Course originally by Hector Garcia-Molina (1954-2019)
My Background

- PhD in 2013
- Open source distributed data processing framework
- Data & ML platform startup
- Research in systems for ML
Outline

Why study data-intensive systems?
Course logistics
Key issues and themes
A bit of history
Why Study Data-Intensive Systems?

Most important computer applications must manage, update and query datasets
  » Bank, store, fleet controller, search app, …

Data quality, quantity & timeliness becoming even more important with AI
  » Machine learning = algorithms that generalize from data
What Are Data-Intensive Systems?

Relational databases: most popular type of data-intensive system (MySQL, Oracle, etc)

Many systems facing similar concerns: message queues, key-value stores, streaming systems, ML frameworks, your custom app?

Goal: learn the main issues and principles that span all data-intensive systems
Typical System Challenges

Reliability in the face of hardware crashes, bugs, bad user input, etc

Concurrency: access by multiple users

Performance: throughput, latency, etc

Access interface from many, changing apps

Security and data privacy
Practical Benefits of Studying These Systems

Learn how to select & tune data systems

Learn how to build them

Learn how to build apps that have to tackle some of these same challenges
  » E.g. cross-geographic-region billing app, custom search engine, etc
Scientific Interest

Interesting algorithmic and design ideas

In many ways, data systems are the highest-level successful programming abstractions
Programming: The Dream

∀

\[ \sum_{x \in S_i \cup T_i} \lambda x. x^2 (...) \]

High-level spec

Working application
∀ i # ∈ & ’ ∪ 𝜆 𝑥 . 𝑥 - (…)

Working application
High-level spec
Programming: The Reality

How to horizontally center a `<div>`?

How can I horizontally center a `<div>` within another `<div>` using CSS?

How to find which version of TensorFlow is installed in my system?

Why does HTML think “chucknorris” is a color?

How come certain random strings produce colors when entered as background colors in HTML? For example:

```
<body bgcolor="chucknorris"> test </body>
```

...produces a document with a red background across all browsers and platforms.

Interestingly, while `chucknorris` produces a red background as well, `chucknorr` produces a yellow background.

What's going on here?
Programming with Databases

High-level spec

Relational algebra

Actually manages:
- Durability
- Concurrency
- Query optimization
- Security
- ...
Outline

Why study data-intensive systems?

Course logistics

Key issues and themes

A bit of history
Teaching Assistants

Pratiksha Thaker  Peter Kraft  Wantong Jiang  Ben Hannel

Office hours will be posted on website
Course Format

Lectures in class

Optional textbook

Assigned paper readings (Q&A in class)

3 programming assignments

Midterm and final
Optional Textbook

Database Systems: The Complete Book

Chapters 13-20

By the original Stanford InfoLab group (Hector Garcia-Molina, Jeff Ullman, Jennifer Widom)
Paper Readings

A few classic or recent research papers

Read the paper **before** the class: we want to discuss it together!

We’ll post discussion questions on the class website 2-3 weeks before lecture
How Should You Read a Paper?

Read: “How to Read a Paper”

TLDR: don’t just go through end to end; focus on key ideas/sections

How to Read a Paper

Version of February 17, 2016

S. Keshav
David R. Cheriton School of Computer Science, University of Waterloo
Waterloo, ON, Canada
keshav@uwaterloo.ca

ABSTRACT
Researchers spend a great deal of time reading research papers. However, this skill is rarely taught, leading to much wasted effort. This article outlines a practical and efficient three-pass method for reading research papers. I also describe how to use this method to do a literature survey.

1. INTRODUCTION
Researchers must read papers for several reasons: to review them for a conference or a class, to keep current in their field, or for a literature survey of a new field. A typical researcher will likely spend hundreds of hours every year reading papers.

Learning to efficiently read a paper is a critical but rarely taught skill. Beginning graduate students, therefore, must learn on their own using trial and error. Students waste much effort in the process and are frequently driven to frustration.

For many years I have used a simple “three-pass” approach to prevent me from drowning in the details of a paper before getting a bird’s-eye view. It allows me to estimate the amount of time required to review a set of papers. Moreover, I can adjust the depth of paper evaluation depending on my needs and how much time I have. This paper describes the approach and its use in doing a literature survey.

2. THE THREE-PASS APPROACH
The key idea is that you should read the paper in up to three passes, instead of starting at the beginning and plowing your way to the end. Each pass accomplishes specific goals and builds upon the previous pass. The first pass gives you a general idea about the paper. The second pass lets you grasp the paper’s content, but not its details. The third pass helps you understand the paper in depth.

