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Distributed System Architectures

Corso di Sistemi Distribuiti e Cloud Computing

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Laurea Magistrale in Ingegneria Informatica

Software vs. system architecture of DS

- **Software architecture**: logical organization and interaction of software components that constitute the DS
- **System architecture**: final instantiation (including deployment) of a software architecture
  - Software components need to be placed on system resources
  - E.g., a container containing a microservice needs to be instantiated on a machine
- Let's first focus on software architectures for DS

Architectural styles for DS

- Architectural style: set of design decisions concerning sw architecture
  - Mainly defined in terms of components and connectors
- Component
  - Modular unit with well-defined interfaces
  - Replaceable within its environment
- Connector
  - Mechanism for interaction among components, mediating communication, coordination or cooperation
  - Example: mechanisms for (remote) procedure call, messaging
- Plus:
  - How components are connected to each other
  - Data exchanged between components
  - How components and connectors are jointly configured into a system

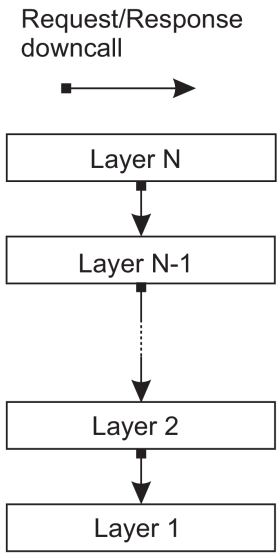
Main architectural styles for DS

- Layered style
- Service-oriented style
  - Object-oriented
  - Microservices
  - RESTful
- Publish-subscribe style

Layered style

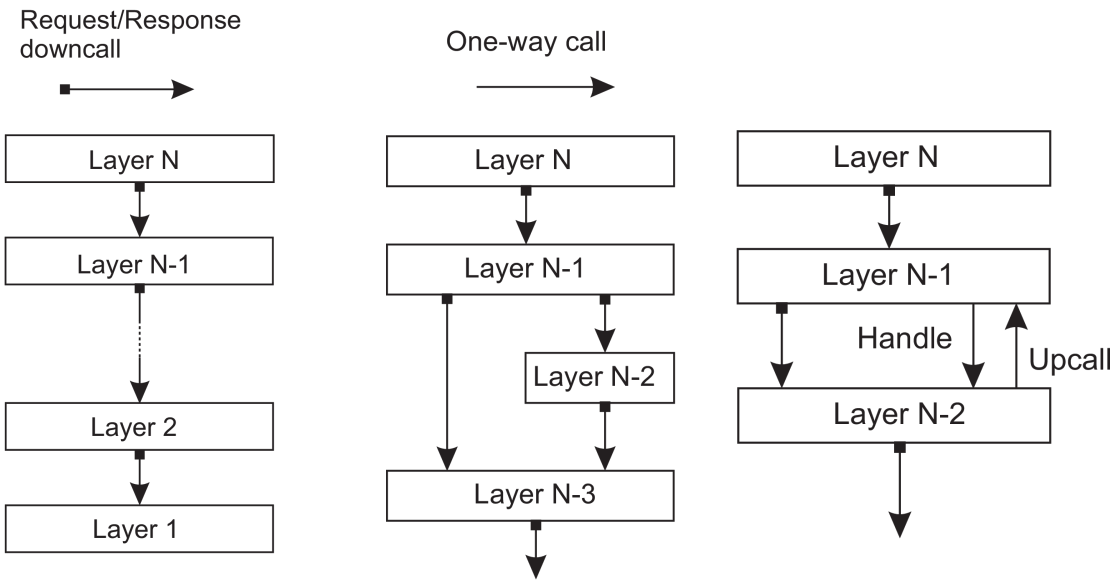
- Components are organized in *layers*
- Component at layer *i* invokes component at layer *j (with j<i)*
- Components communicate by message exchange
  - Request/response downcall

✓ Separation of concerns among components
  - E.g., web app based on MVC design



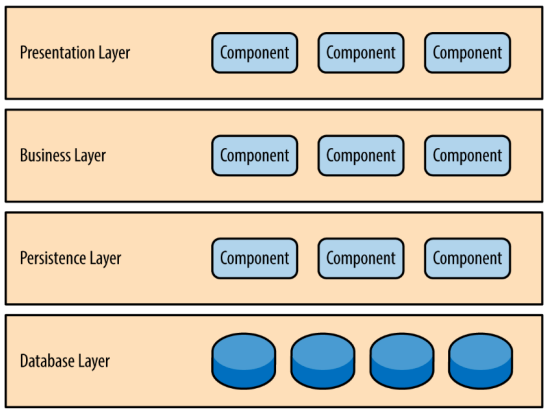
Layered style

- Different layered organizations



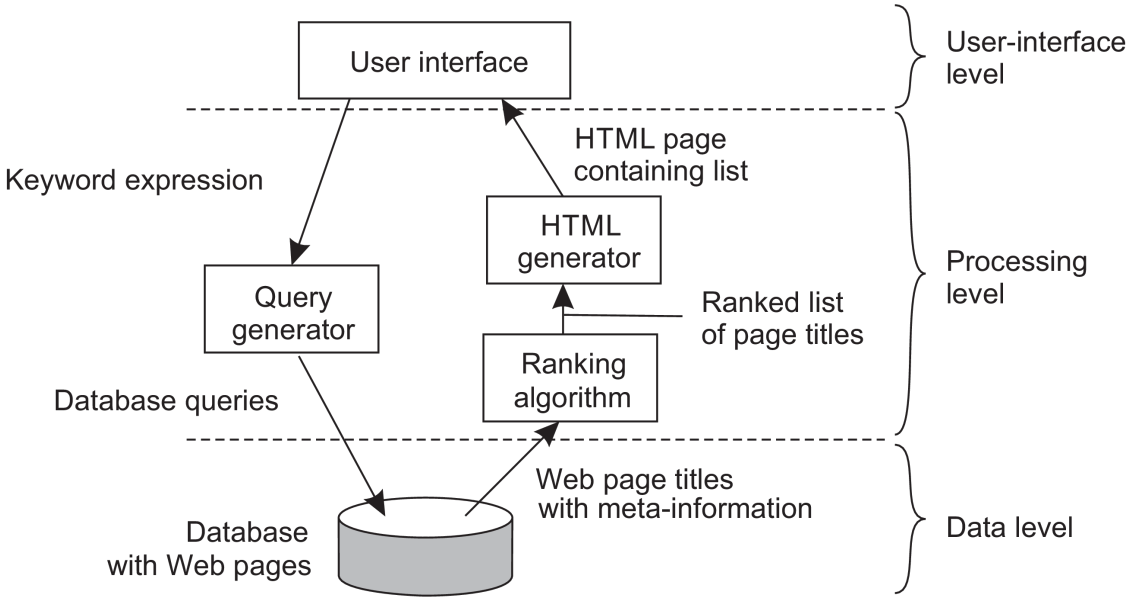
Application layering

- Traditional layered architecture: presentation, business, persistence, database
  - In some cases, business and persistence layers are combined into a single business layer
  - Found in many distributed information systems, using traditional DB technology and accompanying applications



Application layering: example

- A simple Web search engine

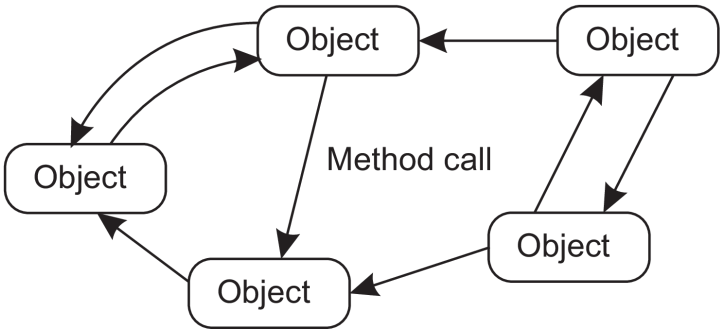


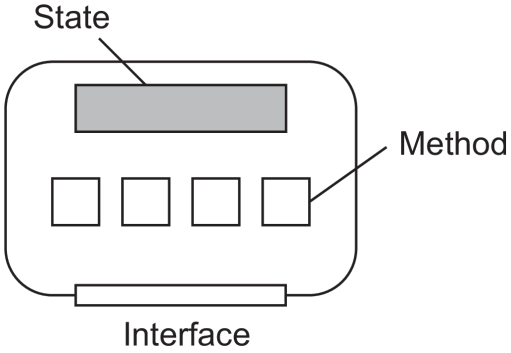
Service-oriented style

- A collection of separate, independent entities
- Each entity encapsulates a service
- Entity = service, object, or microservice
- Includes
  - Object-based architectural style
  - Microservices architectural style
  - RESTful architectural style

Object-based style

- Component = object: encapsulates data and offers methods on data
  - Encapsulation and information hiding reduce management complexity
  - Reusability among different apps
  - Wrapping of legacy components
- Communication between components through RPC



