7. Intro to Object-Oriented Classes

Now that you have a basic understanding of standard types, variables, and functions, and how to organize a multi-module program, we will venture forth into advanced types. Advanced types are programmer defined, and usually aggregate (sometimes called composite) types. By this I mean that YOU will be able to specify the details of a new type, each instance of which is possibly made up of several standard types. For instance, a string of characters, or a university's student record (e.g. name, address, phone number).

Readings:

- Chapter 4 [Savitch2001]
- It is optional, if you understand the lectures, whether you read Chapter 5. The same material is taught in my lectures the way I like (e.g. static functions and static attributes, overloading, constructors, design info hiding). Some of these topics will definitely be on the midterm. I would encourage you to read Chapter 5 (except 5.6-5.8), though I would not say it is a requirement if you fully understand this section of the lecture notes. But if you are struggling with the material in this course, there is no substitute for seeing more code and more source code explanations like that in Chapter 5.0-5.5.
- Chapter 5.6-5.8 are relevant for good students, or those going on in Computing Science, or will be covered much later in the course.

7.1 Structure/Records

The C and C++ programming languages have an aggregate/composite ’structure’ type. Pascal has something similar called RECORD. Java does NOT have structures. However, I want to introduce structures to you so that you can see why Java and C++ have the class construct, and why C++ doesn’t really need structures, and Java even have have structures.

Structures are way of allowing programmers to define a new kind of type, and give it a type name of the programmer’s own choosing! Thus our programming will not just be confined to the primitive types like int, float, etc. For example, we could define a new **composite** type called ‘Student’ which had record fields ***within it*** for name, address, phone number, date of birth. Once you have a new type name, you can create many variables of that new type (just like creating many variables of type int). e.g.

```
Student student1;
Student graduatingStudent;
```

Each variable is called an ‘**instance**’ of the type.

The nice thing about structures is that:

- they can hold several ***different*** types of fields (e.g. name string, integer age) in one composite container (i.e. in one composite variable; think of it like an ice cube tray.).
- they can be assigned from one to another as a whole. This is easy in Pascal/C++, and possible but not as direct in Java. In C++:

```
graduatingStudent = student1   //C++
```

Note that we do not have to assign the various parts of student1 (e.g. name, address, phone, age), each individually, to graduatingStudent. We can treat student records as a whole.

Structures are the first step on the road of encapsulation and abstraction: putting things together that belong together, and be able to treat the composite as a whole. Often a client programmer can treat structures as a whole without needing or wanting to know their internal details. Client programmers are those who use composites types defined and programmed by other programmers. (Do you really need to know how System.out works as long as it does its job?)

7.1.1 Example of Struct

Here is how you declare a new, *programmer-defined* structure type called AirPosition in C++. You use the keyword **struct**, create your own name for the type, and in braces {} specify the list of elements you want in your new type.

```
struct AirPosition{        //C++
  double latitude;
  double longitude;
  long altitude;
};
```

It is convention to name user defined types to begin with an upper case letter!

Note why the individual record fields have their own names: If a structure contains two data attributes of the same type, we must have a field/attribute name for each so that we can later specify which one we may want to assign to or from (if we want to mess with the individual parts of the structure). In Pascal these would be called (record) 'field names'. In C++ they are called structure or class 'data members' or 'member attributes', or just 'attributes' (as in the attributes of a student).

For those unfamiliar with geographic position terms, latitude is a measure of the angle north or south of the equator. Let us assume the south pole has a latitude of -90 degrees. Longitude is a measure of East-West position relative to Greenwich, England.

Here is how you can use a structure in C++.

```
AirPosition pos1, pos2;

pos1.latitude = -23.;
pos1.longitude = 49.5;
pos1.altitude = 35000;

pos2 = pos1;         //C++ only.

int height = pos1.altitude;

//Here is how you do output in C++.
cout  << pos2.latitute
      << pos2.longitude
      << pos2.altitude;
```

That is all there is to structures. You define as many instances of AirPosition as you need. You use the so-called '**dot operator'** to 'reach' into a structure to either set or access the individual record fields. Assignment of a whole structure instance is possible in C++ and most languages because the three fields are stored adjacent to one and other in RAM, and the compiler just arranges to have the whole section of RAM occupied by the source record instance copied to pos2's record location.

One thing that doesn't work is outputting a structure instance as a whole:

```
cout << pos2;    // <--does not work!
```

This is because the compiler doesn't know which of the many possible ways you might like the output presented:

- -123   49.5   35000
- -123, 49.5, 35000
- (-123, 49.5, 35000)
- -123 deg. longitude, 49.50000 deg. latitude, 35000 feet

There are 3 ways to handle this:

1) As shown above, specify the attributes separately in a compound output statement.
2) Write a print function that prints the individual attributes one of a time, then call that function any time you need the record printed.
3) In C++ only, overload '<< ' with a new meaning to handle AirPositions (not possible in Java).

7.2 Modules as Abstract Types

Since we find it nice to put all the attributes of a record together into one entity, it is interesting to ask the question where do we put the functions that are particularly related to the record?

It is very good program design to put all the stuff that is related (e.g. attributes and functions) together. This is for a number of reasons:

- Humans like the simplicity of working with abstract concepts that are cohesive (belong together) and encapsulated (located together). This applies to the functions that go with new programmer defined composite types. Programmers begin to think of the attributes and functions together as a whole entity, just like we began to think of Student and AirPosition as whole 'things'.
- Putting such program elements together is good, because if we have to change something about the way we programmed AirPositions, it would be nice if the attributes and functions are all in one single source code module/file, rather than scattered about several 100,000 lines of code in 100s of source code files.
- It turns out that such program entities are very good intermediate level building blocks with which to construct programs. Though we may in future maintenance need to add an attribute to a Student entity, or change or add a function that deals with students, it is unlikely that we will need to rip a student module apart, or join two together.

This is because the ‘Student type’ ***is fundamental to*** our University Registration system, and the Airplane type is fundamental to an airline computer application.

So how do we provide functions that can be put together with the structure? Java does not have structures/records, at least not in the way that C++ and PASCAL have them. However, in Java and almost any other language you can define both variables and functions in one source code file. Here is a crude way to do it using static attributes and static functions;

```
class AirPosition{

  static double latitude;
  static double longitude;
  static long altitude;

  static void drop(int dropHt){
    altitude = altitude - dropHt;
  }

  static void climb(int climbIncr){
    altitude = altitude + climbIncr;
  }

  static void initialize(
                   double lat,
                   double myLong,
                   long alt){
    latitude = lat;
    longitude = myLong;
    altitude = alt;
  }

}
```

So here we have a useful source code module. We can do lots of things with it. From another Java main program class module, we could do this:

```
public MyMainClass {

  public static void main(String[] args){

    AirPosition.latitude = 135.;

    AirPosition.longitude = 23.;

    AirPosition.altitude = 40000;

    AirPosition.drop(1000);

    AirPosition.climb(5000);

    long height = AirPosition.altitude;

    System.out.println(AirPosition.altitude);

    AirPosition.initialize(50.38, 23.5, 29000);

    System.out.println(
      AirPosition.latitude + " " +
      AirPosition.longitude + " " +
      AirPosition.altitude);
  }
}
```

Notice that from MyMainClass, you have to specify the name of the Airposition class and a dot ‘.’ before each use of a static variable or static function in another class. The reason for this is that the class MyMainClass may ***also*** have a static variable called altitude, and you need to differentiate between the one within MyMainClass and the one within AirPosition!

