Normalization

Motivation

- We have designed ER diagram, and translated it into a relational db schema R = set of R1, R2, ...
- Now what?
- We can do the following
  - specify all relevant constraints over R
  - implement R in SQL
  - start using it, making sure the constraints always remain valid
- However, R may not be well-designed, thus causing us a lot of problems

Example of Bad Design

Persons with several phones:

Name	SSN	Phone Number
Fred	123-321-99	(201) 555-1234
Fred	123-321-99	(206) 572-4312
Joe	909-438-44	(908) 464-0028
Joe	909-438-44	(212) 555-4000

Problems (also called "Anomalies"):

Redundancy	= repetition of data
update anomalies	= update one item and forget others
	= inconsistencies
deletion anomalies	= delete many items, delete one item, loose other information
insertion anomalies	= can't insert one item without inserting others

Better Designs Exist

Break the relation into two:

SSN	Name
123-321-99	Fred
909-438-44	Joe

SSN	Phone Number
123-321-99	(201) 555-1234
123-321-99	(206) 572-4312
909-438-44	(908) 464-0028
909-438-44	(212) 555-4000

How do We Obtain a Good Design?

- Start with the original db schema R
- Transform it until we get a good design R*
- Desirable properties for R*
  - must preserve the information of R
  - must have minimal amount of redundancy
  - must be dependency-preserving
    - if R is associated with a set of constraints C, then it should be easy to also check C over R*
  - (must also give good query performance)

OK, But ...

- How do we recognize a good design R*?
- How do we transform R into R*?
- Answers: use normal forms

Normal Forms

- DB gurus have developed many normal forms
- Most important ones
  - Boyce-Codd, 3rd, and 4th normal forms
- If R* is in one of these forms, then R* is guaranteed to achieve certain good properties
  - e.g., if R* is in Boyce-Codd NF, it is guaranteed to not have certain types of redundancy
- DB gurus have also developed algorithms to transform R into R* that is in some of these normal forms

Normal Forms (cont.)

- DB gurus have also discussed trade-offs among normal forms
- Thus, all we have to do is
  - learn these forms
  - transform R into R* in one of these forms
  - carefully evaluate the trade-offs
- Many of these normal forms are defined based on various constraints
  - functional dependencies and keys

Functional Dependencies and Keys

Functional Dependencies

- A form of constraint (hence, part of the schema)
- Finding them is part of the database design
- Used heavily in schema refinement

Definition:

If two tuples agree on the attributes

$A_1, A_2, \ldots A_n$

then they must also agree on the attributes

$B_1, B_2, \ldots B_m$

Formally: $A_1, A_2, \ldots A_n \longrightarrow B_1, B_2, \ldots B_m$

Examples

EmpID	Name	Phone	Position
E0045	Smith	1234	Clerk
E1847	John	9876	Salesrep
E1111	Smith	9876	Salesrep
E9999	Mary	1234	Lawyer

- EmpID $\longrightarrow$ Name, Phone, Position
- Position $\longrightarrow$ Phone
- but Phone $\not\longrightarrow$ Position

In General

- To check A $\longrightarrow$ B, erase all other columns

…	A	…	B	
	X1		Y1	
	X2		Y2	
	…		…	

- check if the remaining relation is many-one (called ***functional*** in mathematics)

Example

EmpID	Name	Phone	Position
E0045	Smith	1234	Clerk
E1847	John	9876	Salesrep
E1111	Smith	9876	Salesrep
E9999	Mary	1234	lawyer

More examples:

Product: name $\rightarrow$ price, manufacturer
Person: ssn $\rightarrow$ name, age
Company: name $\rightarrow$ stock price, president

More about FDs

- A ➔ B, we say "A functionally determines B"
- When creating a DB schema, we should list all FDs we believe are valid
- These FDs should be valid on ALL DB database instances conforming to our schema
  - can't just be valid on one database instance
  - and not valid on another database instance

