Database Design: Functional Dependencies

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CS411: Database Systems

Some slides were adopted from L. Delcambre and D. Maier with permission

Overview of Database Design

- Conceptual design: (ER & UML Models are used for this.)
  - What are the **entities** and **relationships** we need?
- Logical design:
  - Transform ER design to Relational Schema
- Schema Refinement: (Normalization)
  - Check relational schema for redundancies and related anomalies.
- Physical Database Design and Tuning:
  - Consider typical workloads; (sometimes) modify the database design; select file types and indexes.

We're here

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
  - implement R in SQL
  - start using it
- However, R may not be well-designed, thus causing us a lot of problems
- OR: people may start without an ER diagram, and you need to reformat the schema R
  - Either way you may need to **improve** the schema

How do We Obtain a Good Design?

- Start with the original db schema R
  - From ER translation or otherwise
- Identify its ***functional dependencies***
- Use them to transform R until we get a good design R*

Desirable Properties of R*

1. must preserve the information of R (lossless)

2. must have minimal amount of redundancy

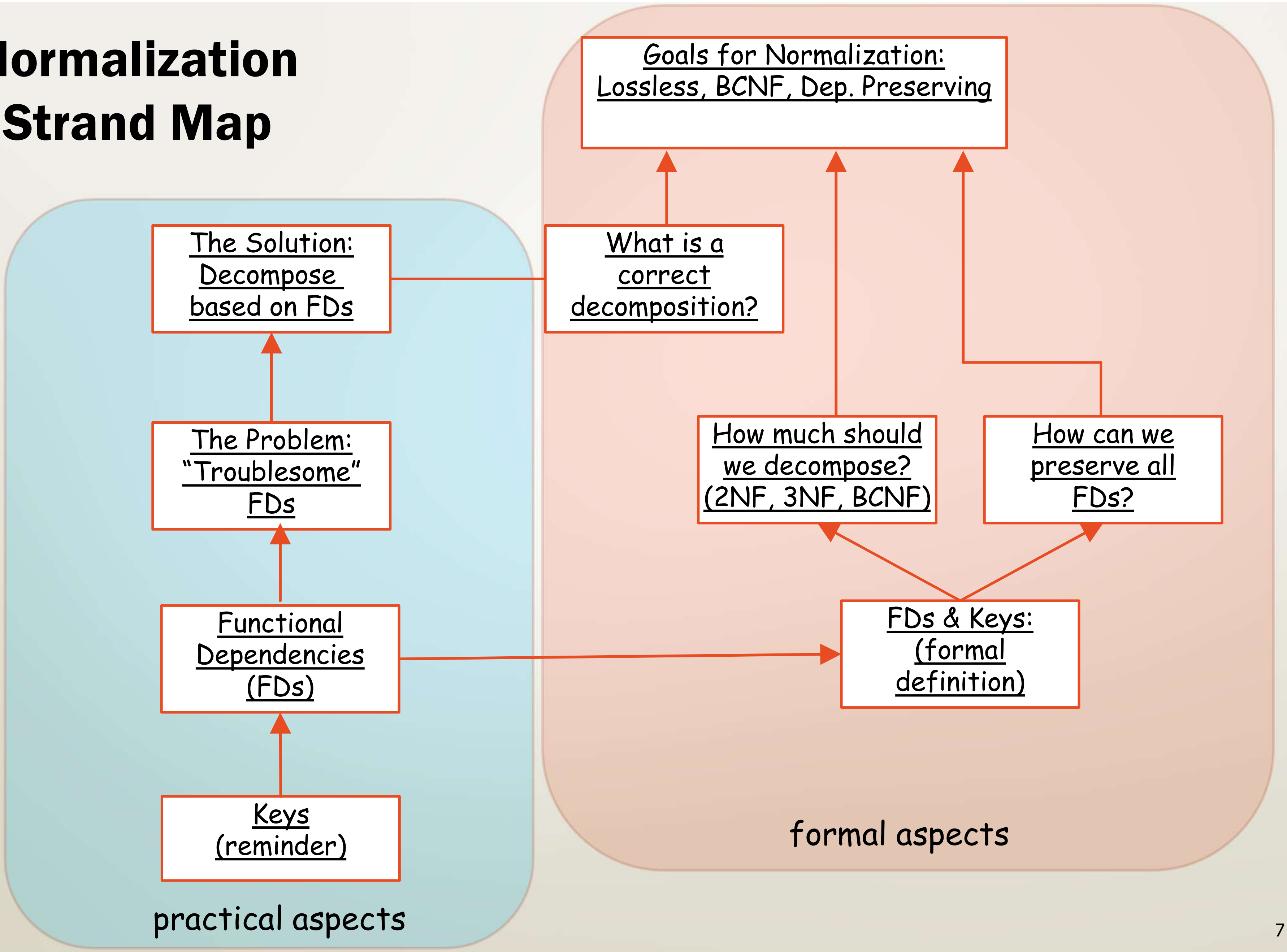
3. must be "dependency preserving"
   - (we'll come to this later)

