Welcome to

CS 660: Grad Intro to Database Systems

https://bu-disc.github.io/CS660/

Instructor: *Manos Athanassoulis*
email: mathan@bu.edu

CS660: Course Overview

Design & implementation of Database Management Systems (DBMSs).

We do **not** study how to use a DBMS to build applications or how to administer a DBMS.

We have a **C++ based project**; we assume you have prior C++ knowledge.

→ that is, while we will offer help we will not teach C++ in the labs

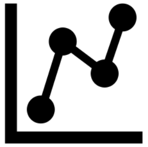
Course Summary

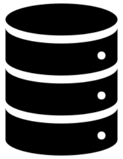
We will learn how to:

- **Model data**
  Relational Model
- **Access** and **Query data**
  SQL
- **Store & manage** data
  Bits to Files to Disks, Storage Layouts, Indexes, Sorting
- **Reason** about query performance
  Query evaluation & optimization
- **Update** data
  Transactions, logging, ACID properties

Today: Why Study Databases?

big data

data-driven world 

databases & database systems 

when you see this, I want you to speak up!
[and you can always interrupt me]

How big is “Big”?

Every day, we create 2.5 exabytes* of data — 90% of the data in the world today has been created in the last two years alone.

[Understanding Big Data, IBM]

*exabyte = 10^9 GB

CS660

we live in a ***data-driven*** world

CS660 is about the ***basics*** for
storing, ***using***, and ***managing*** data

your lecturer (that's me!)

Manos Athanassoulis

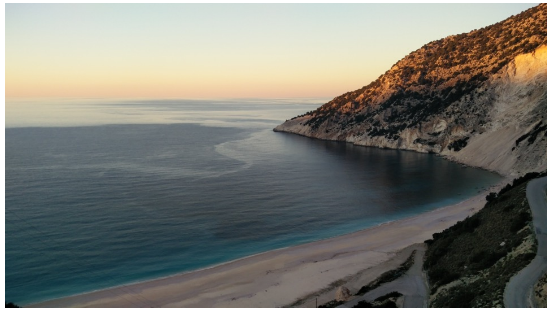
name in greek: Μάνος Αθανασούλης

grew up in Greece
enjoys playing basketball and the sea

BSc and MSc @ University of Athens, Greece
PhD @ EPFL, Switzerland
Research Intern @ IBM Research Watson, NY
Postdoc @ Harvard University
Visiting Faculty @ Meta

some awards:
Facebook Faculty Research Award
NSF CAREER Award
Best Demo @ VLDB 2023
Best of SIGMOD 2017, VLDB 2017


photo for VISA / conferences



Myrtos, Kefalonia, Greece

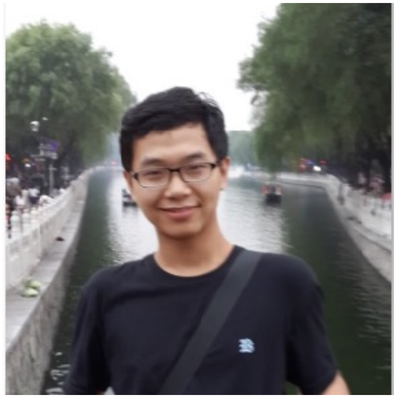
http://cs-people.bu.edu/mathan/
Office: CDS928
Office Hours: Tue @ 10am and Thu @2pm

your awesome TFs

Head TF

Kostas Karatsenidis
PhD student in DB
karatse@bu.edu
OH: M@12-1pm & Tu@11am-12pm

Aneesh Raman
PhD student in DB
aneeshr@bu.edu
OH: W@11am-12pm



Zichen Zhu
PhD student in DB
zczhu@bu.edu
OH: Th@5-6pm

Data

to make data **usable** and **manageable**

we organize them in **collections**

Databases

a large, integrated, *structured* collection of data

intended to model some <u>real-world</u> enterprise

<u>Examples</u>: a university, a company, social media

<u>Social media:</u> users, posts, photos

what is missing?

