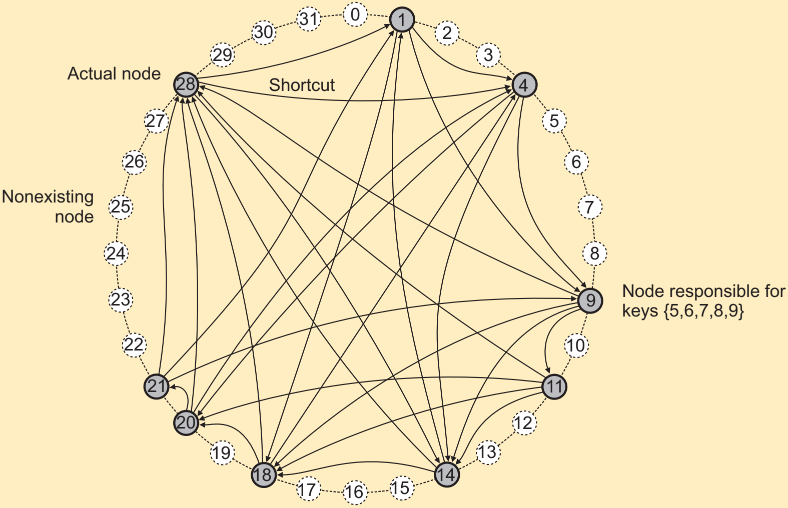
Looking up d with key $k \in \{0, 1, 2, \ldots, 2^4 - 1\}$ means routing request to node with identifier k.

Example: Chord

Principle

- Nodes are logically organized in a ring. Each node has an m-bit identifier.
- Each data item is hashed to an m-bit key.
- Data item with key k is stored at node with smallest identifier $id \geq k$, called the successor of key k.
- The ring is extended with various shortcut links to other nodes.

Example: Chord



lookup(3)@9 : $28 \to 1 \to 4$

Unstructured P2P

Essence

Each node maintains an ad hoc list of neighbors. The resulting overlay resembles a random graph: an edge $\langle u, v\rangle$ exists only with a certain probability $\mathbb{P}[\langle u, v\rangle]$.

Searching

- Flooding: issuing node *u* passes request for *d* to all neighbors. Request is ignored when receiving node had seen it before. Otherwise, *v* searches locally for *d* (recursively). May be limited by a Time-To-Live: a maximum number of hops.
- Random walk: issuing node *u* passes request for *d* to randomly chosen neighbor, *v*. If *v* does not have *d*, it forwards request to one of *its* randomly chosen neighbors, and so on.

Flooding versus random walk

Model

Assume N nodes and that each data item is replicated across r randomly chosen nodes.

Random walk

$\mathbb{P}[k]$ probability that item is found after k attempts:

$$\mathbb{P}[k] = \frac{r}{N}(1 - \frac{r}{N})^{k-1}.$$

S ("search size") is expected number of nodes that need to be probed:

$$S = \sum_{k=1}^{N} k \cdot \mathbb{P}[k] = \sum_{k=1}^{N} k \cdot \frac{r}{N}(1 - \frac{r}{N})^{k-1} \approx N/r \text{ for } 1 \ll r \leq N.$$

Flooding versus random walk

Flooding

- Flood to d randomly chosen neighbors
- After k steps, some $R(k) = d \cdot (d-1)^{k-1}$ will have been reached (assuming k is small).
- With fraction r/N nodes having data, if $\frac{r}{N} \cdot R(k) \geq 1$, we will have found the data item.

Comparison

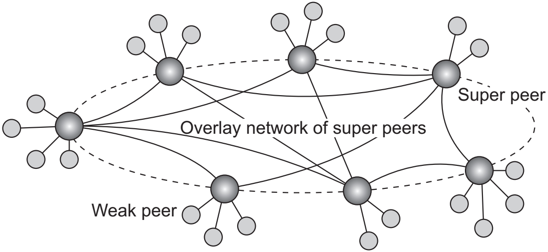
- If $r/N = 0.001$, then $S \approx 1000$
- With flooding and $d = 10, k = 4$, we contact 7290 nodes.
- Random walks are more communication efficient, but might take longer before they find the result.

