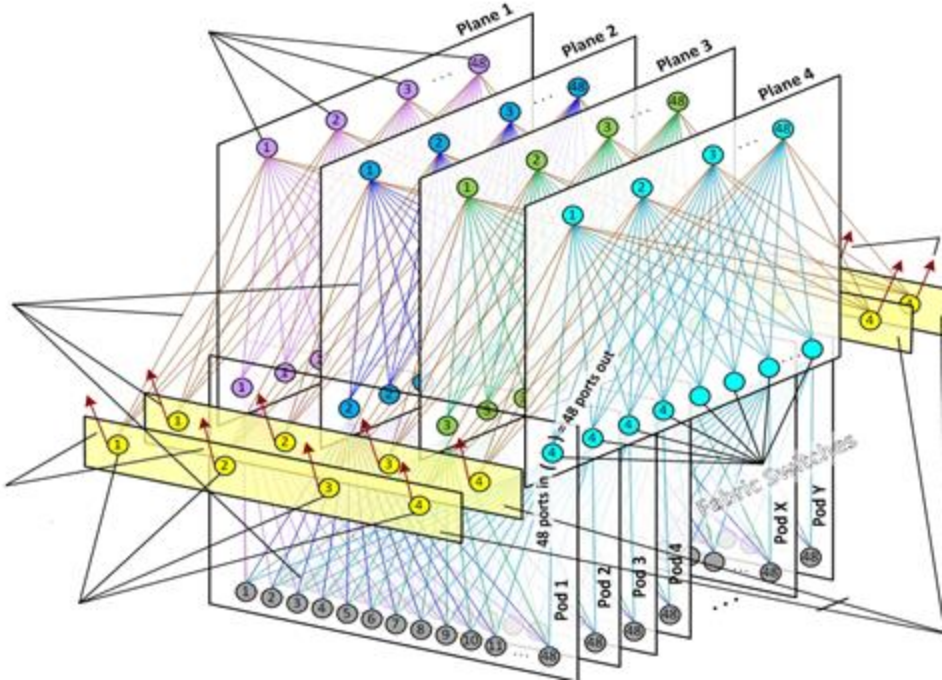
UNIVERSITEIT VAN AMSTERDAM

Large Systems:

Design + Implementation + Administration

2024-2025

➤ Large Systems Introduction



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28 oktober 2024

Large Systems

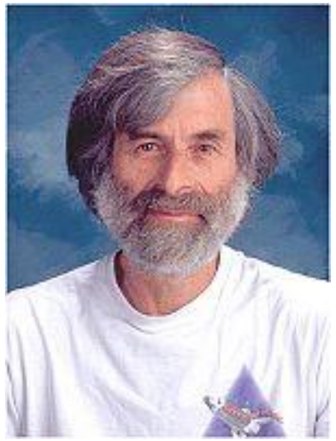
- Obviously not running on a single server
- Large systems today are distributed systems*:
  - *A system in which hardware or software components located at networked computers communicate and coordinate their actions only by message passing.”* [Coulouris]
  - *“A distributed system is a collection of independent computers that appear to the users of the system as a single computer.”* [Steen, Tanenbaum]
- Example Distributed Systems
  - Cluster Computing
  - Cloud Computing
  - Any Computing System that is loosely connected over communication networks

* Current large systems are inherently distributed in nature. So, we will use the words “Large Systems” and “Distributed Systems” interchangeably

Leslie Lamport's Definition

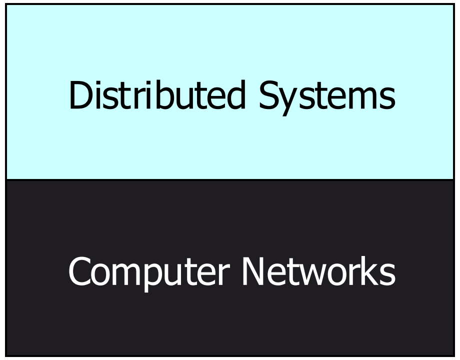
- *"A distributed system is one on which I cannot get any work done because some machine I have never heard of has crashed."*

- Leslie Lamport – a famous researcher on timing, message ordering, and clock synchronization in distributed systems. Turing Award, 2013.



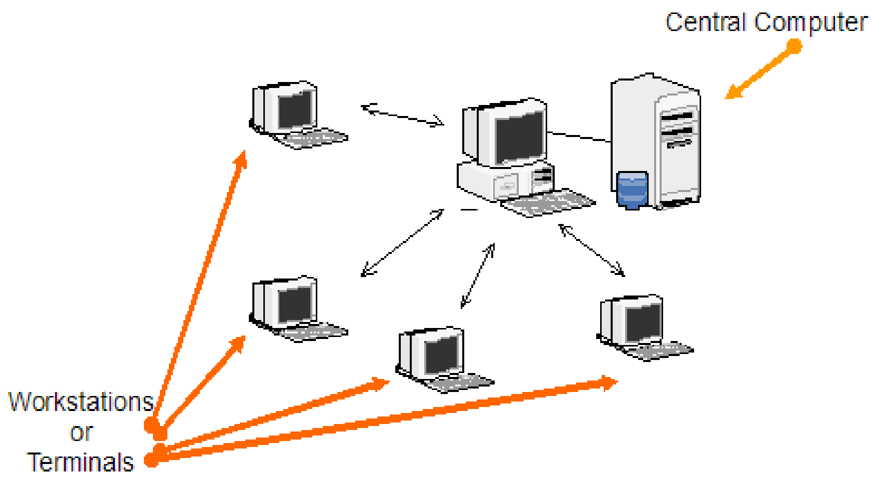
Networks vs. Distributed Systems

- Networks: A media for interconnecting local and wide area computers and exchanging messages based on protocols. Network entities are visible and they are explicitly addressed (IP address).
- Distributed System: existence of multiple autonomous computers is transparent
- However,
  - many problems (e.g., openness, reliability) in common, but at different levels.
    - Networks focuses on packets, routing, etc., whereas distributed systems focus on applications.
    - Every distributed system relies on services provided by a computer network.



Reasons for Distributed Systems

- Functional Separation:
  - Existence of computers with different capabilities and purposes:
- Clients and Servers
  - Data collection and data processing
- Inherent distribution
  - Information:
    - Different information is created and maintained by different people (e.g., Web pages)
  - People
    - Computer-supported collaborative work (virtual teams, engineering, virtual surgery)
    - Retail store and inventory systems for supermarket chains (e.g., Albert Heijn,)