Notice from MyMainClass how we can set the AirPosition static attributes, how we can call functions within the AirPosition class that operate on the AirPosition static attributes, and how we can get the values of the AirPosition attributes for use in other computations within MyMainClass, or output them from MyMainClass. This is the essense of cohesion and encapsulation, where AirPosition provides a nice set of attributes and functions for some programming problem.

An important aspect of static variables, is that because they are outside of all functions, they can be used by all the functions in the AirPosition class. One AirPosition function can leave a value in an AirPosition static variable that can later be picked up and used by another AirPosition function, or even later by the same function invoked again. In addition, if we have not labelled the AirPosition static variables ’private’ (to be discussed later), even functions in other classes like MyMainClass can access AirPosition’s static variables. Note: It is not considered wise to have all variables publicly usable to other classes and we will discuss this later in the course.

Also notice how you define and call a function with multiple parameters. Just separate the parameters with commas. The formal arguments that you pass in the function call can be literals, variables, or expressions. There must be exactly the correct number of parameters and each must be of the correct type (or at least be assignment compatible with the formal parameters in the function definition). At the start of the function call, the first argument is copied to the first formal parameter, the second argument is copied to the second formal parameter, etc.

Also, you might notice how in the AirPosition initialize( ) function definition that we can copy the incoming parameters to the static attributes. Obviously, your formal parameters have to have different names than the static attributes or else the compiler will not understand which you are referring two at any particular point in the initialize( ) function.

7.3 A Conceptual Problem

Now we have a problem. What if we need two AirPositions in our main program? And what if we wanted to assign one air position to another.

If we were programming in C++ or Pascal, we would just create an AirPosStruct structure type within the AirPosition source code module, and allow the main program to create multiple instances of it.

In addition, we could modify the AirPosition class functions to have member functions parameter lists like:

```
static void drop(int dropHt,
          AirPosStruct & position){

  position.altitude =
         position.altitude - dropHt;
}
```

Now MyMainClass could create hundreds of AirPosition structures, and have the AirPosition class functions operate on it in any way necessary. e.g.

```
AirPosStruct pos1, pos2;
pos1.altitude = 5000;
AirPosition.drop(1000, pos1);
```

I have been a little sneaky here. The ’&’ character in the formal parameter list has special meaning. It tells C++ not to pass a copy of a structure, but just to pass a reference to (i.e. the address of) the actual argument to the function when it is called. This prevents the need to wastefully make a copy of the structure at the start of the call, modify it in the drop function, and make a copy of the result to be returned to the calling program. Passing by reference allow the compiler to set things up so the called function can reach back into the caller’s memory and manipulate the parameter remotely. Java has a similar mechanism, however it is not optional like the ’&’ is in C++. In fact, the **only** way to pass an record object to a function in Java is ’by reference’.

C++ doesn’t need structures because it has a better mechanism, called object classes. However, because the older C language had structures, they were retained in C++ because for the most part you can compile C programs with a C++ compiler. So structures were retained in C++ for backwards compatibility.

However, Java is a completely new language. Though it looks a little bit like C++, the Java language designers had a clean slate when they designed Java. So they didn’t bother with structures since a class can do anything that a structure can, and more.

7.4 Classes

A class is a concept from so-called ’object-oriented’ programming languages. The word ’class’ has the same meaning as a ’type’. It is a classification of variables that are all the same. Like the classification all ’int’ variables. Or the classification all ’Student’ variables. Or all ’AirPosition’ variables.

So these English terms are equivalent in computing science:

class = = type

instance = = variable

A class has 4 major parts:

1) static attributes shared by every function in the class.
2) static functions shared by every function in the class.
3) instance attributes, which provide a template by which we can make any structure-like instances.
4) instance functions, which provide the programmer with the illusion that each structure instance has particular functions that are available with it.

Instance functions makes the instances seem alive, because they can respond to function calls.

So, this is like a flock of sheep. There is the shepherd’s memory (like a memory of how many sheep are in the flock), and the shepherd's ability to react to requests. There is also zero, one, or many sheep in the flock. Each has a memory (e.g. the instance attributes), and each sheep can respond to stimuli (e.g. you shear all the wool off the sheep and he will say "Baaaah").

I admit this is not a great analogy, but I have not found a better one that is better, more visual, and easy to understand. In many textbooks, there are mistakes made about object-oriented classes. They don't make clear that:

- one of the nice thing about static methods is that they are always there, even if the flock has no sheep in it currently (i.e. even if you have not created any variables of type sheep). This is why they are called static!
- Most textbooks also WRONGLY state that the static member functions cannot call instance member functions. This is completely wrong. If a shepherd can find a sheep, then he can get it to respond to some function invoking stimuli (e.g. kick it and it will say "baaaah"). All that the shepherd needs to know is the name of a sheep variable.

Though this is a crazy analogy, it is particularly vivid in alleviating some gross misconceptions about classes.

So now let's look at a class:

```
public class AirPos{
  //---------------------------
  //shepherd attribute(s).
  static int population = 0;

  //---------------------------
  //shepherd function(s).
  static AirPos newAirPos(){
    population = population + 1;
    return new AirPos();
  }

  //--------------------------
  //sheep/instance attributes.
  double latitude;
  double longitude;
  long altitude;

  //--------------------------
  //sheep/instance functions.
  void drop(int dropHt){
    altitude = altitude - dropHt;
  }

  void climb(int climbIncr){
    altitude = altitude + climbIncr;
  }

  void initialize(double lat,
           double myLong,long alt){
    latitude = lat;
    longitude = myLong;
    altitude = alt;
  }
}
```

Notice the 4 standard parts in this class definition.

The static attribute ’population’ is an example of a class’s shepherd-like memory. It is there all the time, I’ve initialized it at the beginning of the program to zero, and every time another program module calls the function newAirPos( ), the population variable is automatically incremented. Well, not automatically --- the programmer wrote that static function to do that.

The second executable statement within the function newAirPos( ) illustrates how you get Java to use the template for new sheep memory to create a new sheep instance. A reference to the newly created sheep is returned to the calling program.

An AirPos variable (i.e. instance) is basically a structure composed of three attributes:

```
  double latitude;
  double longitude;
  long altitude;
```

Notice these to NOT have the static keyword on them. This means they are instance attributes and these three statements provide the template for manufacturing new variables of class (i.e. type classification) ’AirPos’! This is like a template for making extra sheep where each sheep has latitude, longitude, and altitude variables in its memory. It tells the compiler how many bytes of RAM are needed for each new AirPos

variable, and what types and names the attribute fields will have.

Finally, see that there are three instance functions. They are instance functions because they do not have the keyword static on them. This means they are only directly usable from an existing AirPos instance (i.e. a particular sheep).

Ok, let’s see how a class is used in a program.

```
public class MyProgClass {

  public static void main(String[] args){

    AirPos pos1, pos2;

    pos1 = AirPos.newAirPos( );

    pos1.latitude = 135.;

    pos1.longitude = 23.;

    pos1.altitude = 40000;

    pos1.drop(1000);

    pos1.climb(5000);

    long height = pos1.altitude;

    System.out.println(pos1.altitude);

    pos2 = AirPos.newAirPos( );

    pos2.initialize(50.38, 23.5, 29000);

    System.out.println(
      pos2.latitude + " " +
      pos2.longitude + " " +
      pos2.altitude);

    System.out.println(AirPos.population);
  }
}
```

Obviously we need to discuss this.

