Distributed Systems
Principles and Paradigms

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Chapter 02: Architectures

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Contents

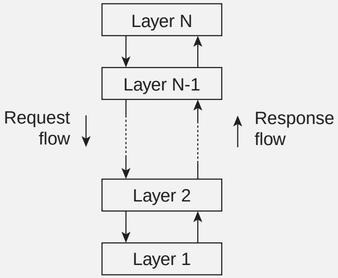
Architectures

- Architectural styles
- Software architectures
- Architectures versus middleware
- Self-management in distributed systems

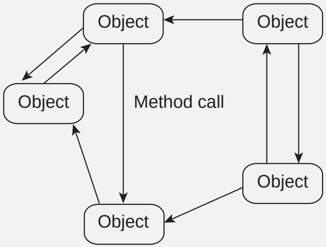
Architectural styles

Basic idea

Organize into logically different components, and distribute those components over the various machines.



(a)



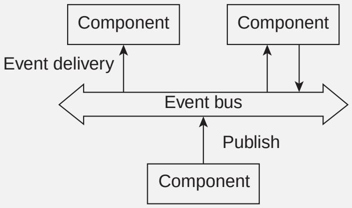
(b)

(a) Layered style is used for client-server system
(b) Object-based style for distributed object systems.

Architectural Styles

Observation

Decoupling processes in space (“anonymous”) and also time (“asynchronous”) has led to alternative styles.



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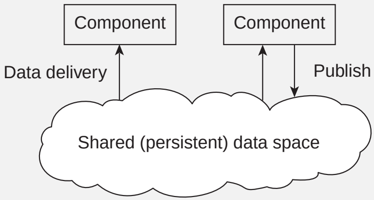


(b)

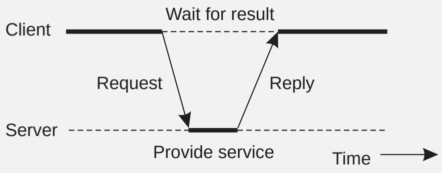
(a) Publish/subscribe [decoupled in space]
(b) Shared dataspace [decoupled in space and time]

Centralized 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 wrt to using services



Application Layering

Traditional three-layered view

- User-interface layer contains units for an application's user interface
- 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

Observation

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

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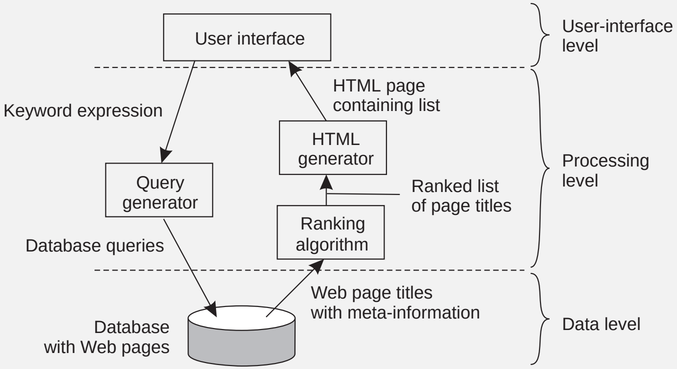
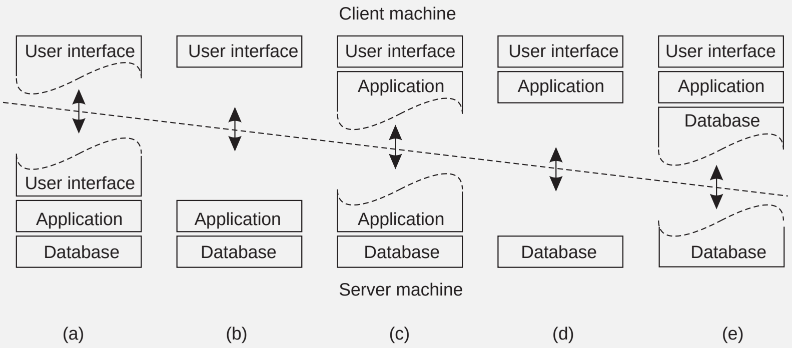


Multi-Tiered Architectures

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

Traditional two-tiered configurations:



Decentralized Architectures

Observation

In the last couple of years we have been seeing a tremendous growth in peer-to-peer systems.

- Structured P2P: nodes are organized following a specific distributed data structure
- Unstructured P2P: nodes have randomly selected neighbors
- Hybrid P2P: some nodes are appointed special functions in a well-organized fashion

Note

In virtually all cases, we are dealing with overlay networks: data is routed over connections setup between the nodes (cf. application-level multicasting)

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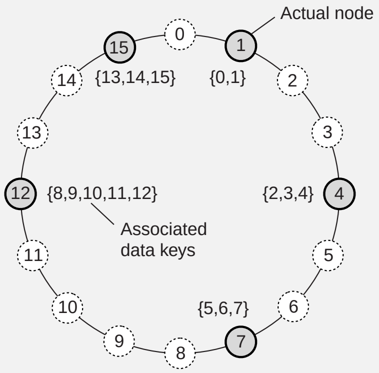
Structured P2P Systems

Basic idea

Organize the nodes in a structured overlay network such as a logical ring, and make specific nodes responsible for services based only on their ID.