4. Read the conclusions
5. Glance over the references, mentally ticking off the ones you’ve already read

At the end of the first pass, you should be able to answer the five Cs:
1. Category: What type of paper is this? A measurement paper? An analysis of an existing system? A description of a research prototype?
2. Context: Which other papers is it related to? Which theoretical bases were used to analyze the problem?
3. Correctness: Do the assumptions appear to be valid?
4. Contributions: What are the paper’s main contributions?
5. Clarity: Is the paper well written?

Using this information, you may choose not to read further (and not print it out, thus saving trees). This could be because the paper doesn’t interest you, or you don’t know enough about the area to understand the paper, or that the authors make invalid assumptions. The first pass is adequate for papers that aren’t in your research area, but may someday prove relevant.

Incidentally, when you write a paper, you can expect most reviewers (and readers) to make only one pass over it. Take care to choose coherent section and sub-section titles and to write concise and comprehensive abstracts. If a reviewer cannot understand the gist after one pass, the paper will likely be rejected, if a reader cannot understand the highlights of the paper after five minutes, the paper will likely never be read. For these reasons, a ‘graphical abstract’ that summarizes a paper with a single well-chosen figure is an excellent way to make the essence of the paper known at first glance.
Our First Paper

We’ll be reading part of “A History and Evaluation of System R” for next class!

Find instructions and questions on website
Programming Assignments

Three assignments implemented in Java or Scala, and submitted online

1. Storage and access methods
2. Query optimization
3. Transactions and recovery

Done individually; A1 posted next week
Midterm and Final

Written tests based on material covered in lectures, assignments and readings

Final will cover the entire course but focus on the second half
Grading

45% Assignments (15% each)

25% Midterm

30% Final
Keeping in Touch

Sign up for Piazza on the course website to receive announcements!

[cs245.stanford.edu](http://cs245.stanford.edu)
Outline

Why study data-intensive systems?

Course logistics

Key issues and themes

A bit of history
Recall: Examples of Data-Intensive Systems

Relational databases: most popular type of data-intensive system (MySQL, Oracle, etc)

Many systems facing similar concerns: message queues, key-value stores, streaming systems, ML frameworks, your custom app?
Basic Components

- Clients / users
- Queries
- Administrator
- Logical dataset (e.g. table, graph)
- Data mgmt. system
- Physical storage (data structures)

### Data mgmt. system

<table>
<thead>
<tr>
<th>First Name</th>
<th>Last Name</th>
<th>Address</th>
<th>City</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ritchie</td>
<td>Hoyle</td>
<td>123 Fantasy Way</td>
<td>Adelaide</td>
<td>73</td>
</tr>
<tr>
<td>Red</td>
<td>Mee</td>
<td>162 Canvas Ave</td>
<td>Gotham</td>
<td>84</td>
</tr>
<tr>
<td>Money</td>
<td>Womac</td>
<td>987 Truth Way</td>
<td>Pencile</td>
<td>39</td>
</tr>
<tr>
<td>Conrad</td>
<td>Dink</td>
<td>199 Quest Street</td>
<td>Hilden</td>
<td>85</td>
</tr>
<tr>
<td>Ogma</td>
<td>Krems</td>
<td>587 Camel Street</td>
<td>Torbal</td>
<td>35</td>
</tr>
<tr>
<td>Eldy</td>
<td>Curley</td>
<td>989 Rave Way</td>
<td>Ceylon</td>
<td>44</td>
</tr>
<tr>
<td>Cel</td>
<td>Womans</td>
<td>246 Parcifal Street</td>
<td>Hallbell</td>
<td>32</td>
</tr>
<tr>
<td>Tooney</td>
<td>Bird</td>
<td>965</td>
<td>Belheav</td>
<td>20</td>
</tr>
</tbody>
</table>
# Examples

<table>
<thead>
<tr>
<th>System</th>
<th>Logical Data Model</th>
<th>Physical Storage</th>
<th>API</th>
<th>Other Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relational databases</td>
<td>Relations (i.e. tables)</td>
<td>B-trees, column stores, indexes, …</td>
<td>SQL, ODBC</td>
<td>Durability, transactions, query planning, migrations, …</td>
</tr>
</tbody>
</table>
## Examples

<table>
<thead>
<tr>
<th>System</th>
<th>Logical Data Model</th>
<th>Physical Storage</th>
<th>API</th>
<th>Other Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relational databases</td>
<td>Relations (i.e. tables)</td>
<td>B-trees, column stores, indexes, …</td>
<td>SQL, ODBC</td>
<td>Durability, transactions, query planning, migrations, …</td>
</tr>
<tr>
<td>TensorFlow</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TensorFlow
## Examples

<table>
<thead>
<tr>
<th>System</th>
<th>Logical Data Model</th>
<th>Physical Storage</th>
<th>API</th>
<th>Other Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relational databases</td>
<td>Relations (i.e. tables)</td>
<td>B-trees, column stores, indexes, ...</td>
<td>SQL, ODBC</td>
<td>Durability, transactions, query planning, migrations, ...</td>
</tr>
<tr>
<td>TensorFlow</td>
<td>Tensors</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
# Examples

