Normalization

Lecture 7

Outline

1. Context
2. Normalization Objectives
3. Functional Dependencies
4. Normal Forms
   - 1NF
   - 2NF
   - 3NF

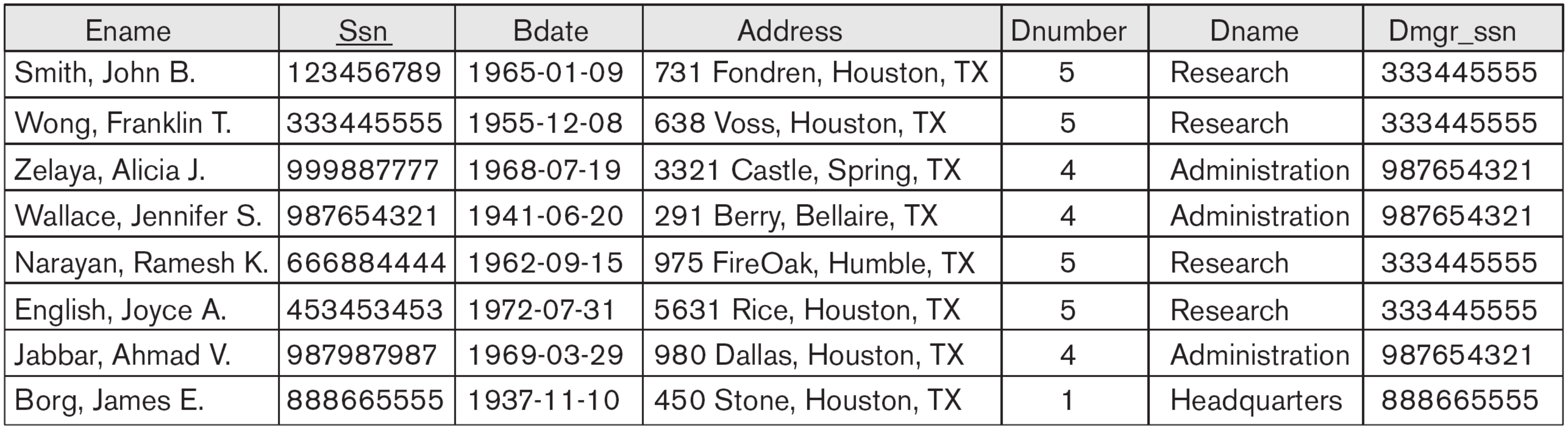
Course Overview

		HW	Project
✓ Using a Database	What is a relational database?		
	How do I get data in/out of a database?	SQL.1	
	How do I create a DB? What is this NoSQL stuff?	SQL.2	
	Exam 1		Plan
Designing a Database	How do I evaluate a database design?	FD/Norm	
	How do I design a database?	ERD/Map	
	How do I design for fast database apps? What is WebDev?	Index	
	Exam 2		Milestone
Apps/ Internals	How do I write secure database applications?	App/Hack	
	How does a DBMS handle multiple users?	Sched	
	Advanced Topics (research, ML)		
			Final

Big Questions

- What does it mean for a design to be good/bad?
- How to describe a problem domain such as to enable objective evaluation of its associated database design?
- How to evaluate a schema and improve it if found to have problems?

Example Schema



Ename	Ssn	Bdate	Address	Dnumber	Dname	Dmgr_ssn
Smith, John B.	123456789	1965-01-09	731 Fondren, Houston, TX	5	Research	333445555
Wong, Franklin T.	333445555	1955-12-08	638 Voss, Houston, TX	5	Research	333445555
Zelaya, Alicia J.	999887777	1968-07-19	3321 Castle, Spring, TX	4	Administration	987654321
Wallace, Jennifer S.	987654321	1941-06-20	291 Berry, Bellaire, TX	4	Administration	987654321
Narayan, Ramesh K.	666884444	1962-09-15	975 FireOak, Humble, TX	5	Research	333445555
English, Joyce A.	453453453	1972-07-31	5631 Rice, Houston, TX	5	Research	333445555
Jabbar, Ahmad V.	987987987	1969-03-29	980 Dallas, Houston, TX	4	Administration	987654321
Borg, James E.	888665555	1937-11-10	450 Stone, Houston, TX	1	Headquarters	888665555

- What is this table about?
- Your intuition: is it well designed?

Normalization

- Theory and process by which to evaluate and improve relational database design

- Typically divide larger tables into smaller, less redundant tables
  - Focus now on correctness (we'll return to the possibility of "denormalization" in physical design for improving efficiency)