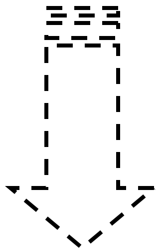
-- how to connect these?

-- shares, likes, friend-relationship

Database Systems

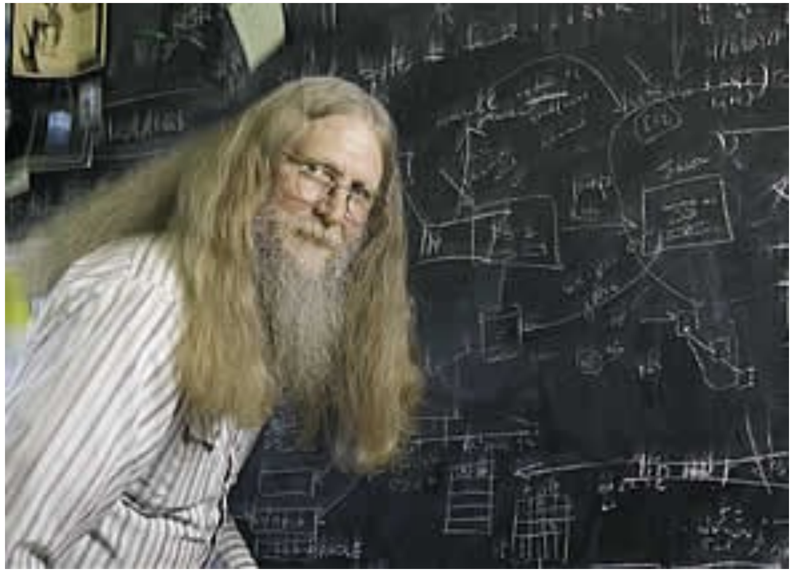
a.k.a. database management systems (DBMS)
a.k.a. data systems

Sophisticated
pieces of software…



… which store, manage,
organize, and facilitate
access to my databases …

… so I can do things (and ask questions) that are
otherwise hard or impossible



"relational databases are the foundation of western civilization"

Bruce Lindsay, IBM Research

ACM SIGMOD Edgar F. Codd Innovations award 2012

Ok but what really IS a database system?

Is the Internet a DBMS?

Is a File System a DBMS?

Are Social Media a DBMS?

Is the Internet a DBMS?

Not really!

Fairly sophisticated search available

web crawler *indexes* pages for fast search

.. but

data is unstructured and untyped

not well-defined “correct answer”

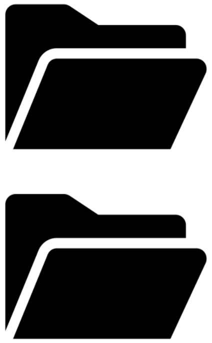
cannot update the data

freshness? consistency? fault tolerance?

web sites **use** a *DBMS* to provide these functions

e.g., amazon.com (Oracle), facebook.com (MySQL and others)

Is a File System a DBMS?

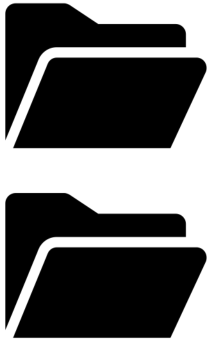


Thought Experiment 1:

- You and your project partner are editing the same file.
- You both save it at the same time.
- Whose changes survive?

A) Yours **B) Partner's** **C) Both** **D) Neither** **E) ???**

Is a File System a DBMS?



Thought Experiment 1:

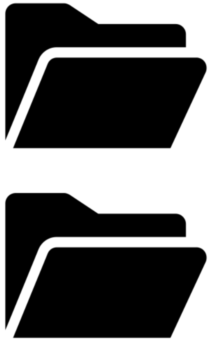
- You and your project partner are editing the same file.
- You both save it at the same time.
- Whose changes survive?

A) Yours B) Partner's C) Both D) Neither E) ???

Thought Experiment 2:

- You're updating a file.
- The power goes out.
- Which of your changes survive?

A) All B) None C) All Since last save D) ???



Is a File System a DBMS?

Not really!

