V. Database Design

How to obtain a good relational database schema

- Deriving new relational schema from ER-diagrams
- Normal forms: use of constraints in evaluating existing relational schema

Translating an E-R Model to a Relational Schema

General approach is straightforward

- Each entity set maps to a new table
- Each attribute maps to a new table column
- Each relationship set maps to either new table columns or to a new table

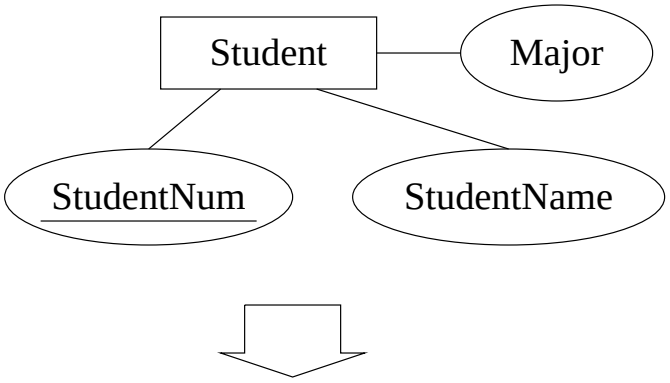
Representing Strong Entity Sets

Entity set E with attributes $a_1, \ldots, a_n$
$\rightarrow$ table E with attributes $a_1, \ldots, a_n$

Entity of type $E \leftrightarrow$ row in table E

Primary key of entity set $\rightarrow$ primary key of table

Ex.



Student

StudentNum	StudentName	Major

Representing Weak Entity Sets

Weak entity set $E \rightarrow$ table E

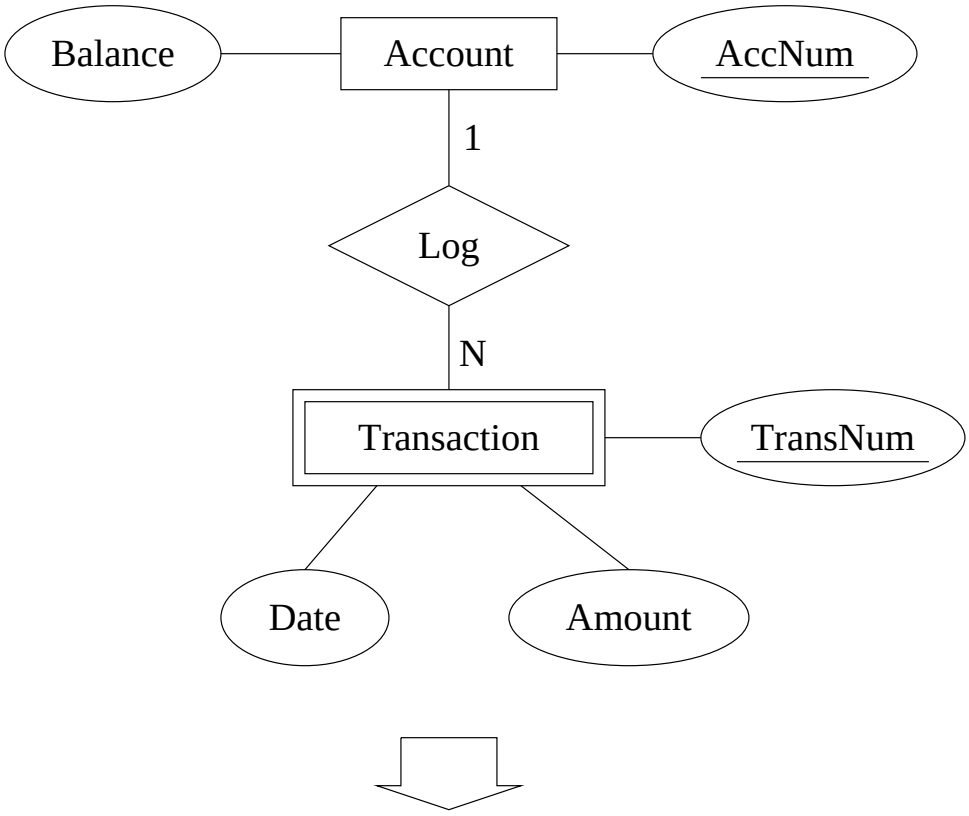
Columns of table E should include

- Attributes of the weak entity set
- Attributes of the identifying relationship set
- Primary key attributes of entity set for dominating entities

Primary key of weak entity set $\rightarrow$ primary key of table

Representing Weak Entity Sets (cont'd)

Ex.