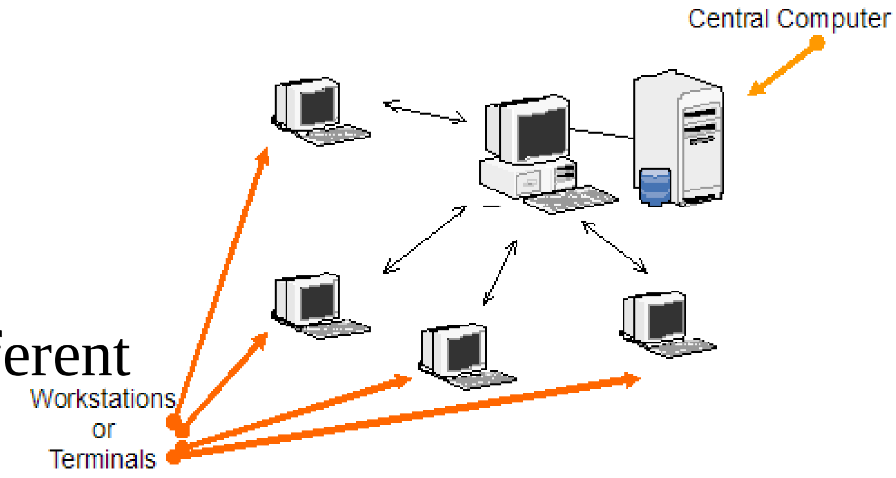


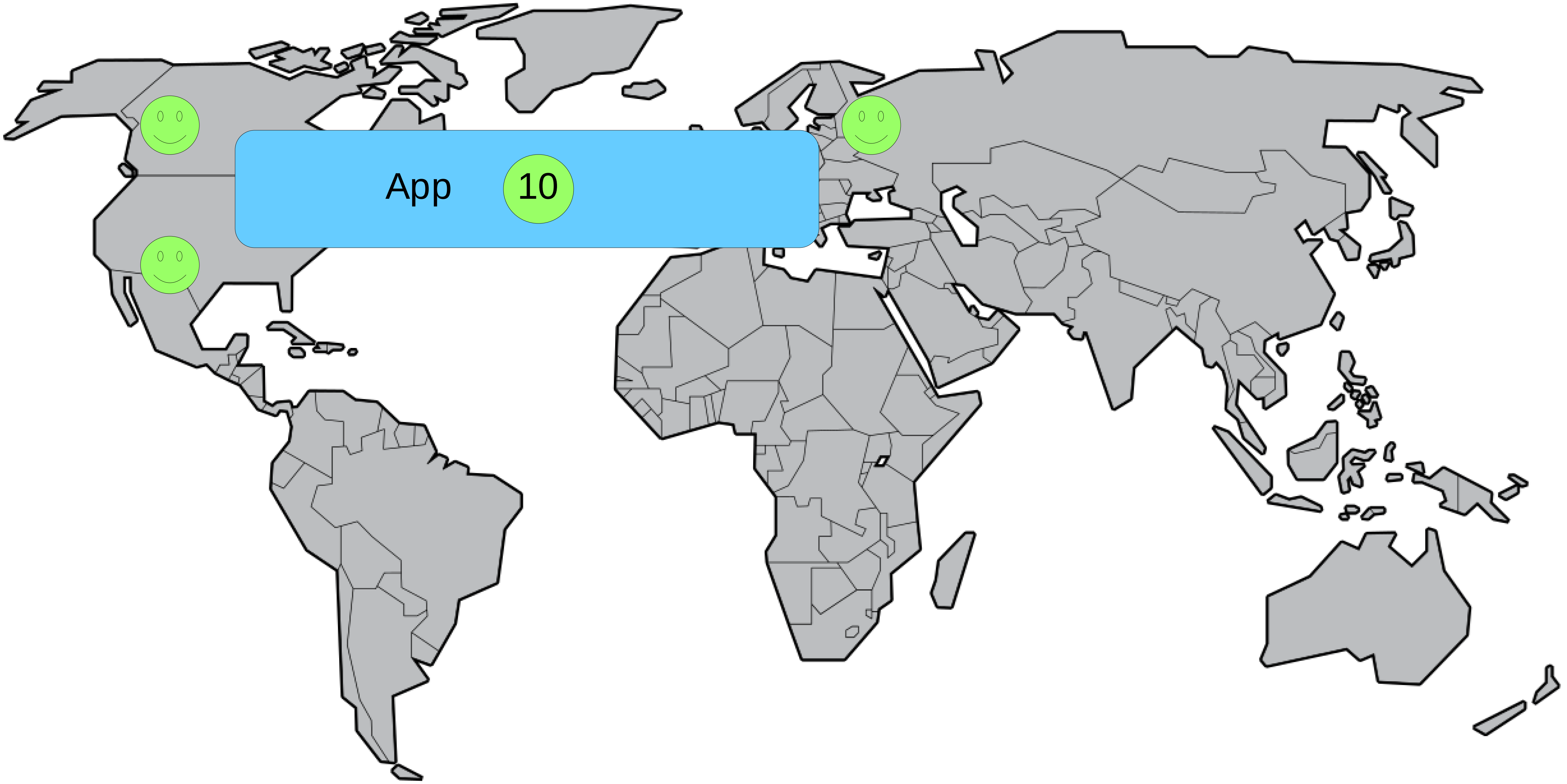
Reasons for Distributed Systems

- Power imbalance and load variation:
  - Distribute computational load among different computers
- Reliability:
  - Long term preservation and data backup (replication) at different locations.
- Economies:

  Sharing a printer by many users and reduce the cost of ownership.

  Building a supercomputer out of a network of computers.

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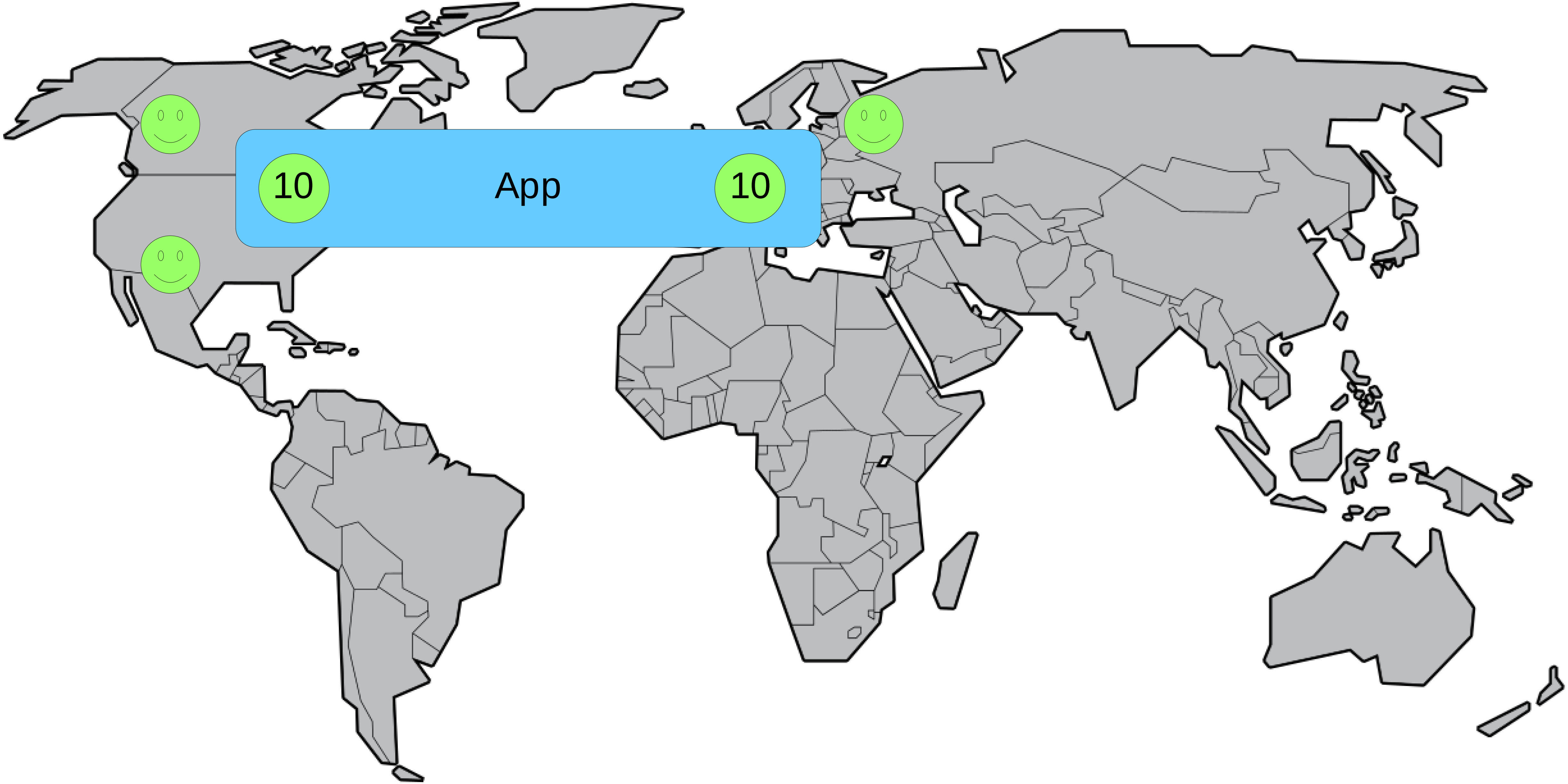
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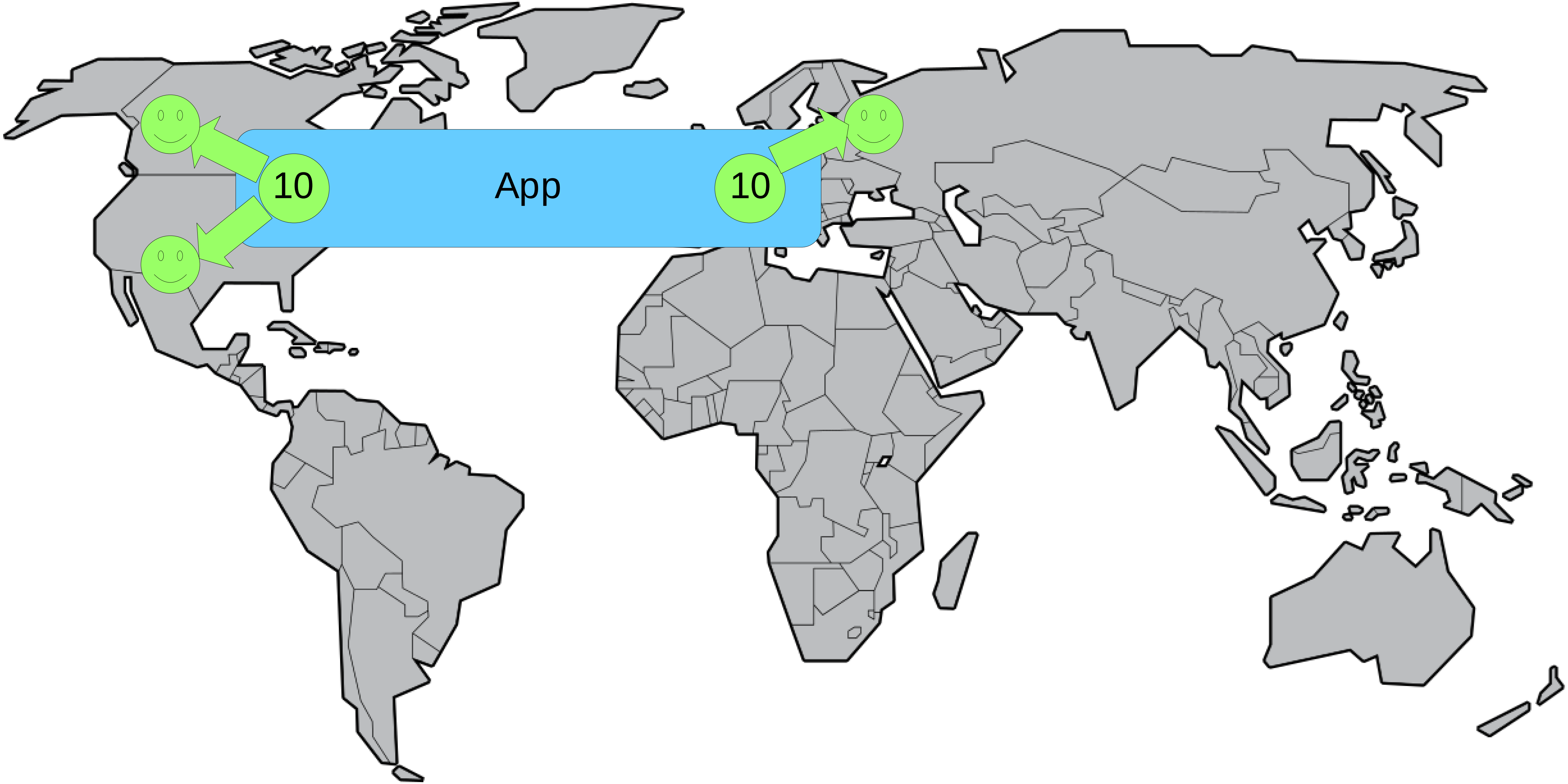
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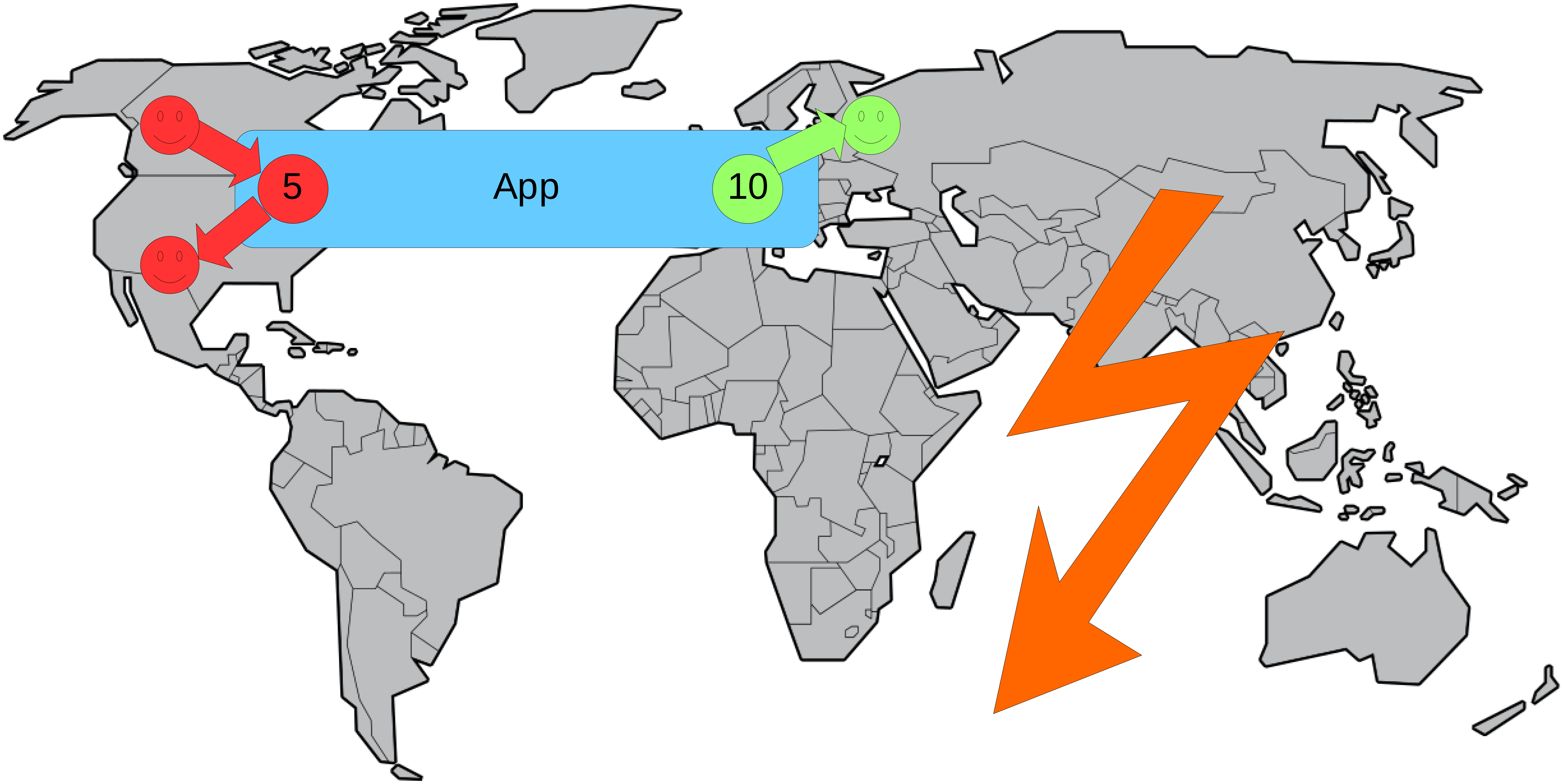
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Transparency

