Principles of Programming Languages

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1.1 Introduction to data types

A *data type* is a classification of the kind of data that can be held by a variable. Examples include numeral types (such as integers, or real numbers), and boolean types (can only assume the values of true or false). Every programming language has data types and ways of combining and abstracting them. For any data type, we are concerned with:

1. The values of the type.
2. The operations on that type.
3. How the values are represented.

Data types can be *simple* or *composite*. Examples of simple data types include booleans, numerals, or symbols (sequences of characters). An example composite data type is the list (see Chapter 2: *Lists I*).

1.2 Data types in Prolog

Prolog's single data type is the *term*. A term can be an *atom* (begins with a lower-case letter), a *number* (can be an integer or a float), a *variable* (begins with an upper-case letter), or a *compound term* (composed of an atom called a *functor* and a number of arguments

which are themselves terms).

For example, consider the binary (of order 2) relation *likes* over the set of all people. One such instance would be *Noodles likes Deborah.* Using words is just one example we can express relations. We can re-write this instance in Prolog syntax as `likes(noodles, deborah).` Note a) the lack of capitalization, and b) the period at the end. The sentence is a proposition that we consider to be true and we refer to it as a *fact* (see next section). The compound term `likes(noodles, deborah).` includes the functor `likes` and the arguments `noodles` and `deborah` which are separated by commas and enclosed in a pair of round brackets. The number of arguments of a compound term is called the *arity* of the term.

1.3 Facts

We will use a running example to express the meaning and constraints of data as well as to construct queries over their representation in order to obtain information. A Prolog program consists of *assertions* (*clauses*). These are divided into *facts* and *rules.* Facts are propositions which are taken to be true. We will discuss rules in a subsequent section.

We will start with a discussion about family trees. Consider an example family genealogy tree shown in Figure 1.1. The clause

```
parent(peter, daphne) :- true.
```

can be simplified to

```
parent(peter, daphne).
```

and can read as "Peter is a parent of Daphne." The proposition can be regarded as an instance of the binary predicate *parent(X, Y)* and is obtained by substituting *Peter* for *X* and *Daphne* for *Y.*

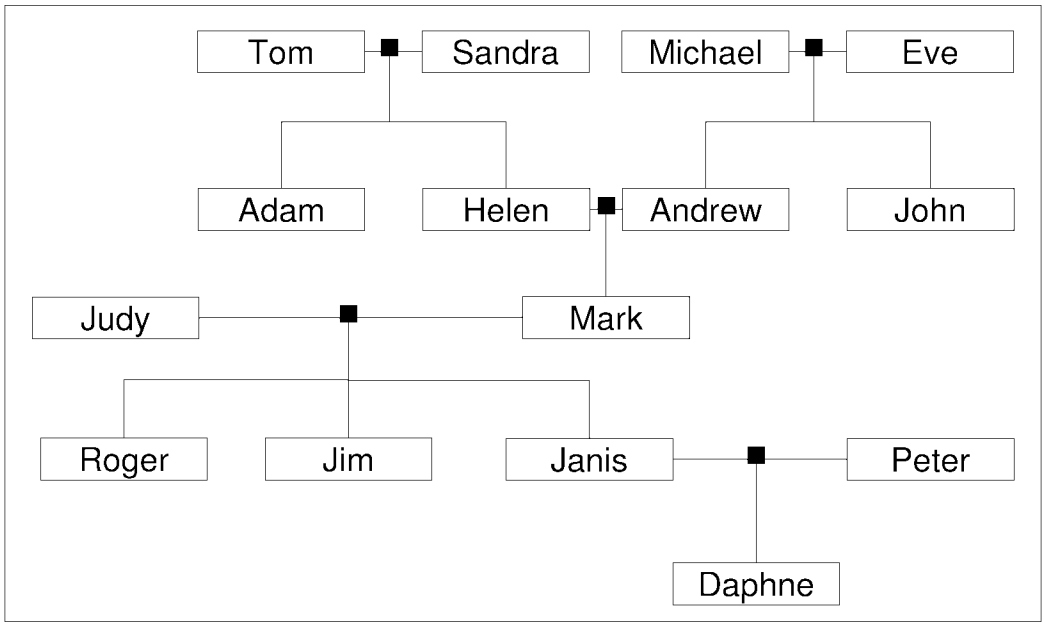

Figure 1.1: An example family genealogy tree.

1.4 Procedures

A procedure consists of one or more clauses where each clause defines a certain relation between its arguments. We will adopt the Prolog programming language to model and process clauses. A Prolog program consists of a collection of *procedures*. For example, the following program segment

```
parent(tom, adam).
parent(tom, helen).
parent(sandra, adam).
parent(sandra, helen).
parent(michael, andrew).
parent(michael, john).
parent(eve, andrew).
parent(eve, john).
parent(helen, mark).
parent(andrew, mark).
parent(judy, roger).
```

```
parent(judy, jim).
parent(judy, janis).
parent(mark, roger).
parent(mark, jim).
parent(mark, janis).
parent(janis, daphne).
parent(peter, daphne).
```

defines procedure `parent` specifying a relationship between its two arguments. The procedure consists of 18 clauses (all of which are facts). Note the dot (.) which signifies the end of a clause. The clauses constitute a *knowledge base* or *(declarative) database*.

1.5 Arity

The number of arguments in a term is called its *arity* and it is usually indicated with the suffix "/" followed by the a number that indicates the arity. For example, our genealogy database defines `parent/2`. Note that terms that have the same name but different arities are treated as different.

1.6 Queries

Is Peter a parent of Daphne? We can codify this question into a *query*. The Prolog representation of this query[1] is as follows:

```
?- parent(peter, daphne).
```

to which the Prolog system will respond

```
Yes
```

[1]The question mark (?) is the prompt of the Prolog system.

implying that it has been successful in obtaining a fact which satisfies the query. This implies that the query has been successfully matched to a given fact.

The family tree of Figure 1.1 is codified into a collection of facts as shown below:

```
man(tom).
man(michael).
man(adam).
man(andrew).
man(john).
man(mark).
man(roger).
man(jim).
man(peter).
woman(sandra).
woman(eve).
woman(helen).
woman(judy).
woman(janis).
woman(daphne).
parent(tom, adam).
parent(tom, helen).
parent(sandra, adam).
parent(sandra, helen).
parent(michael, andrew).
parent(michael, john).
parent(eve, andrew).
parent(eve, john).
parent(helen, mark).
parent(andrew, mark).
```

```
parent(judy, roger).
parent(judy, jim).
parent(judy, janis).
parent(mark, roger).
parent(mark, jim).
parent(mark, janis).
parent(janis, daphne).
parent(peter, daphne).
```

Note that even though we are flexible in deciding the format of a fact, we must ensure that all facts denoting the same relation are consistent. In this example, we have decided to follow the convention that `parent(X, Y)` will denote the relation "X is the parent of Y." This means that `parent(tom, adam)` and `parent(helen, tom)` are not consistent.

Variables can be used in queries (and must always start with a capital letter) to find all values which can be substituted for, in order to make the clause true. On the fact `parent(peter, daphne)`, a new question can be formed: "Who is a parent of Daphne?" which can be codified into a query as follows:

```
?- parent(X, daphne).
```

to which the Prolog system will respond

```
X = janis
```

In reaching this response, Prolog searches the database starting from the top to see under what conditions the query can be satisfied, i.e. whether a value for `X` exists which can result in a match.

The response we obtain is a correct answer but we know that it is not complete according to our collection of facts, since Daphne has two parents. Prolog allows an interaction during a query. We can now ask "Are there more matches?" With the semicolon symbol (`;`) we instruct the Prolog system to continue its search.

```
?- parent(X, daphne).
X = janis ;
X = peter
```

"Are there still more matches?"

```
?- parent(X, daphne).
X = janis ;
X = peter ;
No
```

The response `No` indicates that this is the system's final response, i.e. there are no (more) matches.

In a similar fashion to the semicolon symbol during an interaction with the Prolog system, a period symbol (`.`) indicates our intention to stop the search.

1.7 Rules

A rule is a clause described in the general form

$$head \ :- \ body$$

which reads *"The head (of the rule) is true, if the body is true."*, or alternatively *"The head of the rule can succeed if the body of the rule can succeed."*. The body consists of predicates, which are called the *goals* of the rule. The predicates in the body of a rule can be combined by conjunction (logical *and*, denoted by comma), disjunction (logical *or*, denoted by semicolon), or combinations of them. The example below

```
H :- P1, P2, ..., Pn.
```

reads that in order to prove (or show) `H`, we need to prove (or show) `P1`, and `P2`, and ..., and `Pn`.

Let us extend the database with a new relation. Suppose we let p stand for the *isParentOf* relation and let g stand for the *isGrandParentOf* relation.

We can then define g in terms of p by the following formula we will call G:

$$G = \forall\ x\ \forall\ y\ \forall\ z\ ((p(x, z) \wedge p(z, y)) \rightarrow g(x, y))$$

In other words, if x is a parent of z and z is a parent of y, then we conclude that x is a grandparent of y. We can represent this in Prolog with the rule below. We use variables to express the feature that a grandparent is a parent whose child is itself a parent. The rule below is a compound proposition comprised by two goals:

```
grandparent(X, Y) :- parent(X, Z), parent(Z, Y).
```

The rule can succeed if `parent(X, Z)` and `parent(Z, Y)` can both succeed. More specifically, for a query to succeed, Prolog moves from left to right attempting to satisfy each of its goals. In this example, once and if the first goal succeeds, we move right to the next goal, otherwise the query fails. If and once the second goal succeeds, then the query has succeeded in finding a match. If the second goal fails, the query fails.

We can now pose the following question: "Is Judy a grandparent of Daphne?" The question can be codified into the following query:

```
?- grandparent(judy, daphne).
```

to which the Prolog system will respond

```
Yes
```

This implies that Prolog has found a match for `Z` for which

```
grandparent(judy, daphne) :- parent(judy, Z), parent(Z, daphne).
```

can become true.

Consider the question: "Is Roger a grandparent of Daphne?" The query is as follows:

```
?- grandparent(roger, daphne).
No
```

Consider the question: "Who are the grandparents of Daphne?" The query is as follows:

```
?- grandparent(X, daphne).
X = judy ;
X = mark ;
No
```

Consider the question: "Who is Helen a grandparent of?" The query is as follows:

```
?- grandparent(helen, X).
X = roger ;
X = jim ;
X = janis ;
No
```

We can now further extend the database: Suppose we let p stand for the *isParentOf* relation and let a stand for the *isAncestorOf* relation. Then we can define a in terms of p by the following formula we will call A:

$$A = \forall\ x\ \forall\ y\ (p(x, y)\ \rightarrow\ a(x, y))$$

$$A = \forall\ x\ \forall\ y\ \forall\ z\ ((p(x, z)\ and\ a(z, y)) \rightarrow a(x, y))$$

In other words, x is an ancestor of y if either x is a parent of y, or x is a parent of an ancestor of y. We can represent this in Prolog with the rules below. We use variables to express the feature that a one's parent is also one's ancestor, as well as the parent of one's ancestor is also one's own ancestor.

```
ancestor(X, Y) :- parent(X, Y).
ancestor(X, Y) :- parent(X, Z), ancestor(Z, Y).
```

Note that the `ancestor` rule is composed of a disjunction. We can combine this into a single line, denoting the disjunction with a semicolon as

```
ancestor(X, Y) :- parent(X, Y); (parent(X, Z), ancestor(Z, Y)).
```

Consider the question: "Is Tom an ancestor of Daphne?" The query is as follows:

```
?- ancestor(tom, daphne).
Yes
```

Consider the question: "Is Tom an ancestor of Peter?" The query is as follows:

```
?- ancestor(tom, peter).
No
```

Consider the question: "Who are the ancestors of Janis?" The query is as follows:

```
?- ancestor(X, janis).
X = judy ;
X = mark ;
X = tom ;
X = sandra ;
X = michael ;
X = eve ;
X = helen ;
X = andrew ;
No
```

Consider the question: "Who are the ancestors of Peter?" The query is as follows:

```
?- ancestor(X, peter).
No
```

Note that Prolog finds no ancestors for Peter not because he has no ancestors (we know that all humans have ancestors), but because no such facts exist in our database which define any.

Consider the question: "Who is Eve an ancestor of?" The query is as follows:

```
?- ancestor(eve, X).
X = andrew ;
X = john ;
X = mark ;
X = roger ;
X = jim ;
X = janis ;
X = daphne ;
No
```

Suppose we let a stand for the *isAncestorOf* relation and let d stand for the *isDescendantOf* relation. Then we can define d in terms of a by the following formula we will call D:

$$D = \forall\, x\, \forall\, y\, (a(x, y) \rightarrow d(y, x))$$

In other words, if x is an ancestor of y then we can conclude that y is a descendant of x. We can represent this in Prolog with the rule below. We use variables to express the feature that the descendant of any person has that person as his or her ancestor.

```
descendant(X, Y) :- ancestor(Y, X).
```

Consider the question: "Is Jim a descendant of Michael?" The query is as follows:

```
?- descendant(jim, michael).
Yes
```

Consider the question: "Is Peter a descendant of Michael?" The query is as follows:

```
?- descendant(peter, michael).
No
```

We can further extend the database by adding more rules. Suppose we let m stand for the *isMan* relation, p stand for *isParentOf* relation and let f stand for the *isFatherOf* relation. Then we can define f in terms of m and p by the following formula we will call F:

$$F = \forall\ x\ \forall\ y\ ((m(x) \wedge p(x, y)) \rightarrow f(x, y))$$

In other words, if x is a man and x is a parent of y, then we conclude that x is the father of y.

We can represent this in Prolog with the rule below. We use variables to express the feature that every man who is a parent of any child is also his or her father.

```
father(X, Y) :- man(X), parent(X, Y).
```

A similar reasoning can be applied to build a rule for the *isMotherOf* relation.

```
mother(X, Y) :- woman(X), parent(X, Y).
```

We can now pose even more different types of questions in our system, such as: "Who is the father of Helen?" The query is as follows:

```
?- father(X, helen).
X = tom
```

We can hit semicolon (;) to instruct Prolog to continue its search for more possible matches:

```
?- father(X, helen).
X = tom ;
No
```

There is no other match, as was expected.

Consider the question: "Who is Sandra the mother of?" The query is as follows:

```
?- mother(sandra, X).
X = adam ;
X = helen ;
No
```

Suppose we let m stand for the *isMan* relation, let p stand for *isParentOf* relation and let s stand for the *isSonOf* relation. Then we can define s in terms of m and p by the following formula we will call S:

$$S = \forall\ x\ \forall\ y\ ((m(x) \wedge p(y, x)) \rightarrow s(x, y))$$

In other words, if x is a man and y is a parent of x, then we conclude that x is the son of y. We can represent this in Prolog with the rule below. We use variables to express the feature that every man who has a parent, is also his parent's son.

```
son(X, Y) :- man(X), parent(Y, X).
```

A similar reasoning can applied to build a rule for the *isDaughterOf* relation:

$$D = \forall\ x\ \forall\ y\ ((w(x) \wedge p(y, x)) \rightarrow d(x, y))$$

```
daughter(X, Y) :- woman(X), parent(Y, X).
```

Consider the question: "Is Adam the son of Tom?" The query is as follows:

```
?- son(adam, tom).
Yes
```

Consider the question: "Who is Adam the son of?" The query is as follows:

```
?- son(adam, X).
X = tom ;
X = sandra ;
No
```

1.8 Anonymous variables

If any parameter of a relation is not important, we can replace it with an *anonymous variable* (denoted by the underscore character _) as follows:

```
is_father(X) :- father(X, _).
is_mother(X) :- mother(X, _).
```

We can now pose more questions such as "Is Tom a father?" To answer this type of question, it is important to realize that it does not matter whom Tom is the father of, as long as Tom is found as the first term in a `father` fact. The query is as follows:

```
?- is_father(tom).
Yes
```

1.9 Ground vs. non-ground queries

We have so far posed many different questions on the family tree database. However, all questions we have posed, fall into two categories. The first category are those which can be answered by a Yes/No and can be expressed as "Is it the case that a given statement is true?" The second category are those which can be expressed as "Under what conditions, if any, is a given statement true?"

This brings us to the notion of ground and non-ground queries:

Ground queries consist only of value identifiers as parameters to the predicate such as `parent(peter, daphne)`. The answer to a ground query is of the form `Yes/No`. The answer "Yes" means that the system has proved that the goal was true under the given database of facts and rules. The answer "No" means that either the goal was proved false or the system was unable to prove it.

Non-ground queries contain variables as parameters such as `parent(X, daphne)`. A non-ground query is satisfiable relative to the program if there is a substitution for its variable which makes the query true.

1.10 The inferencing process

To prove that a goal is true, the inferencing process must find a chain of *inference rules* and/or *inference facts* in the database that connect the goal to one or more facts in the database. Given a goal Q, then either Q must be found as a fact in the database or the inferencing process must find a fact P_1 and a sequence of propositions $P_2, \ldots P_n$ such that:

$$P_2 :- P_1$$
$$P_3 :- P_2$$
$$\ldots$$
$$Q :- P_n$$

The process of proving a goal is called *matching*.

1.11 Unification and resolution

The mechanisms of *unification* and *resolution* are vital to query evaluation.

Unification The process of taking two terms (one from the query and the other being a fact or the head of a rule) and determining if there is a substitution which makes them the same. If such a substitution exists, then one or more variables are instantiated to reflect this. For example, `parent(X, daphne)` can be unified with `parent(peter, daphne)` since `X` can be substituted for `peter` (in which case it is instantiated to `peter`).

Resolution When a term from the query has been unified with the head of a rule (or a fact), resolution replaces the term with the body of the rule (or nothing, if a fact) and then applies the substitution to the new query.

Given a query, Prolog searches the database of clauses from top to bottom:

- If it finds a fact, it tries to unify the query with the fact. If successful, one solution has been found. If not successful, it tries the next clause.
- If it finds a rule, it tries to unify the query with the head of the rule. If successful, the goals of the body of the clause are treated as those queries which must be satisfied in order for the initial query to be satisfied. If not successful, it tries the next clause in the program.

Example 1.1. Consider the question "Who is Helen the daughter of?" translated into the query `daughter(Helen, Y)`. Prolog will search the database from top to bottom trying to find a clause that can be matched with the query.

The query `daughter(helen, Y)` will unify with the `daughter(X, Y)` rule, instantiating `X` to `helen`.

Resolution will apply the *substitution* of the variables and produce a new rule:

`daughter(helen, Y) :- woman(helen), parent(Y, helen).}`

Both goals in the body of the rule have to be satisfied for the head of the rule to be satisfied. The first goal is unified with the fact `woman(helen).` The second goal is also unified with the fact `parent(tom, helen).` instantiating Y to `Tom`.

Example 1.2. Consider the evaluation of the query `grandparent(judy, daphne).` Prolog will search the database from top to bottom, trying to unify the query with one of the clauses of the database. It will unify the query with the head of the rule `grandparent(X, Y) :- parent(X, Z), parent(Z, Y)` instantiating `X` to `judy` and `Y` to `daphne`, and apply the substitution as follows:

```
grandparent(judy, daphne) :- parent(judy, Z), parent(Z, daphne).
```

For the head of the new query to be true, both goals of the body of the clause must be evaluated to true. To evaluate the two goals, Prolog will consider the two new queries

```
parent(judy, Z), parent(Z, daphne).
```

and it will perform a new search of the database to unify each one, looking for an instantiation which can satisfy them both. Variable `Z` can be instantiated to `janis` thus making the original query true.

Example 1.3. Suppose we let p stand for the *isParentOf* relation and let s stand for the *isSiblingWith* relation. Then we can define s in terms of p by the following formula we will call S:

$$S = \forall\, x\ \forall\, y\ \forall\, z\ (p(z, x) \wedge p(z, y)) \rightarrow s(x, y))$$

In other words, if z is a parent of both x and y, then we conclude that x and y are siblings. We can represent this in Prolog with the rule `siblings` below. We use variables to express the feature that two different persons with a common parent are siblings.

```
siblings(X, Y) :- parent(P, X), parent(P, Y), X \= Y.
```

The above rule does not consider full siblings (those with both common parents). We can define this new relation based on previous relations. Suppose we let f stand for the *isFatherOf* relation, m stand for the *isMotherOf* relation and let fs stand for the *isFullSiblingWith*

relation. Then we can define fs in terms of p and m by the following formula we will call FS:

$$FS = \forall\ x\ \forall\ y\ \forall\ w\ \forall\ z\ (f(w,x) \wedge f(w,y) \wedge m(z,x) \wedge m(z,y)) \rightarrow fs(x,y)).$$

In other words, if x and y have both father and mother in common, then we conclude that x and y are full siblings. We use variables to express the feature that two different persons with the same father and mother are full siblings. We can follow a similar reasoning to provide the alternative implementation `full_siblings2`.

```
full_siblings1(X, Y) :-
    father(F, X), father(F, Y), mother(M, X), mother(M, Y),
    X \= Y.

full_siblings2(X, Y) :-
    parent(F, X), parent(F, Y),  parent(M, X), parent(M, Y),
    X \= Y, F \= M.
```

Use can now use the rule `siblings` to define rules for uncle and aunt relations as shown below:

```
uncle(U, N) :- man(U), siblings(U, P), parent(P, N).
aunt(A, N) :- woman(A), siblings(A, P), parent(P, N).
```

Example 1.4. Consider the following database of facts which represents a *directed graph*:

```
edge(a,b).
edge(b,c).
edge(a,c).
edge(c,d).
```

```
edge(d,e).
edge(f,e).
edge(f,g).
```

We define a rule `path(N1, N2)` which succeeds if there is a path from node `N1` to node `N2`.

```
path(N1, N2) :- edge(N1, N2).
path(N1, N2) :- edge(N1, N), path(N, N2).
```

We additionally define a rule `is-connected(N1, N2)` specifying that a source node `N1` is connected to a destination node `N2` if there is a path from `N1` to `N2`.

```
is-connected(N1, N2) :- path(N1, N2).
```

Consider the following questions which we will subsequently translate into queries:

- Is there a path from `b` to `e`?
- Is there a path from `d` to `a`?
- Is node `a` connected to node `d`?
- Which node(s) is node `c` connected to?

The queries and the responses are shown below:

```
?- path(b,e).
Yes
?- path(d,a).
No
?- is-connected(a, d).
Yes
?- is-connected(c, X).
```

```
X = d ;
X = e ;
No
```

Let us concentrate on the last query above and see how unification and resolution work during its evaluation:

- Unify with the rule `is-connected(N1, N2)`, and instantiate `N1` to `c`, and `N2` to `X`. Resolve to new query `path(c, X)`.
- Unify first `path(N1, N2)` rule with the fact `edge(c, d)`, and instantiate `X` to `d`.
- Unify first goal of second `path(N1, N2)` rule with the fact `edge(c, d)`, and instantiate `X` to `d`. Resolve to new query `path(d, N2)`.
- Unify `path(d, N2)` with the fact `edge(d, e)`, and instantiate `N2` to `e`.

The system will respond with `d` and `e` as the values for `X`.

Example 1.5. Consider a declarative database, representing a graph, that contains facts of the form

```
edge(a, b).
```

where `edge(a, b)` defines a directed edge from node `a` to node `b`. Construct a Prolog rule `path(Source, Destination)` that succeeds if there exists a path from node `Source` to node `Destination`. Translate the graph of Figure 1.2 into a Prolog database, and execute and trace a query to determine whether there exists a path from node `a` to node `c`. In tracing the query, clearly indicate all steps.