Relation Keys

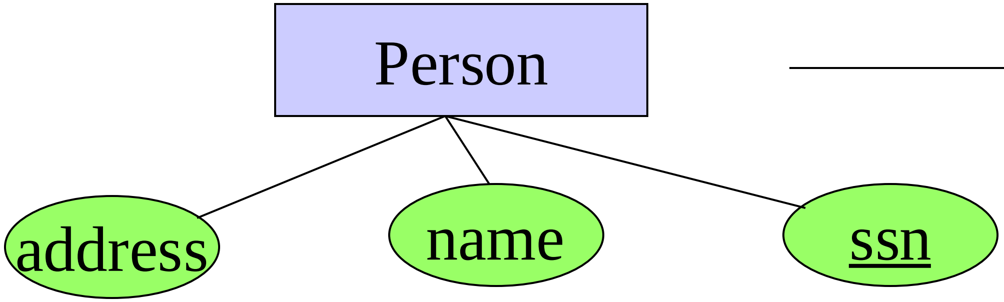
- Key of a relation R is a set of attributes that
  - functionally determines all attributes of R
    - this creates a FD A ➔ B
  - none of its subsets determines all attributes of R
- Superkey
  - a set of attributes that contains a key
  - so a key is also a superkey

Finding the Keys of a Relation

Given a relation constructed from an E/R diagram, what is its key?

Rules:

1. If the relation comes from an entity set,
   the key of the relation is the set of attributes which is the key of the entity set.

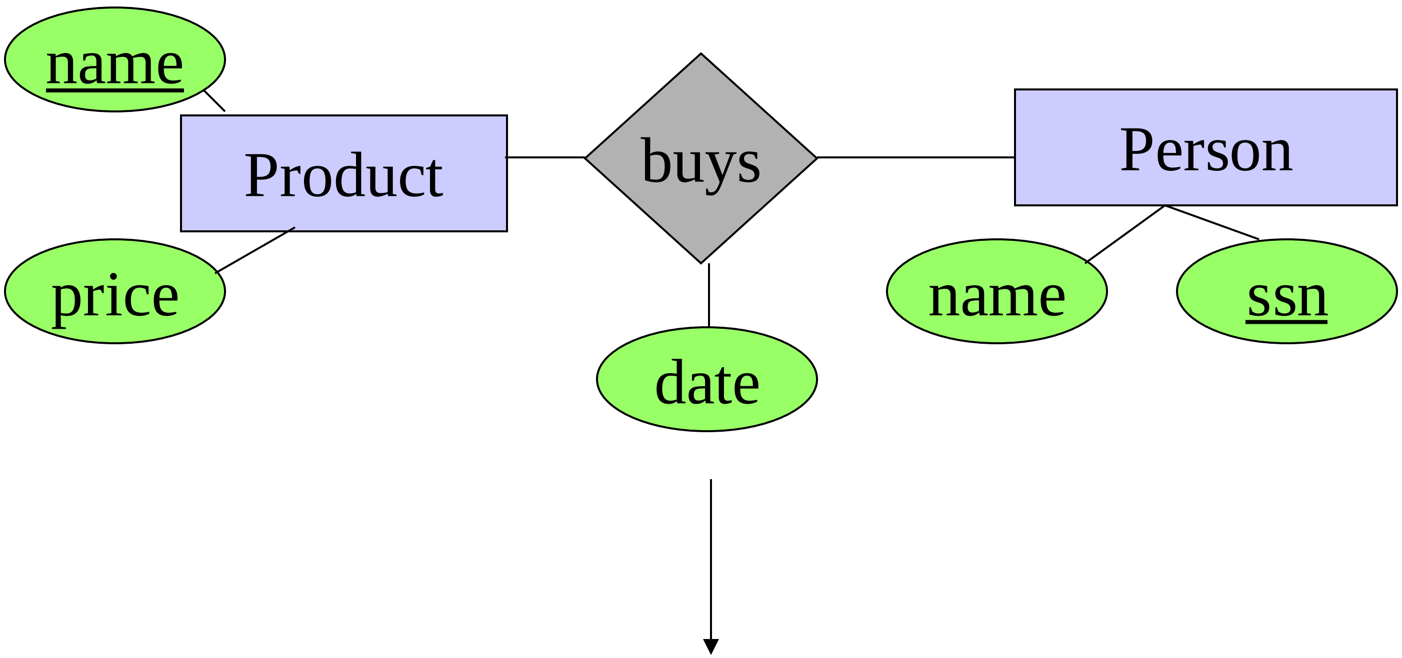


Person(address, name, <u>ssn</u>**)**

Finding the Keys

Rules:

2. If the relation comes from a many-many relationship, the key of the relation is the set of all attribute keys in the relations corresponding to the entity sets



buys(<u>name, ssn</u>, date)

Finding the Keys

More rules:

- Many-one, one-many, one-one relationships
- Multi-way relationships
- Weak entity sets

Note that if you say the set of attributes A is a key, you are basically saying certain FDs are true.

Reasoning with FDs

1) closure of FD sets
2) closure of attribute sets

Closure of FD sets

- Given a relation schema R & a set S of FDs
  - is the FD f logically implied by S?
- Example
  - R = {A,B,C,G,H,I}
  - S = A $\rightarrow$ B, A $\rightarrow$ C, CG $\rightarrow$ H, CG $\rightarrow$ I, B $\rightarrow$ H
  - would A $\rightarrow$ H be logically implied?
  - yes (you can prove this, using the definition of FD)
- Closure of S: S+ = all FDs logically implied by S
- How to compute S+?
  - we can use Armstrong's axioms

Armstrong's Axioms

- Reflexivity rule
  - A1A2...An ➔ a subset of A1A2...An
- Augmentation rule
  - A1A2...An ➔ B1B2...Bm, then
    A1A2...An C1C2..Ck ➔ B1B2...Bm C1C2...Ck
- Transitivity rule
  - A1A2...An ➔ B1B2...Bm and
    B1B2...Bm ➔ C1C2...Ck, then
    A1A2...An ➔ C1C2...Ck

Inferring S+ using Armstrong's Axioms

- S+ = S
- Loop
  - for each f in S, apply reflexivity and augment. rules
  - add the new FDs to S+
  - for each pair of FDs in S, apply the transitivity rule
  - add the new FD to S+
- Until S+ does not change any further

Additional Rules

- Union rule
  - X ➔ Y and X ➔ Z, then X ➔ YZ
  - (X, Y, Z are sets of attributes)
- Decomposition rule
  - X ➔ YZ, then X ➔ Y and X ➔ Z
- Pseudo-transitivity rule
  - X ➔ Y and YZ ➔ U, then XZ ➔ U
- These rules can be inferred from Armstrong's axioms

Closure of a Set of Attributes

Given a set of attributes $\{A1, \ldots, An\}$ and a set of FDs S.
Problem: find all attributes B such that:

any relation which satisfies S also satisfies:

$A1, \ldots, An \rightarrow B$

The **closure** of $\{A1, \ldots, An\}$, denoted $\{A1, \ldots, An\}^+$,
is the set of all such attributes B

➔ *basically all attributes that are functionally determined by A1, …, An*

We will discuss the motivations for attribute closures soon

Algorithm to Compute Closure

Start with X={A1, …, An}.

Repeat until X doesn't change **do**:

if $B_1, B_2, \ldots B_n \longrightarrow C$ is in S, **and**

$B_1, B_2, \ldots B_n$ are all in X, **and**

C is not in X

then

add C to X.

Example

$$
\begin{aligned}
A\ B &\longrightarrow C \\
A\ D &\longrightarrow E \\
B &\longrightarrow D \\
A\ F &\longrightarrow B
\end{aligned}
$$