Account

AccNum	Balance

Transaction

TransNum	AccNum	Date	Amount

Representing Relationship Sets

If the relationship set is an identifying relationship set for a weak entity set then no action needed

If we can deduce the general cardinality constraint (1,1) for a component entity set E then add following columns to table E

- Attributes of the relationship set
- Primary key attributes of remaining component entity sets

Otherwise: relationship set $R \rightarrow$ table R

Representing Relationship Sets (cont'd)

Columns of table R should include

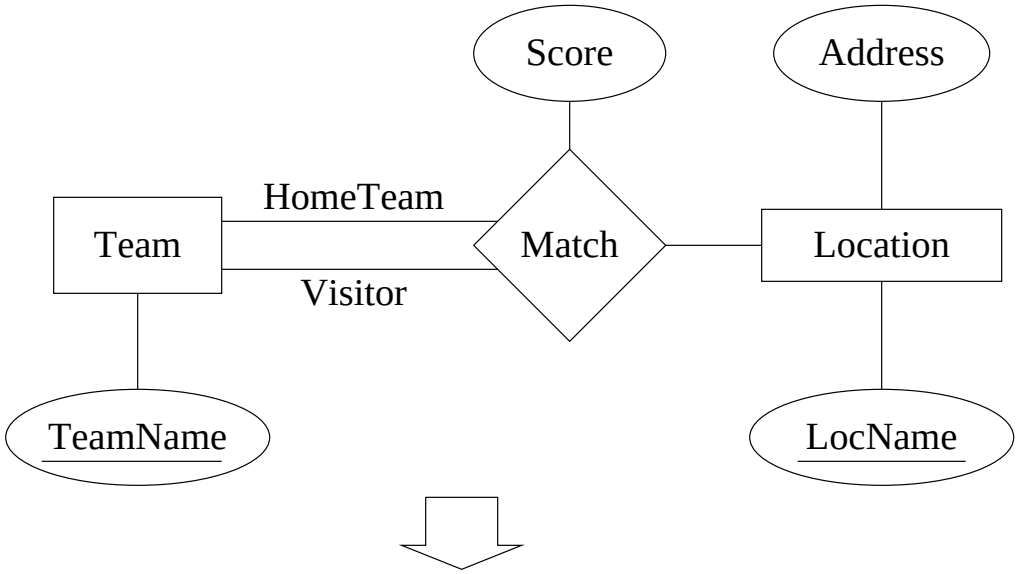
- Attributes of the relationship set
- Primary key attributes of each component entity set

Primary key of table R determined as follows

- If we can deduce the general cardinality constraint (0,1) for a component entity set E, then choose the primary key attributes for E
- Otherwise, choose primary key attributes of each component entity

Representing Relationship Sets (cont'd)

Ex.



