Chapter 14
Object Databases

What's in This Module?
• Motivation
• Conceptual model
• ODMG
  – ODL – data definition language
  – OQL – query language
• SQL:1999 object extensions
• CORBA

Problems with Flat Relations
Consider a relation
Person(SSN, Name, PhoneN, Child)
with:
• FD: SSN → Name
• Any person (identified by SSN) can have several
phone numbers and children
• Children and phones of a person are not related to
each other except through that person
An Instance of Person

<table>
<thead>
<tr>
<th>SSN</th>
<th>Name</th>
<th>PhoneN</th>
<th>Child</th>
</tr>
</thead>
<tbody>
<tr>
<td>111-22-3333</td>
<td>Joe Public</td>
<td>516-123-4567</td>
<td>222-33-4444</td>
</tr>
<tr>
<td>111-22-3333</td>
<td>Joe Public</td>
<td>516-345-6789</td>
<td>222-33-4444</td>
</tr>
<tr>
<td>111-22-3333</td>
<td>Joe Public</td>
<td>516-123-4567</td>
<td>333-44-5555</td>
</tr>
<tr>
<td>111-22-3333</td>
<td>Joe Public</td>
<td>516-345-6789</td>
<td>333-44-5555</td>
</tr>
<tr>
<td>222-33-4444</td>
<td>Bob Public</td>
<td>212-987-6543</td>
<td>444-55-6666</td>
</tr>
<tr>
<td>222-33-4444</td>
<td>Bob Public</td>
<td>212-987-1111</td>
<td>555-66-7777</td>
</tr>
<tr>
<td>222-33-4444</td>
<td>Bob Public</td>
<td>212-987-6543</td>
<td>555-66-7777</td>
</tr>
<tr>
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<td>Bob Public</td>
<td>212-987-1111</td>
<td>444-55-6666</td>
</tr>
</tbody>
</table>

Dependencies in Person

Join dependency (JD):

Person = (SSN, Name, PhoneN) \( \bowtie \) (SSN, Name, Child)

Functional dependency (FD):

\( SSN \rightarrow Name \)

Redundancies in Person

- Due to the JD:
  Every PhoneN is listed with every Child SSN
  Hence Joe Public is twice associated with 222-33-4444 and with 516-123-4567
  Similarly for Bob Public and other phones/children
- Due to the FD:
  Joe Public is associated with the SSN 111-22-3333 four times (for each of Joe’s child and phone)!
  Similarly for Bob Public
Dealing with Redundancies

- What to do? Normalize!
  - Split Person according to the JD
  - Then each resulting relation using the FD
  - Obtain four relations (two are identical)

Normalization removes redundancy:

<table>
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<td>212-987-6543</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SSN</th>
<th>Phone</th>
</tr>
</thead>
<tbody>
<tr>
<td>212-135-7924</td>
<td>222-33-4444</td>
</tr>
<tr>
<td>212-987-6543</td>
<td>222-33-4444</td>
</tr>
<tr>
<td>516-123-4567</td>
<td>111-22-3333</td>
</tr>
<tr>
<td>516-345-6789</td>
<td>111-22-3333</td>
</tr>
</tbody>
</table>

But querying is still cumbersome:

Get the phone numbers of Joe’s grandchildren.

Against the original relation: three cumbersome joins

```
SELECT P.PhoneN
FROM Person P, Person C, Person G
WHERE P.Name = 'Joe Public' AND P.Child = C.SSN AND C.Child = G.SSN
```

Against the decomposed relations is even worse: four joins

```
SELECT N.Phone
FROM ChildOf C, ChildOf G, Person P, Phone N
WHERE P.Name = 'Joe Public' AND P.SSN = C.SSN AND C.Child = G.SSN AND G.SSN = N.SSN
```
Objects Allow Simpler Design

Schema:
Person(SSN: String, Name: String, PhoneN: {String}, Child: {SSN})

No need to decompose in order to eliminate redundancy: the set data type takes care of this.

Object 1: (111-22-3333, "Joe Public", {516-345-6789, 516-123-4567}, {222-33-4444, 333-44-5555})

Objects Allow Simpler Queries

Schema (slightly changed):
Person(SSN: String, Name: String, PhoneN: {String}, Child: {Person})

- Because the type of Child is the set of Person-objects, it makes sense to continue querying the object attributes in a path expression

Object-based query:
SELECT P.Child.Child.PhoneN FROM Person P WHERE P.Name = 'Joe Public'

- Much more natural!

ISA (or Class) Hierarchy

Person(SSN, Name)
Student(SSN, Major)

Query: Get the names of all computer science majors

Relational formulation:
SELECT P.Name FROM Person P, Student S WHERE P.SSN = S.SSN and S.Major = 'CS'

Object-based formulation:
SELECT S.Name FROM Student S WHERE S.Major = 'CS'

Student-objects are also Person-objects, so they inherit the attribute Name
Object Methods in Queries

- Objects can have associated operations (methods), which can be used in queries. For instance, the method `frameRange(from, to)` might be a method in class `Movie`. Then the following query makes sense:

```sql
SELECT M.frameRange(20000, 50000)
FROM Movie M
WHERE M.Name = 'The Simpsons'
```

The “Impedance” Mismatch

- One cannot write a complete application in SQL, so SQL statements are embedded in a host language, like C or Java.
- SQL: Set-oriented, works with relations, uses high-level operations over them.
- Host language: Record-oriented, does not understand relations and high-level operations on them.
- SQL: Declarative.
- Host language: Procedural.
- Embedding SQL in a host language involves ugly adapters (cursors/iterators) – a direct consequence of the above mismatch of properties between SQL and the host languages. It was dubbed “impedance” mismatch.

