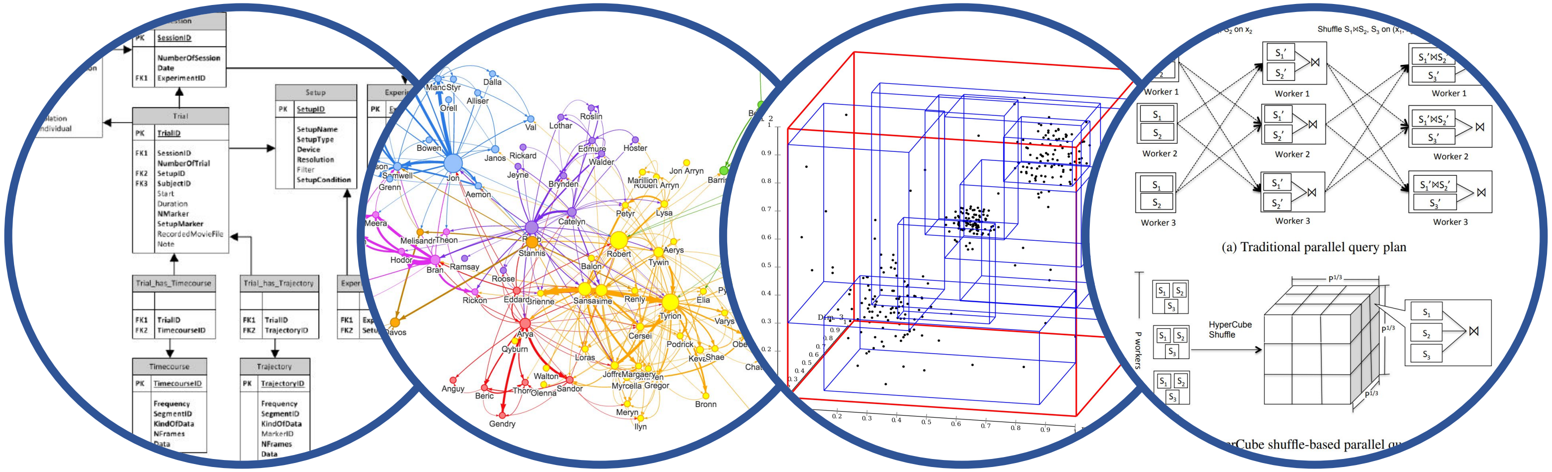


Introduction to Data Management

Design Theory

Alyssa Pittman
Based on slides by Jonathan Leang, Dan Suciu, et al

Paul G. Allen School of Computer Science and Engineering
University of Washington, Seattle

Recap: Other Constraints

- `CHECK (condition)`
  - Single attribute
  - Single tuples

```
CREATE TABLE User (
    uid INT PRIMARY KEY,
    firstName TEXT,
    lastName TEXT,
    age INT CHECK (age > 12 AND age < 120),
    email TEXT,
    phone TEXT,
    CHECK (email IS NOT NULL OR phone IS NOT NULL)
);
```

Assertions

- Hard to support
- Usually impractical
- Usually not supported
  - Simulated with triggers

```
CREATE ASSERTION myAssert CHECK
    (NOT EXISTS (
        SELECT Product.name
          FROM Product, Purchase
         WHERE Product.name = Purchase.prodName
         GROUP BY Product.name
        HAVING count(*) > 200));
```

