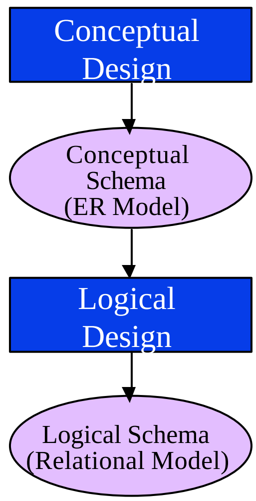
Design Process - Where are we?

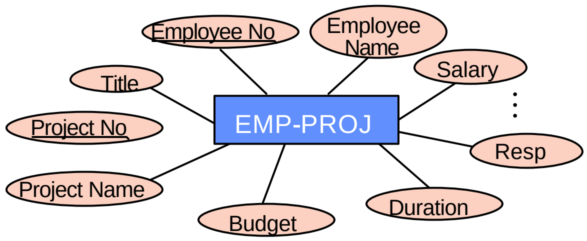


Step 1: ER-to-Relational Mapping
Step 2: Normalization: "Improving" the design

Relational Design Principles

- Relations should have semantic unity
- Information repetition should be avoided
  - Anomalies: insertion, deletion, modification
- Avoid null values as much as possible
  - Difficulties with interpretation
    - don't know, don't care, known but unavailable, does not apply
  - Specification of joins
- Avoid spurious joins

Bad Design



EMP-PROJ

ENO	ENAME	TITLE	SALARY	PNO	PNAME	BUDGET	DURATION	RESP
E1	J. Doe	Elect. Eng.	40000	P1	Instrumentation	150000	12	Manager
E2	M. Smith	Analyst	34000	P1	Instrumentation	150000	24	Analyst
E2	M. Smith	Analyst	34000	P2	Database Develop.	135000	6	Analyst
E3	A. Lee	Mech. Eng.	27000	P3	CAD/CAM	250000	10	Consultant
E3	A. Lee	Mech. Eng.	27000	P4	Maintenance	310000	48	Engineer
E4	J. Miller	Programmer	24000	P2	Database Develop.	135000	18	Programmer
E5	B. Casey	Syst. Anal.	34000	P2	Database Develop.	135000	24	Manager
E6	L. Chu	Elect. Eng.	40000	P4	Maintenance	310000	48	Manager
E7	R. Davis	Mech. Eng.	27000	P3	CAD/CAM	250000	36	Engineer
E8	J. Jones	Syst. Anal.	34000	P3	CAD/CAM	250000	40	Manager

Information Repetition

- The TITLE, SALARY, BUDGET attribute values are repeated for each project that the engineer is involved in.
  - Waste of space
  - Complicates updates

This example instance of EMP-PROJ relation violates one of the constraints in our earlier design. Which one?

EMP-PROJ

ENO	ENAME	TITLE	SALARY	PNO	PNAME	BUDGET	DURATION	RESP
E1	J. Doe	Elect. Eng.	40000	P1	Instrumentation	150000	12	Manager
E2	M. Smith	Analyst	34000	P1	Instrumentation	150000	24	Analyst
E2	M. Smith	Analyst	34000	P2	Database Develop.	135000	6	Analyst
E3	A. Lee	Mech. Eng.	27000	P3	CAD/CAM	250000	10	Consultant
E3	A. Lee	Mech. Eng.	27000	P4	Maintenance	310000	48	Engineer
E4	J. Miller	Programmer	24000	P2	Database Develop.	135000	18	Programmer
E5	B. Casey	Syst. Anal.	34000	P2	Database Develop.	135000	24	Manager
E6	L. Chu	Elect. Eng.	40000	P4	Maintenance	310000	48	Manager
E7	R. Davis	Mech. Eng.	27000	P3	CAD/CAM	250000	36	Engineer
E8	J. Jones	Syst. Anal.	34000	P3	CAD/CAM	250000	40	Manager

Insertion Anomaly

- It is difficult (impossible?) to store information about a new project until an employee is assigned to it. Why?