Closure of {A,B}: X = {A, B, C, D, E}

Closure of {A, F}: X = {A, F, B, D, C, E}

Usage for Attribute Closure

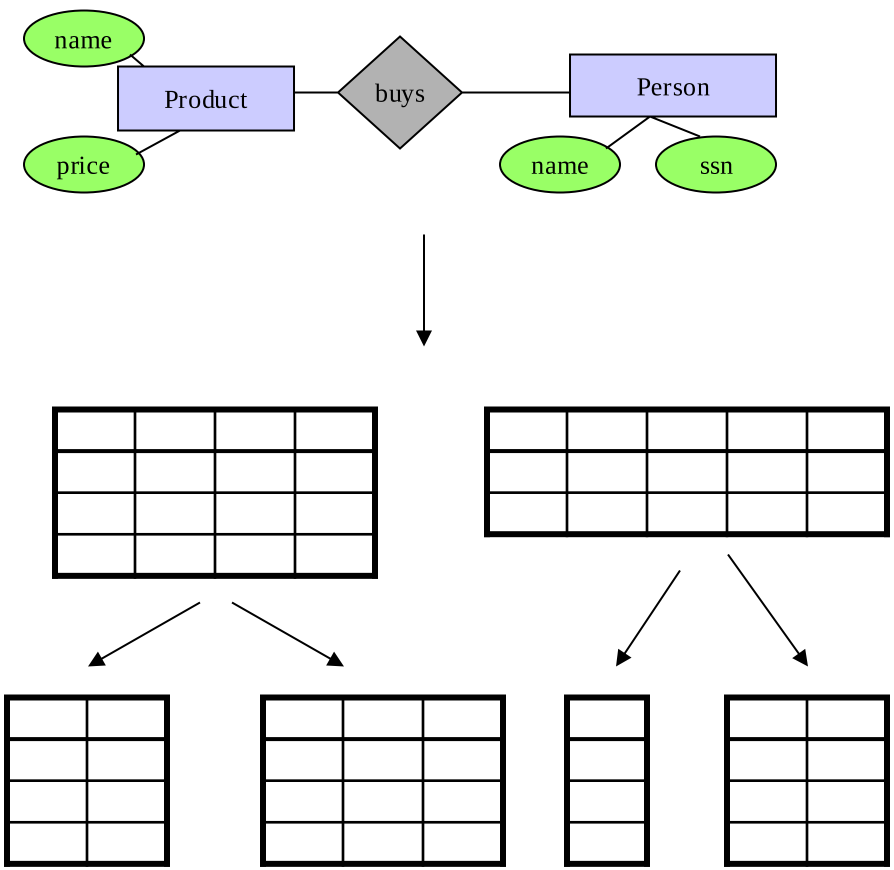
- Test if X is a superkey
  - compute X+, and check if X+ contains all attrs of R
- Check if X ➔ Y holds
  - by checking if Y is contained in X+
- Another way to compute closure S+ of FDs
  - for each subset of attributes X in relation R, compute X+
  - for each subset of attributes Y in X+, output the FD X ➔ Y

Desirable Properties of Schema Refinement

1) minimize redundancy
2) avoid info loss
3) preserve dependency
4) ensure good query performance

Relational Schema Design (or Logical Design)

Conceptual Model:



Relational Model:
- create tables
- specify FD's
- find keys

Normalization
- use FDs to decompose tables to achieve better design

Recall: Relation Decomposition

The original relation schema

Name	SSN	Phone Number
Fred	123-321-99	(201) 555-1234
Fred	123-321-99	(206) 572-4312
Joe	909-438-44	(908) 464-0028
Joe	909-438-44	(212) 555-4000

Relation Decomposition (cont.)

Break the relation into two:

SSN	Name
123-321-99	Fred
909-438-44	Joe

SSN	Phone Number
123-321-99	(201) 555-1234
123-321-99	(206) 572-4312
909-438-44	(908) 464-0028
909-438-44	(212) 555-4000

- Desirable Property #1: Minimize redundancy

Decompositions in General

Let *R* be a relation with attributes $A_1, A_2, \ldots A_n$

Create two relations *R1* and *R2* with attributes

$$B_1, B_2, \ldots B_m \qquad\qquad C_1, C_2, \ldots C_l$$

Such that:

$$B_1, B_2, \ldots B_m \cup C_1, C_2, \ldots C_l = A_1, A_2, \ldots A_n$$

And

-- *R1* is the projection of *R* on $B_1, B_2, \ldots B_m$

-- *R2* is the projection of *R* on $C_1, C_2, \ldots C_l$

Certain Decomposition May Cause Problems

Name	Price	Category
Gizmo	19.99	Gadget
OneClick	24.99	Camera
DoubleClick	29.99	Camera