Notice:

- We can create one, two, or thousands of AirPos instances (i.e. sheep).
- However, they are not really created yet. Defining an instance of type AirPos only reserves room in RAM for a pointer (called a ’reference’ in Java) to an actual sheep. Unlike other programming languages, in Java, every object instance variable does NOT actually contain the instance data itself.
- To actually get an instance created, we need to use the ’new’ operator as shown inside the newAirPos() static function I wrote. I will show you how to simplify this later. This operator returns a reference to (i.e. the address of some memory for) a new instance. This is in turn returned to my main function and assigned to the waiting reference variable called pos1 (which is exactly the kind of variable needed to hold a pointer to an AirPos instance).
- I can set any non-private attributes of the instance. However, note that I use pos1.latitude rather than (as I did previously) AirPos.latitude. I have to do this because there are actually two AirPos references in my main program file, pos1 and pos2. **I have to specify which _*one*_ I am wanting to set the latitude of!**
- I can also get and use the value of any non-private attribute of any instance by using the particular instance name, a dot, and the attribute name.

- I can have an object manipulate itself and do ANYTHING else its instance function is programmed to do, by invoking an instance function. Instead of prefixing the function name with a class name and dot, I now have to specify an instance name. **This is because the function invocation needs to contain not only the name of the function and its parameters, but also _which_ particular instance needs to be told to drop altitude**.

  This is sort of like the function signature we had back in the Section 8.3 that looked like:

  ```
  AirPosition.drop(1000, pos1);
  ```

  Compare that with:

  ```
  pos1.drop(1000);
  ```

  All the information is available in the latter more compact form, at least if you assume that pos1 knows the class of object that it is pointing too (and Java assures that it does). So although it looks like each instance has its own drop( ) function, we do not wastefully duplicate it dozens of times for perhaps dozens of AirPos instances. Instead, Java, and all object oriented languages, just make it look like it does. Behind the scenes, Java just has one drop( ) function usable by all the AirPos instances, and passes one extra but hidden parameter containing the instance reference to the function. This allows humans to write programs that allow us to feel like we are telling reactive object instances to do some particular function. This is the basis of 'object-orientation': that a program is the sum of a bunch of

  reactive software entities that send messages (i.e. function calls) back and forth to each other to get the job (i.e. user command) done.

- Finally, at the bottom of the main function, you can see that I can get a printout of the current population of AirPos objects by accessing the population static variable in the normal way.

I don't want to give the impression that the static parts of a class are necessarily supervisory like a shepherd is of a flock of sheep. Sometimes the static member functions are not even present if all you need are instances and instance functions. However, the static part of a class often has supervisory kinds of roles. It may keep track of population, it may keep track of where each sheep is, it may keep track of what file the sheep are perhaps being written too, etc.

So now you know why the main function of every program is static. It is static, so that it is present when the program starts up and there aren't any sheep yet to call upon. Also it is static because we only need one main function, not one for each sheep we create.

So you can think of a class as 1+N reactive software entities: the shepherd memory and functions, and the memory and functions of N sheep you have created. Each sheep has the exact same attribute field _types_ and functional behaviour. However, a sheep's attribute values may be different than its neighbor's. That's what makes each sheep different (other than the name of its reference). And those attribute value differences may cause it to behave slightly differently when one of its functions is called, because the instance functions uses that particular sheep's attribute values when executing (e.g. if (myAge > 2) then die!). This is why we sort of think of object instances as having intelligence: They have the ability to make decisions about how they respond to function calls. They also have self-awareness, because they know their own attribute values and also can react differently to a function call depending on its own particular attribute values.

Read the above paragraph again as it is VERY IMPORTANT!

7.5 Appendix - Object Orientation

This rest of this lecture is an appendix containing multiple subsections of an introduction to object orientation, to object-oriented analysis (OOA), and one very nice technique for object-oriented design (OOD).

Read this Section as far as you can. If you are a beginner and become too confused, you should stop reading. If you are an advanced student, you will find this appendix an amazingly enlightening introduction to software engineering object-oriented analysis and design!

7.5.1 Software Engineering Phases

Most projects have several phases. Software projects normally have:

- An analysis phase to gather and record the requirements,
- A design phase to plan the architecture and implementation strategies to be used, and
- An implementation phase where code is written.
- A quality assurance aspect. Final quality of the product is assured by actions taken throughout the project. e.g.
  - requirements, design, and code reviews,
  - unit and system testing, and
  - appropriate configuration management.

Approximately 15% of projects fail or are cancelled, usually because of failure to do some these aspects of the project properly.

7.5.2 What Is Object-Orientation?

Often there are specialists who work on each aspect of a large project. Object orientation means something different to each of them:

- To business system analysts it means determining and focusing on the business entities (e.g. sales item, customer, invoice, etc.) about which information must be processed or recorded. This pre-dates object-oriented languages.
- To a software designer, it is the architectural view that a system satisfies each external command by the set of actions resulting from the trace of calls or messages sent among various reactive software objects to implement that request.
- To a programmer, it usually means programming language syntax that allows the programmer to easily:
    - view data as having reactive abilities, and
    - re-use code via inheritance hierarchies, and
    - have both type flexibility and ease of maintenance via polymorphism.

7.6 Object Modeling

7.6.1 Introduction to Modeling in General

A model is a representation of a actual thing. To a child, a model is something created which is a ‘smaller’ but adequate likeness of the real thing. To a car dealer, a model is a bunch of cars which are near identical (cf. object ‘class’). In systems analysis, a model captures the essential nature of something by indicating the essential details that need to be stored about things of that ‘class’, or by illustrating the flow of stuff required through a system, or by specifying the sequential ordering (e.g. making paper in a pulp mill, getting a university degree) within a process, etc.

Definition: A model is an alternate representation with an ‘adequate likeness’ of the real thing.

Some of the alternate representations we in systems design may use for the actual things are:

- a diagram or picture
- a form or computer record
- a process description, data flow diagram, or finite state machine

The purpose of creating a model is to represent <u>only the essential characteristics</u> of the thing so that:

- we may understand and clearly document the nature of the thing,
- we may store the essence of the thing for later retrieval,
- we may communicate the nature of the thing to someone else,
- they can think and/or reason about the correctness of the model without:
    - being distracted by the complexities of the complete real thing (i.e. abstraction)
    - having to travel to where the real thing is located
    - having to see the function of a real thing while it is operating very fast

- we needn't waste space storing useless information about the thing,
- we may write a program to implement a system which allows humans to better administrate the processes in which the thing participates.

7.6.2 Entities vs. Objects

The data that a system needs to store is mainly computer records of the instances of various record types in the application domain (e.g. orders, customers). Traditionally in information systems analysis, these things were called **entities**. Each entity class has a record/structure type with a different layout of attribute fields. Order instances have order ID number, part ID designator, and quantity of order fields. Customer records have name, address, and phone number record fields.

More recently, is has instead become popular to call domain entities **objects**. The term 'objects' has an additional implied meaning that the model of the object we are documenting contains data **plus reactive abilities** (i.e. plus 'functions', or 'operations', 'behavior', 'ability to control things', 'intelligence', 'liveliness'(e.g. can be sent messages or 'activated')).

In fact, this idea is carried even further by OO languages. **Rather than procedures having data parameters, instead object data is regarded as having operations/procedures that can be triggered by a message.** In fact, individual ***instance*** records (not just ADT modules) are regarded as having procedures.

e.g. Instead of (in C):

```
struct CustomerType custRecord;
printRec(custRecord, theFastPrinter);
```

You do this (in C++):

```
CustomerType custInstance;
custInstance.print(theFastPrinter);
```

Notice this is not like C, nor like Modula-2 where you would have done ModuleName.print(). The symbolic name to the left of the

dot is a **variable name** (i.e. instance), *not* a module or class/type name. The procedure now appears to be a field of the instance, as if the instance 'has/owns' its procedures!