- must also give good query performance

Normal Forms

- DB researchers have developed many "**normal forms**"
- These are basically schemas obeying certain rules
  - Converting a schema that doesn't obey rules to one that does is called "**normalization**"
  - This typically involves some kind of decomposition into smaller tables.
  - (the opposite: grouping tables together, is called "**denormalization**")

Normalization Strand Map



Keys for a Table (reminder)

The key(s) for a table must have unique values and the key(s) for a table help us understand what the table is “about.”

Table Keys

Account	Number	Owner	Balance	Type
	101	J. Smith	1000.00	checking
	102	W. Wei	2000.00	checking
	103	J. Smith	5000.00	savings
	104	M. Jones	1000.00	checking
	105	H. Martin	10,000.00	checking

Deposit	AcctNo	Transaction-id	Date	Amount
	102	1	10/22/00	500.00
	102	2	10/29/00	200.00
	104	3	10/29/00	1000.00
	105	4	11/02/00	10,000.00

Check	AcctNo	Check-number	Date	Amount
	101	924	10/23/00	125.00
	101	925	10/24/00	23.98

Each table has a key.... where the values must be unique.

Notice … only one value for non-key attributes (for each key value)

Employee	ssn	name	salary	job-code
	111111111	John Smith	40,000	15
	123456789	Mary Smith	50,000	22
	123456789	Marie Jones	50,000	24

For one particular SSN value, 123-45-6789, there is only ONE name because

1. there is only one tuple and
2. we assume that attributes values are atomic.

Notice … only one value for non-key attributes (for each key value)

Employee	ssn	name	salary	job-code
	111111111	John Smith	40,000	15
	123456789	Mary Smith	50,000	22
	~~123456789~~	~~Marie Jones~~	~~50,000~~	~~24~~

1. NOT allowed because SSN is key!

2. Only one name (and one salary and one job-code) for each row.

For one particular SSN value, 123-45-6789, there is only ONE name because

1. there is only one tuple and
2. we assume that attributes values are atomic.

Functional Dependencies (FDs) generalize keys

Functional dependencies (FDs) for relational tables are a generalization of the notion of key for a table.

Functional Dependencies

Definition:

If two tuples agree on the attributes

$\boxed{A_1, A_2, \ldots A_n}$

then they must also agree on the attributes

$\boxed{B_1, B_2, \ldots B_m}$

Where have we seen this before?

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

Functional Dependencies (from semantics of the application)

Likely functional dependencies:

$ssn \rightarrow employee\text{-}name$

$course\text{-}number \rightarrow course\text{-}title$

Unlikely functional dependencies

$course\text{-}number \not\rightarrow book$

$birthdate \not\rightarrow ssn$

Will FDs be enforced?

Consider this table:

Emp(<u>ssn</u>, name, phone, dnum, dept-name)

Suppose there is an FD from *dnum* $\rightarrow$ *dept-name*

But *ssn* is the key for this table.

What will prevent two names for one dept?

Will this FD be enforced? Let's try it.

Consider this table:

Emp(<u>ssn</u>, name, phone, dnum, dept-name)

Employee	<u>ssn</u>	Nam e	Phone	Dnum	Dept name
	111111111	John	555-1234	12	Sales
	222222222	Mary	555-7890	12	Marketing
	…				

Can we put these two rows in this table?

Yes, it doesn't violate the key constraint.

But, the FD from dept to dept-name is violated! We shouldn't have two different names for dnum 12!

The Problem: “Troublesome” FDs

“Troublesome” FDs (FD where the left-hand-side of the FD is NOT a key for the table where its attributes appear) cause redundancy and update anomalies.

Sometimes Redundancy is Caused by FDs

Consider this table:

EMP(name, SSN, birthdate, address, dnum, dname, dmgr)

Then *dname* and *dmgr* are stored redundantly – whenever there are multiple employees in a department.