Decompose on : **Name, Category** and **Price, Category**

Name	Category
Gizmo	Gadget
OneClick	Camera
DoubleClick	Camera

Price	Category
19.99	Gadget
24.99	Camera
29.99	Camera

When we put it back:

Cannot recover information

Name	Price	Category
Gizmo	19.99	Gadget
OneClick	24.99	Camera
OneClick	**29.99**	**Camera**
DoubleClick	**24.99**	**Camera**
DoubleClick	29.99	Camera

Lossless Decompositions

A decomposition is *lossless* if we can recover:

R(A,B,C)

Decompose

R1(A,B) R2(A,C)

Recover

R'(A,B,C) should be the same as R(A,B,C)

R' is in general larger than R. Must ensure R' = R

- Desirable Property #2: Lossless decomposition

Put Another Way: "Lossless" Joins

- The main idea: if you decompose a relation schema, then join the parts of an instance via a natural join, you might get more rows than you started with, i.e., spurious tuples
  - This is bad!
  - Called a "lossy join".
- Goal: decompositions which produce only "lossless" joins
  - "non-additive" join is more descriptive

Dependency Preserving

- Given a relation R and a set of FDs S
- Suppose we decompose R into R1 and R2
- Suppose
  - R1 has a set of FDs S1
  - R2 has a set of FDs S2
  - S1 and S2 are computed from S
- We say the decomposition is dependency preserving if by enforcing S1 over R1 and S2 over R2, we can enforce S over R

An Example

Unit	Company	Product

FD's: Unit $\rightarrow$ Company;   Company, Product $\rightarrow$ Unit

So, there is a BCNF violation, and we decompose.

Unit	Company

Unit $\rightarrow$ Company

Unit	Product

No FDs

So What's the Problem?

Unit	Company
Galaga99	UI
Bingo	UI

Unit	Product
Galaga99	databases
Bingo	databases

No problem so far. All *local* FD's are satisfied.

Let's put all the data back into a single table again:

Unit	Company	Product
Galaga99	UW	databases
Bingo	UW	databases

Violates the dependency: company, product -> unit!

Preserving FDs

- What if, when a relation is decomposed, the X of an $X \rightarrow Y$ ends up only in one of the new relations and the Y ends up only in another?
- Such a decomposition is not "dependency-preserving."
- Desirable Property #3: always have FD-preserving decompositions

- We will talk about "Desirable Property #4: Ensure Good Query Performance" later

Review

- When decomposing a relation R, we want to decomposition to
  - minimize redundancy
  - avoid info loss
  - preserve dependencies (i.e., constraints)
  - ensure good query performance
- These objectives can be conflicting
- Various normal forms achieve parts of the objectives

Normal Forms

First Normal Form = all attributes are atomic

Second Normal Form (2NF) = old and obsolete

Boyce Codd Normal Form (BCNF) ⇦

Third Normal Form (3NF)

Fourth Normal Form (4NF)

Others...

Recall: What We Want to Do with Normal Forms

- Take a relation schema…
- Test it against a normalization criterion…
- If it passes, fine!
  - Maybe test again with a higher criterion
- If it fails, decompose into smaller relations
  - Each of them will pass the test
  - Each can then be tested with a higher criterion

Boyce-Codd Normal Form

A simple condition for removing anomalies from relations:

A relation R is in BCNF if and only if:

Whenever there is a nontrivial FD $A_1, A_2, \ldots A_n \longrightarrow B$ for R, it is the case that $\{ A_1, A_2, \ldots A_n \}$ is a super-key for R.

In English (though a bit vague):

Whenever a set of attributes of *R* is determining another attribute, it is a super-key, and thus should determine ***all*** attributes of *R*. (A key is also a super-key)

Example

Name	SSN	Phone Number
Fred	123-321-99	(201) 555-1234
Fred	123-321-99	(206) 572-4312
Joe	909-438-44	(908) 464-0028
Joe	909-438-44	(212) 555-4000

What are the FDs?

