Relational Data Model

Relational Data Model

The relational data model describes the world as:

- a collection of inter–related relations (or tables)

Goal of relational model:

- a simple, general data modelling formalism
- which maps easily to file structures (i.e. implementable)

Can be viewed as an attempt to formalise the file organisations that were in common use at the time the model was developed.

Relational Data Model (cont)

The relational data model has existed for over 30 years.

(The original description is Codd, *Communications of the ACM*, 13(6), 1970)

The relational model has provided the basis for:

- research on the theory of data/relationships/constraints
- numerous database design methodologies
- the standard database access language SQL
- almost all modern commercial database management systems

It is a very influential development in CS, for which Codd received a Turing award.

Terminology

A note on the terminology used in the relational model ...

The relational model is a mathematical theory; it has no "standard".

However, it also has a close connection to file/data structures.

There are thus two kinds of terminology in use:

- mathematical: relation, tuple, attribute, ...
- data-oriented: table, record, field/column, ...

Textbooks alternate between the two; treat them as synonyms.

Relations

The relational model has one structuring mechanism ...

- a relation corresponds to a mathematical "relation"
- a relation can also be viewed as a "table"

Each relation schema (denoted *R,S,T,...*) has:

- a name (unique within a given database)
- a set of attributes (which can be viewed as column headings)

Each attribute (denoted *A,B,...* or $a_1,a_2,...$) has:

- a name (unique within a given relation)
- an associated domain (set of allowed values)

Relations (cont)

Attribute values are atomic (no composite or multi-valued attributes).

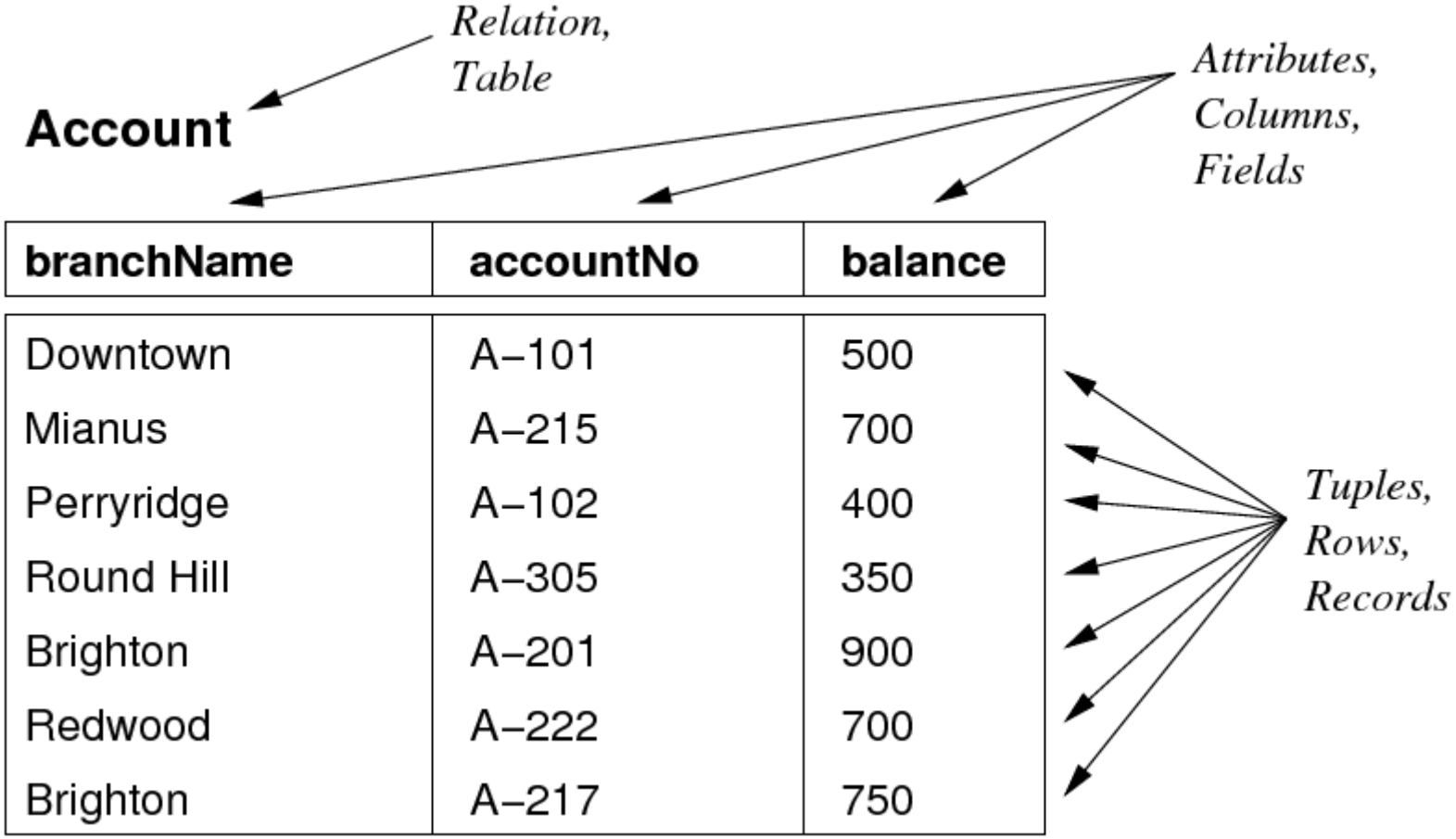
Attribute domains are typically: numbers, strings, booleans.

There is a distinguished value **`NULL`** that belongs to all domains.

A database is a collection of associated relations.

Relations (cont)

Example relation (bank accounts):



Example Database

Account

branchName	accountNo	balance
Downtown	A–101	500
Mianus	A–215	700
Perryridge	A–102	400
Round Hill	A–305	350
Brighton	A–201	900
Redwood	A–222	700

Branch

branchName	address	assets
Downtown	Brooklyn	9000000
Redwood	Palo Alto	2100000
Perryridge	Horseneck	1700000
Mianus	Horseneck	400000
Round Hill	Horseneck	8000000
North Town	Rye	3700000
Brighton	Brooklyn	7100000

Customer

name	address	customerNo	homeBranch
Smith	Rye	1234567	Mianus
Jones	Palo Alto	9876543	Redwood
Smith	Brooklyn	1313131	Downtown
Curry	Rye	1111111	Mianus

HeldBy

account	customer
A–101	1313131
A–215	1111111
A–102	1313131
A–305	1234567
A–201	9876543
A–222	1111111
A–102	1234567

Example Database (cont)

A tuple is a set of values; a relation is a set of tuples.

Since a relation is a set, there is no ordering on rows.

Normally, we define a standard ordering on components of a tuple.

The following are different presentations of the same relation:

branchName	accountNo	balance
Downtown	A–101	500
Mianus	A–215	700
Perryridge	A–102	400
Round Hill	A–305	350
Redwood	A–222	700

accountNo	branchName	balance
A–305	Round Hill	350
A–222	Redwood	700
A–215	Mianus	700
A–102	Perryridge	400
A–101	Downtown	500

Example Database (cont)

Consider a relation R :

- which has n attributes $a_1, a_2, \ldots a_n$
- with corresponding domains $D_1, D_2, \ldots D_n$

$R(a_1, a_1, \ldots a_n)$ (alternatively, $D_1 \times D_2 \times \ldots \times D_n$)

- is a schema for the relation (intensional)

A particular subset r of $D_1 \times D_2 \times \ldots \times D_n$

- is an instance of the schema (extensional)

Example Database (cont)

Schema names are typically unique within a given database.

So, we often use R as a synonym for $R(a_1, a_1, \ldots a_n)$.

$r(R)$ is used to denote that r is an instance of the schema R.

The number of attributes (n) in a schema is its degree (arity).

Note: the phrase " the relation R " can refer to either

- the schema for R *or*

- the current instance of *R* stored in a DBMS

The intended usage is generally clear from the context.

Example Database (cont)

E.g. the **`Accounts`** schema has type *String* × *String* × *Int* :

```
Account(branchName, accountNo, balance)
```

E.g. the **`Account`** instance (set of tuples) from the diagram:

```
{
  (Downtown, A-101, 500),   (Mianus, A-215, 700),
  (Perryridge, A-102, 400), (Round Hill, A-305, 350),
  (Brighton, A-201, 900),   (Redwood, A-222, 700),
  (Brighton, A-217, 750)
}
```

Notes:

- values in tuples are comma-separated, so we don't normally quote strings

- choose an order for attributes/values in tuples and use that consistently
- relations are sets ⇒ no duplicates, order of tuples is not important

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Changing Relations

In making changes to relations, it is ...

- easy to add new tuples (rows) (relation update)
- difficult to add new attributes (columns) (schema update)

The reasons:

- relation update ⇒ insertion of one new tuple into a set
  (in file terms: writing one record to the end of a data file)
- schema update ⇒ insertion of new data into every tuple
  (in file terms: re-writing the entire file to modify each record)

Schema update is a well-known and not well-solved problem in RDBMSs.