Thought Experiment 1:

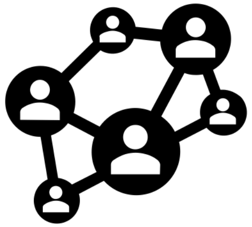
- You and your project partner are editing the same file.
- You both save it at the same time.
- Whose changes survive?

A) Yours B) Partner’s C) Both D) Neither E) ???

Thought Experiment 2:

- You’re updating a file.
- The power goes out.
- Which of your changes survive?

A) All B) None C) All Since last save D) ???



Are Social Media a DBMS?

Not really!

Is the data structured & typed?

Does it offer well-defined queries?

Does it offer properties like “durability” and “consistency”?

For example, Facebook is a data-driven company that uses several database systems (>10) for different use-cases (internal or external).

Are Large Language Models Databases?

What happens if I ask the same query multiple times?

Not really!

How does it get updated?

Does it offer properties like “durability” and “consistency”?

Why take this class?

computation to *information*

corporate, personal (web), science (big data)

database systems *everywhere*

data-driven world, data companies

DBMS: much of CS as a practical discipline

languages, theory, OS, logic, architecture, HW

CS660 in a nutshell

model
data representation model

query
query languages – ad hoc queries

access (concurrently multiple reads/writes)
ensure *transactional* semantics

store (reliably)
maintain *consistency/semantics* in *failures*

A “free taste” of the class

data modeling

query languages

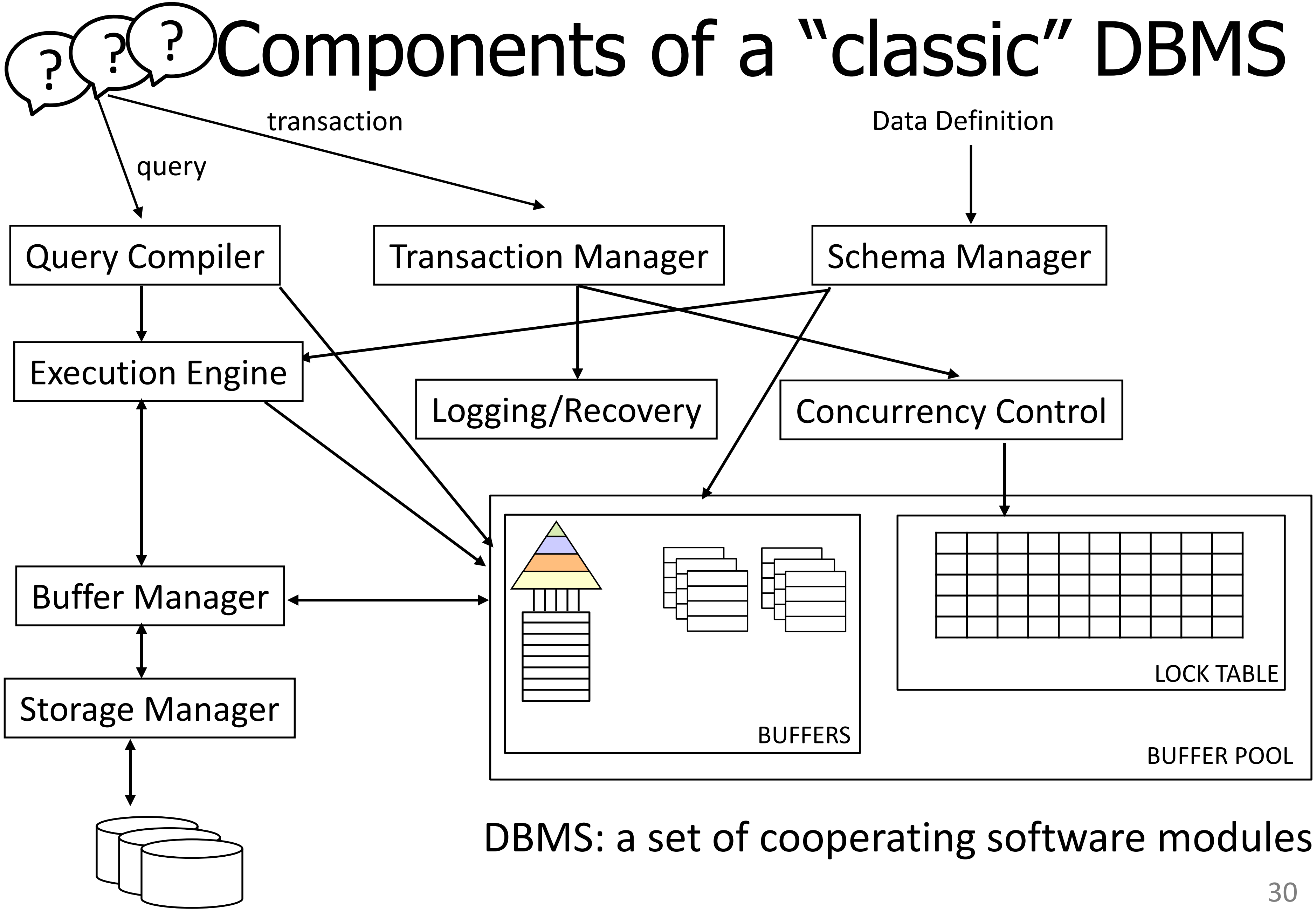
concurrent, fault-tolerant data management