EMP-PROJ

ENO	ENAME	TITLE	SALARY	PNO	PNAME	BUDGET	DURATION	RESP
E1	J. Doe	Elect. Eng.	40000	P1	Instrumentation	150000	12	Manager
E2	M. Smith	Analyst	34000	P1	Instrumentation	150000	24	Analyst
E2	M. Smith	Analyst	34000	P2	Database Develop.	135000	6	Analyst
E3	A. Lee	Mech. Eng.	27000	P3	CAD/CAM	250000	10	Consultant
E3	A. Lee	Mech. Eng.	27000	P4	Maintenance	310000	48	Engineer
E4	J. Miller	Programmer	24000	P2	Database Develop.	135000	18	Programmer
E5	B. Casey	Syst. Anal.	34000	P2	Database Develop.	135000	24	Manager
E6	L. Chu	Elect. Eng.	40000	P4	Maintenance	310000	48	Manager
E7	R. Davis	Mech. Eng.	27000	P3	CAD/CAM	250000	36	Engineer
E8	J. Jones	Syst. Anal.	34000	P3	CAD/CAM	250000	40	Manager

Deletion Anomaly

- If an engineer, who is the only employee on a project, leaves the company, his personal information cannot be deleted, or the information about that project is lost.
- May have to delete many tuples.

EMP-PROJ

ENO	ENAME	TITLE	SALARY	PNO	PNAME	BUDGET	DURATION	RESP	MGR
E1	J. Doe	Elect. Eng.	40000	P1	Instrumentation	150000	12	Manager	E1
E2	M. Smith	Analyst	34000	P1	Instrumentation	150000	24	Analyst	E1
E2	M. Smith	Analyst	34000	P2	Database Develop.	135000	6	Analyst	E5
E3	A. Lee	Mech. Eng.	27000	P3	CAD/CAM	250000	10	Consultant	E8
E3	A. Lee	Mech. Eng.	27000	P4	Maintenance	310000	48	Engineer	E6
E4	J. Miller	Programmer	24000	P2	Database Develop.	135000	18	Programmer	E5
E5	B. Casey	Syst. Anal.	34000	P2	Database Develop.	135000	24	Manager	E5
E6	L. Chu	Elect. Eng.	40000	P4	Maintenance	310000	48	Manager	E6
E7	R. Davis	Mech. Eng.	27000	P3	CAD/CAM	250000	36	Engineer	E8
~~E8~~	~~J. Jones~~	~~Syst. Anal.~~	~~34000~~	~~P3~~	~~CAD/CAM~~	~~250000~~	~~40~~	~~Manager~~	~~E8~~

Modification Anomaly

- If any attribute of project (say BUDGET of P1) is modified, all the tuples for all employees who work on that project need to be modified.

EMP-PROJ

ENO	ENAME	TITLE	SALARY	PNO	PNAME	BUDGET	DURATION	RESP	MGR
E1	J. Doe	Elect. Eng.	40000	P1	Instrumentation	150000	12	Manager	E1
E2	M. Smith	Analyst	34000	P1	Instrumentation	150000	24	Analyst	E1
E2	M. Smith	Analyst	34000	P2	Database Develop.	135000	6	Analyst	E5
E3	A. Lee	Mech. Eng.	27000	P3	CAD/CAM	250000	10	Consultant	E8
E3	A. Lee	Mech. Eng.	27000	P4	Maintenance	310000	48	Engineer	E6
E4	J. Miller	Programmer	24000	P2	Database Develop.	135000	18	Programmer	E5
E5	B. Casey	Syst. Anal.	34000	P2	Database Develop.	135000	24	Manager	E5
E6	L. Chu	Elect. Eng.	40000	P4	Maintenance	310000	48	Manager	E6
E7	R. Davis	Mech. Eng.	27000	P3	CAD/CAM	250000	36	Engineer	E8
E8	J. Jones	Syst. Anal.	34000	P3	CAD/CAM	250000	40	Manager	E8

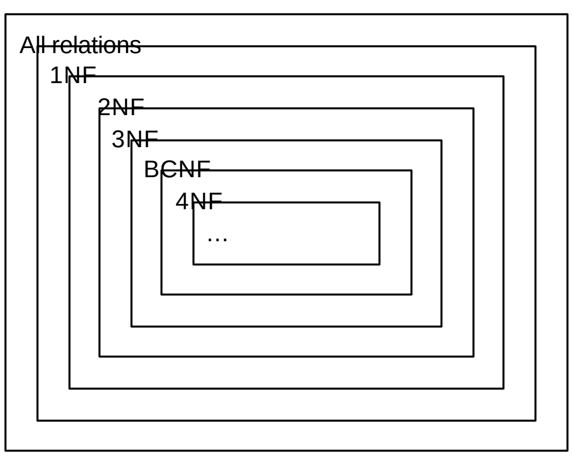
What to do?