7.6.3 Object Data Analysis

In object data analysis, we try to determine an organized way of diagramming and storing information about the various *relevant* object types involved in the application domain. To a new analyst, sometimes it is not immediately apparent what kinds of data might need to be modeled. Examples of the object classes needed to be modeled within an application might be:

- a physical object (e.g. person, aircraft, robot, printer).
- an incident or transaction that needs to be recorded either for immediate use, for transmission to someone else, or for a historical log (e.g. order, purchase, sale, boarding an airplane, graduation, marriage, phone call). Note a purchase is from the purchaser's application's point of view, while a sale is from the seller's. Interactions between two other objects sometimes fall in this category.
- a role (e.g. student, client, customer, manager, spouse).
- an intangible concept (e.g. bank account, time delay, date, sound recording),
- a place (e.g. parking space, warehouse #3, the 13th floor heat control),
- a relationship (e.g. customer's sales representative, a flight's captain),
- a structure - e.g. the list of an airplane's component part numbers (body, wings, engines, tail), possibly even a hierarchy.
- an organization or organizational unit (e.g. university, department, corporation, submarine crew, sports team).
- a displayable field (e.g. string, icon, image) or printed report, or an I/O signal

- Specifications or procedures- e.g. organic compound or recipe.

7.6.4 Object Attributes and Attribute Values

We use the terms 'object class' to mean group of instances of things which have the same set of attribute names (e.g. car's each have a licence number, color, and weight), but which have different values for each of those characteristics (this is what makes the instances of the same class different from each other).

It is common for a class of entity instances to be modeled as a table of fixed length records:

STUDENT TABLE

student-id	student-name	student-address	student-phone	high-school
93010-1234	Smith, Bill	123 Second St.	420-1234	Mt. Douglas
92010-4321	Jones, Jane	234 Third St.	123-4567	Burnaby
91111-1056	Able, Jim	345 Fourth Rd.	822-9876	John Oliver

This concept is in keeping with the view that a student file is a list of fixed length records.

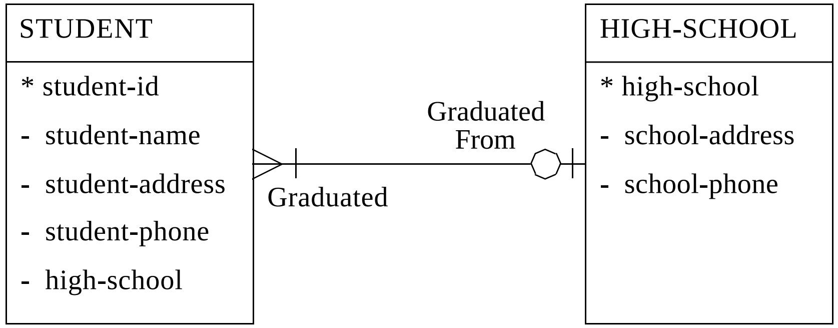
Each column represents an **attribute** of the type 'student' (i.e. a field of a student record). The legal set of values that an attribute may take on is called the **domain** of the attribute. Examples are date = (1..31), and day= (Sunday..Saturday).

Each row represents a particular **instance** of a student. Often the rows are sorted in order by a particular column or columns. That column(s) is called the **primary key**.

7.7 Object Relationship Diagrams

7.7.1 Object Icons

Let's examine an example of an Object Relationship Diagram (ORD) carefully. The one below shows two objects.

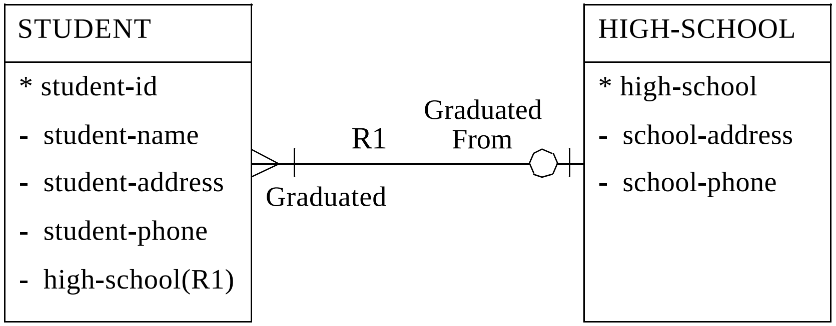


In is not clear whether they are object instances (since there titles are singular) or entity classes (since only their attribute names and not attribute values are shown). Normally in ORDs it is not really important that you differentiate between whether the boxes are classes or instances. You will probably find it ***best to think of them as generic instances*** (not having had attribute values assigned yet). i.e. they are an object storage/record layout plan.

Note that instead of having the attributes listed horizontally, as in the column titles of a table, we have the attributes listed vertically. This is widely done, though there is no reason for this except it makes the entity icons have a smaller maximum dimension. Also, note that the attribute(s) on which the records are sorted are called the **primary key** of the entity, and are labelled with a '*'.

7.7.2 Relationships

Object-Relationship Diagrams (ORDs) contain both entity classes and the ***relationships*** between them. An example of a relationship is that between a student and a high school.



Fundamentally, ***relationships are illustrations of links between entities***. These links are simply (but importantly) the referential routes that could be traversed by the application code to find other related data. Note that the high school attribute in the student class is a **foreign key** which provides the information needed to traverse R1. A foreign key is a value- or pointer-based reference to particular related instance (e.g. particular high school). Value-based foreign keys refer to the primary key of the other related (i.e. foreign) object.

ORDs provide a **map** showing **all possible** 'routes' over which the application can **navigate around the data**. For instance, given a student object, how does the application code find out the phone number of the high school she went to? Answer: Look in the High School attribute of that student to find out which high school, then find that high school record in the high school database, then look at the school-phone attribute in that record.

7.8 System Behavior

Recent methodologies suggests that you start analysis by determining an application's data model first. Even for non-database projects, this identifies early the application domain objects which will most likely **form core software elements of the eventual implementation**. In particular, the names of the important objects, their attributes, and their relationships are researched. Once this is done, we are in a better position to plan the implementation of the *behavior* of the system.

Previously, programs were regarded as a main module and subprograms which implementing an application's functionality. The newer, more object-oriented view is that a system's behavior is simply made up of the ***sum of the behaviors of the object classes and instances in the system***. The objects collaborate together during execution to get each user command done.

You can see why we had to identify the core object classes first, **as it is they what we now propose to embody with a behavioral nature**. But before we start writing code for the system's objects, we have to decide what behavior each will contribute to the whole. The next question then, is what behavior does each object class and instance need to export to the system, in order to that it satisfy it's behavioral responsibilities to the application? In the next few sub-sections of the lectures, I plan to introduce a very beautiful mechanism to synthesize the required behavior for each object class and instance.

7.8.1 Event-based Partitioning

Modern applications are event-driven in nature. Think of your personal computer; it idles for billions of instructions waiting for an event like a mouse click or a clock tick.

With this view, we will design the system by looking at how each external command or scenario-starting event is handled by the system. By looking at each external command/event one at a time, we can reduce the scope of what we have to think about at any point in the design process to handleable proportions. When writing a requirements specification for a system, it is not uncommon to first list or diagram all the sources of external commands/events that the application must interact with (e.g. keyboard, mouse, clock, network, printer, etc.). Then in more detail, you should name/list each kind of event/command that the application program is to handle from each source.