Can the Impedance Mismatch be Eliminated?

- This was the original idea behind object databases:

  *Use an object-oriented language as a data manipulation language. Since data is stored in objects and the language manipulates objects, there will be no mismatch!*

- Problems:
  - Object-oriented languages are procedural – the advantages of a high-level query language, such as SQL, are lost.
  - C++, Java, Smalltalk, etc., all have significantly different object modeling capabilities. Which ones should the database use? Can a Java application access data objects created by a C++ application?
  - Instead of one query language we end up with a bunch (one for C++, one for Java, etc.)
Is Impedance Mismatch Really a Problem?

- The jury is out
- Two main approaches/standards:
  - ODMG (Object Database Management Group): Impedance mismatch is worse than the ozone hole!
  - SQL:1999: Couldn’t care less – SQL rules!
- We will discuss both approaches.

Object Databases vs. Relational Databases

- **Relational**: set of relations; relation = set of tuples
- **Object**: set of classes; class = set of objects
- **Relational**: tuple components are primitive (int, string)
- **Object**: object components can be complex types (sets, tuples, other objects)
- **Unique features of object databases**:
  - Inheritance hierarchy
  - Object methods
  - In some systems (ODMG), the host language and the data manipulation language are the same

The Conceptual Object Data Model (CODM)

- Plays the same role as the relational data model
- Provides a common view of the different approaches (ODMG, SQL:1999 & 2003)
- Close to the ODMG model, but is not burdened with confusing low-level details
Three Schemas in the Relational Data Model

- **Physical schema**: How data (tables) is stored?
- **Conceptual schema**: Set of tables
- **External schemas**: Set of relations

Data Model

- Tools and language for describing:
  - Conceptual and external schema (a schema: description of data at some level, e.g., tables, attributes, constraints, domains)
    - Data definition language (DDL)
    - Integrity constraints, domains (DDL)
    - Operations on data
      - Data manipulation language (DML)
    - Optional: Directives that influence the physical schema (affects performance, not semantics)
    - Storage definition language (SDL)

Conceptual Object Data Model
Object Id (Oid)

- Every object has a unique Id: different objects have different Ids
- Immutable: does not change as the object changes
- Different from primary key!
  - Like a key, identifies an object uniquely
  - But key values can change – oids cannot

Objects and Values

- An object is a pair: (oid, value)
- Example: A Joe Public’s object
  (#32, [ SSN: 111-22-3333,
  Name: “Joe Public”,
  PhoneN: [“516-123-4567”, “516-345-6789”],
  Child: {#445, #73} ] )

Complex Values

- A value can be of one of the following forms:
  - Primitive value: an integer (eg, 7), a string (“John”), a float (eg, 23.45), a Boolean (eg, false)
  - Reference value: An oid of an object, e.g., #445
  - Tuple value: [A₁: v₁, …, Aₙ: vₙ]
    - A₁, …, Aₙ – distinct attribute names
    - v₁, …, vₙ – values
  - Set value: {v₁, …, vₙ}
    - v₁, …, vₙ – values
- Complex value: reference, tuple, or set.
- Example: previous slide
Classes

• **Class**: set of semantically similar objects (e.g., people, students, cars, motorcycles)

• A class has:
  – **Type**: describes common structure of all objects in the class (semantically similar objects are also structurally similar)
  – **Method signatures**: declarations of the operations that can be applied to all objects in the class.
  – **Extent**: the set of all objects in the class

• Classes are organized in a class hierarchy
  – The extent of a class contains the extent of any of its subclasses

Complex Types: Intuition

• Data (relational or object) must be properly structured

• Complex data (objects) – complex types


  Its type: [SSN: String, Name: String, PhoneN: {String}, Child: {Person} ]

Complex Types: Definition

• A **type** is one of the following:
  – **Basic types**: String, Float, Integer, etc.
  – **Reference types**: user defined class names, e.g., Person, Automobile
  – **Tuple** types: [A₁; T₁, ..., Aₙ; Tₙ]
    – A₁, ..., Aₙ – distinct attribute names
    – T₁, ..., Tₙ – types
    – Eₘ [SSN: String, Child: {Person}]
  – **Set** types: {T}, where T is a type
    – Eₘ [String], {Person}

• Complex type: reference, tuple, set
Subtypes: Intuition

- A **subtype** has “more structure” than its supertype.
- Example: Student is a subtype of Person

  ```plaintext
  Person: [SSN: String, Name: String,
  Address: [StNum: Integer, StName: String]]
  Student: [SSN: String, Name: String,
  Address: [StNum: Integer, StName: String, Rm: Integer],
  Majors: {String},
  Enrolled: {Course} ]
  ```

