Fundamentals of Database Systems
COMPSCI 351

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The Relational Model of Data

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Its inventor is E.F. Codd

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A Foundation for Database R&D

- distinguishes between syntax (schemata) and semantics (instances),
- enables physical data independence,
- basis for powerful languages, e.g. relational algebra and calculus,
- properties can be discovered and justified

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Industry standard SQL founded on the relational model

- vendors: IBM, Informix, Microsoft, Oracle, Sybase, etc.
- syntheses emerging: object-oriented models, Web, NewSQL

A Simple Approach to Managing Data

- Information systems deal with storage and retrieval of data
  - use tuples to represent data about real-world objects

Example

The tuple

(13 Assassins, Miike Takashi, Japan, 2010)

represents the movie with title "13 Assassins", director "Miike Takashi", country of production "Japan", and production year "2010"

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The relational data model (RDM) is based on this approach

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- Relations are sets of tuples
  - suitable to represent collections of data of any size
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The Yellow Sea	Na Hong-jin	Korea	2010
Tyrannosaur	Paddy Considine	UK	2011

Tuples and Attributes

- Entries in a tuple capture some *property* of a real-world object

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- These properties are called *attributes*

Tuples in a relation all have the same structure

- entries capture the same properties for all real-world objects
- e.g., for movies we capture the attributes *Title*, *Year*, *Director* and *Country*

Example: Tuples and Attributes

In table illustrations we use these properties (attributes) as column headers

Example

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For movies, the attributes could have the following domains:

- $\mathit{dom}(\text{title}) = \texttt{string}$, $\mathit{dom}(\text{year}) = \texttt{nat}$,
- $\mathit{dom}(\text{director}) = \texttt{string}$, and $\mathit{dom}(\text{country}) = \texttt{string}$,

where `string` is the set of all strings over a fixed alphabet, while `nat` is just the set $\mathbb{N}$ of natural numbers.

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Definition (Relation Schema)

A *relation schema* is a finite set, usually denoted by R. The elements of R are called *attributes*, and each attribute $A \in R$ is associated with a domain $dom(A)$.

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Notation

- To emphasize the sequence of attributes, use $R(A_1, \ldots, A_n)$, e.g. $\textsc{Movie}$(title, director, country, year)
- To emphasize domains, write $R(A_1 : dom(A_1), \ldots, A_n : dom(A_n))$, e.g. $\textsc{Movie}$(title:`string`,director:`string`, country:`string`, year:`nat`)

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An R-**relation** is a finite set r of R-tuples, that is, a finite relation

$$r \subseteq dom(A_1) \times \cdots \times dom(A_n).$$

Example: Tuple and Relation

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$$t = (\text{13 Assassins}, \text{Miike Takashi}, \text{Japan}, 2010)$$

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Conventions

- Write $t = (A_1 : v_1, \ldots, A_n : v_n)$ to emphasize that v_i belongs to attribute A_i
- $t = (\mathit{title} : \text{13 Assassins}, \mathit{director} : \text{Miike Takashi}, \mathit{country} : \text{Japan}, \mathit{year} : 2010)$

An Alternative Definition for a Tuple

Definition

An R-tuple is a function

$$t : R \to \bigcup_{A \in R} dom(A)$$

mapping every attribute $A \in R$ to some element $t(A) \in dom(A)$.

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Example

A database schema consisting of four relation schemata:

- MOVIE(title, year, country, run_time, genre)
- PERSON(id, first_name, last_name, year_born)
- DIRECTOR(id, title, year)
- ACTOR(id, title, year, role)

Relational Database

A relational database over a database schema consists of a relation for every relation schema that is a member of the database schema.

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Definition (Relational Database)

Let $\mathcal{S}$ a database schema. An $\mathcal{S}$-**database**, usually denoted by $\mathcal{I}$, consists of just one R-relation $\mathcal{I}(R)$ for each relation schema R in $\mathcal{S}$, that is,

$$\mathcal{I} = \{\mathcal{I}(R) | R \in \mathcal{S}\}.$$

An Example for a Relational Database

Movie

title	year	country	run_time	genre
13 Assassins	2010	Japan	126	Drama
La dolce vita	1960	Italy	174	Classic
Mana Waka	1937	New Zealand	85	History
Nosferatu	1922	Germany	80	Horror
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Director

id	title	year
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Person

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Actor

id	title	year	role
2	13 Assassins	2010	Shinzaemon Shimada
4	La dolce vita	1960	Marcello Rubini
5	La dolce vita	1960	Sylvia
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8	Nosferatu	1922	Nosferatu

$$R \mapsto \mathcal{I}(R)$$

An Example for a Relational Database

Movie

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Mana Waka	1937	New Zealand	85	History
Nosferatu	1922	Germany	80	Horror
Tyrannosaur	2011	UK	91	Drama

Director

id	title	year
1	13 Assassins	2010
3	La dolce vita	1960
6	Mana Waka	1937
7	Nosferatu	1922

Person

id	first_name	last_name	year_born
1	Miike	Takashi	1960
2	Koji	Yakusho	1956
3	Federico	Fellini	1920
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Fast Data Access through Unique Column Combinations

Fast access to tuples is important for data processing (eg. queries and updates)

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- no two different movies have the same title, year, and country of production
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- no two different movies have the same title, year, and country of production
- no two different people have the same id

minimal combinations of columns with this property are particularly interesting

- no two different movies have the same title and the same year of production
- but there are different movies with the same title and
- there are obviously different movies produced in the same year

Keys and Superkeys

Definition (Superkey)

A **superkey** over a relation schema R is a finite subset $K \subseteq R$ of R. An R-relation r is said to **satisfy** the superkey K over R if every pair of distinct tuples $t_1, t_2 \in r$ deviates on at least one attribute of K, that is, $t_1(A) \neq t_2(A)$ for some $A \in K$.