Triggers

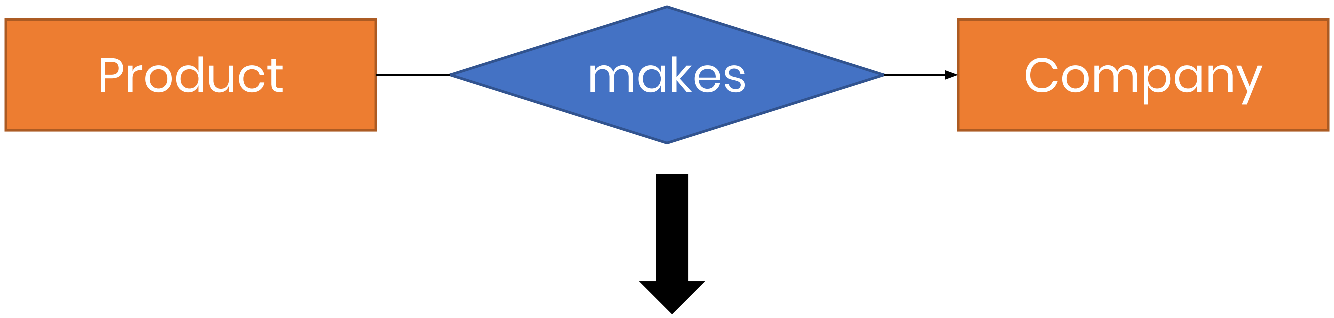
- Triggers activate on a specified event

```
CREATE TRIGGER LowCredit ON Purchasing.PurchaseOrderHeader
AFTER INSERT AS
  IF (ROWCOUNT_BIG() = 0) RETURN;
  IF EXISTS (SELECT *
             FROM Purchasing.PurchaseOrderHeader AS p
             JOIN inserted AS i
             ON p.PurchaseOrderID = i.PurchaseOrderID
             JOIN Purchasing.Vendor AS v
             ON v.BusinessEntityID = p.VendorID
             WHERE v.CreditRating = 5
            )
    BEGIN
      RAISERROR ('A vendor''s credit rating is too
                  low to accept new purchase orders.', 16, 1);
      ROLLBACK TRANSACTION;
      RETURN
    END;
GO
```

= you don't need to study this for the class

Recap

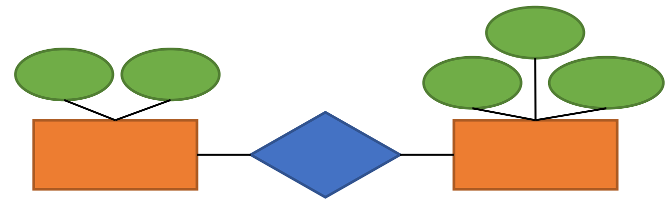
- ER Diagrams
  - Conceptual modeling
  - Rules of thumb for converting diagram into schema



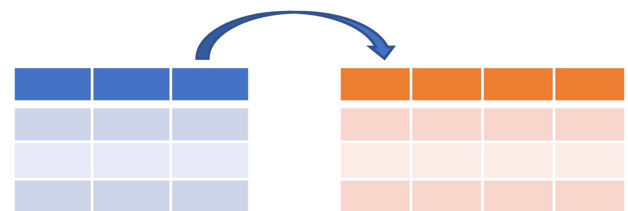

```
CREATE TABLE Company (
    name VARCHAR(100) PRIMARY
KEY,
    ...);
CREATE TABLE Product (
    name VARCHAR(100) PRIMARY
KEY,
    cname VARCHAR(100)
      REFERENCES Company
    ...);
```

The Database Design Process

Conceptual Model



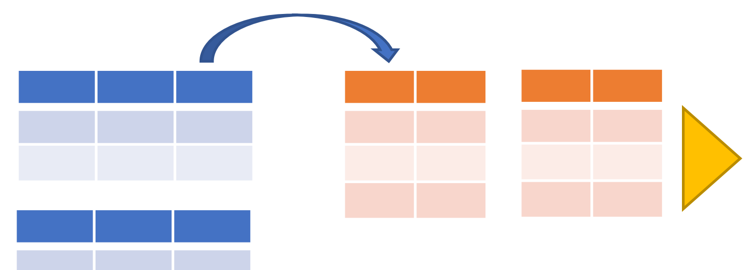
Relational Model
- + Schema
- + Constraints