Team

TeamName

Location

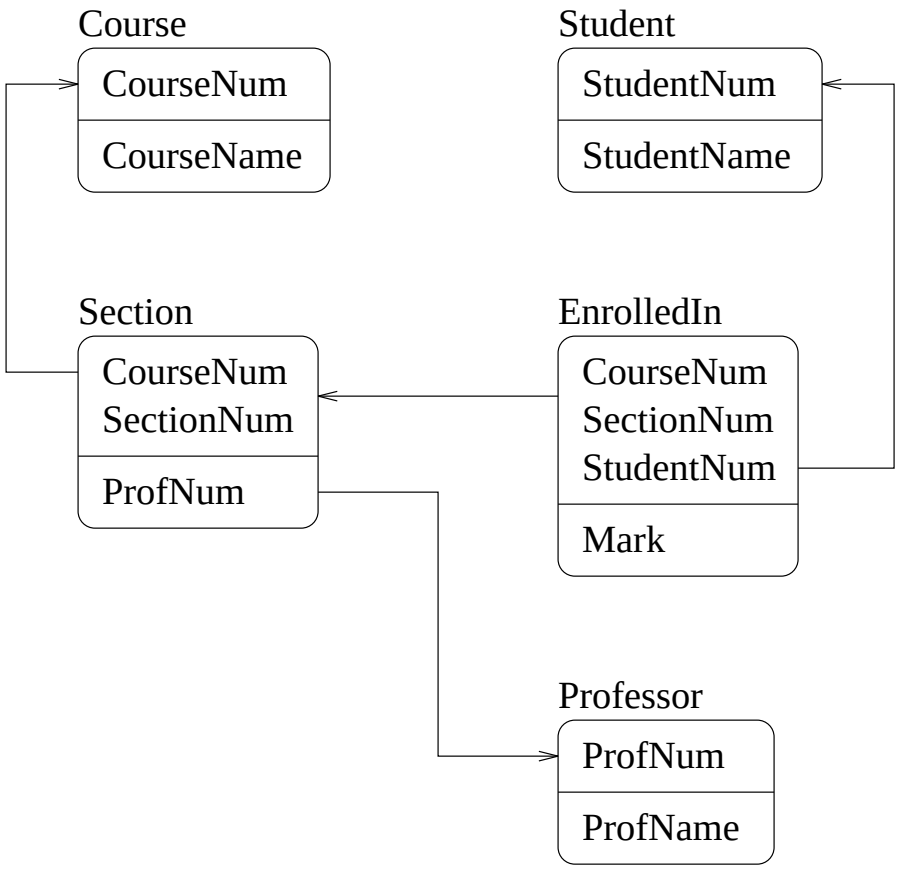
LocName	Address

Match

HomeTeamName	VisitorTeamName	LocName	Score

Note that the role name of a component entity set should be prepended to its primary key attributes, if supplied

Example Translation



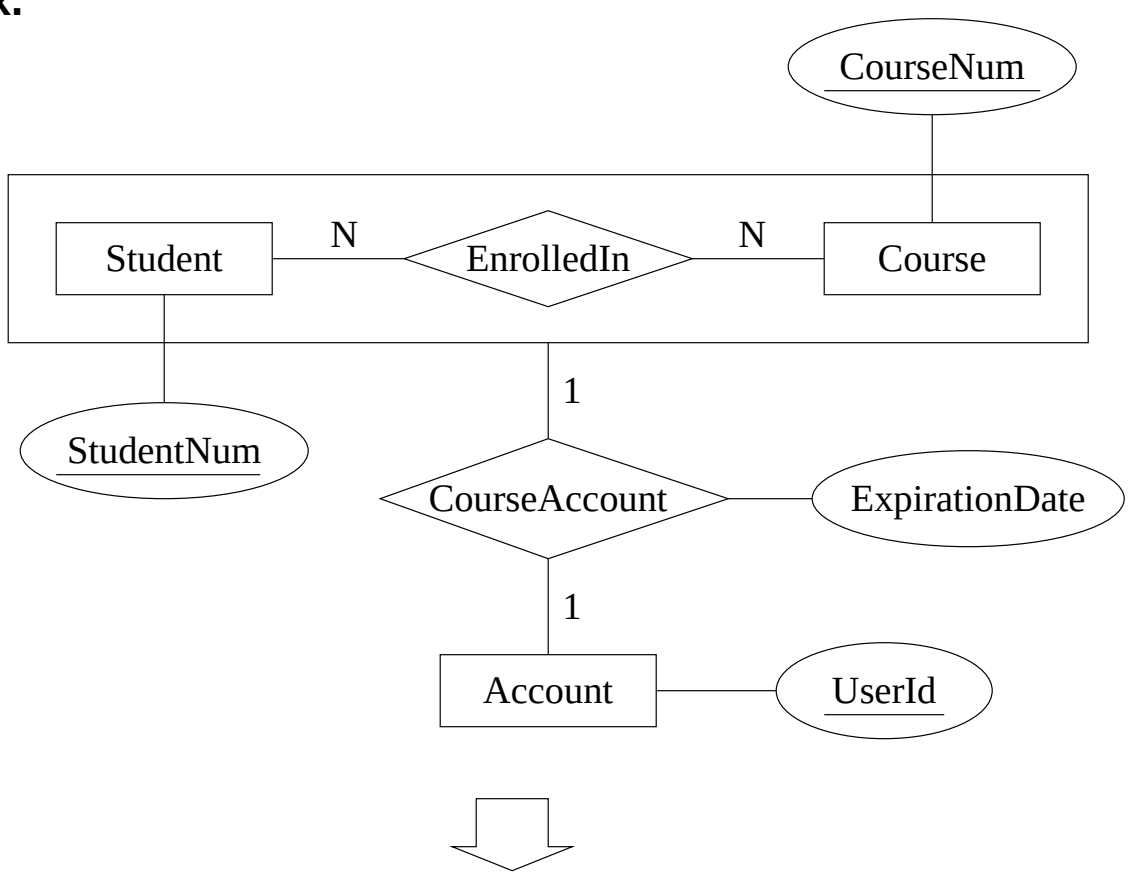
Representing Aggregation

Tabular representation for aggregation of relationship set R
$=$ tabular representation for relationship set R

To represent relationship set involving aggregation of R, treat the aggregation like an entity set whose primary key $=$ primary key of the table for R

Representing Aggregation (cont'd)

Ex.