7.8.2 External Design (User Manual)

Before beginning architectural design, it is not uncommon to write a draft user manual to firm up the behavior expected of the system for each user command. This sounds weird to some people who feel the manual is written after the coding is done. But those who finish Cmpt 275 realize that:

- you can't write the code until everyone on the team knows what the program is supposed to 'look like and behave like'!
- Often this look and behavior must be approved by someone else, so rather than spending months first writing a program that is not what the customer wants, you instead spend a week writing a draft version of the user manual for customer pre-approval.

7.8.3 Use Case Scenarios

An individual command may have several steps that should be documented in the draft manual. An example sequence might be clicking a menu command, entering several pieces of data in a dialog box, then clicking OK, the application checking and saving the entered data (often different pieces in different objects), then finally telling the user that the command is done and waiting for the user to click OK again. This is called a **use case scenario**.

Later during architectural design, we must plan what part of each step of a use case scenario will be handled by which different object.

We could thus define:

- 'scenario appearance design' to be deciding how a use case would appear to a user (i.e. write the user manual), and
- 'scenario call trace design' (or 'scenario implementation design') to be deciding the internal software architecture for a use case.

7.9 Object-Oriented Architectural Design

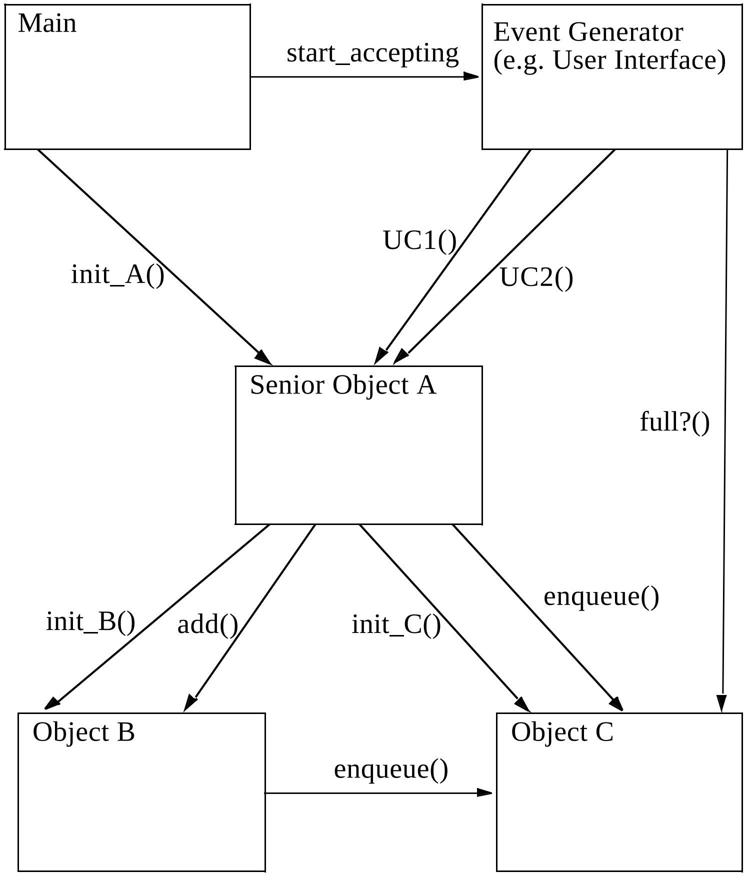
Though there are many aspects to architectural design, we will concentrate here on the design of internal call traces for the scenarios. [Rumbaugh96] states "designing the message flows is the main activity of the design phase of development".

7.9.1 Object Communication Diagrams (OCD)

It has been common for many years to sketch a diagram indicating which procedures, or more recently which modules, *call/communicate*/*interact* with which others. This provides an interaction context which provides further understanding and documentation of the purpose, responsibilities, and dependencies of a module (often one module depends on services provided by another via exported procedures).

Very recently, we have started to diagram *object* (rather than module) interactions, and thus named such diagrams Object Communication Diagrams (OCDs) or Object Interaction Diagrams. Typically, each object class in your ORD which is reactive should be put in your OCD (note: some structures which are simply data records are not reactive and needn't show in the OCD). Also, you may consider modules which are not objects (e.g. the main program or other utility modules) to be reactive objects. *The primary consideration here is that we identify* ***islands*** *of reactive ability/behavior/intelligence/data/control*. These islands (i.e. components), working together, implement the behavior of system.

Note that such a diagram is not to show 'relationships', but instead *interactions*. Two objects which have no data relationship could potentially send messages (i.e. call) each other. So an OCD is a somewhat orthogonal view of the objects in a system, and provides a kind of 2nd dimension to their definition.



Though this looks like a call structure chart, in fact the rectangles are to be regarded as components (i.e. modules or object classes) which export several differently named functions!

The main concept here is to regard and diagram the system as a collection of interacting **reactive objects**. The arrows show messages (e.g. procedure calls) from one object to another. Receiving objects should be programmed to react appropriately to each message which they receive.

7.9.2 Scenario Call Trace Design

In order to determine each reactive component's responsibilities and the operations it must export, we will examine how *each* module participates in *each* use case scenario. In order to reduce the complexity of this design step, we do this **one scenario at a time**.

In the movie industry, planning for a film segment to be shot is often done on a 'story board'. The sketches on this board provide anticipated camera shots (angles, scenery, costumes) at various moments through the progression of the scene. In essence, the user manual provides sketches of what the application will look like and do, at various points through each scenario. It is a story board. Scenario call trace design will also be done using a kind of story board. A visual plan and textural explanation of which procedure calls will be made (and why) between which objects at each point during the execution of the scenario.

Note: We could also call this scenario message trace design, because in the Smalltalk OO language, function calls are termed 'sending a message' to another object. Yet other names could be scenario implementation design, scenario event trace design, or scenario internal interaction design.

External events will be the primary driver in our design process. More specifically, a ***scenario-starting*** *external event* is a special kind of external event which initiates a *sequence* of interactions between the user and the application which carries out a use case scenario as described by the use manual. In menu-driven applications, menu selection events start most use case scenarios. The activation of a menu command results in the application receiving a message from MS-Windows. The user interface component of the application which handles these messages subsequently makes procedure calls to other application objects appropriate for the command, and these objects may in turn call other objects or modules.

If the menu command starts a long dialog with the user to enter a number of pieces of data (e.g. customer name, address, phone number) one after the other, the calls may solicit *other external* events associated with that scenario. These latter events are termed 'solicited' as the application subsequently solicits *specific* further input from the user as is needed to complete the command. The application responds to each solicited event in the appropriate way for that step of the scenario (e.g. read the data, do something with it, prompt for the next entry).