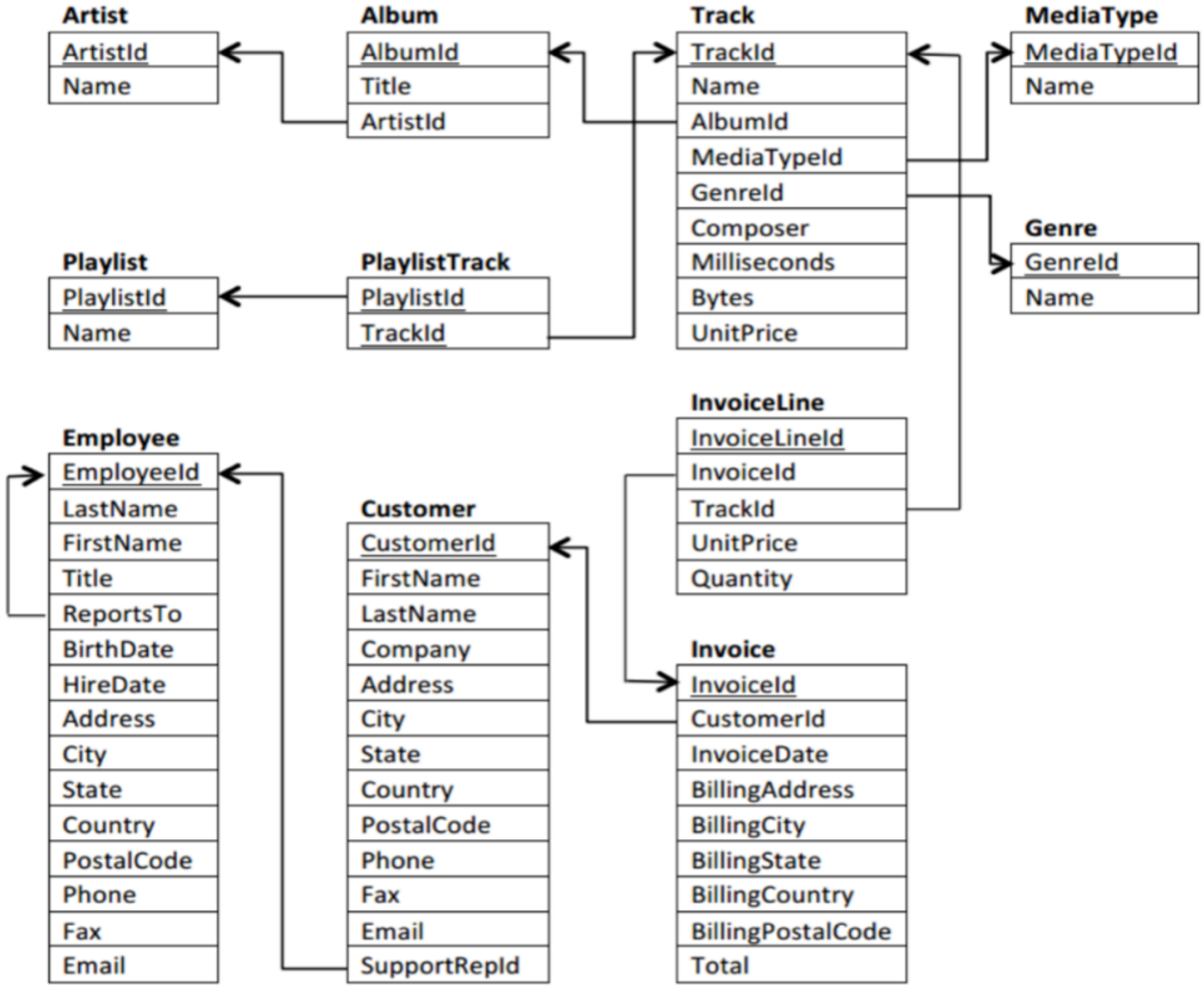
Objectives of Normalization

- Make the schema informative
- Minimize information duplication
- Avoid **modification anomalies**
- Disallow **spurious tuples**

Make the Schema Informative

- Design a relational schema so that it is easy to explain its meaning
- Do **not** combine attributes from multiple entity types and relationship types into a single relation
  - Can make explaining/understanding difficult
- Ideally, tables & constraints mirror real-world concepts & relationships

Tracks from the Past



Artist
ArtistId
Name

Album
AlbumId
Title
ArtistId

Track
TrackId
Name
AlbumId
MediaTypeId
GenreId
Composer
Milliseconds
Bytes
UnitPrice

MediaType
MediaTypeId
Name

Genre
GenreId
Name

Playlist
PlaylistId
Name

PlaylistTrack
PlaylistId
TrackId

InvoiceLine
InvoiceLineId
InvoiceId
TrackId
UnitPrice
Quantity

Employee
EmployeeId
LastName
FirstName
Title
ReportsTo
BirthDate
HireDate
Address
City
State
Country
PostalCode
Phone
Fax
Email

Customer
CustomerId
FirstName
LastName
Company
Address
City
State
Country
PostalCode
Phone
Fax
Email
SupportRepId

Invoice
InvoiceId
CustomerId
InvoiceDate
BillingAddress
BillingCity
BillingState
BillingCountry
BillingPostalCode
Total

Example Schema

What is this table about?

- Employees? Departments?

EMP_DEPT

Ename	Ssn	Bdate	Address	Dnumber	Dname	Dmgr_ssn
Smith, John B.	123456789	1965-01-09	731 Fondren, Houston, TX	5	Research	333445555
Wong, Franklin T.	333445555	1955-12-08	638 Voss, Houston, TX	5	Research	333445555
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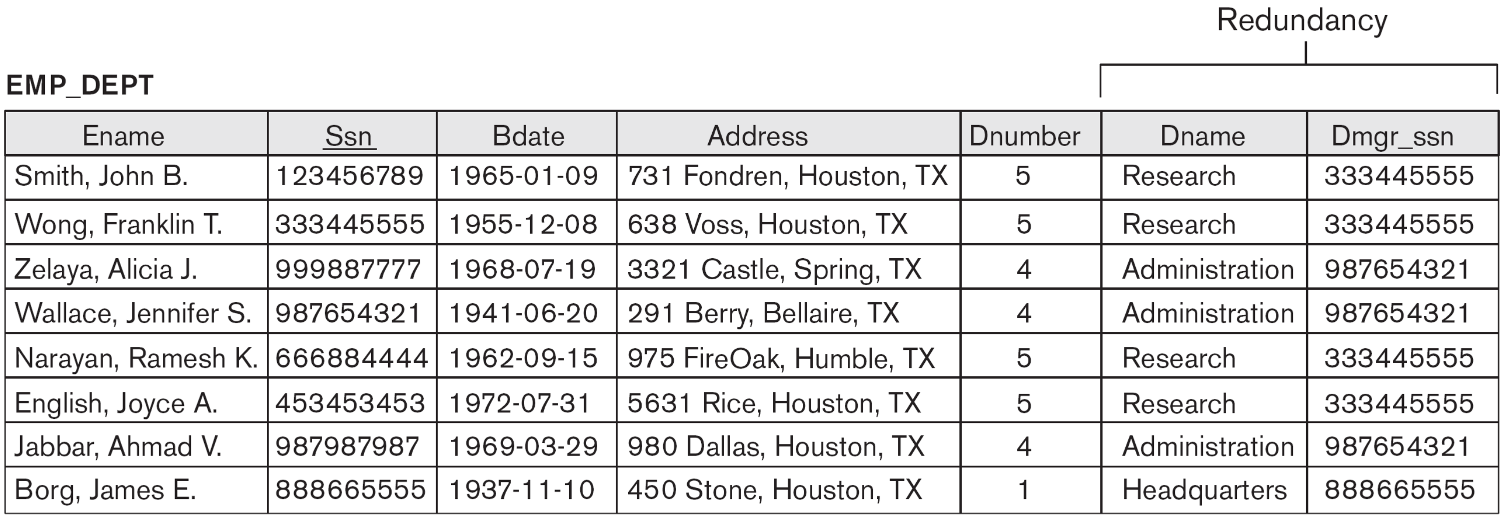
Minimize Information Duplication