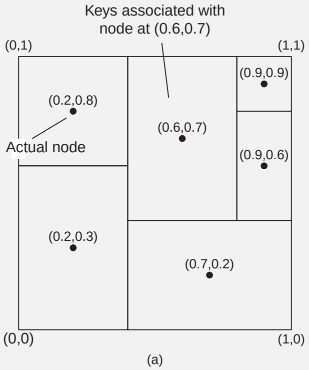
Note

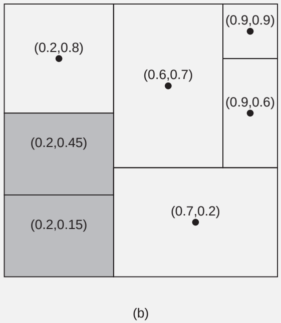
The system provides an operation *LOOKUP(key)* that will efficiently route the lookup request to the associated node.

Structured P2P Systems

Other example

Organize nodes in a *d*-dimensional space and let every node take the responsibility for data in a specific region. When a node joins ⇒ split a region.





Unstructured P2P Systems

Observation

Many unstructured P2P systems attempt to maintain a random graph.

Basic principle

Each node is required to contact a randomly selected other node:

- Let each peer maintain a partial view of the network, consisting of c other nodes
- Each node P periodically selects a node Q from its partial view
- P and Q exchange information **and** exchange members from their respective partial views

Note

It turns out that, depending on the exchange, randomness, but also robustness of the network can be maintained.

What is gossiping?