DBMS architecture

Coming in next class

Discussion on *database systems* *designs*

Components of a "classic" DBMS



DBMS: a set of cooperating software modules

Describing Data: Data Models

data model : a collection of concepts describing data

Relational ← Most Database Systems

Key / Value
Graph
Document / Object
Wide-Column / Column-Family

NoSQL

Array / Matrix / Vectors
Hierarchical
Network
Multi-valued

Relational	Key/Value
tables with rows and columns	collections of documents
well-defined schema	schema-less (each document can have different schema)
data model fits data rather than functionality	data stored in an application-friendly way
deduplication	possible duplication

based on a table from http://readwrite.com

Describing Data: Data Models

data model : a collection of concepts describing data

Relational ← Most Database Systems

- Key / Value
- Graph
- Document / Object
- Wide-Column / Column-Family

NoSQL

- Array / Matrix / Vectors

Machine Learning Workloads

- Hierarchical
- Network
- Multi-valued

Legacy/Obsolete/Rare

Relational Model: Definitions

relational database: a collection (set) of *relations*

each relation: basically a table with rows and columns, made up of 2 parts

(1) *schema:* describes the columns (or fields) of each table

Name of relation

Students (*sid*: string, *name*: string, *login*: string, *age*: integer, *gpa*: real)

Name and type of each column

(2) *instance* : a *table,* with rows and columns.

#rows = *cardinality*

#fields = *degree / arity*

a relation is a *set* of *tuples* (a.k.a. rows)

1. all rows are distinct
2. no order among rows

Schema of "University" Database

Students

***sid**: string, **name**: string, **login**: string, **age**: integer, **gpa**: real*

Courses

***cid**: string, **cname**: string, **credits**: integer*

Enrolled

***sid**: string, **cid**: string, **grade**: string*

Instance of Students Relation

sid	name	login	age	gpa
53666	Jones	jones@cs	18	3.4
53688	Smith	smith@cs	18	3.2
53650	Smith	smith@math	19	3.8

cardinality = 3, arity = 5, all rows distinct

do all values in each column of a relation instance have to be distinct?

SQL - A language for Relational DBs

SQL* (a.k.a. "Sequel"), standard language

Data Definition Language (DDL)

create, modify, delete relations

specify constraints

administer users, security, etc.