Redundancy

EMP_DEPT

Ename	Ssn	Bdate	Address	Dnumber	Dname	Dmgr_ssn
Smith, John B.	123456789	1965-01-09	731 Fondren, Houston, TX	5	Research	333445555
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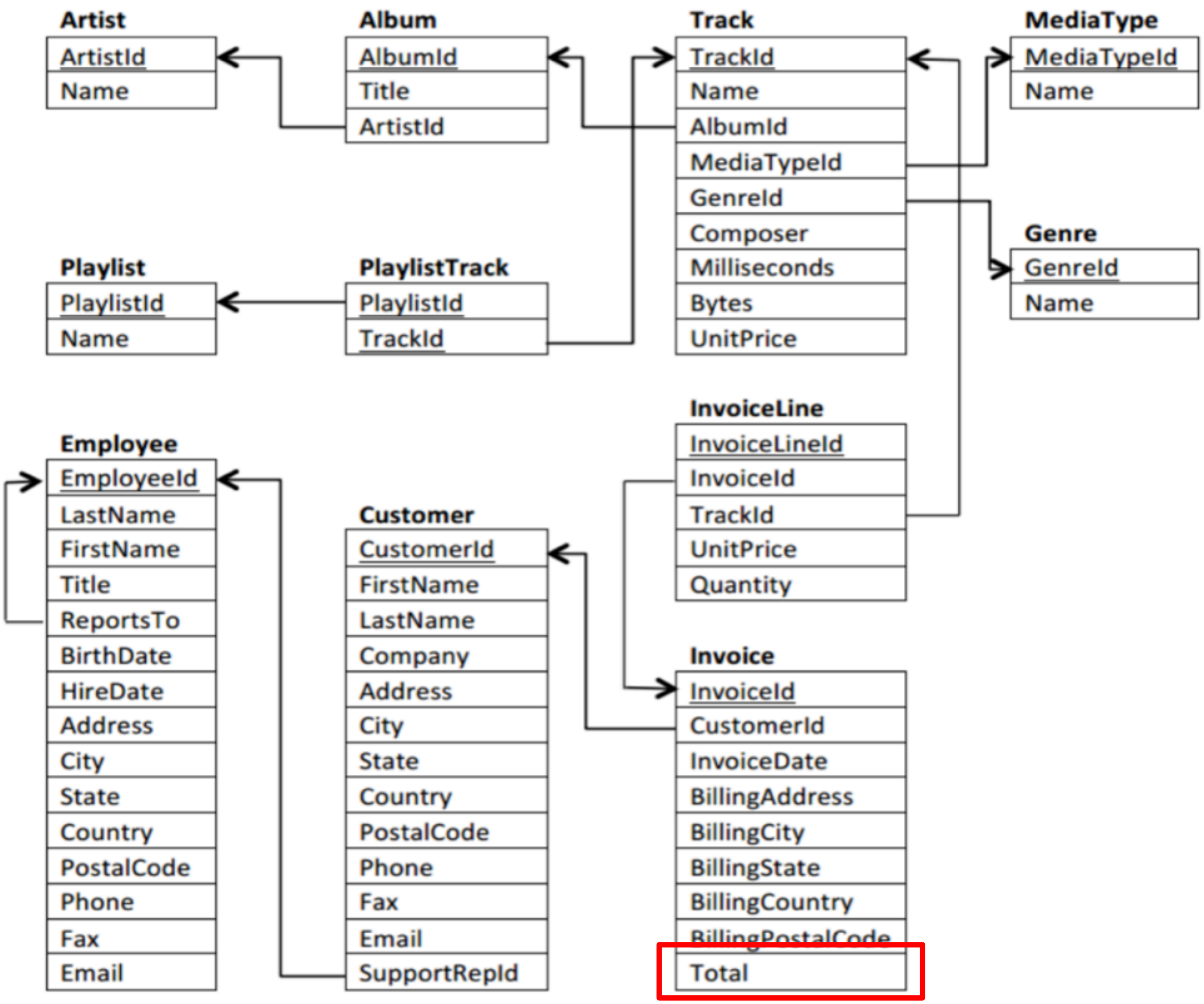
Chinook Duplication?



Artist
ArtistId
Name

Album
AlbumId
Title
ArtistId

Track
TrackId
Name
AlbumId
MediaTypeId
GenreId
Composer
Milliseconds
Bytes
UnitPrice

MediaType
MediaTypeId
Name

Genre
GenreId
Name

Playlist
PlaylistId
Name

PlaylistTrack
PlaylistId
TrackId

InvoiceLine
InvoiceLineId
InvoiceId
TrackId
UnitPrice
Quantity

Employee
EmployeeId
LastName
FirstName
Title
ReportsTo
BirthDate
HireDate
Address
City
State
Country
PostalCode
Phone
Fax
Email

Customer
CustomerId
FirstName
LastName
Company
Address
City
State
Country
PostalCode
Phone
Fax
Email
SupportRepId

Invoice
InvoiceId
CustomerId
InvoiceDate
BillingAddress
BillingCity
BillingState
BillingCountry
BillingPostalCode
Total

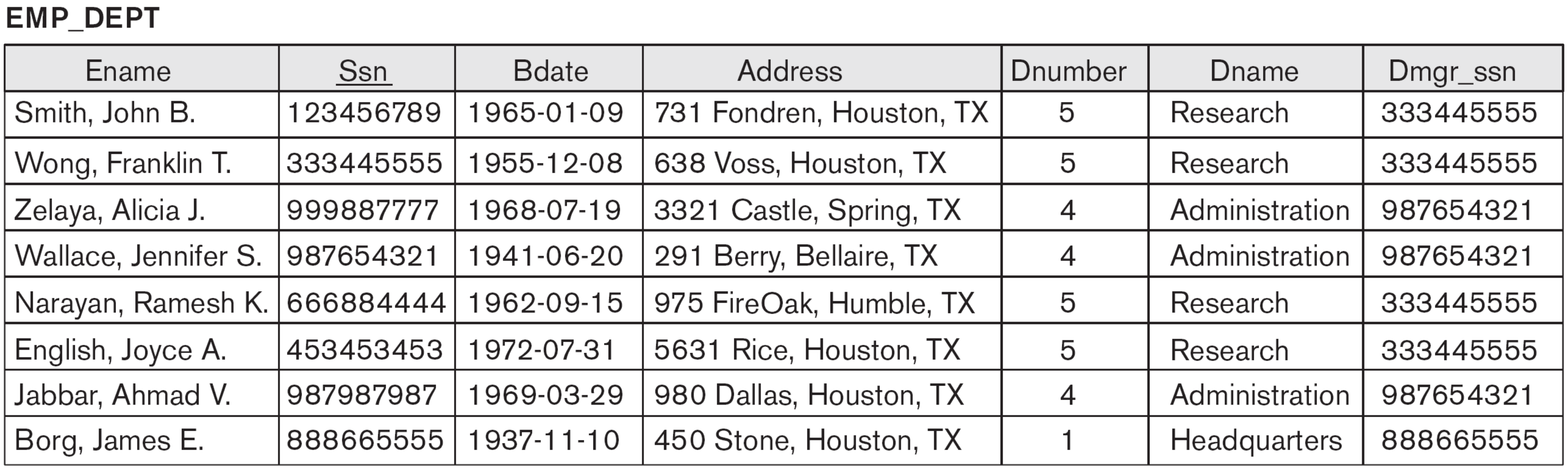
Avoid **Modification Anomalies**

An undesired side-effect resulting from an attempt to modify a table (that has not been sufficiently normalized)

Insertion Anomaly

Difficult or impossible to insert a new row

- Create the new “Marketing” department



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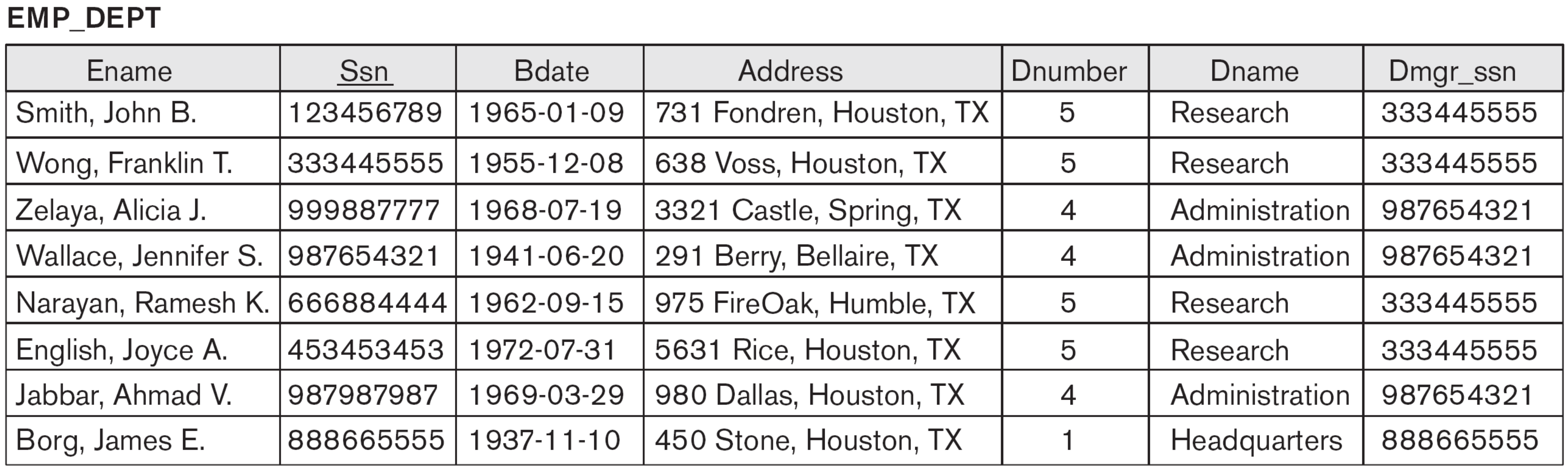
Update Anomaly