- To appear as a single system, things must be hidden:
  - **Distribution transparency:** The location should be unknown to users
  - **Failure transparency:** A failure in hardware/software components shouldn’t be observable by end users.
  - **Replication transparency:** Transparent Data or Service replication should be designed to handle dynamic workloads and provide reliability
  - **Relocation transparency:** Any service migrations shouldn’t hinder performance or visibility

But

- Aiming at full distribution transparency may be too much:
  - There are communication latencies that cannot be hidden
  - Completely hiding failures of networks and nodes is (theoretically and practically) impossible. A very hard problem. Imagine the recent Windows blue screen problem
  - You cannot distinguish a slow computer from a failing one
  - You can never be sure that a server actually performed an operation before a crash

  …

Source: Maarten van Steen, “Distributed Systems”, 2017

But

- Full transparency will cost performance, exposing the distribution of the system
  - Keeping replicas exactly up-to-date with the master takes time
  - Immediately flushing write operations to disk for fault tolerance has costs

Hiding Failures

- Theoretically impossible to tell failed machine from slow machine
  - “No consensus protocol is totally correct in spite of one fault.” Mathematical proof [Fischer *et al*, 1985]*
  - If packets can take infinite time to arrive
  - Cannot tell whether packet late or the machine dead
- Cannot tell whether remote operation succeeded
  - Due to packet loss and server crashes

*https://groups.csail.mit.edu/tds/papers/Lynch/jacm85.pdf

Failures in Practice

The Joys of Real Hardware

Typical first year for a new cluster:

~1 network rewiring (rolling ~5% of machines down over 2-day span)

~20 rack failures (40-80 machines instantly disappear, 1-6 hours to get back)

~5 racks go wonky (40-80 machines see 50% packetloss)

~8 network maintenances (4 might cause ~30-minute random connectivity losses)

~12 router reloads (takes out DNS and external vips for a couple minutes)

~3 router failures (have to immediately pull traffic for an hour)

~dozens of minor 30-second blips for dns

~1000 individual machine failures

~thousands of hard drive failures

slow disks, bad memory, misconfigured machines, flaky machines, etc.

Long distance links: wild dogs, sharks, dead horses, drunken hunters, etc.

Source: Jeff Dean, Google

Transparency Costs Performance

Numbers Everyone Should Know

L1 cache reference	0.5 ns
Branch mispredict	5 ns
L2 cache reference	7 ns
Mutex lock/unlock	25 ns
Main memory reference	100 ns
Compress 1K w/cheap compression algorithm	3,000 ns
Send 2K bytes over 1 Gbps network	20,000 ns
Read 1 MB sequentially from memory	250,000 ns
Round trip within same datacenter	500,000 ns
Disk seek	10,000,000 ns
Read 1 MB sequentially from disk	20,000,000 ns
Send packet CA->Netherlands->CA	150,000,000 ns

Source: Jeff Dean, Google

Google

We’re Doomed!

Well, Partially

- Often can tell whether the machine is dead
  - Internet is partially synchronous
  - Most applications do not need up-to-date replicas in both California and The Netherlands
- General solutions are a few
  - Need application-specific solutions! (Mostly requiring middleware systems)

Dev+Ops Challenge

- So building distributed systems is a challenge
- So is administrating them
  - 24x7 users, no “scheduled downtime”
  - If many many components, failures are frequent
  - No more manual solutions (patch servers with CD)
  - Size of backups
  - Complexity!
- Additional complication: fast pace of business innovation

Dimensions of Scale

- Numerical Size

  #users

  #machines

  #data

- Geographical

  LAN / Region / Country / Continent / Global

- Administrative

  One owner / Many owners / Anarchy

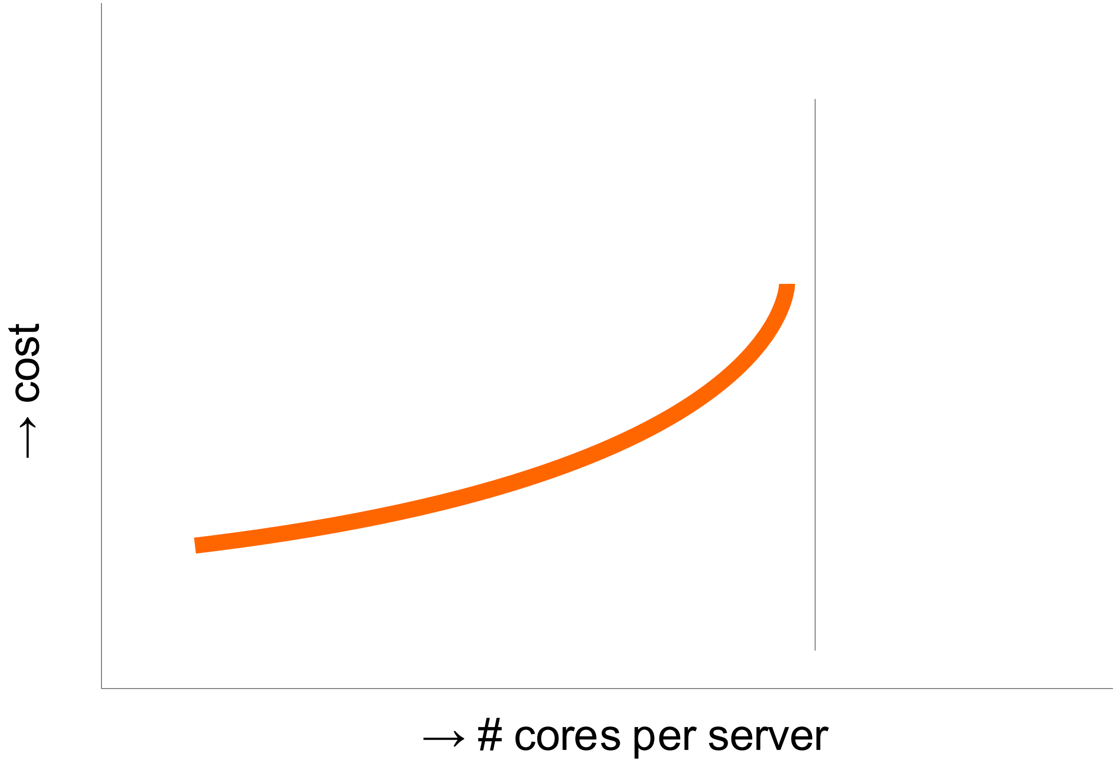
Source: [Neumann, 1994]

Scaling Techniques

- Bigger machines ("Scale up")
- Replication:
  - Caching: temporary replication
- Partitioning:
  - AKA Sharding
- Asynchronous communication
- Virtualization
  - Aggregate physical parts into a larger logical whole
  - Decouple interface from implementation, e.g. NFS

Scaling Up

- Buying bigger hardware
- Costs do not increase linearly!
- At some point, there is no bigger model...
- Complex hardware has complex behaviour
- Software must be able to use it!