Active thread

```
selectPeer(&B);
selectToSend(&bufs);
sendTo(B, bufs);

receiveFrom(B, &bufr);
selectToKeep(cache, bufr);
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Passive thread

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Foundation: Gossip-based peer sampling

Unify partial view and local cache ⇒ exchange neighbors

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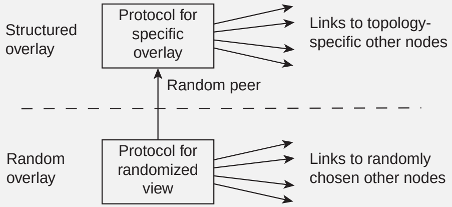
Topology Management of Overlay Networks

Basic idea

Distinguish two layers: (1) maintain random partial views in lowest layer; (2) be selective on who you keep in higher-layer partial view.


Structured overlay
Protocol for specific overlay
Links to topology-specific other nodes
Random peer
Random overlay
Protocol for randomized view
Links to randomly chosen other nodes

Note

Lower layer feeds upper layer with random nodes; upper layer is selective when it comes to keeping references.

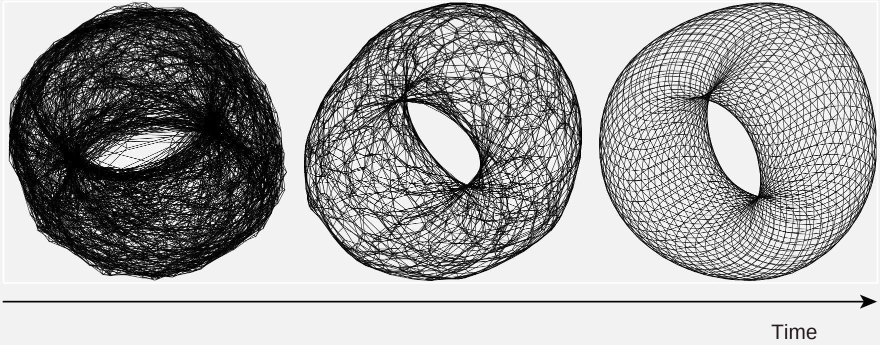
Topology Management of Overlay Networks

Constructing a torus

Consider a $N \times N$ grid. Keep only references to nearest neighbors:

$$\| (a_1, a_2) - (b_1, b_2) \| = d_1 + d_2$$

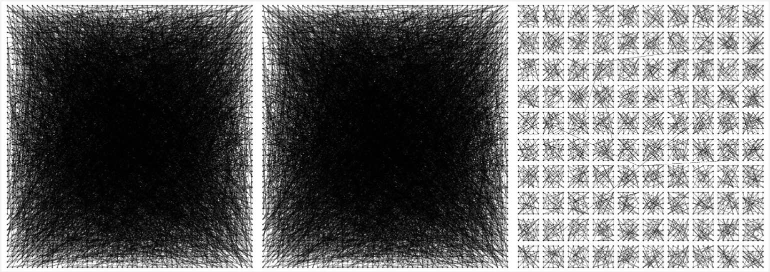
$$d_i = \min\{N - |a_i - b_i|, |a_i - b_i|\}$$



Example: Clustering nodes

Basics: Every node i is assigned a group identifier $GID(i) \in \mathbb{N}$. Our goal is to partition the overlay into disjoint components (clusters) such that

$$dist(i,j) = \begin{cases} 1 & \text{if } i \text{ and } j \text{ are in the same group } [GID(i) = GID(j)] \\ 0 & \text{otherwise} \end{cases}$$



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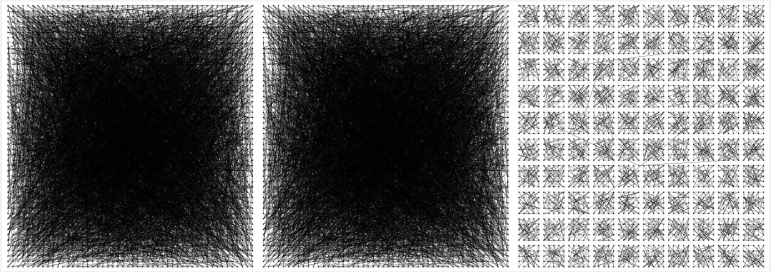