Updates may result in logical inconsistencies

- Change Ramesh’s department name to R&D



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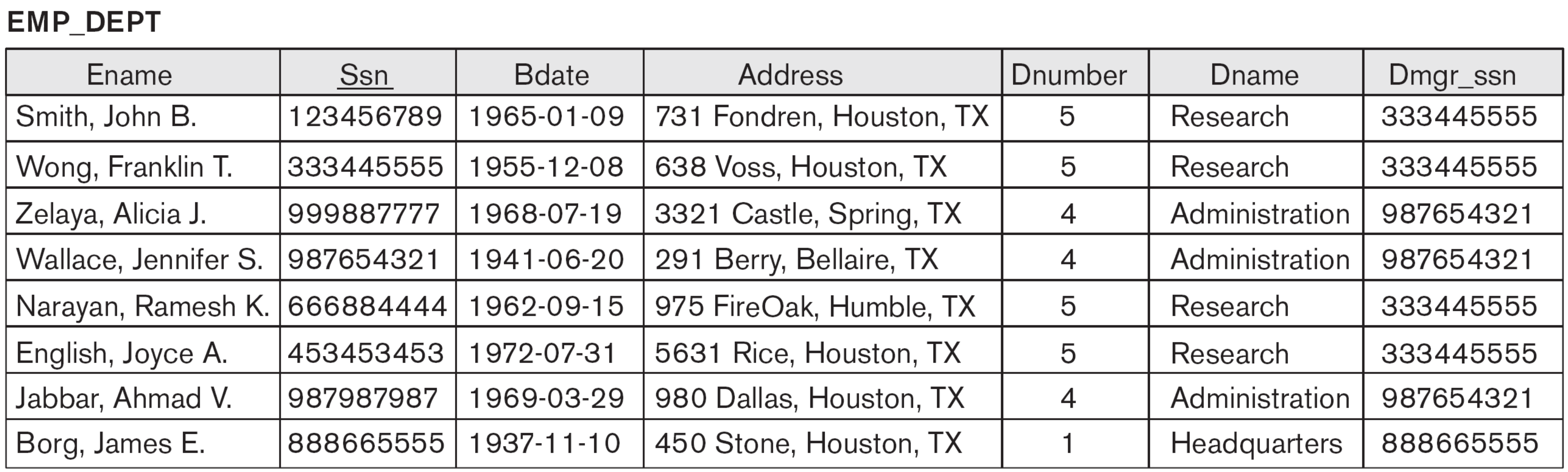
Deletion Anomaly

Deletion of data representing certain facts necessitates deletion of data representing completely different facts

- Delete James E. Borg



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Disallow **Spurious Tuples**

Avoid relational design that matches attributes across relations that are not (foreign key, primary key) combinations because joining on such attributes may produce invalid tuples

Example Decomposition

CAR

ID	Make	Color
1	Toyota	Blue
2	Audi	Blue
3	Toyota	Red

CAR1

ID	Color
1	Blue
2	Blue
3	Red

CAR2

Make	Color
Toyota	Blue
Audi	Blue
Toyota	Red

Natural Join

ID	Make	Color
1	Toyota	Blue
1	Audi	Blue
2	Toyota	Blue
2	Audi	Blue
3	Toyota	Red

CAR1

ID	Color
1	Blue
2	Blue
3	Red

CAR2

Make	Color
Toyota	Blue
Audi	Blue
Toyota	Red

Additive Decomposition

CAR

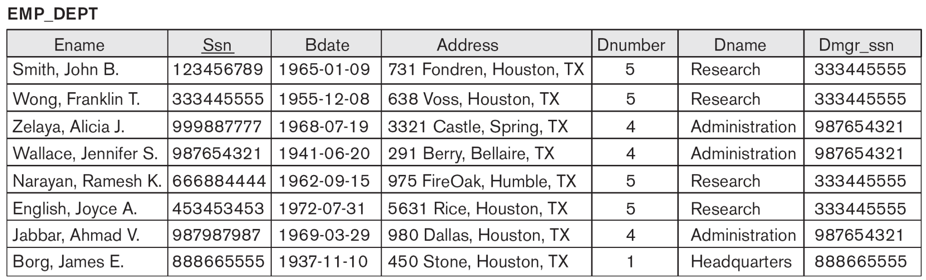
ID	Make	Color
1	Toyota	Blue
2	Audi	Blue
3	Toyota	Red

JOIN

ID	Make	Color
1	Toyota	Blue
1	**Audi**	**Blue**
2	**Toyota**	**Blue**
2	Audi	Blue
3	Toyota	Red

Game Plan

Build up to a set of “tests” (*Normal Forms*) that indicate cumulatively improving degrees of design quality



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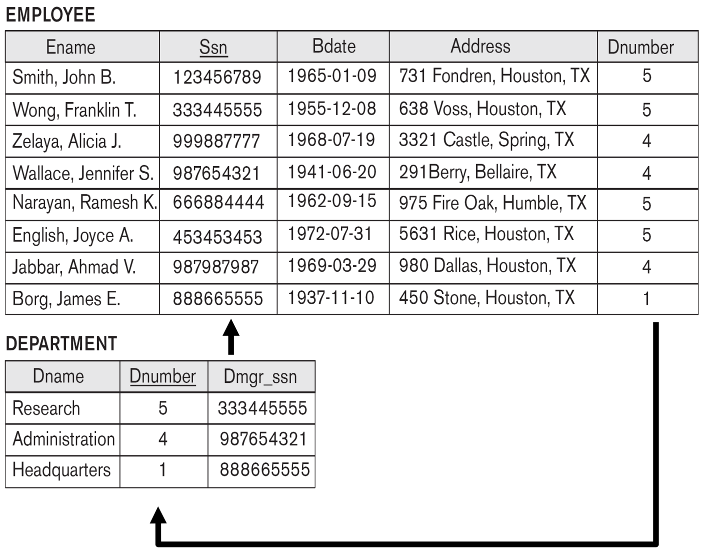


EMPLOYEE

Ename	Ssn	Bdate	Address	Dnumber
Smith, John B.	123456789	1965-01-09	731 Fondren, Houston, TX	5
Wong, Franklin T.	333445555	1955-12-08	638 Voss, Houston, TX	5
Zelaya, Alicia J.	999887777	1968-07-19	3321 Castle, Spring, TX	4
Wallace, Jennifer S.	987654321	1941-06-20	291Berry, Bellaire, TX	4
Narayan, Ramesh K.	666884444	1962-09-15	975 Fire Oak, Humble, TX	5
English, Joyce A.	453453453	1972-07-31	5631 Rice, Houston, TX	5
Jabbar, Ahmad V.	987987987	1969-03-29	980 Dallas, Houston, TX	4
Borg, James E.	888665555	1937-11-10	450 Stone, Houston, TX	1

DEPARTMENT

Dname	Dnumber	Dmgr_ssn
Research	5	333445555
Administration	4	987654321
Headquarters	1	888665555

Detour: Formalization

- We need a way of understanding how data in our tables depend on each other (termed: functional dependencies)

- With just this information, we can identify (candidate) keys and analyze/improve schema design
  - Even without knowing what the data is about!