The declarative representation of the graph and the rule to define a path between two nodes are shown below:

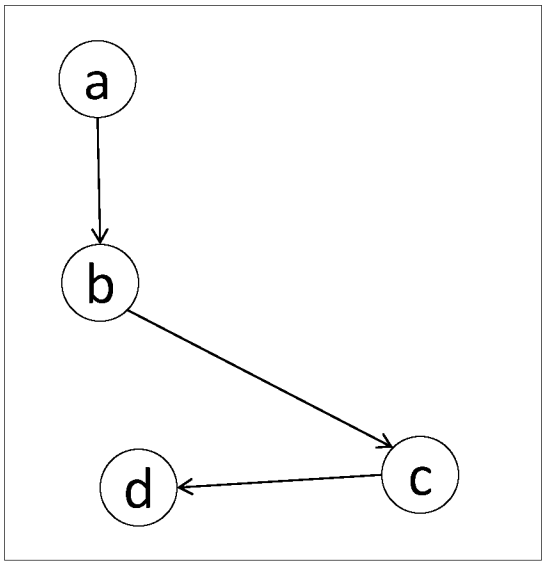

Figure 1.2: Directed graph.

```
edge(a, b).
edge(b, c).
edge(c, d).
path(Source, Destination) :- edge(Source, Destination).
path(Source, Destination) :- edge(Source, IntermediateNode),
                             path(IntermediateNode, Destination).
```

For the query `path(a, c)`, we have the following trace:

1. We search the database from top to bottom, looking to unify the query to a fact or a rule. We unify with `edge(Source, Destination)`, instantiating `Source` to `a` and `Destination` to `c`, thus resolving to `edge(a, c)`.

2. We now attempt to satisfy this query, searching again from top to bottom; We will fail.

3. We unify with the second rule, instantiating `Source` to `a` and `Destination` to `c`, thus resolving to `edge(a, IntermediateNode), path(IntermediateNode, c)`. We must satify both goals of this resolution if we were to satify the original query.

4. We search the database from top to bottom and we unify `edge(a, IntermediateNode)` with `edge(a, b)`, instantiating `IntermediateNode` to `b`, and resolving to `path(b, c)`.

5. We unify `path(b, c)` with the first rule, instantiating `Source` to `b` and `Destination` to `c`, thus resolving to `edge(b, c)`.

6. We search for `edge(b, c)` which we can unify to one of the facts, thus returning `True` (recall that we are resolving a ground query).

Example 1.6. Consider the following Prolog database:

```
clerk(jones).
clerk(smith).
typist(brown).
manager(patel).
manager(lee).
supervises(X,Y):- manager(X), clerk(Y).
supervises(X,Y):- clerk(X), typist(Y).
supervises(X,Y):- manager(X), typist(Y).
```

We will follow the search of the query `supervises(Supervisor, brown)` and describe how Prolog deploys unification, instantiation and resolution to perform an evaluation until the first successful match. There are three `Supervises(X, Y)` rules. Prolog will try all of them in the order from top to bottom.

1. Unify `supervises(Supervisor, brown)` with the rule `supervises(X, Y)`, instantiating `Supervisor` to `X` and `Y` to `brown`. Resolve to

   ```
   supervises(Supervisor, brown) :- manager(Supervisor), clerk(brown).
   ```

   Prolog tries `manager(Supevisor)`. Unify `manager(Supervisor)` with `manager(patel)`, instantiating `Supervisor` to `patel`. Prolog now tries to find `clerk(brown)` and **fails**.

Unify `manager(Supervisor)` with `manager(lee)`, instantiating `Supervisor` to `lee`. It tries again to find `clerk(brown)` and it fails. As a result, the first `supervises(X, Y)` fails.

2. Unify `supervises(Supervisor, brown)` with the rule `supervises(X, Y)`, instantiating `Supervisor` to `X` and `Y` to `brown`. Resolve to

   ```
   supervises(Supervisor, brown) :- clerk(Supervisor), typist(brown).
   ```

   Unify `clerk(Supervisor)` with the fact `clerk(jones)`. Prolog tries `typist(brown)` and succeeds. As a result, the second rule for `supervises(X, Y)` succeeds. Prolog replies *Yes* and *Supervisor* = *jones*.

Example 1.7. Consider a declarative database composed by a number of facts of the following procedure:

```
likes(Name, Liking).
```

Construct a rule `likes_to_go_out_with(X, Y)` that succeeds for two persons `X` and `Y` which have common interests.

```
likes_to_go_out_with(X, Y) :- likes(X, Something),
                              likes(Y, Something),
                              X \= Y.
```

Example 1.8. Consider a declarative database composed of the following facts and one rule:

```
man(X).
woman(Y).
parent(P, C). %% P is the parent of C.
father(X, Y) :- man(X), parent(X, Y).
```

1. Let f stand for *isFatherOf* relation, and a stand for *isMaleAncestorOf* relation. Construct a predicate formula, call it A, defining a in terms of f.

2. Translate the predicate into a Prolog rule `male_ancestor(A, P)` that succeeds if A is a male ancestor or `P`.

$$A = \forall\ x\ \forall\ y\ (f(x, y)\ \rightarrow\ a(x, y))$$

$$A = \forall\ x\ \forall\ y\ \forall\ z\ (f(x, z) \wedge a(z, y)) \rightarrow a(x, y))$$

```
male_ancestor(A, P) :- father(A, P).
male_ancestor(A, P) :- father(A, P2), male_ancestor(P2, P).
```

Example 1.9. On the genealogy database:

1. Let m stand for *man* relation, w stand for *woman* relation, p stand for the *isParentOf* relation, and s stand for the *isSiblingWith* relation where the two parameters of the last relation are of different gender. Define s in terms of m, w and *isParentOf* by a predicate formula, call it S.

2. Translate the predicate into a Prolog rule `siblings(X, Y)` that succeeds if X and `Y` is a male-female siblings pair.

For full-siblings we need two common parents:

$$S = \forall\ x\ \forall\ y\ \forall\ f\ \forall\ m\ (p(f, x) \wedge p(f, y) \wedge p(m, x) \wedge p(m, y) \wedge f \neq m \wedge m(x) \wedge w(y)) \rightarrow s(x, y))$$

```
siblings(X, Y) :-
            parent(F, X),
            parent(F, Y),
            parent(M, X),
```

```
            parent(M, Y),
            F \= M,
            man(X),
            woman(Y).
```

For half-siblings we need one common parent:

$$S = \forall\ x\ \forall\ y\ \forall\ z\ (p(z,x) \wedge p(z,y) \wedge m(x) \wedge w(y)) \rightarrow s(x,y))$$

```
siblings(X, Y) :-
            parent(Z, X),
            parent(Z, Y),
            man(X),
            woman(Y).
```

1.12 Qualifiers

What if we now wanted to pose a different type of question: "Are all men parents?" We can do this with the *qualifier* `forall`.

```
qualify(X) :- forall(man(X), parent(X, _)).
```

The body of the rule will be true only if *each* instantiation of `man(X)` appears as a first term in a `parent(X, _)` clause.

```
?- qualify(X).
No
```

1.13 Arithmetic operators

We can evaluate the truth value of an arithmetic expression. The operators `+`, `-`, `*` and `/` denote their respective *arithmetic operations* and `mod` denotes the remainder operation.

The keyword `is` is a built-in arithmetic operator. It takes an arithmetic expression as its right-hand side (RHS) operand and a variable as its left-hand side (LHS) operand. In the example below, we are asking if it is true that 7 can be expressed as $6 + 1$.

```
?- (7 is 6 + 1).
Yes
```

Alternatively we can ask under what conditions a given expression can be evaluated:

```
?- (X is 6 + 1).
X = 7 ;
No
```

```
?- (X is 7 mod 2).
X = 1 ;
No
```

We can use arithmetic operators in the definition of rules. For example, we can specify that `Y` is considered the double of `X` if it can be expressed by the RHS operand of the operator `is`, as defined below:

```
double(X, Y) :- Y is X * 2.
```

```
?- double(2, 4).
Yes
```

```
?- double(3, X).
```

```
X = 6 ;
No
```

In general, a function that takes n arguments will be represented in Prolog as a relation that takes $n + 1$ arguments, the last one being used to hold the result, as shown in the example above. An important point to remember is that all variables on the RHS of the operator `is` must already be instantiated. In the example below,

```
?- double(X, 16).
```

the variable `X` that appears on the RHS of `is` is not instantiated. As a result, the query will result in an error.

1.14 Relational and logical operators

We can evaluate *relational operators* such as *less than* ($<$) as shown below:

```
?- 1 < 3.
Yes
?- (1 < 3).
Yes
```

Other relational operators are `<=`, `>`, `>=`, and `==`, the last one indicating equality.

We can also have *logical operators* as in the examples below:

```
?- (1 < 3), (4 < 2).
No

?- (1 < 3); (4 < 2).
Yes
```

Example 1.10. Consider function `max` to return the maximum between two numbers:

```
max(X, Y, X) :- X > Y.
max(X, Y, Y) :- X < Y.
```

The first rule reads "The maximum of X and Y is X, provided that $X > Y$."

```
?- max(9, 5, X).
X = 9 ;
No
```

Chapter 2

Lists I

A list is a finite ordered sequence of zero or more elements that can be repeated. We can only access two things in a list: the first element of the list (*head*) and the list made up of all except the head, called the *tail* of the list. The number of elements in a list is called the *length* of the list. For example, the list $L = \langle a, b, c, d \rangle$ has length 4, its head is a and its tail is $\langle b, c, d \rangle$. We will use the notation $head(L)$ and $tail(L)$ to denote the head of L and the tail of L. The empty list, denoted by $\langle\rangle$ does not have a head or tail.

Note that

$$a \neq \langle a \rangle \neq \langle \langle a \rangle \rangle$$

The elements of a list can be any kind of objects, including lists themselves in which case a list is said to be *nested* (as opposed to being *flat*).

L	$head(L)$	$tail(L)$
$\langle a, \langle b \rangle \rangle$	a	$\langle \langle b \rangle \rangle$
$\langle \langle a \rangle, \langle b, c \rangle \rangle$	$\langle a \rangle$	$\langle \langle b, c \rangle \rangle$
$\langle a \rangle$	a	$\langle\rangle$

2.1 Clauses and lists

Syntactically, a Prolog list is represented by square brackets `[...]`. The empty list is represented as `[]`. Every non-empty list can be represented in two parts: head and tail. Consider the list `L = [a, b, c, d, e]`. The notation `[H|T]` is used to represent a list whose head is `H` and its tail is `T`. So `L` can be represented as

$$
\begin{aligned}
L &= \texttt{[a, b, c, d, e]} \\
&= \texttt{[a | [b, c, d, e]]} \\
&= \texttt{[a | [b | [c, d, e]]]} \\
&= \texttt{[a | [b | [c | [d, e]]]]} \\
&= \texttt{[a | [b | [c | [d | [e]]]]]} \\
&= \texttt{[a | [b | [c | [d | [e | []]]]]]}
\end{aligned}
$$

Example 2.1. In this example we want to define a clause `first/2` which succeeds if an element is the head of a list. The rule below,

```
first(F, [F|_]).
```

reads "Clause `first` succeeds if an element `F` is found to be the first element of a given list, represented as `[F|_]`, since we are not really interested in the contents of the tail."

The query below reads "Is element `a` the head of the list `[a b c]`?" to which Prolog responds with a *Yes*.

```
?- first(a, [a, b, c]).

Yes
```

Let us now rephrase the question. We ask "Under what conditions an element is the head

of the list `[a b c]`?" The condition is that an element must be equal to `a`. Let us translate the question in Prolog and see its response:

```
?- first(F, [a, b, c]).

F = a
```

which means that the condition under which the statement can be true is when `F = a`.

Example 2.2. In this example, we want to define a clause `c/3` which succeeds if a list can be broken down into a head and a tail. The rule below,

```
c([H|T], H, T).
```

reads "Clause `c` succeeds if a list, represented as `[H|T]`, can be broken down into a head `H` and a tail `T`.

The query below reads "Given the list `[a b c d]`, is `a` the head and `[b c d]` the tail?" to which Prolog responds with a *Yes*. (What type of question is this?)

```
?- c([a, b, c, d], a, [b, c, d]).

Yes
```

The query below reads "Given the list `[a b c d]`, what are the head and tail, if any?" (What type of question is this?)

```
?- c([a, b, c, d], H, T).

H = a
T = [b, c, d]
```

to which Prolog will respond by providing the conditions under which the statement can be true.

The query below reads "Given the list `[]`, what are the head and tail, if any?" (What type of question is this?)

```
?- c([], H, T).
```

```
No
```

which means that there are no conditions under which the empty list can have a head or tail.

Example 2.3. Consider a procedure to define a predicate `member(X,L)` which is true if `X` is an element of the list `L`. An element `X` is a member of the list `L` if `X` is the head of `L` (regardless of what its tail is):

```
member(X, [X|_]).
```

Additionally, `X` can be a member of `L` if `X` is a member of the tail of `L` (regardless of what its head is).

```
member(X, [_|T]) :- member(X, T).
```

Let us execute some queries:

```
?- member(a, [a, b, c]).
Yes
?- member(e, [a, b, c, d, e]).
Yes
?- member(X, [a,b]).
X = a ;
X = b ;
No
```

Let us trace the call to `member(e, [a, b, c, d, e])`:

```
?- member(e, [a, b, c, d, e]).
   member(e, [b,c,d,e]).
   member(e, [c,d,e]).
   member(e, [d,e]).
   member(e, [e]).
Yes
```

Example 2.4. In this example, we want to define a clause `add/3` which succeeds if a new list can be created by placing an element as the head of some other list. The rule below,

```
add(X, L, [X|L]).
```

reads "Clause `add` succeeds if a new list, represented as `[X|L]`, can be created whose head is an element `X` and whose tail is a list `L`."

The query below reads "Is the list `[a, b, c]` created when placing element `a` as the head and list `[b c]` as the tail?" to which Prolog responds with a *Yes*.

```
?- add(a, [b, c], [a, b, c]).

Yes
```

The query below reads "Is the list `[a, b, c]` created when placing element `b` as the head and list `[b c]` as the tail?" to which Prolog responds with a *No*.

```
?- add(b, [b, c], [a, b, c]).

No
```

The query below reads "Under what conditions, if any, can a list be comprised with `a` as its head and with the list `[b c]` as its tail?" to which Prolog provides the condition as the list `[a b c]`.

```
?- add(a, [b, c, d], NewList).

NewList = [a, b, c, d]
```

The query below reads "Under what conditions, if any, an element `a` can be added to a list creating the list `[a b c d e]`?"

```
?- add(a, L, [a, b, c, d, e]).

L = [b, c, d, e]
```

which means that the condition under which the statement can be true is when the list is `[b c d e]`.

Example 2.5. In this example, we would like to define a rule `last/2` which succeeds if an element is the last element of a given non-empty list. We can identify two cases for this:

1. The list has one element.
2. The list has more than one element.

Case 1: The list has only one element. In this case, the last element is the only existing element of the list. Let us translate this into Prolog. The following rule,

```
last(L, [L]).
```

reads "Rule `last` succeeds if an element `L` is found to be the only element of a given list."

The query below reads "Is element `a` the last element of the list `[a]`?" to which Prolog responds with a *Yes*.

```
?- last(a, [a]).

Yes
```

The query below reads "Under what conditions, if any, is an element the last element of the list `[a]`?"

```
?- last(L, [a]).
```

```
L = a
```

which means that the condition under which the statement can be true is when `L = a`.

Case 2: The list has more than one element. In this case, we need to reduce the problem to the one that can be handled by **case 1**. In other words, the clause will succeed once it chops off all elements, one by one, until it ends up with one element. The following rule,

```
last(L, [H|T]) :- last(L, T).
```

reads "Rule `last` can be proven true for a list whose head is `H` and whose tail is `T`, if it can be proven true for a new list which is the tail `T` of the original list."

In other words, let us get rid of the first element and see if we end up with only one element in which case the rule of **case 1** will determine that this remaining element is indeed the last element.

However, if after getting rid of the first element we end up with something which has a non-empty tail (i.e. there is still more than one element in the list), we must repeat this chopping off the head of the list, until we end up with a list which has only one element and subsequently handled by the first rule (of **case 1**).

The query below reads "Is element `c` the last element of the list `[a b c]`?" to which Prolog responds with a *Yes*.

```
?- last(c, [a, b, c]).

Yes
```

The query below reads "Under what conditions, if any, is an element the last element of the list `[a b c]`?".

```
?- last(L, [a, b, c]).

L = c
```

which means that the condition under which the statement can be true is when `L = c`.

Example 2.6. Consider the rule `size/2` to read in a list and calculate its length:

```
size([],0).
size([H|T],N) :- size(T,N1), N is N1+1.
```

We can execute queries as follows:

```
?- size([],N).
N = 0.
?- size([a,b,c],N).
N = 3.
?- size([[a,b],c],N).
N = 2.
?- size([[a,b,c]],N).
N = 1.
```

Example 2.7. Consider the following Prolog program, `a2b`, which behaves as follows:

```
?- a2b([a,a,a,a],[b,b,b]).
No
?- a2b([a,a,a,a],[b,b]).
Yes
?- a2b([a,a,a,a,a,a],[b,b,b]).
Yes
?- a2b([a,a,a,a],[b]).
No
?- a2b([a,d,f,a,a],[b,b]).
No
?- a2b([a,a],[b]).
Yes
?- a2b([a,a],[b,b,b,b]).
No
?- a2b([a,a,a,a,a,r],[b,b,b]).
No
?a2b([a,a],[b,b]).
No
?- a2b([a,a,a,a],[b,d]).
No
```

Our task is to describe what the program does, and write a Prolog program to perform this task. The program takes two lists as arguments, and succeeds if the first argument is a list of a's, and the second argument is a list of b's where the list of a's is twice the size of the list of b's.

The program is as follows:

```
;; shortest possible list is the empty list
a2b([],[]).
;; need to have two a's for one b
a2b([a,a|Ta],[b|Tb]) :- a2b(Ta, Tb).
```

2.2 Controlling backtracking with 'cut'

Recall the rule `member/2`:

```
member(X, [X|_]).
member(X, [_|T]) :- member(X, T).
```

If the first clause succeeds, it would be inefficient to attempt to satisfy the second. Prolog provides a special built-in predicate called 'cut' and spelled '`!`.' When called, the 'cut' always succeeds and removes any alternative choices. We can now re-write the above example as follows:

```
member(X, [X|_]) :- !.
member(X, [_|T]) :- member(X, T).
```

Let us execute the program:

```
?- member(a, [a, b, c]).
true.
?- member(d, [a, b, c]).
false.
?- member(X, [a, b, c]).
X = a.
```

We see that in the last case the interpreter discards alternative choices once it has found an instantiation for variable `X`.

The 'cut' can also be used to specify mutually exclusive cases. Consider the rule `max/3`:

```
max(X, Y, X) :- X >= Y.
max(X, Y, Y) :- X < Y.
```

A version using 'cut' would be as follows:

```
max(X, Y, X) :- X >= Y, !.
max(X, Y, Y).
```

Let us execute the program:

```
?- max(5, 3, X).
X = 5.
?- max(5, 7, X).
X = 7.
```

If the first clause succeeds, the 'cut' ensures that the second clause is disregarded as an alternative choice and it is never evaluated.

Let us now try a ground query as follows:

```
?- max(10, 0, 0).
true.
```

Why is that? The first clause fails, and Prolog evaluates the second clause which now succeeds. To rectify this we can re-write the rule as follows:

```
max(X, Y, X) :- X >= Y, !.
max(X, Y, Y) :- X < Y.
```

Let us now re-try the previous ground query:

```
?- max(10, 0, 0).
false.
```

2.3 List construction with `findall`

The built-in function `findall(X,P,L)` returns a list `L` with all values for `X` that satisfy predicate `P`. For example, for the database below

```
likes(bill, movies).
likes(bill, walks).
likes(james, beer).
likes(peter, beer).
likes(peter, movies).
likes(mike, soccer).
likes(mike, walks).
likes(michael, cars).
```

the query `findall(X,likes(X, movies), L).` will return `L = [bill, peter]`.

The built-in function `list_to_set(List, Set)` converts a list (with possibly repeated elements) into a set. For example, `list_to_set([a, b, b, a, c], X).` will return `X = [a, b, c]`.

Finally, the built-in function `length(List, L)` returns the length `L` of a given list. For example, `length([a, b, c], X).` will return `X = 3`.

Example 2.8. Construct a Prolog rule `qualifies_for_benefits(P)` that succeeds if P is a mother of more than three children.

```
qualifies_for_benefits(P) :- woman(P),
                             findall(P, parent(P, _), L),
                             length(L, N),
                             N >= 3.
```

Example 2.9. Define a Prolog procedure `second_to_last(A, L)` that succeeds when `A` is the second to last element in a list `L`. Sample runs are shown below:

```
?- second_to_last(a, []).
false.

?- second_to_last(a, [a,b]).
true.

?- second_to_last(a, [a,b,c,d,e,f]).
false.

?- second_to_last(X, [a,b,c,d,e,f]).
X = e.
```

The procedure is as follows:

```
second_to_last(A, [A,_]).
second_to_last(A, [_|T]) :- second_to_last(A, T).
```

Example 2.10. Consider the following database:

```
object(sun).
object(mercury).
object(venus).
object(earth).
object(mars).
object(jupiter).
object(saturn).
object(uranus).
object(neptune).
object(pluto).
object(moon).
object(deimos).
object(phobos).
object(arche).
object(callisto).
object(europa).
object(io).
object(themisto).
object(atlas).
object(calypso).
object(helene).
object(desdemona).
object(titania).
object(despina).
object(galatea).
object(larissa).
object(thalassa).
```

```
mass(mercury, 0.33).  %% mass in 10^24 KG
mass(venus, 4.87).
mass(earth, 5.98).
mass(mars, 0.64).
mass(jupiter, 1900).
mass(saturn, 569).
mass(uranus, 569).
mass(neptune, 86.8).
mass(pluto, 0.02).

orbits(mercury, sun).
orbits(venus, sun).
orbits(earth, sun).
orbits(mars, sun).
orbits(jupiter, sun).
orbits(saturn, sun).
orbits(uranus, sun).
orbits(neptune, sun).
orbits(pluto, sun).
orbits(moon, earth).
orbits(deimos, mars).
orbits(phobos, mars).
orbits(arche, jupiter).
orbits(callisto, jupiter).
orbits(europa, jupiter).
orbits(io, jupiter).
orbits(themisto, jupiter).
orbits(atlas, saturn).
orbits(calypso, saturn).
orbits(helene, saturn).
```

```
orbits(desdemona, uranus).
orbits(titania, uranus).
orbits(despina, neptune).
orbits(galatea, neptune).
orbits(larissa, neptune).
orbits(thalassa, neptune).
```

Suppose we let *obj* stand for the *isObject* relation, let *orb* stand for the *orbits* relation and let p stand for *isPlanet* relation. We can define a formula (call it P), to say that if o is an object with mass equal to or greater than 0.3 and o orbits around the sun, then we conclude that o is a planet. We use $mass(o)$ to represent the mass of object o.

$$P = \forall o\ (obj(o)\ \wedge\ (mass(o)\ >=\ 0.3)\ \wedge\ orb(o, sun))\ \ \rightarrow\ \ p(o))$$

We can now define a rule, `planet(P)`, for the *isPlanet* relation:

```
planet(P) :- object(P), mass(P, M), M >= 0.3, orbits(P, sun).
```

Consider the following query and its result:

```
?- planet(X).
X = mercury ;
X = venus ;
X = earth ;
X = mars ;
X = jupiter ;
X = saturn ;
X = uranus ;
X = neptune ;
false.
```

Let s stand for *isSatellite* relation. We can define a formula (call is S), to say that if an object o orbits around a planet, then we conclude that o is a satellite.

$$S = \forall o \forall x \ (obj(o) \ \wedge \ orb(o, x) \ \wedge \ p(x)) \ \ \rightarrow \ \ s(o))$$

We can now define a rule, `satellite(S)`, for the *isSatellite* relation:

```
satellite(S) :- object(S), orbits(S, P), planet(P).
```

Consider the following query and its result:

```
?- satellite(X).
X = moon ;
X = deimos ;
X = phobos ;
X = arche ;
X = callisto ;
X = europa ;
X = io ;
X = themisto ;
X = atlas ;
X = calypso ;
X = helene ;
X = desdemona ;
X = titania ;
X = despina ;
X = galatea ;
X = larissa ;
X = thalassa.
```

We can deploy rule `planet(P)` to define a new rule `obtain_satellites(P, L)` which succeeds when `P` contains all satellites in the collection `L`.