SSN $\rightarrow$ Name

Does this FD satisfy the BCNF condition?

Is the relation in BCNF?

Decompose it into BCNF

SSN	Name
123-321-99	Fred
909-438-44	Joe

SSN $\rightarrow$ Name

SSN	Phone Number
123-321-99	(201) 555-1234
123-321-99	(206) 572-4312
909-438-44	(908) 464-0028
909-438-44	(212) 555-4000

What About This?

Name	Price	Category
Gizmo	$19.99	gadgets
OneClick	$24.99	camera

Name $\longrightarrow$ Price, Category

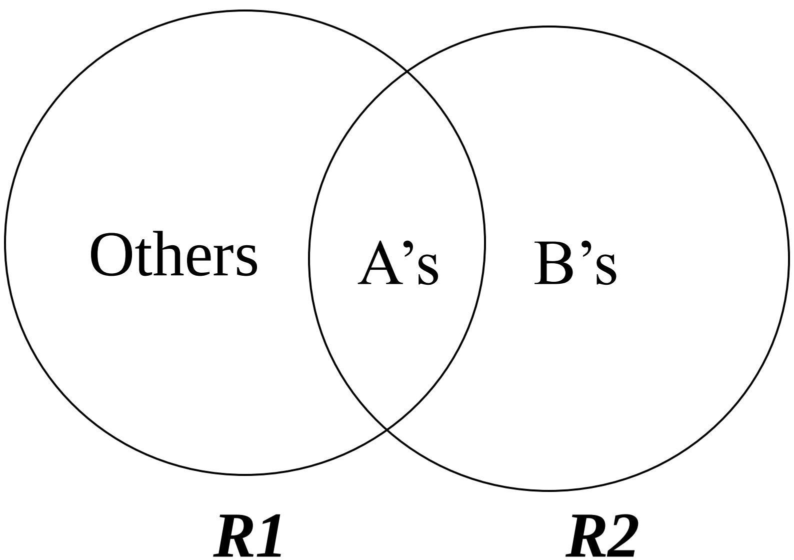
BCNF Decomposition

Find a dependency that violates the BCNF condition:

$$A_1, A_2, \ldots A_n \longrightarrow B_1, B_2, \ldots B_m$$

Heuristics: choose B_1 , B_2, … B_m “as large as possible”

Decompose:



Continue until there are no BCNF violations left.

Any 2-attribute relation is in BCNF.

Example Decomposition

Person:

Name	SSN	Age	EyeColor	PhoneNumber

Functional dependencies:

SSN $\longrightarrow$ Name, Age, Eye Color

BNCF: Person1(SSN, Name, Age, EyeColor),
Person2(SSN, PhoneNumber)

What if we also had an attribute Draft-worthy, and the FD:

Age $\longrightarrow$ Draft-worthy

Thus,

- BCNF removes certain types of redundancy
- For examples of redundancy that it cannot remove, see "multivalued redundancy"
- BCNF avoids info loss

Recall: Lossless Decompositions

A decomposition is *lossless* if we can recover:

R(A,B,C)

Decompose

{ R1(A,B) , R2(A,C) }

Recover

R'(A,B,C) = R(A,B,C)

R' is in general larger than R. Must ensure R' = R

Decomposition Based on BCNF is Necessarily Lossless

R(A, B, C), $A \rightarrow C$

BCNF: R1(A,B), R2(A,C)

Some tuple (a,b,c) in R (a,b',c') also in R
decomposes into (a,b) in R1 (a,b') also in R1
and (a,c) in R2 (a,c') also in R2

Recover tuples in R: (a,b,c), (a,b,c'), (a,b',c), (a,b',c') also in R ?

Can (a,b,c') be a bogus tuple? What about (a,b',c') ?

However,

- BCNF is not always dependency preserving
- In fact, some times we cannot find a BCNF decomposition that is dependency preserving
- Can handle this situation using 3NF
- Not covered in this course, see book for examples