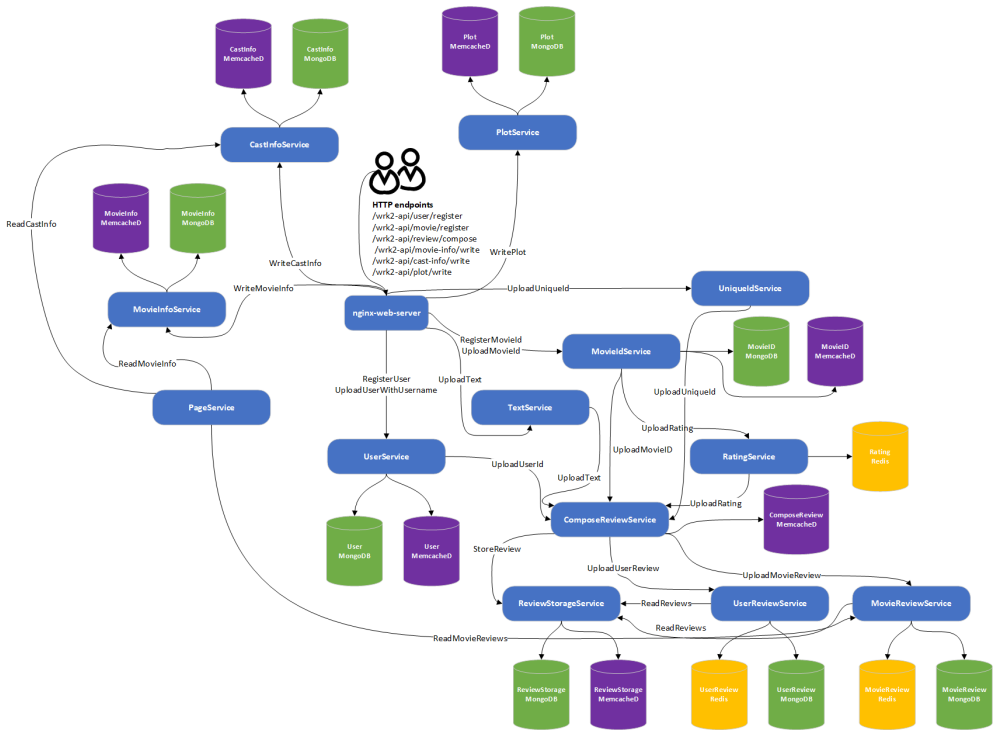


Microservices style

- A “new” emerging architectural style for distributed apps that structures an application as a collection of loosely coupled services
- Address how to build, manage, and evolve architectures out of small, self-contained and independently-scalable services that communicate over well-defined APIs
  - *Modularization*: decompose app into a set of independently deployable services, that are loosely coupled and cooperating and can be rapidly deployed and scaled
- See upcoming lessons

Microservices style: example

- A social-media microservice architecture



https://github.com/delimitrou/DeathStarBench

RESTful style

- DS as a collection of resources, individually managed by components
- **Representational State Transfer (REST)**: proposed by Roy Fielding, co-author of HTTP/1.1
  - Resources may be added, removed, retrieved, and modified by (remote) applications (HTTP methods)
  - Resources are identified through a single naming scheme (Uniform Resource Identifier, URI)

```
URI = scheme:[//authority]path[?query][#fragment]
authority = [userinfo@]host[:port]
```

- Components expose a uniform interface
- Messages sent to/from component are self-described
- Interactions are stateless
  - State must be transferred from clients to servers

REST operations

- Basic operations
  - Use HTTP methods: GET, PUT, POST and DELETE

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: S3 REST API

- S3: cloud storage service by AWS, organized as a key-based object store
- Objects (files) are stored into buckets (directories)
  - Flat structure: no directory hierarchy
    - Logical hierarchy simulated by using object names with directory structure: `photos/puppy.jpg`
  - Object *`objectname`* stored in bucket *`bucketname`* is uniquely referred to by its URI:
    `https://`*`bucketname`*`.s3.`*`Region`*`.amazonaws.com/`*`objectname`*
    e.g., `https://example-bucket.s3.us-west-2.amazonaws.com/photos/puppy.jpg`
- Operations carried out through HTTP requests:
  - Create bucket/object: `PUT`, along with its URI
  - List objects in bucket: `GET` on bucket
  - Read object: `GET` on full URI

Example: S3 REST API

- Retrieve object from bucket (`GetObject`)

```
GET /photos/puppy.jpg HTTP/1.1
Host: example-bucket.s3.us-west-2.amazonaws.com
Date: date
Authorization: authorization string
```

- Add object to bucket (`PutObject`)

```
PUT /photos/puppy.jpg HTTP/1.1
Host: example-bucket.s3.us-west-2.amazonaws.com
Date: date
Authorization: authorization string
```

See Amazon S3 REST API
https://docs.aws.amazon.com/AmazonS3/latest/API/Welcome.html

Notes:

- HTTP Authorization header to authenticate S3 request
- You need permission for operations (e.g., WRITE permission on bucket): use IAM to create roles and manage permissions

Decoupling

- Strong dependencies between components introduce limitations
- Solution: let components indirectly communicate through some intermediary
  - Clean separation between computation and coordination

"All problems in computer science can be solved by another level of indirection"

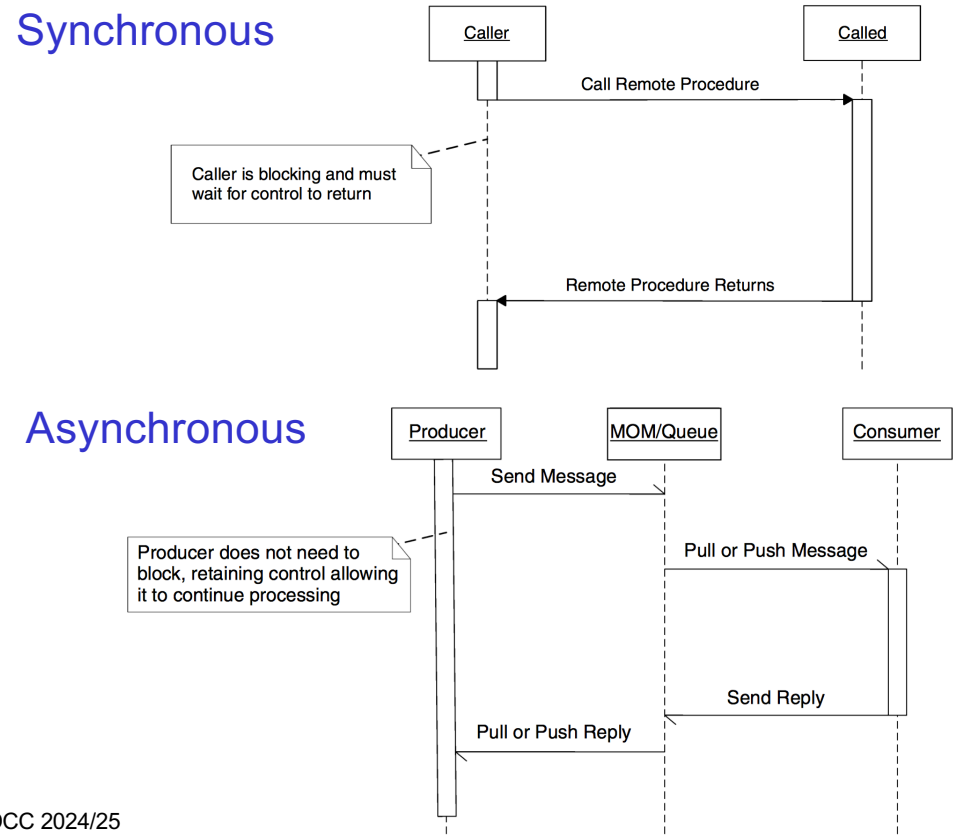
(David Wheeler, Titan project)

- **Decoupling**: enabling factor to
  - Achieve greater flexibility
  - Define architectural styles that allow to better exploit distribution, scalability, and elasticity

Decoupling properties

- ***Space*** (or referential) decoupling
  - Anonymous components: do not need to know each other in order to communicate and cooperate
- ***Time*** (or temporal) decoupling
  - Interacting components do not need to be present at the same time when communication occurs
- ***Synchronization*** decoupling
  - Interacting components do not need to wait each other and are not reciprocally blocked

Synchronous vs. asynchronous interaction



Decoupling: pros and cons

✓ Thanks to decoupling, DS can be flexible while dealing with changes and provide more dependable and elastic services

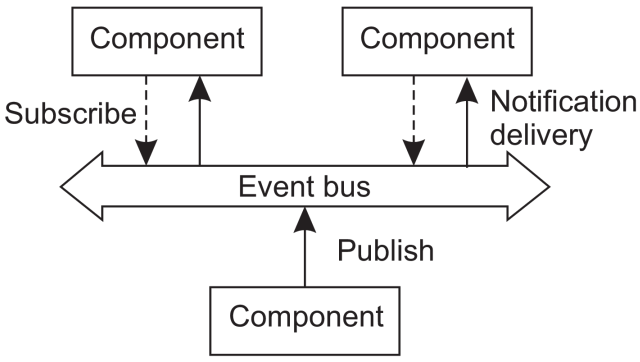
- Space decoupling: components can be replaced, updated, replicated or migrated
- Time decoupling: allows to manage volatility (senders and receivers can come and go)
- Synchronization decoupling: no blocking

✗ Indirection can add performance overhead

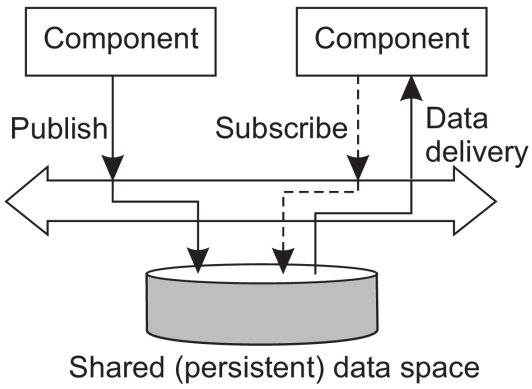
Architectural style evolution

- Introducing decoupling, alternative architectural styles where components communicate indirectly

Event-driven



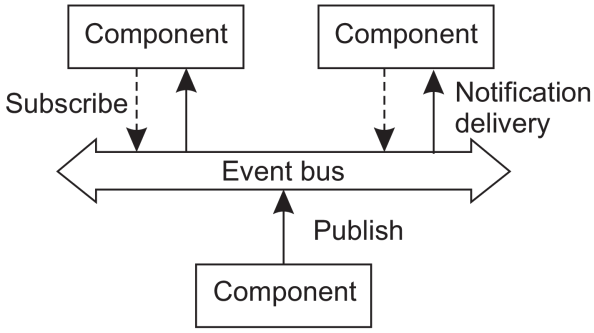
Data-oriented



Publish-subscribe

Event-driven style

- Components communicate through an event bus
  - Event: significant change in state (e.g., change in temperature, door opening)
- Components
  - Publish events
  - Subscribe to events they are interested in being notified
  - Receive notifications about events
- Communication
  - Anonymous
  - Based on message exchange
  - Asynchronous
  - Multicast

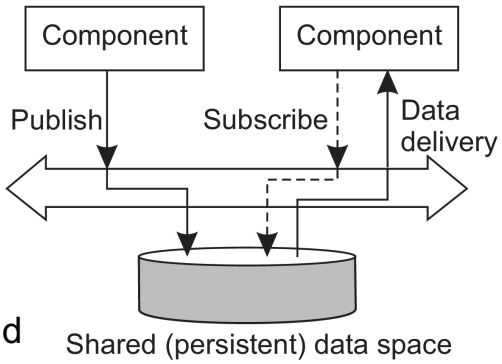


- Example: Java Swing

Which decoupling?