Today

Conceptual Schema
- + Normalization

Physical Schema
- + Partitioning
- + Indexing



Goals for Today

- Figure out the fundamentals of what makes a good schema

Outline

- Background
  - Anomalies, i.e. things we want to avoid
  - Functional Dependencies (FDs)
  - Closures and formal definitions of keys
- Normalization: BCNF Decomposition
- Losslessness

Think About This

Make a simple directory that can:

- Hold information about name, SSN, phone, and city
- Associate **people** with the **city** they live in
- Associate **people** with any **phone numbers** they have

Name	SSN	Phone	City
Fred	123-45-6789	206-555-9999	Seattle
Fred	123-45-6789	206-555-8888	Seattle
Joe	987-65-4321	415-555-7777	San Francisco

The above instance does the job, but are there issues?

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Anomalies:

- **Redundancy □ Slow Update**
  - Change Fred's city to Bellevue (two rows!)
- **Deletion Anomalies**
  - How to delete Joe's phone without deleting Joe?

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Think About This

We can solve the anomalies by converting this

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into this

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Joe	987-65-4321	San Francisco

SSN	Phone
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123-45-6789	206-555-8888
987-65-4321	415-555-7777

How can we systematically avoid anomalies?

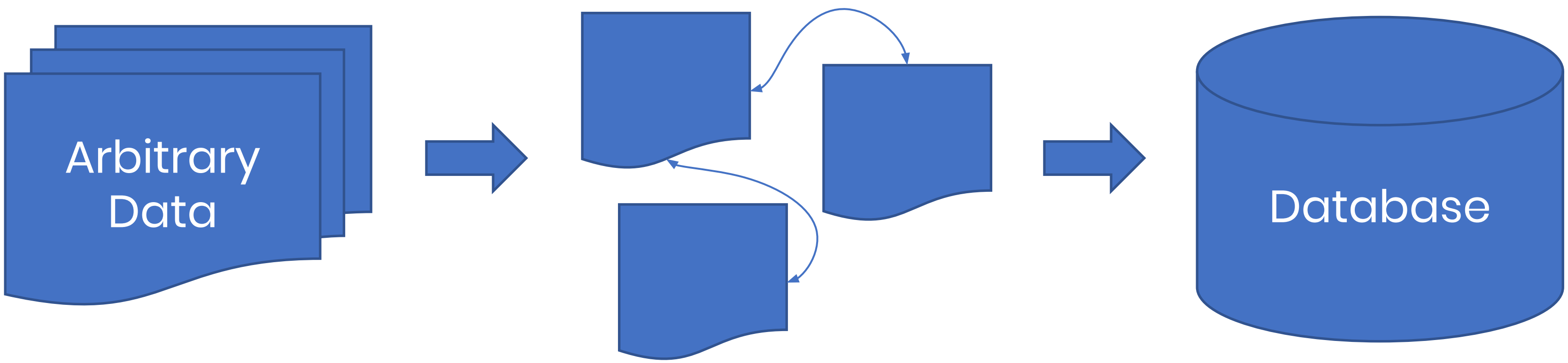
Informal Design Guidelines

- Semantics of attributes should be self-evident
- Avoid redundant information in tuples
- Avoid NULL values in tuples
- Disallow the generation of “spurious” tuples
  - If certain tuples shouldn’t exist, don’t allow them

Database Design

Database Design

Database Design or **Logical Design** or **Relational Schema Design** is the process of organizing data into a database model. This is done by considering what data needs to be stored and the interrelationship of the data.



Database Design

Database Design is about
(1) characterizing data and (2) organizing data

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Database Design

Database Design is about
(1) characterizing data and (2) organizing data

How to talk about properties
we know or see in the data

Data Interrelationships

How do we start talking about data interrelationships?