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Definition (Key)

A superkey K over R is said to be a **key** if there is no other superkey K' over R that is a proper subset of K, that is, $K' \subset K$.

Every key is a superkey, but only some superkeys are keys.

Example: Keys and Superkeys

Superkeys that are satisfied

Example

title	year	country
The Magnificent Seven	2016	USA
The Magnificent Seven	1960	USA
Psycho	1960	USA

Example: Keys and Superkeys

Example

title	year	country
The Magnificent Seven	2016	USA
The Magnificent Seven	1960	USA
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Superkeys that are satisfied

- {title, year}

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Superkeys that are satisfied

- {title, year}
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Example: Keys and Superkeys

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Superkeys that are satisfied

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- {title, year, country}

Keys that are satisfied

Example: Keys and Superkeys

Example

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Superkeys that are satisfied

- {title, year}
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Example: Keys and Superkeys

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title	year	country
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- {title, year}
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Keys that are satisfied

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Superkeys that are violated

Example: Keys and Superkeys

Example

title	year	country
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Superkeys that are satisfied

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Keys that are satisfied

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Superkeys that are violated

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Example: Keys and Superkeys

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Discussion on Keys and Superkeys

Of practical interest are ...

- Keys that are satisfied *every* relation representing a real-world instance
- but not keys that are only satisfied by some particular relation (accidental keys)

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Example

Is $\{$title$\}$ a good key over $\textsc{Movie}$(title, year, country, run_time, genre)?

- The NZ film festival snapshot relation satisfies $\{$title$\}$
- Our last example shows there are different movies with the same title
- Are there different movies with the same title in the New Zealand Film Festival?

Comprehending keys is important and difficult in practice

What is a good key over ACTOR(id, title, year, role)?

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Example

Business analysts need answers for the following questions:

- Can the same role in the same movie be played by different people?

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- Can the same role in the same movie be played by different people?
  - If yes, then {title, year, role} is not a good key
  - If no, then {title, year, role} is a good key
- Can the same person in the same movie play different roles?

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  - If no, then {title, year, role} is a good key
- Can the same person in the same movie play different roles?
  - If yes, then {id, title, year} is not a good key
  - If no, then {id, title, year} is a good key
- Can the same person play the same role in different movies?

Comprehending keys is important and difficult in practice

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Example

Business analysts need answers for the following questions:

- Can the same role in the same movie be played by different people?
  - If yes, then {title, year, role} is not a good key
  - If no, then {title, year, role} is a good key
- Can the same person in the same movie play different roles?
  - If yes, then {id, title, year} is not a good key
  - If no, then {id, title, year} is a good key
- Can the same person play the same role in different movies?
  - If yes, then {id, role} is not a good key
  - If no, then {id, role} is a good key

More comments on keys

- Database designers specify all keys that make sense

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- This helps reduce database instances to those which are more realistic, and helps identify objects in a database more efficiently

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- Database designers specify all keys that make sense
- The specification of keys restricts the number of possible database instances
- This helps reduce database instances to those which are more realistic, and helps identify objects in a database more efficiently
- In the literature:
  - our term *key* is sometimes referred to as *minimal key* or as *candidate key*
  - our term *superkey* is sometimes referred to as *key*

Keys enforce Codd's principle of entity integrity, that is, the unique identification of entities within a relation

Acessing Data Across Tables

Data entries in one table may identify tuples in other tables

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Benefits

- This ensures Codd's principle of referential integrity, that is, the correct reference of entities across relations
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Acessing Data Across Tables

Data entries in one table may identify tuples in other tables

Benefits

- This ensures Codd's principle of referential integrity, that is, the correct reference of entities across relations
  - for example, the id of an actor provides a reference to a unique person
- It eliminates data redundancy which speeds up updates
  - for example, we do not need to store the names of actors in the ACTOR table

Foreign Keys defined

Definition

A **foreign key** over a relation schema R in a database schema $\mathcal{S}$ is

- a sequence of attributes $A_1, \ldots, A_n \in R$ together with
- a key $K = \{B_1, \ldots, B_n\}$ on some relation schema $S \in \mathcal{S}$ where
- with $dom(A_i) = dom(B_i)$ for $i = 1, \ldots, n$.

This is usually denoted by $[A_1, \ldots, A_n] \subseteq S[B_1, \ldots, B_n]$.

