Data Management in Large-Scale Distributed Systems

Introduction

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Organization of the course

18 hours

- 12 hours of lectures
- 6 hours of practical sessions

Grading

- Graded Lab (30% of the final grade)
- Written exam (70% of the final grade)
Covered topics

- The challenges of Big Data and distributed data processing
- The Map/Reduce programming model
- Batch and stream processing systems
- Distributed (NoSQL) databases
- About the design of these systems:
  - Their underlying design principles
  - The impact of Cloud characteristics
Overview of this lecture

• Introduction to the Big Data challenges
• Challenges of distributed computing
• Introduction to Cloud Computing
• Scalability techniques
Agenda

The challenges of Big Data

Distributed and Parallel Systems

Cloud Computing

Running at scale
References

- Coursera – *Big Data*, University of California San Diego
- The lecture notes of V. Leroy
- The lecture notes of R. Lachaize
- Designing Data-Intensive Applications by Martin Kleppmann
The data deluge

Many sources of data
The data deluge

Many sources of data

- Sensors
- Social media
- Scientific experiments
- Industry activity
- Etc.
Some numbers

• Every 2 days, we create as much information as we did since 2013\(^1\)
  ➤ 90% of all data has been created in the last two years
• 40K search queries on Google every second\(^2\)
• 45M messages on WhatsApp every minute
• 40 Billions of IoT devices by 2025.
• 570 new web sites every minute
• Largest database: 3.2 Trillions rows (AT&T)
• 40 TB of data every second during an experiment at the Large Hadron Collider

\(^1\)https://www.slideshare.net/BernardMarr/big-data-25-facts
Hardware capacity

Storage

• All the music of the world stored for $\sim 500$
• Large Amazon EC2 instance: 3.9TB of RAM, 8x7.5TB of SSD

Computing resources

• Google data-centers: more than 2.5M servers (2016)
• Amazon capacity increase each day = size of Amazon in 2005

Huge opportunities for storing and processing data
Big data challenges: The V’s

source: Big Data for Modern Industry: Challenges and Trends
Big data challenges: The V’s
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Big data challenges: The V’s

- **Volume**: Amount of data generated
- **Variety**: all kinds of data are generated (text, image, voice, time series, etc.)
- **Velocity**: Rate at which data are produced and should be processed
- **Veracity**: Noise/anomalies in data, truthfulness
- **Value**: How do we extract/learn valuable knowledge from the data
Big data challenges: The V’s

In this course we are going to deal with:

- **Volume**
- **Velocity**
- **Variety**

Questions to be answered:

- How to build a system and algorithms that can process huge amount of data?
- How to build a system and algorithms that can process data in a timely manner?
- (Bonus questions) How to build software that can deal with the variety of data?
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Motivation

The solution to process large amount of data:

**Using large amount of resources**

Note that:
- Different strategies can be used to leverage these resources
- Using large amount of resources presents new challenges
Increasing the processing power and the storage capacity

Goals

- Increasing the amount of data that can be processed (weak scaling)
- Decreasing the time needed to process a given amount of data (strong scaling)

Two solutions

- Scaling up
- Scaling out
Vertical scaling (scaling up)

Idea
Increase the processing power by adding resources to existing nodes:
• Upgrade the processor (more cores, higher frequency)
• Increase memory volume
• Increase storage volume

Pros and Cons
Vertical scaling (scaling up)

Idea
Increase the processing power by adding resources to existing nodes:
  • Upgrade the processor (more cores, higher frequency)
  • Increase memory volume
  • Increase storage volume

Pros and Cons
😊 Performance improvement without modifying the application
😊 Limited scalability (capabilities of the hardware, cf *The end of Moore’s law*)
😊 Expensive (non linear costs)
Horizontal scaling (scaling out)

Idea
Increase the processing power by adding more nodes to the system
- Cluster of commodity servers

Pros and Cons
Horizontal scaling (scaling out)

Idea
Increase the processing power by adding more nodes to the system
• Cluster of commodity servers

Pros and Cons
😊 Often requires modifying applications
😊 Less expensive (nodes can be turned off when not needed)
😊 Infinite scalability
Horizontal scaling (scaling out)

**Idea**
Increase the processing power by adding more nodes to the system
- Cluster of commodity servers

**Pros and Cons**
- 😞 Often requires modifying applications
- 😊 Less expensive (nodes can be turned off when not needed)
- 😊 *Infinite* scalability

The solution studied in this course
Large scale infrastructures

Figure: Google Data-center

Figure: Amazon Data-center

Figure: Barcelona Supercomputing Center
A distributed computing system is a system including several computational entities where:

- Each entity has its own local memory
- All entities communicate by message passing over a network

Each entity of the system is called a node.
Distributed computing: Challenges

1 Read Chapter 1 of *Designing Data-Intensive Applications* for further details.
Distributed computing: Challenges

Scalability

• How to take advantage of a large number of distributed resources?

Performance

• How to take full advantage of the available resources?
• Moving data is costly
  ▶ How to maximize the ratio between computation and communication?
• How to ensure that the latency of requests processing remains below some upper bound?