- What rules govern our data?
  - Domain knowledge
    - Dimension vs measure
  - Pattern analysis

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[ex] An engineer knows that a plane model determines the plane's wingspan

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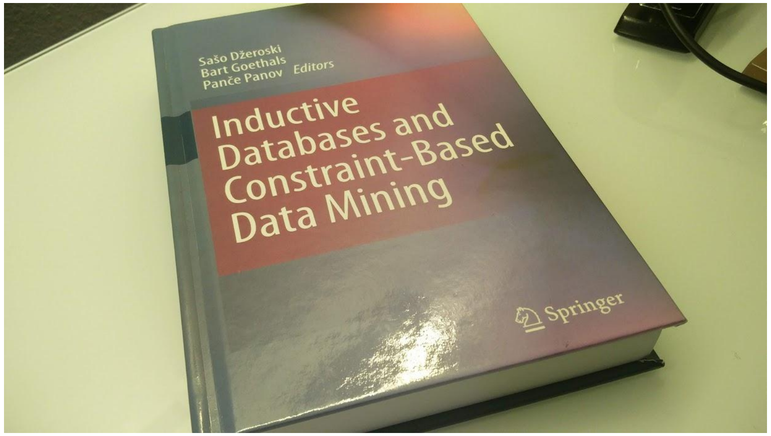

- Data mining
- Knowledge Discovery in Databases (KDD)

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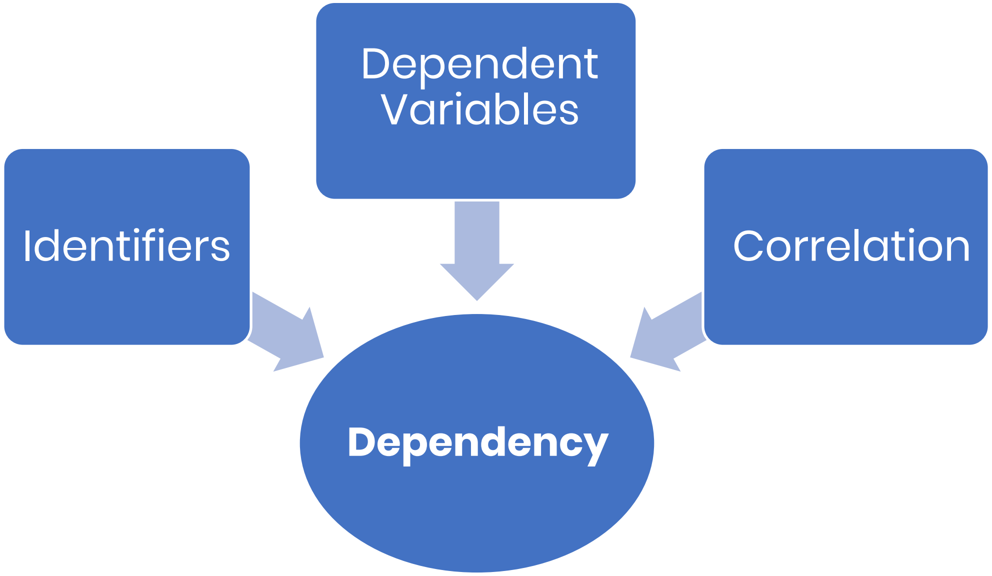

Data Interrelationships

Functional Dependency

A ***Functional Dependency*** $A_1, \dots, A_m \rightarrow B_1, \dots, B_n$ holds in the relation R if:

$$\forall t, t' \in R, (t.A_1 = t'.A_1 \wedge \dots \wedge t.A_m = t'.A_m \rightarrow t.B_1 = t'.B_1 \wedge \dots \wedge t.B_n = t'.B_n)$$

Informally, some attributes determine other attributes.

$$A_1, \dots, A_m \rightarrow B_1, \dots, B_n$$

This is the antecedent

This is the consequent

Warning! Dependency does not imply causation!