<table>
<thead>
<tr>
<th>System</th>
<th>Logical Data Model</th>
<th>Physical Storage</th>
<th>API</th>
<th>Other Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relational databases</td>
<td>Relations (i.e. tables)</td>
<td>B-trees, column stores, indexes, ...</td>
<td>SQL, ODBC</td>
<td>Durability, transactions, query planning, ...</td>
</tr>
<tr>
<td>TensorFlow</td>
<td>Tensors</td>
<td>NCHW, NHWC, sparse arrays, ...</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
# Examples

<table>
<thead>
<tr>
<th>System</th>
<th>Logical Data Model</th>
<th>Physical Storage</th>
<th>API</th>
<th>Other Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relational databases</td>
<td>Relations (i.e. tables)</td>
<td>B-trees, column stores, indexes, …</td>
<td>SQL, ODBC</td>
<td>Durability, transactions, query planning, migrations, …</td>
</tr>
<tr>
<td>TensorFlow</td>
<td>Tensors</td>
<td>NCHW, NHWC, sparse arrays, …</td>
<td>Python DAG construction</td>
<td></td>
</tr>
</tbody>
</table>
# Examples

<table>
<thead>
<tr>
<th>System</th>
<th>Logical Data Model</th>
<th>Physical Storage</th>
<th>API</th>
<th>Other Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relational databases</td>
<td>Relations (i.e. tables)</td>
<td>B-trees, column stores, indexes, …</td>
<td>SQL, ODBC</td>
<td>Durability, transactions, query planning, migrations, …</td>
</tr>
<tr>
<td>TensorFlow</td>
<td>Tensors</td>
<td>NCHW, NHWC, sparse arrays, …</td>
<td>Python DAG construction</td>
<td>query planning, distribution, specialized HW</td>
</tr>
</tbody>
</table>
## Examples

<table>
<thead>
<tr>
<th>System</th>
<th>Logical Data Model</th>
<th>Physical Storage</th>
<th>API</th>
<th>Other Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relational databases</td>
<td>Relations (i.e. tables)</td>
<td>B-trees, column stores, indexes, …</td>
<td>SQL, ODBC</td>
<td>Durability, transactions, query planning, migrations, …</td>
</tr>
<tr>
<td>TensorFlow</td>
<td>Tensors</td>
<td>NCHW, NHWC, sparse arrays, …</td>
<td>Python DAG</td>
<td>query planning, distribution, specialized HW</td>
</tr>
<tr>
<td>Apache Kafka</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>System</td>
<td>Logical Data Model</td>
<td>Physical Storage</td>
<td>API</td>
<td>Other Features</td>
</tr>
<tr>
<td>----------------------</td>
<td>-----------------------------</td>
<td>-----------------------------------</td>
<td>----------------------</td>
<td>-----------------------------------</td>
</tr>
<tr>
<td>Relational databases</td>
<td>Relations (i.e. tables)</td>
<td>B-trees, column stores, indexes,</td>
<td>SQL, ODBC</td>
<td>Durability, transactions, query planning, migrations, …</td>
</tr>
<tr>
<td>TensorFlow</td>
<td>Tensors</td>
<td>NCHW, NHWC, sparse arrays, …</td>
<td>Python DAG construction</td>
<td>query planning, distribution, specialized HW</td>
</tr>
<tr>
<td>Apache Kafka</td>
<td>Streams of opaque records</td>
<td>Partitions, compaction</td>
<td>Publish, subscribe</td>
<td>Durability, rescaling</td>
</tr>
</tbody>
</table>
## Examples

<table>
<thead>
<tr>
<th>System</th>
<th>Logical Data Model</th>
<th>Physical Storage</th>
<th>API</th>
<th>Other Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relational databases</td>
<td>Relations (i.e. tables)</td>
<td>B-trees, column stores, indexes, …</td>
<td>SQL, ODBC</td>
<td>Durability, transactions, query planning, migrations, …</td>
</tr>
<tr>
<td>TensorFlow</td>
<td>Tensors</td>
<td>NCHW, NHWC, sparse arrays, …</td>
<td>Python DAG construction</td>
<td>query planning, distribution, specialized HW</td>
</tr>
<tr>
<td>Apache Kafka</td>
<td>Streams of opaque records</td>
<td>Partitions, compaction</td>
<td>Publish, subscribe</td>
<td>Durability, rescaling</td>
</tr>
<tr>
<td>Apache Spark RDDs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
# Examples