Data-oriented style

- Communication among components happens through shared data space: passive, sometimes (pro)active
  - Data added to or removed from shared space
- Shared data space API
  - `write`, `take`, `read` and variants (`takeIfExists`, `readIfExists`)
  - If active space: `notify` or `push` (avoid polling)
  - Concurrency control
- Examples of shared data spaces
  - GigaSpaces https://tinyurl.com/bdtc5yk6, TIBCO ActiveSpaces https://tinyurl.com/bkkxm768

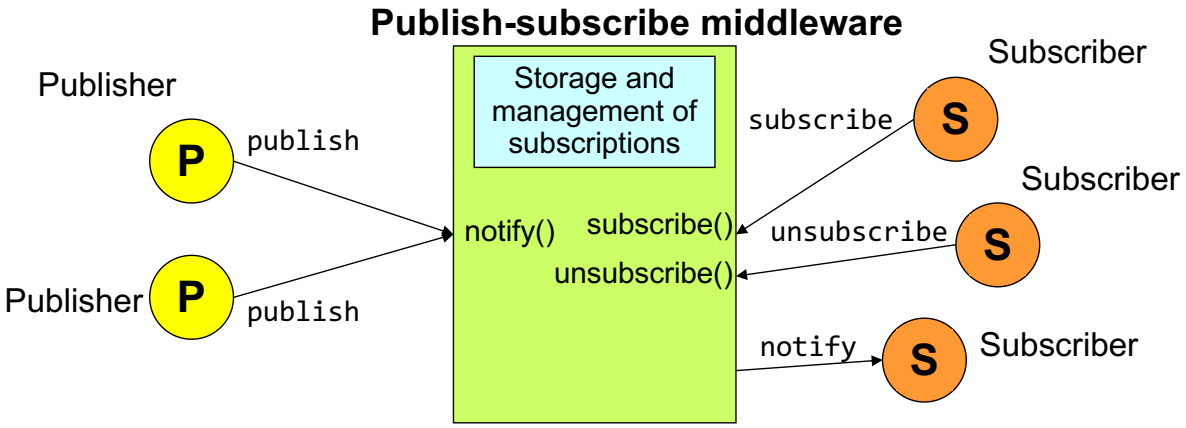


Which decoupling?

How to implement shared space?

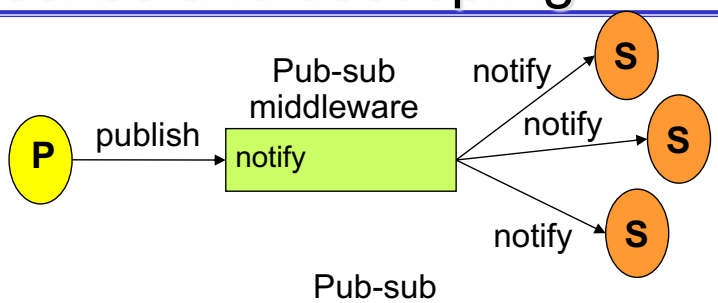
Publish-subscribe style

- Publishers (aka producers) generate events (`publish`) and are not interested in their delivery to subscribers (aka consumers)
- Consumers register as interested to events (`subscribe`) and are notified (`notify`) of their occurrence
- Full decoupling among components

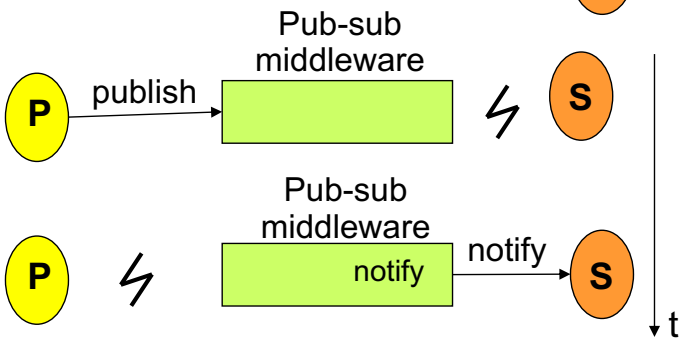


Publish-subscribe and decoupling

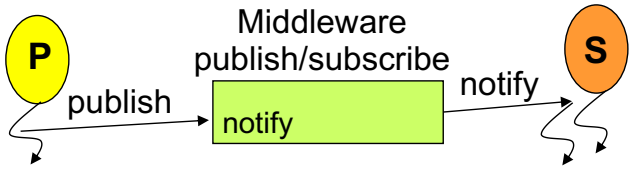
Space decoupling



Time decoupling



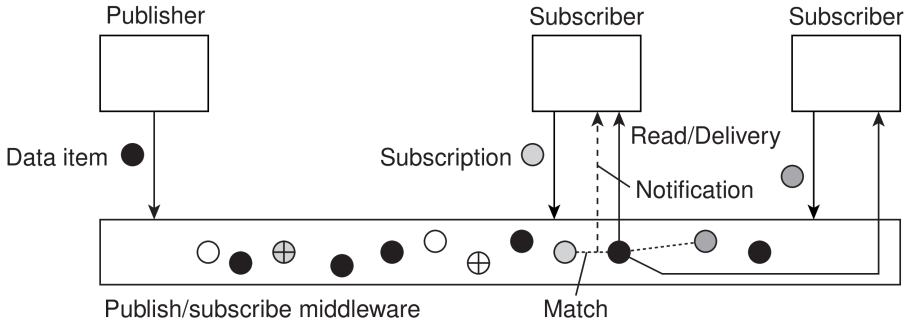
Synchronization decoupling



Eugster et al., The many faces of publish/subscribe, *ACM Comput. Surv.*, 2003

Publish-subscribe: subscription

- Issue: how to match events
  - Assume events are described by (attribute,value) pairs



- Topic-based subscription
  - Specify a "attribute = value" series
  - ✗ Expressiveness is limited
- Content-based subscription
  - Specify a "attribute ∈ range" series, i.e., subscribers specify filters
  - ✗ May easily have serious scalability problems, why?

Choosing an architectural style

- No single solution: can tackle same problem with different architectural styles

- Choice depends often on extra-functional requirements:
  - Costs (resource usage, development effort needed)
  - Scalability and elasticity (effects of scaling and amount of available resources)
  - Performance (e.g., response time, latency)
  - Reliability and fault tolerance
  - Maintainability (extending system with new components)
  - Usability (ease of configuration and usage)
  - Reusability

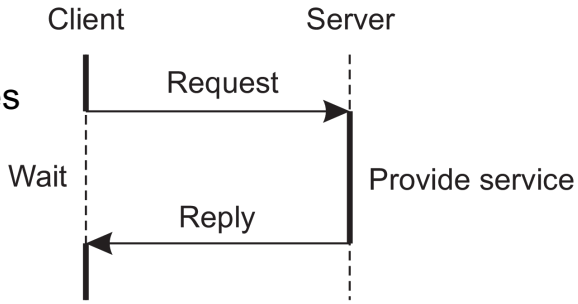
System architecture of DS

- Runtime instantiation of DS software architecture
  - Which components?
  - How do they interact with each other?
  - Where to deploy them?

- Types of system architectures
  - Centralized architectures
  - Decentralized architectures
  - Hybrid architectures

Centralized system architectures

- Basic client-server model
  - Two groups: servers offer services and clients use services
  - Clients and servers can be on different machines
  - E.g., Web clients and servers



- Request/reply model
- Communication
  - based on message exchange
  - often *synchronous* and *blocking*
- Strong coupling: e.g., coexistence of interacting entities

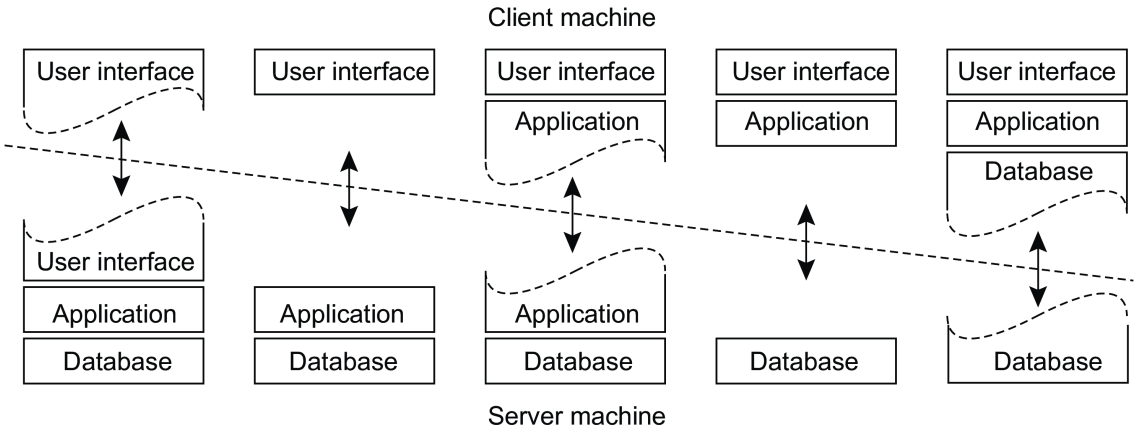
Multi-tiered client-server architectures

- How to map logical levels (***layers***) into physical levels (***tiers***)?
  - Two-tiered architectures
  - Three-tiered architectures

- Different configurations, depending on distribution of:
  1. presentation layer
  2. logic (aka application, business, processing) layer
  3. data layer

Multi-tiered client-server architectures

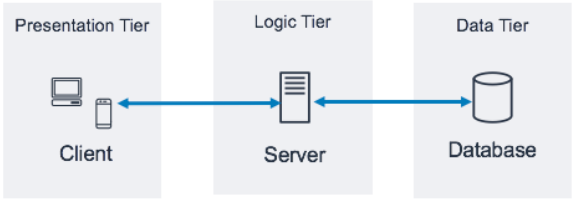
- Example: two-tiered configurations



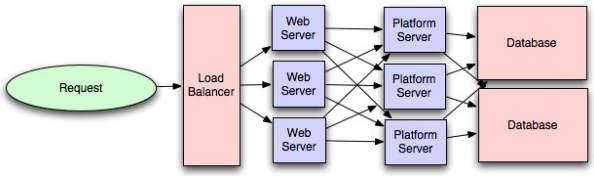
- More than three tiers?