Student

StudentNum

Course

CourseNum

Account

UserId

EnrolledIn

StudentNum	CourseNum

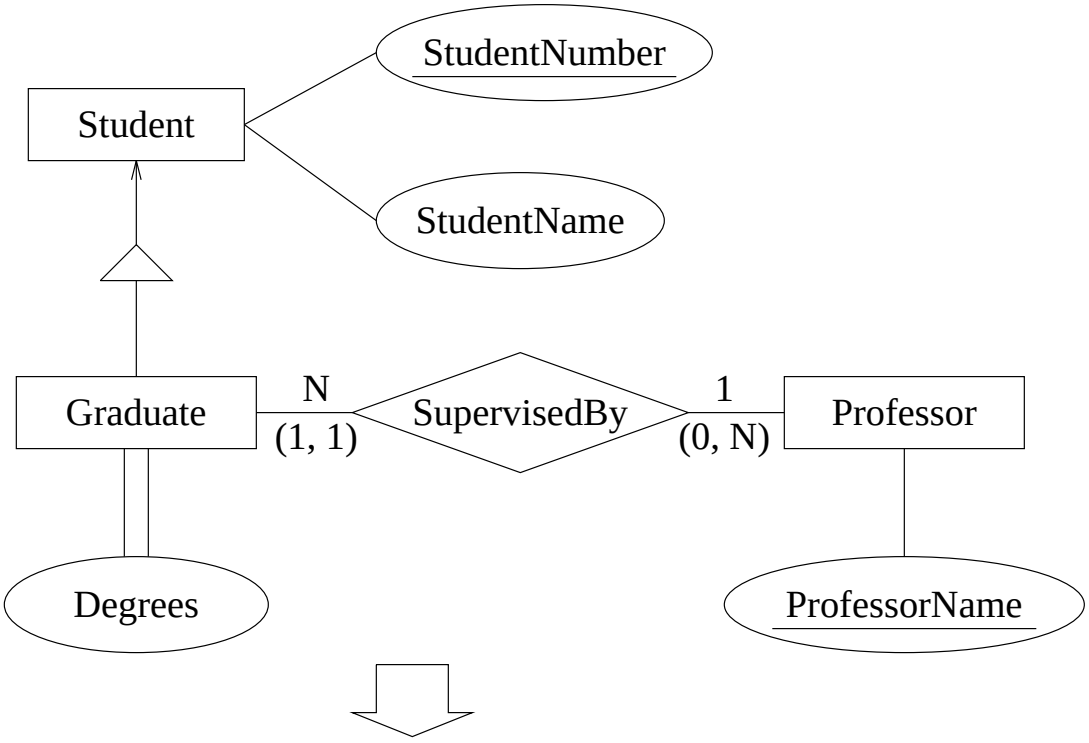
CourseAccount

UserId	StudentNum	CourseNum	ExpirationDate

Representing Specialization

Create table for higher-level entity set, and treat specialized entity subsets like weak entity sets

Ex.