Functional Dependency (FD)

In a relation *r*, a set of attributes **Y** is *functionally dependent* upon another set of attributes **X** ($X \rightarrow Y$) iff…

for all pairs of tuples t_1 and t_2 in *r…*

if t_1[**X**]=t_2[**X**]…

it MUST be the case that t_1[**Y**]=t_2[**Y**]

FD Example (1)

	StudentID	Year	Class	Instructor
t_1	1	Sophomore	CS3200	Rachlin
t_2	2	Sophomore	DS2500	Rachlin
t_3	3	Junior	CS3200	Rachlin
t_4	3	Junior	DS2500	Rachlin
t_5	2	Sophomore	CS3200	Derbinsky
t_6	4	Sophomore	CS3200	Derbinsky

What FDs hold in the current state of this relation?

$$\{StudentID\} \rightarrow \{Year\}$$

$$\{StudentID, Class\} \rightarrow \{Instructor\}$$

FDs & Keys

- One cannot determine whether FDs hold for *all* relation states unless the meaning of and relationships among the attributes are known

FD Example (2)

	StudentID	Year	Class	Instructor
t_1	1	Sophomore	CS3200	Rachlin
t_2	2	Sophomore	DS2500	Rachlin
t_3	3	Junior	CS3200	Rachlin
t_4	3	Junior	DS2500	Rachlin
t_5	2	Sophomore	CS3200	Derbinsky
t_6	4	Sophomore	CS3200	Derbinsky

What FDs hold in the current state of this relation?

$$\{StudentID\} \rightarrow \{Year\}$$

$$\{StudentID, Class\} \rightarrow \{Instructor\}$$

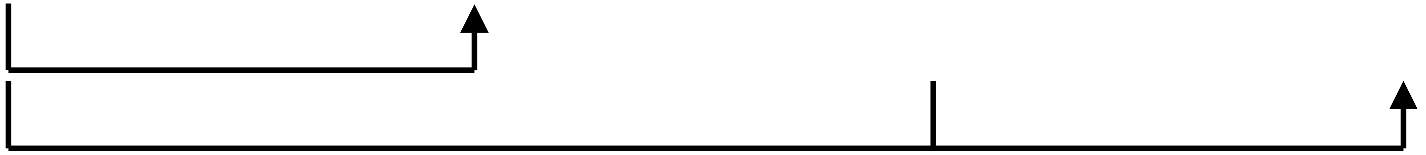
Multiple sections?
Co-instruction?
Re-takes?

FDs & Keys

- One cannot determine whether FDs hold for *all* relation states unless the meaning of and relationships among the attributes are known
  - These are the "data dependencies" foreshadowed in Lecture 2 (Relational Model)
  - If you *do* have this domain knowledge, it is possible to identify candidate keys (minimal subsets of attributes that FD all attributes)

FD Example (3)

	StudentID	Year	Class	Instructor
t_1	1	Sophomore	CS3200	Rachlin
t_2	2	Sophomore	DS2500	Rachlin
t_3	3	Junior	CS3200	Rachlin
t_4	3	Junior	DS2500	Rachlin
t_5	2	Sophomore	CS3200	Derbinsky
t_6	4	Sophomore	CS3200	Derbinsky



$$\{StudentID\} \rightarrow \{Year\}$$

$$\{StudentID, Class\} \rightarrow \{Instructor\}$$

- *Every student is classified as either a Freshman, Sophomore, Junior, or Senior.*
- *Students can take only a single section of a class, taught by a single instructor.*

Key(s): $\{StudentID, Class\}$

FDs & Keys

- One <u>cannot</u> determine whether FDs hold for *all* relation states unless the meaning of and relationships among the attributes are known
  - These are the "data dependencies" foreshadowed in Lecture 2 (Relational Model)
  - If you *do* have this domain knowledge, it is possible to identify candidate keys (minimal subsets of attributes that FD all attributes)
- One <u>can</u> state an FD does *not* hold given a relation state by identifying violating tuple(s)

FD Example (4)

	StudentID	Year	Class	Instructor
t_1	1	Sophomore	CS3200	Rachlin
t_2	2	Sophomore	DS2500	Rachlin
t_3	3	Junior	CS3200	Rachlin
t_4	3	Junior	DS2500	Rachlin
t_5	2	Sophomore	CS3200	Derbinsky
t_6	4	Sophomore	CS3200	Derbinsky

$\{StudentID\} \nrightarrow \{Instructor\}$

$\{StudentID\} \nrightarrow \{Class\}$

$\{Year\} \nrightarrow \{StudentID\}$

$\{Year\} \nrightarrow \{Instructor\}$

$\{Year\} \nrightarrow \{Class\}$

$\{Class\} \nrightarrow \{Year\}$

$\{Class\} \nrightarrow \{StudentID\}$

$\{Class\} \nrightarrow \{Instructor\}$

$\{Instructor\} \nrightarrow \{Class\}$

$\{Instructor\} \nrightarrow \{Year\}$

$\{Instructor\} \nrightarrow \{StudentID\}$

FD Example (5)

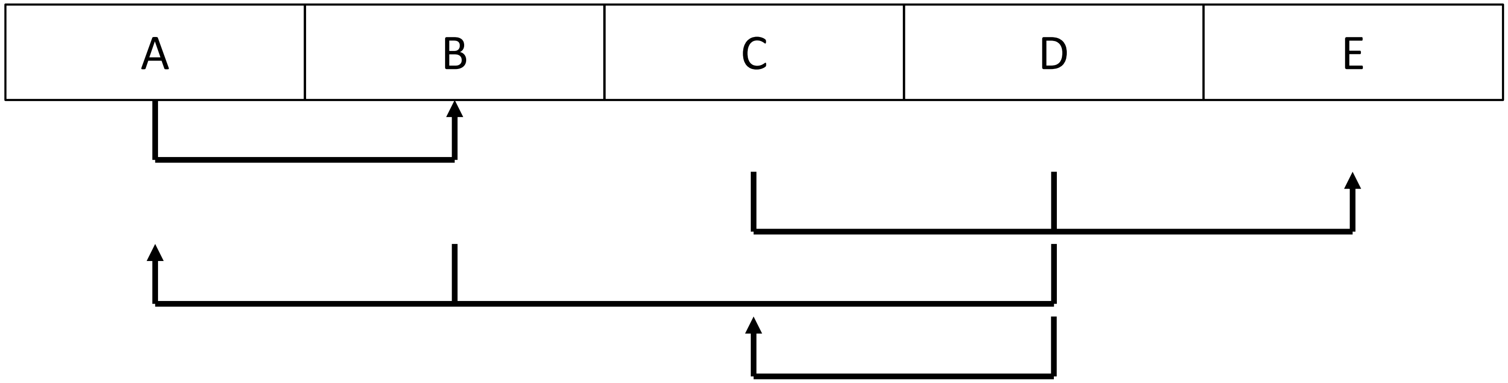
	StudentID	Year	Class	Instructor
t_1	1	Sophomore	CS3200	Rachlin
t_2	2	Sophomore	DS2500	Rachlin
t_3	3	Junior	CS3200	Rachlin
t_4	3	Junior	DS2500	Rachlin
t_5	2	Sophomore	CS3200	Derbinsky
t_6	4	Sophomore	CS3200	Derbinsky

$$\{StudentID, Instructor\} \nrightarrow \{Class\}$$
$$\{Year, Class\} \nrightarrow \{Instructor\}$$
$$\{Year, Class\} \nrightarrow \{StudentID\}$$
$$\{Class, Instructor\} \nrightarrow \{StudentID\}$$
$$\{Class, Instructor\} \nrightarrow \{Year\}$$
$$\{Year, Class, Instructor\} \nrightarrow \{StudentID\}$$

Exercise

Consider the following visual depiction of the functional dependencies of a relational schema.