From multi-tiered architectures to…

- Vertical distribution
  - Divide distributed applications into 3 logical layers and run each layer on a different tier

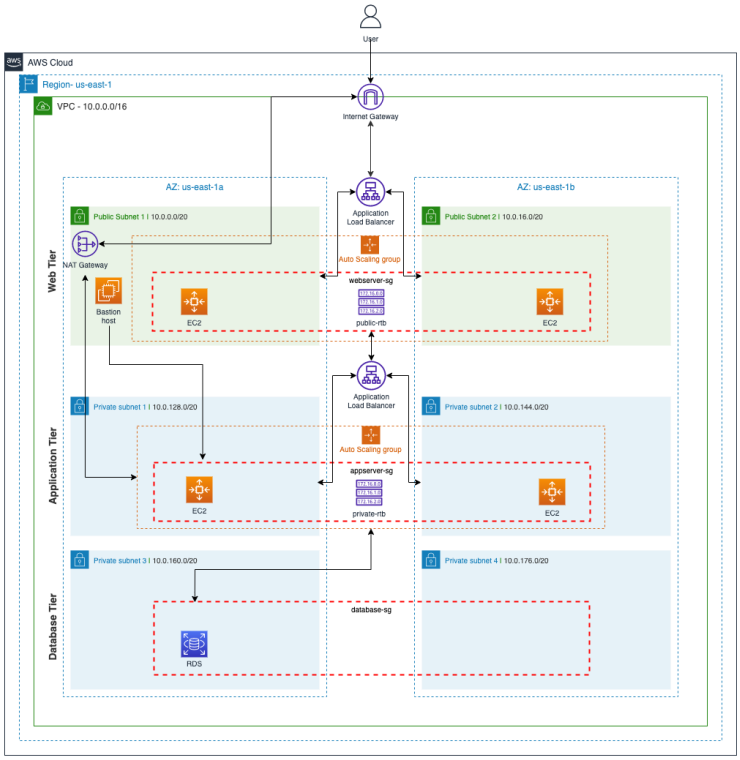


- Horizontal distribution
  - Distribute each layer on multiple servers
  - Balance load among multiple servers through a load balancer
  - E.g.,: distributed Web cluster



Example: Web application in AWS

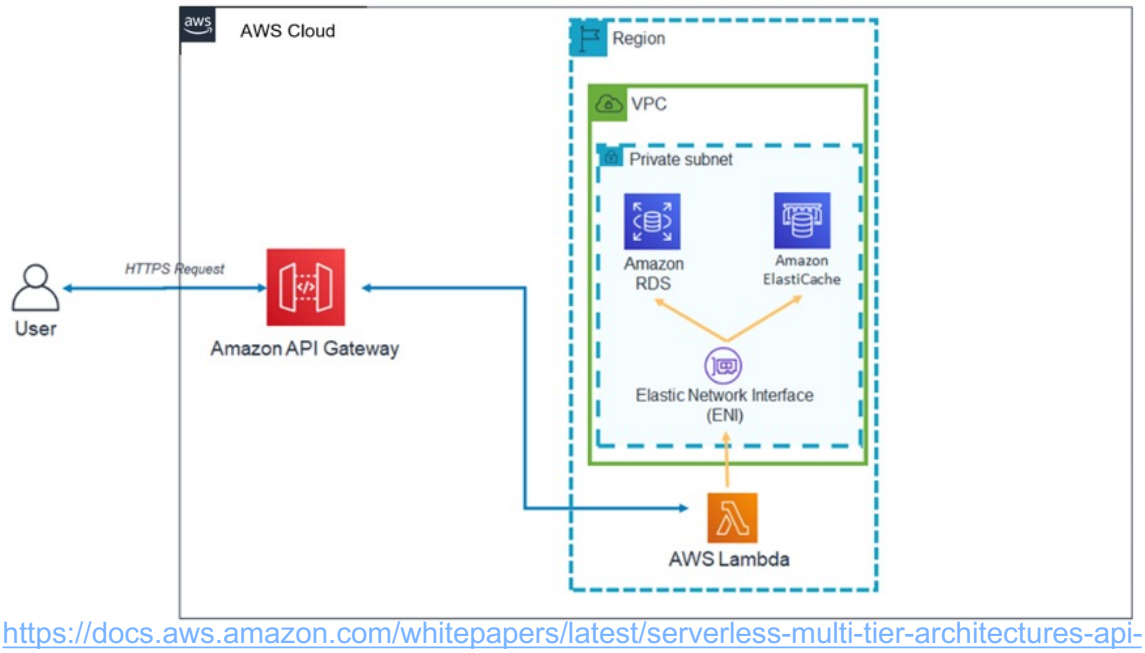
- Web application with horizontal distribution in AWS
  - Elasticity: tiers can scale out/in
  - High availability: replication in different availability zones
  - Security: tiers communicate with private IP



https://medium.com/@aaloktrivedi/building-a-3-tier-web-application-architecture-with-aws-eb5981613e30

Example: 3-tier serverless architecture

- Horizontal distribution is not visible: AWS Lambda has elastic scalability already built in



https://docs.aws.amazon.com/whitepapers/latest/serverless-multi-tier-architectures-api-gateway-lambda/three-tier-architecture-overview.html

Decentralized system architectures

- **Peer-to-peer** (P2P) systems

- P2P: class of systems and applications that use distributed resources to perform functions (even critical) in a decentralized way
  - "P2P is a class of applications that takes advantage of resources available at the edges of the Internet" (Shirny, 2000)
- Shared resources: files, storage space, computing power, bandwidth
  - Give and receive resources from community of peers

P2P systems: features

- Peers are roughly symmetric in roles, privileges and responsibilities
  - Autonomous nodes located at network edge
  - With the exception of super-peer (more functionalities than other nodes)
- No centralized control
  - A peer behaves as client and server and shares resources and services (symmetric functionality: *servent* = server + client)
- Highly distributed
  - Up to hundreds of thousands of nodes
  - Highly dynamic and autonomous nodes
    - Node can enter or exit the P2P network at any time (join/leave operations)
  - Redundancy of information

P2P: applications

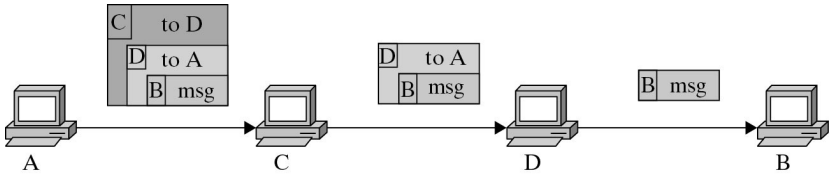
- Content distribution and storage
  - Content: file, video streaming, …
  - Networks, protocols and clients for *file sharing* (P2P “killer application”): Gnutella, eMule, Kademlia, BitTorrent, uTorrent, …
  - Video streaming: PPLive, …
  - File storage: Freenet, …
- Computing resource sharing
  - SETI@home (search for extraterrestrial intelligence), Folding@home (protein folding)
- Voice/video telephony
  - e.g., Chat/IRC, Instant Messaging, XMPP, Skype, …
- Blockchain

P2P: challenges

- Heterogeneity in peer resources
  - Hardware, software and network heterogeneity
- Scalability
  - System scaling related to performance and bandwidth
- Location
  - Data location, data locality, network proximity, and interoperability
- Fault tolerance
  - Failure management
- Performance
  - Routing efficiency, load balancing, self-organization
- Free-riding avoidance
  - Free-rider: selfish peer, unwilling to contribute anything

P2P: challenges

- Anonymity and privacy
  - *Onion routing* for anonymous communications



- Trust and reputation management
  - Lack of trust among peers who are unknown to each other
- Network threats and defense against attacks
- Churn resilience
  - Peers come, leave and even fail at random
  - Resources are dynamically added or removed

Main tasks of a P2P node

- Let's consider file sharing
- P2P node performs the operations:

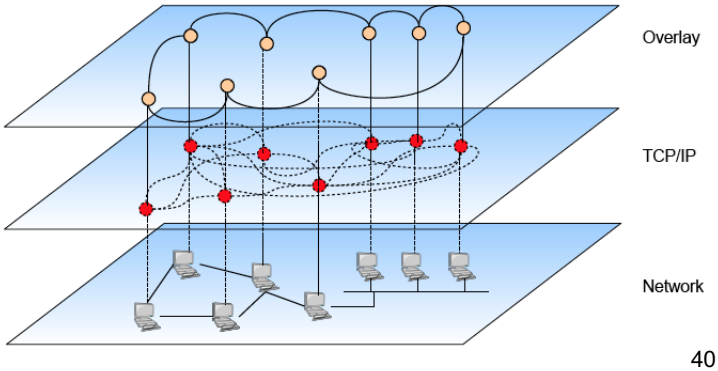
1. Bootstrap: how a new peer who intends to join a P2P system discover contact information for other peers in the network
   - Solutions: static configuration, pre-existing caches, well-known nodes
2. Resource lookup: how to locate resources
3. Resource retrieval: how to get localized resource

- We focus on resource lookup

P2P overlay

- P2P networks are commonly called overlays
- **Overlay network**: logical network connecting peers laid over the IP network
  - Based on underlying physical network
  - Logical links between peers, not corresponding to physical connections
  - Provides a resource location service by means of application-level routing

Application-level abstraction



Overlay routing

- Basic idea:
  - The P2P system finds the path to reach a resource
- Compared to traditional routing
  - Resource: no network node address, but files, available CPUs, free disk space, ...
- We focus on routing
- Once resource has been localized, easy to retrieve it
  - Retrieval typically occurs with a direct interaction between peers, e.g., using HTTP