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This is usually denoted by $[A_1, \ldots, A_n] \subseteq S[B_1, \ldots, B_n]$.
The foreign key $[A_1, \ldots, A_n] \subseteq S[B_1, \ldots, B_n]$ over R is said to be **satisfied** by the database instance $\mathcal{I}$ of $\mathcal{S}$ if

- for each tuple $t \in \mathcal{I}(R)$ there is
- a tuple $s \in \mathcal{I}(S)$ such that
- $t(A_i) = s(B_i)$ for all $i = 1, \ldots, n$.

Examples for Foreign Keys

Example

Foreign keys on $\textsc{Director}$(id, title, year) are

- [id] $\subseteq$ $\textsc{Person}$[id]:
  the id of a director identifies a unique person

Examples for Foreign Keys

Example

Foreign keys on DIRECTOR(id, title, year) are

- [id] $\subseteq$ PERSON[id]:
  the id of a director identifies a unique person
- [title,year] $\subseteq$ MOVIE[title,year]:
  the title and year of a director identify a unique movie

Examples for Foreign Keys

Example

Foreign keys on DIRECTOR(id, title, year) are

- [id] $\subseteq$ PERSON[id]:
  the id of a director identifies a unique person
- [title,year] $\subseteq$ MOVIE[title,year]:
  the title and year of a director identify a unique movie

The specification of foreign keys restricts the possible database instances to those considered meaningful by the application domain.

Foreign key on DIRECTOR: $[\mathit{title}, \mathit{year}] \subseteq$ MOVIE$[\mathit{title}, \mathit{year}]$?

MOVIE

title	year	country	run_time	genre
13 Assassins	2010	Japan	126	Drama
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DIRECTOR

id	title	year
1	13 Assassins	2010
3	La dolce vita	1960
6	Mana Waka	1937
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PERSON

id	first_name	last_name	year_born
1	Miike	Takashi	1960
2	Koji	Yakusho	1956
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ACTOR

id	title	year	role
2	13 Assassins	2010	Shinzaemon Shimada
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Example for a Common Pitfall

$\textsc{Movie}$(title, year, country) with key {title, year}
$\textsc{Actor}$(id, title, year, role) with

- key {id, title, year, role} and
- foreign key [title, year] $\subseteq$ $\textsc{Movie}$[title, year]

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The foreign key does not permit the same databases as the two inclusion dependencies

- [title] $\subseteq$ $\textsc{Movie}$[title] and
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Example for a Common Pitfall

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Gran Torino	2008	USA
Moana	2016	USA

ACTOR

actor	title	year	role
11	Gran Torino	2016	Walt
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Integrity Constraints

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Integrity constraints enforce the business rules of applications in databases

- they are specified on the database schema
- classify databases into those that are
  - meaningful (i.e. those databases satisfying all constraints),
  - and not meaningful (i.e. those databases not satisfying some constraint)

Integrity Constraints continued

Databases are restricted to those considered meaningful for applications

Primary examples are: domain, key, and foreign key constraints

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- explicit enforcements of some constraints enforces others implicitly
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- efficient database maintenance means minimization of costs to enforce constraints

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Integrity constraints greatly determine the design of a database schema

- to process most common queries efficiently, and
- to process most common updates efficiently, but
- in many cases compromises are necessary

Example for Challenges in Schema Design

Application domain: *suppliers* deliver *articles* from a *location* at a *cost*

- for every article there is at most one supplier
- the article and location determine the cost
- the set of locations a supplier delivers from is independent of the set of articles delivered and costs charged for delivery

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$\mathcal{S}_1 = \{R_1$(article, supplier, location, cost)$\}$

article	*supplier*	*location*	*cost*
Kiwi	G6Fruitz	Tauranga	NZD1
Kiwi	G6Fruitz	Gisborne	NZD1

$\mathcal{S}_2 = \{R_2$(supplier, location), R_3(article, supplier, cost)$\}$

supplier	*location*
G6Fruitz	Tauranga
G6Fruitz	Gisborne

article	*supplier*	*cost*
Kiwi	G6Fruitz	NZD1

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$\mathcal{S}_2 = \{R_2(\text{supplier, location}), R_3(\text{article, supplier, cost})\}$

supplier	*location*
G6Fruitz	Tauranga
G6Fruitz	Gisborne

article	*supplier*	*cost*
Kiwi	G6Fruitz	NZD1

Design choice depends on workload of database

- most common queries (e.g. choose $\mathcal{S}_1$ to query locations of articles)
- most common updates (e.g. choose $\mathcal{S}_2$ to update costs of articles)
- maintenance costs (efficiency of integrity enforcement)

Summary for the Relational Model of Data

- Relational DBMSs are based on the relational data model
- The relational data model is formally defined, its properties can be proven, explained and justified, and formal query languages such as relational calculus and algebra have been defined on it.
- The most important concepts in the relational data model are:
  - syntactic level: attributes, relation schemata, database schemata
  - semantic level: domains, tuples, relations, databases
- Integrity constraints play an important part in schema design
  - determine efficiency of updates
  - determine efficiency of queries
  - DBMSs offer support for enforcement of some constraints
    - domain constraints, key constraints, foreign key constraints