1. List all FDs in algebraic notation
2. Identify all candidate key(s) of of this relation



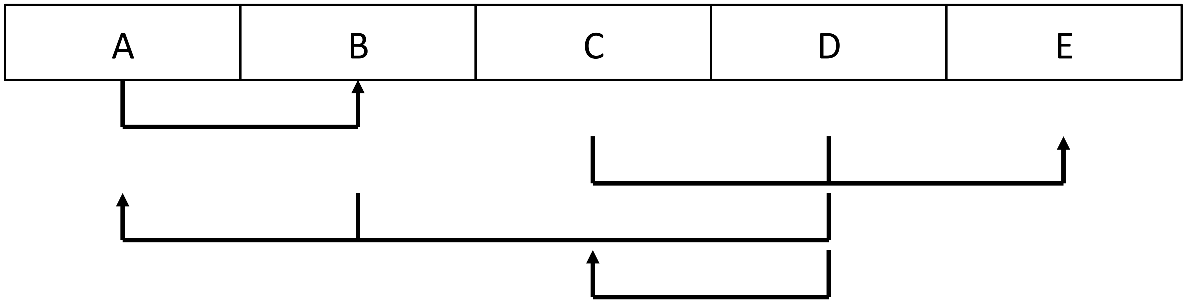
Answer

Functional Dependencies

$$A \rightarrow B$$
$$CD \rightarrow E$$
$$BD \rightarrow A$$
$$D \rightarrow C$$

Keys

$$DA$$
$$DB$$



Normalization Process

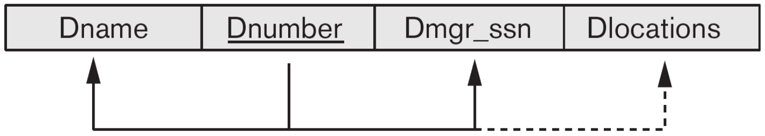
- Submit a relational schema to a set of tests (related to FDs) to certify whether it satisfies a **normal form**
- If it does not pass, decompose into smaller relations that satisfy the normal form
  - Must be non-additive (i.e. no spurious tuples!)
- The normal form of a relation refers to the highest normal form that it meets
  - As of 2003 the most constraining is 6NF
- The normal form of a database refers to the lowest normal form that any relation meets
  - Practically, a database is normalized if all relations ≥ 3NF

1NF – First Normal Form

- The domain of an attribute must include only atomic values and that the value of any attribute in a tuple must be a single value from the domain of that attribute
- No relations within relations or relations as attribute values within tuples
- Considered part of the formal definition of a relation in the basic (flat) relational model
  - In other words, an *implicit* constraint (Lecture 2)

1NF Violation (1)

DEPARTMENT



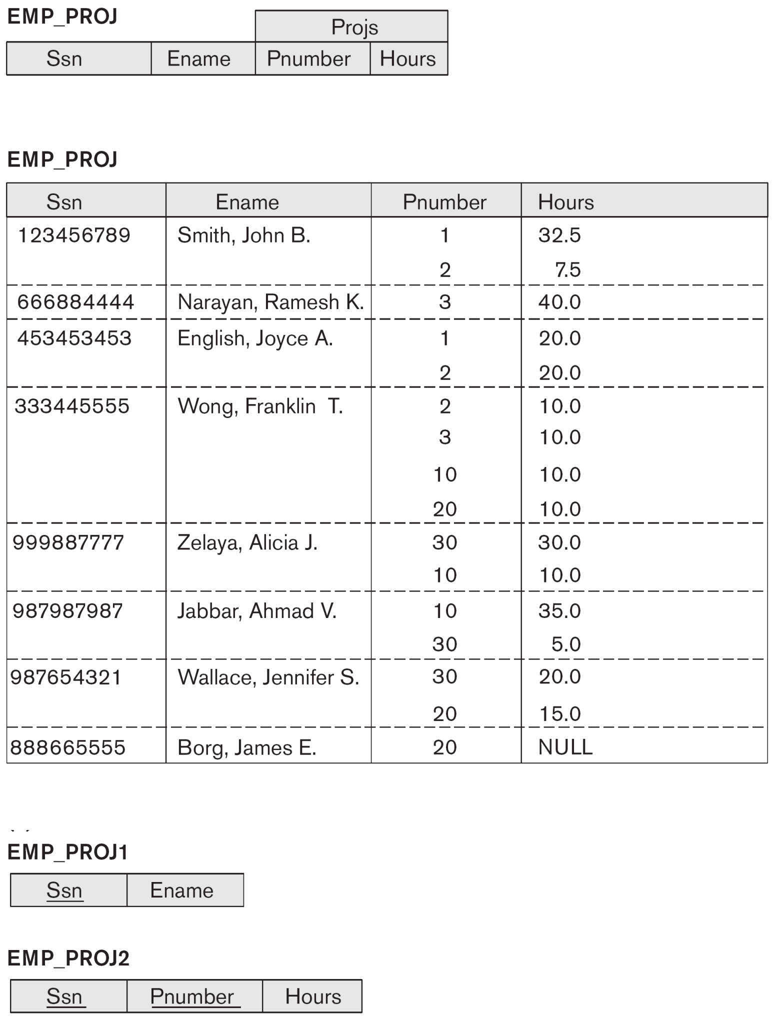
DEPARTMENT

Dname	Dnumber	Dmgr_ssn	Dlocations
Research	5	333445555	{Bellaire, Sugarland, Houston}
Administration	4	987654321	{Stafford}
Headquarters	1	888665555	{Houston}

DEPARTMENT

Dname	Dnumber	Dmgr_ssn	Dlocation
Research	5	333445555	Bellaire
Research	5	333445555	Sugarland
Research	5	333445555	Houston
Administration	4	987654321	Stafford
Headquarters	1	888665555	Houston

1NF Violation (2)



EMP_PROJ

Ssn	Ename	Projs	
		Pnumber	Hours

EMP_PROJ

Ssn	Ename	Pnumber	Hours
123456789	Smith, John B.	1 2	32.5 7.5
666884444	Narayan, Ramesh K.	3	40.0
453453453	English, Joyce A.	1 2	20.0 20.0
333445555	Wong, Franklin T.	2 3 10 20	10.0 10.0 10.0 10.0
999887777	Zelaya, Alicia J.	30 10	30.0 10.0
987987987	Jabbar, Ahmad V.	10 30	35.0 5.0
987654321	Wallace, Jennifer S.	30 20	20.0 15.0
888665555	Borg, James E.	20	NULL