Recall that the query

```
findall(Object, Goal, List).
```

produces a list `List` of all the objects `Object` that satisfy the goal `Goal`.

```
obtain_satellites(P, L) :- planet(P), findall(S, orbits(S, P), L).
```

Consider the following query and its result:

```
?- obtain_satellites(P, L).
P = mercury,
L = [] ;
P = venus,
L = [] ;
P = earth,
L = [moon] ;
P = mars,
L = [deimos, phobos] ;
P = jupiter,
L = [arche, callisto, europa, io, themisto] ;
P = saturn,
L = [atlas, calypso, helene] ;
P = uranus,
L = [desdemona, titania] ;
P = neptune,
L = [despina, galatea, larissa, thalassa] ;
false.
```

The above query contained two variables, so the result considered all possible sucessful pairs. How about if we wanted to obtain the satellites for planet Mars?

```
?- obtain_satellites(mars, L).
L = [deimos, phobos].
```

We deploy rule `obtain_satellites(P, L)` to define a new rule `moonless(P)` which succeeds when `P` contains no satellites.

```
moonless(P) :- obtain_satellites(P, L), length(L, 0).
```

We can now invoke this rule as follows::

```
?- moonless(X).
X = mercury ;
X = venus ;
false.
```

Phobos is an object in our solar system. Is Phobos a satellite? Let us translate this question into a query. What type of query would that be? The query would be `satellite(phobos).` and it is a ground query.

Let us demonstrate step-by-step how the above query proceeds until indicating success or failure. We want to explain this only in terms of unification, instantiation and resolution and substitution: Prolog will search the database from top to bottom trying to find a clause that can be matched with the query. The query `satellite(phobos)` will unify with the rule `satellite(S)` rule, instantiating `S` to `phobos`. Resolution will apply the substitution of the variables and produce a new rule:

```
satellite(phobos) :- object(phobos), orbits(phobos, P), planet(P).
```

All three goals in the body of the rule have to be satisfied for the head of the rule to be satisfied.

1. The first goal is unified with the fact `object(phobos).`

2. The second goal is unified with the fact `orbits(phobos, mars).` instantiating `P` to `mars`.

3. Prolog will now try to satisfy the third goal. It will unify `planet(mars)` with the rule `planet(P)` instantiating `P` to `mars`. Resolution will apply the substitution of the variables and produce a new rule:

```
planet(mars) :- object(mars), mass(mars, M), M >=0.3, orbits(mars, sun).
```

4. The first and fourth goals are unified with the facts `object(mars)`, and `orbits(mars, sun)` respectively. The second goal unifies with the fact `mass(mars, 0.64)` instantiating `M` to 0.64. The third goal will be evaluated and succeed. As a result the original query succeeds.

Chapter 3

Finite state machines

A *finite state machine (FSM)* (or *state machine*, or *finite state automaton*), is an abstract model of a machine with a primitive internal memory. The behavior of an FSM is composed of a finite number of states, transitions between those states, and possibly actions. In the example of Figure 3.1 the machine includes two states `state 1` (the initial state) and `state 2`. While at `state 1`, if event `event a` occurs, there is a transition to state `state 2`. Similarly, while at `state 2` if `event b` occurs, there is a transition to `state 1`.
A *parser state machine* (also: *acceptor*, *recognizer*, *sequence detector*) produces a binary output, accepting or rejecting an input. On the other hand, a *transducer* generates output (take an action) based on a given input and/or a state.

3.1 Deterministic finite state machines

Formally, a parser state machine is defined as a 5-tuple (read: "quintuple") as follows:

$$(Q, \Sigma, \delta, q_0, F)$$

where

- Q is a finite, non-empty set of *states*.
- Σ is a finite, non-empty set of symbols, called the *input alphabet*.

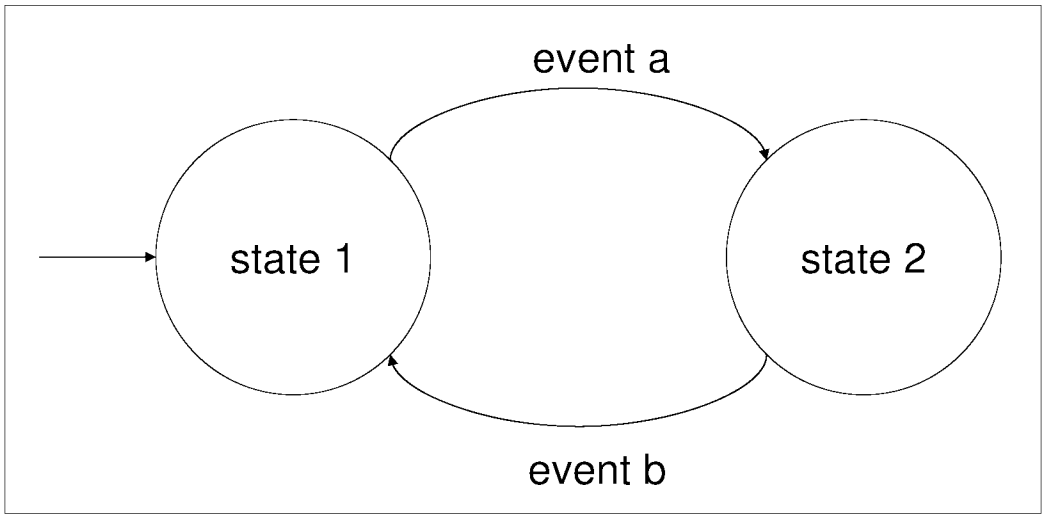

Figure 3.1: An example finite state machine.

- δ is a *state transition function*: $\delta : Q \times \Sigma \rightarrow Q$. This function defines a *deterministic finite state machine* as opposed to a *nondeterministic finite state machine* whose state transition function returns a set of states.
- $q_0 \in Q$ is the *initial state*.
- $F \subset Q$ is a set of *final states*.

What does it mean "to execute a parser FSM over an input alphabet Σ"? Given an FSM and a string w in Σ^*, the FSM accepts each one of the letters of w as input (from left to right) following a path starting from the start state. Each letter causes a state transition from the start state to the next and so forth. If this path eventually ends in the final state, then we say that the FSM accepts w. Otherwise we say that the FSM rejects w. The *language* of an FSM is the set of all strings that it accepts.

3.2 Deterministic finite state machines for a regular expression

Suppose we need to build a deterministic FSM to recognize the language represented by the FSM of Figure 3.2. The following are valid strings: *aab*, *aaaab*, *babaab*, *bbabaab*, *aababaab*. All valid strings end in *aab*.

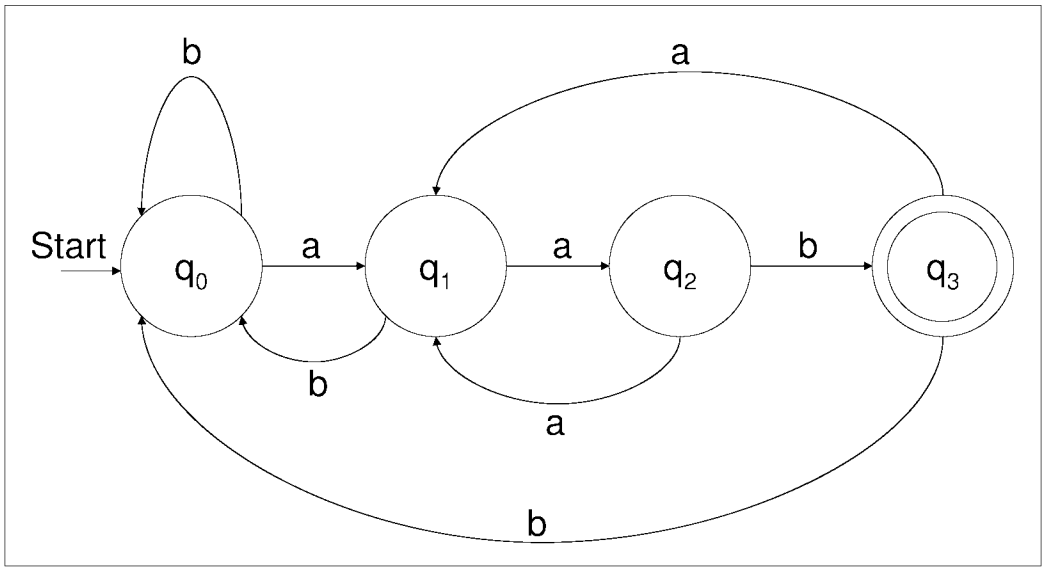

Figure 3.2: A deterministic finite state machine.

We can represent the states and their transitions with a *transition table* as follows:

		a	b
initial state	q_0	q_1	q_0
	q_1	q_2	q_0
	q_2	q_2	q_3
final state	q_3	q_1	q_0

3.3 A logic program interpreter for deterministic FSMs

In problems of this kind, we need two pieces of information: a) the representation of an FSM by a sequence of facts, and b) an interpreter to recognize a language. The interpreter is made up of a sequence of rules and the language that it is meant to recognize is expressed as a regular expression.

FSM representation

We can represent an FSM by facts of the following form:

```
start(state).
transition(currentState, condition, nextState).
```

```
end(state).
```

The start and final states can be taken directly from the figure, whereas the transitions can be more easily taken from the transition table.

```
start(q0).
final(q3).
transition(q0, a, q1).
transition(q0, b, q0).
transition(q1, a, q2).
transition(q1, b, q0).
transition(q2, a, q2).
transition(q2, b, q3).
transition(q3, a, q1).
transition(q3, b, q0).
```

Building an interpreter

Given a set of facts as above, we need to build rules to determine whether or not a given string can be accepted by the FSM. A string w is accepted by an FSM if its reading from left to right (i.e. each symbol in turn is taken as a condition which determines some transition) causes a path from the start state to the final state.

Consider a predicate `accept(Xs)`, where `Xs` is a an input string, represented by a list. A parsing is only valid if initiated from the start state.

```
accept(Xs) :- start(Q), path(Q, Xs).
```

The second goal above needs to be defined as a new rule. While at the start state `Q`, a string `Xs` will be accepted if its head causes a transition to a new state `Q1` as well as if starting from `Q1` the tail of `Xs` is accepted.

```
path(Q, [X|Xs]) :- transition(Q, X, Q1), path(Q1, Xs).
```

If our input string is valid, we will eventually reach the final state, having exhausted all symbols in the string, i.e. once we reach the final state and we have an empty string.

```
path(Q, [ ]) :- final(Q).
```

Putting everything together, we can provide the full listing of our interpreter program for the FSM of Figure 3.2 as follows:

```
start(q0).
final(q3).
transition(q0, a, q1).
transition(q0, b, q0).
transition(q1, a, q2).
transition(q1, b, q0).
transition(q2, a, q2).
transition(q2, b, q3).
transition(q3, a, q1).
transition(q3, b, q0).
accept(Xs) :- start(Q), path(Q, Xs).
path(Q, [X|Xs]) :- transition(Q, X, Q1), path(Q1, Xs).
path(Q, [ ]) :- final(Q).
```

We are now ready to execute the interpreter program:

```
?- accept([a,a,b]).
Yes
?- accept([a,a,b,a,b,a,a,b]).
Yes
```

```
?- accept([]).
No
?- accept([b,a,a]).
No
?- accept([b,b,b,b,b,a,a,a]).
No
?- accept([a,a,b,a]).
No
```

Chapter 4

Boolean algebra and digital gates

In this chapter we will deploy clauses to model and simulate Boolean expressions and digital circuits.

4.1 Boolean operations

We have already seen that a proposition is a sentence that is either true or false (but not both). Many statements can be constructed by combining one or more propositions. New propositions, called *compound propositions*, can be formed from existing propositions using *logical operations* (or *logical connectives*) which are expressed as functions, called *truth functions*. Commonly used logical connectives include:

Conjunction (*and* connective) constructs a new proposition whose truth value is *true* if both of its operands are true, otherwise is *false*. It is denoted by $\times$, $\wedge$, or $\cdot$, e.g. $p \times q$. Many authors prefer to omit the conjunction symbol and simply write pq instead of $p \times q$.

Disjunction (*or* connective) constructs a new proposition whose truth value is *true* if either or both of its operands are true, otherwise is *false*. It is denoted by $+$, or $\vee$, e.g. $p + q$.

Inverse (*not* connective) constructs a new proposition whose truth value is the reverse truth value of its operand. It is denoted by $'$, $\sim$, or $\neg$. Some authors use $\overline{q}$ to denote the inverse of proposition q.

The relationships between the truth values of the above compound propositions can be displayed in a *truth table* as follows:

x	y	x'	$x \times y$	$x + y$
1	1	0	1	1
1	0	0	0	1
0	1	1	0	1
0	0	1	0	0

We can define procedures to represent logical connectives in Boolean algebra and consequently digital gates which are the building blocks of digital circuits. In defining clauses, we will follow the convention *operation(in, out)* to denote an operation whose input is *in* and whose output is *out*. For example, the Boolean operation $'$ (*inverse*) is a unary operation whose procedure `inv` will include the clause

```
inv(0, 1).
```

which reads "The inverse of 0 is 1."

The Boolean operation *or* is a *binary* operation whose procedure `or` will include the clause

```
or(0, 1, 1).
```

which reads "The disjunction of 0 and 1 is 1."

Knowing the truth-table definitions for Boolean operations, we can define the corresponding procedures as follows:

```
and(1, 0, 0).
and(0, 1, 0).
and(0, 0, 0).
and(1, 1, 1).
```

```
or(1, 0, 1).
or(0, 1, 1).
or(0, 0, 0).
or(1, 1, 1).

inv(0, 1).
inv(1, 0).
```

The above would be enough to be able to represent any Boolean expression. However, for convenience we can also define operations *nor* (not or), *xor* (exclusive or), and *nand* (not and) as follows:

```
nand(1, 0, 1).
nand(0, 1, 1).
nand(0, 0, 1).
nand(1, 1, 0).

nor(1, 0, 0).
nor(0, 1, 0).
nor(0, 0, 1).
nor(1, 1, 0).

xor(1, 0, 1).
xor(0, 1, 1).
xor(0, 0, 0).
xor(1, 1, 0).
```

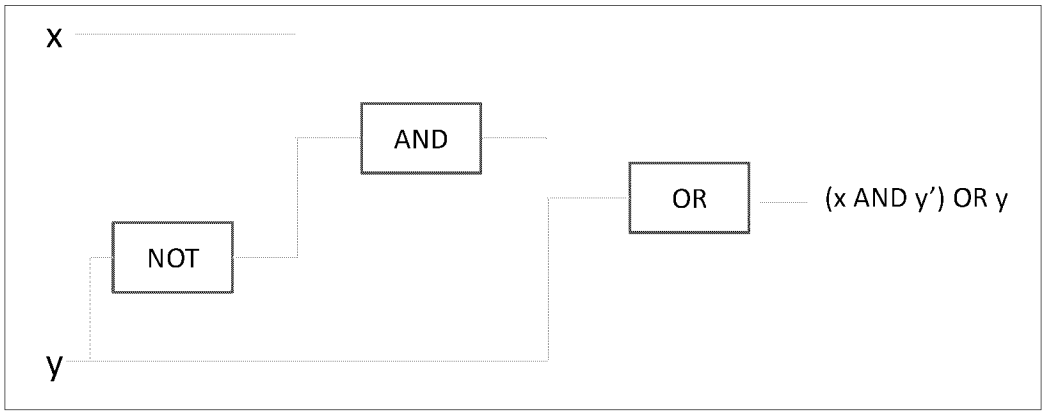

Figure 4.1: Digital circuit for the expression $(x \times y') + y$.

4.2 Evaluating Boolean expressions

We can build rules to represent Boolean expressions. Consider the expression $(x \times y') + y$ whose truth table is given below:

x	y	y'	$x \times y'$	$(x \times y') + y$
1	1	0	0	1
1	0	1	1	1
0	1	0	0	1
0	0	1	0	0

The expression can be built as the digital circuit shown in Figure 4.1. We can define a rule to represent the Boolean expression (and consequently the digital circuit) as follows:

```
circuit(X, Y, Out) :-
      inv(Y, Tmp1),
      and(X, Tmp1, Tmp2),
      or(Tmp2, Y, Out).
```

We can now test the digital circuit by executing queries over particular input sequences as follows:

```
?- circuit(1, 1, Out).
Out = 1 .
?- circuit(1, 0, Out).
Out = 1 .
?- circuit(0, 1, Out).
Out = 1 .
?- circuit(0, 0, Out).
Out = 0 .
```

We can ask questions that correspond to ground and non-ground queries. For example, we can ask "Is it indeed the case that for $X = 1$ and for $Y = 1$, the output is 1?", and the corresponding query is

```
?- circuit(1, 1, 1).
true
```

We can also ask questions like "For what input values, if any, is the output 0?"

```
?- circuit(X, Y, 0).
X = 0,
Y = 0 ;
false.
```

We can also simulate the digital circuit by executing the program as follows:

```
?- circuit(X, Y, OUT).
X = 0,
Y = 0,
OUT = 0 ;
X = 1,
```

```
Y = 0,
OUT = 1 ;
X = 1,
Y = 1,
OUT = 1 ;
X = 0,
Y = 1,
OUT = 1 ;
false.
```

It turns out that the Boolean expression of this example (and its corresponding digital circuit) can be simplified to a single logic gate `or`. How can we be sure? If we use simulation to investigate the behavior of the two circuits, then we see that for the same input, the output of the two circuits is the same.

```
?- or(X, Y, OUT).
X = 1,
Y = 0,
OUT = 1 ;
X = 0,
Y = 1,
OUT = 1 ;
X = 0,
Y = 0,
OUT = 0 ;
X = 1,
Y = 1,
OUT = 1.
```

Part II

Functional Programming with Common Lisp (CL)

Chapter 5

Lists II

Written in 1958, Lisp[1] is a family of programming languages and the second-oldest high-level programming language in use today[2]. We will adopt Common Lisp[3] (CL), one of the two most widely known dialects[4] of Lisp to model, construct and manipulate lists and subsequently define functions.

A list is the central notion of functional programming. An element of a list can be either an atom or a list. A list can also be empty. Consider the following examples:

```
()              ; The empty list.
(1 3 5 7)       ; A list of four elements, the numbers 1, 3, 5, and 7.
((1 2)(3 4))    ; A list of two elements, the list (1 2) and
                ; the list (3 4).
(((1 2)(3 4))) ; A list of one element, the list ((1 2)(3 4)).
(a (b 1) 2)     ; A list with three elements: the symbol a,
                ; the list (b 1) and the number 2.
```

[1]Historically known as LISP as this is an abbreviation of LISt Processing.
[2]The oldest high-level language in use today is Fortran.
[3]ANSI INCITS 226-1994 (R2004).
[4]The second most widely known dialect of Lisp is Scheme.

5.1 Expressions and functions

A function f is a mapping from each element in a set A to exactly one element in a set B. The function is denoted by $f : A \to B$. The set A is the *domain* of f and the set B is the *codomain* of f. We also say that f has *type* $A \to B$.

If $f(x) = y$, then x is called an *argument* of f, and y is called a *value* of f. If the domain of f is the Cartesian product $A_1 \times ... \times A_n$, we say f has *arity* n.

Expressions are written as lists, using prefix notation. Prefix notation is a form of notation for logic, arithmetic, and algebra. It places operators to the left of their operands. For example, the (infix) expression $14 - (2 \times 3)$ is written as $(-14(\times 23))$.

The first element in an expression list is the name of a function and the remainder of the list are the arguments:

$$(functionName \;\; arguments)$$

When an expression is evaluated, it produces a value (or list of values), which then can be embedded into other expressions. In the above example, `(* 2 3)` will invoke the `*` (multiplication) function on the arguments `2` and `3` returning `6` which will in turn become the second argument to the invocation of the `-` (subtraction) function which will return `8`. This shows that we can invoke Lisp as a calculator.

As in arithmetic, we can nest expressions. Nested expressions are evaluated by reducing the innermost parenthesized expressions to numbers, followed by the next layer, and so on. Unlike in regular arithmetic where multiplication has priority over addition the evaluation of prefix expressions is unambiguous. For example, the expression

$$\frac{a \;-\; b \;\times\; c}{d \;\times\; e \;+\; f}$$

is translated in prefix notation as

$$(/\ (-\ a\ (*\ b\ c))\ (+\ (*\ d\ e)\ f))$$

The term *arity* is used to describe the number of *arguments* or *operands* that a function takes. A *unary* function (arity `1`) takes one argument. A *binary* function (arity `2`) takes two arguments. A ternary *function* (arity `3`) takes three arguments, and an `n`-ary function takes `n` arguments. Furthermore, *variable arity* functions can take any number of arguments. For example,

```
(+ 1 2 3 4) ; Equivalent to infix (1 + 2 + 3 + 4). Returns 10.
(* 2 3 4)   ; Equivalent to infix (2 * 3 * 4). Returns 24.
(< 1 3 2)   ; Equivalent to (1 < 3 < 2). Returns false (NIL).
```

5.2 Prohibiting expression evaluation

The subexpressions of a procedure application are evaluated, whereas the subexpressions of a quoted expression are not.

```
 (/ (* 2 6) 3)   ; Returns 4.
'(/ (* 2 6) 3)   ; Returns (/ (* 2 6) 3).
```

5.3 Boolean operations

Lisp supports Boolean logic with operators `and`, `or`, and `not`. The two former have variable arity, and the last one is a unary operator.

The `or` Boolean operator evaluates its subexpressions from left to right and stops immediately (without evaluating the remaining expression) if any subexpression evaluates to *true*. In the example below the `or` function will return *true* which is the value of `(> x 3)`. Note that the values *true*/*false* are denoted in Lisp by `t`/`nil` respectively.

```
> (let ((x 5))
(or (< x 2) (> x 3)))
T
```

The `and` Boolean operator evaluates its subexpressions from left to right and stops immediately (without evaluating the remaining expression) if any subexpression evaluates to *false*. In the example below the `and` function will return `nil` which is the value of `(< x 3)`.

```
> (let ((x 5))
(and (< x 7) (< x 3)))
NIL
```

Consider another example:

```
>(or (and (= 1 1) (< 5 6)) (not (> 3 1)))
T
```

5.4 Constructing lists

We have three mechanisms to create a list which are summarized below:

1. `cons`: creates a list by adding an element as the head of an existing list.
2. `list`: creates a list comprised of its arguments.
3. `append`: creates a list by concatenating existing lists.