Constraints on Relational Data

Constraints

A very important feature of the relational model:

- well-defined theory of constraints on attributes/tables

This is useful because it allows

- formal reasoning about databases and operations on them
- designers to specify precisely the semantics of the data
- DBMSs to check that new data satisfies the semantics

Integrity Constraints

Relations allow us to represent data and associations.

Domains limit the values that attributes can take.

However, to fully represent the semantics of real–world problems, we need more detailed ways of specifying

- what values are/are not allowed
- what combinations of values are/are not allowed

Integrity constraints are logical statements about data that provide such information.

Some examples:

- employees must be over 16 and under 65 years of age
- account numbers must be unique
- each account is held at one particular branch

Integrity Constraints (cont)

Several kinds of constraints exist e.g.

key	combination of attributes must be unique
entity integrity	no attribute in key may be **NULL**
referential integrity	references to tuples in other relations must be valid
domain	value of attribute must satisfy certain property

Functional dependencies are another important kind of constraint, related to database design; we cover them in considerable detail later.

Integrity Constraints (cont)

Associating an attribute to a domain restricts its possible values to a well–defined set (e.g. integer).

Domain constraints allow more "fine–grained" definition of potential attribute values.

Example:

An **`age`** attribute is typically defined as **`integer`** ...

- but integer values like **`-5`** and **`199`** are not valid ages
- better modelled by adding a condition **`(15 < age < 66)`**

Note: the **`NULL`** value satisfies any domain constraint.

Integrity Constraints (cont)

Relational tuples have no notion of identity like OIDs.

Identity is value–based (as in ER model)

- keys are a way of uniquely identifying tuples.

Relational model supports same notions of key as ER model:

- superkey – set of attributes that distinguishes tuples
- candidate key – minimal super–key (no unnecessary attributes)
- primary key – distinguished/chosen candidate key

Keys are often implemented by introducing an artificial attribute specifically for the purpose of being a key (e.g. student ID, account number).

Integrity Constraints (cont)

Referential integrity constraints are relevant for inter–relation references.

Example:

- the **`Account`** relation needs to take note of the branch where each account is held
- implemented by storing information in each **`Account`** tuple to identify the associated branch (e.g. primary key **`branchName`**)
- it would not make sense to store a **`branchName`** that did not refer to one of the existing branches

The notion that the **`branchName`** must refer to a valid branch is a referential integrity constraint.

Foreign Keys

Referential integrity is related to the notion of a foreign key.

A set of attributes *FK* from a relation schema R_1 is a foreign key if:

- the attributes in *FK* correspond to the attributes in the primary key of another relation schema R_2
- the value for *FK* in each tuple of R_1
  - either occurs as a primary key in R_2
  - or is entirely **NULL**

Foreign Keys (cont)

Foreign keys are critical in relational databases

- they provide the "glue" that links individual relations into a cohesive database structure

- they provide the basis for "reconnecting" individual relations to assemble query answers

Special notation for foreign/primary keys:

- each relation is a sequence of "attribute boxes"
- attributes that are part of primary key are underlined
- arrows are drawn from foreign key attributes to their corresponding primary key attributes

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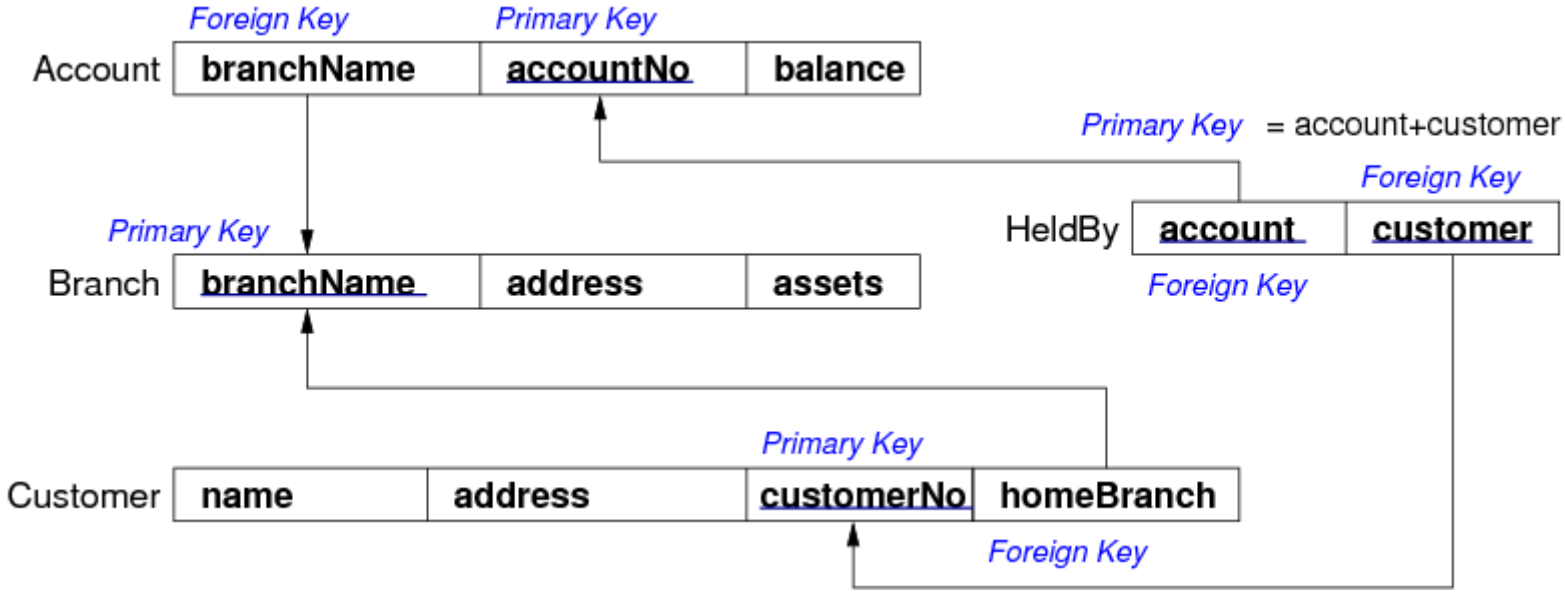
Foreign Keys (cont)

Foreign key examples:



Relational Databases

Relations, keys, foreign keys, and integrity constraints provide a complete toolkit for building relational databases.

A relational database schema is

- a set of relation schemas $\{ R_1, R_2, \ldots R_n \}$, and
- a set of integrity constraints

A relational database instance is

- a set of relation instances $\{ r_1(R_1), \quad r_2(R_2), \quad \ldots \quad r_n(R_n) \}$
- where all of the integrity constraints are satisfied

Constraint Checking

If we have a database instance that satisfies all integrity constraints, what can go wrong?

The data might change $\Rightarrow$ constraints need to be re-checked.

Possible changes:

- insert (add) a new record
- delete (remove) an existing record
- update (modify) an existing record

Constraint Checking (cont)

For domain constraints ...

Insert:

- check each attribute value for type and additional domain constraints

Delete:

- no need to check any domain constraints

Update:

- check each modified attribute value for type and additional domain constraints

---

Constraint Checking (cont)

These changes satisfy domain constraints:

```
insert Account(Downtown, A-456, 600)
insert Account(Perryridge, A-321, 200)
```

```
insert Account(Perryridge, A-102, 750)
    # but note duplicate key value
insert Account(Perryrige, A-131, 450)
    # value looks ok, but isn't correct
```

These changes do **not** satisfy domain constraints:

```
insert Account(Downtown, A-321, money)
    # 3rd attribute (a3) fails type check
insert Account(XYZZY, Hello, 300)
    # if we check for "lexically sensible" values on a1,a2
insert Account(Brighton, A-402, -500)
    # if we check for positive opening balance
```

Constraint Checking (cont)

For key constraints ...

Insert:

- check that key does not occur in any tuple already in the relation

Delete:

- no need to check anything

Update:

- if key attributes modified, same check as for insertion

Constraint Checking (cont)

These changes satisfy key constraints:

```
insert Account(Downtown, A-456, 600)
insert Depositor(A-101, 9876543)
   # ok, only part of key duplicated
update Account(Downtown, A-101, 500)
    to Account(Downtown, A-101, 600)
   # ok, key attributes were not changed
insert Depositor(A-305, 8888888)
   # but no such customer
```

These changes do **not** satisfy key constraints:

```
insert Account(Perryridge, A-102, 750)
   # key A-102 already exists in relation
update Account(Downtown, A-101, 500)
    to Account(Downtown, A-201, 500)
   # key A-201 already exists in relation
```

Constraint Checking (cont)

For referential integrity constraints ...

Insert:

- check that any foreign keys occur as primary keys in their own relation

Delete:

- check all relations that have foreign keys referring to this relation

Update:

- treat as delete–then–insert for constraint checking

Constraint Checking (cont)

Example of deletion with foreign keys:

Account

branchName	accountNo	balance
Sydney	A-101	500
Coogee	A-205	700
Parramatta	A-102	400
Rouse Hill	A-305	350

...