EMP_PROJ1

Ssn	Ename

EMP_PROJ2

Ssn	Pnumber	Hours

Important FD Definitions

Trivial FD	$X \rightarrow Y,\ Y \subseteq X$
Non-Prime	An attribute that does not occur in any key (opposite: Prime)
Full FD	$X \rightarrow Y,\ \forall A \in X((X - \{A\}) \nrightarrow Y)$
Transitive FD	$X \rightarrow Z \because X \rightarrow Y\ and\ Y \rightarrow Z$

2NF – Second Normal Form

- 1NF **AND** every non-prime attribute is fully FD on the primary key
  - – Must test all FDs whose LHS is part of the PK
- To fix, decompose into relations in which non-prime attributes are associated only with the part of the primary key on which they are fully functionally dependent

2NF Example

StudentID	Course	StudentAddress
1	CS5200	EV
1	DS2500	EV
2	CS5200	WV
3	CS3200	IV
3	CS4100	IV

$$\{StudentID, Course\} \rightarrow \{StudentAddress\}$$

$$\{StudentID\} \rightarrow \{StudentAddress\}$$

StudentID	StudentAddress
1	EV
2	WV
3	IV

StudentID	Course
1	CS5200
1	DS2500
2	CS5200
3	CS3200
3	CS4100

2NF Can Suffer Update Anomalies

Year	Winner	Nationality
1994	Miguel Indurain	Spain
1995	Miguel Indurain	Spain
1996	Bjarne Riis	Denmark
1997	Jan Ullrich	Germany

- Relation is in 2NF?
  - – Trivially true (why?)
- List all non-trivial FDs for this relation state

$$\{Year\} \rightarrow \{Winner, Nationality\}$$

$$\{Winner\} \rightarrow \{Nationality\}$$

- What if we insert (1998, Jan Ullrich, USA)?

3NF – Third Normal Form

- 2NF **AND** every non-prime attribute is non-transitively dependent on every key

  “A non-key field must provide a fact about the key, the whole key, and nothing but the key. So help me Codd.”

- To fix, decompose into multiple relations, whereby the intermediate non-key attribute(s) functionally determine other non-prime attributes

3NF Example

Year	Winner	Nationality
1994	Miguel Indurain	Spain
1995	Miguel Indurain	Spain
1996	Bjarne Riis	Denmark
1997	Jan Ullrich	Germany

$Year \rightarrow Nationality \because$

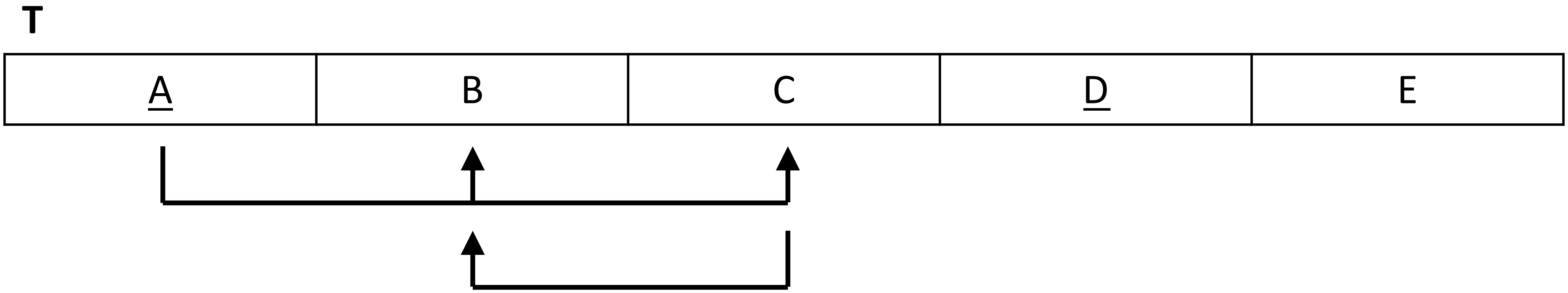
$Year \rightarrow Winner$ **and**

$Winner \rightarrow Nationality$

Year	Winner
1994	Miguel Indurain
1995	Miguel Indurain
1996	Bjarne Riis
1997	Jan Ullrich

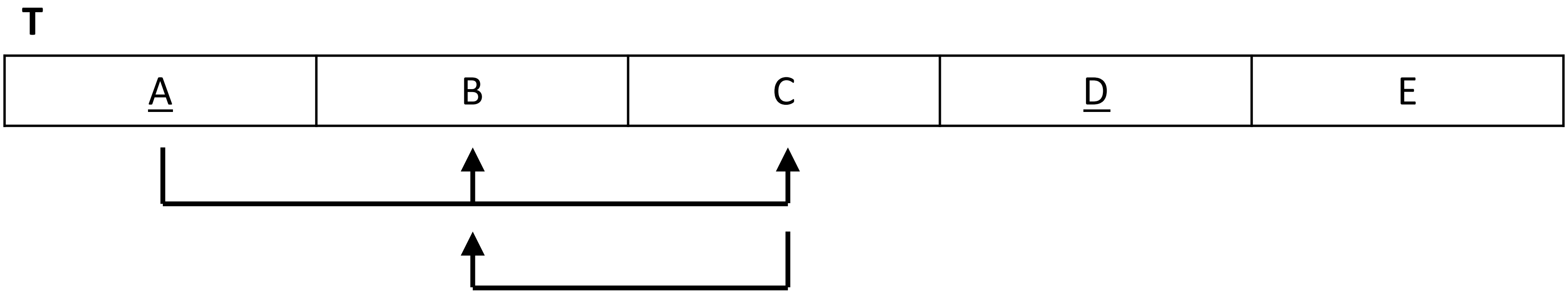
Winner	Nationality
Miguel Indurain	Spain
Bjarne Riis	Denmark
Jan Ullrich	Germany

Exercise



Consider the schema for relation **T**, as well as all FDs. What is the normal form of **T**? If **T** violates 3NF, provide a 3NF decomposition that satisfies the FDs (including the primary key) and does not produce spurious tuples. Show and explain all steps of your analysis and decomposition (if applicable).

Answer (1)



T

A	B	C	D	E

List non-trivial FDs

$$AD \to BCE$$
$$A \to BC$$
$$C \to B$$

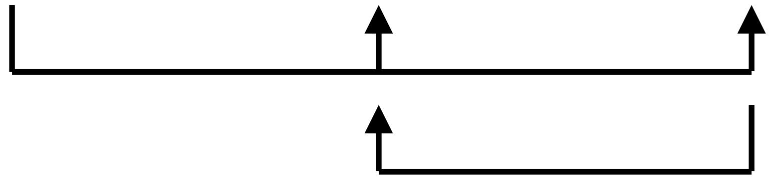
Written algebraically

$$T(\underline{A}, B, C, \underline{D}, E)$$

Answer (2)