This redundancy is caused by what we informally call "troublesome" FDs. The FDs shown in blue are "troublesome".

Redundancy Caused by Troublesome FD – Sample Data

EMP(name, SSN, birthdate, address, dnum, dname, dmgr)

John	111	June 3	123 St.	D1	sales	222
Sue	222	May 15	455 St.	D1	sales	222
Max	333	Mar. 5	678 St.	D2	research	333
Wei	444	May 2	999 St.	D2	research	333
Tom	555	June 22	888 St.	D2	research	333

dname and *dmgr* are stored redundantly – whenever there are multiple employees in a department.

This redundancy is caused by what we informally call “troublesome” FDs. The FDs shown in blue are “troublesome”.

Update Anomalies

caused by "troublesome" FDs

EMP(name, <u>SSN</u>, birthdate, address, dnum, dname, dmgr)

Insertion anomalies:

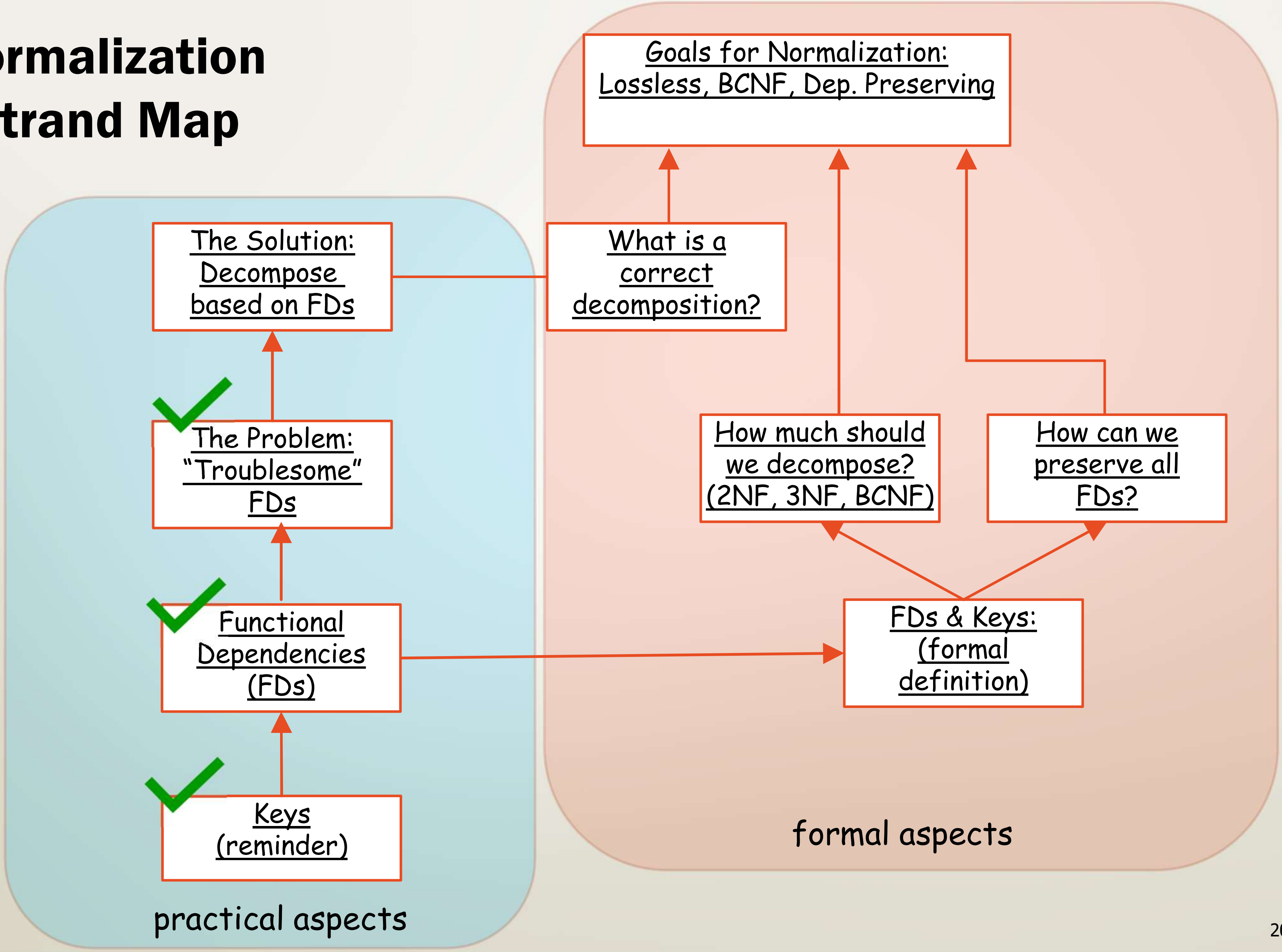
if you want to insert a department, you can't ... until there is at least one employee.