- Take each relation individually and "improve" it in terms of the desired characteristics
  - Normal forms
    - Atomic values (1NF)
    - Can be defined according to keys and dependencies.
    - Functional Dependencies (2NF, 3NF, BCNF)
    - Multivalued dependencies (4NF)
  - Normalization
    - Normalization is a process of concept separation which applies a top-down methodology for producing a schema by *subsequent refinements and decompositions*.
    - Do not combine unrelated sets of facts in one table; each relation should contain an independent set of facts.
    - Universal relation assumption
    - 1NF to 3NF; 1NF to BCNF

Normalization Issues

- How do we decompose a schema into a desirable normal form?
- What criteria should the decomposed schemas follow in order to preserve the semantics of the original schema?
  - Reconstructability: recover the original relation $\Rightarrow$ no spurious joins
  - Lossless decomposition: no information loss
  - Dependency preservation: the constraints (i.e., dependencies) that hold on the original relation should be enforceable by means of the constraints (i.e., dependencies) defined on the decomposed relations.
- What happens to queries?
  - Processing time may increase due to joins
  - Denormalization

Normal Forms



Functional Dependence

- Given relation R defined over $U = \{A_1, A_2, ..., A_n\}$ where $X \subseteq U$, $Y \subseteq U$. If, for all pairs of tuples t_1 and t_2 in any legal instance of relation scheme R,

  $$t_1[X] = t_2[X] \Rightarrow t_1[Y] = t_2[Y],$$

  then the functional dependency $X \rightarrow Y$ holds in R.
- Example
  - In relation EMP-PROJ
    - (ENO, PNO) → (ENAME, TITLE, SALARY, DURATION, RESP)
    - ENO → (ENAME, TITLE, SALARY)
    - PNO → (PNAME, BUDGET)
    - TITLE → SALARY

Some Basics

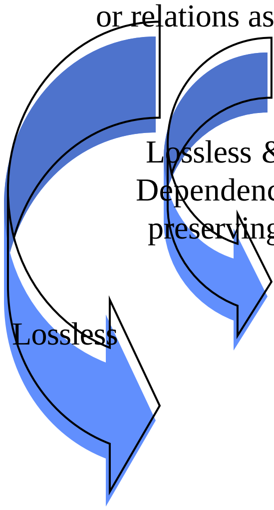
- Superkey
  - A set of one or more attributes, which, taken collectively, allow us to identify uniquely a tuple in a relation.
  - Let R be a relation scheme. A subset K of R is a superkey of R if, in any legal relation [instance] r of R, for all pairs t_1 and t_2 of tuples in r such that $t_1[K] = t_2[K] \Rightarrow t_1 = t_2$.
- Candidate key
  - A superkey for which no proper subset is a superkey.
- Primary key
  - The candidate key that is chosen by the database designer as the principle key.

Some Basics

- Attributes
  - Prime attribute is a member of any key
  - Non-prime attribute is any attribute which is not prime
- Full functional dependency
  - A FD $X \to Y$ is a full functional dependency if X is minimal, i.e., removal of any attribute A from X means the dependency does not hold anymore.
  - Formally - $X \xrightarrow{f} Y$ iff for all $A \in X$, $(X - \{A\}) \not\to Y$.
- Partial functional dependency
  - Formally - $X \xrightarrow{p} Y$ iff for some $A \in X$, $(X - \{A\}) \to Y$.
- Transitive dependency
  - Formally - $X \to Y$ and $Y \to Z$ and $X \to Z$ and $Y \not\to X$ and $Z \not\subseteq Y$

Normal Forms Based on FDs

1NF eliminates the relations within relations or relations as attributes of tuples.



First Normal Form (1NF)

↓ eliminate the partial functional dependencies of non-prime attributes to key attributes

Second Normal Form (2NF)

↓ eliminate the transitive functional dependencies of non-prime attributes to key attributes

Third Normal Form (3NF)

↓ eliminate the partial and transitive functional dependencies of prime (key) attributes to key.

Boyce-Codd Normal Form (BCNF)

First Normal Form

- All attribute values are atomic
- 1NF relation cannot have an attribute value that is:
  - a set of values (set-value)
  - a tuple of values (nested relation)
- This is a standard assumption in relational DBMSs and in the rest of this section
- In object-oriented DBMSs this assumption is relaxed.