Subtypes: Definition

- **T** is a subtype of **T'** iff **T** ≠ **T'** and
  - Reference types:
    - **T**, **T'** are reference types and **T** is a subclass of **T'**
  - Tuple types:
    - **T** = [A₁: **T**₁, ..., Aₙ: **T**ₙ, ..., An+1: **T**ₙ+1]
    - **T'** = [A₁: **T’₁**, ..., Aₙ: **T’ₙ**, ...
      are tuple types and for each i=1,...,n, either **T**ᵢ = **T’ᵢ** or **T**ᵢ is a subtype of **T’ᵢ**
  - Set types:
    - **T** = {**T**₀} and **T’** = {**T’₀**} are set types and **T**₀ is a subtype of **T’₀**

Domain of a Type

- domain(**T**) is the set of all objects that conform to type **T**. Namely:
  - domain(Integer) = set of all integers,
  - domain(String) = set of all strings, etc.
  - domain(**T**), where **T** is reference type is the extent of **T**, i.e., oids of all objects in class **T**
  - domain([A₁: **T**₁, ..., Aₙ: **T**ₙ]) is the set of all tuple values of the form [v₁, ..., vₙ], where each vᵢ ∈ domain(**T**ᵢ)
  - domain({**T**}) is the set of all finite sets of the form {w₁, ..., wₙ}, where each wᵢ ∈ domain(**T**]}
Database Schema

- For each class includes:
  - Type
  - Method signatures. E.g., the following signature could be in class `Course`:
    ```
    Boolean enroll(Student)
    ```
- The subclass relationship
- The integrity constraints (keys, foreign keys, etc.)

Database Instance

- *Set of extents* for each class in the schema
- Each object in the extent of a class must have the type of that class, i.e., it must belong to the domain of the type
- Each object in the database must have *unique oid*
- The extents must satisfy the constraints of the database schema

Object-Relational Data Model

- A straightforward subset of CODM: only tuple types at the top level
- More precisely:
  - Set of classes, where each class has a tuple type (the types of the tuple component can be anything)
  - Each tuple is an object of the form (oid, tuple-value)
- Pure relational data model:
  - Each class (relation) has a tuple type, but
  - The types of tuple components must be primitive
  - Oids are not explicitly part of the model – tuples are pure values
Objects in SQL:1999 & SQL:2003

- Object-relational extension of SQL-92
- Includes the legacy relational model
- SQL:1999 & 2003 database = a finite set of relations
- relation = a set of tuples (extends legacy relations) or a set of objects (completely new)
- object = (oid, tuple-value)
- tuple = tuple-value
- tuple-value = [Attr₁: v₁, ..., Attrₙ: vₙ]

SQL:1999 & 2003 Tuple Values

- Tuple value: [Attr₁: v₁, ..., Attrₙ: vₙ]
  - Attrᵢ are all distinct attributes
  - Each vᵢ is one of these:
    - Primitive value: a constant of type CHAR(...), INTEGER, FLOAT, and BOOLEAN
    - Reference value: an object Id
    - A tuple value
    - A collection value: Created using the MULTISET construct

Row Types

- The same as the original (legacy) relational tuple type. However:
  - Row types can now be the types of the individual attributes in a tuple
  - In the legacy relational model, tuples could occur only as top-level types

CREATE TABLE PERSON (
  Name CHAR(20),
  Address ROW(Number INTEGER, Street CHAR(20), ZIP CHAR(5))
)
Row Types (Contd.)

- Use path expressions to refer to the components of row types:
  ```sql
  SELECT P.Name
  FROM PERSON P
  WHERE P.Address.ZIP = '11794'
  ```

- Update operations:
  ```sql
  UPDATE PERSON
  SET Address.ZIP = '66666'
  WHERE Address.ZIP = '55555'
  UPDATE PERSON
  SET Address = ROW(21, 'Main St', '12345') AND Name = 'J. Public'
  ```

User Defined Types (UDT)

- UDTs allow specification of complex objects/tuples, methods, and their implementation
- Like ROW types, UDTs can be types of individual attributes in tuples
- UDTs can be much more complex than ROW types (even disregarding the methods): the components of UDTs do not need to be elementary types

A UDT Example

```sql
CREATE TYPE PersonType AS (
  Name CHAR(20),
  Address ROW(Number INTEGER, Street CHAR(20), ZIP CHAR(5))
);
CREATE TYPE StudentType UNDER PersonType AS (
  Id INTEGER,
  Status CHAR(2)
);
METHOD award_degree() RETURNS BOOLEAN;
CREATE METHOD award_degree() FOR StudentType
  LANGUAGE C
  EXTERNAL NAME 'file:/home/admin/award_degree';
```
Using UDTs in CREATE TABLE

• As an attribute type:

```sql
CREATE TABLE TRANSCRIPT (  
  Student StudentType,  
  CrsCode CHAR(6),  
  Semester CHAR(6),  
  Grade CHAR(1)  
)  
```

• As a table type:

```sql
CREATE TABLE STUDENT OF StudentType;  
```

Such a table is called typed table.

Objects

• Only typed tables contain objects (i.e., tuples with oids)
• Compare:

```sql
CREATE TABLE STUDENT OF StudentType;  
and  
CREATE TABLE STUDENT1 (  
  Name CHAR(20),  
  Address ROW(Number INTEGER, Street CHAR(20), ZIP CHAR(5)),  
  Id INTEGER,  
  Status CHAR(2)  
)  
```

• Both contain tuples of exactly the same structure
• Only the tuples in STUDENT—not STUDENT1—have oids
• Will see later how to reference objects, create them, etc.