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1Read Chapter 1 of Designing Data-Intensive Applications for further details
Distributed computing: Challenges

Fault tolerance

- The more resources, the higher the probability of failure
- MTBF (Mean Time Between Failures)
  - MTBF of one server = 3 years
  - MTBF of 1000 servers ≃ 19 hours (beware: over-simplified computation)

- How to ensure computation completion?
- How to ensure that results are correct?

Programmability

- How to provide programming models that hide the complexity of distributed computing? (while remaining efficient)
- What high level services should be made available to ease life of programmers?
A warning about distributed computing

You can have a second computer once you've shown you know how to use the first one. (P. Braham)

Horizontal scaling is very popular.

• But not always the most efficient solution (both in time and cost)

Examples

• Processing a few 10s of GB of data is often more efficient on a single machine that on a cluster of machines
• Sometimes a single threaded program outperforms a cluster of machines (F. McSherry et al. “Scalability? But at what COST!”. 2015.)
Agenda

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Cloud Computing

Running at scale
Where to find computing resources?

Cloud computing

- A service provider gives access to computing resources through an internet connection.

Pros and Cons

© Pay only for the resources you use
© Get access to large amount of resources
▶ Amazon Web Services features millions of servers
▶ Volatility
▶ Low control on the resources
▶ Example: Access to resources based on bidding
▶ See “The Netflix Simian Army”
▶ Performance variability
▶ Physical resources shared with other users
Where to find computing resources?

Cloud computing

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Pros and Cons

😊 Pay only for the resources you use

😊 Get access to large amount of resources
  - Amazon Web Services features millions of servers

🚫 Volatility
  - Low control on the resources
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😊 Performance variability
  - Physical resources shared with other users
Architecture of a data center

Simplified

Switch

- : storage
- : memory
- : processor
Architecture of a data center

A shared-nothing architecture

• Horizontal scaling
• No specific hardware

A hierarchical infrastructure

• Resources clustered in racks
• Communication inside a rack is more efficient than between racks
• Resources can even be geographically distributed over several datacenters
A hybrid system

Two paradigms for communicating between computing entities:

- Shared memory
- Message passing
Shared memory

- Entities share a global memory
- Communication by reading and writing to the globally shared memory
- Communication between threads inside one node
Message passing

- Entities have their own private memory
- Communication by sending/receiving messages over a network
- Communication between nodes
Agenda

The challenges of Big Data

Distributed and Parallel Systems

Cloud Computing

Running at scale
Running at scale

How to distribute data?

• Partitioning

• Replication

- Several nodes host a copy of the data
- Main goal: Fault tolerance
  ▶ No data lost if one node crashes

- Splitting the data into partitions
- Partitions are assigned to different nodes
- Main goal: Performance
  ▶ Partitions can be processed in parallel
Running at scale

How to distribute data?

- Partitioning
- Replication

Replication

- Several nodes host a copy of the data
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Partitioning

- Splitting the data into partitions
- Partitions are assigned to different nodes
- Main goal: Performance
  - Partitions can be processed in parallel
Replication

Purposes

• Continuing to serve requests when parts of the system fail
• Keep data close to the users
• Having multiple servers able to answer read requests

Challenges

• How to handle operations that modify data? (write operations)
  ▶ Consistency (Consensus in a distributed system is a very difficult problem)
  ▶ Performance
Replication

Client 1

read A

Switch

write A

write A=1

write A=2

??
Replication

Client 1

Switch

read A

write A

write A=1

write A=2

??
Replication

Client 1

read A

Switch

Client 2

write A=1
write A=2

??
Replication

Client 1

read A

Switch

Client 2

write A=1

write A=2
Replication

Client 1
read A

Client 2
read A

Switch

A

A

A

A

A
Replication

Client 1
write A
Client 2

write A = 1
write A = 2
Replication

write $A=1$

Client 1

write $A=2$

Client 2

Switch
Replication

write $A=1$
Client 1

write $A=2$
Client 2

write $A=1$
Switch

write $A=2$
Switch
Partitioning

Sharding

Purposes

• Performance
  ▶ Distributing the load over several nodes

Challenges

• How to partition the data?
  ▶ Evenly distributed load (even for skewed workloads)
  ▶ Range queries
Partitioning

Client 1

Switch

Client 2

- Client 1: read A, write A
- Client 2: read C, write C
- Switch: read A-D
Partitioning

Client 1

- read A

Client 2

- read C

Switch

- B

- C

- D

A

read A

write A

read A-D
Partitioning

write A
Client 1

B

write C
Client 2

A

D

C
Partitioning

Client 1

read A-D

Switch

A

B

C

D
Partitioning + Replication
More references

Mandatory reading

• *Big data and its technical challenges*, by Jagadish et al, CACM 2014.

Suggested reading

• Chapter 1 of *Designing Data-Intensive Applications* by Martin Kleppmann
• The Netflix Simian Army\(^1\)

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\(^1\)https://medium.com/netflix-techblog/the-netflix-simian-army-16e57fbab116