Tasks of overlay network

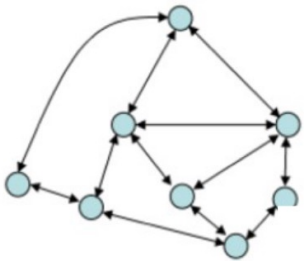
- Besides routing of requests to resources, an overlay network also allows to:
  - Insert and delete resources
  - Add and remove nodes
  - Identify resources and nodes

- How to identify resources?
  - Globally Unique IDentifier (GUID): obtained by applying a secure hash function to some of (or all) resource's state
- How to identify peers?
  - Again, usually computed through a secure hash function

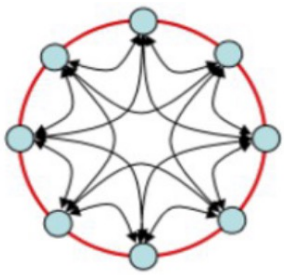
P2P overlay classification

- How to manage resources and nodes?
  - Depends on overlay network's type

Unstructured overlay networks



Structured overlay networks

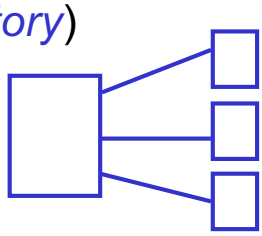


Unstructured overlay network

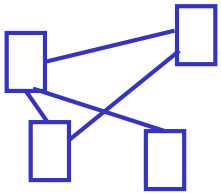
- Overlay network built on random graphs
  - No structure of overlay network *by design*
  - Peers are arbitrarily connected: each peer joins the network following some simple and local rule
  - A joining node contacts a set of neighbors, somehow selected
  - No control over resource placement on nodes
- Goal: manage nodes with highly dynamic behavior
- Examples: Gnutella, Bitcoin
- Pros and cons:
  - ✓ Easy maintenance because insertion and deletion of nodes and resources are easily managed
  - ✓ Highly resilient
  - ✗ High lookup cost: resource location is complicated by the lack of structure

Unstructured overlay network: routing

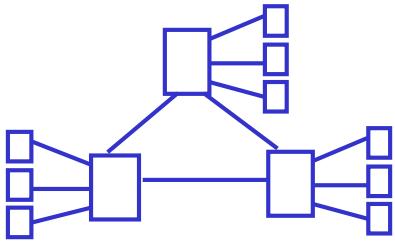
- Let's classify unstructured overlays according to distribution of peer-resource index (*directory*)
- Centralized unstructured overlay: central directory (e.g., Napster)



- Decentralized unstructured overlay: distributed directory (e.g., Gnutella)



- Hybrid unstructured overlay: semi-centralized directory
  - Routing limited to *super-peers*

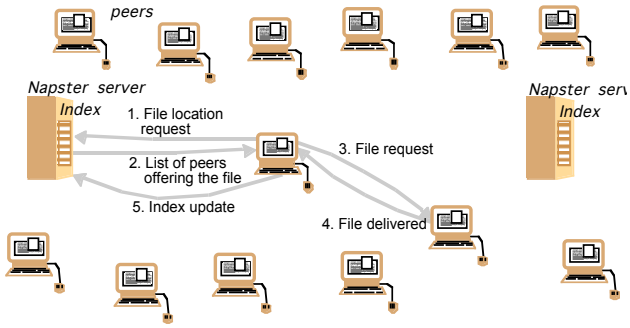


Centralized unstructured overlay

- Directory server responsible for resource-peer index: lookup(resource name) → {list of peers}

✓ Simple: search is centralized on a single directory server

✓ Directory server is a single point of control: provides definitive answer to query



✗ Expensive management of centralized directory

✗ Single directory server: performance bottleneck (limited scalability) and SPOF (technical and legal reasons)

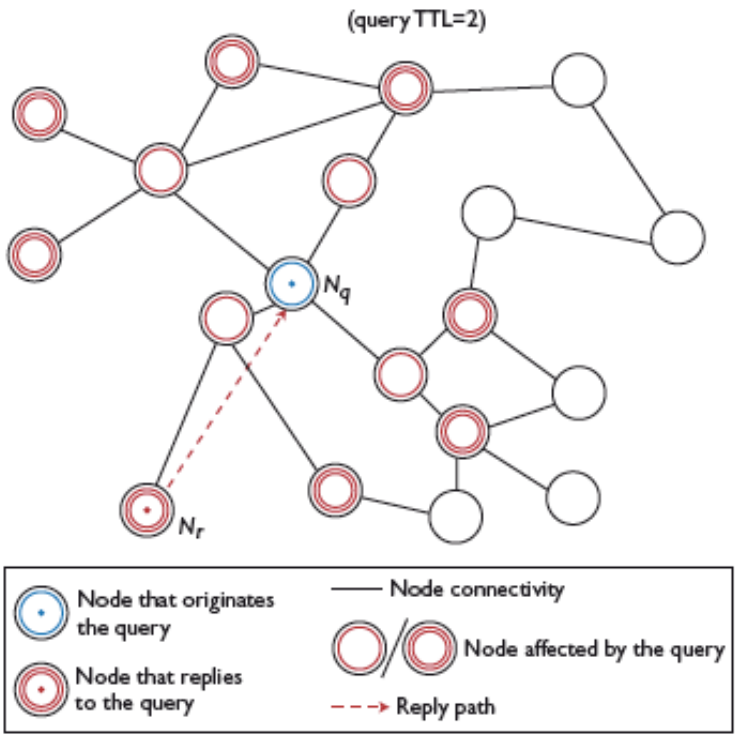
Decentralized unstructured overlay

- Fully decentralized approach to lookup resources
- How to lookup resources?
  - Query flooding
  - Random walk
  - Gossiping (upcoming lesson)

Query flooding

- Originator sends lookup query to its neighboring peers
- Each peer either responds if it owns the resource or forwards the query to its neighbors (excluding the neighbor from whom it received the query)
- Optimization #1: avoid indefinite query forwarding
  - Use Time-to-Live (TTL) to limit search range
  - At each forwarding, decrease TTL by 1; when TTL=0, lookup query is no longer forwarded
- Optimization #2: avoid cyclic paths
  - Assign unique query ID so to not process lookup query again
- Lookup cost: O(*N*), *N* = number of nodes in P2P network

Query flooding: example



Query flooding

- Options for sending response back to query originator

1. Direct routing: from peer that owns the resource to query originator
2. Backward routing
   - Response is forwarded back along the same path followed by lookup query until it reaches its originator
   - Query ID can be used to locate backward path
   - Which pros wrt direct routing?

Query flooding: cons

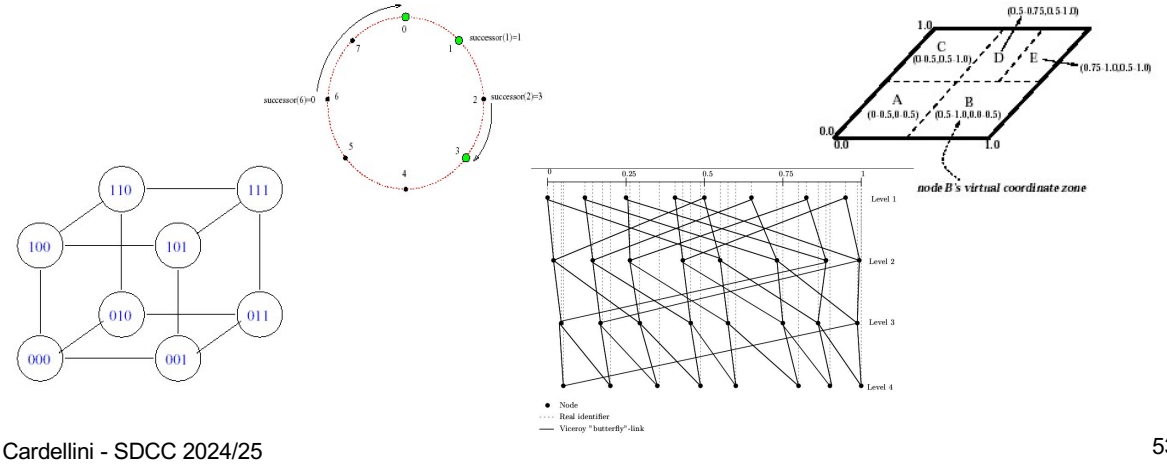
- Communication overhead
  - Large number of messages
  - Unsuccessful messages consume network bandwidth
- High lookup cost
  - How to choose TTL value?
- Denial-of-service attacks are possible
  - Black-hole nodes in case of congestion
- False negatives
  - No guarantee that (all) nodes that own the resource will be queried
- Lack of relationship between overlay and physical network topology
  - How far apart are “neighbor” peers?

Random walk

- In standard random walk, the originator forwards the lookup query to one randomly chosen neighbor
  - This neighbor randomly chooses one of its neighbors and forwards the request to that neighbor
  - This procedure continues until the resource is found
- With respect to flooding
  - ✓ Message traffic is cut down
  - ✗ Lookup time increases
- To decrease lookup time, the querying peer can start *k* random walks simultaneously
  - With *k* random walks the originator forwards *k* copies of the query to *k* randomly selected neighbors
  - Then, each request takes its own random walk

Structured overlay networks

- Lookup query is forwarded using a well-defined set of information about other peers in the network
- Overlay network is structured
  - Constraints on how resources and peers are positioned on network
  - Overlay network topology: ring, tree, hypercube, grid, ...