<table>
<thead>
<tr>
<th>System</th>
<th>Logical Data Model</th>
<th>Physical Storage</th>
<th>API</th>
<th>Other Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relational databases</td>
<td>Relations (i.e. tables)</td>
<td>B-trees, column stores, indexes, …</td>
<td>SQL, ODBC</td>
<td>Durability, transactions, query planning, migrations, …</td>
</tr>
<tr>
<td>TensorFlow</td>
<td>Tensors</td>
<td>NCHW, NHWC, sparse arrays, …</td>
<td>Python DAG construction</td>
<td>query planning, distribution, specialized HW</td>
</tr>
<tr>
<td>Apache Kafka</td>
<td>Streams of opaque records</td>
<td>Partitions, compaction</td>
<td>Publish, subscribe</td>
<td>Durability, rescaling</td>
</tr>
<tr>
<td>Apache Spark RDDs</td>
<td>Collections of Java objects</td>
<td>Read external systems, cache</td>
<td>Functional API, SQL</td>
<td>Distribution, query planning, transactions*</td>
</tr>
</tbody>
</table>

*Transactions enabled through specialized hardware.
Some Typical Concerns

Access interface from many, changing apps

Performance: throughput, latency, etc

Reliability in the face of hardware crashes, bugs, bad user input, etc

Concurrency: access by multiple users

Security and data privacy
Example

Message queue system

What should happen if two consumers read() at the same time?
Example

Message queue system

What should happen if a consumer reads a message but then immediately crashes?
Example

Message queue system

Can a producer put in 2 messages atomically?
Two Big Ideas

Declarative interfaces
» Apps specify *what* they want, not *how* to do it
» Example: “store a table with 2 integer columns”, but not how to encode it on disk
» Example: “count records where column1 = 5”

Transactions
» Encapsulate multiple app actions into one *atomic* request (fails or succeeds as a whole)
» Concurrency models for multiple users
» Clear interactions with failure recovery
Declarative Interface Examples

SQL
  » Abstract “table” data model, many physical implementations
  » Specify queries in a restricted language that the database can optimize

TensorFlow
  » Operator graph gets mapped & optimized to different hardware devices

Functional programming (e.g. MapReduce)
  » Says what to run but not how to do scheduling
Transaction Examples

SQL databases
- Commands to start, abort or end transactions based on multiple SQL statements

Apache Spark, MapReduce
- Make the multi-part output of a job appear atomically when all partitions are done

Stream processing systems
- Count each input record exactly once despite crashes, network failures, etc
Outline

Why study data-intensive systems?

Course logistics

Key issues and themes

A bit of history
Early Data Management

At first, each application did its own data management directly against storage.

I’d like a computerized account system

I have just the thing

Ye Olde Bank

write_block()

read_block()

Stores 5 MB!
Problems with App Storage Management

How should we lay out and navigate data?
How do we keep the application reliable?
What if we want to share data across apps?

Every app is solving the same problems!
Navigational Databases (1964)

CODASYL, IDS

Data is graph of records

Procedural API based on navigating links:

```plaintext
get department with name='Sales'
get first employee in set department-employees
until end-of-set do {
    get next employee in set department-employees
    process employee
}
```

“Data independence”: app code not tied to storage details
I raise the example of Copernicus today to illustrate a parallel that I believe exists in the computing or, more properly, the information systems world. We have spent the last 50 years with almost Ptolemaic information systems. These systems, and most of the thinking about systems, were based on a "computer centered" concept.

A new basis for understanding is available in the area of information systems. It is achieved by a shift from a computer-centered to the database-centered point of view. This new understanding will lead to new solutions to our database problems and speed our conquest of the $n$-dimensional data structures which best model the complexities of the real world.

Charles W. Bachman, "The Programmer as Navigator"
Edgar F. (Ted) Codd

Proposed the relational DB model, with declarative queries & storage (1970)

Relation = table with unique key identifying each row

Data independence++: apps don’t even specify how to execute query
Key Ideas in Relational DBMS

Clients / users

Relational algebra (e.g. SQL)

Logical data model: tables with references across them (foreign keys)

Data mgmt. system

Query planning, access methods, transactions, etc

Physical storage: raw files, B-trees, hash indexes, etc
Early Relational DBMS

IBM System R (1974): research system
   » Led to IBM SQL/DS in 1981

Ingres (1974): Mike Stonebraker at Berkeley
   » Led to PostgreSQL

Oracle database (released 1979)

Next class, we’ll cover database architecture by looking at System R
Rest of the Course

We’ll explore both “big ideas” we saw, focusing on relational DBs but showing examples in other areas.

- Declarative interfaces
  - Data independence and data storage formats
  - Query languages and optimization
- Transactions, concurrency & recovery
  - Concurrency models
  - Failure recovery
  - Distributed storage and consistency

Don’t forget to sign up for Piazza!