Querying UDTs

• Nothing special – just use path expressions

```sql
SELECT T.Student.Name, T.Grade  
FROM TRANSCRIPT T  
WHERE T.Student.Address.Street = 'Main St.'  
```

Note: T.Student has the type StudentType. The attribute Name is not declared explicitly in StudentType, but is inherited from PersonType.
Updating User-Defined Types

• Inserting a record into TRANSCRIPT:

  INSERT INTO TRANSCRIPT(Student, Course, Semester, Grade)
  VALUES (????, 'CS308', '2000', 'A')

The type of the Student attribute is StudentType. How does one insert a value of this type (in place of ???)?

Further complication: the UDT StudentType is encapsulated, i.e., it is accessible only through public methods, which we did not define.

Do it through the observer and mutator methods provided by the DBMS automatically.

Observer Methods

• For each attribute \( A \) of type \( T \) in a UDT, an SQL:1999 & 2003 DBMS is supposed to supply an observer method, \( A(\cdot) : T \), which returns the value of \( A \) (the notation \( \cdot \) means that the method takes no arguments).

• Observer methods for StudentType:
  - \( \text{Id}(\cdot) : \text{INTEGER} \)
  - \( \text{Name}(\cdot) : \text{CHAR}(20) \)
  - \( \text{Status}(\cdot) : \text{CHAR}(2) \)
  - \( \text{Address}(\cdot) : \text{ROW}((\text{INTEGER}, \text{CHAR}(20), \text{CHAR}(5))) \)

• For example, in

  SELECT T.StudentName, T.Grade
  FROM TRANSCRIPT T
  WHERE T.Student.Address.Street = 'Main St.'

  \( \text{Name} \) and \( \text{Address} \) are observer methods, since T.Student is of type StudentType.

Note: Grade is not an observer, because TRANSCRIPT is not part of a UDT, but this is a conceptual distinction – syntactically there is no difference.

Mutator Methods

• An SQL:1999 DBMS is supposed to supply, for each attribute \( A \) of type \( T \) in a UDT \( U \), a mutator method

  \( A : T \to U \)

  For any object \( o \) of type \( U \), it takes a value \( t \) of type \( T \) and replaces the old value of \( o.A \) with \( t \); it returns the new value of the object. Thus, \( o.A(t) \) is an object of type \( U \).

• Mutators for StudentType:
  - \( \text{Id} : \text{INTEGER} \to \text{StudentType} \)
  - \( \text{Name} : \text{CHAR}(20) \to \text{StudentType} \)
  - \( \text{Address} : \text{ROW}((\text{INTEGER}, \text{CHAR}(20), \text{CHAR}(5))) \to \text{StudentType} \)
Example: Inserting a UDT Value

```
INSERT INTO TRANSCRIPT(Student,Course,Semester,Grade)
VALUES (NEW StudentType(Add11111111,Status'G5',Name'Joe Public'),
        'CS532',
        'S2002',
        'A')
```

'CS532', 'S2002', 'A' are primitive values for the attributes Course, Semester, Grade

Example: Changing a UDT Value

```
UPDATE TRANSCRIPT
SET Student = Student.Address(ROW(21,'Maple St.','12345'),
      Name'John Smith'),
    Grade = 'B'
WHERE Student.Id = 111111111 AND CrsCode = 'CS532' AND Semester = 'S2002'
```

- Mutators are used to change the values of the attributes Address and Name

Referencing Objects

- Consider again
  ```
  CREATE TABLE TRANSCRIPT ( 
      Student StudentType, 
      CrsCode CHAR(6), 
      Semester CHAR(6), 
      Grade CHAR(1) 
  )
  ```

- **Problem:** TRANSCRIPT records for the same student refer to distinct values of type StudentType (even though the contents of these values may be the same) – a maintenance/consistency problem

- **Solution:** use self-referencing column (next slide)
  - Bad design, which distinguishes objects from their references
  - Not truly object-oriented
Self-Referencing Column

- Every typed table has a **self-referencing column**
  - Normally invisible
  - Contains explicit object Id for each tuple in the table
  - Can be given an explicit name – the only way to enable referencing of objects

```
CREATE TABLE STUDENT2 OF StudentType
  REF STUDENT2.id;
```

Self-referencing columns can be used in queries just like regular columns.

Reference Types and Self-Referencing Columns

- To reference objects, use self-referencing columns + reference types: `REF(some-UDT)`

```
CREATE TABLE TRANSCRIPT1 (Student REF StudentType) SCOPE STUDENT2.
```

- Two issues:
  - How does one query the attributes of a reference type
  - How does one provide values for the attributes of type `REF(…)`
    - Remember: you can’t manufacture these values out of thin air – they are oids!

Querying Reference Types

- Recall: `Student REF(StudentType) SCOPE STUDENT2` in `TRANSCRIPT1`

How does one access, for example, student names?