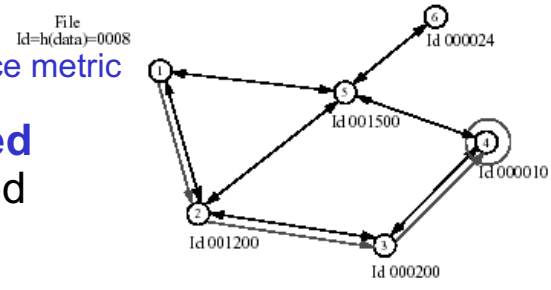


Structured overlay networks

- Goals: improve scalability by lowering lookup cost and reduce communication overhead with respect to unstructured overlays
  - Efficient key-based resource lookup
    - Overlay structure keeps lookup cost limited
  - Complexity guarantees also for peer join and leave
- Cons: peer join and leave become more expensive operations
  - Topology structure must be maintained

Routing in structured overlays

- Basic ideas
  - Each peer is responsible for some resources and knows some peers according to the overlay structure
  - Each resource is assigned a GUID
  - Each peer is assigned a GUID
  - GUIDs are computed using a hash function
  - Same large identifier space used for peers and resources GUIDs
  - Lookup query is routed to the peer whose GUID is the "closest" to the resource GUID
    - Closest: according to some distance metric
- Routing is based on **Distributed Hash Table (DHT)**: a distributed key-value data store

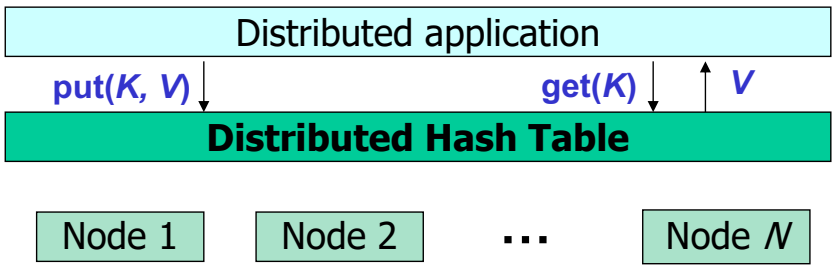


Distributed Hash Table

- Distributed abstraction of conventional hash table (HT) that maps keys to values
- Recall conventional HT
  - Table of *(key, value)* tuples of size *M*
  - Key lookup: hash function maps *keys* to range *0 ... M*-1
  - Lookup is very efficient: O(1)
  - Need to handle collisions because multiple keys may hash to same value
- DHT
  - Lookup similar to conventional HT: map resource key to find bucket (or slot) containing that resource
  - But DHT buckets are spread across multiple nodes (peers): how to map resource key to find the peer responsible of the bucket?

Distributed Hash Table: API

- Key-value pairs (key *K*, value *V*) stored in DHT
  - *K* is the key that identifies the resource (contained in *V*) and corresponds to the resource GUID
- API for accessing DHT (common to many DHT-based systems)
  - *V* = **get**(*K*): retrieve *V* associated with *K* from the node that stores it
  - **put**(*K*, *V*): store the resource *V* in the node responsible for the resource identified by *K*
  - **remove**(*K*): delete the reference to *K* and the associated *V*



Why might DHT design be hard?

- Decentralized: no central authority
- Scalable: low network traffic overhead
- Efficient: find items quickly (latency)
- Dynamic: nodes fail, new nodes join

Designing a DHT

- Resources and nodes are mapped onto the same identifier space using a hash function
  - GUID composed of *m* bits (usually *m* = 128 or 160)
  - E.g., SHA-1 cryptographic hash function
  - Hash function applied on metadata and/or data of resources (name, creation date, content, ...) and nodes
- Resources are partitioned among nodes: each node manages a portion of the resources stored in DHT
  - Each node is assigned a contiguous portion of keys and stores information about resources mapped to its own portion of keys
- Routing in DHT: given *K*, map it into the GUID of the node "closest" to *K*
- Resource replication can be exploited to improve availability

Issues related to DHTs

- Avoid hotspots by evenly distributing key responsibility among peers
- Avoid remapping all keys if DHT size changes (i.e., when peers join or leave)
  - **Consistent hashing** to address these issues

- Only directly support *exact-match* search
  - Since each resource is identified only by its key, to lookup for a resource we need to know its key
  - Easy to make exact-match search queries, e.g. based on resource name
  - Difficult and expensive to support more complex queries
    - E.g., wildcard query, range query
  - We will consider only exact-match

P2P systems based on DHTs

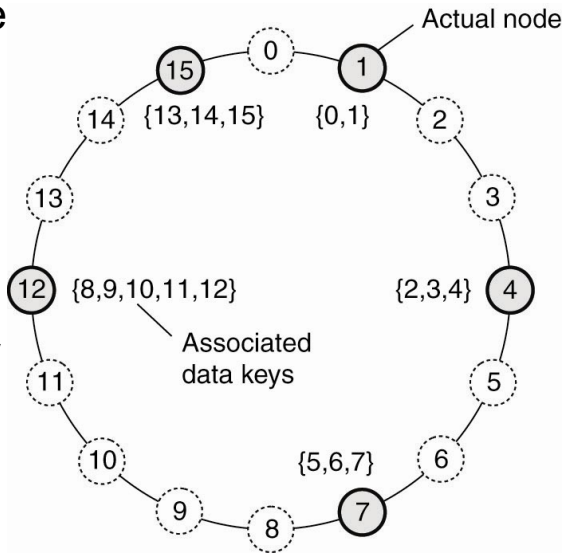
- Characterized by high scalability with respect to system size (i.e., *N*)
- Several proposals for DHT-based P2P systems
  - How do they differ?
    1. Definition of identifier space (and therefore network topology)
    2. Selection of peers to communicate with (i.e., distance metric)
  - More than 20 protocols and implementations for structured P2P networks, including:
    - **Chord** (MIT)
    - Pastry (Rice Univ., Microsoft)
    - Tapestry (Berkeley Univ.)
    - CAN (Berkeley Univ.)
    - Kademlia (NY Univ.)

Why Chord?

- Elegant resource lookup algorithm for DHT
- Efficient: O(log *N*) message per lookup
- Scalable: O(log *N*) state per node
- Robust: survives massive failures
- Simple to analyze

Chord https://github.com/sit/dht/wiki

- Nodes (peers) and resources are mapped onto a **ring** using **consistent hashing**
- Each node is responsible for the keys placed between itself and the preceding node in counter-clockwise direction
  - Resource with key *K* is managed by the node whose identifier is the smallest id ≥ *K*
  - This node is called *succ*(*K*), ***successor*** of key *K*
    - E.g., *succ*(1)=1, *succ*(10)=12



- Distance metric: based on linear difference between identifiers

Stoica et al., Chord: A Scalable Peer-to-peer Lookup Protocol for Internet Applications, IEEE/ACM TON, 2003

Consistent hashing

- A special hashing technique
  - Both items (resources) and buckets (nodes) are uniformly mapped on the same identifier space (ring) using a standard hash function (e.g., SHA-1, MD5)
  - Each node manages an interval of consecutive hash keys, not a set of sparse keys
- Original devised by Karger et al. at MIT for distributed caching

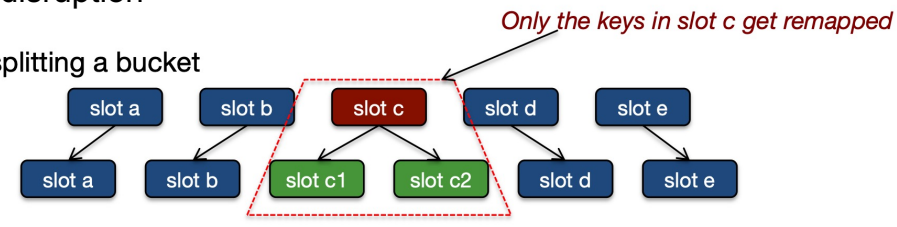
  Consistent hashing and random trees: Distributed caching protocols for relieving hot spots on the World Wide Web, STOC 1997
- Gave birth to Akamai https://www.akamai.com/
- Some details and Java implementation

  https://tom-e-white.com/2007/11/consistent-hashing.html
- Repurposed for new technologies and largely used in real systems, e.g., Amazon Dynamo and Memcached https://memcached.org

Chord: consistent hashing

- Consistent hashing is integral to Chord robustness and performance
  1. In case of DHT resizing (adding or removing a bucket): most keys will hash to the same bucket as before
     - Practical impact: peers can join and leave the network with minimal disruption

Example: splitting a bucket



  2. All buckets get roughly the same number of keys: load balancing among nodes

Chord: towards routing

- The simplest approach: lookup can be performed by traversing the ring, going one node at a time
- Can we do better than O(*N*) lookup?

- Simple approach for great performance
  - Have all nodes know about each other
    - When a peer gets a query, it searches its table of nodes for the node that owns that key
    - Gives us O(1) performance
  - Join/leave node operations must inform everyone
  - Maybe not a good solution if we have lots of peers (large tables)

- Chord uses a compromise to avoid large tables at each node: **finger table**
  - A partial list of nodes, progressively more distant

Chord: finger table

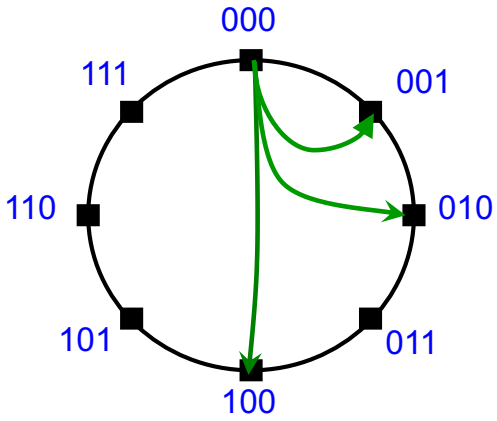
- Finger table (FT): routing table of each node
  - FT has *m* rows, with *m* = # GUID bits
  - If FT_p is the FT of node *p*, then $FT_p[i] = succ(p + 2^{i-1}) \bmod 2^m$, $1 \le i \le m$
    - $succ(p+1)$, $succ(p+2)$, $succ(p+4)$, $succ(p+8)$, $succ(p+16)$, …

- Example with *m*=3
  - Finger table of node 0?