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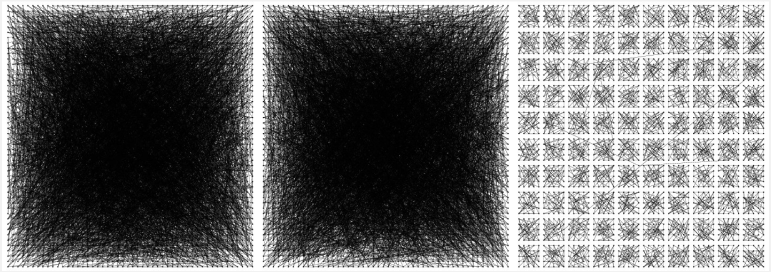

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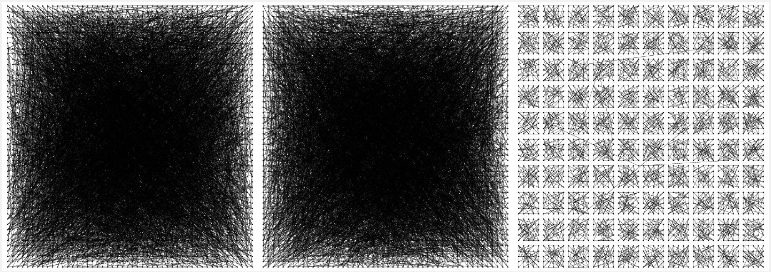

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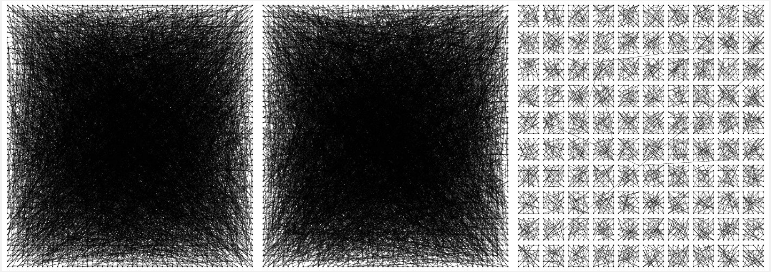

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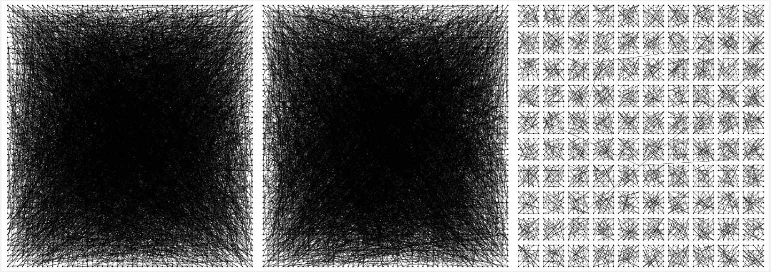

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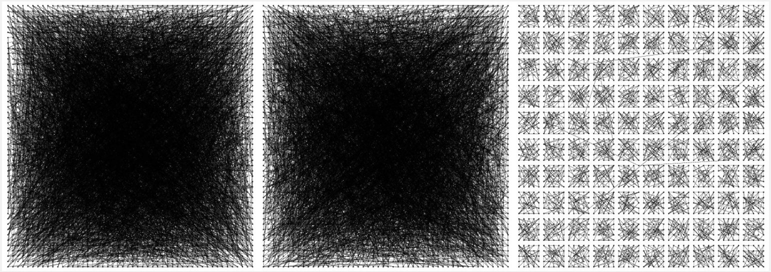

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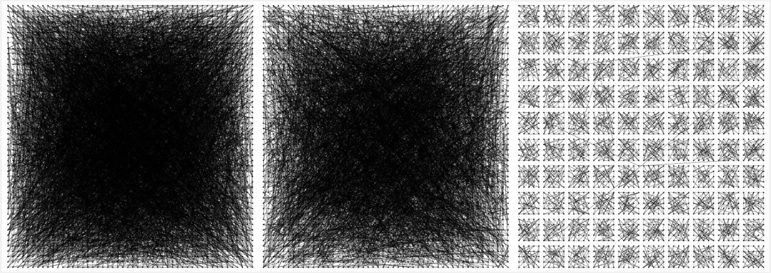

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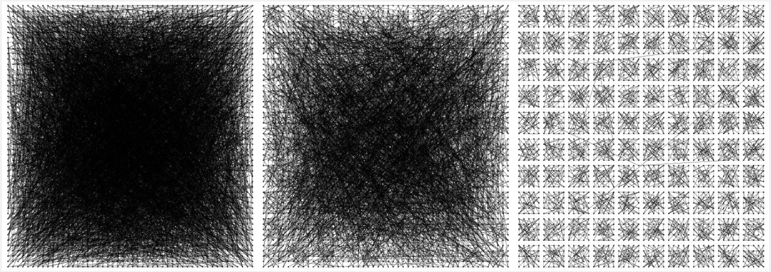

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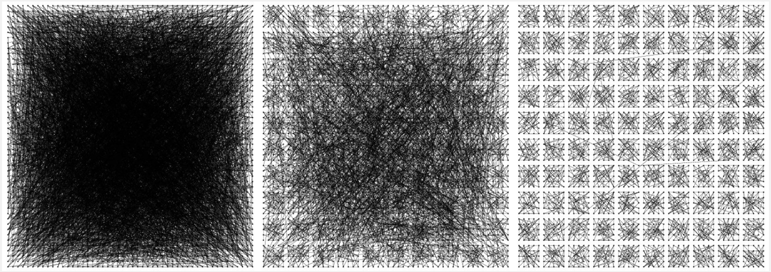

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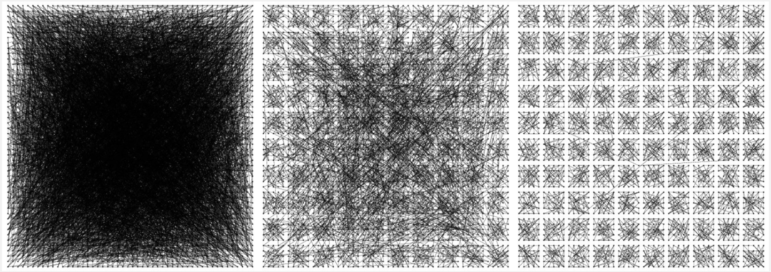

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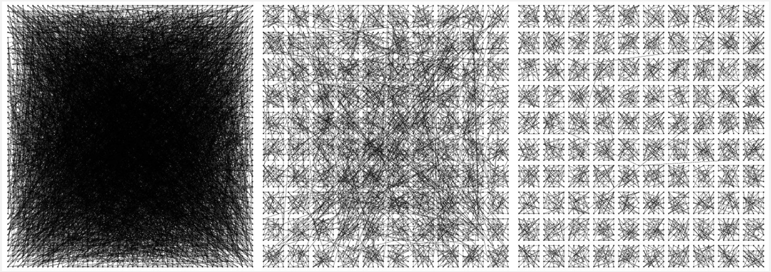

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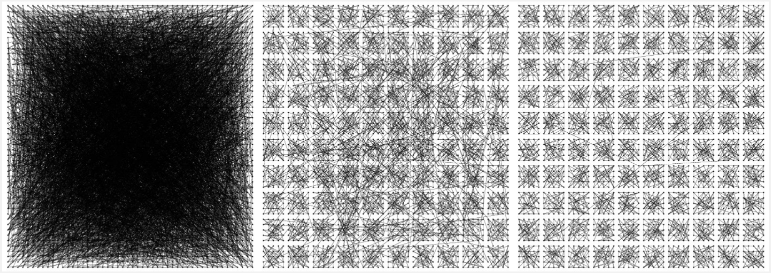

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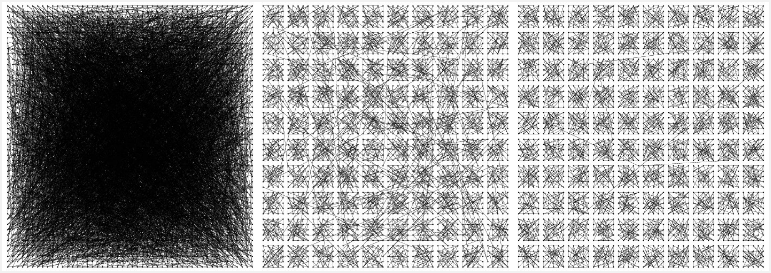

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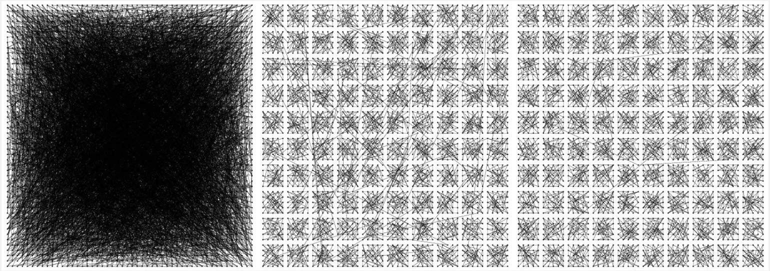

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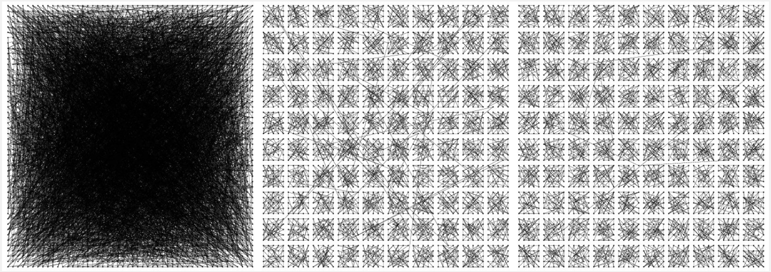

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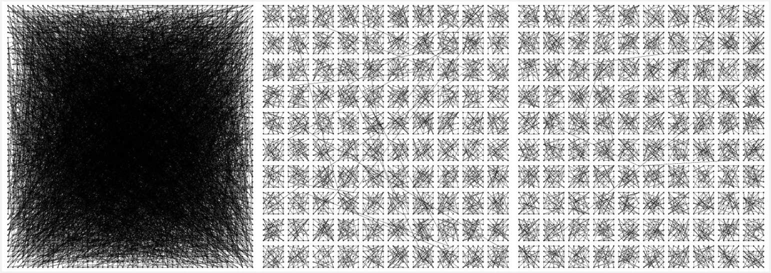

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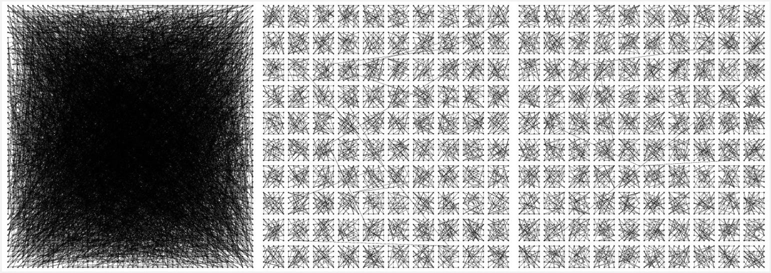

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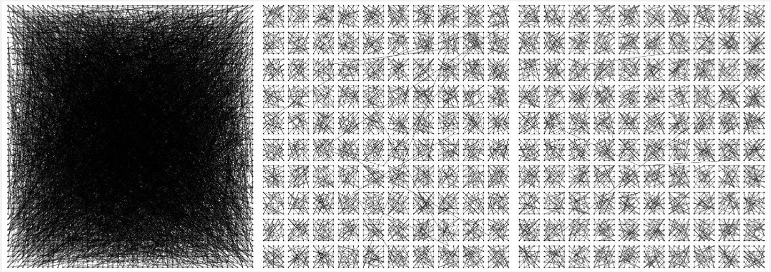

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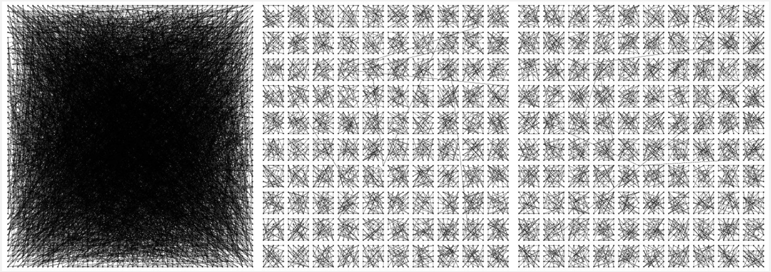