Data Manipulation Language (DML)

specify *queries* to find tuples that satisfy criteria

add, modify, remove tuples

* Structured Query Language

SQL Overview

```
CREATE TABLE <name> ( <field> <domain>, … )

INSERT INTO <name> (<field names>)
     VALUES (<field values>)

DELETE FROM <name>
      WHERE <condition>

UPDATE <name>
   SET <field name> = <value>
 WHERE <condition>

SELECT <fields>
  FROM <name>
 WHERE <condition>
```

Creating Relations in SQL

type (domain) of each field is specified

also enforced whenever tuples are added or modified

```
CREATE TABLE Students
     (sid CHAR(20),
      name CHAR(20),
      login CHAR(10),
      age INTEGER,
      gpa FLOAT)
```

Table Creation (continued)

Enrolled: holds information about courses students take

```
CREATE TABLE Enrolled
     (sid CHAR(20),
      cid CHAR(20),
      grade CHAR(2))
```

Adding and Deleting Tuples

Can insert a single tuple using:

```
INSERT INTO Students (sid, name, login, age, gpa)
 VALUES  ('53688', 'Smith', 'smith@cs', 18, 3.2)
```

Can delete all tuples satisfying some condition (e.g., name = Smith):

```
DELETE
  FROM Students S
 WHERE S.name = 'Smith'
```

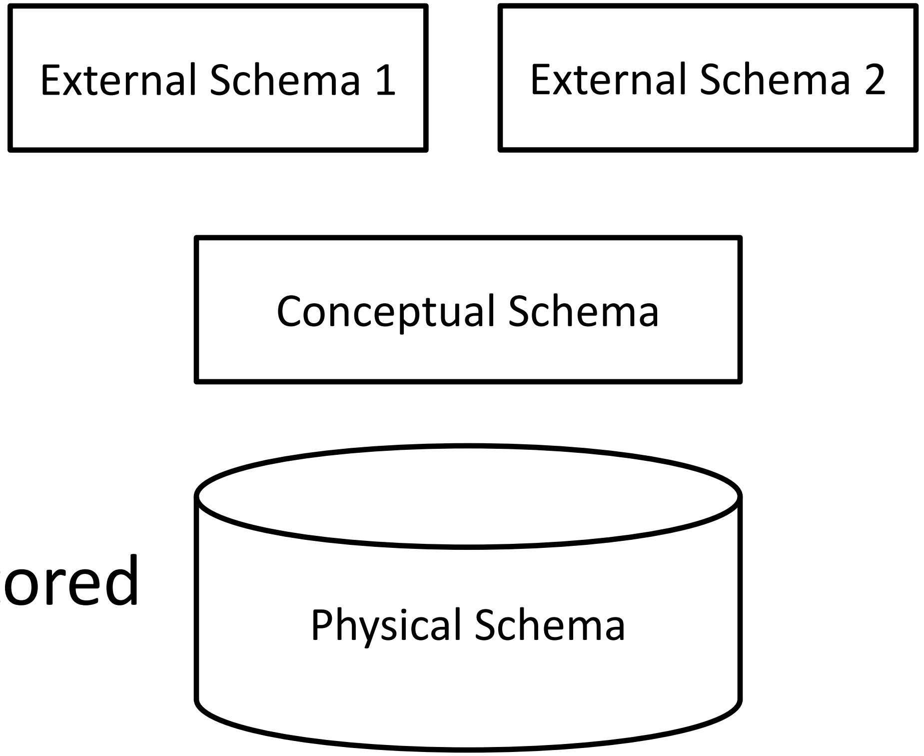
Powerful variants of these commands are available; more later!

Levels of Abstraction

what the users *see*

what is the *data model*

how the data is *physically* stored
e.g., files, indexes



Schemas of "University" Database

Conceptual Schema

Students

***sid**: string, **name**: string, **login**: string, **age**: integer, **gpa**: real*

Courses

***cid**: string, **cname**: string, **credits**: integer*

Enrolled

***sid**: string, **cid**: string, **grade**: string*

Physical Schema

relations stored in files on disk

indexes on sid/cid for performance

External Schema

a "view" of data that can be derived from the existing data

*conceptual + Course_Info (**cid**: string, **enrollment**:integer)*

*which **combines** information from <u>Courses & Enrolled</u>*

Data Independence

Abstraction offers "application independence"

Logical data independence

Protection from changes in *logical* structure of data

Physical data independence

Protection from changes in *physical* structure of data

Q: Why is this particularly important for DBMS?