Constructing lists with `cons`

Function *cons* constructs a new list by adding a new element at the head of an existing list. For an element h and a list L, $cons(h, L)$ denotes a list whose head is h and whose tail is L. Consider the following examples:

$$cons(a, \langle\rangle) = \langle a \rangle$$

$$cons(a, \langle b, c \rangle) = \langle a, b, c \rangle$$

For any non-empty list L, the operations *cons*, *head* and *tail* are related as follows:

$$cons(head(L), tail(L)) = L$$

The function `cons` is a binary function: it expects two arguments, an element and a list. If an element is added to an empty list, then `cons` is essentially used to create a list, as in the first of the examples below:

```
(cons 'a '())         ; Returns (a).
(cons 1 '(2 3))       ; Returns (1 2 3).
(cons '(1 2) '(3 4)) ; Returns ((1 2) 3 4).
```

A list in Lisp is singly-linked where each node is a pair of two pointers, the first one pointing to a data element and the second one pointing to the tail of the list with the last node's second pointer pointing to the empty list (See Figure 5.1).

For example, the list `(a)` can be constructed (and represented) as `(cons 'a '())` or `(cons 'a nil)`.

```
> (cons 'a '())
(A)
(cons 'a nil)
(A)
```

The list `(a b)` can be constructed as `(cons 'a (cons 'b '()))` or `(cons 'a (cons 'b nil))`.

```
> (cons 'a (cons 'b '()))
(A B)
> (cons 'a (cons 'b nil))
(A B)
```

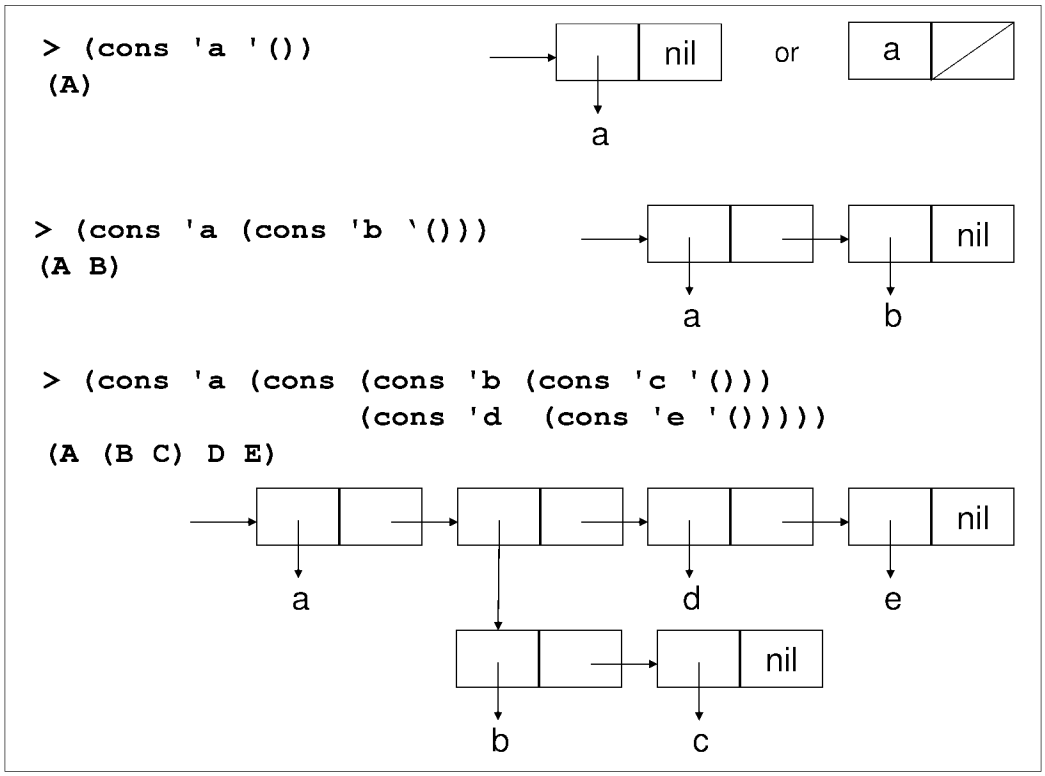

Figure 5.1: List representations.

The list `(a (b c) d e)` can be constructed as `(cons 'a (cons (cons 'b (cons 'c '())) (cons 'd (cons 'e '()))))`.

```
> (cons 'a (cons (cons 'b (cons 'c '())) (cons 'd  (cons 'e '()))))
(A (B C) D E)
```

5.5 Mutability

An object is said to be *mutable* (as opposed to *immutable*) if it can be modified once it is created. In the example `(cons '(a b) '(c d))` the function `cons` produces a new list, as opposed to modifying any of its list arguments.

Example 5.1. Consider the following sequence of list constructions using `cons`:

```
> (cons (+ 2 3) '(b c))
```

Is the above syntactically correct? Yes, because there are indeed two arguments supplied to `cons` and the second argument is a list. Here, the parenthesized form `(+ 2 3)` is evaluated and replaced by an element, 5, which is now the head of a newly created list, whose tail is the list `(b c)` passed as a second argument. As a result, the function will return the list `(5 B C)`.

What if we had placed a quote in front of the first argument, i.e.

```
>(cons '(+ 2 3) '(b c))
```

Lisp would *not* proceed to evaluate the expression, thus taking the parenthesized form as is. The result would be the list `((+ 2 3) B C)`.

Consider the following:

```
> (cons a)
```

Is this syntactically correct? No, because there are two errors here. First, `a` cannot be evaluated. Second, there is only one argument. A list as a second argument is missing. As a result, the function will return `Error` (*The variable A is unbound.*)

How about the following:

```
> (cons 'a)
```

Is this syntactically correct? No, because there is only one argument. Even though we use quotation to tell Lisp not to evaluate `a`, a list (as a second argument) is missing. As a result, the function will return `Error` (*The call does not match definition.*)

Consider the following:

```
> (cons 'a '())
```

Is this syntactically correct? Yes, because we have an element and a list. This creates a new list whose head is `a`, and whose tail is the list passed as the second argument (the empty

list). As a result, the function will return `(A)`.

Yet one more example:

```
> (cons 'a '(b c d))
```

Is this syntactically correct? Yes, because we have an element and a list. This is very similar to the previous problem, only the second argument is not the empty list. As a result, the function will return `(A B C D)`.

Constructing lists with `list`

Function `list` takes any number of arguments and constructs a list comprised of these arguments. Function `list` has variable arity, i.e. it can take any number of arguments.

```
(list 1 2 'a 3)                ; Returns (1 2 A 3).
(list 1 '(2 3) 4)              ; Returns (1 (2 3) 4).
(list '(+ 2 1) (+ 2 1))        ; Returns ((+ 2 1) 3).
(list 1 2 3 (list 'a 'b 4) 5) ; Returns (1 2 3 (a b 4) 5).
```

Example 5.2. Consider the following sequence of list constructions using `list`:

```
> (list a 1)
```

Is this syntactically correct? No, because `a` cannot be evaluated. If we wanted to pass it as an element, we needed to precede it with a quote. As a result, the function will return `Error` (*The variable A is unbound*).

Consider the following:

```
> (list 'a 1)
```

This is very similar to the above, only now we tell the interpreter not to attempt to evaluate `a`. The function will create a list with all its arguments as its elements and will return `(A 1)`.

One more example:

```
> (list 'a '())
```

Note that as a list can be nested (i.e. it can contain other lists), the empty list is a valid list element. The function will return `(A NIL)`. It is interesting to query on the length of this list with the built-in function `length`:

```
> (length (list 'a '()))
2
```

Let us now extend the previous problem:

```
> (list 'a '() '() '())
```

This will create and return the list `(A NIL NIL NIL)`. What is the length of this list?

```
> (length (list 'a '() '() '()))
4
```

Consider the following:

```
> (list 'a)
```

This will create the singleton list `(A)`.

One more example:

```
> (list (a b) 2)
```

Is this syntactically correct? No, because Lisp will attempt to resolve `(a b)` (remember: it assumes that it is an expression to be evaluates) but will fail. As a result, the function will return `Error` (*Undefined operator A in form (A B)*). From the error message you can see that it assumes the first element of the parenthesized form, `a`, to be an operator (function).

A slight variation:

```
> (list '(a b) 2)
```

This is very similar to the above, only now we tell the interpreter not to attempt to evaluate `(a b)`. This will create a list with two elements, the first of which is the list `(a b)`: `((A B) 2)`.

How about an example where we have compound list constructions?

```
> (list (list 'a 'b) 2)
```

Whenever you see examples like this, work your way from the innermost parentheses outwards. The inner parenthesis contains function `list` which takes two arguments and it will create the list `(a b)`. Thus, the outer function is now interpreted as `(list '(a b) 2)`, and it will return `((A B) 2)`.

Yet another compound list construction:

```
> (list (cons 'a (cons 'b '())) 2)
```

We follow exactly the same approach like the previous problem: We work our way from the innermost parentheses outwards. The innermost `cons` will create the list `(b)`, thus making the outer `cons` as `(cons 'a '(b))` which returns the list `(a b)`. The list `(a b)` will be the first element in a newly created list, whose second (and last) element is `2`. Thus, the `list` function will now create the list `((A B) 2)`.

Constructing lists with append

Concatenation is the operation of joining two sequences of elements end to end. Concatenation can be applied to strings or lists. In the latter case, we can demonstrate the operation of concatenation with the following example:

$$concatenate(\langle a, b\rangle, \langle c, d\rangle) \rightarrow \langle a, b, c, d\rangle$$

Function `append` constructs a new list by concatenating any number of lists that are supplied as its arguments. Much like `list`, function `append` has variable arity, i.e. it can take any number of arguments. There is a restriction on the types of its arguments: they must all be lists.

```
(append '(1 2) '(3 4))                      ; Returns (1 2 3 4).
(append '(1 2 3) '() '(a) '(5 6))           ; Returns (1 2 3 a 5 6).
(append '(1 2 3 '(a b c)) '() '(d) '(4 5)) ; Returns (1 2 3 (QUOTE (a b c)) d 4 5).
```

Note that `append` expects only lists as its arguments. The following call to `append` will cause an error since the first argument, 1, is not a list.

```
> (append 1 '(4 5 6))
Error: 1 is not of type LIST.
```

To create the list `(1 4 5 6)` we must first transform 1 into a list:

```
> (append (list 1) '(4 5 6))
(1 4 5 6)
```

Example 5.3. Consider the following sequence of list constructions using `append`:

First, our intention is to create the list `(a b c)`.

```
> (append 'a '(b c))
```

Is the above syntactically correct? No, because the first argument is not a list. As a result, the function will return an `Error` (*A is not of type LIST).* What if we insisted to create the list `(a b c)` using `append`? We must transform the first argument from an atom to a list. We have a few options here as shown below:

```
> (append '(a) '(b c))
(A B C)
```

```
> (append (cons 'a '()) '(b c))
(A B C)

> (append (list 'a) '(b c))
(A B C)
```

Consider the following evaluation:

```
> (append (cons 'a '()) (list 'b 'c))
```

We have nested expressions, therefore we must work our way from the innermost outwards. The first expression will create the list `(a)` and the second expression will create the list `(b c)`. The outermost expression now becomes `(append '(a) '(b c))` and it will create the list `(A B C)`.

Consider the following:

```
> (append '() '(a) '(b c) '())
```

This problem is straightforward. Function `append` will concatenate all elements of all its list arguments, returning `(A B C)`.

Yet one more example:

```
> (append '(nil) '(a) '(b c) '())
```

As in the previous problem: Function `append` will concatenate all elements of all its list arguments and it will return `(NIL A B C)`.

Example 5.4. At first, the following expression may seem rather complicated:

```
> (append (list 'a '(c d)) (cons 'f (list 'g (cons 'k '()))))
```

Do not get intimidated with problems like this. The approach should always be the same: Let us work our way from innermost parenthesized expressions outwards. There are two expressions which are passed as arguments to `append`, both of which are evaluated as lists (thus the form is syntactically correct).

- First argument: `(list 'a '(c d))` will return the list `(a (c d))`.
- Second argument:
  - `(cons 'k '())` will return the list `(k)`.
  - `(list 'g (cons 'k '()))` is now interpreted as `(list 'g '(k))`, returning the list `(g (k))`.
  - `(cons 'f (list 'g (cons 'k '())))` is now interpreted as `(cons 'f '(g (k)))`, returning the list `(f g (k))`.

The outermost expression can thus be interpreted as

```
> (append '(a (c d)) '(f g (k)))
```

and it will return `(A (C D) F G (K))`.

5.6 Accessing a list

We can only access either the head of a list, or the tail of a list. Hence, only two operations are available: car and cdr. The names are indeed cryptic. Operation `car` is sometimes referred to (and implemented) as `first`, and operation `cdr` is referred to and implemented as `rest`[5]. In this text we will adopt `car, crd`.

Operation `car` takes a list as an argument and returns the head of the list. Note that the head of a list can be either an atom or itself a list. For example,

[5]If your Lisp implementation supports both notations, my suggestion is to adopt one pair only, i.e. chose between car/cdr and first/rest and keep a consistency. It is confusing to mix the two notations.

```
(car '(a s d f))   ; Returns a.
(car '((a s) d f)) ; Returns (a s).
```

Operation `cdr` takes a list as an argument and returns the tail of the list. Note that the tail of a list is itself a list. For example,

```
(cdr '(a s d f))     ; Returns (s d f).
(cdr '((a s) d f))   ; Returns (d f).
(cdr '((a s) (d f))) ; Returns ((d f)).
```

In the following example, we are interested in accessing the second element in a list. The second element is the head of the tail of the list:

```
(car (cdr '(1 (3 5) (7 11)))) ; Returns (3 5).
```

Example 5.5. Consider the following operations to construct and access a list:

```
> (car (list '() '(a b c)))
NIL
```

As in previous examples, we should work our way from the innermost parentheses outwards. The inner function `list` will create the list `(nil (a b c))`. This list has two elements. Function `car` will return the head of this list. It so happens that the head is not an atom, but a list. In fact it is the empty list.

What if instead of the head we wanted to obtain the tail of the list? The tail of any list is a list containing all elements except the first (head).

```
> (cdr (list '() '(a b c)))
((A B C))
```

This list contains one element which is itself the list `(a b c)`.

Consider the following:

```
> (cdr (append '() '() '()))
```

Function `append` will concatenate all elements of all (list) arguments. There are *no* elements in its arguments, so the result is the empty list: `NIL`. There is no tail to the empty list, thus the result is `NIL`.

How about if in the previous example, we used `list` instead?

```
> (cdr (list '() '() '()))
```

Unlike function `append` which looks at the contents of its arguments, function `list` will take all its arguments (even if empty) as elements in the newly created list, i.e. the result of `(list '() '() '())` is the list `(nil nil nil)`. The tail of this list is the list `(nil nil)`.

Example 5.6. Consider the following expression evaluation:

```
(append (list 'b '(d e) (* 2 3)) (cons '(+ 2 3) (list 'f (cons 'g '()))))
```

Let us work our way from innermost to outermost expressions:

```
> (list 'b '(d e) (* 2 3))
(B (D E) 6)

> (cons '(+ 2 3) (list 'f (cons 'g '())))
((+ 2 3) F (G))
```

The value of the outermost expression is `(B (D E) 6 (+ 2 3) F (G))`. Its length is 6.

Example 5.7. Consider the following expression evaluation:

```
(list (append '(+ 1 4) '() (list '() '()))
      (cons (+ 1 4) (list 'a (cons (+ 1 7) '()))))
```

Let us work our way from innermost to outermost expressions:

```
> (append '(+ 1 4) '() (list '() '()))
(+ 1 4 NIL NIL)

>  (cons (+ 1 4) (list 'a (cons (+ 1 7) '())))
(5 A (8))
```

The value of the outermost expression is `((+ 1 4 NIL NIL) (5 A (8)))`. Its length is 2.

Example 5.8. Consider the following expression evaluation:

```
(car (cdr (cdr (append (list '() '(a))
               (cons 'b (list (+ 2 3 4)))))))
```

Let us first evaluate the values of the two expressions supplied as arguments to function `append`:

```
> (list '() '(a))
(NIL (A))

> (cons 'b (list (+ 2 3 4)))
(B 9)
```

Thus, the `append` expression becomes

```
(append (list '() '(a)) (cons 'b (list (+ 2 3 4))))
```

and it is evaluated to `(NIL (A) B 9)`.

```
(cdr (append (list '() '(a)) (cons 'b (list (+ 2 3 4)))))
```

evaluates to `((A) B 9)`.

```
(cdr (cdr (append (list '() '(a)) (cons 'b (list (+ 2 3 4))))))
```

evaluates to `(B 9)` and its head (the overall evaluation) is `B`. This is an atom (not a list) so there is no notion of length.

Example 5.9. Consider the following expression:

```
(car (cdr (cdr (append (append '() '(a) '()) (list 'b '() (cons (+ 3 4) '()))))))
```

```
> (append '() '(a) '())
(A)

> (list 'b '() (cons (+ 3 4) '()))
(B NIL (7))
```

Thus, the `append` expression becomes

```
(append (append '() '(a) '()) (list 'b '() (cons (+ 3 4) '())))
```

and it evaluates to `(A B NIL (7))`.

```
(cdr (append (append '() '(a) '()) (list 'b '() (cons (+ 3 4) '()))))
```

evaluates to `(B NIL (7))`.

```
(cdr (cdr (append (append '() '(a) '()) (list 'b '() (cons (+ 3 4) '())))))
```

evaluates to `(NIL (7))` and its head (the overall evaluation) is `NIL` (the empty list). The length of the empty list is zero.

5.7 Predicate functions

A function whose return value is intended to be interpreted as truth or falsity is called a *predicate function*. The built-in function `listp` returns true if its argument is a list. For example,

```
(listp '(a b c)) ; Returns true (T).
(listp 7)        ; Returns false (NIL).
```

Other common predicate functions include:

Predicate	Description
(`numberp` *argument*)	Returns *true* if *argument* is a number.
(`zerop` *argument*)	Returns *true* if *argument* is zero.
(`evenp` *argument*)	Returns *true* if *argument* is an even number.
(`oddp` *argument*)	Returns *true* if *argument* is an odd number.

We provide a larger list of such predicate functions in Chapter 7: *Functions I*.

5.8 Advanced mathematical operations

Lisp provides a number of built-in advanced mathematical operations. For example, `(sqrt a)` returns $\sqrt{a}$, `(expt a b)` returns a^b and `(log a)` returns the natural logarithm of a.

```
> (sqrt 9)
3.0
> (expt 2 3)
8
> (log 10)
2.3025852
```

Chapter 6

Control flow

The simplest single conditional is `if`:

(`if` *testExpression*

thenExpression)

An alternative form is

(`if` *testExpression*

thenExpression

elseExpression)

The *testExpression* is a predicate while the *thenExpression* and the (optional) *elseExpression* are expressions to be evaluated.

Consider the following example:

```
(if (listp '(a b c)) ; If (a b c) is a list...
    (+ 3 7)          ; ...then evaluate this expression,
    (+ 1 3))         ; ...else evaluate this one.
```

Multiple selection can be formed with a `cond` expression which contains a list of clauses where each clause contains two expressions, called *question* (condition) and *answer*. Optionally, we can have an `else` clause.

```
( cond  (question  answer)
        ...
        (else  answer) )   ; Optional.
```

Questions are predicate expressions evaluated to true or false whereas answers are expressions. Questions are evaluated sequentially. For the first question that evaluates to true, Lisp evaluates the corresponding answer, and the value of the answer is the value of the entire `cond` expression. If the last condition is `else` and all other conditions fail, the answer for the `cond` expression is the value of the last answer expression. We can also use `t` (true) in place of `else`.

6.1 Variables and binding

Binding is a mechanism for implementing *lexical scope* for variables. The `let` syntactic form takes two arguments: a list of bindings and an expression (the body of the binding) in which to use these bindings.

```
( let
      ( (binding_1)
        (binding_2)
        ...          )
      (expression)  )
```

where $(binding_n)$ is of the form $(variable_n\ value)$.

The `let` values are computed and bindings are done in parallel, which requires all of the definitions to be independent. In the example below, x and y are let-bound variables; they are only visible within the body of the let.

```
(let ((x 2) (y 3))
    (+ x y))
; Returns 5.
```

6.2 Context and nested binding

An operator like `let` creates a new lexical context. Within this context there are new variables, and variables from outer contexts may become invisible. A binding can have different values at the same time:

```
(let ((a 1))
   (let ((a 2))
      (let ((a 3))
         ...)))
```

Here, variable `a` has three distinct bindings by the time the body (marked by ...) executes in the innermost `let`. The inner binding for a variable shadows the outer binding and the region where a variable binding is visible is called its scope. Consider the following example:

```
(let ((x 1))              ; x is 1.
     (let ((x (+ x 1))) ; x is 2.
     (+ x x)))            ; Returns 4.
```

What if we want the value of one new variable to depend on the value of another variable established by the same expression? In that case we have to use a variant called `let*`. A `let*` is functionally equivalent to a series of nested lets.

Consider the following example:

```
(let* ((x 10)
       (y (* 2 x))) ; Not legal for let.
       (* x y))
; Returns 200.
```

Chapter 7

Functions I

7.1 Introduction to mathematical functions

A function is a relation between a set of inputs and a set of (potential) outputs where each element of the input set maps (i.e. it is related) to exactly one element of the output set. Given a function $f : X \to Y$, where X and Y are sets, then X is called the *domain* of f and Y is called the *codomain* of f. In the expression $f(x)$, x is called the *argument* and $f(x)$ is called the *value* for the function. The definition of a function is not confined to numbers. In fact a function may relate elements of any two sets.

7.2 Defining functions

We can define new functions using `defun`. A function definition looks like this:

(`defun` *name* (*formal parameter list*)
body)

We will demonstrate function construction through a number of examples.

Example 7.1. Consider function `absdiff` takes two numbers as arguments and returns

their absolute difference:

```
(defun absdiff (x y)
  (if (> x y)
    (- x y)
    (- y x)))
```

We can execute the function as follows:

```
> (absdiff 3 5)
2
```

In the function definition above, `absdiff (x y)`, x and y are the *formal parameters* of the function. In `(absdiff 3 5)`, 3 and 5 are the *arguments* (or *actual parameters*) to the function `absdiff` and they are *bound* to its formal parameters.