Branch

branchName	address	assets
Sydney	Pitt St	9000000
Coogee	Coogee Bay Rd	750000
Parramatta	Church St	888000

...

Customer

name	address	custNo	homeBranch
John Smith	Liverpool	11234	Sydney
Wei Wang	Randwick	74665	Coogee
Arun Shah	Liverpool	99987	Parramatta
Dave Dobbin	Penrith	35012	Rouse Hill

...

HeldBy

account	customer
A-101	11234
A-205	74665
A-102	99987
A-999	11234

...

Constraint Checking (cont)

How to handle violation of referential constraints on deletion?

One approach:

- simply disallow the deletion
- user must then find referring tuples and
  - either remove each one manually
  - or change their foreign keys to an acceptable value

Another approaches:

- remove all referring tuples automatically (cascade)
- set foreign key attributes to **`NULL`** in all referring tuples
  (not possible if the foreign key also forms part of the primary key)

Constraint Checking (cont)

These changes satisfy referential integrity constraints:

```
insert Account(Downtown, A-456, 600)
insert Depositor(A-215, 9876543)
update Account(Downtown, A-101, 500)
    to Account(Perryridge, A-101, 500)
   # ok, a1 changed to valid FK
```

These changes do **not** satisfy referential integrity constraints:

```
insert Account(Wombatville, A-987, 500)
   # no such branch
insert Depositor(A-305, 8888888)
   # valid account, but no such customer
update Account(Downtown, A-101, 500)
    to Account(Nowhere, A-101, 500)
   # no such branch
```

Constraint Checking (cont)

These changes satisfy referential integrity constraints:

```
delete Depositor(A-102, 1234567)
delete Depositor(A-101, 1313131)
    # although A-101 now has no "owner"
delete Branch(North Town, Rye, 3700000)
    # ok, since no accounts or customers (but assets?)
```

These changes do **not** satisfy referential integrity constraints:

```
delete Branch(Perryridge, Horseneck, 1700000)
    # some accounts are held at Perryridge
delete Customer(Smith, Rye, 1234567, Mianus)
    # Depositor records become invalid
```

Mapping ER Designs to Relational Schemas

ER to Relational Mapping

As noted earlier, one useful strategy for database design:

- perform initial data modelling using ER or OO
  (conceptual–level modelling)
- transform conceptual design into relational model
  (implementation–level modelling)

By examining semantic correspondences, a formal mapping between the ER and relational models has been developed.

Because it is formal, it can be automated, and commercial tools now exist to perform it.

ER to Relational Mapping (cont)

If we have tools, why worry about the mapping process itself?

It is still useful to understand how mapping occurs because:

- tools produce correct but (sometimes) incomprehensible relational descriptions

- to do performance tuning, you need to understand these descriptions
- you may need to use a different mapping to improve DB performance

Also, you're CSE students and you like to know how things work.

Relational Model vs ER Model

The relational and ER data models have some obvious correspondences:

Entity/Relationship	Relational
Attributes	Attributes (atomic)
Entity Relationship	Relation schema
Entity instance Relationship instance	Tuple (row, record)
Entity set Relationship set	Relation instance

Relational Model vs ER Model (cont)

There are also differences between relational and ER models.

Compared to ER, the relational model:

- uses relations to model both entities *and* relationships
- has no composite or multi-valued attributes (only atomic-valued)
- has no object-oriented notions (e.g. subclasses, inheritance)

Relational Model vs ER Model (cont)

At first glance, Relational looks less powerful than ER:

- less "mechanisms" and "weaker" data structuring tools

However, the relational model:

- can be used to represent any ER design
  (although relational design may not be as "natural" as ER one)

- is simple, elegant and formal
  ⇒ provides a theory for evaluating relational designs
- has a model for query processing
  ⇒ provides a basis for efficient implementations

Mapping Strong Entities

An entity consists of:

- a collection of attributes;
  attributes can be simple, composite, multi–valued

A relation schema consists of:

- a collection of attributes;
  all attributes have atomic data values

So, even the mapping from entity to relation schema is not simple.

Mapping Strong Entities (cont)

In one special case, there is an obvious mapping:

- an entity set E with atomic attributes a_1, a_2, ... a_n

maps to

- a relation R with attributes (columns) a_1, a_2, ... a_n

Each row in the relation R corresponds to an entity in E.

The key for the relation is the same (set of attributes) as for the entity set.

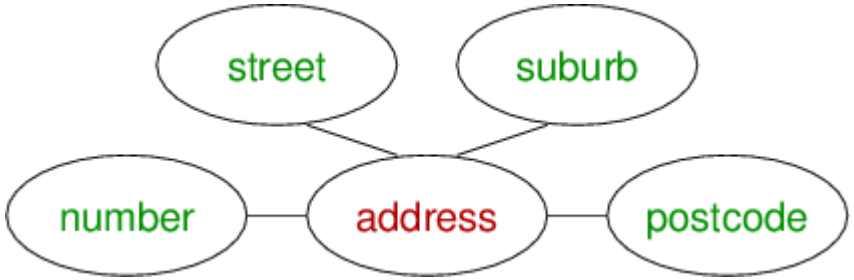
Mapping Strong Entities (cont)

ER supports composite (hierarchical) attributes.

The relational model supports only atomic attributes.

Composite attributes consist of

- structuring attributes (non–leaf attributes)
- data attributes (containing atomic values)



Mapping Strong Entities (cont)

One approach to mapping composite attributes:

- remove structuring attributes
- map atomic components to a set of atomic attributes (possibly with renaming)

E.g. **`Struct A {W, Struct B {X,Y}, Z}`** → **`(W,X,Y,Z)`**

It is common to retain structuring attribute as part of name to resolve name conflicts.

E.g. **`Struct Addr {number,street,suburb,pcode}`**
maps to **`(AddrNumber,AddrStreet,AddrSuburb,AddrPcode)`**

Mapping Strong Entities (cont)

Alternative approach to mapping composite attributes:

- concatenate atomic attribute values into a string

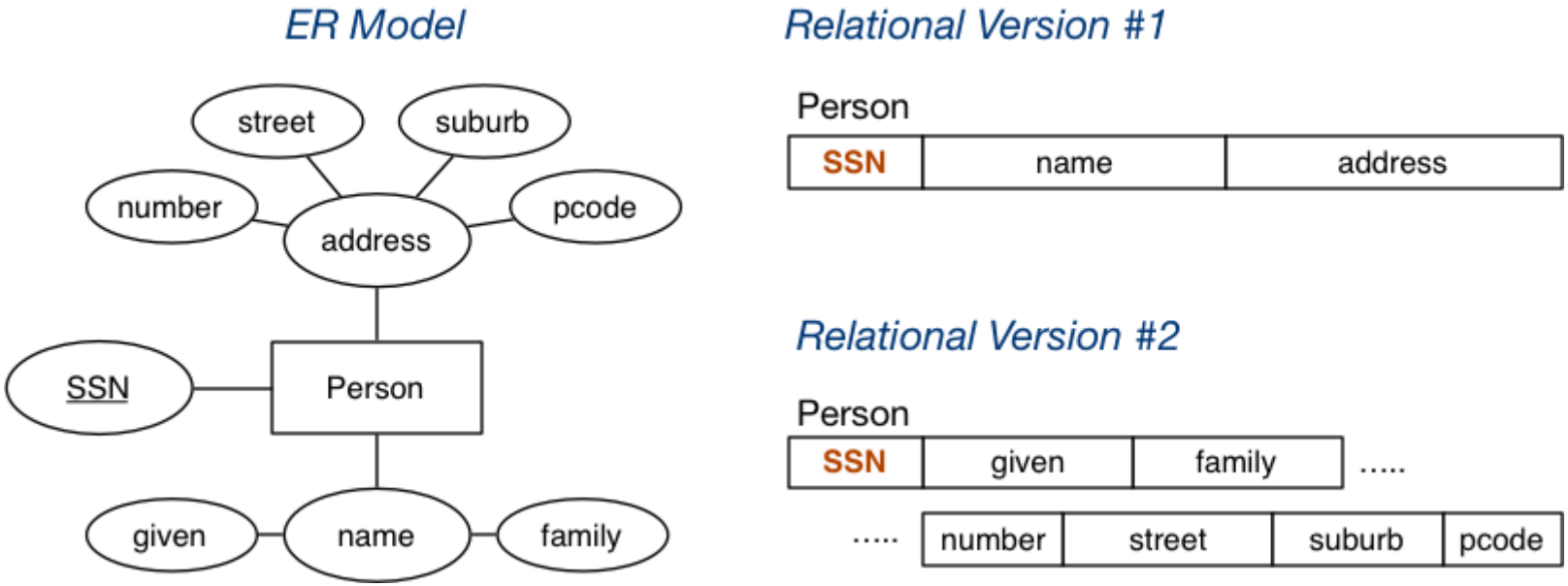
E.g. **`Struct name {"John","Smith"}`** → **`"John Smith"`**

However, this approach "hides" information from data manipulation languages:

- requires extra extraction effort if components *are* required
- cannot exploit efficient query capabilities on components

Mapping Strong Entities (cont)

Example:



Mapping Weak Entities

A weak entity set *W*

- has some attributes that form a discriminator, BUT
- is dependent on some other entity set *E* to form a key

If we simply form a relation for *W* by mapping its attributes, it would not be a valid relation because it would not have a key.