T

A	B	C	D	E



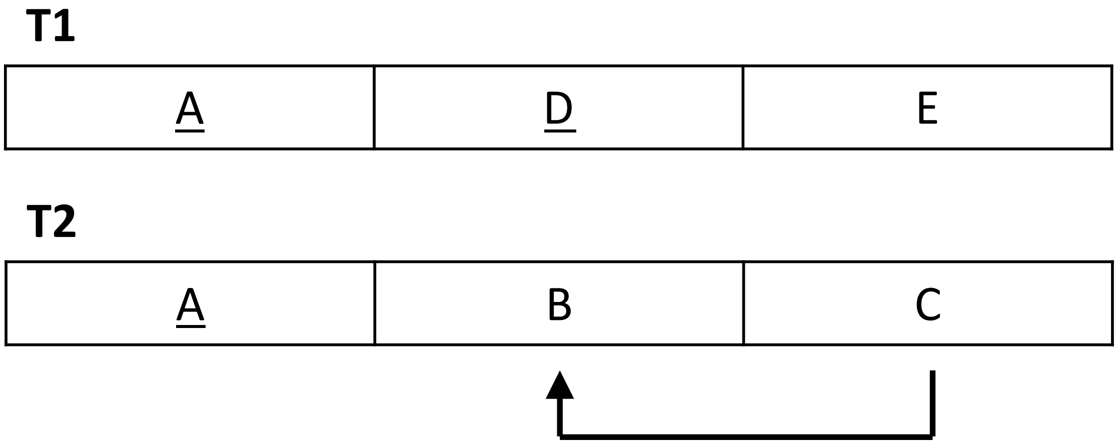
$$T(\underline{A}, B, C, \underline{D}, E)$$
$$AD \rightarrow BCE$$
$$A \rightarrow BC$$
$$C \rightarrow B$$

T is in …

- Both B & C are FD on A
  - – Thus not fully FD on PK (AD)

Decompose!

Answer (3)



T1

A	D	E

T2

A	B	C

$$T1(\underline{A}, \underline{D}, E)$$
$$T2(\underline{A}, B, C)$$

$$AD \rightarrow E$$
$$A \rightarrow BC$$
$$C \rightarrow B$$

T1 is in …

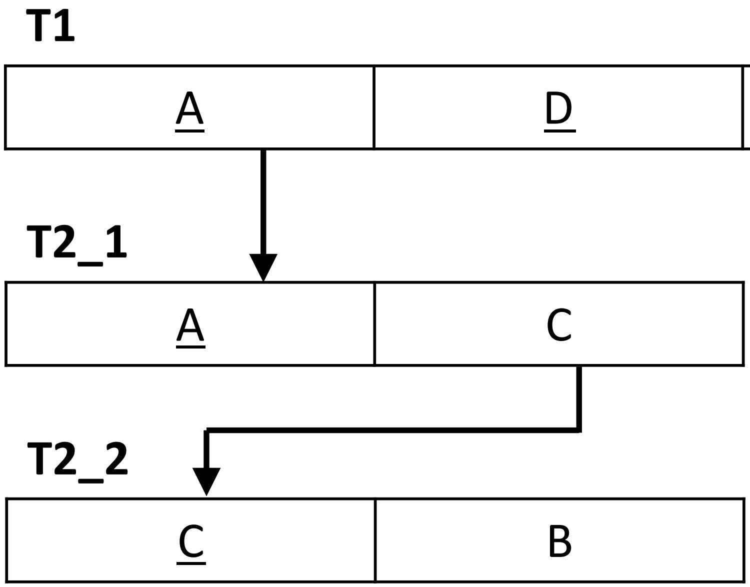
- 2NF: E is fully FD on AD
- 3NF: No transitive FDs (trivially true)

T2 is in …

- 2NF: B and C fully FD on A (trivially true)
- !3NF: B is transitively FD on A [via C]

Decompose!

Answer (4)



T1

A | D | E

T2_1

A | C

T2_2

C | B

$$T1(\underline{A}, \underline{D}, E)$$
$$T2\_1(\underline{A}, C)$$
$$T2\_2(\underline{C}, B)$$

$$AD \rightarrow E$$

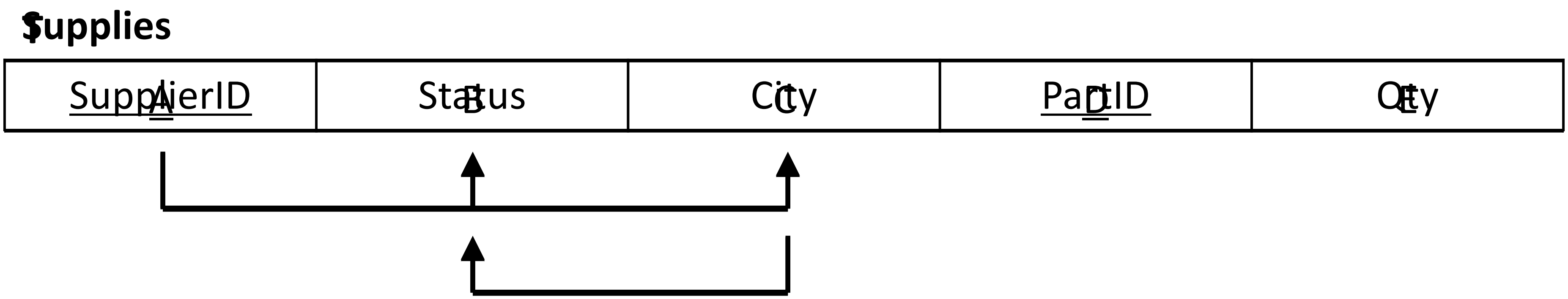
$$A \rightarrow C$$

$$C \rightarrow B$$

Database is in 3NF

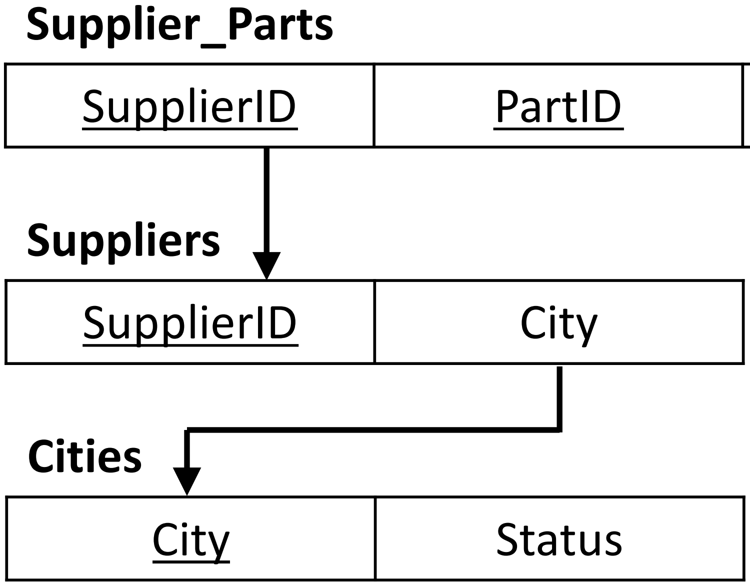
- Why?

Answer (5)



Supplies

SupplierID A	Status B	City C	PartID D	Qty E



Supplier_Parts

SupplierID	PartID	Qty

Suppliers

SupplierID	City

Cities

City	Status

$$\{SupplierID, PartID\} \rightarrow \{Qty\}$$

$$\{SupplierID\} \rightarrow \{City\}$$

$$\{City\} \rightarrow \{Status\}$$

Summary

- Normalization is the theory and process by which to evaluate and improve relational database design
  - Makes the schema informative
  - Minimizes information duplication
  - Avoids modification anomalies
  - Disallows spurious tuples
- By default, make sure all your relations are *at least* 3NF!
  - Higher normal forms exist
  - We may reduce during physical design