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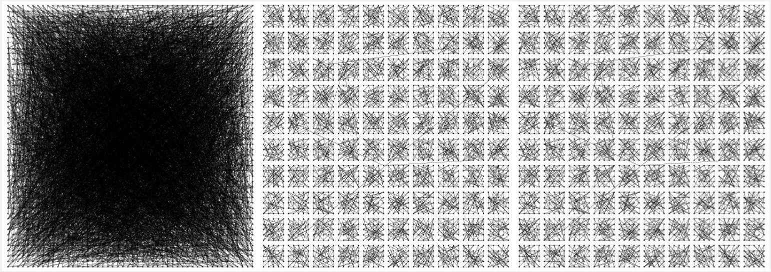

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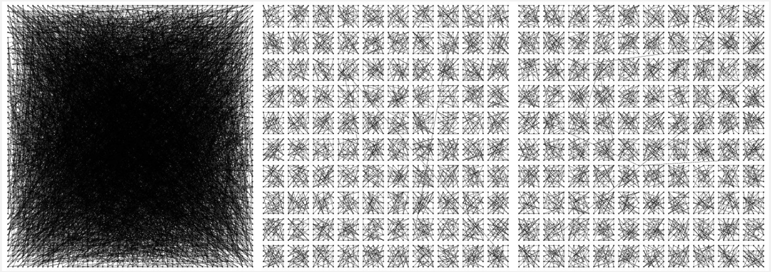

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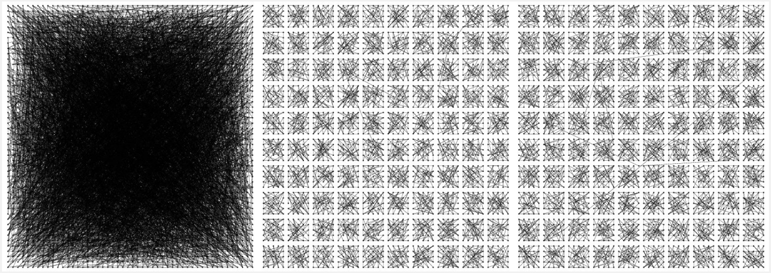

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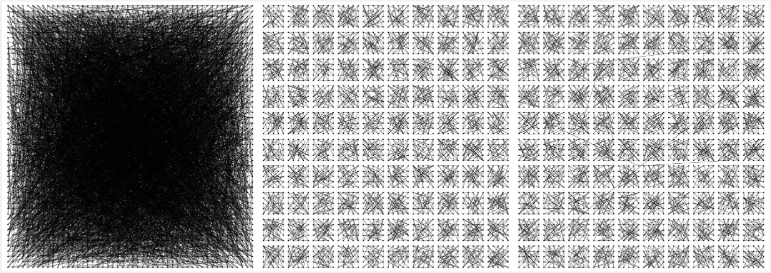
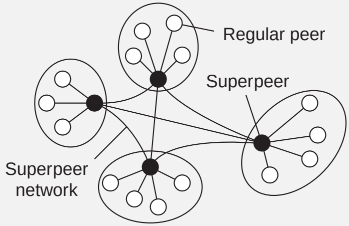


Superpeers

Observation

Sometimes it helps to select a few nodes to do specific work: superpeer.



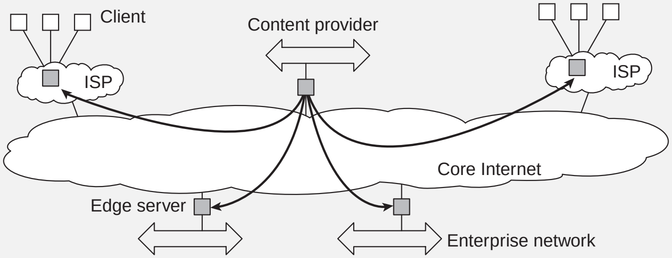
Examples

- Peers maintaining an index (for search)
- Peers monitoring the state of the network
- Peers being able to setup connections

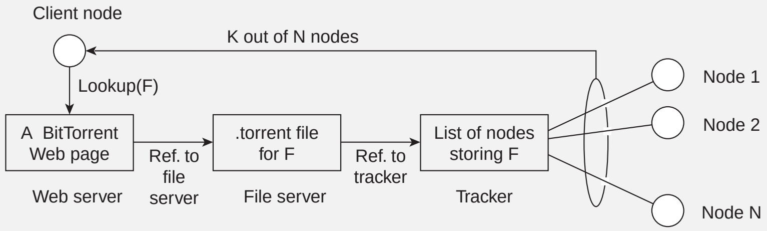
Hybrid Architectures: Client-server combined with P2P

Example

Edge-server architectures, which are often used for Content Delivery Networks



Hybrid Architectures: C/S with P2P – BitTorrent



Basic idea

Once a node has identified where to download a file from, it joins a swarm of downloaders who in parallel get file chunks from the source, but also distribute these chunks amongst each other.

Architectures versus Middleware

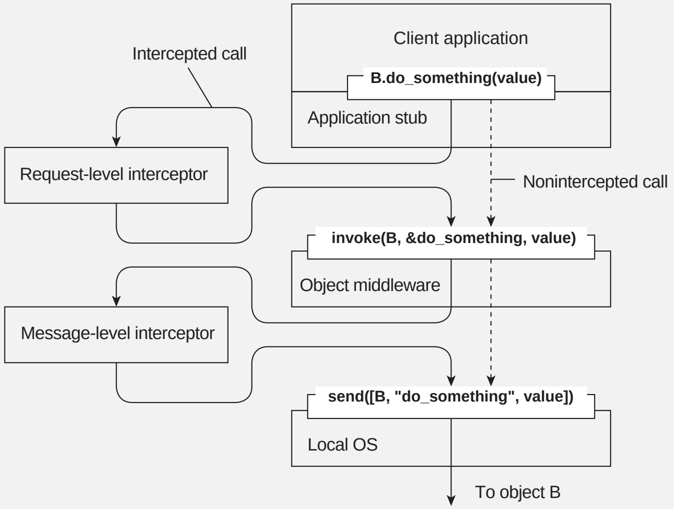
Problem

In many cases, distributed systems/applications are developed according to a specific architectural style. The chosen style may not be optimal in all cases $\Rightarrow$ need to (dynamically) adapt the behavior of the middleware.

Interceptors

Intercept the usual flow of control when invoking a remote object.

Interceptors



Adaptive Middleware

Separation of concerns: Try to separate extra functionalities and later weave them together into a single implementation ⇒ only toy examples so far.