Fundamentals of FDs

Armstrong's Axioms

- Axiom of ***Reflexivity*** (***Trivial FD***)
- Axiom of ***Augmentation***
- Axiom of ***Transitivity***

Fundamentals of FDs

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  If $B \subseteq A$ then $A \rightarrow B$

  [ex] $\{name\} \subseteq \{name, job\}$ so $\{name, job\} \rightarrow \{name\}$

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Fundamentals of FDs

Armstrong's Axioms

- Axiom of ***Reflexivity*** (***Trivial FD***)

  If $B \subseteq A$ then $A \to B$

  [ex] $\{name\} \subseteq \{name, job\}$ so $\{name, job\} \to \{name\}$

- Axiom of ***Augmentation***

  If $A \to B$ then $\forall C,\ AC \to BC$

- Axiom of ***Transitivity***

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  [ex] $\{ID\} \rightarrow \{name\}$ so $\{ID, job\} \rightarrow \{name, job\}$

- Axiom of ***Transitivity***

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  [ex] $\{ID\} \rightarrow \{name\}$ so $\{ID, job\} \rightarrow \{name, job\}$

- Axiom of ***Transitivity***

  If $A \rightarrow B$ and $B \rightarrow C$ then $A \rightarrow C$

Fundamentals of FDs

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  [ex] $\{ID\} \rightarrow \{name\}$ so $\{ID, job\} \rightarrow \{name, job\}$

- Axiom of ***Transitivity***

  If $A \rightarrow B$ and $B \rightarrow C$ then $A \rightarrow C$

  [ex] $\{ID\} \rightarrow \{name\}$ and $\{name\} \rightarrow \{initials\}$

  so $\{ID\} \rightarrow \{initials\}$

Fundamentals of FDs

Interesting Secondary Rules

- ***Pseudo Transitivity***

If $A \rightarrow BC$ and $C \rightarrow D$ then $A \rightarrow BD$

- ***Extensivity***

If $A \rightarrow B$ then $A \rightarrow AB$

Fundamentals of FDs

Can I do this to FDs?

I only know $\{ID\} \rightarrow \{name\}$

So $\{ID, hair\ color\} \rightarrow \{name\}$

Fundamentals of FDs

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Yes!

Fundamentals of FDs

Can I do this to FDs?

I only know $\{ID\} \to \{name\}$

So $\{ID, hair\ color\} \to \{name\}$

Yes!

Adding more attributes to the antecedent can never remove attributes in the consequent.

Fundamentals of FDs

What about this?

I only know $\{ID\} \rightarrow \{name\}$

So $\{ID\} \rightarrow \{name, hair\ color\}$

Fundamentals of FDs

What about this?

I only know $\{ID\} \rightarrow \{name\}$

So $\{ID\} \rightarrow \{name, hair\ color\}$

No!

Fundamentals of FDs

What about this?

I only know $\{ID\} \rightarrow \{name\}$

So $\{ID\} \rightarrow \{name, \textcolor{red}{hair\ color}\}$

No!

No way to use the axioms to introduce hair color to the consequent without also introducing it to the antecedent.

Finding Keys

All this talk about FDs sounds awfully similar to keys…

Closure

Closure

The ***Closure*** of the set $\{A_1, \dots, A_m\}$, written as $\{A_1, \dots, A_m\}^+$, is the set of attributes B is such that $A_1, \dots, A_m \rightarrow B$.

A closure finds everything a set of attributes determines.