Example 7.2. A *palindrome* is a string which can be read the same way in any direction. For example `abba` is a palindrome, but `abb` is not. Define a function `ispalindrome` which receives a list argument `list` and returns true if `list` is a palindrome; it returns false otherwise. Function `equal` returns *true* if its arguments have the same value.

```
(defun ispalindrome (list)
  (equal list (reverse list)))
```

We can execute the function as follows:

```
> (ispalindrome '(a b b a))
T
> (ispalindrome '())
T
> (ispalindrome '(a b b))
NIL
```

Example 7.3. Consider function `third2`[1] which takes a list as an argument and returns its

[1]Lisp provides a number of built-in functions, including `third` in some implementations. Our naming convention in the cases where we provide our own implementation as in this and other similar examples must reflect this fact.

third element. The third element of a list is the head of the tail of the tail of the original list.

```
(defun third2 (lst)
  (car (cdr (cdr lst))))
```

We can execute the function as follows:

```
> (third2 '(a b c d))
C
> (third2 '(a (b c) (d e f) (g)))
(D E F)
```

7.3 Side effects

In computer science, a function or expression is said to produce a *side effect* if it modifies some state in addition to its return value. For example, a function might modify some global variable, modify one of its arguments, write data to a display or file, or read some data from other side-effecting functions. We discuss side effects in detail in Chapter 8.

7.4 Pure functions

A function may be described as *pure* if both these statements about the function hold:

1. The function always evaluates the same result value given the same argument value(s).
2. The evaluation of the result does not cause any semantically observable side effect or output, such as mutation of mutable objects or output to I/O devices.

Consider the following examples:

- A function `length(string)` is pure because it returns the size of a string.
- A function `today()` is impure because at different times it will yield different results.

- A function `print(arg)` is impure because it causes output as an effect.

Pure functions allow optimization of expressions through a process called *common subexpression elimination*. For example, consider $y = f(x) \times f(x)$. The evaluation of $f(x)$ can be costly. A compiler can perform an optimization by factoring out $f(x)$ if it is pure, transforming the program to

$$z = f(x)$$
$$y = z \times z$$

thus eliminating the second evaluation of $f(x)$.

If a function is impure, common subexpression elimination is not possible. For example, in $y = random() \times random()$, then the second call to $random()$ cannot be eliminated, because its return value will (most likely) be different from that of the first call.

7.5 Referential transparency

An expression is said to be *referentially transparent* (as opposed to *referentially opaque*) if it can be replaced with its value without changing the program (in other words, yielding a program that has the same effects and output on the same input). Since referential transparency involves the concept of *determinacy* (producing the same result for each input), all referentially transparent functions are determinate. If all functions involved in the expression are pure functions, then the expression is referentially transparent. In pure functional programming, referential transparency is enforced for all functions.

Examples where referential transparency holds:

- `(* 5 5)` can be replaced by `25`.
- $sin(x)$ will always give the same result for any given x.

Examples where referential transparency does not hold:

- The expression `x++` in languages such as C++ or Java is not transparent, as it changes the value of `x`.
- `System.out.println("Hello world")` cannot be replaced by its value (say, `0`) since *Hello world* will not be displayed.
- Function `today()` cannot be replaced by its value (say, "June 27, 2009") since it will not yield the same result the day after.

Being side-effect free is necessary but not sufficient for referential transparency. Referential transparency implies that an expression (such as a function call) can be replaced with its value; this requires that the expression has no side effects and is determinate.

7.6 Idempotence

The notion of *idempotence* is a property of a mathematical operation that has the same effect if used multiple times as it does if used only once. For example, the absolute value, $abs()$, function is idempotent, as

$$\begin{aligned} abs(x) &= abs(abs(x)) \\ &= abs(abs(abs(x))) \\ &= ...for\ all\ x. \end{aligned}$$

In other words, applying *abs* exactly once yields the same result as repeatedly applying *abs* any number of times.

7.7 Higher-order functions

Functions are called *higher-order* if they do at least one of the following:

1. Take one or more functions as their arguments.
2. Return a function.

The derivative function in calculus is a common example, since it maps a function to another function, e.g.

$$\frac{d}{dx}\left(x^2\right) = 2x$$

As an example, consider function `sort` which takes as an argument a list, constructed through function `list`, and the comparison operator greater-than (>) and returns a sorted list.

```
>(sort (list 5 0 7 3 9 1 4 13 23) #'>)
(23 13 9 7 5 4 3 1 0)
```

Common higher-order functions in Lisp that take functions as arguments are:

`mapcar` takes as its arguments a function and one or more lists and applies the function to the elements of the list(s) in order.

```
> (mapcar #'* '(2 3) '(10 10)) ; Multiplication applies to successive pairs.
(20 30)
```

`funcall` takes as its arguments a function and a list of arguments (does not require arguments to be packaged as a list), and returns the result of applying the function to the elements of the list.

```
> (funcall #'+ 1 3 4)  ; Equivalent to (+ 1 3 4).
8
```

`apply` works like `funcall`, but requires that the last argument is a list.

```
> (apply #'+ 3 4 '(1 3 4))
15
```

Example 7.4. Consider each of the following expressions and their corresponding output:

1. `(car (cdr (append (cons (list (* 2 4 2) '(* 2 4 2)) (list '(a b c) (+ 1 2 3))))))`

   `> (A B C)`

2. `(mapcar #'max (append (cons 9 (list 6 15)) '(3)) (append '() (cons 10 '(4 17 3))))`

   `> (10 6 17 3)`

3. `(funcall #'min (- 9 6) 1 (+ 2 3 5))`

   `> 1`

4. `(apply #'+ 3 5 (append '() '(4) (cons 4 (list 3 2))))`

   `> 21`

5. `(apply #'+ 4 (mapcar #'* '(2 4) '(3 2)))`

   `> 18`

7.8 Anonymous functions

An *anonymous function* is one that is defined, and possibly called, without being bound to an identifier. Unlike functions defined with `defun`, anonymous functions are not stored in memory. The general syntax of an anonymous function in Lisp (also called *lambda expression*) is

(`lambda` (*formal parameter list*) (*body*))

where *body* is an expression to be evaluated.

An anonymous function can be applied in the same way that a named function can, e.g.

```
> ((lambda (x) (* x x)) 3)
9
```

Example 7.5. In this example we combine a higher-order function with an anonymous function. Consider a function that takes a list as an argument and returns a new list whose elements are the elements of the initial list multiplied by 2. We can perform the multiplication with an anonymous function, and deploy `mapcar` to apply the anonymous function to the elements of the list as follows:

```
>  (mapcar (lambda (n) (* n 2)) '(2 3 5 7))
(4 6 10 14)
```

Essentially, a lambda expression is a non-reusable inline function. We can deploy lambda expressions when we want to avoid having one-line functions which are unlikely to be reused.

7.8.1 Equivalence between `let` and `lambda`

We can demonstrate the equivalence between `let` and `lambda` through the following example:

```
> (let ((x a)) (list x x))
(A A)
> (setf lst ((lambda (x) (list x x)) 'a))
(A A)
```

where `x` is called a *bound variable* within the function.

7.9 Parameter lists

In this section we will discuss rest, optional and keyword parameters.

7.9.1 Developing variable arity functions with rest parameters

So far, we developed functions that would take a predetermined number of arguments. We should, however, be able to write a function of variable arity and we can do this through a

rest parameter. The token `&rest` before the last parameter in the parameter list, makes this last parameter a list that will contain all the remaining arguments.

In the following example, we define function `construct-list` that takes any number of arguments and places them in a list. Notice that in the case where no second (or third etc.) argument is provided, the list represented by `args` is empty.

```
(defun construct-list (thing &rest args)
  (cons thing args))
```

We can execute the function as follows:

```
> (construct-list 'a)
(A)
> (construct-list 'a '())
(A NIL)
> (construct-list 'a 'b 'c 'd)
(A B C D)
> (construct-list 'a '(b c))
(A (B C))
```

7.9.2 Optional parameters

As the term suggests, an *optional parameter* (as opposed to *required*) is one that can be omitted. Additionally, an optional parameter can have a default value. The implicit default value is `nil`, but we can provide an explicit default.

In the next example, we leave the default implicit value for the optional parameter `arg`:

```
(defun make-quote (thing &optional arg)
  (list thing arg))
```

```
>(make-quote 'all)
(ALL NIL)
```

Let us now modify the function slightly and also provide an explicit default value to parameter `arg` which we specify by enclosing it in a list with the parameter:

```
(defun make-quote (thing &optional (arg 'die))
  (list thing 'men 'must arg))
```

We can execute the function as follows:

```
> (make-quote 'all)
(ALL MEN MUST DIE)
> (make-quote 'all 'serve)
(ALL MEN MUST SERVE)
```

7.9.3 Keyword parameters

A more flexible kind of optional parameter is the *keyword parameter*. In a parameter list, all parameters after the `&key` symbol are optional. Additionally, they can be identified not by their position in the parameter list, but by symbolic tags that precede them.

In the following example, function `make-pairs` takes four optional paremeters that combines into a list of two pairs:

```
(defun make-pairs (&key a b c d)
  (list (list a b) (list c d)))
```

We now can execute the function by passing arguments under symbolic tags that would correspond to the function parameters:

```
> (make-pairs :c 3 :a 5 :d 1 :b 9)
((5 9) (3 1))
```

As the implicit default is `nil`, consider the following example:

```
> (make-pairs)
((NIL NIL) (NIL NIL))
```

Consider another execution where we combine implicit defaults and symbolic tags:

```
> (make-pairs :a 7 :d 6)
((7 NIL) (NIL 6))
```

To specify explicit defaults we have to modify our function:

```
(defun make-pairs (&key a b c (d 'last))
  (list (list a b) (list c d)))
```

Finally, consider the example where we combine implicit and explicit defaults, and symbolic tags:

```
>  (make-pairs :a 7)
((7 NIL) (NIL LAST))
```

Example 7.6. In the following example, we build a utility function, `fn`, that will read an argument and return a function based on the type of the argument. If the argument is a number, then the function will return `+`, otherwise if the argument is a list, then the function will return `append`.

```
(defun fn (x)
  (cond
    ((numberp x) #'+)
    ((listp  x) #'append)))
```

Function `combine` takes any number of arguments (note that the assumption is that all arguments are of the same type and are either numbers or lists). It will call the utility function `fn` to read in the first argument and return a function that will in turn be used to combine all arguments accordingly: If the arguments are numbers, then they will be added. If the arguments are lists, then they will be concatenated.

```
(defun combine (&rest args)
  (apply (fn (car args)) args))
```

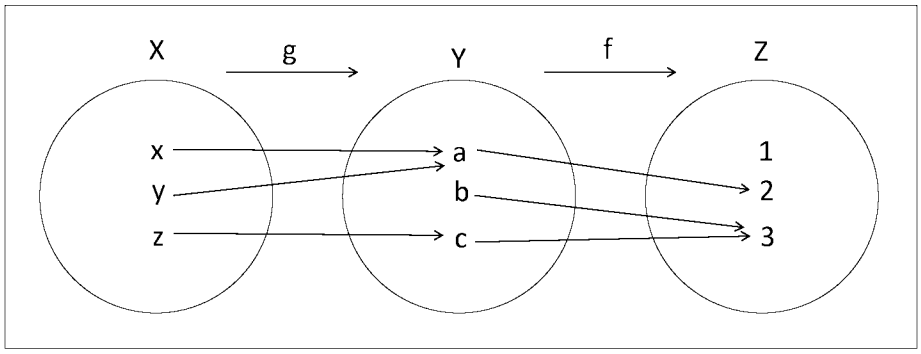

Figure 7.1: Example of function composition.

```
> (combine 2 3 4)
9
> (combine '(a b) '(c d))
(A B C D)
```

7.10 Function composition

We can construct a new function by combining simpler functions. Many times we use *composition* of functions even though we may not refer to it explicitly as such. The composition of two functions f and g is the function denoted by $f \circ g$ is defined as

$$(f \circ g)(x) = f(g(x))$$

The composition makes sense only for values of x in the domain of g such that $g(x)$ is in the domain of f.

Example 7.7. In Figure 7.1, X is the domain of g and Y is the codomain of g. Values of $g(x)$ are in Y which is the domain of f. For example, $g(x) = a$, and $f(g(x)) = 2$.

Example 7.8. For the list $L = \langle a, b \rangle$, $head(tail(L))$ is a valid function composition, whereas $tail(head(L))$ is not a valid function composition because $head(L)$ is an atom.

Example 7.9. For $f(x) = x + 2$ and $g(x) = x^2 - 1$, then $(f \circ g)(x)$ yields $(x^2 - 1) + 2$.

Example 7.10. Consider function *consR* which places an element to the right of a list, just as function *cons* places an element on the left of a list. For example,

$$consR(\langle a, b, c\rangle, d) = \langle a, b, c, d\rangle.$$

We can provide a recursive computable function definition for `consR(L, e)` (either in mathematical or in natural language notation).

$$consR(L, e) = if\ L\ =\ \langle\rangle\ then\ \langle e\rangle$$
$$else\ \ concatenate(head(L), consR(tail(L), e)).$$

We can translate the above definition into Common Lisp function `consr(lst elt)`. Note that for the purpose of this example, we may not use `append` or anything equivalent to just attach an element to the end of the list.

```
(defun consr (lst elt)
    (if (null lst) (list elt)
       (cons (car lst) (consr (cdr lst) elt))))
```

Example 7.11. Let us define a Common Lisp function which takes two lists as its arguments and returns a list whose elements are the products of the corresponding pairs of its arguments. For example,

```
> (product '(2 3) '(4 5))
(8 15)
> (product '(2 2 4) '(3 4 5))
(6 8 20)
```

In the case of arguments of different length, the function should ignore any remaining elements. For example,

```
> (product '(2 3) '(4 5 6 7))
(8 15)
```

The function is defined as follows:

```
(defun product (lst1 lst2)
  (if (or (null lst1) (null lst2))
    nil
    (let ((a (* (car lst1) (car lst2))))
       (cons a (product (cdr lst1) (cdr lst2))))))
```

7.11 Common built-in and predicate functions

A non-exhaustive list of Common Lisp built-in functions and predicates is shown below:

abs Returns the absolute value of its argument.

```
> (abs -3)
3
> (abs 5.5)
5.5
```

atom Returns true if its argument is an atom; Returns false otherwise.

```
> (atom 'a)
T
> (atom 1)
T
> (atom '())
T
> (atom '(a b c))
NIL
```

equal Returns true if its arguments have the same value; Returns false otherwise. Compare it with function `eq` in Chapter 8: *Side effects*.

```
> (equal 'a 'a)
T
> (equal 3 3.0)
NIL
> (equal 5 5)
T
> (equal 'a '(a))
NIL
```

evenp Returns true if argument is an even integer number; Returns false otherwise. An error occurs if the argument is not an integer number.

```
> (evenp 2)
T
> (evenp 0)
T
> (evenp 3)
NIL
> (evenp -1)
NIL
> (evenp -2)
T
```

integerp Returns true if its argument is an integer number; Returns false otherwise.

```
> (integerp 2)
T
> (integerp 2.5)
NIL
> (integerp -2)
T
```

```
> (integerp (car '(1 2.5 ())))
T
```

listp Returns true if its agrument is a list; Returns false otherwise.

```
> (listp '())
T
> (listp (car (cdr '(a (bc)))))
T
```

null Returns true if its argument is the empty list; Returns false otherwise.

```
>(null '())
T
> (null '(a b c))
NIL
```

numberp Returns true if its argument is a number; Returns false otherwise.

```
> (numberp 0)
T
> (numberp 'a)
NIL
> (numberp '(1 2 3))
NIL
> (numberp (car '(1 2 3)))
T
```

oddp Returns true if its argument is an add integer number; Returns false otherwise. An error occurs if the argument is not a positive integer number.

```
> (oddp 0)
NIL
> (oddp 1)
T
```

plusp Returns true if its argument is a positive number; Returns false otherwise.

```
> (plusp 0)
NIL
> (plusp -3.5)
NIL
> (plusp 2)
T
```

Chapter 8

Side effects

Common Lisp is not a pure functional language as it allows side effects.

8.1 Variables and assignments

A variable is *global* if it is visible everywhere as opposed to a *local variable* which is visible only within the code block in which it is defined. A global variable is accessible everywhere except in expressions that create a new local variable with the same name. Inside code blocks, local values are always looked for first. If a local value for the variable does not exist, then a global value is sought. If no global value is found then the result is an error.

To define a global variable we use

(`defparameter` *name value*)

where *name* is the name of the global variable and *value* is an expression to be evaluated and will set the initial value of the variable. In order to avoid unexpected name conflicts with local variables, it is conventional to give global variable names that lie within asterisks, e.g.

```
> (defparameter *pi* 3.14)
*PI*
```

```
> *pi*
3.14
```

We can now use `defparameter` again to modify the value of the variable.

```
> (defparameter *pi* 3.14159265)
*PI*

> *pi*
3.1415928
```

To define a global constant we use

(`defconstant` *name value*)

where *name* is the name of the global constant and *value* is an expression to be evaluated and will set the value of the constant.

```
> (defconstant limit 100)
LIMIT

> limit
100
```

Once a constant is defined, if we attempt to modify it using `defparameter`, we will receive an error:

```
> (defparameter limit 90)
Error: LIMIT is a constant and cannot be set or bound.
```

To verify whether or not a symbol is already in use to define a global variable or global constant, we can use

(`boundp` *'name*)

For example:

```
 > (boundp 'limit)
T
```

whereas

```
> (boundp 'speed)
NIL
```

We use `setf` to assign both global and local variables. The general format is

(`setf` *place value*)

and it is used to assign a new value to a place (variable). More specifically, `setf` uses its first argument to define a memory location. it then evaluates its second argument and stores the result in this memory location.

```
> (setf x '(a b c))
(A B C)
> (car x)
A
> (cdr x)
(B C)
> (cdr (cdr (cdr x)))
NIL
> (setf x (append x '(d e)))
(A B C D E)
```

Variables are essentially pointers. Function `eql` will return *true* if its arguments point to the same object, whereas function `equal` returns *true* if its arguments have the same value.

```
> x
(A B C D E)
> (setf y '(a b c d e))
(A B C D E)
> (eql x y)
NIL
> (equal x y)
T
> (setf z x)
(A B C D E)
> (eql x z)
T
> (equal x z)
T
> (eql y z)
NIL
> (equal y z)
T
```

The function `copy-list` takes a list and returns a copy of it.

```
> (setf w (copy-list x))
(A B C D E)
> (eql x w)
NIL
> (equal x w)
T
```

We can define our own function to copy a list, as follows:

```
(defun copy-list2 (lst)
  (if (atom lst)
    lst
    (cons (car lst) (copy-list2 (cdr lst)))))
```

```
> (setf k '(a b (cd) (e f g)))
(A B (CD) (E F G))
> (setf l (copy-list2 k))
(A B (CD) (E F G))
> (eql k l)
NIL
> (equal k l)
T
```

We can use `setf` to modify a list. Consider the example below:

```
> (setf x '(a b c d))
(A B C D)
> (setf (car x) '(a b c))
(A B C)
> x
((A B C) B C D)
> (setf (cdr x) '((b c d)))
((B C D))
> x
((A B C) (B C D))
```

8.2 Shared structure

Lists can share structure. This implies that two variables may share elements. If the value of an element is modified through accessing one variable, this modification is reflected on

the other variable as well as both variables have common (shared) structure.

Example 8.1. Consider the following example:

```
(setf list1 '(a b c d))
(setf list2 (cons 'x (cdr list1)))
```

We can verify the contents of the two lists as

```
> list1
(A B C D)

> list2
(X B C D)
```

Let us now modify the value of an element in `list1` as follows:

```
(setf (car (cdr list1)) 'y)
```

This has changed `list1` but also `list2` which can be an undesired result.

```
> list1
(A Y C D)

> list2
(X Y C D)
```

The example is illustrated in Figure 8.1.

Example 8.2. Consider the following:

```
> (setf lst1 '(a b c))
(A B C)

> (setf lst2 (cons 'x (cdr lst1)))
(X B C)
```

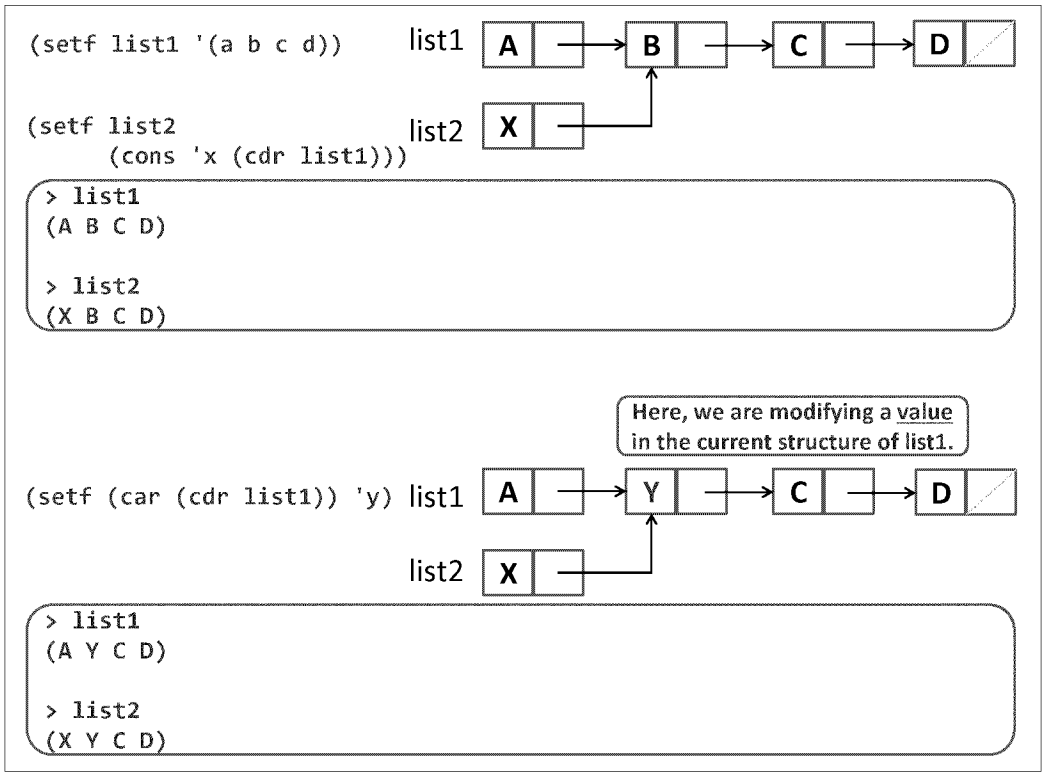

Figure 8.1: Shared structure - Part 1 of 2.

```
> (setf (cdr lst1) '(y z))
(Y Z)

> lst1
(A Y Z)

> lst2
(X B C)
```

Why has `lst2` not changed? To answer the question we need to take a closer look at shared structure through a comparison between the current and the previous examples (Figures 8.1, and 8.2). Observe that since each element in a Common Lisp list is a two-compartmental box (one containing the value and another containing a pointer to the second element), for `lst2` to have been changed, the pointer of the head of `lst2` should be pointing not to `B`, but

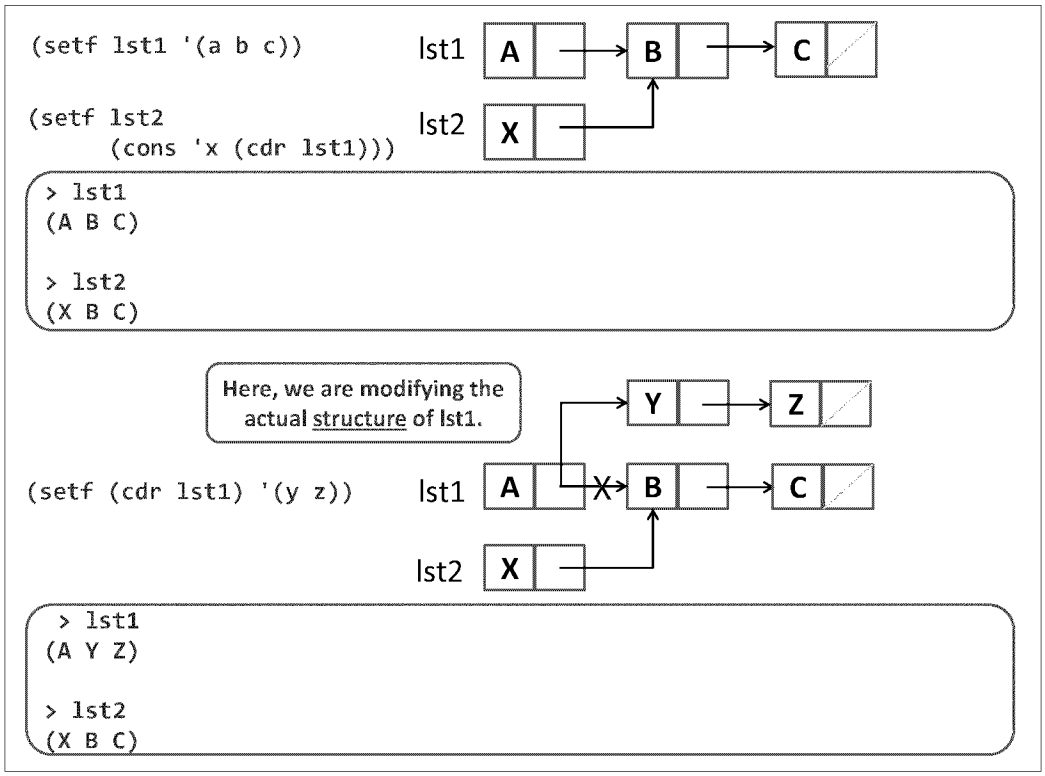

Figure 8.2: Shared structure - Part 2 of 2.

to the pointer (the second compartment) of the head of `lst1`. However, it does not. As a result, as we break the pointer from the head of `lst1` to `(B C)` and we create a new pointer from that head to `(Y Z)`, the structure of `lst2` is not affected. The pointer of the head of `lst2` still points to `(B C)`.