From: “Scalability Rules”, 2nd Ed. Abbott and Fischer, 2017

Case Study: Google Evolution

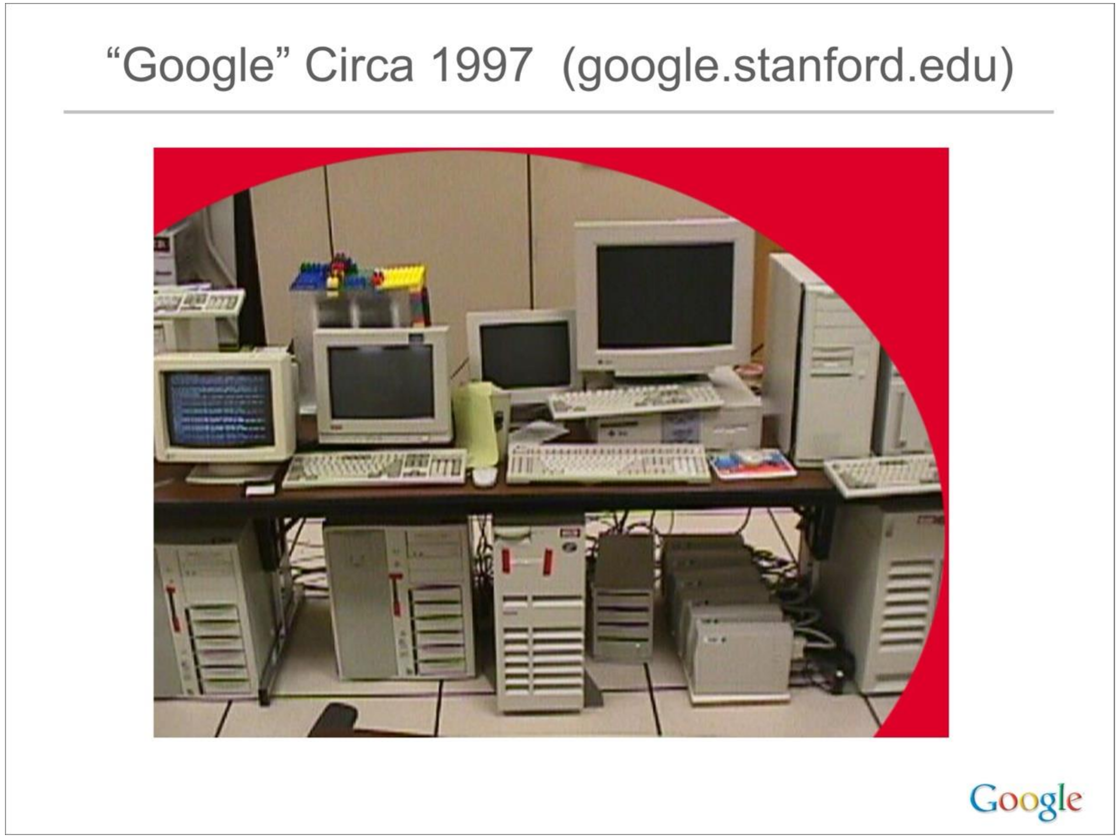
- Jeff Dean, "Building Software Systems at Google and Lessons Learned", Stanford Computer Science Department, Distinguished Computer Scientist Lecture, November, 2010

- https://research.google.com/pubs/jeff.html
- https://www.youtube.com/watch?v=modXC5IWTJI

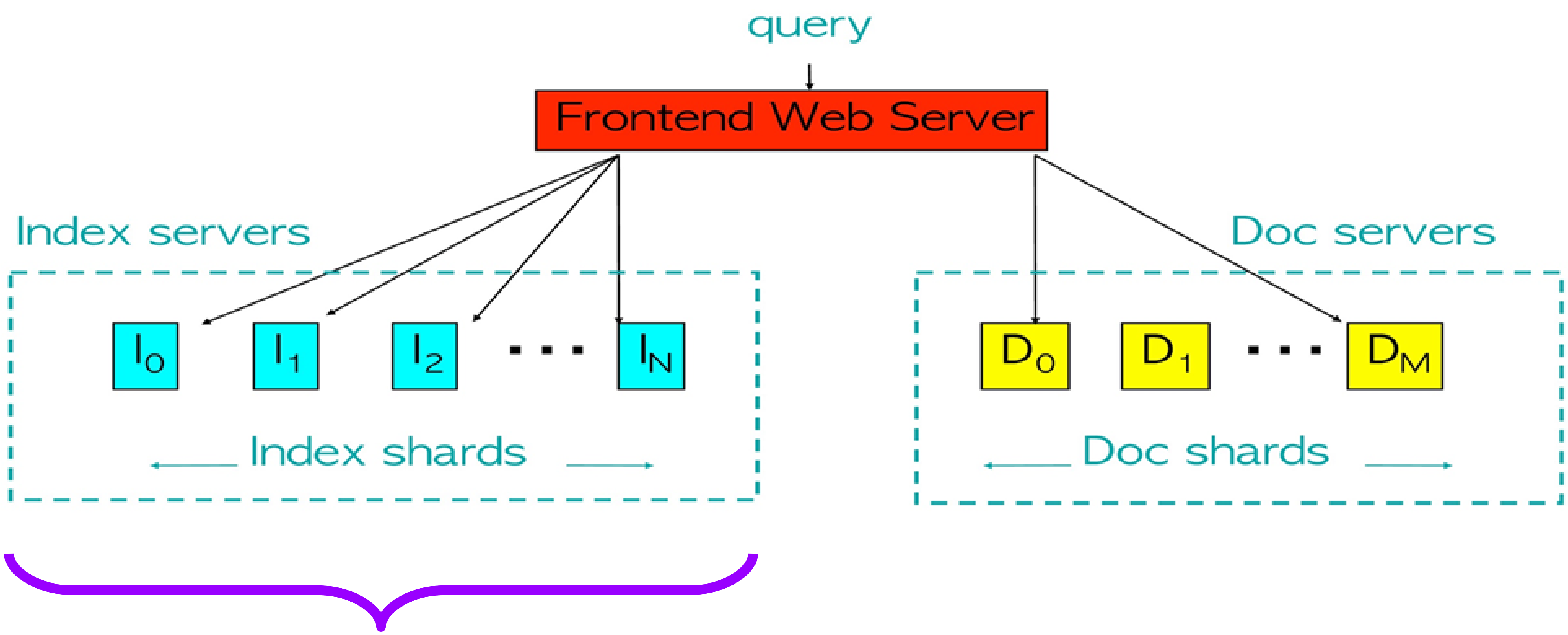
Google Search

- User types query: “uva-sne”
- Google needs to find documents on Web that match
- Step 1: Find out which documents match
  - From <query> get list of <docid,score> pairs
  - <” uva-sne”> → <1234,10.0>,<5678,8.0>
- Step 2: Get document summary
  - From <docid,query> generate <title,snipplet>
  - <1234,” uva-sne”> → <”uva/masters”,”SNE homepage”>
- Step 3: Generate HTML

Google Infra in 97….