Deletion anomalies: if you delete an employee, is that dept. gone? Was this the last employee in that dept.?

Update anomalies: If you want to change *dname*, for example, you need to change it everywhere! And you have to find them all first.

Troublesome FDs cause (redundancy and) update anomalies.

Normalization Strand Map



The Solution: Lifting "Troublesome" FDs

Normalization by decomposition, based on FDs (where "troublesome" FDs are lifted into a separate table), reduces redundancy and update anomalies.

Example:
Finding Troublesome FDs

EMP(name, <u>ssn</u>, birthdate, address, dnum, dname, dmgr)

We have a problem!
dnum is NOT the key for this table!

So these blue FDs will not be enforced automatically by the DBMS (using only keys).
And there can be redundancy and update anomalies

Example:
Lifting Troublesome FDs

1. Lift the "troublesome" FD into its own table with dnum as the key. Now they will be enforced.

Dept(dnum, dname, dmgr)

EMP(name, ssn, birthdate, address, dnum, dname, dmgr)

New-Emp(name, ssn, birthdate, address, dnum)

2. Leave the LHS of the "troublesome" FDs behind.
   Define a foreign key where
   New-Emp.dnum REFERENCES Dept.dnum

Table is Split onto New Schemas

New-EMP(name, SSN, birthdate, address, dnum)

John	111	June 3	123 St.	D1
Sue	222	May 15	455 St.	D1
Max	333	Mar. 5	678 St.	D2
Wei	444	May 2	999 St.	D2
Tom	555	June 22	888 St.	D2

Dept(dnum, dname, dmgr)

D1	sales	222
D2	research	333

Less redundancy!

Insert anomalies: No Problem

Delete anomalies: No Problem

Update anomalies:

dname is only stored once!

Basic Idea: Normalize based on FDs

- Identify all the (non-trivial) FDs in an application.
  - Identify FDs that are implied by the keys.
  - Identify FDs that are NOT implied by the keys – the "troublesome" ones.