Student

StudentNumber	StudentName

Professor

ProfessorName

Graduate

StudentNumber	ProfessorName

Degree

StudentNumber	Degree

Representing Generalization

Create a table for each lower-level entity set only

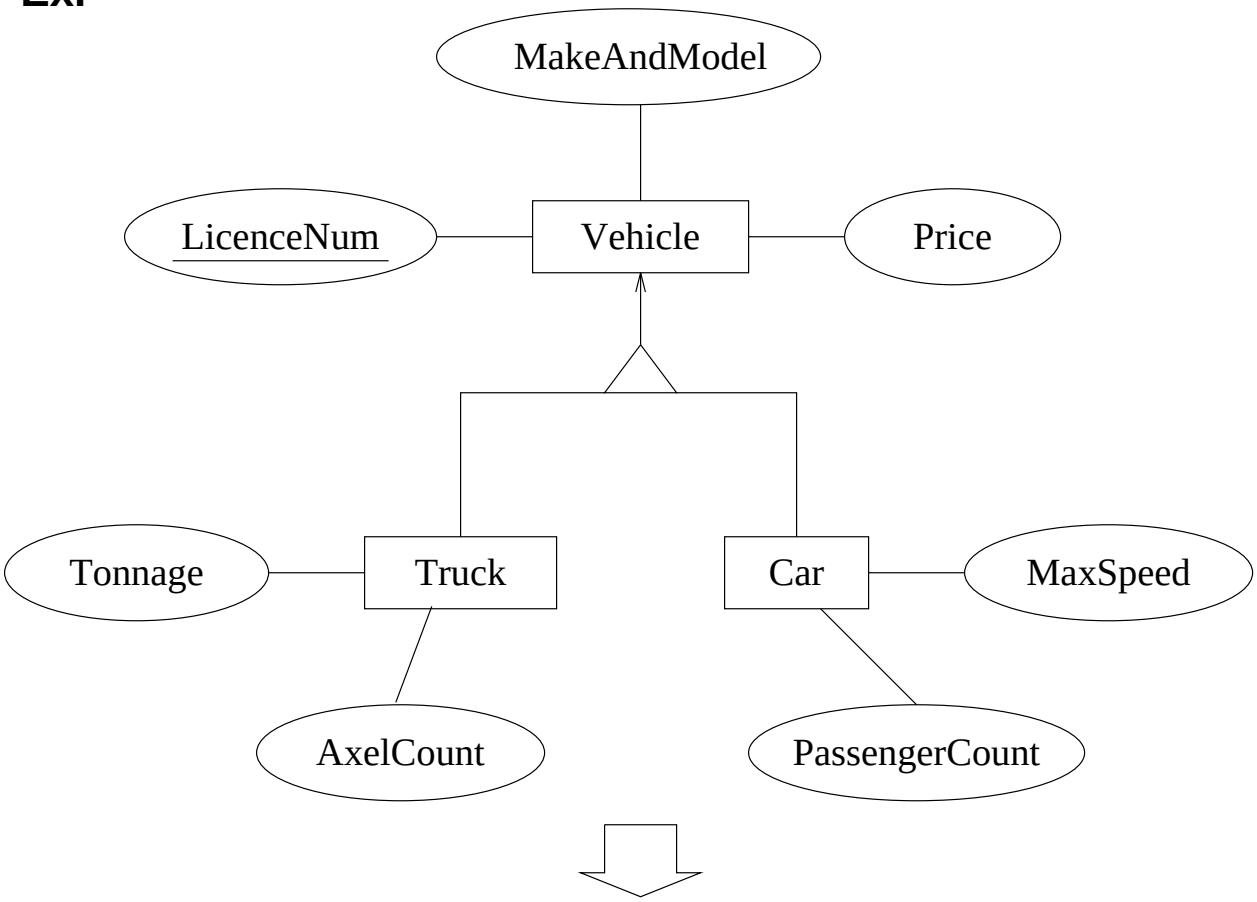
Columns of new tables should include

- Attributes of lower level entity set
- Attributes of the superset

The higher-level entity set can be defined as a view on the tables for the lower-level entity sets

Representing Generalization (cont'd)

Ex.



Truck

LicenceNum	MakeAndModel	Price	Tonnage	AxelCount

Car

LicenceNum	MakeAndModel	Price	MaxSpeed	PassengerCount

Normal Forms

What is a good relational database schema?

How can we evaluate an existing relational schema?

Goals:

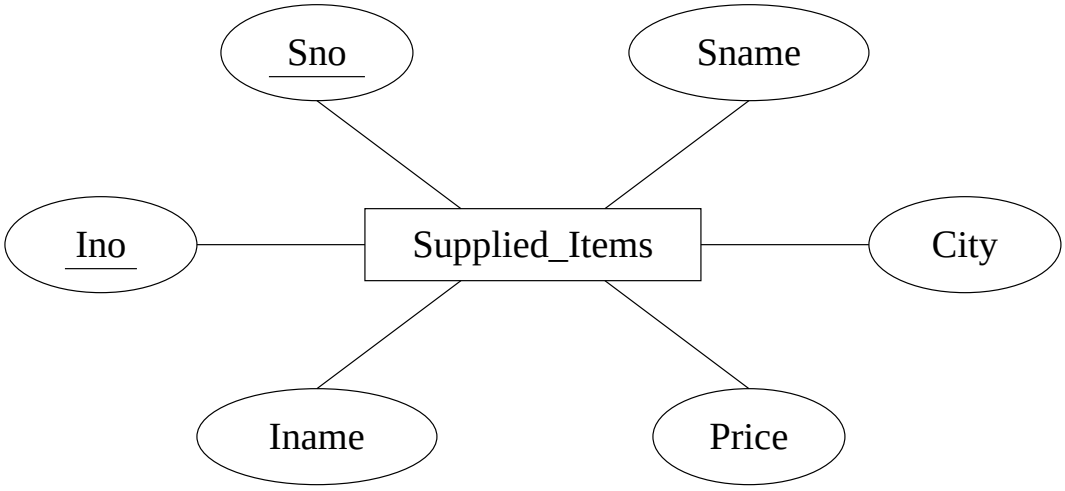
- Intuitive and straightforward changes
- Nonredundant storage of data