The solution:

- map the weak entity set to a relation, BUT also
- augment the relation by including *E*'s key

This always yields a relation with a valid key.

Mapping Weak Entities (cont)

More formally:

- let *W* be a weak entity set with attributes $w_1, w_2, \ldots w_n$
- let *E* be its strong entity set with key $e_1, e_2, \ldots e_m$
- represent *W* by a table with columns
  $\{ w_1, w_2, \ldots w_n \} \cup \{ e_1, e_2, \ldots e_m \}$

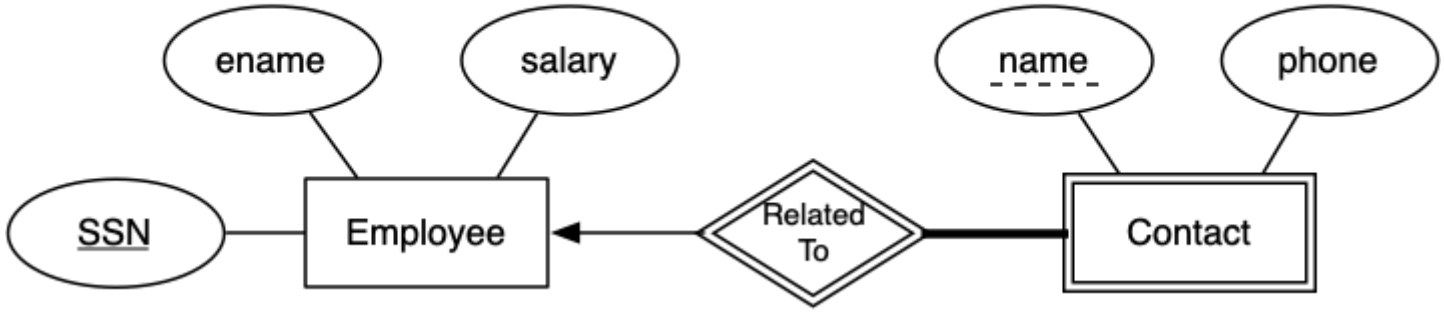
The key is *E*'s key (foreign key in *W*) plus the discriminator of *W*.

The weak relationship set between *W* and *E* is not explicitly represented.

Mapping Weak Entities (cont)

Example:

ER Model



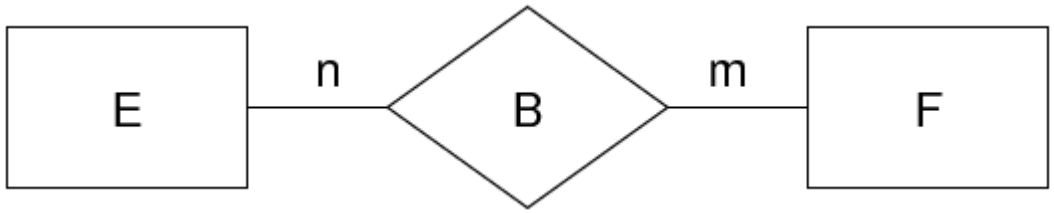
Relational Version

Employee	SSN	ename	salary

Contact	SSN	name	phone

Mapping N:M Relationships

A binary relationship set *B* between entity sets *E* and *F* gives associations between pairs of entities in *E* and *F*



We can represent

- entity set *E* by relation *S* (using attribute mappings as above)
- entity set *F* by relation *T* (using attribute mappings as above)

But how to represent *B*?

Mapping N:M Relationships (cont)

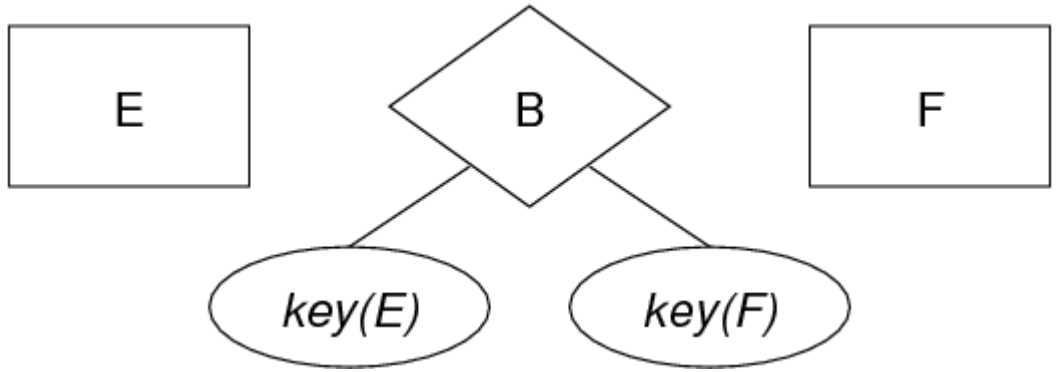
One possibility: represent the relationship set *B* explicitly by a relation *R*.

Each tuple (row) in *R* represents the relationship between a specific pair of entities from *E* and *F*.

For this to work, the tuple would need to contain information to identify the entities involved

This is achieved by storing the keys of the related entities.

It is somewhat like breaking the ER diagram up as follows:



Mapping N:M Relationships (cont)

A relationship set *B(E,F)* is represented by a relation *R* containing:

- all attributes from the primary keys of *S* and *T*
- all attributes associated with the relationship set *B*

where S and T are relations representing entity sets E and F.

The key for R is the union of the key attributes for S and T.

Mapping N:M Relationships (cont)

This approach for representing relationships works generally:

- relationship degree $\geqslant 2$
- relationship multiplicity 1:1, 1:N, N:M
- associated attributes are simply included in R

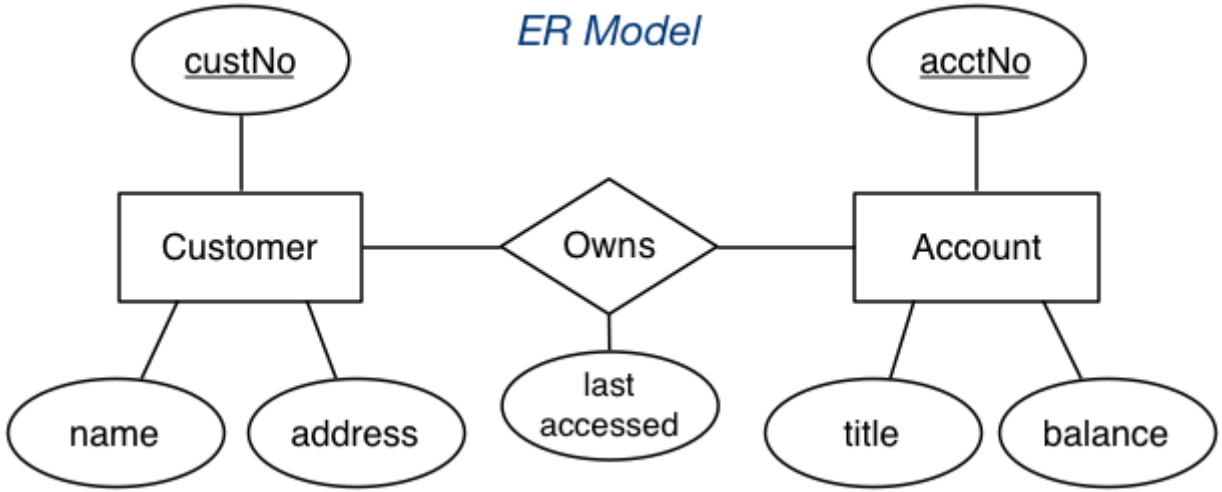
but requires a new relation to be created for each relationship set.

This can slow down query processing considerably.

In certain special cases, we do not need to create a new relation (see later).

Mapping N:M Relationships (cont)

Example:



Relational Version

Customer	**custNo**	name	address
Account	**acctNo**	title	balance
Owns	**acctNo**	**custNo**	lastAccessed

Mapping 1:N Relationships

Consider a 1:N relationship *R* between entity sets *E* and *F*

- an entity in *F* is associated with at most one entity in *E*
- an entity in *E* may be associated with many entities in *F*

As above, we represent *E* and *F* by relations *S* and *T*.

How to capture the association between an entity in *F* and the corresponding entity in *E*?

We have already seen one solution: introduce a new relation for *R*.