Closure (example)

Given the functional dependencies:

- $SSN \rightarrow Name$
- $Name \rightarrow Initials$

We can derive some closures:

- $Name^+ =$
- $SSN^+ =$
- $Initials^+ =$
- $\{SSN, Initials\}^+ =$

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- $Initials^+ =$
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Closure

Closure Algorithm

Find the closure of $\{A_1, \ldots, A_m\}$

	$X = \{A_1, \ldots, A_m\}$ ***Repeat until*** X ***does not change***: ***if*** $B1, \ldots, Bn \rightarrow C$ is a FD ***and*** $B1, \ldots, Bn \in X$ ***then*** $X \leftarrow X \cup C$	

In practice:

Repeated use of transitivity

Closure

Closure Algorithm

Find the closure of $\{A_1, \ldots, A_m\}$

$X = \{A_1, \ldots, A_m\}$

Repeat until X ***does not change***:
  if $B1, \ldots, Bn \rightarrow C$ is a FD ***and*** $B1, \ldots, Bn \in X$
  then $X \leftarrow X \cup C$

If a FD applies, add the consequent to the answer

In practice:

Repeated use of transiti

Closure Example

Let's say we have the following relations and FDs:

Restaurants(rid, name, rating, popularity)

rid → name

rid → rating

rating → popularity

Compute $\{rid\}^+$

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Compute $\{rid\}^+$

$\{rid\}^+ = \{rid, name, rating, popularity\}$

it's a key!

Finding Keys

What do FDs and Closures do for us?

- Characterize the interrelationships of data
- Able to find keys

Finding Keys

Superkey

A ***Superkey*** is a set of attributes $A_1, \ldots, A_n$ s.t. for any single attribute B:

$$A_1, \ldots, A_n \rightarrow B$$

In other words, for the set of all attributes C in the relation R, the set $\{A_1, \ldots, A_n\}$ is a superkey iff $\{A_1, \ldots, A_n\}^+ = C$

Key

A **Key** is a minimal superkey, i.e. no subset of a key is a superkey.

Candidate Key

When a relation has multiple keys, each key is a **Candidate Key**.

Usefulness of Keys in Design

What intuitions do we get from data interrelationships?

- FDs that are not superkeys hint at redundancy
  - If a FD antecedent is ***not*** a superkey, we can remove redundant information, i.e. the FD consequent

Usefulness of Keys in Design

What intuitions do we get from data interrelationships?

- FDs that are not superkeys hint at redundancy
  - If a FD antecedent is ***not*** a superkey, we can remove redundant information, i.e. the FD consequent
- Rephrased
  - $A \rightarrow B$ is fine if A is a superkey
  - Otherwise, we can extract B

Usefulness of Keys in Design

Restaurants(rid, name, rating, popularity)

rid □ name

rid □ rating

rating □ popularity

rid	name	rating	popularity
1	Mee Sum Pastry	3	OK
2	Café on the Ave	4	High
3	Guanaco’s Tacos	4	High
4	Aladdin Gyro-Cery	5	High

Usefulness of Keys in Design

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Redundancy!

Database Design

Database Design is about

(1) characterizing data and (2) organizing data

How to talk about properties
we know or see in the data

Database Design

Database Design is about
(1) characterizing data and (2) organizing data

How to organize data to promote
ease of use and efficiency

Normal Forms

Normal Forms

- 1NF Flat
- 2NF No partial FDs (obsolete)
- 3NF Preserve all FDs, but allow anomalies
- BCNF No transitive FDs, but can lose FDs
- 4NF Considers multi-valued dependencies
- 5NF Considers join dependencies (hard to do)

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Normal Forms

1NF

A relation R is in ***First Normal Form*** if all attribute values are atomic. Attribute values cannot be multivalued. Nested relations are not allowed.

We call data in 1NF "flat."

BCNF

BCNF

A relation R is in ***Boyce-Codd Normal Form (BCNF)*** if for every non-trivial dependency, $X \rightarrow A$, X is a superkey.