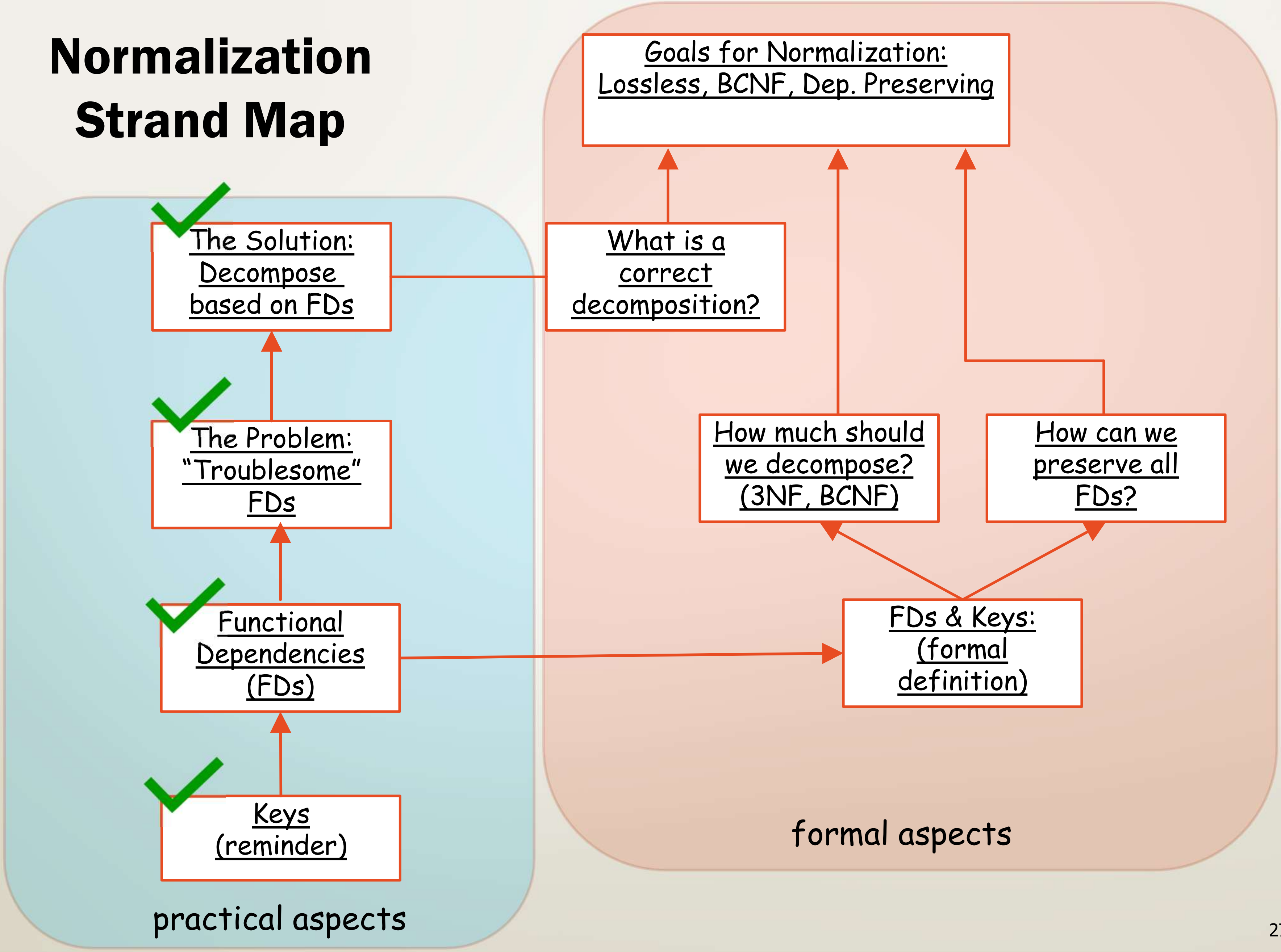
- Decompose a table with a "troublesome" FD into two or more tables by "lifting" each troublesome FD into a table of its own.

Note: when there are two or more "troublesome" FDs with the same left side, then they can be lifted, together, into a single table.

Questions about normalization

- How do we know which FDs we have?
  Talk to domain experts; identify FDs; use them as the starting point for normalization.
- How do we know if the decomposition is correct?
- How do we know how much to normalize? How far should we go?

Normalization Strand Map



Formal Aspect of FDs

- Functional Dependencies and Keys
- Inference Rules of Functional Dependencies
- Attribute Closure

Reminder: Keys, Candidate Keys, Primary Keys

Reminders:

A **key** is the same as a **candidate key** (synonyms).

If we have two or more keys in a table, we pick one to be the **primary key**.

Example:

(EmpID, SSN, Name, Address)

EmpID is a key (candidate key)

SSN is a key (candidate key)

We may choose EmpId to be the primary key.

Definition of a Key for a Relation

A key is a minimal set of attributes in a relation whose values are guaranteed to uniquely identify tuples in the relation.

- minimal? studentID, studentName is not a key because studentID is a key.
- minimal? No subset of the fields that comprise a key is a key

- Two distinct tuples have distinct key values
- Can be more than one key for a table

Definition of a Superkey for a Relation

Every key is (automatically) a superkey.

A superkey is NOT necessarily a key.

Example:

Emp (<u>SSN</u>, name, phone, dept)

SSN is a key for this relation.

(dept, SSN) is a superkey for this relation (but not a key).

Keys and FDs are Constraints

- We need to know if keys and FDs (always) hold in the application.
- We need to consult a domain expert to find out what the keys and FDs are. The keys and FDs serve as input to the database design process.
- We would like to enforce the keys and FDs constraints.

Formal Aspect of FDs

- ✓ Functional Dependencies and Keys
- Inference Rules of Functional Dependencies
- Attribute Closure

Goal: Find ALL Functional Dependencies

- Anomalies occur when certain “troublesome” FDs hold
- We can identify some FDs
- But we need to find *all* FDs, and then look for the bad ones.