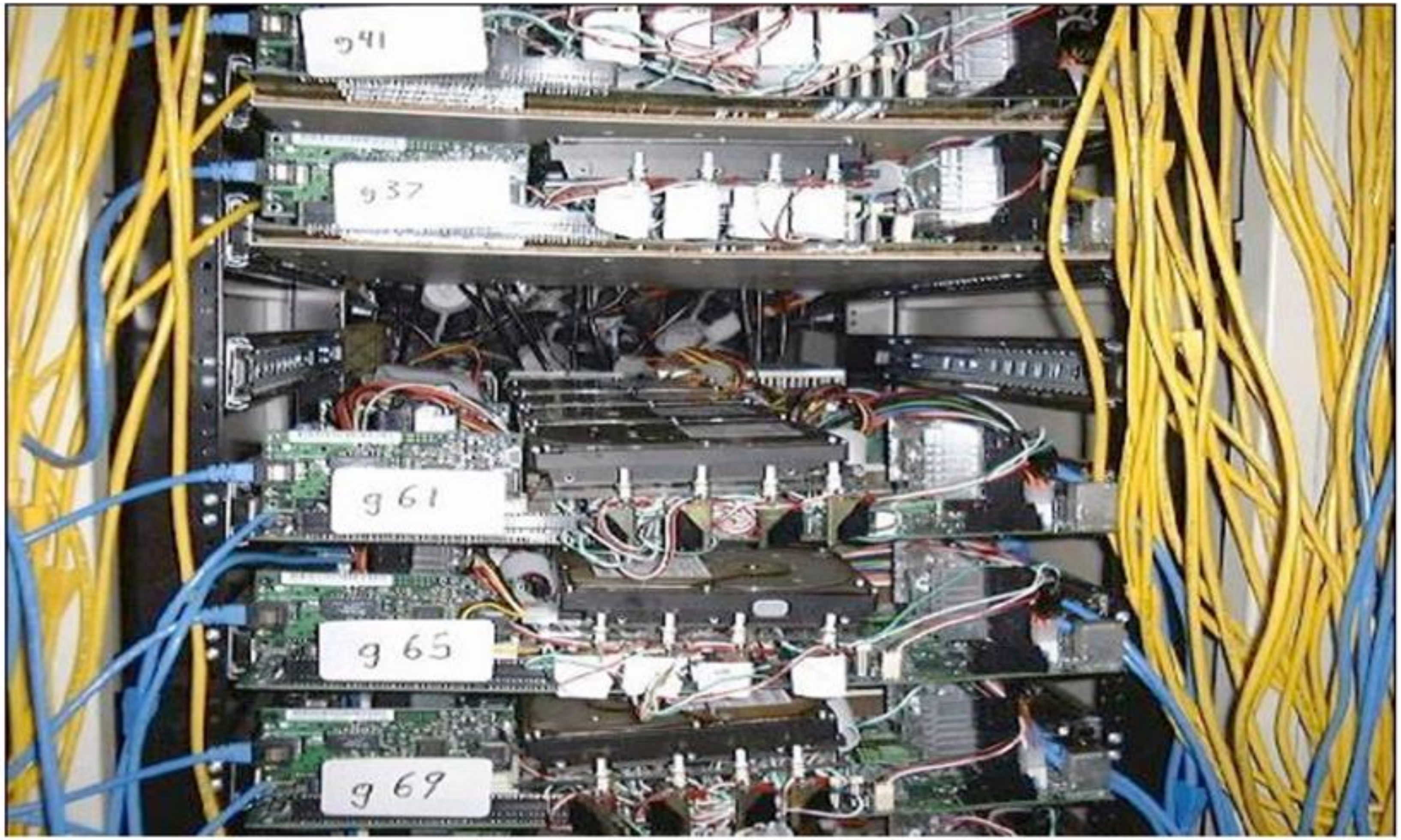


Research Project, circa 1997

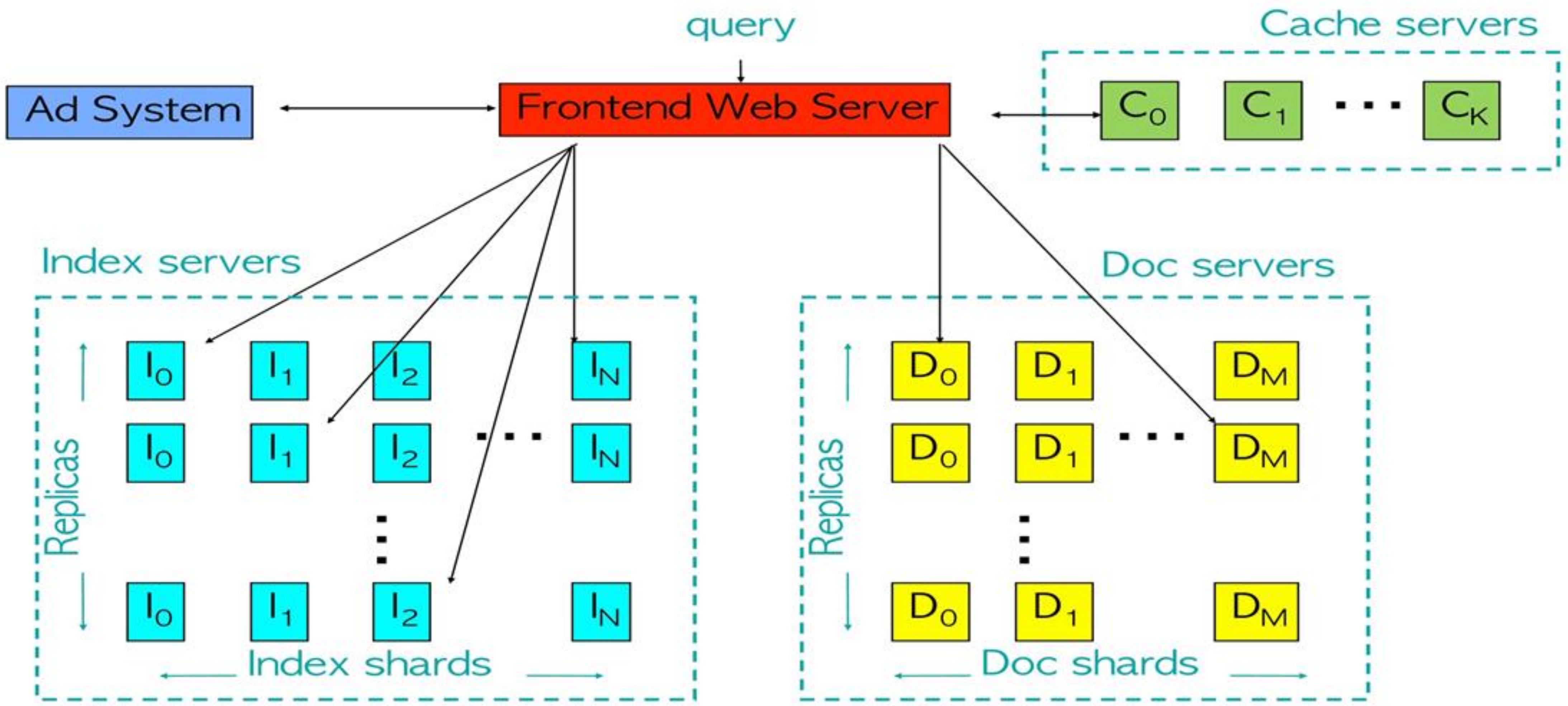


Index of all documents on the Internet

"Corkboards" (1999)



Serving System, circa 1999



Google

Caching in Web Search Systems

- Cache servers:
  - cache both index results and doc snippets
  - hit rates typically 30-60%
    - depends on frequency of index updates, mix of query traffic, level of personalization, etc
- Main benefits:
  - performance! a few machines do work of 100s or 1000s
  - much lower query latency on hits
    - queries that hit in cache tend to be both popular and expensive (common words, lots of documents to score, etc.)
- Beware: big latency spike/capacity drop when index updated or cache flushed

Google

Indexing (circa 1998-1999)

- Simple batch indexing system
  - No real checkpointing, so machine failures painful
  - No checksumming of raw data, so hardware bit errors caused problems
    - Exacerbated by early machines having no ECC, no parity
    - Sort 1 TB of data without parity: ends up "mostly sorted"
    - Sort it again: "mostly sorted" another way

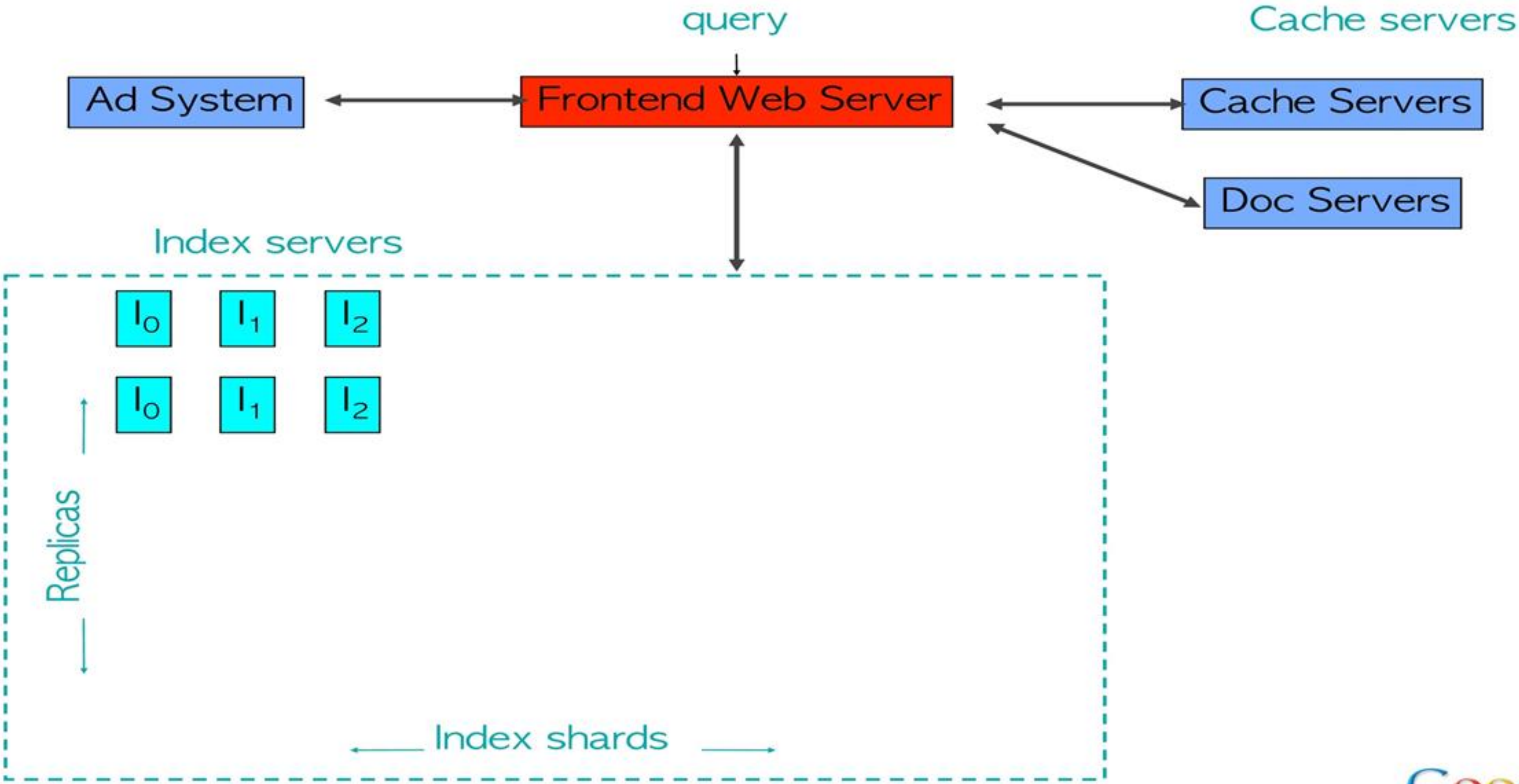
- "Programming with adversarial memory"
  - Developed file abstraction that stores checksums of small records and can skip and resynchronize after corrupted records