$FT_0[1]=0+2^0=1$

$FT_0[2]=0+2^1=2$

$FT_0[3]=0+2^2=4$



Chord: FT's characteristics

- Each node stores information about only a small number of other nodes
  - Only *m* rows
- Each node knows more about nodes closely following it than about nodes farther away
- However, a node's FT generally does not contain enough information to directly determine the successor of any key
  - We need a routing algorithm to map each key *K* into *succ*(*K*)

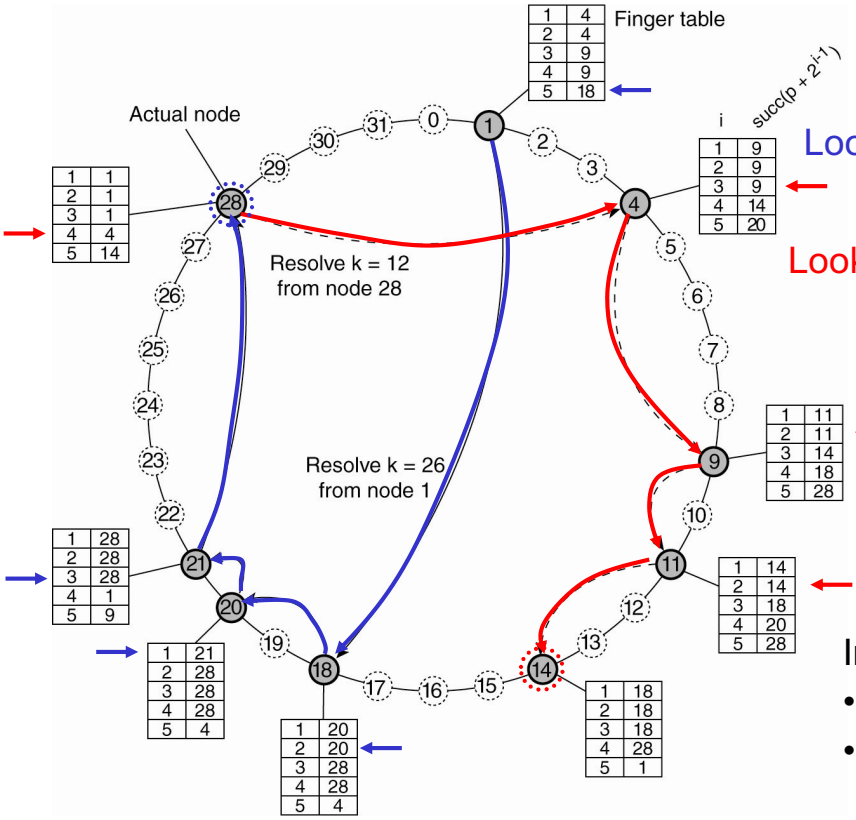
Chord: routing algorithm

- How to map key *K* into *succ*(*K*) starting from node *p*
  - If *K* belongs to the ring portion managed by *p*, lookup ends
  - If $p < K \leq FT_p[1]$, p forwards the request to its successor
  - Else *p* forwards the request to node *q* with index *j* in FT_p by considering the clockwise ordering

    $$FT_p[j] \leq K < FT_p[j+1]$$

    q is the farthest node from *p* whose key is less than or equal to *K*
- Features
  - It quickly reaches the vicinity of the searched point, and then proceeds with gradually smaller jumps
  - Lookup cost: O(log *N*), being *N* the number of nodes
    … not as cool as O(1) but way better than O(*N*)

Chord: routing algorithm example

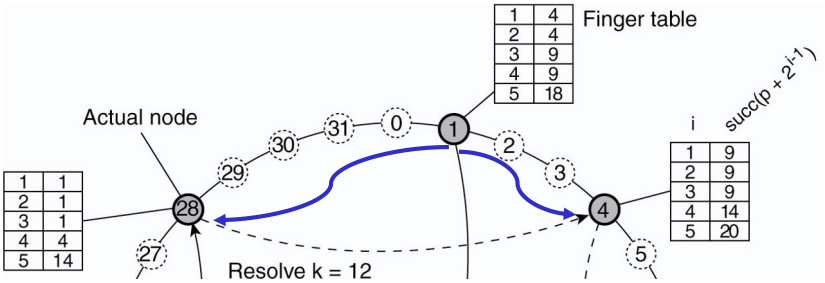


In the example:

- m=5
- Keys from 0 to 2^5-1

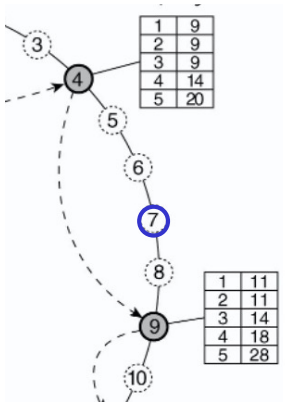
Chord: node join and leave

- In addition to successor pointer, each node also keeps the pointer to its predecessor (i.e., linked list) so to simplify ring maintenance operations
  - Predecessor of node p is the first node met in counter-clockwise direction starting at p-1
  - When a node joins or leaves, successor and predecessor pointers should be updated



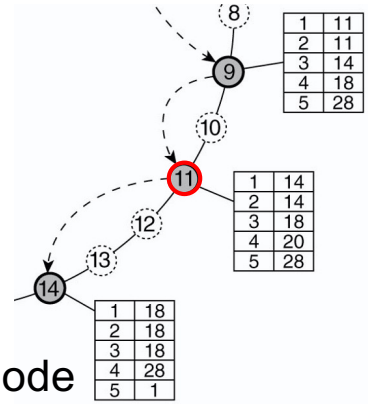
Chord: node join and leave

- When node *p* joins the overlay network, it has to find its place in the Chord ring:
  - Asks to a node to find its successor *succ*(*p*+1) on the ring
  - Joins the ring linking to its successor and informs its successor of its presence
  - Initialize its FT looking for $succ(p + 2^{i-1})$, $2 \leq i \leq m$
  - Informs its predecessor to update the FT
  - Transfers from its successor to itself the keys for which it becomes responsible
- Example: node 7 joins
  - Node 7 successor is node 9
  - Node 9 predecessor changes to node 7
  - Node 4 successor changes to node 7
  - Keys 5, 6 and 7 are transferred to node 7



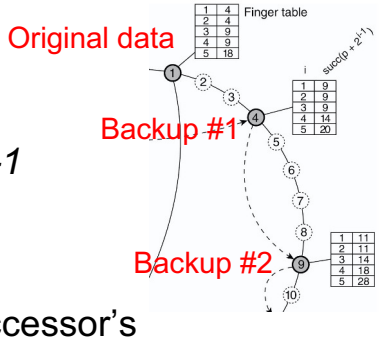
Chord: node join and leave

- When node *p* voluntary leaves the overlay network:
  - Transfers the keys it is responsible for to its successor
  - Updates the predecessor pointer held by its successor to the node that precedes *p*
  - Updates the successor pointer of its predecessor to its successor
- Example: node 11 leaves
  - Keys 10 and 11 are transferred to node 14
  - Node 14 predecessor changes to node 9
  - Node 9 successor changes to node 14
- Join/leave operations require $O(\log^2 N)$
- To keep the finger tables updated, each node periodically executes a ring stabilization procedure
  - Nodes can also leave the network abruptly because of failure



Chord: fault tolerance

- Nodes might crash
  - (*K, V*) data should be replicated
  - Create *R* replicas, storing each one at *R-1* successor nodes in the ring
- Need to know multiple successors
  - A node needs to know how to find its successor's successor (or more)
    - Easy only if it knows all nodes!
  - When a node is back up, it needs to:
    - Check with successors for updates of data it owns
    - Check with predecessors for updates of data it stores as backups



Chord: summing up

- Pros
  - ✓ Simple and elegant
  - ✓ Load balancing
    - Keys are evenly distributed among nodes
  - ✓ Scalability
    - Efficient lookup operations: O (log (N))
  - ✓ Robustness
    - Periodically update of nodes finger tables to reflect changes in the network
- Cons
  - ✗ Proximity in the underlying Internet is not considered
  - ✗ Expensive support for searches without exact matching
  - ✗ Original Chord ring-maintenance protocol is not correct
    - Reasoning about Identifier Spaces: How to Make Chord Correct, IEEE TSE, 2017 https://arxiv.org/pdf/1610.01140.pdf

DHTs: summing up

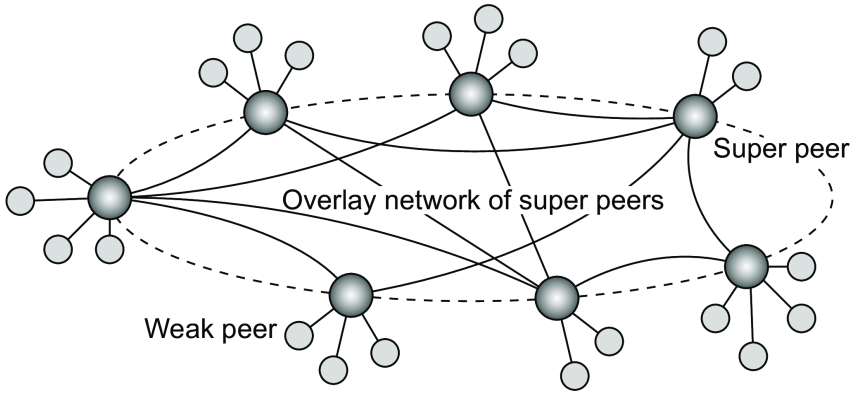
- DHTs in retrospective
  - Seem promising for finding data in large P2P systems
  - Decentralization is good for load balancing and fault tolerance
  - But: security problems are difficult
  - But: churn is a problem, particularly if log(*N*) is big
  - DHTs have not had the hoped-for impact
- However, DHTs got right for
  - Consistent hashing: elegant way to spread load across machines (e.g., used in Amazon Dynamo, Cassandra)
  - Incremental scalability: add nodes, capacity increases
  - Replication for high availability, efficient recovery after node failures
  - Self-management: minimal configuration
  - No single server to shut down/monitor

Hybrid architectures

- So far we have considered centralized and decentralized architectures
- In hybrid architectures, elements from centralized and decentralized organizations are combined
- Goal: take the benefits of both
- 3 examples of hybrid architectures (with different degree of decentralization)
  - Super-peer network
  - BitTorrent
  - Blockchain