8.3 Control flow

The `loop` form repeats until some condition is satisfied or when an explicit exit statement is encountered. This form allows you not to specify a condition, thus creating an infinite loop as follows:

```
(loop (print                    ))
```

The above is obviously bad programming. A `return` from anywhere inside the `loop` will cause control to exit the loop; any value you specify becomes the value of the loop form.

The example below will display "Inside a loop" and return 7.

```
(loop
  (print                    )
  (return 7)
  (print                              ))
```

`return` can also be used in a conditional form to determine when the loop should terminate, as follows:

```
(let ((n 0))
  (loop
    (when (> n 3) (return))
    (print n) (write (* n n n))
    (incf n)))
```

```
0 0
1 1
2 8
3 27
NIL
```

The `dotimes` form repeats for some fixed number of iterations: `dotimes (<counter> <limit> <result>) <body>)`

```
(dotimes (n 3)
  (print n)
  (write (* n n n)))
```

```
0 0
1 1
2 8
NIL
```

8.4 Blocks

There are three basic operations for creating blocks of code: `progn`, `block`, and `tagbody`. With `progn`, the expressions within its body are evaluated in order, and the value of the last is returned:

```
(progn
   (format t    )
   (format t    )
   (+ 1 2))
```

```
xy
3
```

A `block` is like a `progn` with a name and an emergency exit. The first argument should be a symbol and it becomes the name of the block. At any point within the body you can halt evaluation and return a value immediately by using `return-from` with the block's name. The second argument to `return-from` is returned as the value of the block named by the first. Expressions after the `return-from` are not evaluated.

```
(block my-label
   (format t                    )
   (return-from my-label  Exit)
   (format t                          ))
```

```
Inside a block.
Exit
```

Within `tagbody` you can use `go`, a statement which instructs execution to jump to the line containing an atom which appears inside the body and interpreted as a label. Consider the following example:

```
(tagbody
   (setf x 0)
```

```
  top
   (setf x (+ x 1))
   (format t      x)
   (if (< x 10) (go top)))
```

```
1 2 3 4 5 6 7 8 9 10
NIL
```

The statement `go` is found (usually by its semantic synonym `goto`) in many programming languages. It causes an unconditional jump of execution to another statement, identified by a label or a line number (depending on the language).

Chapter 9

Recursion

Recursion is a fundamental notion in Computer Science. In problem solving, the deployment of *recursion* implies that the solution to a problem depends on solutions to smaller instances of the same problem. Recursion refers to the practice of defining an object, such as a function or a set, in terms of itself. Every recursive function consists of:

- One or more *base cases*, and
- One or more *recursive cases* (also called *inductive cases*).

Each recursive case consists of:

1. Splitting the data into smaller pieces (for example, with `car` and `cdr`),
2. Handling the pieces with calls to the current method (note that every possible chain of recursive calls must eventually reach a base case), and
3. Combining the results into a single result.

A mathematical function uses only recursion and conditional expressions. A mathematical conditional expression is in the form of a list of pairs, each of which is a *guarded expression.* Each guarded expression consists of a predicate guard and an expression:

$$functionName(arguments) = expression_1 - predicateGuard_1, \ldots$$

which implies that the function is evaluated by $expression_n$ if $predicateGuard_n$ is true.

Example 9.1. Suppose we need to define the function $f : \mathbb{N} \to lists(\mathbb{N})$ that accepts an integer argument and returns a list, such that

$$f(n) = \langle n, n-1, ..., 0 \rangle$$

In this and similar problems, we can transform the definition of $f(n)$ into a computable function using available operations on the underlying structure (list). We can use *cons* as follows:

$$\begin{aligned} f(n) &= \langle n, n-1, ..., 1, 0 \rangle \\ &= cons(n, \langle n-1, ..., 1, 0 \rangle) \\ &= cons(n, f(n-1)). \end{aligned}$$

We can therefore define f recursively by

$$\begin{aligned} f(0) &= \langle 0 \rangle. \\ f(n) &= cons(n, f(n-1)), \ for\ n > 0. \end{aligned}$$

We can visually show how this works with a technique called "unfolding the definition" (or "tracing the algorithm").

We can unfold this definition for $f(3)$ as follows:

$$\begin{aligned} f(3) &= cons(3, f(2)) \\ &= cons(3, cons(2, f(1))) \\ &= cons(3, cons(2, cons(1, f(0)))) \\ &= cons(3, cons(2, cons(1, \langle 0 \rangle))) \\ &= cons(3, cons(2, \langle 1, 0 \rangle)) \\ &= cons(3, \langle 2, 1, 0 \rangle) \\ &= \langle 3, 2, 1, 0 \rangle. \end{aligned}$$

We can implement function `bsequence` as follows:

```
(defun bsequence (n)
  (if (= n 0)
    (cons 0 '())
    (cons n (bsequence(- n 1)))))
```

We can execute the function as follows:

```
> (bsequence 0)
(0)
> (bsequence 3)
(3 2 1 0)
```

Example 9.2. Function $factorial : \mathbb{N}_0 \to \mathbb{N}_1$ is defined for non-negative integers by two guarded expressions as follows:

$$factorial(n) = \begin{cases} 1 & \text{for} \quad n = 0 \\ n \times factorial(n-1) & \text{for} \quad n > 0 \end{cases}$$

We can implement function `factorial` as follows:

```
(defun factorial (n)
  (if (= n 0)
    1
    (* n (factorial (- n 1)))))
```

We can execute the function as follows:

```
> (factorial 3)
6
> (factorial 5)
120
```

Example 9.3. The Ackermann function[1] is defined as follows:

$$Ack(m,n) = \begin{cases} n+1 & \text{for} \quad m = 0 \\ Ack(m-1,1) & \text{for} \quad m > 0, n = 0 \\ Ack(m-1, Ack(m,n-1)) & \text{for} \quad m > 0, n > 0 \end{cases}$$

We can implement function `ackermann` as follows:

```
(defun ackermann (m n)
  (cond ((zerop m) (+ n 1))
    ((zerop n) (ackermann (- m 1) 1))
    (t         (ackermann (- m 1) (ackermann m (- n 1))))))
```

The function grows very quickly (i.e. many steps) and results in large numbers even for small arguments. We can execute the function as follows:

```
> (ackermann 0 1)
2
> (ackermann 0 0)
```

[1] After German mathematician Wilhelm Friedrich Ackermann (1896 - 1962).

```
1
> (ackermann 1 0)
2
> (ackermann 1 1)
3
> (ackermann 1 2)
4
> (ackermann 1 3)
5
> (ackermann 2 3)
9
> (ackermann 3 4)
125
```

Example 9.4. Consider function `append2` which takes as its arguments two lists `lst1` and `lst2` and returns a new list which forms a concatenation of `lst1` and `lst2`.

Base case: If `lst1` is empty, then return `lst2`.

Recursive case: Return a list containing as its first element the head of `lst1` with its tail being the concatenation of the tail of `lst1` with `lst2`.

We can implement function `append2` as follows:

```
(defun append2 (lst1 lst2)
  (if (null lst1)
    lst2
    (cons (car lst1) (append2 (cdr lst1) lst2))))
```

We can execute the function as follows:

```
> (append2 '() '(a))
(a)
> (append2 '(a b c) '(d e f))
(a b c d e f)
```

We can trace the execution of `(append2 '(a b c) '(d e f))` as follows:

```
(append2 '(a b c) '(d e f))
   = cons ('a (append2 '(b c) '(d e f)))
   = cons ('a (cons 'b (append2 '(c) '(d e f))))
   = cons ('a (cons 'b (cons 'c (append2 '() '(d e f)))))
   = cons ('a (cons 'b (cons 'c '(d e f))))
   = '(a b c d e f)
```

Example 9.5. Consider function `sum` which takes a list `lst` as its argument and returns the summation of its elements.

Base case: If the list is empty, then sum is `0`.

Recursive case: Add the head element to the sum of the elements of the tail.

We can unfold this definition for $sum(\langle 2, 4, 5\rangle)$ as follows:

$$\begin{aligned} sum(\langle 2, 4, 5\rangle) &= 2 + sum(\langle 4, 5\rangle) \\ &= 2 + 4 + sum(\langle 5\rangle) \\ &= 2 + 4 + 5 + sum(\langle\rangle) \\ &= 2 + 4 + 5 + 0 \\ &= 11 \end{aligned}$$

We can implement function `sum` as follows:

```
(defun sum (lst)
  (cond ((null lst) 0)
        (t (+ (car lst) (sum (cdr lst))))))
```

We can execute the function as follows:

```
> (sum '(1 2 3 4 5))
15
```

We can trace the execution of `(sum '(1 2 3 4 5))` as follows:

```
(sum '(1 2 3 4 5))
   = (+ 1 sum '(2 3 4 5))
   = (+ 1 (+ 2 sum '(3 4 5)))
   = (+ 1 (+ 2 (+ 3 sum '(4 5))))
   = (+ 1 (+ 2 (+ 3 (+ 4 sum '(5)))))
   = (+ 1 (+ 2 (+ 3 (+ 4 (+ 5 sum '())))))
   = (+ 1 (+ 2 (+ 3 (+ 4 (+ 5 0)))))
   = 15
```

Example 9.6. Consider a function `last2` which takes a list `lst` as its argument and returns the last element in the list.

Base case: If the list has one element (its tail is the empty list), then return this element.

Recursive case: Return the last element of the tail of the list.

We can implement function `last2` as follows:

```
(defun last2 (lst)
  (cond ((null lst) nil)
        ((null (cdr lst)) (car lst))
        (t (last2 (cdr lst)))))
```

We can execute the function as follows:

```
> (last2 '(a b 3 4 c d 5 6))
6
> (last2 '(a b (c d 1)))
(C D 1)
```

Example 9.7. Consider a recursive function `length2` which takes a list `lst` as its argument and returns the length of `lst`.

Base case: If the list is empty, then the length of the list is `0`.

Recursive case: Add 1 to the length of the tail.

We can implement function `length2` as follows:

```
(defun length2 (lst)
  (if (null lst)
    0
    (+ 1 (length2 (cdr lst)))))
```

We can execute the function as follows:

```
> (length2 '(a d c 1 2 3))
6
> (length2 '(a (bc) (1 2 3)))
3
```

Example 9.8. Consider function `reverse2` which takes a list as its argument and returns the reversed list.

Base case: If the list is empty, then return the empty list.

Recursive case: Recur on the tail of the list and the head of the list.

We can implement function `reverse2` as follows:

```
(defun reverse2 (lst)
  (cond ((null lst) '())
        (t (append (reverse2 (cdr lst)) (list (car lst))))))
```

We can execute the function as follows:

```
> (reverse2 '(a b c d))
(D C B A)
```

Example 9.9. Consider function `product` which takes a list `lst` as its argument and returns the product of its elements. This function is very similar to `sum`.

Base case: If the list is empty, then the product is 1 (by convention).

Recursive case: Multiply the head of `lst` to the product of the elements of the tail.

We can implement function `product` as follows:

```
(defun product (lst)
  (cond ((null lst) 1)
        (t (* (car lst) (product (cdr lst))))))
```

We can execute the function as follows:

```
> (product '(3 5 7))
105
```

Example 9.10. Consider a function called `cube-list`, which takes as argument a list of numbers and returns the same list with each element replaced with its cube.

We can implement function `cube-list` as follows:

```
(defun cube-list (lst)
  (cond ((null lst) nil)
        (t (let ((elt (car lst)))
          (cons (* elt elt elt)
                (cube-list (cdr lst)))))))
```

We can execute the function as follows:

```
> (cube-list '(1 3 5))
(1 27 125)
```

Example 9.11. Consider function `interleave` which takes two lists `lst1` and `lst2` as its arguments and returns a new list whose elements correspond to lists `lst1` and `lst2` interleaved, i.e. the first element is the from `lst1`, the second is from `lst2`, the third from `lst1`, etc.

Base cases:

1. If `lst1` is empty, then return `lst2`.
2. If `lst2` is empty, then return `lst1`.

Recursive case: Concatenate the head of `lst1` with a list containing the concatenation of the head of `lst2` with the interleaved tails of `lst1` and `lst2`.

We can implement function `interleave` as follows:

```
(defun interleave (lst1 lst2)
  (cond ((null lst1) lst2)
        ((null lst2) lst1)
        (t (cons (car lst1) (cons (car lst2)
           (interleave (cdr lst1) (cdr lst2)))))))
```

We can execute the function as follows:

```
> (interleave '() '(1))
(1)
> (interleave '(a b c) '(1 2 3))
(A 1 B 2 C 3)
> (interleave '(a b c d) '(1))
(A 1 B C D)
> (interleave '(a b c) '(1 2 3 4 5))
(A 1 B 2 C 3 4 5)
```

Example 9.12. Consider function `remove-first-occurrence` which takes as arguments a list `lst` and an element `elt`, and returns `lst` with the first occurrence of `elt` removed.

Base cases:

1. If `lst` is empty, then return the empty list.
2. If the head of `lst` is the symbol we want to remove then return the tail of `lst`.

Recursive case: Keep the head of `lst` and recur on the tail of `lst`.

We can implement function `remove-first-occurrence` as follows:

```
(defun remove-first-occurrence (lst elt)
  (cond ((null lst) nil)
        ((equal (car lst) elt) (cdr lst))
        (t (cons (car lst)(remove-first-occurrence (cdr lst) elt)))))
```

We can execute the function as follows:

```
> (remove-first-occurrence '(a e b c d e) 'e)
(A B C D E)
```

Let us trace the execution of `(remove-first-occurrence '(a e b c d e) 'e)`:

```
(remove-first-occurrence '(a e b c d e) 'e)
   = (cons 'a ((remove-first-occurrence '(e b c d e) 'e))
   = (cons 'a '(b c d e))
   = '(a b c d e)
```

Example 9.13. Consider function `remove-all-occurrences` which takes as arguments a list `lst` and an element `elt`, and returns `lst` with all occurrences of `elt` removed.

Base case: If `lst` is empty, return the empty list.

Recursive cases: There are two cases to consider when the list is not empty.

1. When the head of the list is the same as `elt`, ignore the head of the list and recur on removing `elt` from the tail of the list.
2. When the head of the list is not the same as `elt`, keep the head and recur on removing `elt` from the tail of the list.

We can implement function `remove-all-occurrences` as follows:

```
(defun remove-all-occurrences (lst elt)
  (if (null lst)
    nil
    (if (equal (car lst) elt)
      (remove-all-occurrences (cdr lst) elt)
      (cons (car lst) (remove-all-occurrences (cdr lst) elt)))))
```

We can execute the function as follows:

```
> (remove-all-occurrences '(z a z b z z c) 'z)
(A B C)
```

Example 9.14. Consider function `merge2` which takes as its arguments two sorted lists of non-repetitive numbers and returns a merged list with no redundancies.

Base cases:

1. If `lst1` is empty, then return `lst2`.
2. If `lst2` is empty, then return `lst1`.

Recursive cases:

1. If the head of `lst1` equals to the head of `lst2` then ignore this element and recur on the tail of `lst1` and `lst2`.
2. If the head of `lst1` is less than the head of `lst2`, then keep this element and recur on the tail of `lst1` and `lst2`.
3. Otherwise keep the head of `lst2` and recur on `lst1` and the tail of `lst2`.

We can implement function `merge2` as follows:

```
(defun merge2 (lst1 lst2)
  (cond ((null lst1) lst2)
        ((null lst2) lst1)
        ((= (car lst1) (car lst2)) (merge2 (cdr lst1) lst2))
```

```
((< (car lst1) (car lst2))
   (cons (car lst1) (merge2 (cdr lst1) lst2)))
(t (cons (car lst2) (merge2 lst1 (cdr lst2))))))
```

We can execute the function as follows:

```
> (merge2 '(3 4 6 8) '(3 4 5 6))
(3 4 5 6 8)
> (merge2 '() '(6 7 8))
(6 7 8)
> (merge2 '(2.5 6 7.5) '(6))
(2.5 6 7.5)
```

9.1 Higher-order recursion

When a recursive call is the last step in the definition of a recursive method, this is referred to as *tail recursion*. All the above examples fall into this category. When a recursive function makes more than a single recursive call, we say that the function uses *higher-order recursion*. This can be *binary recursion* (two recursive calls, each to solve two similar halves of the problem) or *multiple recursion* (potentially many recursive calls).

The Fibonacci sequence

The Fibonacci sequence[2] is defined as follows:

$$F_0 = 0.$$
$$F_1 = 1.$$
$$F_i = F_{i-1} + F_{i-2} \; for \; i \geq 2.$$

We can unfold this definition for F_5 as follows:

$$\begin{aligned} F_5 &= F_4 + F_3 \\ &= (F_3 + F_2) + (F_2 + F_1) \\ &= ((F_2 + F_1) + (F_1 + F_0)) + ((F_1 + F_0) + 1) \\ &= (((F_1 + F_0) + F_1) + (F_1 + F_0)) + ((F_1 + F_0) + 1) \\ &= 5 \end{aligned}$$

We can now define function `fibonacci` which takes as its argument a non-negative integer k and returns the k^{th} Fibonacci number F_k.

We can implement function `fibonacci` as follows:

```
(defun fibonacci (k)
  (if (or (zerop k) (= k 1))
    k
    (+ (fibonacci (- k 1)) (fibonacci (- k 2)))))
```

[2]After Italian mathematician Leonardo Pisano Bigollo, also known as Leonardo Fibonacci (c. 1170 - c. 1250).

We can execute the function as follows:

```
> (fibonacci 5)
5
```

The above program is correct but rather slow, the reason for this is that both F_k and F_{k-1} must compute F_{k-2}. A *iterative* solution would be our best choice.

Example 9.15. Suppose we need to define function $max : lists(\mathbb{N}) \to \mathbb{N}$ which accepts a list of integers and returns an integer which represents the maximum element in that list. The function is not defined for an empty list and the function should issue *false* in that case.

Let us transform the definition into a recursive computable function:

$$max(lst) = \begin{cases} false & \text{if } lst \text{ is empty.} \\ head(lst) & \text{if } tail(lst) \text{ is empty.} \\ greater-of\ (head(lst), max(tail(lst))) & \text{if } tail(lst) \text{ is not empty.} \end{cases}$$

Let us unfold the definition for $max(\langle 3,7,5,2\rangle)$:

$$\begin{aligned} max(\langle 3,7,5,2\rangle) &= greater-of(3,\ max(\langle 7,5,2\rangle)) \\ &= greater-of(3,\ greater-of(7,\ max(\langle 5,2\rangle))) \\ &= greater-of(3,\ greater-of(7,\ greater-of(5,\ max(\langle 2\rangle)))) \\ &= greater-of(3,\ greater-of(7,\ greater-of(5,\ 2))) \\ &= greater-of(3,\ greater-of(7,\ 5)) \\ &= greater-of(3,\ 7) \\ &= 7. \end{aligned}$$

We can implement the mathematical function `max` as function `max2`:

```
(defun max2 (lst)
  (cond ((null lst) nil)
        ((null (cdr lst)) (car lst))
        (t (let ((a (car lst))
                 (b (max2 (cdr lst))))
                 (if (> a b) a b)))))
```

Let us trace the execution of the function with the following sample input data:

- The list `(3 7 5 2)`:

```
(max2 '(3 7 5 2))
  1. a = 3, b = max(7 5 2)
                2. a = 7, b = max(5 2)
                              3. a = 5, b = max(2)
                                            4. singleton list
                                            4. return 2
                              3. (5 > 2) is true, return 5
                2. (7 > 5) is true, return 7
  1. (3 > 7) is false, return 7
```

- The empty list: For the empty list the code is straightforward: The function returns false (NIL).

- The list `(3)`: For any singleton list (i.e. one that has only one element) the function returns its only element.

Example 9.16. Let us define a recursive definition and an implementation for function `min2` which takes a list `lst` of integers as its argument and returns the minimum element of the list.

The recursive definition of `min2` is as follows:

Base case:

1. If `lst` is empty, then return nil.
2. If `lst` contains one element, then return that element.

Recursive case: Return the smaller between the head of the list and the minimum of the tail of the list.

We can implement function `min2` as follows:

```
(defun min2 (lst)
  (cond ((null lst) '())
        ((null (cdr lst)) (car lst))
        (t (let ((a (car lst))
                 (b (min2 (cdr lst))))
                 (if (< b a) b a)))))
```

```
> (min2 '())
NIL
> (min2 '(3))
3
>  (min2 '(6 7 2 4 1))
1
> (min2 '(13 24 2 6 8 23))
2
```

Example 9.17. Consider function `swap` which takes as an argument a list and returns a new list which represents the argument list where each two consecutive elements are swapped. Example runs are as follows:

```
> (swap '())
NIL
```

```
> (swap '(a))
(A)
> (swap '(a (b)))
((B) A)
> (swap '(1 "two" -3 "four"))
("two" 1 "four" -3)
```

We can implement function **swap** as follows:

```
(defun swap (lst)
  (if (or (null lst) (null (cdr lst)))
      lst
    (cons (car (cdr lst))
          (cons (car lst) (swap (cdr (cdr lst)))))))
```

Example 9.18. Consider function **guess** below.

```
(defun guess (arg1 arg2)
  (cond ((null arg1) arg2)
        ((null arg2) arg1)
        ((< (car arg1) (car arg2)) (cons (car arg2)
                                         (guess (cdr arg1) (cdr arg2))))
        (t (cons (car arg1) (guess (cdr arg1) (cdr arg2))))))
```

Let us execute the function with different arguments and from the output we will try to provide a brief description on what the function does.

```
> (guess '(4 6 8 9 2) '(5 1))
(5 6 8 9 2)
> (guess '(3 4 5) '(1 2 3))
(3 4 5)
> (guess '() '(6 1 9))
(6 1 9)
```

The function takes two lists as arguments and returns a list constructed by the maximum elements after a pairwise comparison, i.e. it compares the corresponding first elements, then it compares the corresponding second elements, etc.