7.10 Synthesizing Object Requirements

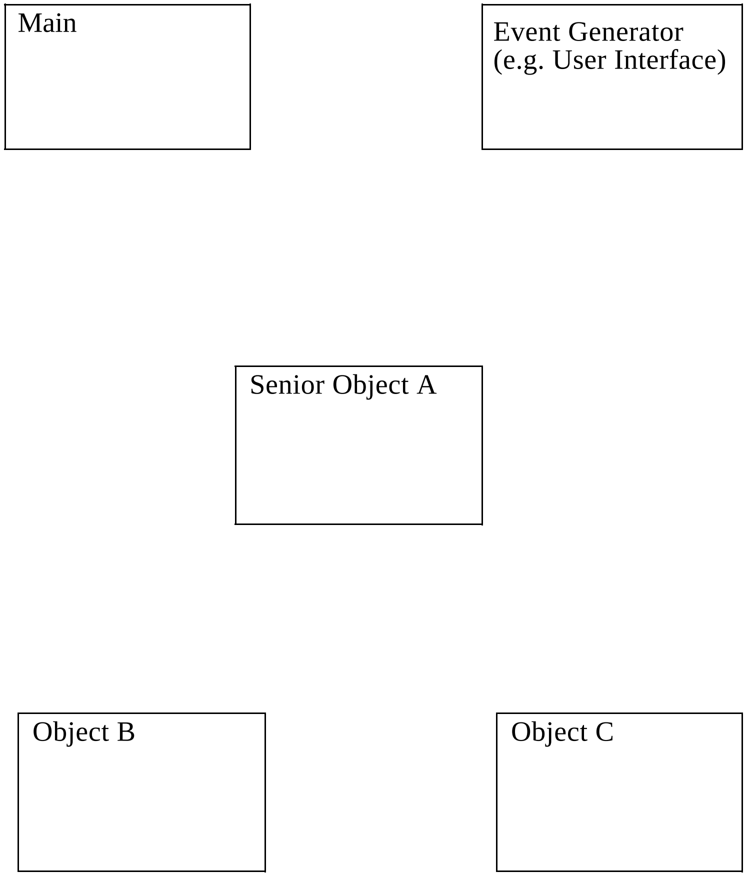
This subsection looks at a beautiful, step-by-step process by which the requirements for individual reactive components can be obtained from the overall system requirements (as embodied in the use cases).

7.10.1 Step 1 - Generate As Scenario-Starting Event List

From the user manual, generate a list of all scenario-starting external events that are required to be handled by the application. There could be dozens or hundreds in a big system.

7.10.2 Step 2 - Blank Master OCD

An Object Communication Diagram is a diagram which shows the objects from the ORD in a diagram without the relationships, and shows additional reactive components such as main, UI, and control modules. Generally, the objects are not placed in the same position on the diagram page as they were in the ORD (where they were arranged to make the relationships most tidy). Instead, place the objects in a hierarchical manner radiating away from the principle external event source (typically the user interface).

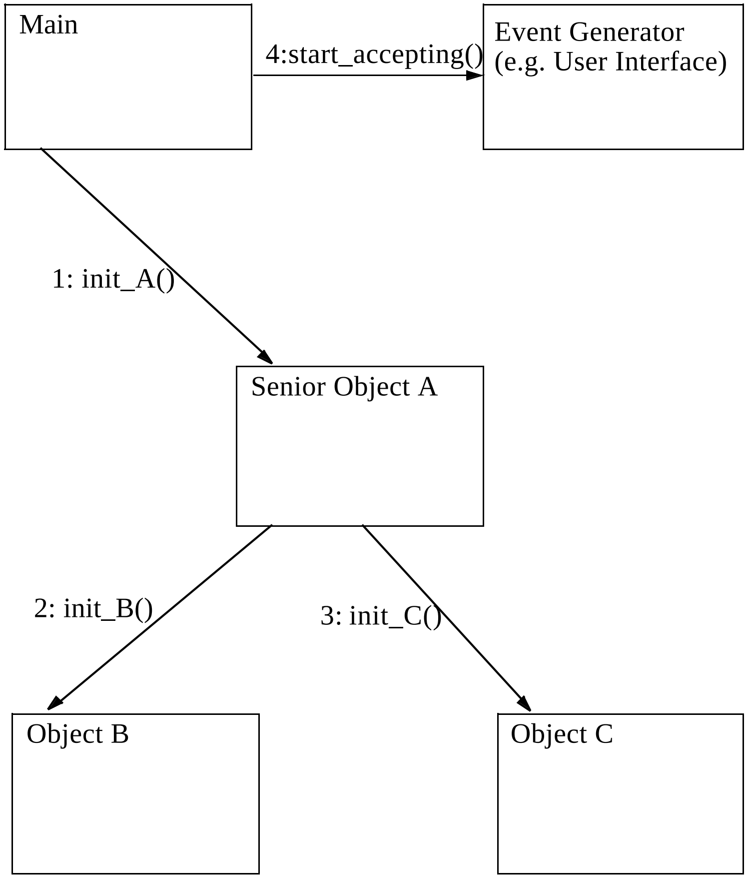


7.10.3 Step 3 - Make an Internal Call Trace for Each Scenario

Make many copies of the blank OCD diagram, one for each scenario-starting external event. For each scenario-starting event, design a trace for the anticipated calls needed to implement the proper response to that external event. (Some of the design issues which impact the choice between different trace options are discussed later). Document the trace on a single, blank OCD page. (By confining ourselves to designing one scenario's implementation at a time, we need not be distracted by arrows involved in other scenarios).

- The first scenario you should consider is the 'program start' event. This scenario should be designed to have the main module send a tree of internal initialization events (i.e. calls) to the key objects telling them to initialize (open their files, set stack to empty, etc.). The principle of low coupling dictates that the main module should not know the name of all the objects/ modules in the system, but only those directly below it. Those mid-level objects in turn send initialization messages to their subordinate objects. Any of these calls might create a number of default RAM objects as necessary for the initial functioning of the program. Once the system is initialized, the main tells the external event source components (e.g. the user interface) that they can start accepting external user events.

Start-up Implementation Call Trace



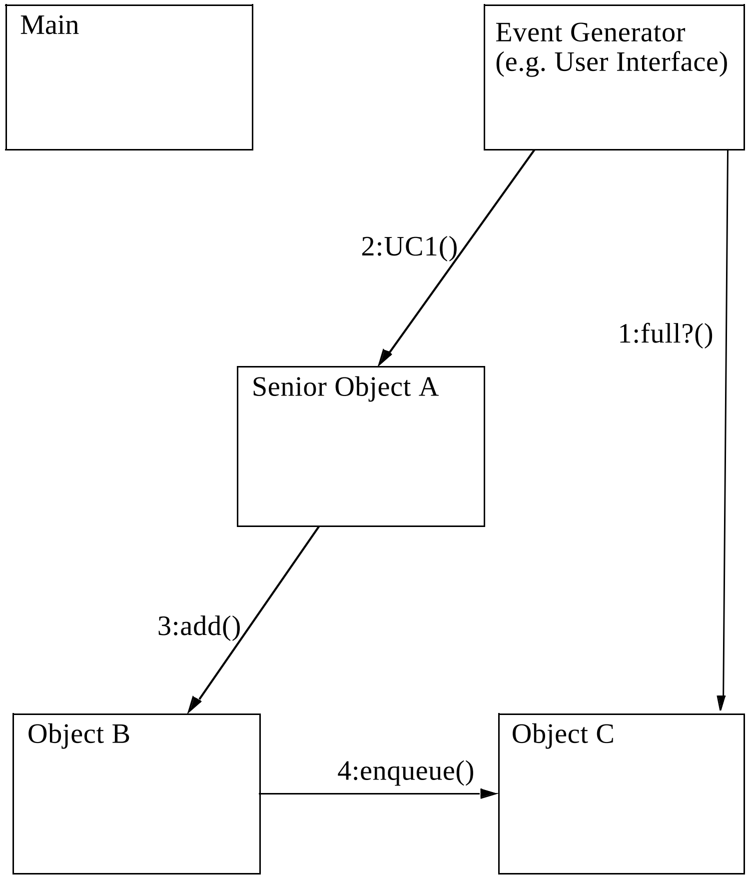
Label each message/call with a number indicating it's sequence in the execution of that scenario, and with the name of the procedure being called.

- On another diagram, for the first **external** scenario-starting event on your list, draw the trace of calls/messages that will be sent from the external interface object receiving the starting event to the principle reactive objects required to implement the response to that event. This will, in turn, sometimes cause an intermediate control/handler object to send one or more internal messages on to one or more other objects. Give each internal message a sequence number and a name which indicates what procedure is being called (or what the purpose of the message is).