Super-peer networks

Essence

It is sometimes sensible to break the symmetry in pure peer-to-peer networks:

- When searching in unstructured P2P systems, having index servers improves performance
- Deciding where to store data can often be done more efficiently through brokers.



Skype's principle operation: *A* wants to contact *B*

Both *A* and *B* are on the public Internet

- A TCP connection is set up between *A* and *B* for control packets.
- The actual call takes place using UDP packets between negotiated ports.

A operates behind a firewall, while *B* is on the public Internet

- *A* sets up a TCP connection (for control packets) to a super peer *S*
- *S* sets up a TCP connection (for relaying control packets) to *B*
- The actual call takes place through UDP and directly between *A* and *B*

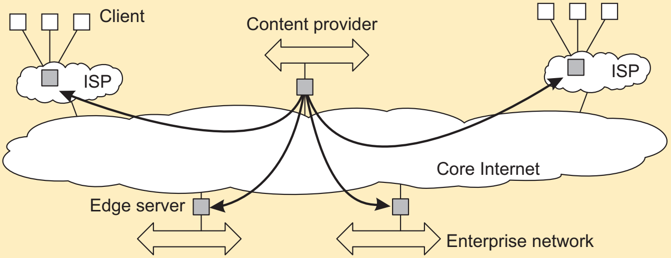
Both *A* and *B* operate behind a firewall

- *A* connects to an online super peer *S* through TCP
- *S* sets up TCP connection to *B*.
- For the actual call, another super peer is contacted to act as a relay *R*: *A* sets up a connection to *R*, and so will *B*.
- All voice traffic is forwarded over the two TCP connections, and through *R*.

Edge-server architecture

Essence

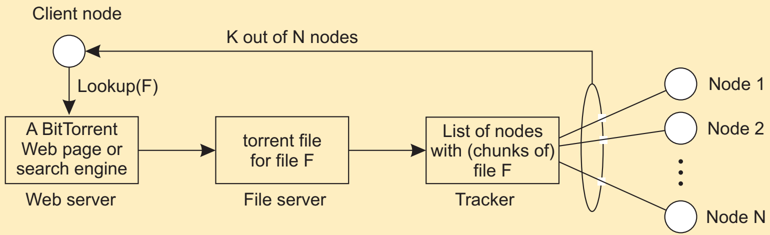
Systems deployed on the Internet where servers are placed at the edge of the network: the boundary between enterprise networks and the actual Internet.



Collaboration: The BitTorrent case

Principle: search for a file *F*

- Lookup file at a global directory ⇒ returns a torrent file
- Torrent file contains reference to tracker: a server keeping an accurate account of active nodes that have (chunks of) *F*.
- *P* can join swarm, get a chunk for free, and then trade a copy of that chunk for another one with a peer *Q* also in the swarm.



BitTorrent under the hood

Some essential details

- A tracker for file F returns the set of its downloading processes: the current swarm.
- A communicates only with a subset of the swarm: the neighbor set N_A.
- if $B \in N_A$ then also $A \in N_B$.
- Neighbor sets are regularly updated by the tracker

Exchange blocks

- A file is divided into equally sized pieces (typically each being 256 KB)
- Peers exchange blocks of pieces, typically some 16 KB.
- A can upload a block d of piece D, only if it has piece D.
- Neighbor B belongs to the potential set P_A of A, if B has a block that A needs.
- If $B \in P_A$ and $A \in P_B$: A and B are in a position that they can trade a block.

BitTorrent phases

Bootstrap phase

A has just received its first piece (through optimistic unchoking: a node from N_A unselfishly provides the blocks of a piece to get a newly arrived node started).

Trading phase

$|P_A| > 0$: there is (in principle) always a peer with whom A can trade.

Last download phase

$|P_A| = 0$: A is dependent on newly arriving peers in N_A in order to get the last missing pieces. N_A can change only through the tracker.

BitTorrent phases

Development of $|P|$ relative to $|N|$.