Computational reflection: Let a program inspect itself at runtime and adapt/change its settings dynamically if necessary ⇒ mostly at language level and applicability unclear.

Component-based design: Organize a distributed application through components that can be dynamically replaced when needed ⇒ highly complex, also many intercomponent dependencies.

Fundamental question

Do we need adaptive software at all, or is the issue adaptive systems?

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Self-managing Distributed Systems

Observation

Distinction between system and software architectures blurs when automatic adaptivity needs to be taken into account:

- Self-configuration
- Self-managing
- Self-healing
- Self-optimizing
- Self-*

Warning

There is a lot of hype going on in this field of autonomic computing.

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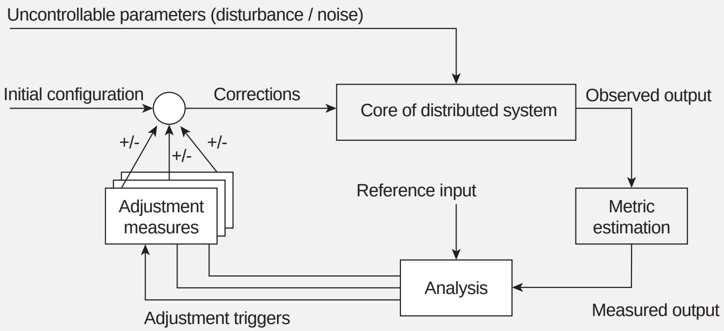
Feedback Control Model

Observation

In many cases, self-* systems are organized as a feedback control system.



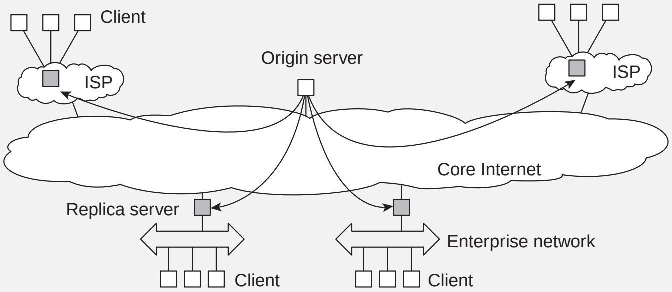
Example: Globule

Globule

Collaborative CDN that analyzes traces to decide where replicas of Web content should be placed. Decisions are driven by a general cost model:

$$cost = (w_1 \times m_1) + (w_2 \times m_2) + \cdots + (w_n \times m_n)$$

Example: Globule

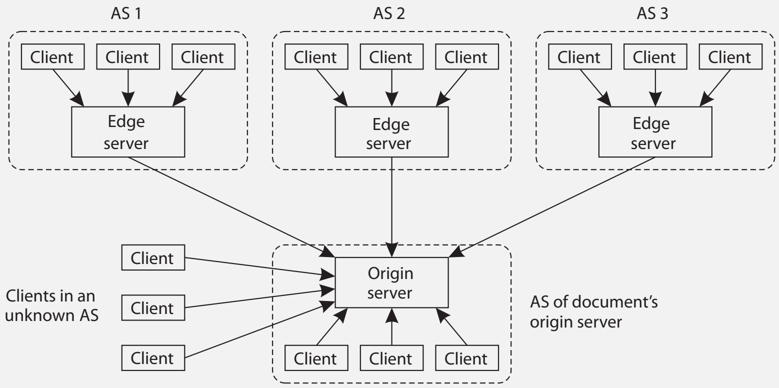


- Globule origin server collects traces and does what-if analysis by checking what would have happened if page *P* would have been placed at edge server *S*.
- Many strategies are evaluated, and the best one is chosen.

An experiment

Research question