Google Data Center (2000)

Increasing Index Size and Query Capacity

- Huge increases in index size in ’99, ’00, ’01, ...
  - From ~50M pages to more than 1000M pages
- At same time as huge traffic increases
  - ~20% growth per month in 1999, 2000, ...
  - ... plus major new partners (e.g. Yahoo in July 2000 doubled traffic overnight)
- Performance of index servers was paramount
  - Deploying more machines continuously, but...
  - Needed ~10-30% software-based improvement every month

Dealing with Growth



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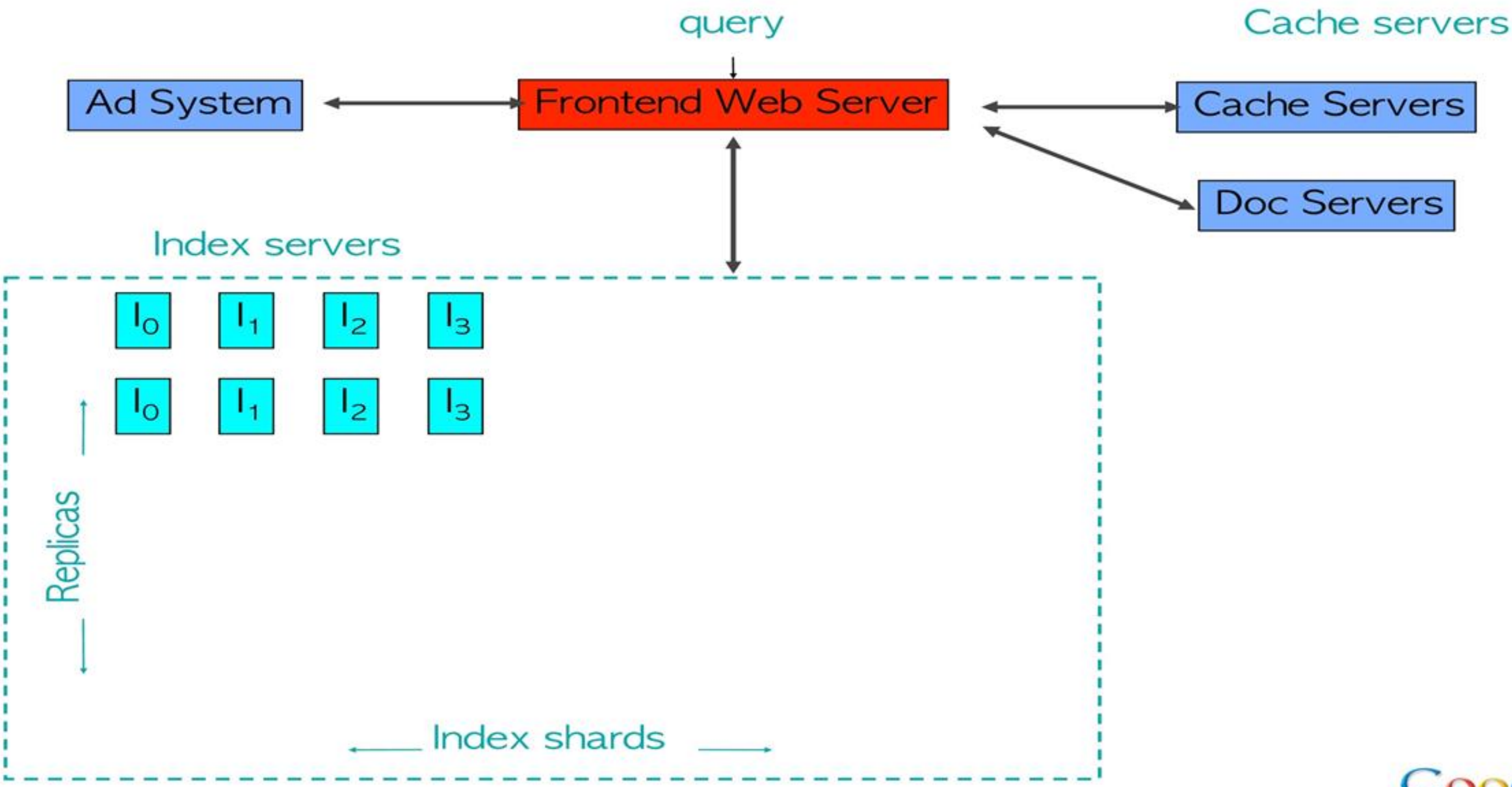
Dealing with Growth



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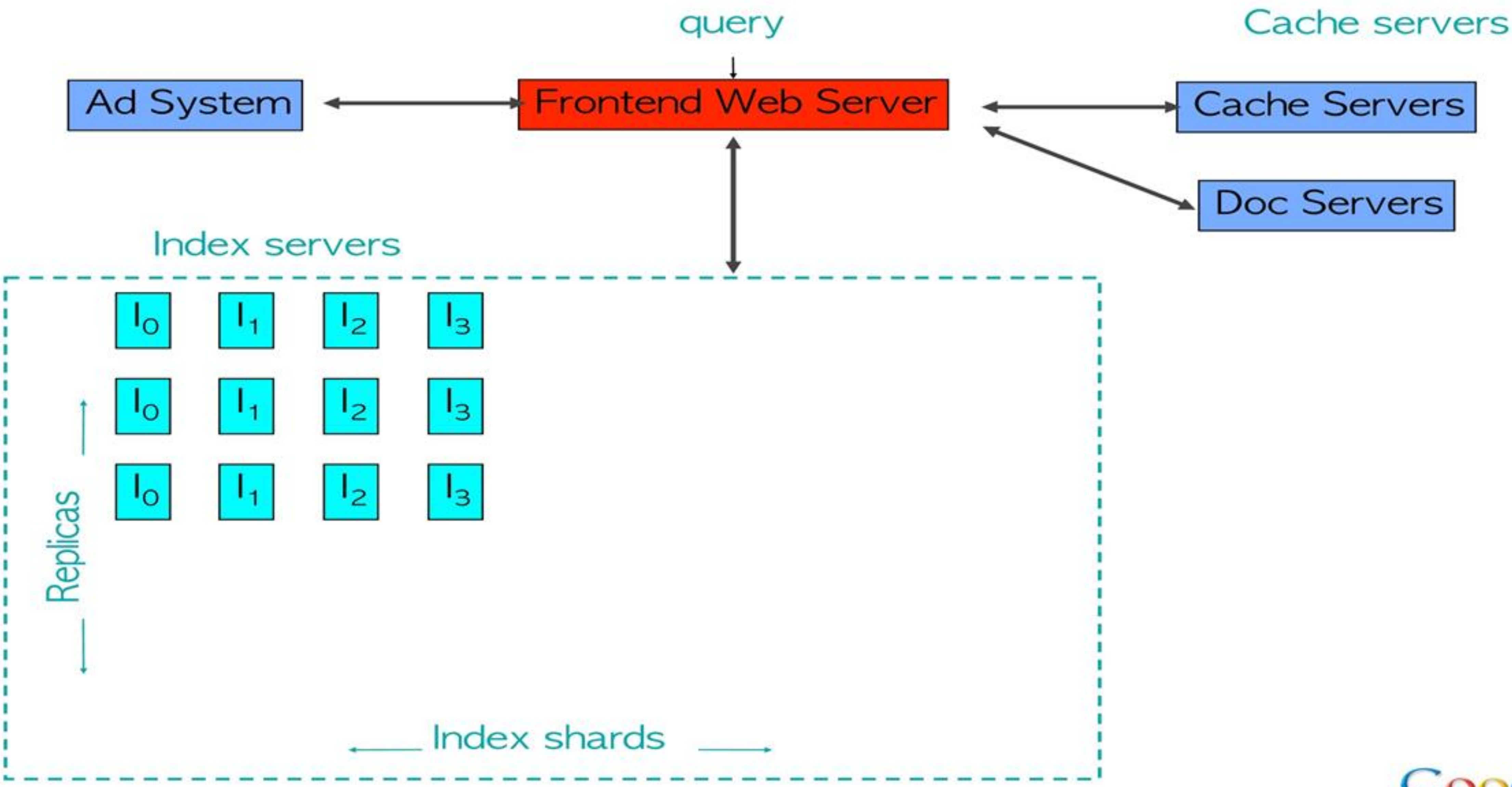