Second Normal Form

- Two possible definitions:
  - A relation $R \in$ 2NF iff all non-prime attributes in R are fully functionally dependent on primary key.
  - A relation $R \in$ 2NF iff the attributes are either
    - a candidate key, or
    - fully dependent on every key.
- Partial functional dependencies cause problems.
- 2NF is only of historical importance, since it is subsumed by 3NF.
- In the example, EMP-PROJ is not 2NF, we turn it into 2NF by decomposing it:
  - EMP(<u>ENO</u>, ENAME, TITLE, SALARY)
  - PROJ(<u>PNO</u>,PNAME,BUDGET,MGR)
  - ASSIGN(<u>ENO,PNO</u>,DURATION,RESP)

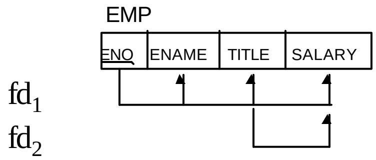
Third Normal Form

- Intuitively: A relation $R \in$ 3NF iff
  - $R \in$ 2NF (i.e., every non-prime attribute is fully functionally dependent on every key)
  - No non-prime attribute of R is transitively dependent on the primary key.
- The issues is to remove the transitive dependencies
- N.B.: The absence of transitive dependencies guarantees absence of partial functional dependencies.

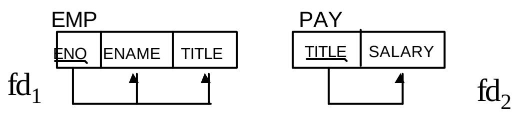
Third Normal Form

- Formally: A relation scheme R defined over $U = \{A_1, A_2, \ldots, A_n\}$ is in 3NF if for all functional dependencies that hold on R of the form $X \to Y$, where $X \subseteq U$ and $X \subseteq U$, at least one of the following holds:
  - $X \to Y$ is a trivial functional dependency (i.e., $Y \subseteq X$)
  - X is a superkey for R
  - Y is contained in a candidate key for R (Y is a set of prime attributes
- The first two conditions deal with transitive dependencies.

3NF – Example



- EMP is not in 3NF because of fd_2
  - TITLE $\rightarrow$ SALARY but TITLE is not a superkey and SALARY is not prime
  - Problem is that ENO transitively determines SALARY (as well as directly determining it)
- Solution:



Boyce-Codd Normal Form

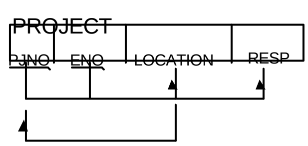
- You can still have transitive dependencies in 3NF if the dependent attribute(s) are prime.
- A 1NF relation scheme R is in BCNF if for every non-trivial functional dependency $X \rightarrow Y$, X is a superkey.
- Properties of BCNF
  - All non-prime attributes are fully dependent on every key.
  - All prime attributes are fully dependent on the keys that they do not belong to.
  - No attribute is non-trivially dependent on any set of non-prime attributes.

Boyce-Codd Normal Form

- Formally: A relation scheme R defined over $U = \{A_1, A_2, \ldots, A_n\}$ is in BCNF if for all functional dependencies that hold on R of the form $X \rightarrow A$, where $X \subseteq U$ and $A \subseteq U$, at least one of the following holds :
  - $X \rightarrow A$ is a trivial functional dependency
  - X is a superkey for R
- No transitive dependencies.

BCNF – Example

- Assume the following definition of the PROJECT relation with:
  - Each employee on a project has a unique location and responsibility with respect to that project, and
  - Only one project can be found at each location
- FDs would be



which makes PROJECT in 3NF but not in BCNF

Inferencing over FDs

- We would like to be able to infer from a given set of FDs F all implied FDs F^+, which is called the closure of F.
- Important because the 3NF and BCNF definitions refer to "all functional dependencies".
- Example:

  ENO $\rightarrow$ (ENAME, TITLE, SALARY,APT#,STREET,CITY)

  $\Longrightarrow$ (ENO $\rightarrow$ ENAME)
- This requires a set of inference rules
  - Armstrong's axioms
  - Additional rules

Inference Rules

- Let X, Y and Z be sets of attributes in relation scheme R
- Armstrong's axioms:
  - Augmentation: $\{X \rightarrow Y\} \Rightarrow \{XZ \rightarrow YZ\}$
  - Transitivity: $\{X \rightarrow Y, Y \rightarrow Z\} \Rightarrow \{X \rightarrow Z\}$
  - Reflexivity: $W \subseteq X \Rightarrow \{X \rightarrow W\}$
- These rules are
  - Sound: do not generate any incorrect FDs – anything derived from F is in F^+
  - Complete: given F as a set of FDs, they permit us to find all of F^+
- Additional Rules:
  - Union: $\{X \rightarrow Y, X \rightarrow Z\} \Rightarrow (X \rightarrow YZ)$
  - Decomposition: $\{X \rightarrow YZ\} \Rightarrow \{X \rightarrow Y, X \rightarrow Z\}$
  - Pseudotransitivity: $\{X \rightarrow Y, WY \rightarrow Z\} \Rightarrow \{XW \rightarrow Z\}$

Why These Rules?