Mapping 1:N Relationships (cont)

Since there is (at most) one corresponding entity, add attributes in *F*:

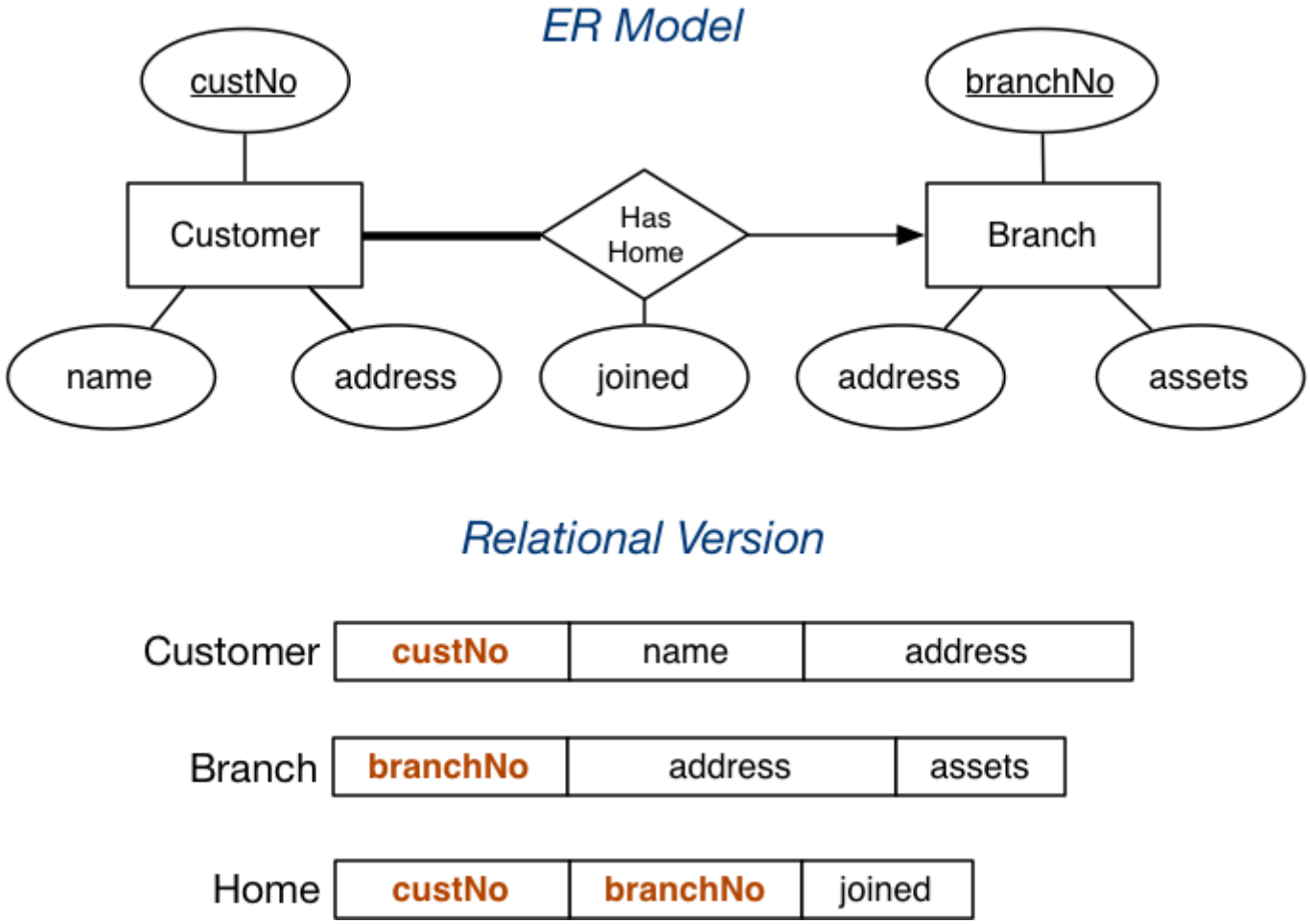
- to identify the corresponding entity (i.e. *E*'s key)
- to represent any attributes associated with *R*

In other words, we insert a foreign key for *E* into *F*,
along with any attributes for the relationship *R*.

If an entity in *F* has no relationship with *E* give **`NULL`** values to the "extra" attributes in *F*.

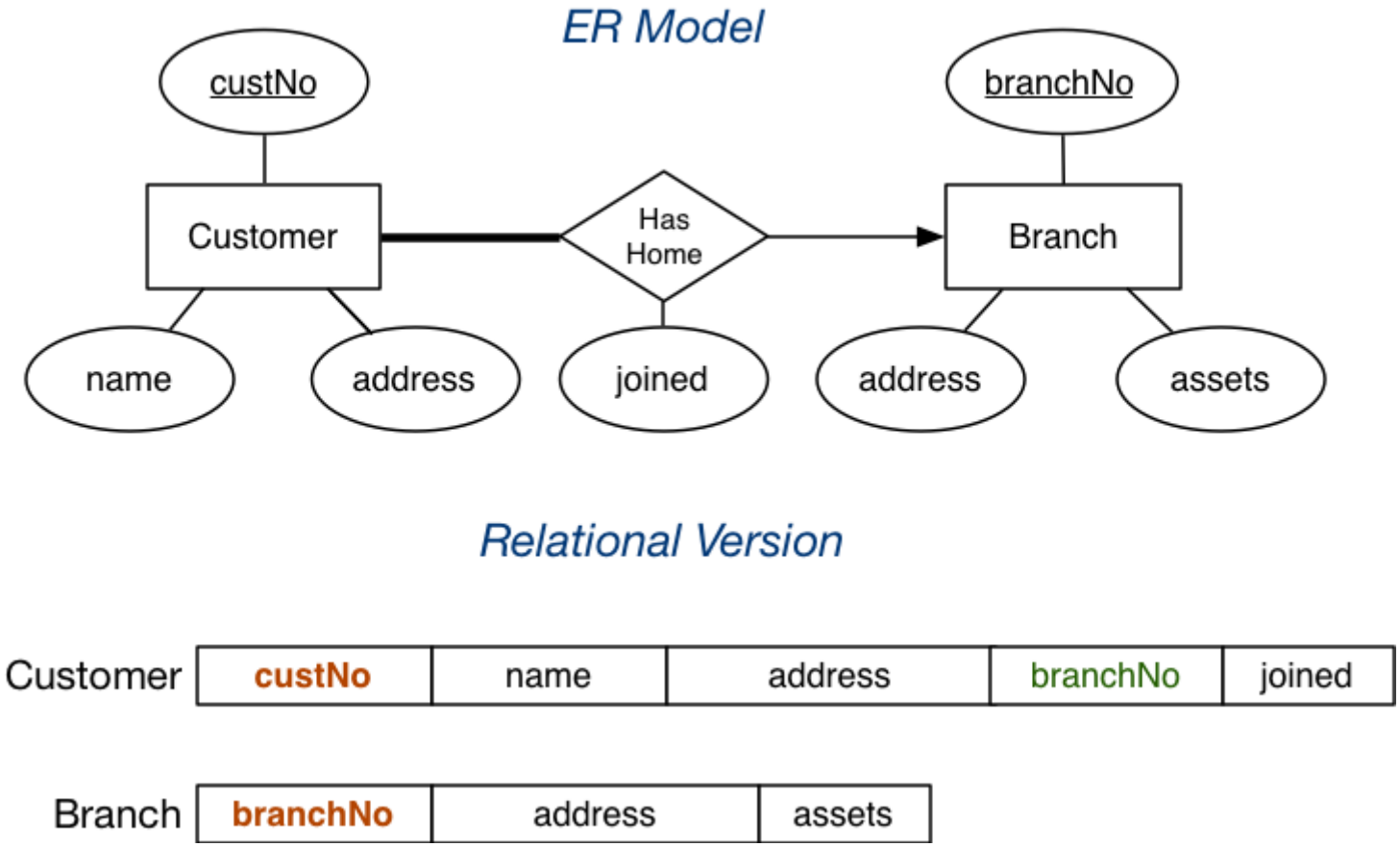
Mapping 1:N Relationships (cont)

Example (generic mapping):



Mapping 1:N Relationships (cont)

Example (optimised mapping):



Mapping 1:1 Relationships

1:1 relationships are handled in a similar manner to 1:N relationships.

The difference is that we could choose either relation to hold the key of the other relation, to represent the correspondence.