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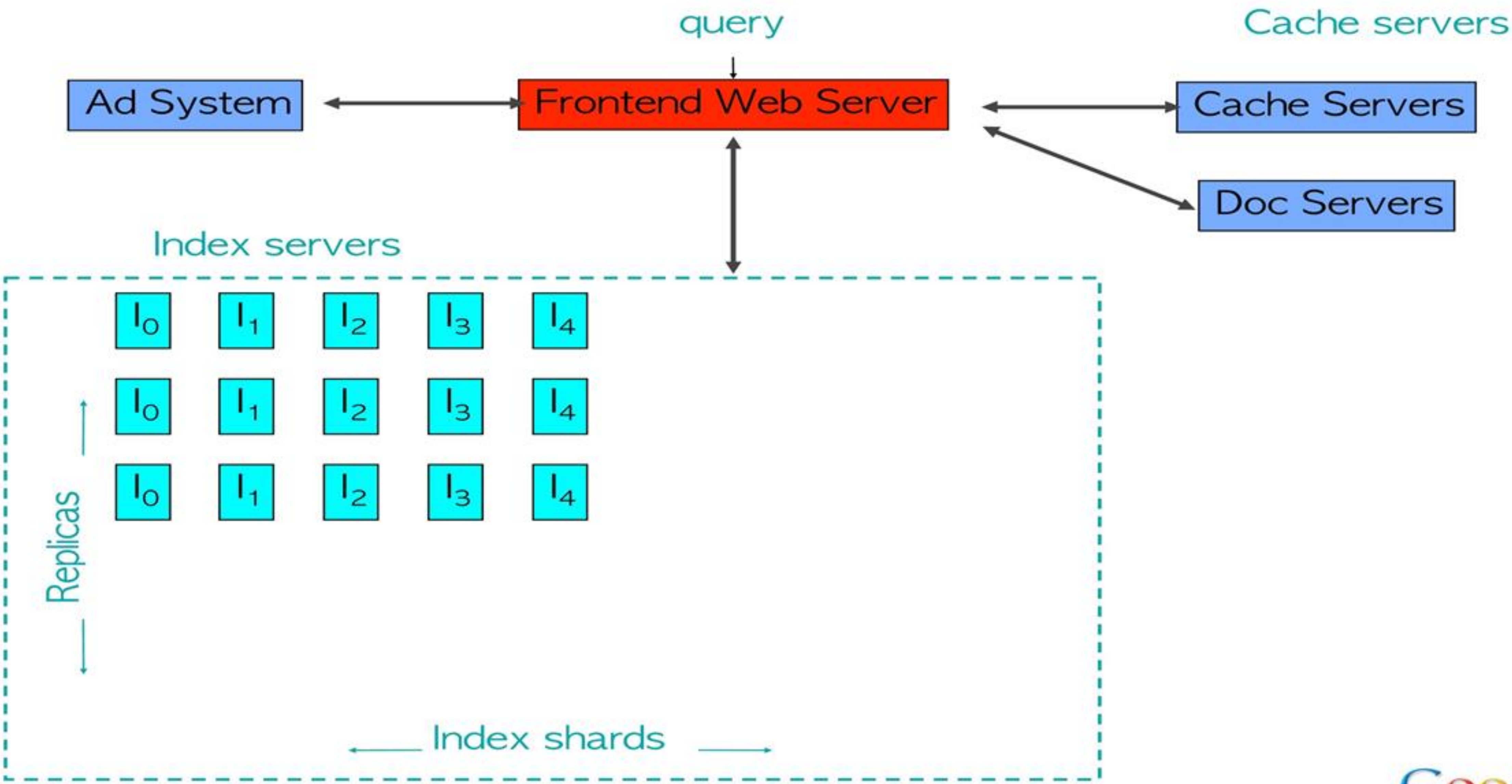

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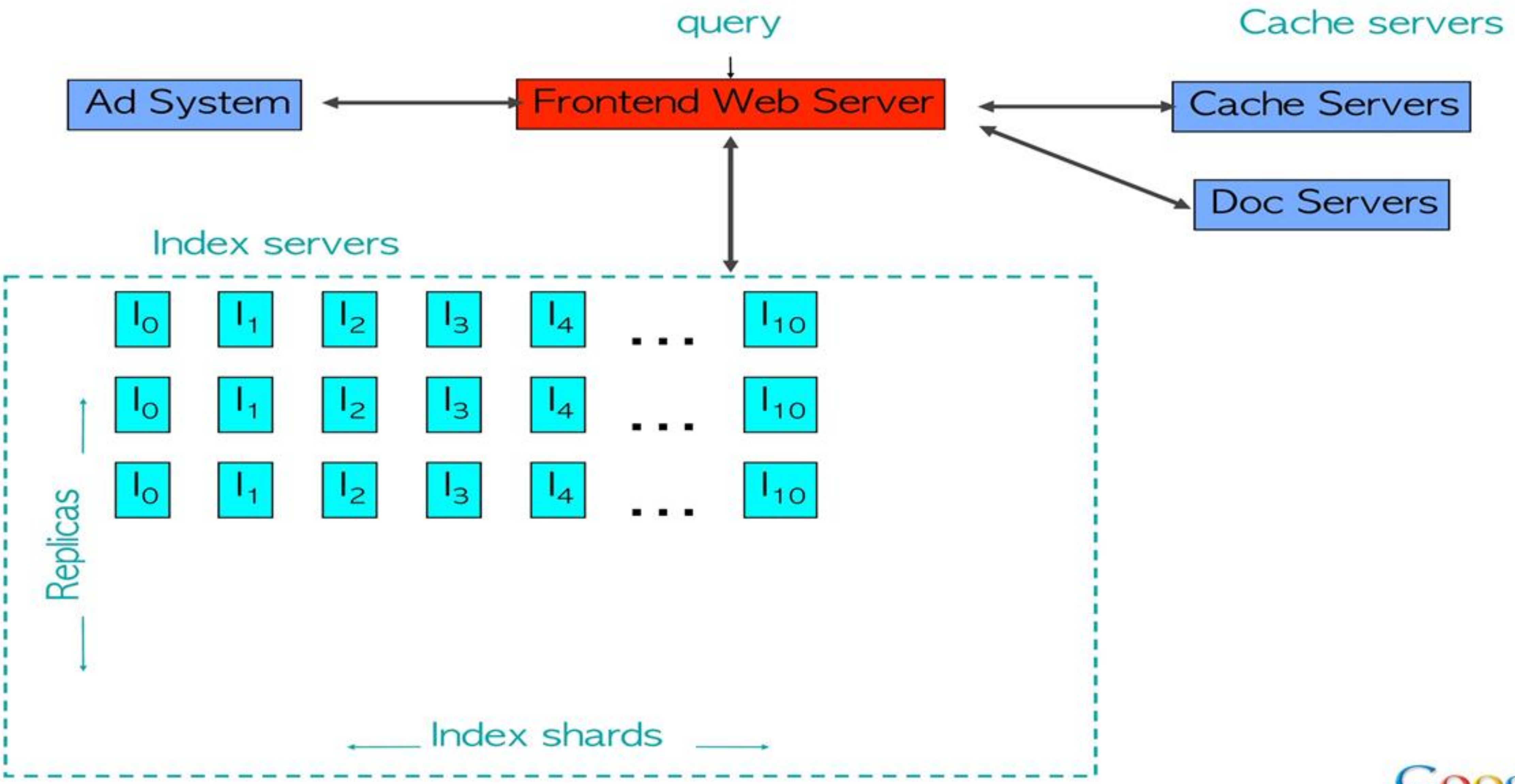
Dealing with Growth