Does it make sense to distribute each Web page according to its own best strategy, instead of applying a single, overall distribution strategy to all Web pages?



An experiment

- We collected traces on requests and updates for all Web pages from two different servers (in Amsterdam and Erlangen)
- For each request, we checked:
  - From which autonomous system it came
  - What the average delay was to that client
  - What the average bandwidth was to the client's AS (randomly taking 5 clients from that AS)
- Pages that were requested less than 10 times were removed from the experiment.
- We replayed the trace file for many different system configurations, and many different distribution scenarios.

An experiment

Issue	**Site 1**	**Site 2**
Start date	13/9/1999	20/3/2000
End date	18/12/1999	11/9/2000
Duration (days)	96	175
Number of documents	33,266	22,637
Number of requests	4,858,369	1,599,777
Number of updates	11,612	3338
Number of ASes	2567	1480

Distinguished strategies: Caching

Abbr.	Name	Description
NR	No replication	No replication or caching takes place. All clients forward their requests directly to the origin server.
CV	Verification	Edge servers cache documents. At each subsequent request, the origin server is contacted for revalidation.
CLV	Limited validity	Edge servers cache documents. A cached document has an associated expire time before it becomes invalid and is removed from the cache.
CDV	Delayed verification	Edge servers cache documents. A cached document has an associated expire time after which the origin server is contacted for revalidation.

Distinguished strategies: Replication

Abbr.	Name	Description
SI	Server invalidation	Edge servers cache documents, but the origin server invalidates cached copies when the document is updated.