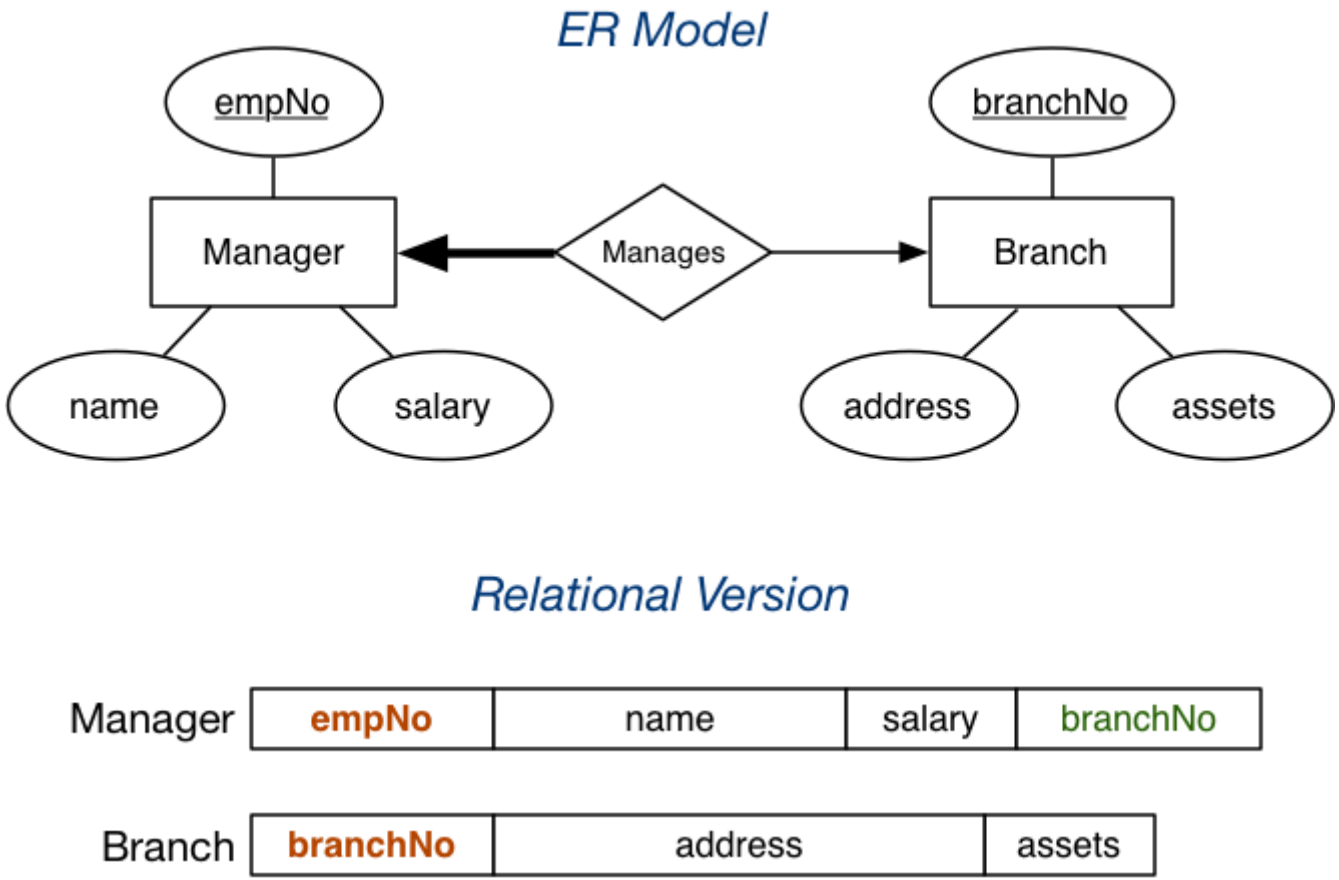
Choose the entity set that participates totally, if only one of them does.

For a 1:1 relationship between entity sets E and F (S and T):

- choose one of S and T (e.g. S)
- add the attributes of T's primary key to S as foreign key
- add the relationship attributes as attributes of S

Mapping 1:1 Relationships (cont)

Example:



Mapping Multi–valued Attributes

An attribute in a relation may hold a single atomic value.

An attribute in an entity may hold multiple (structured) values.

A multi–valued attribute may be viewed as:

- a collection of values associated with an entity

so treat it like an N:M relationship between entities and values.

Create a new relation where each tuple contains:

- the primary key attributes from the entity
- one value for the multi–valued attribute from the corresponding entity

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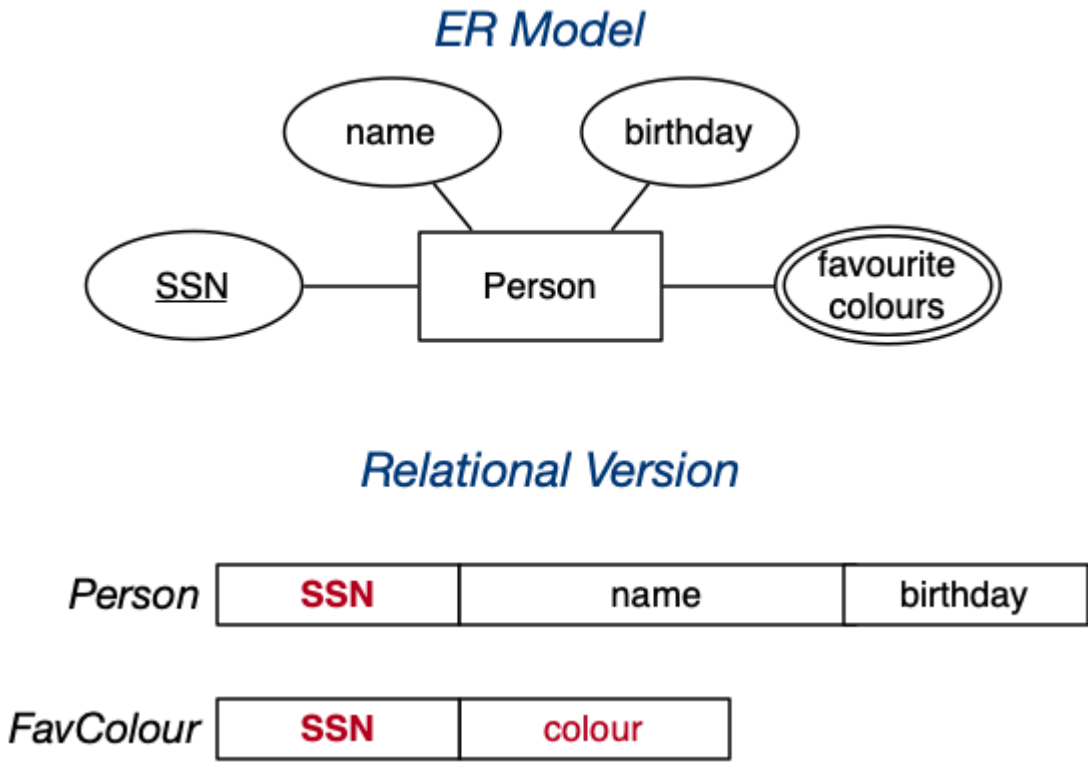
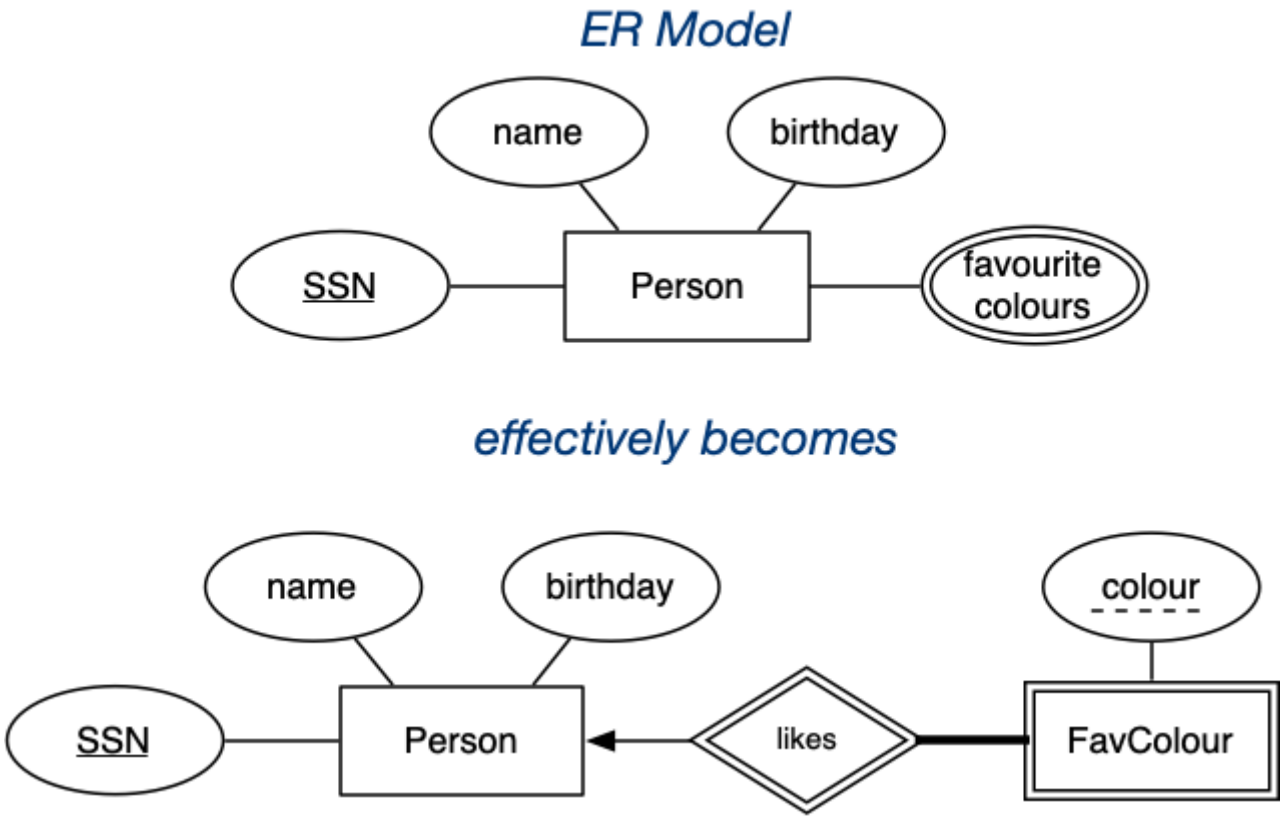
Mapping Multi–valued Attributes (cont)