- SQL:1999 has the same misfeature as C/C++ has (and which Java and OQL do not have): it distinguishes between objects and references to objects. To pass through a boundary of `REF(…)` use “/” instead of “.”

```
SELECT T.Student.Name, T.Grade
FROM TRANSCRIPT1 T
WHERE T.Student.Address.Street = "Main St.";
```
Inserting REF Values

• How does one give values to REF attributes, like Student in TRANSCRIPT1?
  • Use explicit self-referencing columns, like stud_oid in STUDENT2
• Example: Creating a TRANSCRIPT1 record whose Student attribute has an object reference to an object in STUDENT2:

```sql
INSERT INTO TRANSCRIPT1(Student, Course, Semester, Grade)
SELECT S.stud_oid, 'HIS666', 'F1462', 'D'
FROM STUDENT2 S
WHERE S.Id = '111111111'
```

Collection Data Types

• The lack of Set data type severely cripples the object-oriented capabilities of SQL:1999. However, sets will likely be added during the next update of SQL. Sets will look something like the following:

```sql
CREATE TYPE StudentType UNDER PersonType AS (
  Id INTEGER,
  Status CHAR(2),
  Enrolled REF(CourseType) MultiSet Scope COURSE
)
```

• For each student, list the Id, street, and the courses in which the student is enrolled:

```sql
SELECT S.Id, S.Address, C.Name
FROM STUDENT S, COURSE C
WHERE C.CrsCode IN (SELECT E.CrsCode
                      FROM S.Enrolled E)
```

• Note: E is bound to a set of object references, so E.CrsCode is also a set
The ODMG Standard

- ODMG 3.0 was released in 2000
- Includes the data model (more or less)
- **ODL**: The object definition language (DDL)
- **OQL**: The object query language (SQL)
- A transaction specification mechanism
- **Language bindings**: How to access an ODMG database from C++, Smalltalk, and Java (expect C# to be added to the mix)

The Structure of an ODMG Application

**Main Idea**: *Host Language = Data Language*

- Objects in the host language are mapped directly to database objects
- Some objects in the host program are **persistent**. Think of them as “proxies” of the actual database objects. Changing such objects (through an assignment to an instance variable or with a method application) directly and transparently affects the corresponding database object
- Accessing an object using its oid causes an “object fault” similar to pagefaults in operating systems. This transparently brings the object into the memory and the program works with it as if it were a regular object defined, for example, in the host Java program
SQL Databases vs. ODMG

- **In SQL**: Host program accesses the database by sending SQL queries to it (using JDBC, ODBC, Embedded SQL, etc.)
- **In ODMG**: Host program works with database objects directly
- ODMG has the facility to send OQL queries to the database, but this is viewed as an impedance mismatch evil doer, a misfeature

ODL: ODMG’s Object Definition Language

- Is rarely used, if at all!
  - *Relational databases*: SQL is the only way to describe data to the DB
  - *ODMG databases*: can do this directly in the host language
  - Why bother to develop ODL then?
- Problem: Making database objects created by applications written in different languages (C++, Java, Smalltalk) interoperable
  - Object modeling capabilities of C++, Java, Smalltalk are very different.
  - How can a Java application access database objects created with C++?
- *Hence*: Need a reference data model, a common target to which to map the language bindings of the different host languages
  - ODMG says: Applications in language A can access objects created by applications in language B if these objects map into a subset of ODL supported by language A
ODMG Data Model

- Classes + inheritance hierarchy + types
- Two kinds of classes: "ODMG classes" and "ODMG interfaces", similarly to Java
  - An ODMG interface:
    - has no attributes or method code – only signatures
    - does not have its own objects – only the objects that belong to the interface’s ODMG subclasses
    - cannot inherit from (be a subclass of) an ODMG class – only from another ODMG interface (in fact, from multiple such interfaces)
  - An ODMG class:
    - can have attributes, methods with code, own objects
    - can inherit from (be a subclass of) other ODMG classes or interfaces
      - can have at most one immediate superclass (but multiple immediate super-interfaces)

ODMG Data Model (Cont.)

- Distinguishes between objects and pure values (which are called literals)
  - Both can have complex internal structure, but only objects have oids

Example

```java
interface PersonInterface: Object {
  // Object is the ODMG topmost interface
  String Name();
  String SSN();
}

class PERSON: PersonInterface {
  // inherits from ODMG interface
  extent PersonExt: PersonInterface;
  keys SSN, (Name, PhoneN); // note: extent have names

  attribute ADDRESS Address;

  relationship PERSON Spouse; // note: relationship vs attribute

  void add_phone_number(in String phone); // method signature
}

struct ADDRESS { // a literal type (for pure values)
  String SNumber;
  String SName;
}
```


More on the ODMG Data Model

- Can specify keys (also foreign keys – later)
- Class extents have their own names – this is what is used in queries
  - As if relations had their own names, distinct from the corresponding tables
- Distinguishes between relationships and attributes
  - Attribute values are literals
  - Relationship values are objects
  - ODMG relationships have little to do with relationships in the E-R model – do not confuse them!

Example (contd.)

```java
class STUDENT extends PERSON {
    ( extent StudentExt )
    attribute Set<String> Major;
    relationship Set<COURSE> Enrolled;
}
```

- STUDENT is a subclass of PERSON (both are classes, unlike the previous example)
- At most one immediate superclass
- No name overloading: a method with a given name and signature cannot be inherited from more than one place (a superclass or super-interface)

Referential Integrity

```java
class STUDENT extends PERSON {
    ( extent StudentExt )
    attribute Set<String> Major;
    relationship Set<COURSE> Enrolled;
}
class COURSE: Object {
    ( extent CourseExt )
    attribute Integer CrsCode;
    attribute String Department;
    relationship Set<STUDENT> Enrollment;
}
```

- Referential integrity: If JoePublic takes CS532, and CS532 ∈ JoePublic.Enrolled, then deleting the object for CS532 will delete it from the set JoePublic.Enrolled
- Still, the following is possible:
  - CS532 ∈ JoePublic.Enrolled but JoePublic & CS532.Enrollment
- Question: Can the DBMS automatically maintain consistency between JoePublic.Enrolled and CS532.Enrollment?
Referential Integrity (Contd.)