Example 9.19. Provide a recursive definition and implementation of function `compress` which takes a list as its argument and returns a new list where all consecutive duplicates of its argument are replaced with a single copy of the element. The order of the elements should not be changed. As example runs, consider the following:

```
> (compress '(a a a a b c c d e e e e))
(A B C D E)
> (compress '(a a b c c c a a))
(A B C A)
```

The recursive definition of `compress` is as follows:

Base case: If `list` is empty, or if `list` has one element then return the list as is.

Recursive case: If the first element is equal to the second element, then ignore the first element and recur on the tail of the list. If the first element is not equal to the second, then keep the first element and recur on the tail of the list.

We can implement function `compress` as follows:

```
(defun compress (lst)
  (cond
     ((or (null lst) (null (cdr lst))) lst)
     ((equal (car lst) (car (cdr lst))) (compress (cdr lst)))
     (t (cons (car lst) (compress (cdr lst))))))
```

Example 9.20. Provide the implementation of function `pairs` that returns a list of pairs of corresponding elements from two lists of equal length. For example,

$$pairs(\langle a, b, c\rangle, \langle x, y, z\rangle) = \langle\langle a, x\rangle, \langle b, y\rangle, \langle c, z\rangle\rangle$$

The function is defined as follows:

```
(defun pairs (lst1 lst2)
   (if (or (null lst1) (null lst2))
      nil
      (cons (list (car lst1) (car lst2)) (pairs (cdr lst1) (cdr lst2) ))))
```

Example 9.21. Provide the implementation of function `insert` that takes an integer n and a sorted list *lst* of integers and inserts n in its proper position. By convention we assume that the empty list is sorted. Assume that *lst* does not include duplicates, and does not already contain n.

The function is defined as follows:

```
(defun insert (n lst)
   (cond  ((null lst) (list n))
          ((< n (car lst)) (cons n lst))
          (t (cons (car lst) (insert n (cdr lst))))))
```

Example 9.22. Provide the implementation of function `dist` that accepts an atom n and a non-empty list *lst*, and returns a list composed of lists of two elements, the first being n and the second being each successive element of *lst*. For example,

$$dist(a, \langle b, c, d\rangle) = \langle\langle a, b\rangle, \langle a, c\rangle, \langle a, d\rangle\rangle$$

To detect recursion, we can re-write the equation by splitting up the list into its head and its tail:

$$\begin{aligned} dist(a, \langle b, c, d\rangle) &= \langle\langle a, b\rangle, \langle a, c\rangle, \langle a, d\rangle\rangle \\ &= \langle\langle a, b\rangle, dist(a, \langle c, d\rangle)\rangle. \end{aligned}$$

We can therefore provide the following computable function definition:

$$dist(x, \langle\rangle) = \langle\rangle,$$
$$dist(x, \langle L\rangle) = cons(\langle x, head(L)\rangle, dist(x,\ tail(L))).$$

We can now unfold the definition as follows:

$$\begin{aligned} dist(w, \langle x, y\rangle) &= cons(\langle w, x\rangle, dist(x, \langle y\rangle)) \\ &= cons(\langle w, x\rangle, cons(\langle w, y\rangle, dist(x, \langle\rangle))) \\ &= \langle\langle w, x\rangle, \langle w, y\rangle\rangle. \end{aligned}$$

The function is defined as follows:

```
(defun dist (n lst)
  (if (null lst)
      nil
      (cons (list n (car lst)) (dist n (cdr lst) ))))
```

We can trace the execution of function `dist` as follows:

```
(dist 'a '(b c d)) = (cons (list 'a 'a) dist ('a '(b c)))
                   = (cons '(a a) (cons ((list 'a 'b) dist ('a '(c)))))
                   = (cons '(a a) (cons '(a b) (cons (list 'a 'c) '())))
                   = (cons '(a a) (cons '(a b) (cons '(a c) '())))
                   = '((a a), (a b) (a c))
```

Example 9.23. Provide the implementation of function `front` that returns the list obtained by removing the last element of a non-empty list. For example $front(\langle a, b, c\rangle) = \langle a, b\rangle$.

The function is defined as follows:

```
(defun front (lst)
     (cond ((null lst)       nil)
           ((null (cdr lst)) '())
           (t                (cons (car lst) (front (cdr lst))))))
```

Example 9.24. Provide the definition of a function that takes a list of integers as its argument and returns the maximum integer among them.

This problem can be addressed in a number of ways. One possible solution is provided by function `max2` that deploys `let` bound variables. Other possible solutions include the following:

```
(defun max3 (lst)
  (cond ((null lst) nil)
        ((null (cdr lst)) (car lst))
        ((> (car lst) (car (cdr lst)))
           (max3 (cons (car lst) (cdr (cdr lst)))))
        (t (max3 (cdr lst)))))


(defun max4 (lst)
  (cond ((null lst) nil)
        ((null (cdr lst)) (car lst))
        (t (greater (car lst) (max4 (cdr lst))))))

(defun greater (a b)
   (if (> a b)
      a
      b))
```

```
(defun max5 (lst)
  (cond ((null lst) nil)
        ((null (cdr lst)) (car lst))
        ((> (car lst) (max5 (cdr lst))) (car lst))
        (t (max5 (cdr lst)))))


(defun max6 (lst)
  (cond ((null lst) nil)
        ((null (cdr lst)) (car lst))
        ((< (car lst) (max6 (cdr lst))) (max6 (cdr lst)))
        (t (max6 (cons (car lst) (cdr (cdr lst)))))))
```

Example 9.25. Let us define function `diff` that takes two non-empty lists of equal length as arguments and produces a list whose elements correspond to the cubed differences between the corresponding elements of the two arguments. We may assume that non-empty list arguments contain only numeral elements. Example executions are as follows:

```
> (diff '3 '(5 1 -4))
NIL

> (diff '() '(3 4))
NIL

> (diff '(5 7) '(1 3 7 9))
NIL

> (diff '(3 5 -2) '(5 1 -4))
(-8 64 8)
```

```
(defun diff (lst1 lst2)
  (cond
    ((or
       (not (and (listp lst1) (listp lst2)))
       (or (null lst1) (null lst2))
       (not (= (length lst1) (length lst2)))) nil)
    (t (let
         ((d (- (car lst1) (car lst2))))
         (cons (expt d 3) (diff (cdr lst1) (cdr lst2)))))))
```

Let us trace the execution of the function for `(diff '(4 2 -2) '(2 -1 -4))`.

```
> (diff '(4 2 -2) '(2 -1 -4))
  -> (cons '8 (diff '(2 -2) '(-1 -4)))
    -> (cons '8 (cons '27 (diff '(-2) '(-4))))
      -> (cons '8 (cons '27 (cons '8 (diff '() '()))))
        -> (cons '8 (cons '27 (cons '8 '())))
           -> (8 27 8)
```

Example 9.26. Let us define function `remove-all-odds` that takes a list as its argument and returns a new list which contains all the elements of its argument with all odd numbers removed. We may assume that a non-empty list argument contains only numeral elements. Example executions are as follows:

```
> (remove-all-odds '7)
NIL

> (remove-all-odds '())
NIL

> (remove-all-odds '(3))
NIL
```

```
> (remove-all-odds '(1 2 3 4 5 6 7 8 9 10))
(2 4 6 8 10)
```

```
(defun remove-all-odds (lst)
  (cond
    ((not (listp lst)) nil)
    ((null lst) '())
    ((oddp (car lst)) (remove-all-odds (cdr lst)))
    (t (cons (car lst) (remove-all-odds (cdr lst))))))
```

Let us trace the execution of the function for `(remove-all-odds '(10 9 8 12 14 3 11))`.

```
> (remove-all-odds '(10 9 8 12 14 3 11))
  -> (cons '10 (remove-all-odds '(9 8 12 14 3 11)))
   -> (cons '10 (remove-all-odds '(8 12 14 3 11)))
     -> (cons '10 (cons '8 (remove-all-odds '(12 14 3 11))))
       -> (cons '10 (cons '8 (cons '12 (remove-all-odds '(14 3 11)))))
         -> (cons '10 (cons '8 (cons '12 (cons '14 (remove-all-odds '(3 11))))))
          -> (cons '10 (cons '8 (cons '12 (cons '14 (remove-all-odds '(11))))))
            -> (cons '10 (cons '8 (cons '12 (cons '14 '()))))
               -> (10 8 12 14)
```

Example 9.27. Let us define function (`mins` *list1 list3 list3*) that takes three non-empty lists of equal length and produces a list whose elements correspond to the cubed minimum between the corresponding elements of the three arguments. We may assume that non-empty list arguments contain only numeral elements. Example executions are as follows:

```
> (mins '1 '(3 1 1) '(2 3 4))
NIL

> (mins '() '(1 2 7) '(2 3 4))
NIL
```

```
> (mins '(2) '(1 2 4) '(2 3 4))
NIL

> (mins '(2 1 5) '(1 2 4) '(2 3 4))
(1 1 64)
```

```
(defun mins (lst1 lst2 lst3)
  (cond
    ((or
       (not (and (listp lst1) (listp lst2) (listp lst3)))
       (or (null lst1) (null lst2) (null lst3))
       (not (= (length lst1) (length lst2) (length lst3)))) nil)
    (t (let
         ((m (min (car lst1) (car lst2) (car lst3))))
         (cons (expt m 3) (mins (cdr lst1) (cdr lst2)(cdr lst3)))))))
```

Let us trace the execution of the function for `(mins '(2 3 5) '(4 2 4) '(7 3 3))`.

```
(mins '(2 8 3) '(2 4 2) '(7 3 3))
 -> (cons '8 (mins '(8 3) '(4 2) '(3 3)))
    -> (cons '8 (cons '27 (mins '(3) '(2) '(3))))
      -> (cons '8 (cons '27 (cons '8 '() '() '())))
       -> (8 27 8)
```

Example 9.28. Let us define function (`filter` *list numeral*) that takes two arguments, a) a non-empty list of integers, and b) a positive integer, and produces a list whose elements are those elements of the first argument that are larger than the second argument. We may assume that a non-empty list argument contains only numeral elements. Example executions are as follows:

```
> (filter '5 3)
NIL
```

```
> (filter '() 5)
NIL

> (filter '(7 9 11) '(2))
NIL

>  (filter '(3 4 5) '0)
NIL

>  (filter '(3 4 5) '2.5)
NIL

> (filter '(3 4 5) '0)
NIL

> (filter '(5 9 3 2 11) '7)
(9 11)
```

```
(defun filter (lst el)
  (cond
    ((not (listp lst)) nil)
    ((null lst) '())
    ((not (atom el)) nil)
    ((or (<= el 0)  (not (integerp el))) nil)
    ((<= (car lst) el) (filter (cdr lst) el))
    (t (cons (car lst) (filter (cdr lst) el)))))
```

Let us trace the execution of the function for `(filter '(12 9 3 2 7) '6)`.

```
> (filter '(12 9 3 2 7) '6)
->  (cons '12 (filter '(9 3 2 7) '6))
```

```
-> (cons '12 (cons '9 (filter '(3 2 7) '6))
   -> (cons '12 (cons '9 (filter '(2 7) '6)))
      -> (cons '12 (cons '9 (filter '(7) '6)))
         -> (cons '12 (cons '9 (cons '7 (filter '() '6))))
            -> (cons '12 (cons '9 (cons '7 '())))
               -> (12, 9, 7)
```

Example 9.29. Let us define a function `list2set (lst)` that takes a list as an argument and returns a set representation of the list. Example executions of the function are as follows:

```
> (list2set '())
NIL

> (list2set '3)
NIL

> (list2set '(a b c 1 4 f))
(A B C 1 4 F)

> (list2set '(a a a a a b b b b c c a a b c))
(A B C)

> (list2set '(a b b a))
(B A)
```

```
(defun list2set (lst)
  (cond
    ((not (listp lst)) nil)
    ((null lst) '())
    ((member (car lst) (cdr lst)) (list2set (cdr lst)))
    (t (cons (car lst) (list2set (cdr lst))))))
```

Let us trace the execution of the function for `(list2set '(a b b a))`.

```
(list2set '(a b b a)
 -> (list2set '(b b a))
   -> (list2set '(b a))
     -> (cons 'b (list2set '(a)))
       -> (cons 'b (cons 'a '()))
         -> (cons 'b '(a))
           -> (b a)
```

Example 9.30. Let us define function `setp (lst)` that takes a list as its argument and returns true if the list represents a set, and it returns false otherwise. Example executions of the function are as follows:

```
> (setp '3)
NIL

> (setp '())
T

> (setp '(9))
T

> (setp '(4 5 7 8))
T

> (setp '(3 2 6 8 2))
NIL
```

```
(defun setp (lst)
  (cond
   ((not (listp lst)) nil)
   ((null lst) t)
   ((not(member (car lst) (cdr lst))) (setp (cdr lst)))
   (t   nil)))
```

Example 9.31. Let us define function `cartesian (lst1 lst2)` that takes as arguments two lists that represent sets and returns the Cartesian product of the two sets. The function deploys `setp (lst)` as auxiliary function. Example executions of the function are as follows:

```
> (cartesian '3 '(4))
NIL

> (cartesian '() '(a b c))
NIL

> (cartesian '(1 1 2) '(a b c))
NIL

> (cartesian '(1 2) '(a b c))
NIL

> (cartesian '(1 2 3) '(a b c))
((1 A) (1 B) (1 C) (2 A) (2 B) (2 C) (3 A) (3 B) (3 C))
```

```
(defun distribute (el lst)
  (cond
     ((null lst) nil)
      (t (cons (list el (car lst)) (distribute el (cdr lst))))))
;; (distribute '1 '(a b))  =>  ((1 A) (1 B))
```

```
(defun cartesian-aux (lst1 lst2)
  (cond
    ((null lst1) '())
    (t  (append (distribute (car lst1) lst2)
                (cartesian-aux (cdr lst1) lst2)))))

(defun cartesian (lst1 lst2)
  (cond
    ((or
      (or (not (listp lst1)) (not (listp lst2)))
      (not (and (setp lst1) (setp lst2)))
      (not (= (length lst1) (length lst2)))) nil)
    (t (cartesian-aux lst1 lst2))))
```

Let us trace the execution of the function for (cartesian '(1 2 3) '(a b c)).

```
(cartesian '(1 2 3) '(a b c))
-> (cartesian-aux '(1 2 3) '(a b c))
 -> (append '((1 A) (1 B) (1 C)) (cartesian-aux '(2 3) '(a b c))))
  -> (append '((1 A) (1 B) (1 C))
             (append '((2 A) (2 B) (2 C))
                       (cartesian-aux '(3) '(a b c)))))
    -> (append '((1 A) (1 B) (1 C))
           (append '((2 A) (2 B) (2 C))
                 (append '((3 A) (3 B) (3 C))
                       (cartesian-aux '() '(a b c))))
      -> (append '((1 A) (1 B) (1 C))
                 (append '((2 A) (2 B) (2 C))
                       (append '((3 A) (3 B) (3 C)) '()))))
        -> (append '(1 A) (1 B) (1 C))
                  (append '((2 A) (2 B) (2 C)) ((3 A) (3 B) (3 C))))
```

```
-> (append '((1 A) (1 B) (1 C)) '((2 A) (2 B) (2 C)
                                  (3 A) (3 B) (3 C)))
  -> ((1 A) (1 B) (1 C) (2 A) (2 B) (2 C) (3 A) (3 B) (3 C))
```

Example 9.32. Let us define a pure function that accepts a non-empty binary tree as an argument and returns a list of nodes that represents the pre-order traversal of the tree. Note that in doing that your function may invoke auxiliary pure functions. The function must reject any other argument as invalid by returning `nil`.

```
(defun btreep (btree)
  (cond
    ((null btree) t)
    ((not (listp btree)) nil)
    ((not (= (length btree) 3)) nil)
    ((listp (car btree)) nil)
    ((not (btreep (car (cdr btree)))) nil)
    ((not (btreep (car(cdr (cdr btree))))) nil)
    (t t)))

(defun preorder (btree)
  (if (btreep btree)
    (pre btree)
    nil))

(defun pre (btree)
  (cond
    ((null btree) nil)
    (t (append (list (car btree))
               (pre (car(cdr btree)))
               (pre(car (cdr (cdr btree))))))))
```

9.2 From specification to code: summary and guidelines

Below is a summary of steps involved in the definition of a computable function starting from a specification:

1. We obtain a specification (definition) in a plain natural language. For example, consider a function f that accepts an integer n and returns the list $< n, n-1, ..., 0 >$.

2. We transform the definition into a computable function. To do that, we reuse available (i.e. built-in, or previously defined) operations (functions). Most likely we would also have to deploy recursion, i.e.

$$f(n) = (cons\ (n, f(n-1))$$

3. We unfold the definition by tracing the algorithm from the previous step, i.e.

$$\begin{aligned} f(3) &= cons(3, f(2)) \\ &= cons(3, cons(2, f(1))) \\ &= cons(3, cons(2, cons(1, f(0)))) \\ &= cons(3, cons(2, cons(1, \langle 0 \rangle))) \\ &= cons(3, cons(2, \langle 1, 0 \rangle)) \\ &= cons(3, \langle 2, 1, 0 \rangle) \\ &= \langle 3, 2, 1, 0 \rangle. \end{aligned}$$

4. Now that we are confident that our function definition (from step 2) produces the desired output, we can translate it into (Common Lisp) code, i.e.

```
(defun f (n)
   (if (= n 0)
       (cons 0 '())
       (cons n (f(- n 1)))))
```

5. We now can trace the execution of the Common Lisp function with sample input data, e.g.

```
f(2)  = (cons 2, f(1))
      = (cons 2, (cons 1, f(0)))
      = (cons 2, (cons 1, (cons 0, ())))
      = (cons 2, (cons 1, (0)))
      = (cons 2, (1 0))
      = (2 1 0).
```

9.2.1 Additional guidelines for defining functions

We list some additional general guidelines below:

- Unless the function is trivial, we can break the logic into cases (multiple selection) with `cond`.
- When handling lists, you would normally adopt a recursive solution. Treat the empty list as a base case.
- Normally you would operate on the head of a list (accessible with `car`) and recur on the tail of the list (accessible with `cdr`).
- To skip the head of the list, simply recur on the tail of the list.
- To keep the head of the list as is, use `cons` to place it as the head of the returning list (whose tail is determined by the recursive call).
- Use `else` (or `t`) to cover remaining (and to protect against forgotten) cases.

Chapter 10

Structures

Structures are collections that hold data and they can be unordered or ordered.

10.1 Unordered structures: Sets and bags

A *set* is a collection of objects, called its *elements* (also: *members*). If S is a set and x is an element in S, then we write $x \in S$. If x is not an element of S we write $x \notin S$. The set of no elements is called the *empty* set (also: *null* set), denoted by $\{\}$ or $\emptyset$. Sets have two characteristics:

1. No element repetition is allowed.

2. The ordering of the elements is not important.

One way to define a set is to explicitly list all its elements, separated by commas and enclosed within braces ($\{\ldots\}$). Two sets are *equal* if they have the same elements. We denote the fact that two sets A and B are equal by $A = B$. If sets A and B are not equal, we write $A \neq B$.

Note that since order is not important,

$$\{a, b, c\} = \{c, a, b\}$$

as opposed to

$$\langle a, b, c\rangle \neq \langle c, a, b\rangle$$

Note also that

$$a \neq \{a\} \neq \{\{a\}\}$$

since a is a single object, $\{a\}$ is a set with one element, namely a, whereas $\{\{a\}\}$ is a set with one element, namely the set $\{a\}$ which contains one element, a.

If A and B are sets and every element of A is also an element of B, then we say that A is a *subset* of B, denoted by $A \subset B$. It follows, from the definition, that every set is a subset of itself. It also follows that the empty set is a subset of any set A, i.e. $\emptyset \subset A$. We can use the notion of subsets to define set equality $A = B$ to mean $A \subset B$ *and* $B \subset A$.

The *cardinality* of a set A, denoted by $|A|$, is a measure of how many elements A has.

10.1.1 Operations on sets

We can define the following operations on sets:

The *union* of two sets A and B, denoted as $A \cup B$, is given by

$$A \cup B = \{x : x \in A \text{ or } x \in B\}$$

The *intersection* of two sets A and B, denoted as $A \cap B$, is given by

$$A \cap B = \{x : x \in A \text{ and } x \in B\}$$

The *difference* between two sets A and B, denoted as $A \backslash B$ (or $A - B$), is given by

$$A \backslash B = \{x : x \in A \text{ and } x \notin B\}$$

The *symmetric difference* of two sets A and B, denoted as $A \oplus B$, is given by

$$\begin{aligned} A \oplus B &= \{x : x \in A \text{ or } x \in B \text{ but not both}\} \\ &= A \backslash B \ \cup \ B \backslash A \end{aligned}$$

Two sets A, B are called *disjoint* iff their intersection is empty, i.e.

$$A \cap B = \emptyset$$

Example 10.1. Consider function `issubsetp` which takes as arguments two lists representing sets, `set1` and `set2`, and returns true if `set1` is a subset of `set2`. Otherwise, it returns false (nil).

Base case: If `set1` is empty, then return true.

Recursive case: If the first element of `set1` is a member of `set2`, then recur on the rest of the elements of `set1`, otherwise return false (nil).

We can implement function `issubsetp` as follows:

```
(defun issubsetp (set1 set2)
  (if (null set1)
    t
    (if (member (car set1) set2)
      (issubsetp (cdr set1) set2)
      nil)))
```

We can now run the function as follows:

```
> (issubsetp '() '(a))
T
> (issubsetp '(a b c) '(a b c d))
T
```

Example 10.2. Consider function `setunion` which takes as its arguments two lists `lst1` and `lst2` representing sets and returns the set union.

Base cases:

1. If `lst1` is empty, then return `lst2`.
2. If `lst2` is empty, then return `lst1`.

Recursive cases:

1. If the head of `lst1` is a member of `lst2`, then ignore this element and recur on the tail of `lst1`, and `lst2`.
2. If the head of `lst1` is not a member of `lst2`, return a list which is the concatenation of this element with the union of the tail of `lst1` and `lst2`.

We can implement function `setunion` as follows:

```
(defun setunion (lst1 lst2)
  (cond
    ((null lst1) lst2)
    ((null lst2) lst1)
    ((member (car lst1) lst2)(setunion (cdr lst1) lst2))
    (t (cons (car lst1) (setunion (cdr lst1) lst2)))))
```

We can execute the function as follows:

```
> (setunion '(a b c d) '(a d))
(B C A D)
```

Example 10.3. Consider function `setintersection` which takes as its arguments two lists `lst1` and `lst2` representing sets, and returns a new list representing a set which forms the intersection of its arguments.

Base case: If either list is empty, then return the empty set.