Inference Rules for FDs

$A_1A_2 \ldots A_n \rightarrow B_1B_2 \ldots B_m$

Equivalent to:

$A_1A_2 \ldots A_n \rightarrow B_1$;

$A_1A_2 \ldots A_n \rightarrow B_2$;

…

$A_1A_2 \ldots A_n \rightarrow B_m$

Splitting/Combining Rule

Inference Rules for FDs

- $A_1A_2\ldots A_n \rightarrow A_1$

- In general,

  $A_1A_2\ldots A_n \rightarrow B_1B_2\ldots B_m$

  if $\{B_1B_2\ldots B_m\} \subseteq \{A_1A_2\ldots A_n\}$

  Example: name, UIN → UIN

  Why does this make sense?

Trivial Functional Dependencies Rule

Inference Rules for FDs

IF	A1A2...An → B1B2...Bm
AND	B1B2...Bm → C1C2...Ck
THEN	A1A2...An → C1C2...Ck

Transitive Closure Rule

Formal Aspect of FDs

- ✓ Functional Dependencies and Keys
- ✓ Inference Rules of Functional Dependencies
- Attribute Closure

Closure of a Set of Attributes

Given a set of attributes {$\boldsymbol{A1, \ldots, An}$} and a set of FDs F.

Problem: find all attributes B such that:

for all relations that satisfy F, they also satisfy:

$A1, \ldots, An \rightarrow B$

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

Example

- Set of attributes A,B,C,D,E,F.
  - Functional Dependencies:

$$AB \longrightarrow C$$

$$AD \longrightarrow E$$

$$B \longrightarrow D$$

$$AF \longrightarrow B$$

Closure of $\{A,B\}^+$:

Closure of $\{A,F\}^+$:

Example

- Set of attributes A,B,C,D,E,F.
  - Functional Dependencies:

$A\ B \longrightarrow C$

$A\ D \longrightarrow E$

$B \longrightarrow D$

$A\ F \longrightarrow B$

Closure of $\{A,B\}^+ = \{A, B, C, D, E\}$

Closure of $\{A,F\}^+ = \{A, F, B, D, C, E\}$

Algorithm to Compute Closure

Split the FDs in F so that every FD has a single attribute on the right. (Simplify the FDs)

Start with $X=\{A_1A_2\ldots A_n\}$.

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

If $(B_1B_2\ldots B_m \rightarrow C)$ is in F,
such that $B_1,B_2,\ldots B_m$ are in X and C is not in X:
add C to X.

// X is now the correct value of $\{A_1A_2\ldots A_n\}^+$

Why does this algorithm converge?

Uses for Attribute Closure

- Use 1: To test if X is a (super)key
  - **How?** By computing X+, and check if X+ contains all attrs of R
  - We can also use it to find candidate keys
    - Compute X+ for all sets X where X+ = all attributes
    - Then list only the minimal X's

- Use 2: To check if X → Y holds
  - **How?** By checking if Y is contained in X+

Finding Keys Example 1

Given R(A, B, C, D, E, F) and F= {A->CD, D->E, A->B)

What are the candidate keys?

LEFT: Attributes that only appear in the LHS of any FD	**MIDDLE**: Attributes that appear in the LHS of some FDs and in the RHS of others	**RIGHT**: Attributes that only appear in the RHS of any FD	**NONE**: Attributes that do not appear in any FD
A	D	B,C,E	F

- Every attribute that appear in the LEFT and NONE columns must be part of any candidate key
- Compute the attribute closure of the LEFT+ NONE attributes: AF+ = {A,B,C,D,E,F}
  - if all attributes are included, then your key is LEFT + NONE: {A,F}
  - Otherwise, try combinations of all LEFT attributes with subset of the MIDDLE attributes

AF is the only Candidate Keys for R

Finding Keys Example 2

Given R(A, B, C, D, E, F) and F= {B->D, C->AE, B->F, A->C)

What are the candidate keys?

LEFT	MIDDLE	RIGHT	NONE
B	A,C	D,E ,F	

- Compute the attribute closure of the LEFT attributes: B+ = {B,D,F}
- We can't get to all attributes from B, so we must try adding subsets of MIDDLE to LEFT.
  - BC+ = {A,B,C,D,E,F}, we can get to all attributes, so BC is a candidate key
  - AB+ ={A,B,C,D,E,F}, we can get to all attributes, so AB is also a candidate key

Two Candidate Keys for R: AB, BC

Formal Aspect of FDs

✓ Functional Dependencies and Keys
✓ Inference Rules of Functional Dependencies
✓ Attribute Closure

Normalization Strand Map