Applications can treat DBMS as black boxes!

Queries

”Bring me all students with gpa more than 3.0”

“**SELECT** * **FROM** Students **WHERE** gpa>3.0”

SQL – a powerful *declarative* query language

treats DBMS as a black box

What if we have multiples accesses?

Concurrency Control

multiple users/apps

Challenges

how frequent access to slow medium

how to keep CPU busy

how to avoid *short jobs* waiting behind *long ones*

e.g., ATM withdrawal while summing all *balances*

interleaving actions of *different* programs

Concurrency Control

Problems with *interleaving* actions of diff. programs

Balance?

Bill

Move 100 from savings to checking

Alice

Bad interleaving:

Savings –= 100

Print balances

Checking += 100

Printout is missing 100$!

Concurrency Control

Problems with *interleaving* actions of diff. programs

Bill

Move 100 from savings to checking

Balance?

Alice

What is a correct interleaving?

- Savings –= 100
- Checking += 100
- Print balances

How to achieve this interleaving?

Scheduling Transactions

Transactions: atomic sequences of **R**eads & **W**rites

T_{Bill}={$R1_{Savings}$, $R1_{Checking}$, $W1_{Savings}$, $W1_{Checking}$}
T_{Alice}={$R2_{Savings}$, $R2_{Checking}$}

How to avoid previous problems?

Scheduling Transactions

All interleaved executions equivalent to a *serial*

All actions of a transaction executed *as a whole*

Time

$R1_{Savings}, R1_{Checking}, W1_{Savings}, W1_{Checking}, R2_{Savings}, R2_{Checking}$

$R2_{Savings}, R2_{Checking}, R1_{Savings}, R1_{Checking}, W1_{Savings}, W1_{Checking}$

~~$R1_{Savings}, R1_{Checking}, W1_{Savings}, R2_{Savings}, R2_{Checking}, W1_{Checking}$~~

$R1_{Savings}, R1_{Checking}, R2_{Savings}, R2_{Checking}, W1_{Savings}, W1_{Checking}$

How to achieve one of these?