We review:

- Boyce-Codd Normal Form (BCNF)
- Third Normal Form (3NF)

Change Anomalies

Assume we are given the E-R diagram



Change Anomalies (cont'd)

This maps to

Supplied_Items

Sno	Sname	City	Ino	Iname	Price
S1	Magna	Ajax	I1	Bolt	0.50
S1	Magna	Ajax	I2	Nut	0.25
S1	Magna	Ajax	I3	Screw	0.30
S2	Budd	Hull	I3	Screw	0.40

Problems

1. Update problems (e.g. changing name of supplier)
2. Insert problems (e.g. add a new item)
3. Delete problems (e.g. Budd no longer supplies screws)
4. Likely increase in space requirements

Change Anomalies (cont'd)

Now compare to

Supplier

Sno	Sname	City
S1	Magna	Ajax
S2	Budd	Hull

Item

Ino	Iname
I1	Bolt
I2	Nut
I3	Screw

Supplies

Sno	Ino	Price
S1	I1	0.50
S1	I2	0.25
S1	I3	0.30
S2	I3	0.40

Change Anomalies (cont'd)

But other extreme is also undesirable (information about relationships is lost)

Snos

Sno
S1
S2

Snames

Sname
Magna
Budd

Cities

City
Ajax
Hull

Inums

Inum
I1
I2
I3

Inames

Iname
Bolt
Nut
Screw

Prices

Price
0.50
0.25
0.30
0.40

Good Database Design

What is a “good” relational database schema?

Rule of thumb: Independent facts in separate tables

or: Each relation schema should consist of a primary key and a set of mutually independent attributes

Functional Dependencies

Generalizes notion of superkey

Used to characterize BCNF and 3NF

Some notation: Allow projection operation on tuples

Ex. when t is the first tuple in Supplier,

- t[Sno] = (S1)
- t[Sname, City] = (Magna, Ajax)

Examples of Functional Dependencies

Consider

EmpProj

SIN	PNum	Hours	EName	PName	PLoc	Allowance

Key constraint forbids two different rows t and u in EmpProj with t[SIN, PNum] = u[SIN, PNum]

Also disallowed

- one SIN with two employee names
- one project number with two project names or two locations
- different allowances for the same number of hours at the same location

Notation

- SIN $\rightarrow$ EName
- PNum $\rightarrow$ PName, Ploc
- PLoc, Hours $\rightarrow$ Allowance

Formal Definitions

Let R be a relation schema, and $X, Y \subseteq R$.
The **functional dependency**

$$X \rightarrow Y$$

holds on R if no legal instance of R contains two tuples t and u with $t[X] = u[X]$ and $t[Y] \neq u[Y]$

X *functionally determines* Y,
Y is *functionally dependent* on X

Keys again: $K \subseteq R$ is a superkey for relation schema R if dependency $K \rightarrow R$ holds on R

Functional dependencies are constraints on *all* instances of a schema; they are design decisions based on the semantics of the attributes

A relation can confirm that a functional dependency does not hold; the relation cannot confirm that a functional dependency must always hold.

Formal Definitions (cont'd)

Ex.

TEACH

Teacher	Course	Text
Smith	Data Structures	Bartram
Smith	Data Management	Al-Nour
Hall	Compilers	Hoffman
Brown	Data Structures	Augenthaler

Let F denote a set of functional dependencies over R.
The **closure of** F, denoted by F^+ is the set of all functional dependencies that are satisfied by every relation instance that satisfies F

(= *logical implications* of F)

Note: $F \subseteq F^+$

Reasoning About Functional Dependencies

Need to be able to

- find superkeys
- decide membership in F^+
- find minimal covers

There are different sets of functional dependencies that have the same logical implications. Small simples sets are desirable, and are called **minimal covers**.