- Lossless join decomposition:
  - If R is decomposed into $R_1, \ldots, R_n$, it should be possible to reconstruct R with no additional (spurious) tuples.
  - If a relation scheme R is decomposed into R_1 and R_2, then at least one of the following FDs should be in F^+
    - $R_1 \cap R_2 \rightarrow R_1$
    - $R_1 \cap R_2 \rightarrow R_2$
- Dependency preservation:
  - If a relation scheme R is decomposed into R_1 and R_2, then every FD in F that holds on relation R (even the implied ones) should be guaranteed to hold whenever the projected dependencies within relations R_1 and R_2 are enforced.

Closure of a Set of FDs

- This is most easily done by converting it to the problem of computing the closure of a set of attributes.
- For each FD defined on the base relations, pick the attribute (or set of attributes) that appear on its left-hand-side
  - Find their closure which gives the set of attributes that are dependent on that attribute
    - Theorem 1: $X \rightarrow Y \in F^+$ iff $Y \subseteq ComputeX^+(X, F)$.
    - Theorem 2: X is a superkey of R iff $ComputeX^+(X, F) = R$.
  - This also gives the set of FDs that can be inferred from the original FD.

Closure of a Set of Attributes

function $ComputeX^+(X, F)$

begin

$X^+ \leftarrow X$

while there exists $Y \rightarrow Z \in F$ such that

$Y \subseteq X^+$ and $Z \not\subseteq X^+$

then $X^+ \leftarrow X^+ \cup Z$

return(X^+)

end

Attribute Closure Example

- Let F consist of
  - A → B
  - C → D, E
  - E, G → H
- $ComputeX^+(\{C, G\}, F)$
  - Initial: $X^+ = \{C, G\}$
  - Iteration 1(C → D, E): $X^+ = \{C, G, D, E\}$
  - Iteration 2 (E, G → H): $X^+ = \{C, G, D, E, H\}$

Lossless Join BCNF Decomposition

Input: Relation $R<U,F>$ /* U={attributes}, F:{FDs} */

Output: Decomposition D for R

Step 1. $D \leftarrow \{R\}$; /* We are talking about attributes of R*/

Step 2. While there is a relation schema $Q \in D$ that is not in BCNF do

if $X \rightarrow Y$ is the FD causing violation

then $D \leftarrow (D-Q) \cup \underbrace{(Q-Y)}_{R_1} \cup \underbrace{(X \cup Y)}_{R_2}$

BCNF Decomposition Example

- Consider the relation and F
  - EMP(ENO, ENAME, TITLE, PNO, PNAME, RESP)
  - F = {ENO $\rightarrow$ ENAME, TITLE,
    PNO $\rightarrow$ PNAME,
    ENO, PNO $\rightarrow$ RESP}
- EMP is not in BCNF, because ENO and PNO are individually not superkeys. Thus,
  - ENO $\rightarrow$ ENAME, TITLE
  - PNO $\rightarrow$ PNAME

  both cause violation of BCNF.

BCNF Decomposition Example

- We start with D = {ENO, ENAME, TITLE, PNO, PNAME, RESP}
- Iteration 1
  - Pick one of the FDs that violate BNCF
  - ENO $\rightarrow$ ENAME, TITLE
- $D = \{R_1, R_2\}$ where
  - R_1(ENO, PNO, PNAME, RESP)
  - R_2(ENO, ENAME, TITLE)
- R_2 is in BCNF, but R_1 is not

BCNF Decomposition Example

- Iteration 2
  - D has R_1 which is not in BCNF
  - Pick one of the FDs that violate BNCF
  - PNO $\rightarrow$ PNAME
- $D = \{R_2, R_3, R_4\}$ where
  - R_3(ENO, PNO, RESP)
  - R_4(PNO, PNAME)
- Both relations are in BCNF
- Threfore, replace EMP with R_2, R_3, R_4

Complexity of Normalization

- Assume we are given a set of attributes A and a set of FDs F, and let $n =$ the size of this input (at most $O(|A|*|F|)$).
  - The number of dependencies in $F+$ may be exponential in n.
  - $A+$ can be found in linear time.
  - Testing whether $X \rightarrow Y$ is in $F+$ can be done in linear time.
  - Testing whether a decomposition is lossless can be done in linear time.
  - Testing whether a decomposition is dependency preserving can be done in polynomial time.
  - Testing whether a relation scheme is in BCNF is NP-complete.
  - There is a quadratic algorithm to find a set of relations over attributes A where
    - Each is in 3NF
    - The set preserves all dependencies in F, and
    - The set correspond to a lossless decomposition of the universal relation covering all of A.