Solution:

class STUDENT extends PERSON {
  (extent StudentExt)
  attribute Set<String> Major;
  relationship Set<COURSE> Enrolled;
  inverse COURSE::Enrollment;
}
class COURSE: Object {
  (extent CourseExt)
  attribute Integer CrsCode;
  attribute String Department;
  relationship Set<STUDENT> Enrollment;
  inverse STUDENT::Enrolled;
}

OQL: The ODMG Query Language

• Declarative
• SQL-like, but better
• Can be used in the interactive mode
  • Very few vendors support that
• Can be used as embedded language in a host language
  • This is how it is usually used
  • Brings back the impedance mismatch

Example: Simple OQL Query

SELECT DISTINCT S.Address
FROM PersonExt S
WHERE S.Name = “Smith”

• Can hardly tell if this is OQL or SQL
• Note: Uses the name of the extent of class PERSON, not the name of the class
Example: A Query with Method Invocation

- Method in the SELECT clause:
  ```sql
  SELECT M.frameRange(100, 1000)
  FROM MOVIE M
  WHERE M.Name = "The Simpsons"
  ```

- Method with a side effect:
  ```sql
  SELECT S.add_phone_number("555-1212")
  FROM PersonExt S
  WHERE S.SSN = "123-45-6789"
  ```

OQL Path Expressions

- Path expressions can be used with attributes:
  ```sql
  SELECT DISTINCT S.Address.StName
  FROM PersonExt S
  WHERE S.Name = "Smith"
  ```

- As well as with relationships:
  ```sql
  SELECT DISTINCT S.Spouse.Name()
  FROM PersonExt S
  WHERE S.Name = "Smith"
  ```

Path Expressions (Contd.)

- Must be type consistent: the type of each prefix of a path expression must be consistent with the method/attribute/relationship that follows
- For instance, if S is bound to a PERSON object, then S.Address.StName and S.Spouse.Name() are type consistent:
  - PERSON objects have attribute Address and relationship Spouse
  - S.Address is a literal of type ADDRESS; it has an attribute StName
  - S.Spouse is an object of type PERSON; it has a method Name(), which is inherited from PersonInterface
Path Expressions (Contd.)

- Is \( P \text{ Child} \text{ Child} \text{ PhoneN} \) type consistent (\( P \) is bound to a \textit{PERSON} objects)?
  - In some query languages, but not in OQL!
- \textbf{Issue}: Is \( P \text{ Child} \) a single set-object or a set of objects?
  - If it is a set of \textit{PERSON} objects, we can apply \text{Child} to each such object and \( P \text{ Child} \text{ Child} \) makes sense (as a set of grandchild \textit{PERSON} objects)
  - If it is a single set-object of type Set<\textit{PERSON}>, then \( P \text{ Child} \text{ Child} \) does not make sense, because such objects do not have the \text{Child} relationship
- OQL uses the second option. Can we still get the phone numbers of grandchildren?
  - Must flatten out the sets:
    $$\text{flatten}(\text{flatten}(P \text{ Child} \text{ Child} \text{ Phone}))$$
  - A bad design decision. We will see in Chapter 17 that XML query languages use option 1.

Nested Queries

- As in SQL, nested OQL queries can occur in
  - The FROM clause, for virtual ranges of variables
  - The WHERE clause, for complex query conditions
- In OQL, nested subqueries can occur in SELECT, too!
  - Do nested subqueries in SELECT make sense in SQL?

What does the next query do?

```sql
SELECT struct{ name: S.Name,
                courses: (SELECT E
                           FROM S.Enrolled E
                           WHERE E.Department = "CS")}
FROM StudentExt S
```

Aggregation and Grouping

- The usual aggregate functions \textit{avg}, \textit{sum}, \textit{count}, \textit{min}, \textit{max}
- In general, do not need the \texttt{GROUP BY} operator, because we can use nested queries in the \texttt{SELECT} clause.
  - For example: Find all students along with the number of Computer Science courses each student is enrolled in

```sql
SELECT name: S.Name,
       count: count(SELECT E.CrsCode
                     FROM S.Enrolled E
                     WHERE E.Department = "CS")
FROM StudentExt S
```
Aggregation and Grouping (Contd.)

• GROUP BY/HAVING exists, but does not increase the expressiveness power (unlike SQL):

```sql
SELECT S.Name, count(E.CrsCode)
FROM StudentExt S, S.Enrolled E
WHERE E.Department = "CS"
GROUP BY S.SSN
```

Same effect, but the optimizer can use it as a hint.

GROUP BY as an Optimizer Hint

```sql
SELECT S.Name, count(E.CrsCode)
FROM StudentExt S, S.Enrolled E
WHERE E.Department = "CS"
GROUP BY S.SSN
```

The query optimizer would compute the inner query for each student, so `Enrolled` will be computed for each s. If enrollment information is stored separately (not as part of the STUDENT Object), then given s, an index is likely to be used to find the corresponding courses. Can be expensive, if the index is not clustered.