Reasoning About Functional Dependencies (cont'd)

Logical implications can be derived by using inference rules called **Armstrong's axioms**

- (reflexivity) $Y \subseteq X \Rightarrow X \rightarrow Y$
- (augmentation) $X \rightarrow Y \Rightarrow XZ \rightarrow YZ$
- (transitivity) $X \rightarrow Y, Y \rightarrow Z \Rightarrow X \rightarrow Z$

Additional rules can be derived

- (union) $X \rightarrow Y, X \rightarrow Z \Rightarrow X \rightarrow YZ$
- (decomposition) $X \rightarrow YZ \Rightarrow X \rightarrow Y$

The axioms are

- sound (anything derived from F is in F^+)
- complete (anything in F^+ can be derived)

Reasoning (cont'd)

Ex. Let F consist of

SIN, PNum $\rightarrow$ Hours
SIN $\rightarrow$ EName
PNum $\rightarrow$ PName, PLoc
PLoc, Hours $\rightarrow$ Allowance

A derivation of: SIN, PNum $\rightarrow$ Allowance

1.	SIN, PNum $\rightarrow$ Hours	($\in F$)
2.	PNum $\rightarrow$ PName, PLoc	($\in F$)
3.	PLoc, Hours $\rightarrow$ Allowance	($\in F$)
4.	SIN, PNum $\rightarrow$ PNum	(reflexivity)
5.	SIN, PNum $\rightarrow$ PName, PLoc	(transitivity, 4 and 2)
6.	SIN, PNum $\rightarrow$ PLoc	(decomposition, 5)
7.	SIN, PNum $\rightarrow$ PLoc, Hours	(union, 6, 1)
8.	SIN, PNum $\rightarrow$ Allowance	(transitivity, 7 and 3)

Reasoning (cont'd)

There is a more efficient way of using Armstrong's axioms

function $ComputeX^+(X, F)$
begin
  $X^+ := X$;
  while true do
    if there exists $(Y \rightarrow Z) \in F$ such that
      (1) $Y \subseteq X^+$, and
      (2) $Z \not\subseteq X^+$
    then $X^+ := X^+ \cup Z$
    else exit;
  return X^+;
end

Let R be a relational schema and F a set of functional dependencies on R. Then

Theorem: X is a superkey of R if and only if

$$ComputeX^+(X, F) = R$$

Theorem: $X \rightarrow Y \in F^+$ if and only if

$$Y \subseteq ComputeX^+(X, F)$$

Finding Minimal Covers

A minimal cover for F can be computed in four steps. Note that each step must be repeated until it no longer succeeds in updating F.

Step 1. Replace $X \rightarrow YZ$ with the pair $X \rightarrow Y$ and $X \rightarrow Z$.

Step 2. Remove $X \rightarrow A$ from F if $A \in ComputeX^{+}(X, F - \{X \rightarrow A\})$.

Step 3. Remove A from the left-hand-side of $X \rightarrow B$ in F if B is in $ComputeX^{+}(X - \{A\}, F)$.

Step 4. Replace $X \rightarrow Y$ and $X \rightarrow Z$ in F by $X \rightarrow YZ$.

Boyce-Codd Normal Form (BCNF)

Formalization of the goal that independent relationships are stored in separate tables

Let R be a relation schema and F a set of functional dependencies. A functional dependency $X \rightarrow Y$ is **trivial** if $Y \subseteq X$.

Schema R is in **BCNF** if and only if whenever $(X \rightarrow Y) \in F^+$ and $XY \subseteq R$, then either

- $(X \rightarrow Y)$ is trivial, or
- X is a superkey of R

A database schema $\{R_1, \ldots, R_n\}$ is in BCNF if each relation schema R_i is in BCNF

BCNF (cont'd)

Why does BCNF avoid redundancy?

For schema Supplied_Items we had

FD: Sno $\rightarrow$ Sname, City

Implies: supplier name "Magna" and city "Ajax" must be repeated for each item supplied by supplier S1.

Assume FD holds over a schema R that is in BCNF. This implies

- Sno is a superkey for R
- each Sno value appears on one row only
- no need to repeat Sname and City values

(Cf. the original Supplier table)

Computing a Normal Form

What to do if a given relational schema is not in BCNF?