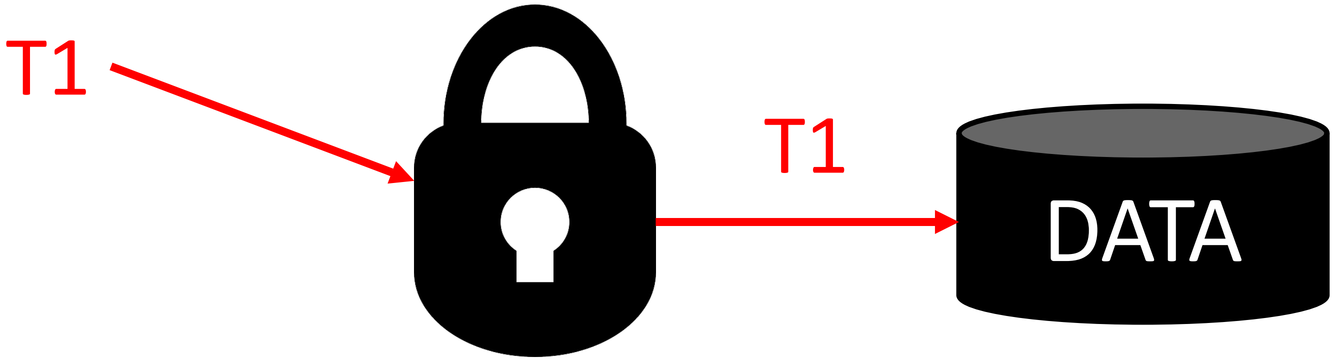
Locking

before an object is accessed a lock is requested

Locking

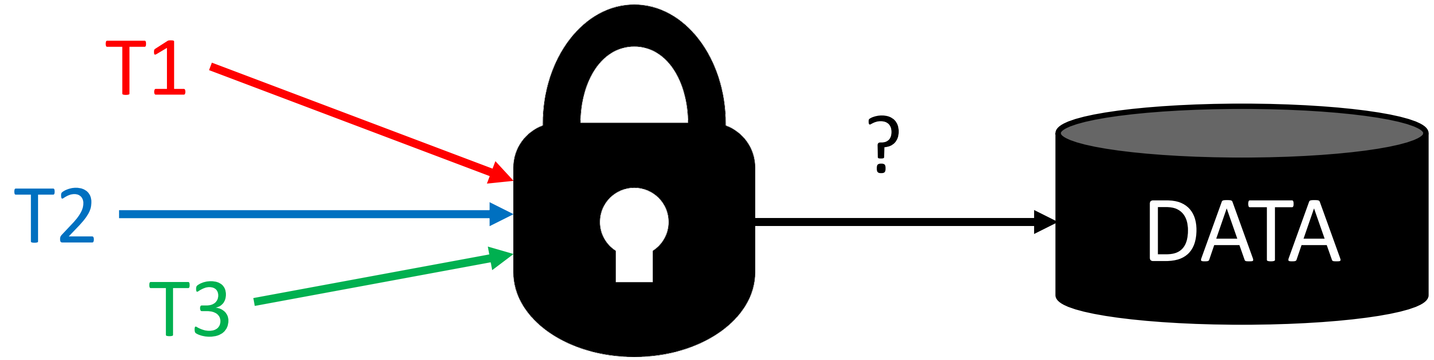
before an object is accessed a lock is requested

Locking



before an object is accessed a lock is requested

Locking



locks are held until the end of the transaction

[this is only one way to do this, called "strict two-phase locking"]

Locking

$T_1=\{R1_{Savings}, R1_{Checking}, W1_{Savings}, W1_{Checking}\}$
$T_2=\{R2_{Savings}, R2_{Checking}\}$

Both should lock *Savings* and *Checking*

What happens:

if T1 locks Savings & Checking ?

T2 has to <u>wait</u>

if T1 locks Savings & T2 locks Checking ?

we have a <u>deadlock</u>

How to solve deadlocks?

we need a mechanism to *undo*

also when a transaction is *incomplete*

e.g., due to a crash

what can be an undo mechanism?

log every action before it is applied!

Transactional Semantics

Transaction: one execution of a user program

multiple executions → multiple transactions

Every transaction:

Logging → ***A**tomic*

***C**onsistent*

***I**solated*

***D**urable*

Transactional Semantics

Transaction: one execution of a user program

multiple executions → multiple transactions

Every transaction:

Logging → ***A**tomic* *"executed entirely or not at all"*

***C**onsistent* *"leaves DB in a consistent state"*

Locking → ***I**solated* *"as if it is executed alone"*

***D**urable* *"once completed is never lost"*

Who else needs transactions?

lots of data

lots of users

frequent updates

background game analytics

Scaling games to epic proportions,

by W. White, A. Demers, C. Koch, J. Gehrke and R. Rajagopalan

ACM SIGMOD International Conference on Management of Data, 2007

Only "classic" DBMS?

No, there is much more!

NoSQL & Key-Value Stores: No transactions, focus on queries

Graph Stores

Querying raw data without loading/integrating costs

Database queries in large datacenters

New hardware and storage devices

Cloud data management

… many exciting open problems!

https://bu-disc.github.io/CS660/

Next time in …

CS 660: Introduction to Database Systems

Database Systems Architectures

Class administrativia

Class project administrativia

Course Summary

We will learn how to:

- **Model data**
  Relational Model
- **Access** and **Query data**
  SQL
- **Store & manage** data
  Bits to Files to Disks, Storage Layouts, Indexes, Sorting
- **Reason** about query performance
  Query evaluation & optimization
- **Update** data
  Transactions, logging, ACID properties

https://bu-disc.github.io/CS660/

Additional Accommodations

If you require additional accommodations please contact the Disability & Access Services office at aslods@bu.edu or 617-353-3658 to make an appointment with a DAS representative to determine which are the appropriate accommodations for your case.

Please be aware that accommodations cannot be enacted retroactively, making timeliness a critical aspect for their provision.

You can optionally choose to disclose this information to the instructor.