The query optimizer can recognize that it needs to find all courses for each student. It can then sort the enrollment file on student oids (thereby grouping courses around students) and then compute the result in one scan of that sorted file.

ODMG Language Bindings

• A set of interfaces and class definitions that allow host programs to:
  – Map host language classes to database classes in ODL
  – Access objects in those database classes by direct manipulation of the mapped host language objects

• Querying
  – Some querying can be done by simply applying the methods supplied with the database classes
  – A more powerful method is to send OQL queries to the database using a statement-level interface (which makes impedance mismatch)
Java Bindings: Simple Example

```java
public class STUDENT extends PERSON {
    public DSet Major;
    ...
}
```

- **DSet class**
  - part of ODMG Java binding, extends Java Set class
  - defined because Java Set class cannot adequately replace ODL’s Set

```java
STUDENT X;
X.Major.add("CS");
...
```

*add* is a method of class DSet (a modified Java’s method). If *X* is bound to a persistent STUDENT object, the above Java statement will change that object in the database.

Language Bindings: Thorny Issues

- **Host as a data manipulation language is a powerful idea, but:**
  - Some ODMG/ODL facilities do not exist in some or all host languages
  - Result is the lack of syntactic and conceptual unity

- **Some issues:**
  - Specification of persistence (which objects persist, i.e., are automatically stored in the database by the DBMS, and which are transient)
    - First, a class must be declared persistence capable (differently in different languages)
    - Second, to actually make an object of a persistence-capable class persistent, different facilities are used
      - In C++, a special form of *new* is used
      - In Java, the method `makePersistent()` (defined in the ODMG-Java interface `Database`) is used
  - Representation of relationships
    - Java binding does not support them; C++ and Smalltalk bindings do
  - Representation of literals
    - Java & Smalltalk bindings do not support them; C++ class

Java Bindings: Extended Example

- **The OQLQuery class:**
  ```java
class OQLQuery |
    public OQLQuery(String query), if the query constructor
    public bind(Object parameter), if explained later
    public Object execute(); if it executes queries
    ...
    several more methods ...
  |
  Constructor: `OQLQuery("SELECT ...")`
  - Creates a query object
  - The query string can have placeholders $1$, $2$, etc., like the `?` placeholders in Dynamic SQL, JDBC, ODBC (Why?)
Extended Example (Cont.)

- Courses taken exclusively by CS students in Spring 2002:

  ```java
  DSet students, courses;
  String semester;
  OQLQuery query1, query2;
  query1 = new OQLQuery("SELECT S FROM STUDENT S " + "WHERE "CS" IN S.Major");
  students = (DSet) query1.execute();
  query2 = new OQLQuery("SELECT T FROM COURSE T " + "WHERE T.Enrollment.subsetOf($1) " + "AND T.Semester = $2");
  semester = new String("S2002");
  query2.bind(students); // bind $1 to the value of the variable students
  query2.bind(semester);  // bind $2 to the value of the variable semester
  courses = (DSet) query2.execute();
  ```

Interface DCollection

- Allows queries (select) from collections of database objects
- DSet inherits from DCollection, so, for example, the methods of DCollection can be applied to variables courses, students (previous slide)

```java
public interface DCollection extends java.util.Collection {
  public DCollection query(String condition);
  public Object selectElement(String condition);
  public Boolean existsElement(String condition);
  public java.util.Iterator select(String condition);
}
```

Extended Example (Cont.)

- query(condition) – selects a subcollection of objects that satisfy condition:
  ```java
  DSet seminars;
  seminars = (DSet) courses.query("this.Credits = 1");
  ```
- select(condition) – like query( ), but creates an iterator; can now scan the selected subcollection object-by-object:
  ```java
  java.util.Iterator seminars;
  seminars = new java.util.Iterator select("this.Credits = 1");
  while (seminars.next()) {
    ... ...
  }
  ```
CORBA:
Common Object Request Broker Architecture

- Distributed environment for clients to access objects on various servers
- Provides location transparency for distributed computational resources
- Analogous to remote procedure call (RPC) and remote method invocation in Java (RMI) in that all three can invoke remote code.
- But CORBA is more general and defines many more protocols (eg, for object persistence, querying, etc.). In fact, RMI is implemented using CORBA in Java 2

Interface Description Language (IDL)

- Specifies interfaces only (ie, classes without extents, attributes, etc.)
- No constraints or collection types