Hybrid architectures: super-peer network

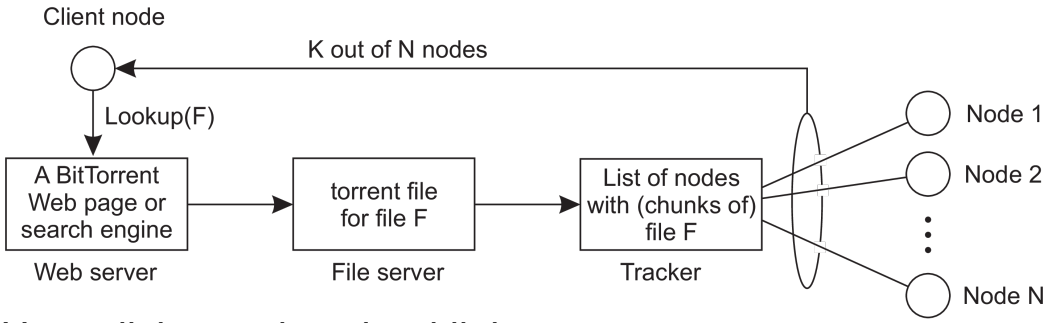
- It is sometimes sensible to break the symmetry in pure P2P networks: super peers
- Super peers (index servers) improve lookup performance



- Issues to address
  - Static or dynamic association of peer-super peer
  - How to select super peers

Hybrid architectures: BitTorrent

- Unstructured P2P system for file sharing
- Steps to search for file F



1. User clicks on download link
   - BT client gets torrent file containing tracker reference
   - Tracker: a server keeping an accurate account of active nodes that have (chunks of) F; bootstrapping node for the torrent
2. BT client contacts tracker
   - Tracker replies with a list of peers who have (chunks of) F

Hybrid architectures: BitTorrent

3. BT client downloads chunks of F from peers, joining a swarm of downloaders, who in parallel get file chunks but also distribute downloaded chunks amongst each other

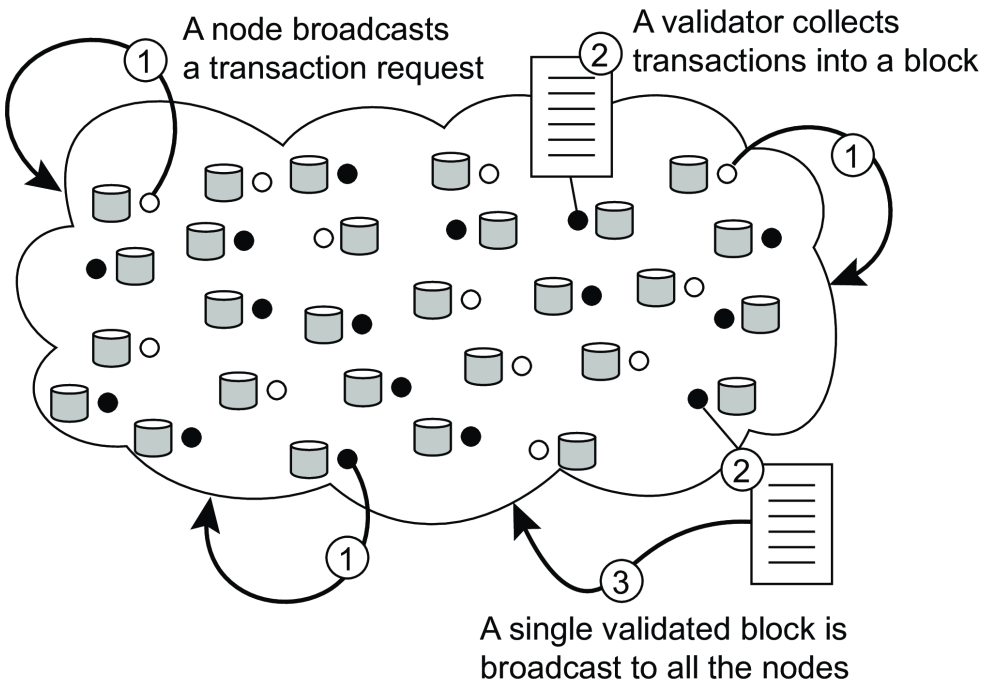
- BitTorrent incentivizes peers to exchange data
  - Chunk selection based on rarest piece first
  - Bandwidth allocation based on tit-for-tat
- Rarest piece first
  - Chunks that are most uncommon in the network are preferably selected for download
  - Goal: make file exchange more robust against node churn
- Tit-for-tat
  - Peers decide to whom they upload data based on downloaded data from a peer
  - Goal: prevent peers from only downloading without providing any resources to others

Blockchain

- A transaction (e.g., Alice transfers €10 to Bob) needs to be validated and then stored for auditing purposes
  - Validation: verify that transaction is legal (not malicious, no double spending, …)
  - How to validate transactions and where to store transactions?
- Which kind of transactions?
  - Not only transfer of cryptocurrency (e.g., Bitcoin)
  - Also identification documents, resource usage and allocation, electronic voting, health records, etc.
- A blockchain provides a kind of collaborative data store of transactions replicated among untrusted peers and guarantees a consistent view of all transactions by peers
  - A type of distributed ledger

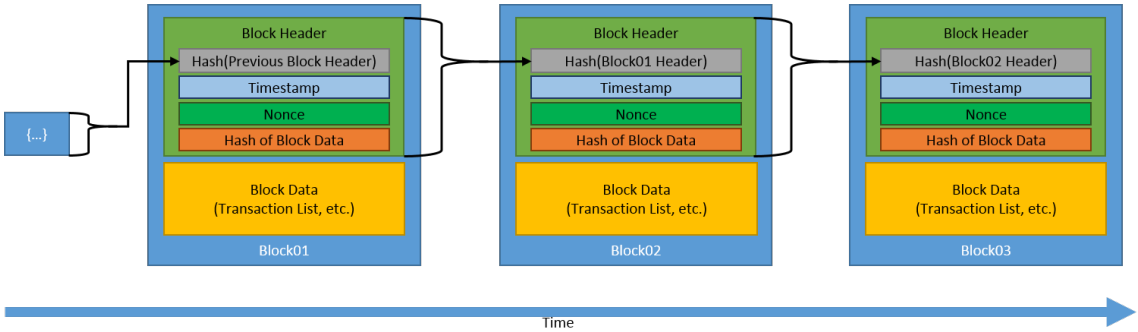
Blockchain: working principle

- Each peer stores a local replica of the ledger



Blockchain: blocks

- Transactions are grouped into blocks
  - Block: header + body (set of transactions)
- Blocks are organized into an unforgeable append-only chain
  - A block is connected to the previous one by including a unique identifier (hash) based on previous block
  - Changing a block invalidates all subsequent blocks
- Each block in the blockchain is immutable ⇒ massive replication

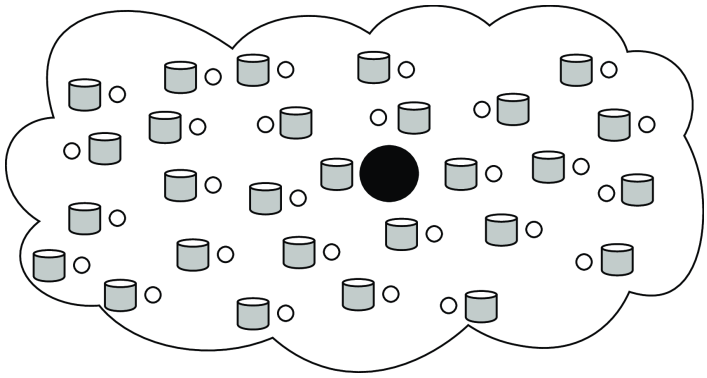


Blockchain: the key aspect

- Which validator is allowed to append a block of validated transactions to the chain?
- Deciding on which validator can move ahead requires (distributed) consensus

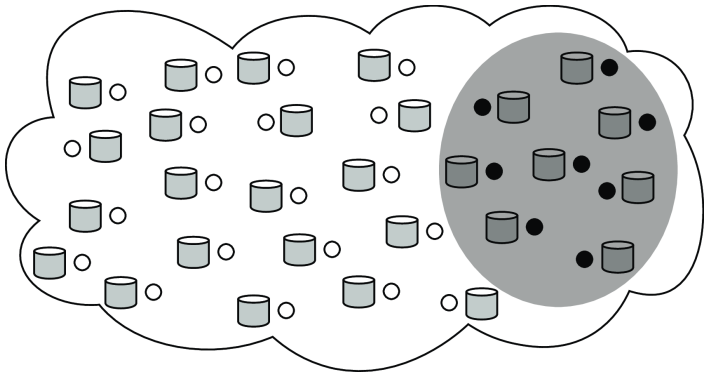
Appending a block: (distributed) consensus

- Centralized solution
  - A trusted single entity decides on which validator can go ahead and append a block
  - ✗ Does not fit the design goals of blockchain (no central authority)



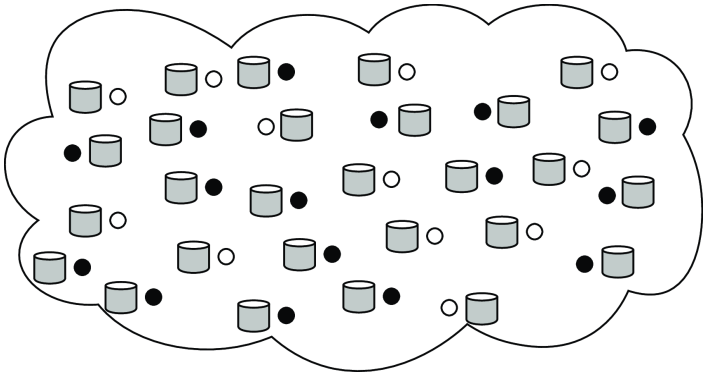
Appending a block: distributed consensus

- Distributed solution (permissioned blockchain)
  - A selected, relatively small group of servers jointly reach consensus on which validator can go ahead
  - None of these servers needs to be trusted, as long as roughly 2/3 behave according to their specifications
  - In practice, only a few tens of servers can be accommodated



Appending a block: distributed consensus

- Decentralized solution (permission-less blockchain)
  - All nodes collectively participate to validate transactions and engage in a leader election. Only the elected leader is allowed to append a block of validated transactions
  - E.g., Bitcoin, Ethereum
  - ✗ Large-scale, decentralized leader election that is fair, robust, secure, energy-efficient and so on, is far from trivial
    - We will study proof-of-work and proof-of-stake



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- Blockchain technology overview
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