Example:



Mapping Multi–valued Attributes (cont)

This approach is like altering the ER diagram as follows:



Mapping Multi-valued Attributes (cont)

Example: the two entities

```
Person(12345, John, 12-feb-1990, [red,green,blue])
Person(54321, Jane, 25-dec-1990, [green,purple])
```

would be represented as

```
Person(12345, John, 12-feb-1990)
Person(54321, Jane, 25-dec-1990)
FavColour(12345, red)
FavColour(12345, green)
FavColour(12345, blue)
FavColour(54321, green)
FavColour(54321, purple)
```

Mapping Subclasses

Each subclass is represented as a separate relation.

Each entity in the subclass:

- contains its own subclass–specific information (attributes)
- needs to be associated with information in the superclass

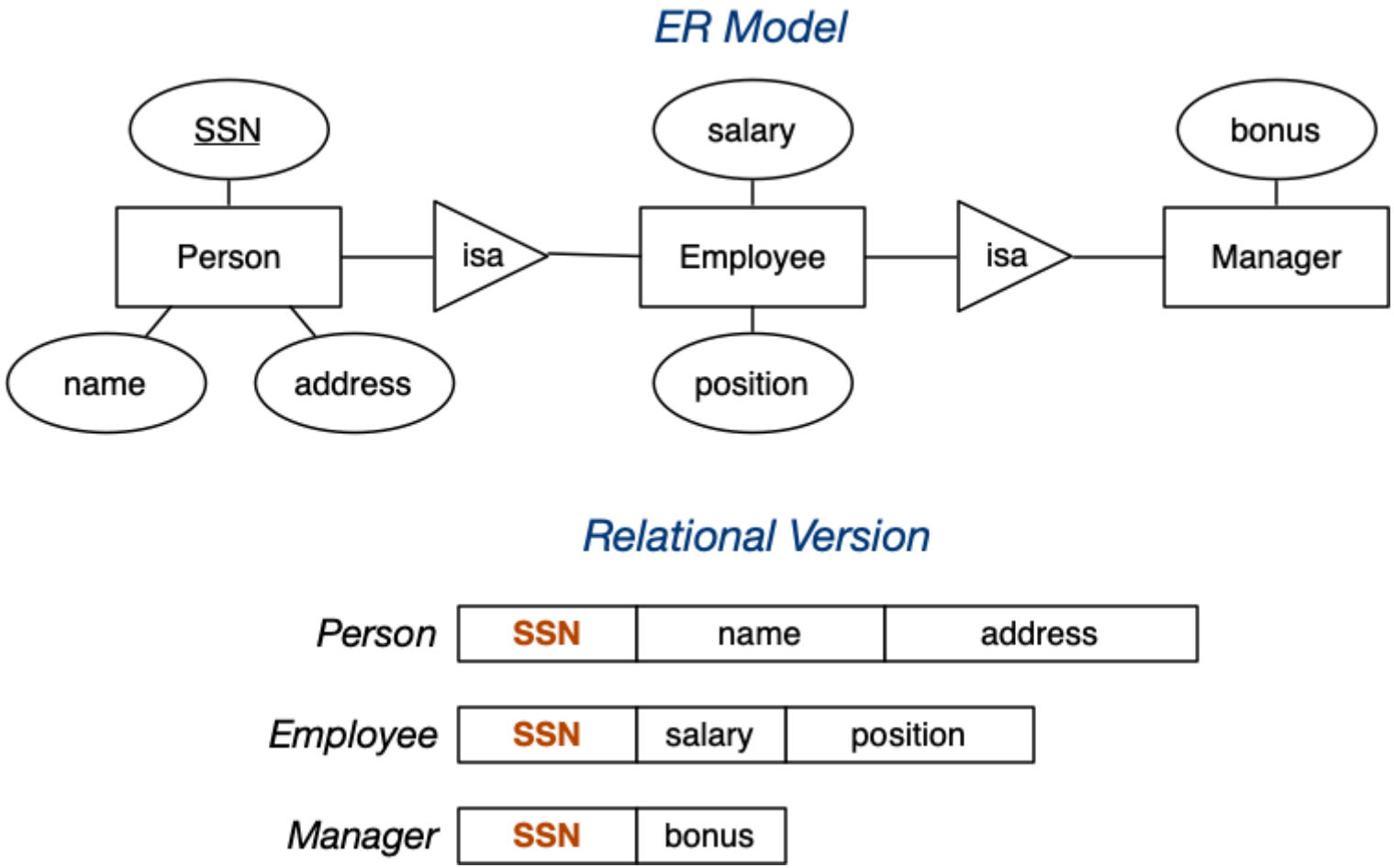
Use the superclass entity's primary key to capture the association.

Each tuple in the subclass relation contains:

- all of the attributes from the parent's key
- all of the subclass–specific attributes

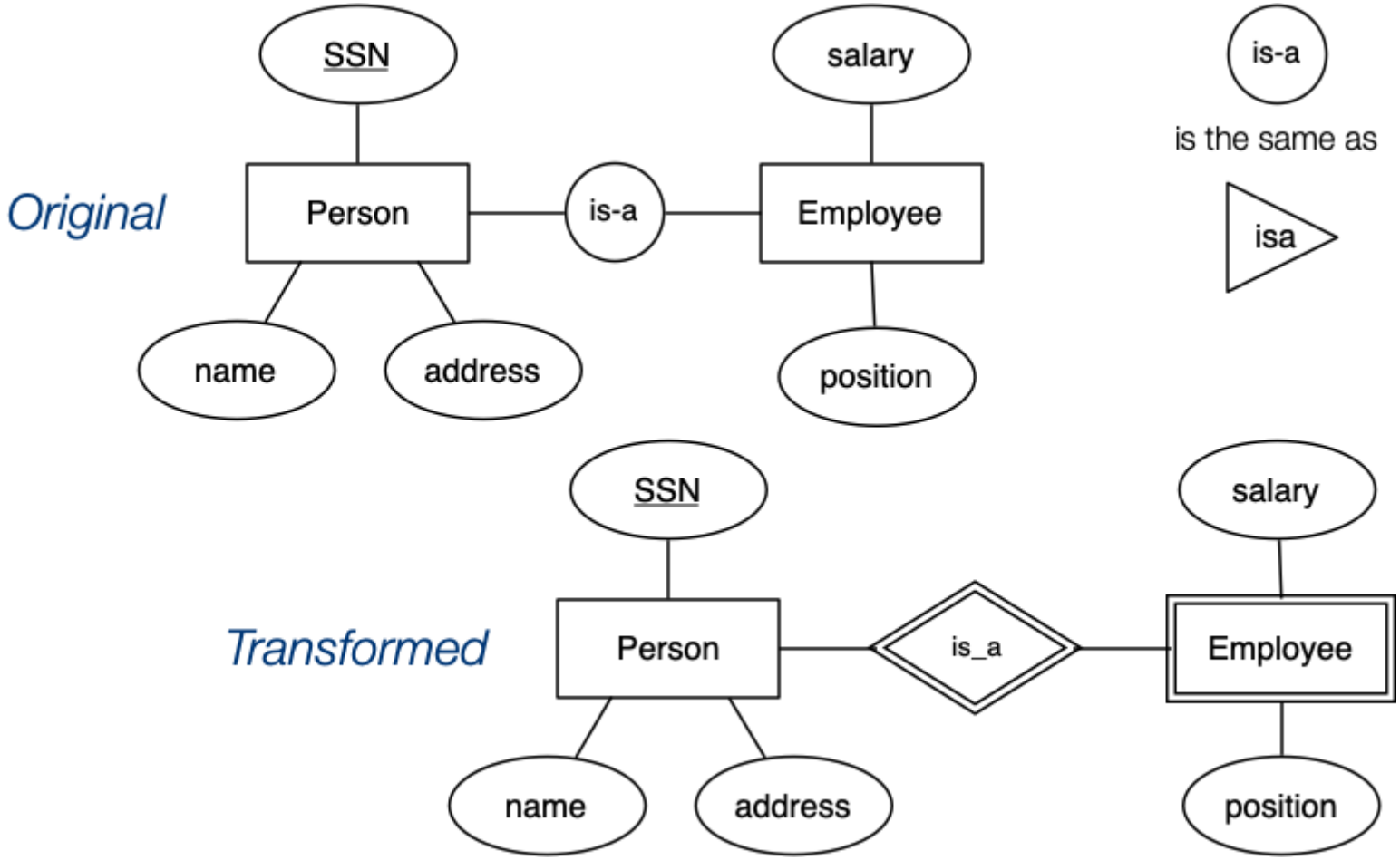
Mapping Subclasses (cont)