  Each time you do this, you must think of **all** the internal object interactions that could take place in handling a particular external event. For instance, to register a student in a course offering, you must first check whether the course offering exists before adding a record to the association object called student-registration.

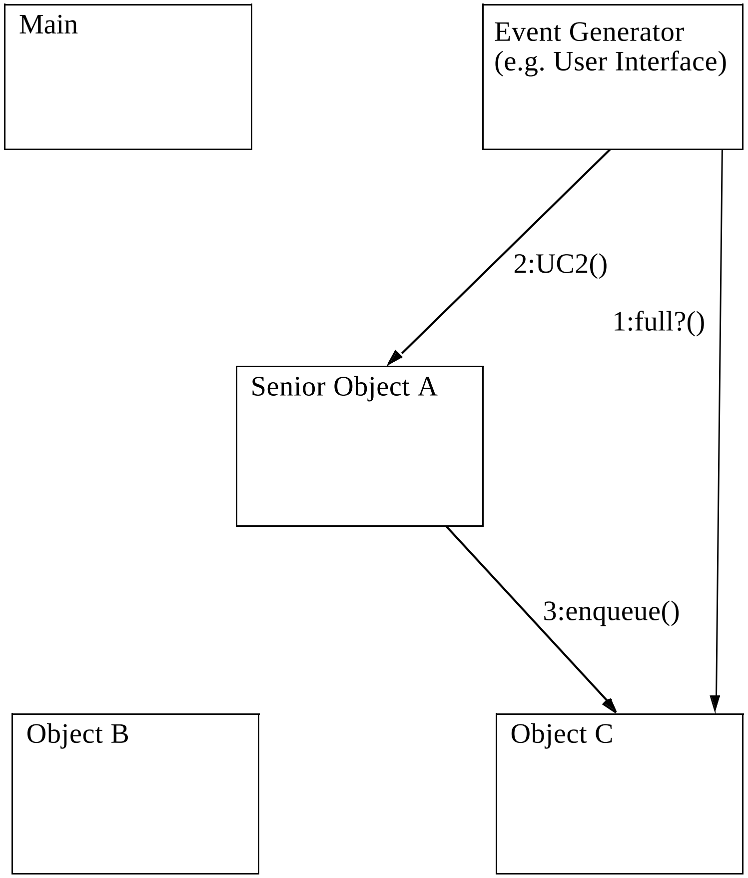
  For each diagram, it is usually necessary to document in either a paragraph, list of steps, or pseudo-code, a textural description of how the scenario is planned to be implemented. e.g. "check course exists and has space, then add student to course offering, and update available remaining course space". This provides reviewers and subsequent implementation programmers with a more understandable idea of how the scenario is to unfold.

User Command #1 Implementation Call Trace



- On a yet another diagram (see next page), do the same for the second user scenario-starting event on your list.

User Command #2 Implementation Call Trace


Main

Event Generator
(e.g. User Interface)

2:UC2()

1:full?()

Senior Object A

3:enqueue()

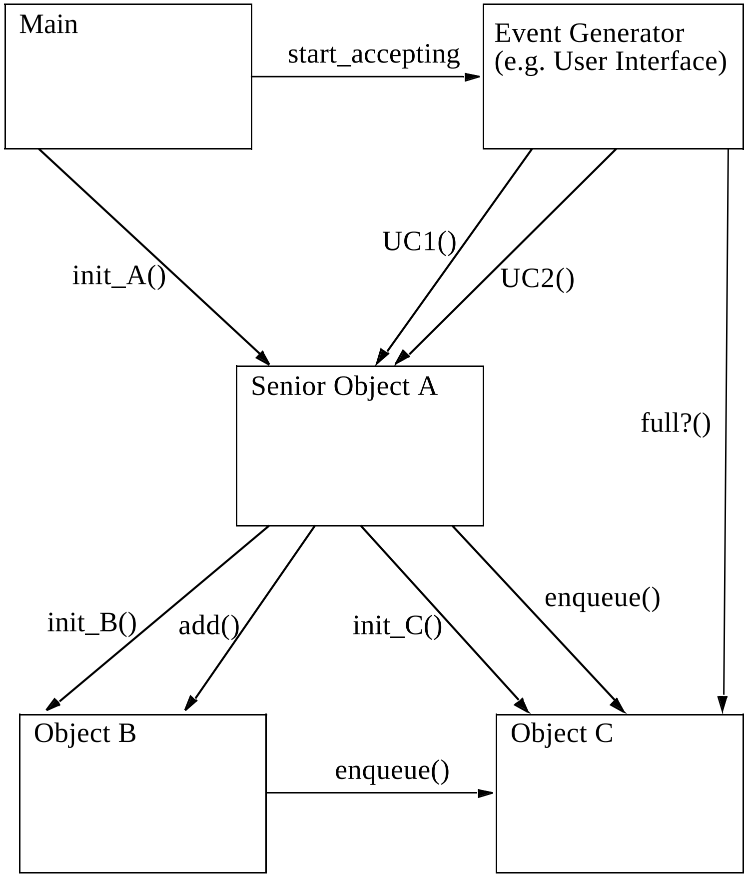
Object B

Object C

- On a last diagram, show which module(s) can initiate program shutdown, and the trace/tree of calls to the reactive components which need to be informed of the upcoming shutdown. Such components, upon being notified, shut files, flush buffers, reset the video display mode (e.g. from MS-Windows graphic mode back to DOS text mode, etc.), and delete themselves as appropriate, before the main program ends. (I have not drawn this trace to keep the resulting OCM simple).

7.10.4 Step 4 - Take the Union of All Traces

The result is the complete Object Communication Diagram:



Notice in particular how two different scenarios both had calls to the full() procedure of class Object_C. The **(first) union** operation has merged these two into one arrow in the overall OCD. All sequence numbers should be removed from the labelled arrows since with so many different scenarios shown, they no longer make sense.

The result is a fantastic diagram!

- The (first) union synthesizes an OCD from which the requirements spec for an object class can be determined. Obviously, the class must export a function for each different type of arrow entering it. e.g.
  - The UI must export start_accepting().
  - Object A must export init(), UC1(), and UC2().
  - Object B must export init_B() and add().
  - Object C must provide/export empty(), enqueue(), init_C(), and enqueue().
- Notice that the above list seems to imply Object_C should export enqueue() twice. By taking a **second union**, you can merge the two different enqueue() calls to Object_C (which are not merged by the first union because they are from different callers), into one item in the list of procedures that Object_C must export. Basically you must regard the list of exported procedures as a true ‘set’ where duplicates are not allowed.
- In addition, you get a requirements spec for each object’s **responsibilities** to call/notify other modules/objects. An object will do some internal processing when called, and then likely some interaction with other objects. *The diagram shows all the other objects that a particular object is planned to get info or processing from, or must notify in order to fulfill its responsibilities. e.g. Senior Object_A has the responsibility to notify those below it that they should initialize themselves.*

7.11 Alternative Control Architectures

The above strategy is very powerful as it constructively **synthesizes** the requirements for individual modules and object classes from an application's external requirements. This makes it an extremely appropriate technique to bridge the so called 'design gap' that exists between the end of analysis and the beginning of writing code for individual modules.

Please note that there are many alternatives in constructing the trace of a scenario. This is where the real design decisions are made. (The diagramming with a CASE tool and the double union are basically just documenting the design decisions and constructively gathering object specifications from the traces). Trace alternatives will be discussed in the next section of the course.