Strategy: identify undesirable dependencies,
decompose schema

Let R be a relation schema (= set of attributes). Collection $\{R_1, \ldots, R_n\}$ of relation schemas is a **decomposition** of R if

$$R = R_1 \cup R_2 \cup \cdots \cup R_n$$

A good decomposition does not

- lose information
- complicate checking of constraints

Lossless-Join Decompositions

We should be able to construct the original table from its decomposition

Ex. Consider replacing

Marks

Student	Assignment	Group	Mark
Ann	A1	G1	80
Ann	A2	G3	60
Bob	A1	G2	60

by decomposing (i.e. projecting) into two tables

SGM

Student	Group	Mark
Ann	G1	80
Ann	G3	60
Bob	G2	60

AM

Assignment	Mark
A1	80
A2	60
A1	60

Lossless-Join Decompositions (cont'd)

But computing the natural join of SGM and AM produces

Student	Assignment	Group	Mark
Ann	A1	G1	80
Ann	A2	G3	60
Ann	A1	G3	60 !
Bob	A2	G2	60 !
Bob	A1	G2	60

We get extra data, **spurious tuples**, and would therefore lose information if we were to replace Marks by SGM and AM.

If converse is true, if re-joining SGM and AM would **always** produce exactly the tuples in Marks, then we call SGM and AM a **lossless-join decomposition**.

Identifying Lossless-Join Decompositions

A decomposition $\{R_1, R_2\}$ of R is lossless if and only if the common attributes of R_1 and R_2 form a superkey for either schema, that is

$$R_1 \cap R_2 \rightarrow R_1 \text{ or } R_1 \cap R_2 \rightarrow R_2$$

Ex. In the previous example we had

R = {Student, Assignment, Group, Mark} ,
F = {(Student, Assignment $\rightarrow$ Group, Mark)} ,
R_1 = {Student, Group, Mark} ,
R_2 = {Assignment, Mark}

Decomposition $\{R_1, R_2\}$ is lossy because $R_1 \cap R_2 (= \{M\})$ is not a superkey of either SGM or AM

Dependency Preservation

Goal: efficient testing of constraints on the decomposed schema

Ex. A table for a company database could be

R

Proj	Dept	Div

with functional dependencies

FD1: Proj $\rightarrow$ Dept,
FD2: Dept $\rightarrow$ Div, and
FD3: Proj $\rightarrow$ Div

Consider two decompositions

$D_1 = \{$R1[Proj, Dept], R2[Dept, Div]$\}$

$D_2 = \{$R1[Proj, Dept], R3[Proj, Div]$\}$

Both are lossless. (Why?)

Dependency Preservation (cont'd)

Decomposition D_1 lets us test FD1 on table R1 and FD2 on table R2; if they are both satisfied, FD3 is automatically satisfied

In decomposition D_2 we can test FD1 on table R1 and FD3 on table R3. Dependency FD2 is an **interrelational constraint**: testing it requires joining tables R1 and R3

Let R be a relation schema and F a set of functional dependencies on R.

A decomposition $D = \{R_1, \ldots, R_n\}$ of R is **dependency preserving** if there is an equivalent set F' of functional dependencies, none of which is interrelational in D

Computing a Lossless-Join BCNF Decomposition

function $ComputeBCNF(R, F)$
begin
    Result := $\{R\}$;
    while some $R_i \in$ Result and $(X \rightarrow Y) \in F^+$
            violate the BCNF condition **do begin**
        Replace R_i by $R_i - (Y - X)$;
        Add $\{X, Y\}$ to Result;
    end;
    return Result;
end

No efficient procedure to do this exists.

It is possible that no dependency preserving BCNF decomposition exists.

Ex. Consider $R = \{\text{A, B, C}\}$ and $F = \{\text{AB} \rightarrow \text{C, C} \rightarrow \text{B}\}$.

Third Normal Form (3NF)

Let R be a relation schema and F a set of functional dependencies.

Schema R is in **3NF** if and only if whenever $(X \rightarrow Y) \in F^+$ and $XY \subseteq R$, then either

- $(X \rightarrow Y)$ is trivial, or
- X is a superkey of R, or
- each attribute of Y is contained in a candidate key of R

A database schema $\{R_1, \ldots, R_n\}$ is in 3NF if each relation schema R_i is in 3NF

Because 3NF is looser than BCNF, it allows more redundancy

A lossless-join, dependency preserving decomposition into 3NF relation schemas always exists.

Computing a 3NF Decomposition

A lossless-join 3NF decomposition that is dependency preserving can be efficiently computed

function $Compute3NF(R, F)$
begin
    Result := $\emptyset$;
    F' := a minimal cover for F;
    for each $(X \rightarrow Y) \in F'$ **do**
        Result := Result $\cup \{XY\}$;
    if there is no $R_i \in$ Result such that
        R_i contains a candidate key for R **then begin**
        compute a candidate key K for R;
        Result := Result $\cup \{K\}$;
    end;
    return Result;
end