Example:



Mapping Subclasses (cont)

This approach is like transforming the ER as follows:



Mapping Subclasses (cont)

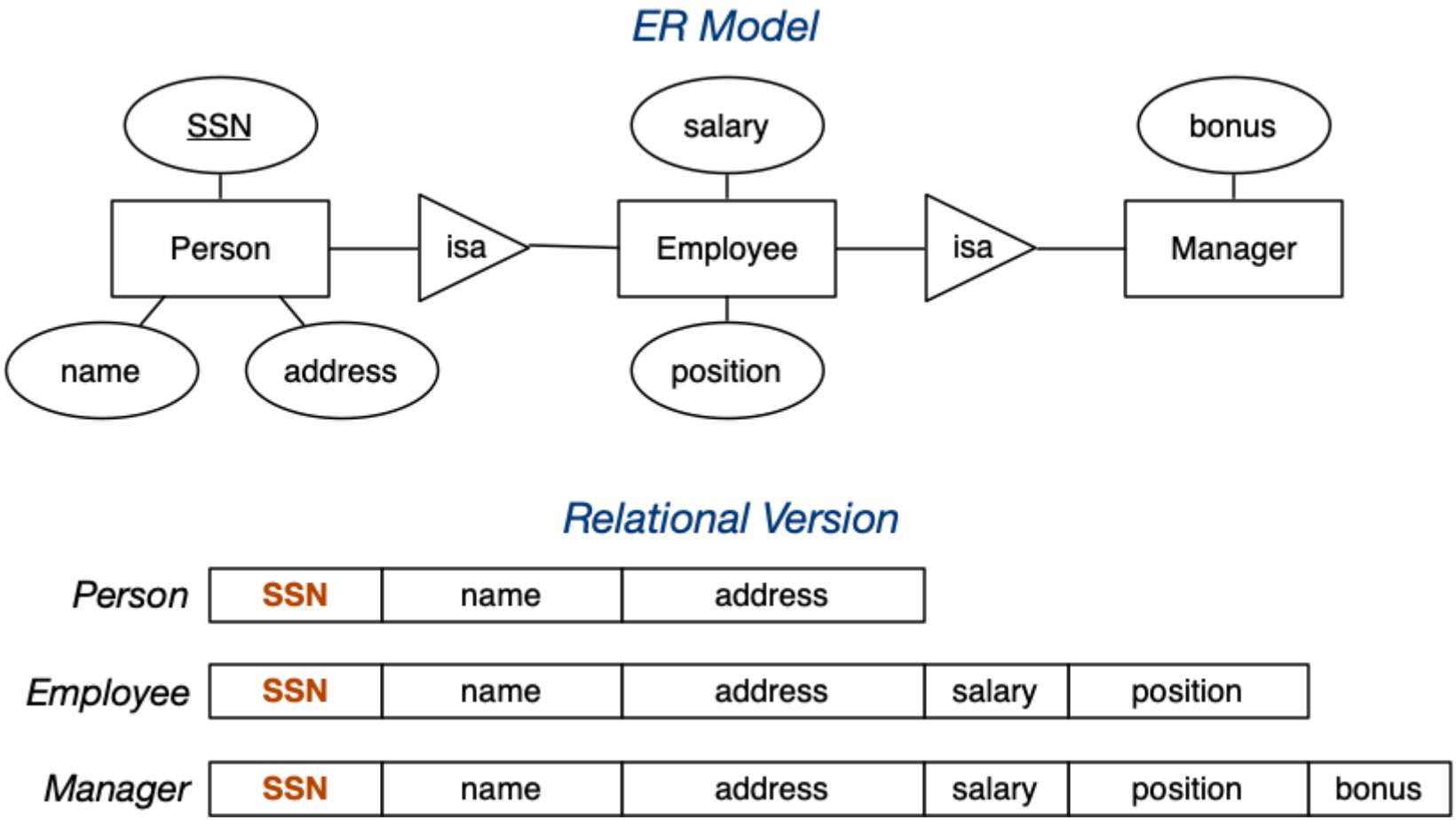
This approach to subclass mapping is called "ER style"

There are two other approaches to subclass mapping:

- object–oriented
  - each entity becomes a table, inheriting superclass attributes
- single table with nulls
  - one table, with all attributes of all subclasses

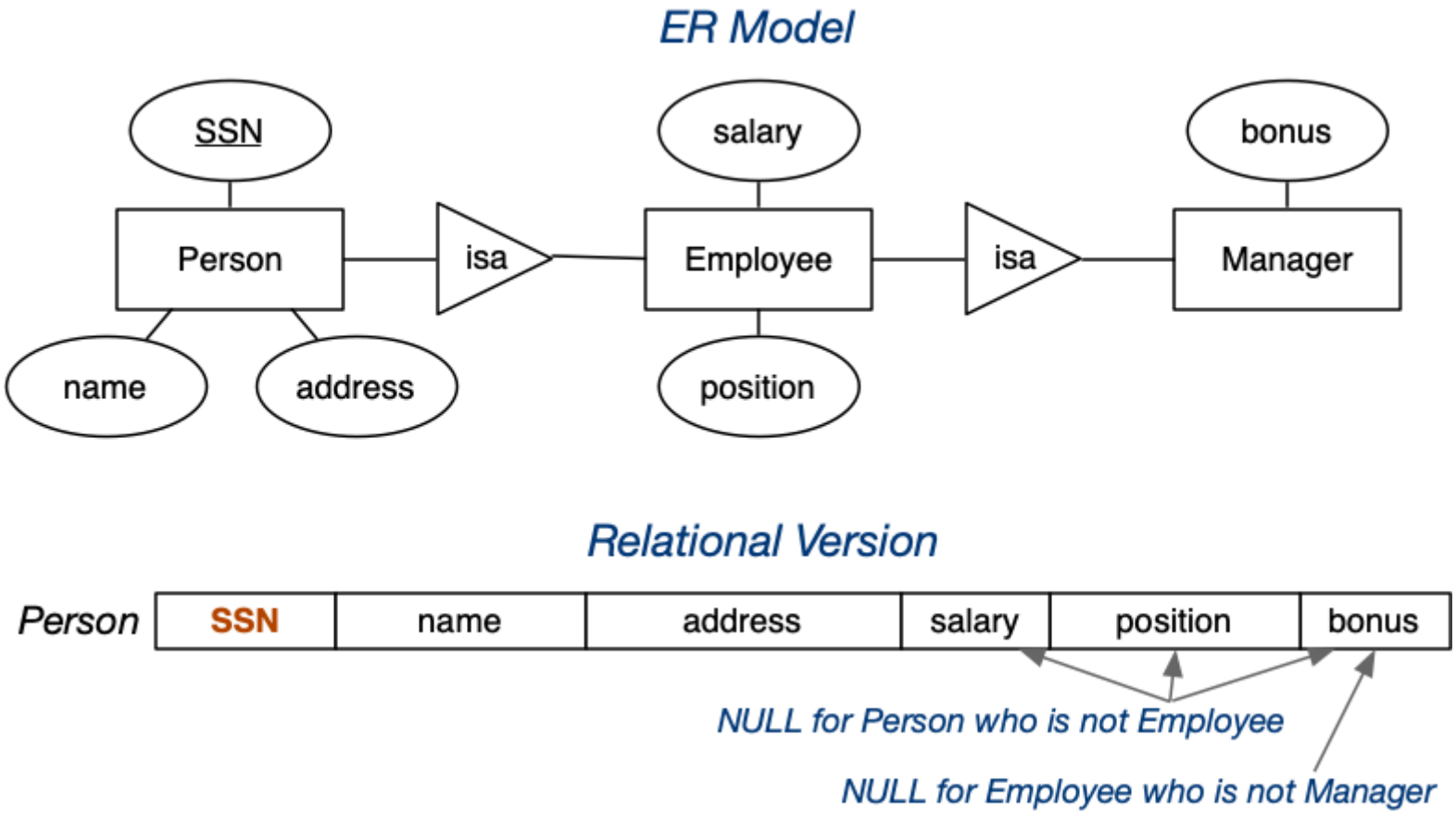
Mapping Subclasses (cont)

Example of object–oriented mapping:



Mapping Subclasses (cont)

Example of single–table–with–nulls mapping:



Mapping Subclasses (cont)

Which mapping is best depends on other requirements ...

- ER-style good for queries like "find average salary"
  - need to look only in (relatively small) **`Employee`** table

- OO-style good for queries like "find manager names and bonuses"
  - need to look only in **`Manager`** table
- Single-table saves space, unless many NULL values

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