As with all design, there are usually several ***alternate*** ways to design a sequence of internal call events that will carry out a particular scenario. For example, when the UI receives an 'exit program' command from the user, should it send messages to all the objects telling them to shut down? Or should it call a procedure in the main module which should then tell the objects to shut down? **'Design' is choosing between workable implementation alternatives to pick the one that is most elegant, most easy to maintain, uses the least memory, and/or is best performing**.

Let us consider a simple reservation system. Generally a reservation instance is for a particular flight, sailing, or video rental instance, etc. A reservation typically is related to a particular, say, sailing via a foreign key. When dealing with user-entered data, we must use every effort to maintain referential integrity of the database. Thus before creating a reservation instance for a person on a sailing, we must check that that particular sailing actually

exists. This scenario implementation can be designed in one of three alternative ways. These three ways will be shown in the next 3 sub-sub-sections.

7.11.1 Centralized Scenario Design

In this design, a particular reactive component which both is informed when the scenario is to be initiated, and which understands the scenario to be carried out, orchestrates the execution of the scenario.

Although often not the ideal design, this component may the event generator itself (e.g. user or network interface module), in which case application scenario code (possibly unfortunately) gets added to the event generator module.

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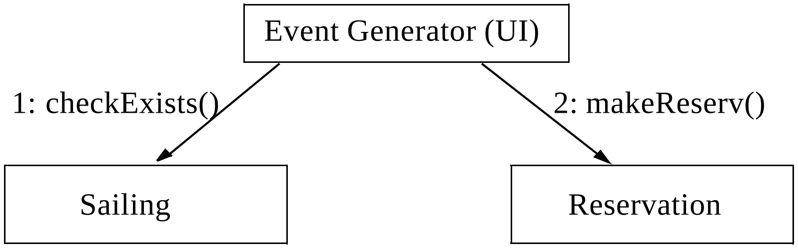
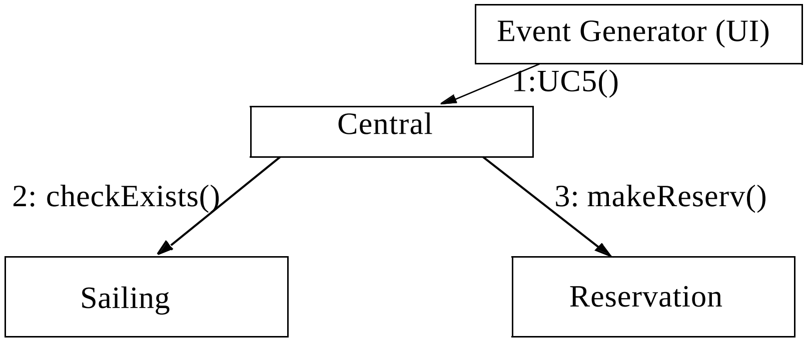


Alternatively, as shown below, an extra control module or object can instead be added whose only job is to orchestrate scenarios. It is not unusual for this module to export more than one function, one in fact for each scenario to be orchestrated in an application (or for a particular subset of scenarios in the application). The event generator is programmed to simply call the correct scenario orchestration function given the event that has just happened.



Scenario Description:

```
1) Prompt user for all info;
2) If Sailing exists
3) THEN make reservation
4) ELSE re-prompt user.
```

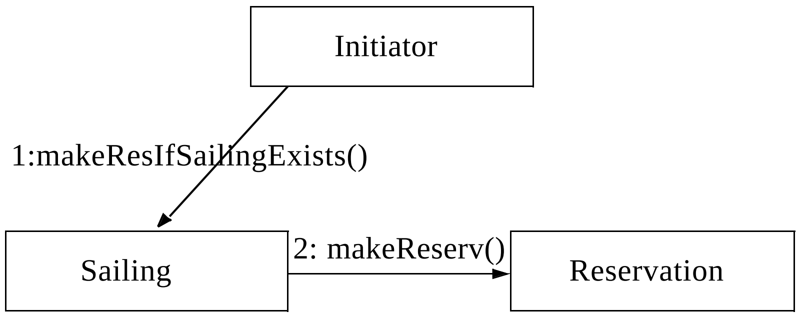
In both the above centralized schemes, the controller sends a message first to the sailing object to check that the sailing exists, *then waits for the return from that call*, then makes a call to the reservation object (supervisor/shepherd) to actually create the new reservation, the waits for that call to return. The centralized control scheme has the advantage of cohesively encapsulating in one function of one module (be it the Event Generator or a special component) the control and sequencing of internal calls needed to carry out the processing needed in the scenario. Its advantage is that if the control or sequencing of the scenario might later during maintenance need change, only one function in one module needs to be updated. Also notice that the sailing and reservation objects do not communicate with each other, and thus don't have to know about each other (this is occasionally a good design feature). On the other hand, the central object unfortunately gets coupled to all the parameter types of all the lower calls.

Notice the explanatory text or pseudo-code that can be included under a scenario trace diagram to more fully document the logic of the scenario. This pseudo-code might, for instance, indicate whether the sailing information needed from the user is read by the sailing module or by the central control module.

This pseudo-code may or may not eventually be put into any particular module. It may end up in the central module, or alternatively be spread out over several modules if either of the following designs is adopted. It is therefore not to be thought of as programming, but instead as documentation of the scenario logic from an architect's point of view, so that programmers could later implement the design properly as per the architect's specifications.

7.11.2 Roundabout Route Scenario Design

The name of this section is a Tront’ism and is not widely used terminology. The idea is that control is passed from the initiator (i.e. event generator) to the first module which must supply preliminary checking or data, and then that module forwards the request to the final object. The control thus travels a rather roundabout path to the terminal object. When the makeReserv() procedure is done, it returns control to the Sailing, which in turn returns from the makeResIfSailingExits() to the initiator.



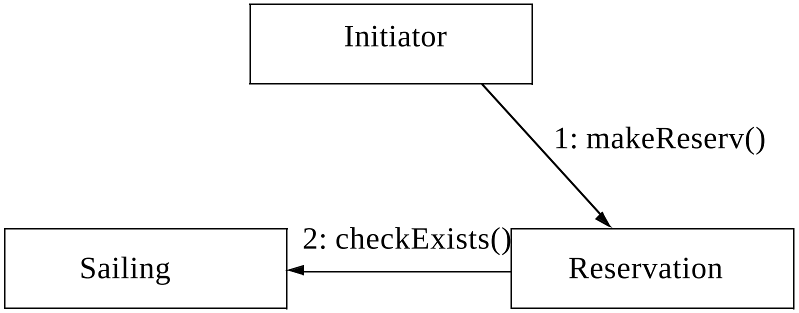
Scenario Description:

1) Ask Sailing if it exists, and if so
2) THEN have it make reservation
3) ELSE have it return an exception to
the initiator which will then
re-prompt the user.

This design strategy is particularly good if using asynchronous one-way messages, rather than procedures calls, as it requires no data to be returned to callers.

7.11.3 Principle Object-based Scenario Design

This design alternative has the initiator first informing the principle application object involved, in our case the reservation object. After that, the principle object (which may understand its creation needs best) does whatever is necessary to accomplish the request. In the example below, the reservation checks the sailing exists, waits for the reply, then if ok makes a new instance of its type, and then finally returns control to the initiator object.



Scenario Description:

1) Ask reservation to make an instance
2) It checks if Sailing exist.
If so reservation makes an instance,
3) ELSE return exception to initiator.

Note that these diagrams do not show the procedure returns, but this design requires an OK to be returned to the reservation via a parameter/return value. Either that, or if using one way messages, a return message would have to be added to the trace.