```idl
// File Library.idl
module Library {  
    interface myLibrary {  
      string searchByKeywords(in string keywords);  
      string searchByAuthorTitle(in string author, in string title);  
    }  
}  
```

Object Request Broker (ORB)

- Sits between clients and servers
- Identifies the actual server for each method call and dispatches the call to that server
- Objects can be implemented in different languages and reside on dissimilar OSs/machines, so ORB converts the calls according to the concrete language/OS/machine conventions
ORB Server Side

- Library.idl ➔ IDL Compiler ➔ Library-stubs.c, Library-skeleton.c ➔ Method signatures to interface repository

- **Server skeleton:** Library-skeleton.c
  - Requests come to the server in OS/language/machine independent way
  - Server objects are implemented in some concrete language, deployed on a concrete OS and machine
  - Server skeleton maps OS/language/machine independent requests to calls understood by the concrete implementation of the objects on the server

- **Object adaptor:** How does ORB know which server can handle which method calls? — Object adaptor, a part of ORB
  - When a server starts, it registers itself with the ORB object adaptor
  - Tells which method calls in which interfaces it can handle. (Recall that method signature for all interfaces are recorded in the interface repository).

- **Implementation repository:** remembers which server implements which methods/interfaces (the object adaptor stores this info when a server registers)

ORB Client Side

- **Static invocation:** used when the application knows which exactly method/interface it needs to call to get the needed service

- **Dynamic invocation:** an application might need to figure out what method to call by querying the interface repository
  - For instance, an application that searches community libraries, where each library provides different methods 
    for searches with different capabilities. For instance, some might allow search by title/author, while others by keywords. Method names, argument semantics, even the number of arguments might be different in each case

Static Invocation

- **Client stub:** Library-stubs.c
  - For static invocation only, when the method/interface to call is known
  - Converts OS/language/machine specific client’s method call into the OS/language/machine independent format in which the request is delivered over the network
    - This conversion is called marshalling of arguments
    - Needed because client and server can be deployed on different OS/machine/etc.
  - Consider: 32-bit machines vs. 64-bit, little-endian vs. big endian, different representation for data structures (eg, strings)
    - Recall: the machine-independent request is unmarshalled on the server side by the server skeleton
  - Conversion is done transparently for the programmer — the programmer simply links the stub with the client program
Dynamic Invocation

- Used when the exact method calls are not known
- Example: Library search service
  - Several community libraries provide CORBA objects for searching their book holdings
  - New libraries can join (or be temporarily or permanently down)
  - Each library has its own legacy system, which is wrapped in CORBA objects. While the wrappers might follow the same conventions, the search capabilities of different libraries might be different (e.g., by keywords, by wildcards, by title, by author, by a combination thereof)
  - User fills out a Web form, unaware of what kind of search the different libraries support
  - The user-side search application should
    • take advantage of newly joined libraries, even with different search capabilities
    • continue to function even if some library servers are down

Dynamic Invocation (Contd.)

- Example: IDL module with different search capabilities
  module Library {
    interface library1 {
      string searchByKeywords(in string keywords);
      string searchByAuthorTitle(in string author, in string title);
    }
    interface library2 {
      void searchByTitle(in string title, out string result);
      void searchByWildcard(in string wildcard, out string result);
    }
  }
  The client application:
  • Examines the fields in the form filled out by the user
  • Examines the interface repository – next slide
  • Decides which methods it can call with which arguments
  • Constructs the actual call – next slide

Dynamic Invocation API

- Provides methods to query the interface repository
- Provides methods to construct machine-independent requests to be passed along to the server by the ORB
- Once the application knows which method/interface to call with which arguments, it constructs a request, which includes:
  - Object reference (which object to invoke)
  - Operation name (which method in which interface to call)
  - Argument descriptors (argument names, types, values)
  - Exception handling info
  - Additional “context” info, which is not part of the method arguments
- Note: The client stub is essentially a piece of code that uses the dynamic invocation API to create the above requests, Thus:
  • With static invocation, the stub is created automatically by the IDL compiler
  • With dynamic invocation, the programmer has to manually write the code to create and invoke the requests, because the requisite information is not available at compile time
Interoperability within CORBA

- ORB allows objects to talk to each other if they are registered with that ORB; can objects registered with different ORBs talk to each other?

- General inter-ORB protocol (GIOP): message format for requesting services from objects that live under the control of a different ORB
  - Often implemented using TCP/IP
  - Internet inter-ORB protocol (IIOP) specifies how GIOP messages are encoded for delivery via TCP/IP
CORBA Services

- Rich infrastructure on top of basic CORBA
- Some services support database-like functions:
  - Persistence services – how to store CORBA objects in a database or some other data store
  - Object query services – how to query persistent CORBA objects
  - Transaction services – how to make CORBA applications atomic (either execute them to the end or undo all changes)
  - Concurrency control services – how to request/release locks. In this way, applications can implement transaction isolation policies, such as two-phase commit

Persistent State Services (PSS)

- PSS – a standard way for data stores (eg, databases, file systems) to define interfaces that can be used by CORBA clients to manipulate the objects in that data store
- On the server:
  - Objects are in storage homes (eg, classes)
  - Storage homes are grouped in data stores (eg, databases)
- On the client:
  - Persistent objects (from the data store) are represented using storage object proxies
  - Storage object proxies are organized into storage home proxies
- Clients manipulate storage object proxies directly, like ODMG applications do
Object Query Services (OQS)

- OQS makes it possible to query persistent CORBA objects
- Supports SQL and OQL
- Does two things:
  - Query evaluator: Takes a query (from the client) and translates it into the query appropriate for the data store at hand (e.g., a file system does not support SQL, so the query evaluator might have quite some work to do)
  - Query collection service: Processes the query result.
    - Creates an object of type collection, which contain references to the objects in the query result
    - Provides an iterator object to let the application to process each object in the result one by one

Transaction and Concurrency Services

- **Transactional services:**
  - Allow threads to become transactions. Provide
    - `begin()`
    - `rollback()`
    - `commit()`
  - Implement two-phase commit protocol to ensure atomicity of distributed transactions
- **Concurrency control services:**
  - Allow transactional threads to request and release locks
  - Implement two-phase locking
  - Only supports – does not enforce – isolation. Other, non-transactional CORBA applications can violate serializability