Equivalently, a relation R is in BCNF if $\forall X$ either $X^+ = X$ or $X^+ = C$ where C is the set of all attributes in R

Decomposition

- "Extracting" attributes can be done with **decomposition** (split the schema into smaller parts)
- For this class, decomposition means the following:

$$R(A_1, \dots, A_n, B_1, \dots, B_m, C_1, \dots, C_k) \begin{array}{l} \nearrow R_1(A_1, \dots, A_n, B_1, \dots, B_m) \\ \searrow R_2(A_1, \dots, A_n, C_1, \dots, C_k) \end{array}$$

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Some common attributes are present so we can rejoin data

BCNF Decomposition Algorithm

$Normalize(R)$
  $C \leftarrow$ the set of all attributes in R
  find X **s.t.** $X^+ \neq X$ ***and*** $X^+ \neq C$
  if X is not found
  then "R is in BCNF"
  else
    decompose R into $R_1(X^+)$ and $R_2\big((C - X^+) \cup X\big)$
    $Normalize(R_1)$
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Determine if R is in BCNF already

Decompose into a relation where X is a superkey

Decompose into a relation with X and attributes X cannot determine

BCNF Decomposition Example

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Restaurants(rid, name, rating, popularity, recommended)

rid □ name, rating

rating □ popularity

popularity □ recommended

BCNF Decomposition Example

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Restaurants(rid, name, rating, popularity, recommended)

rid □ name, rating

rating □ popularity

popularity □ recommended

rid	name	rating
1	Mee Sum Pastry	3
2	Café on the Ave	4
3	Guanaco's Tacos	4
4	Aladdin Gyro-Cery	5

rating	popularity	recommended
3	OK	no
4	High	yes
5	High	yes

BCNF Decomposition Example

$Normalize(R)$
  $C \leftarrow$ the set of all attributes in R
  find X **s.t.** $X^+ \neq X$ ***and*** $X^+ \neq C$
  if X is not found
  then "R is in BCNF"
  else
    decompose R into $R_1(X^+)$ and $R_2((C - X^+) \cup X)$
    $Normalize(R_1)$
    $Normalize(R_2)$

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rating	popularity
3	OK
4	High
5	High

popularity	rec
OK	no
High	yes

Losslessness

Definition

Lossless Decomposition is a reversible decomposition, i.e. rejoining all decomposed relations will always result exactly with the original data.

This is the opposite of a **Lossy Decomposition**, an irreversible decomposition, where rejoining all decomposed relations may result something other than the original data, specifically with extra tuples.

This concept might be familiar if you have ever encountered lossless data compression (e.g. Huffman encoding or PNG) or lossy data compression (e.g. JPEG).

Losslessness

Is BCNF decomposition lossless?

Losslessness

Is BCNF decomposition lossless?

Yes!

Losslessness

Definition – Heath's Theorem

Suppose we have the relation R and three disjoint subsets of the attributes of R we will write as $A_1, \dots, A_n$, $B_1, \dots, B_m$, and $C_1, \dots, C_k$. Suppose we also have a FD that is $A_1, \dots, A_n \rightarrow B_1, \dots, B_m$.

Heath's Theorem states that the decomposition of R into $R_1(A_1, \dots, A_n, B_1, \dots, B_m)$ and $R_2(A_1, \dots, A_n, C_1, \dots, C_k)$ is lossless where R_1 and R_2 are the projections of R on their respective attributes.

$$R(A_1, \dots, A_n, B_1, \dots, B_m, C_1, \dots, C_k) \begin{cases} \nearrow R_1(A_1, \dots, A_n, B_1, \dots, B_m) \\ \searrow R_2(A_1, \dots, A_n, C_1, \dots, C_k) \end{cases}$$

By reflection, the same decomposition of R under the alternate FD $A_1, \dots, A_n \rightarrow C_1, \dots, C_k$ is also lossless.

On A Practical Note

- You may inherit a database that could be lossy. Before you use it, it may be worth your time to check if it is lossy.
- Full normalization is nice but can be inefficient
    - Denormalization □ don't normalize all the way

Takeaways

- We can characterize the relationships in our data using domain knowledge or pattern analysis.
- Functional dependencies give us ways of normalizing our data to avoid anomalies.