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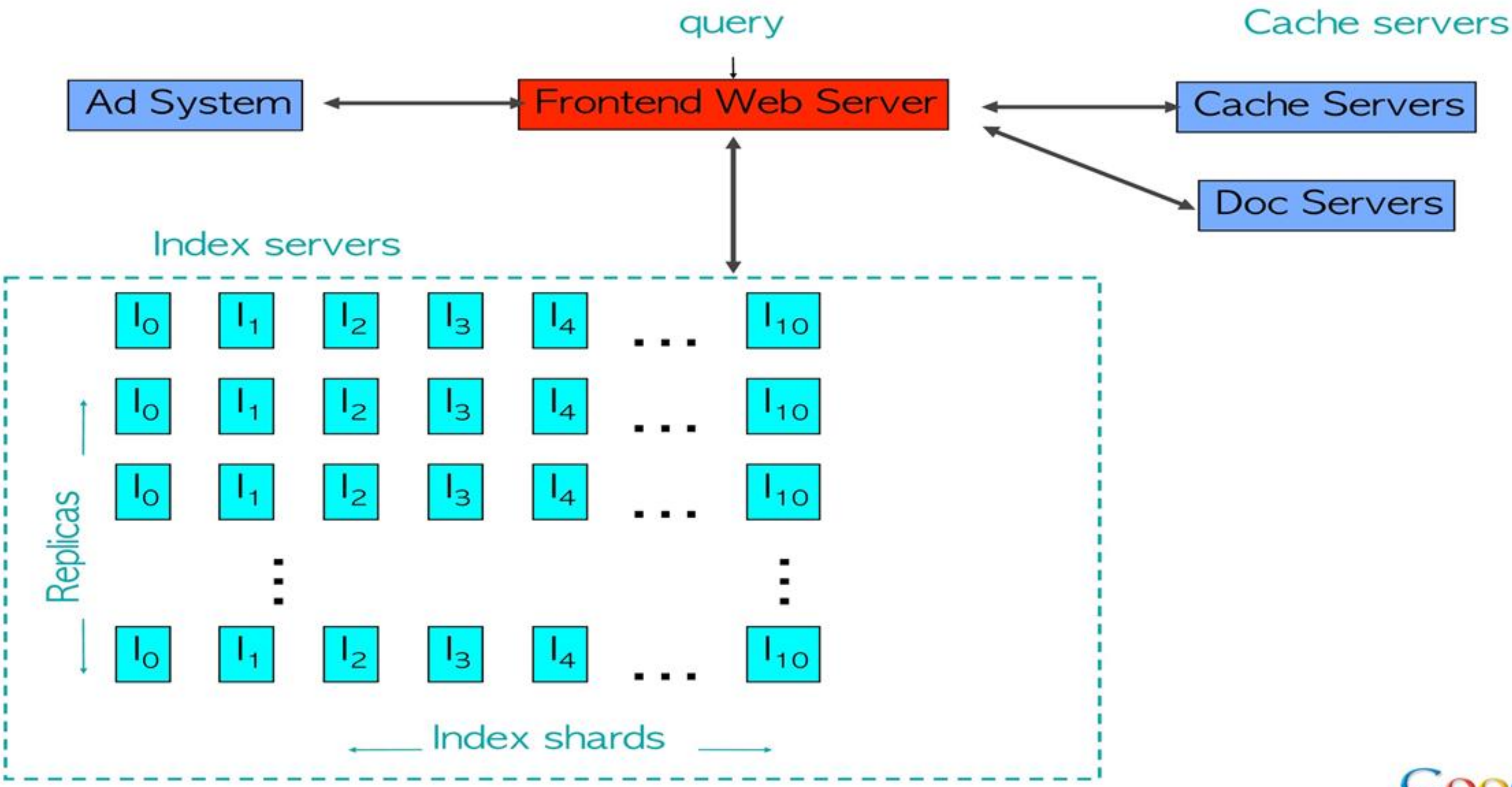
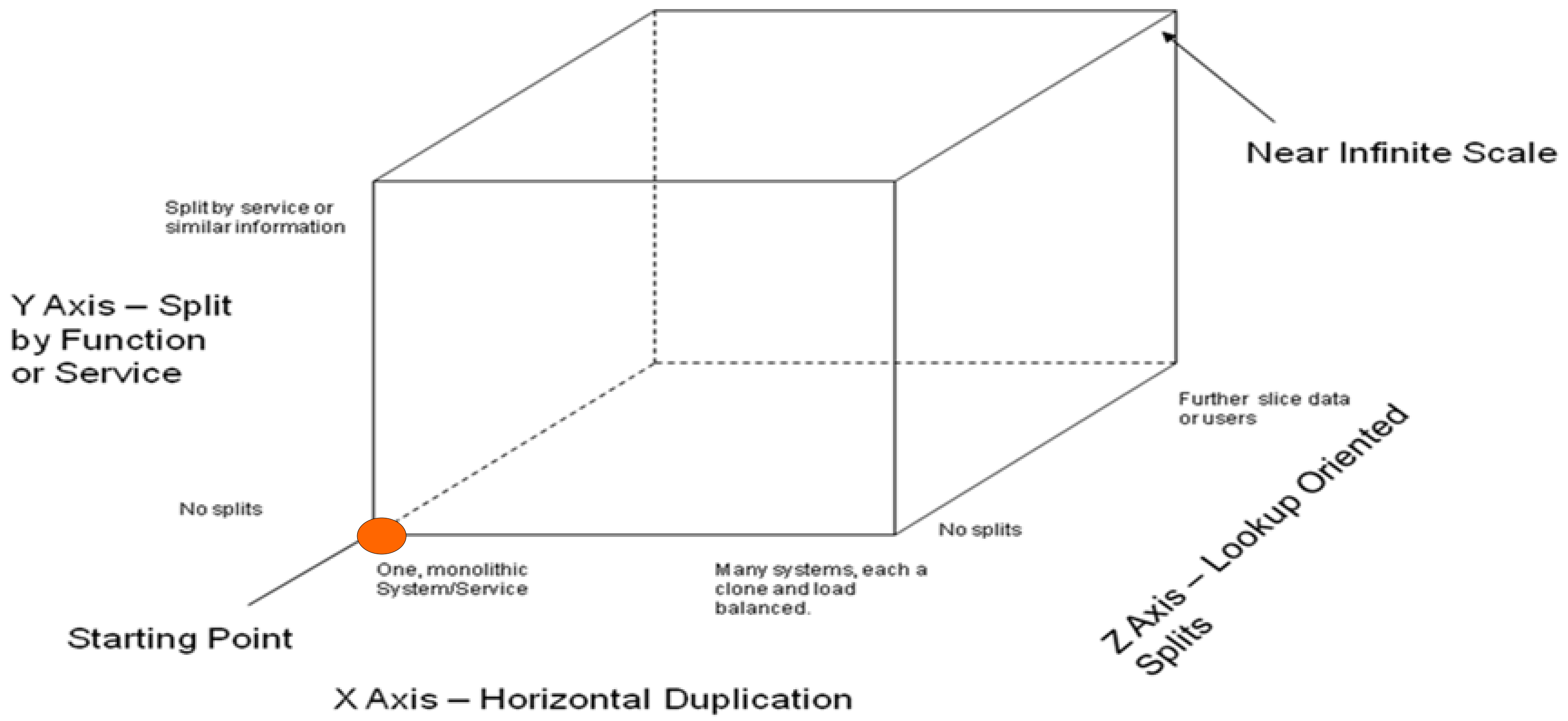


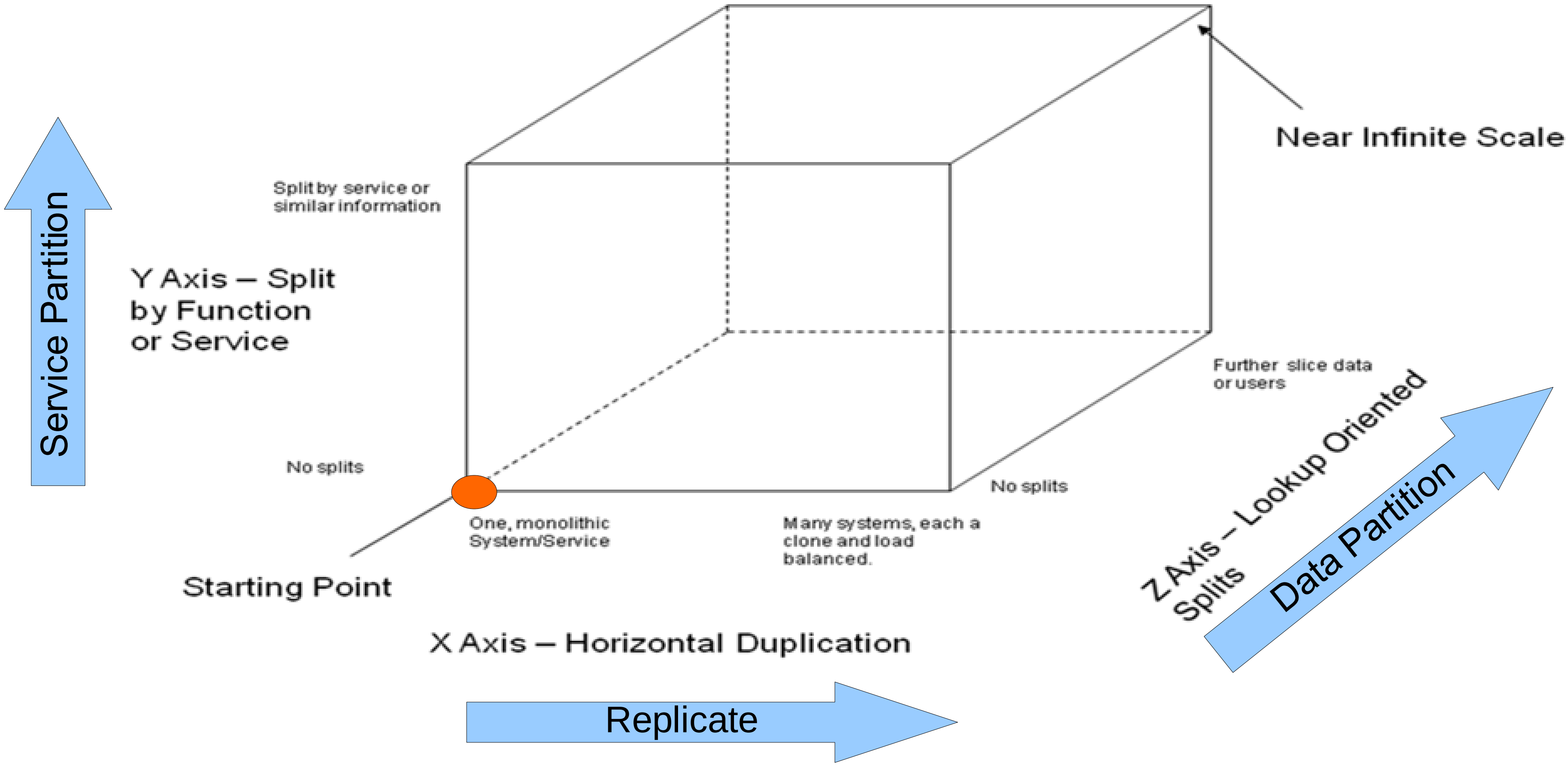
Google

AKF Scale Cube



Source: http://akfpartners.com/growth-blog/splitting-applications-or-services-for-scale

AKF Scale Cube



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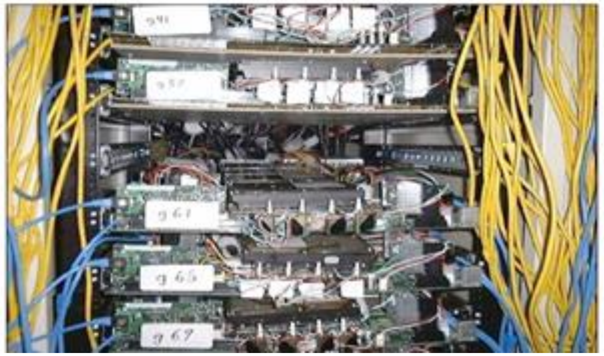
A Single Google Data Center now…

[CyrusOne Middenmeer, Netherlands]

*Each Data center is now easily equivalent to a 40-50 football stadium in size, consuming more than 100 megawatt s power

A Global View of Google Data Centers …

"Corkboards" (1999)



Google Data Center (2000)

Google Cloud regions. With around ~ 40 geographically distributed data centres [as of 2024]

Source: https://cloud.google.com/about/locations

Scaling Techniques

- Bigger machines
- Virtualization
- Asynchronous communication
- Replication & Caching
- Partitioning

➢Virtualization