SU*x*	Server updates	The origin server maintains copies at the *x* most relevant edge servers; *x* = 10, 25 or 50
SU50 + CLV	Hybrid SU50 & CLV	The origin server maintains copies at the 50 most relevant edge servers; the other intermediate servers follow the CLV strategy.
SU50 + CDV	Hybrid SU50 & CDV	The origin server maintains copies at the 50 most relevant edge servers; the other edge servers follow the CDV strategy.

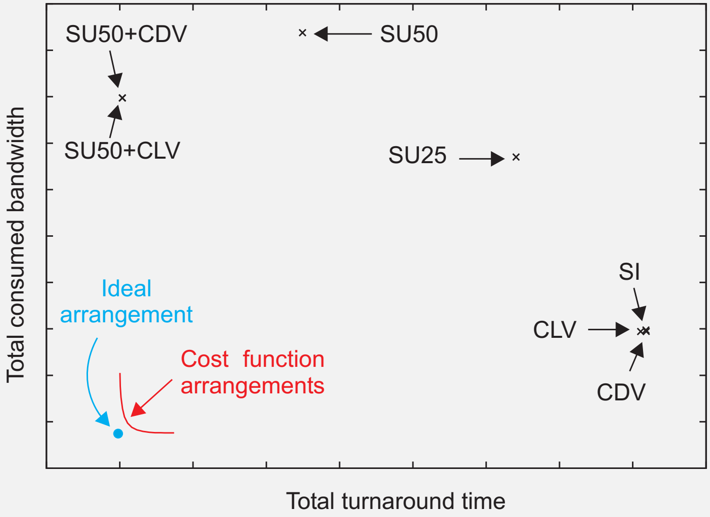
Trace results: One global strategy

Turnaround time (TaT) and bandwidth (BW) in relative measures; stale documents as fraction of total requested documents.

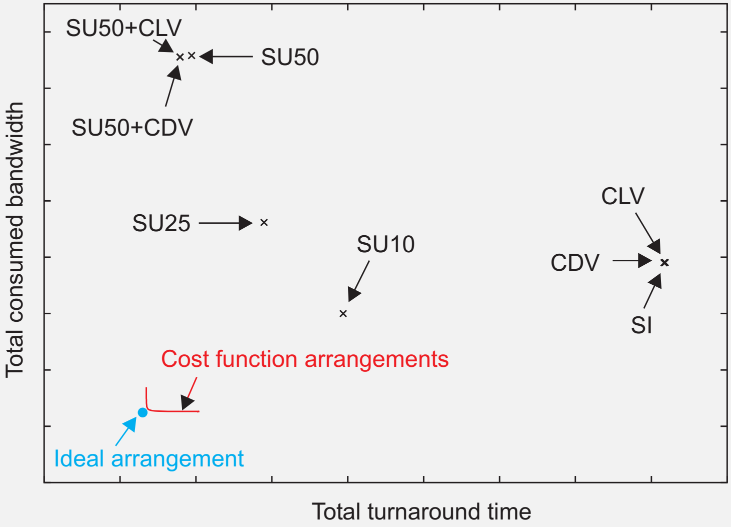
	Site 1			Site 2		
Strategy	**TaT**	**Stale docs**	**BW**	**TaT**	**Stale docs**	**BW**
NR	203	**0**	118	183	**0**	115
CV	227	**0**	113	190	**0**	**100**
CLV	182	0.0061	113	142	0.0060	**100**
CDV	182	0.0059	113	142	0.0057	**100**
SI	182	**0**	113	141	**0**	**100**
SU10	128	**0**	**100**	160	**0**	114
SU25	114	**0**	123	132	**0**	119
SU50	102	**0**	165	114	**0**	132
SU50+CLV	**100**	0.0011	165	**100**	0.0019	125
SU50+CDV	**100**	0.0011	165	**100**	0.0017	125

Conclusion: No single global strategy is best

Assigning an optimal strategy per document: Site 1



Assigning an optimal strategy per document: Site 2



Useful strategies

Fraction of documents to which a strategy is assigned.

Strategy	**Site 1**	**Site 2**
NR	0.0973	0.0597
CV	0.0001	0.0000
CLV	0.0131	0.0029
CDV	0.0000	0.0000
SI	0.0089	0.0061
SU10	0.1321	0.6087
SU25	0.1615	0.1433
SU50	0.4620	0.1490
SU50+CLV	0.1232	0.0301
SU50+CDV	0.0017	0.0002

Conclusion: It makes sense to differentiate strategies

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