Recursive cases:

1. If the head of `lst1` is a member of `lst2`, then keep this element and recur on the tail of `lst1` and `lst2`.

2. If the head of `lst1` is not a member of `lst2`, ignore this element and recur on the tail of `lst1` and `lst2`.

We can implement function `setintersection` as follows:

```
(defun setintersection (lst1 lst2)
  (cond
    ((null lst1) '())
    ((null lst2) '())
    ((member (car lst1) lst2)
         (cons (car lst1) (setintersection (cdr lst1) lst2)))
    (t (setintersection (cdr lst1) lst2))))
```

We can execute the function as follows:

```
> (setintersection '(a b c) '())
NIL
> (setintersection '(a b c) '(a d e))
(A)
```

Example 10.4. Consider function `setdifference` which takes as its arguments two lists `lst1` and `lst2` representing sets and returns the set difference.

Base case: If `lst1` is empty, then return the empty set. If `lst2` is empty, then return `lst1`.

Recursive cases:

1. If the head of `lst1` is a member of `lst2`, then ignore this element and recur on the tail of `lst1`, and `lst2`.
2. If the head of `lst1` is not a member of `lst2`, keep this element and recur on the tail of `lst1` and `lst2`.

We can implement function `setdifference` as follows:

```
(defun setdifference (lst1 lst2)
  (cond
    ((null lst1) '())
    ((null lst2) lst1)
    ((member (car lst1) lst2)(setdifference (cdr lst1) lst2))
    (t (cons (car lst1) (setdifference (cdr lst1) lst2)))))
```

We can execute the function as follows:

```
> (setdifference '(a b c) '(a d e f))
(B C)
```

Example 10.5. Consider function `setsymmetricdifference` which takes as its arguments two lists representing sets and returns a list representing their symmetric difference. We can define this function as the difference between the union and the intersection sets, i.e.

$$A \oplus B = (A \cup B) \setminus (A \cap B)$$

We can implement function `setsymmetricdifference` as follows:

```
(defun setsymmetricdifference (lst1 lst2)
  (setdifference (union lst1 lst2)(intersection lst1 lst2)))
```

Alternatively we can say

$$A \ominus B = (A \backslash B) \cup (B \backslash A)$$

We can implement function `setsymmetricdifference2` as follows:

```
(defun setsymmetricdifference2 (lst1 lst2)
  (union (setdifference lst1 lst2)(setdifference lst2 lst1)))
```

We can now run the function as follows:

```
> (setsymmetricdifference '(a b c d e f) '(d e f g h))
```

```
(H G A B C)
> (setsymmetricdifference2 '(a b c d e f) '(d e f g h))
(H G A B C)
> (setsymmetricdifference '(a b (cd) e) '(e (f h)))
((F H) A B (CD))
> (setsymmetricdifference2 '(a b (cd) e) '(e (f h)))
((F H) A B (CD))
```

10.1.2 Bags

A *bag* (or *multiset*) is a structure which contains a collection of elements. Like a set, the ordering of the elements in not important in a bag. However, unlike a set, repetitions are allowed in a bag.

Note that since order is not important and repetitions are allowed,

$$\{a, b, b, c\} = \{c, a, b, b\}$$

$$\{a, b, c\} \neq \{c, a, b, b\}$$

Example 10.6. Consider function `bag-to-set` which takes as its argument a list representing a bag and returns the corresponding set.

Base case: If the list is empty, then return the empty list.

Recursive cases:

1. If the head of the list is a member of the tail of the list, then ignore this element and recur on the tail of the list.
2. If the head of the list is not a member of the tail of the list, keep the head element and recur on the tail of the list.

We can implement function `bag-to-set` as follows:

```
(defun bag-to-set (bag)
  (cond ((null bag) '())
        ((member (car bag) (cdr bag)) (bag-to-set (cdr bag)))
        (t (cons (car bag) (bag-to-set(cdr bag))))))
```

We can execute the function as follows:

```
> (bag-to-set '(a a b c))
(A B C)
> (bag-to-set '(a a a b b c b a))
(C B A)
> (bag-to-set '(a b c d))
(A B C D)
```

10.2 Ordered structures: Tuples

We have already seen an ordered structure, namely the list. A *tuple* is a structure which contains a collection of elements. Unlike sets and bags, the ordering of the elements matters in a tuple. Unlike a set repetitions are allowed in a tuple.

Note that since order is important and repetitions are allowed,

$$(a, b, b, c) \neq (c, a, b, b)$$

$$(a, b, c) \neq (c, a, b, b)$$

Summary

We can summarize the restrictions imposed by the collections discussed in this chapter as follows:

Collection	Order	Repetitions allowed
Set	No	No
Bag (multiset)	No	Yes
Tuple	Yes	Yes

Chapter 11

Trees

We can use a list to represent a non-empty binary tree as $\langle atom, l-list, r-list \rangle$, where *atom* is the root of the tree, and $l-list$ and $r-list$ are lists that represent the left and right subtrees respectively. For an empty binary tree, the list representation can be $\langle\rangle$.

Example 11.1. Consider the binary tree in Figure 11.1. Let us translate this representation into Lisp.

```
'(40                ; Root.
  (...)             ; Left subtree.
  (...)             ; Right subtree.
 )
```

The left subtree of 40 can be represented as

```
(30                 ; Root of left subtree of 40.
  (...)
  (...)
)
```

with the left and right subtrees of 30 can be represented as

```
(25 () ())          ; Left subtree of 30.
(35 () ())         ; Right subtree of 30.
```

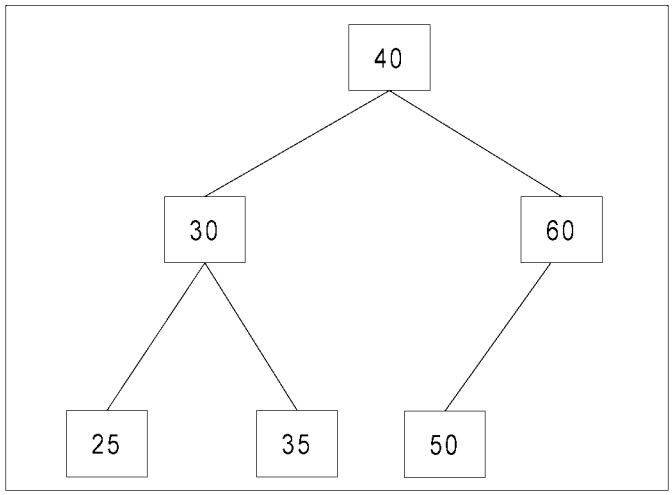

Figure 11.1: Binary tree.

where their respective left and right subtrees are null, represented by the empty list.

The right subtree of 40 can be represented as

```
(60
  (...)                ; Left subtree of 60.
  ()                   ; Right subtree of 60.
)
```

where the left subtree of 60 can be represented as

```
(50 ()())
```

We can now put everything together and represent the entire tree as one list:

```
'(40                   ; Root.
    (30                ; Root of left subtree.
       (25 () ())
       (35 () ())
    )
    (60                ; Root of right subtree.
       (50 () ()) ()))
```

or '(40 (30 (25 () ())(35 () ()))(60 (50 () ())()))

Recall that the entire tree is represented by the list $\langle atom, l-list, r-list \rangle$. We can obtain the root of the tree by getting the head of the list:

```
> (car '(40 (30 (25 () ())(35 () ()))(60 (50 () ())())))
40
```

We can obtain the left subtree, $l-list$, of the tree by getting the head of the tail of the list:

```
> (car (cdr '(40 (30 (25 () ())(35 () ()))(60 (50 () ())()))))
(30 (25 NIL NIL) (35 NIL NIL))
```

We can obtain the right subtree, $r-list$, of the tree by getting the head of the tail of the tail of the list:

```
> (car (cdr (cdr '(40 (30 (25 () ())(35 () ()))(60 (50 () ())())))))
(60 (50 NIL NIL) NIL)
```

Example 11.2. Consider the binary tree in Figure 11.2. The height of this tree is 3. Recall that the height of an empty tree, or the height of a tree with a single node is zero.

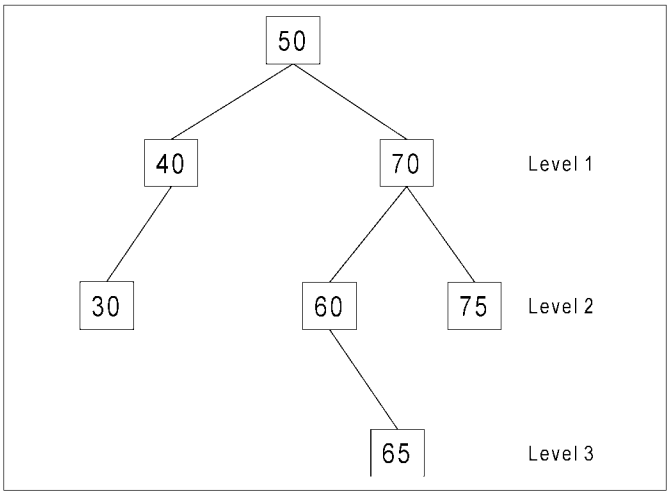

Figure 11.2: A binary tree of height 3.

We can represent the tree as follows:

```
'(50
  (40 (30 () ()) ())
  (70 (60 () (65 () ())) (75 () ())))
```

Consider function `tree-height`, which takes as an argument a list representing a tree and returns the height of the tree.

We can provide a recursive definition of `tree-height` is as follows:

Base case: If `tree` is empty, or if the tree has one node (root) then return 0.

Recursive case: Add one to the maximum of the heights of the left and right subtrees.

We can implement function `tree-height` as shown below. Note that the implementation needs an auxiliary function `take-max`.

```
(defun tree-height (tree)
  (if (or (null tree)
          (and (null (car (cdr tree)))
               (null (car (cdr (cdr tree))))))
      0
    (+ 1 (take-max (tree-height (car (cdr tree)))
                   (tree-height (car (cdr (cdr tree))))))))

(defun take-max (n1 n2)
  (if (> n1 n2)
      n1
    n2))
```

We can execute `tree-height` as follows:

```
> (tree-height '(50  (40 (30 () ()) ()) (70 (60 () (65 () ())) (75 () ()))))
3
```

Example 11.3. Let us define and implement function `count-nodes` which takes as argument a list representing a binary tree and returns the total number of (non-null) nodes. We can transform the above problem specification into a recursive computable function definition in mathematical notation and in English notation as follows:

$$count - nodes(\langle\rangle) = 0.$$
$$count - nodes(\langle atom, l - list, r - list\rangle) = 1+$$
$$count - nodes(l - list)+$$
$$count - nodes(r - list).$$

Base case: If `tree` is empty, then return 0.

Recursive case: Add one to the number of nodes of the left and of the right subtree.

We can implement function `count-nodes` as follows:

```
(defun count-nodes (tree)
    (if (null tree)
        0
        (+ 1
           (count-nodes (car (cdr tree)))
           (count-nodes (car (cdr (cdr tree)))))))
```

Let us execute `count-nodes` with the tree of the previous example:

```
> (count-nodes '(50  (40 (30 () ()) ()) (70 (60 () (65 () ())) (75 () ()))))
7
```

For the tree of Figure 11.3 we can trace `count-nodes` as follows:

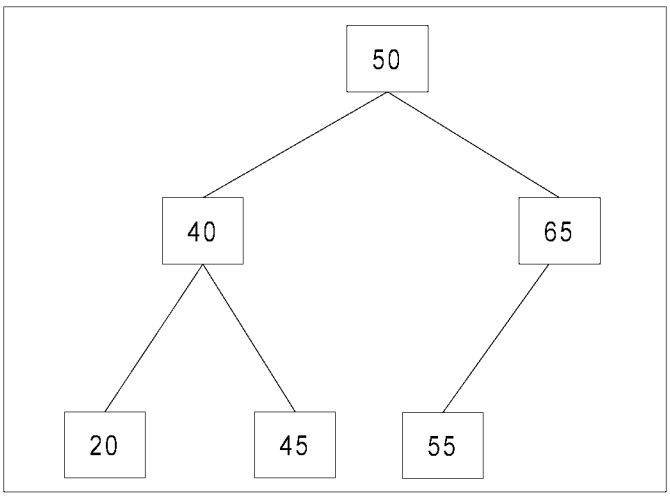

Figure 11.3: Binary tree.

```
(count-nodes '(50 (40 (20 () ()) (45 () ()) ))(65 (55 () ())()))

  (+ 1 count-nodes(40 (20 () ()) (45 () ())) count-nodes(65 (55 ()()) ()))

  (+ 1 (+ 1 count-nodes (20 () ()) count-nodes(45 () ()))
               (+ 1 count-nodes (55 () ()) count-nodes(())))

  (+ 1 (+ 1 (+ 1 (count-nodes(()) count-nodes(()))
               (+ 1 count-nodes(()) count-nodes(()))
                     (+ 1 (+ 1 count-nodes(()) count-nodes(())) 0))))

  (+ 1 (+ 1 (+ 1 0 0) (+ 1 0 0) (+ 1 1 0 0))))

  6
```

Chapter 12

Numbers

12.1 Exponentiation

The exponentiation operation, a^n, involves two numbers, the base a and the exponent n. When n is a positive integer, exponentiation corresponds to repeated multiplication. We can define $power(a, n)$ as follows:

$$power(a, 0) = 1$$
$$power(a, 1) = a = a \times power(a, 0)$$
$$power(a, 2) = a \times a = a \times power(a, 1)$$

We can then define a recursive pattern as follows:

Base case: $power(a, 0) = 1$

Recursive case: $power(a, n) = a \times power(a, n - 1)$

We can unfold the definition of $power(3, 4)$ as follows:

$$\begin{aligned} power(3,4) &= 3 \times power(3,3) \\ &= 3 \times 3 \times power(3,2) \\ &= 3 \times 3 \times 3 \times power(3,1) \\ &= 3 \times 3 \times 3 \times 3 \times power(3,0) \\ &= 3 \times 3 \times 3 \times 3 \times 1 \\ &= 81. \end{aligned}$$

We can now define function `power` as follows:

```
(defun power (a n)
  (if (zerop n)
    1
    (* a (power a (- n 1)))))
```

We can execute the function as follows:

```
> (power 3 0)
1
> (power 3 2)
9
> (power 3 4)
81
```

12.2 Cartesian system

For two points (x_1, y_1) and (x_2, y_2), the distance between them is given by

$$d = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}.$$

Example 12.1. A point on the Cartesian plane can be represented as a two-element list. The first element of the list represents the x coordinate and it can be obtained by the head of the list. The second element of the list defines the y coordinate and it can be accessed as the head of the tail of the list. We can define function `second2` to take as its argument a Cartesian point and return the y coordinate:

```
(defun second2 (lst)
  (car (cdr lst)))
```

We can now use `second2` as an auxiliary to function `distance`, which takes as arguments two two-atom lists, each one representing a point on the Cartesian plane. The function returns the distance between the points. To improve readability, we will use `first` in place of the (admittedly less readable) `car`.

```
(defun distance (p1 p2)
  (sqrt (+ (expt (- (first p1) (first p2)) 2)
           (expt (- (second2 p1) (second2 p2)) 2))))
```

We can execute the function as follows:

```
> (distance '(0 0) '(2 2))
2.828427
```

12.3 Factorial of a number

The factorial of an integer number is defined as follows:

Base case: If the number is zero, return `1`.

Recursive case: Return the product between `n` and the factorial of `n - 1`.

Consider the unfolding of the definition for $f(5)$ as follows:

$$\begin{aligned} factorial(5) &= 5 \times factorial(4) \\ &= 5 \times 4 \times factorial(3) \\ &= 5 \times 4 \times 3 \times factorial(2) \\ &= 5 \times 4 \times 3 \times 2 \times factorial(1) \\ &= 5 \times 4 \times 3 \times 2 \times 1 \times factorial(0) \\ &= 5 \times 4 \times 3 \times 2 \times 1 \times 1 \\ &= 120. \end{aligned}$$

We can now define function `factorial` as follows:

```
(defun factorial (n)
  (if (= n 0)
    1
    (* n (factorial (- n 1)))))
```

We can now execute the function as follows:

```
>(factorial 5)
120
```

12.4 Prime numbers

An integer $p > 1$ is called *prime* if it cannot be the product of two integers greater than 1, or alternatively if its only positive factors are 1 and itself. Positive integers which can be expressed as the product of two integers greater than 1 are called *composite*.

12.5 Greatest common divisor

The *greatest common divisor (gcd)* of two integers a and b (not both zero) is the largest integer d that is a divisor both of a and of b. We can implement function `gcd` as follows:

```
(defun gcd (a b)
  (cond ((equal a b) a)
        ((> a b) (gcd (- a b) b))
        (t (gcd a (- b a)))))
```

12.6 Relative primality

Two numbers are *relatively prime* (or *coprime*) if their greatest common divisor (gcd) is 1. We can implement a predicate function `coprimep` which determines whether or not two positive integer numbers a and b are coprime.

```
(defun coprime (a b)
  (equal (gcd a b) 1))
```

We can now run the function as follows:

```
>(coprime 35 64)
T
```

12.7 Division remainder

Example 12.2. Consider function `remainder`, which takes as arguments two positive non-zero numbers, n and m, and returns the remainder of the division n/m.

Base case: If $n < m$ then return n.

Recursive case: Return the remainder of $(n - m)$ and m.

```
(defun remainder (n m)
  (cond ((< n m) n)
        (t (remainder (- n m) m))))
```

We can now run the function as follows:

```
> (remainder 3 5)
3
> (remainder 5 3)
2
```

Chapter 13

Sorting

Sorting is a technique that puts the elements of an unordered collection in a certain order.

13.1 Bubble sort

Bubble sort is based on successive pairwise comparisons between elements of a collection performed possibly over many iterations. Each iteration results in a single element eventually ending up in its proper position (like a bubble moving up).

We can demonstrate this with an example: Consider the collection $(9, 8, 13, 6)$. The first iteration will work as follows:

Collection	Observations and actions
$(\boxed{9,\ 8}, 13, 6)$	Compare 1st with 2nd. Not in order. Swap them!
$(8, \boxed{9,\ 13}, 6)$	Compare 2nd with 3rd. In order.
$(8, 9, \boxed{13,\ 6})$	Compare 3rd with 4th. Not in order. Swap them!
$(8, 9, 6, \mathbf{13})$	One element (13) has reached its proper position.
	We have reached the end of the collection and
	the end of the current iteration.

Note that the collection is not yet sorted and more iterations are required.

Example 13.1. Consider the implementation of function `bubble-sort` which takes as its argument a list, and returns the same list with its elements sorted in ascending order. We first need to build some auxiliary functions, the first one is `bubble` which performs one iteration, thus placing one element in its proper position.

```
(defun bubble (lst)
  (cond ((or (null lst) (null (cdr lst))) lst)
        (( < (car lst) (car (cdr lst)))
           (cons (car lst) (bubble (cdr lst))))
        ( t (cons (car (cdr lst))
           (bubble (cons (car lst) (cdr (cdr lst))))))))
```

We can test the function as follows:

```
> (bubble '(3 2 1))
(2 1 3)
```

Another auxiliary function is `is-sortedp` which returns True or False based on whether or not its list argument is sorted.

```
(defun is-sortedp (lst)
  (cond ((or (null lst) (null (cdr lst))) t)
    ((< (car lst) (car (cdr lst))) (is-sortedp (cdr lst)))
    (t nil)))
```

We can test the function as follows:

```
> (is-sortedp '(2 1 3))
NIL
> (is-sortedp '(1 2 3))
T
```

We can now put everything together and define `bubble-sort` as follows:

```
(defun bubble-sort (lst)
  (cond ((or (null lst) (null (cdr lst))) lst)
        ((is-sortedp  lst) lst)
        (t (bubble-sort (bubble lst)))))
```

We can execute the function as follows:

```
> (bubble-sort '(4 2 7 5 9))
(2 4 5 7 9)
```

Chapter 14

Searching

Searching is a technique to locate a given element from a sorted collection of elements. We will deploy a list to represent a collection of elements.

14.1 Linear search

If element `elt` appears in list `lst` then we would like to return its position in the list. Consider the following function:

```
(defun search (lst elt pos)
  (if (null lst)
      nil
      (if (equal (car lst) elt)
          pos
          (search (cdr lst) elt (+ 1 pos)))))

(defun linear-search (lst elt)
  (search lst elt 1))
```

We can execute the function as follows:

```
> (linear-search '(4 6 1 5 8 9) 9)
6
```

```
> (linear-search '(a (bc) d) '(bc))
2
```

14.2 Binary search

Recall that we can use a list to represent a non-empty tree as $\langle atom, l-list, r-list \rangle$, where $atom$ is the root of the tree and $l-list$ and $r-list$ represent the left and right subtrees respectively.

```
(defun binary-search (lst elt)
  (cond ((null lst) nil)
    ((= (car lst) elt) t)
    ((< elt (car lst)) (binary-search (car (cdr lst)) elt))
    ((> elt (car lst)) (binary-search (car (cdr (cdr lst))) elt))))
```

We can execute the function as follows:

```
> (binary-search '() 9)
NIL
> (binary-search '(7 (3 (1 () ())) (9 () ())) 1)
T
> (binary-search '(7 (3 (1 () ())) (9 () ())) 9)
T
> (binary-search '(7 (3 (1 () ())) (9 () ())) 7)
T
> (binary-search '(7 (3 (1 () ())) (9 () ())) 6)
NIL
```

Part III

Procedural Programming with C

Chapter 15

Functions II

15.1 Functions

We have already seen that similarly to its mathematical counterpart, a computing *function* is a (named) block that normally receives some input, performs some task and normally returns a result. Unlike its mathematical counterpart, a computing function may receive no input or may produce no output. A function call implies transfer of control of execution to the function. When a function completes its task and terminates, control of execution is transferred back to the client.

Synonyms for *function* exist in various languages (such as *method*, *procedure*, or *subroutine*). It is also important to note that some languages make a distinction between functions that return a result and those that do not, the latter ones being referred to as procedures.

We will use the C programming language to discuss procedural programming. The general form of a function definition in C is

```
return-type function-name ( parameter-list ) { body }
```

where *return-type* is the type of the value that the function returns, *function-name* is the name of the function, and *parameter-list* is the list of parameters that the function takes, defined as

```
( type1 parameter1, type2 parameter2, ... )
```

If no type is in front of a variable in the parameter list, then `int` is assumed. Finally, the body of the function is a sequence of statements.

If the function will be accessed before it is defined, then we must let the compiler know about the function by defining the function's *prototype* (or *declaration*) as follows:

```
return-type function-name (parameter-type-list);
```

where *return-type* and *function-name* must correspond to the function definition. The *parameter-type-list* is a list of the types of the function's parameters. Function `main()` requires no prototype.

15.2 Recursion

C supports recursion. Like its mathematical counterpart and very similarly to the Lisp functions that we have seen, a function in C can call itself.

Example 15.1. Consider the program below that computes the factorial of a non-negative integer. The program is composed by two functions: `main()` and `factorial(..)`. The statement

```
long factorial(int);
```

defines the prototype for function `factorial`. The code below

```
long factorial(int n) {
  ...
}
```

is the actual function definition. In C, execution always starts from `main()` which calls all other functions, directly or indirectly.

```
#include<stdio.h>
long factorial(int);
int main() {
  int n;
  long f;
  printf(                                    );
  scanf(     , &n);
  if (n < 0)
    printf(                                          );
  else {
    f = factorial(n);
    printf(              , n, f);
  }
  return 0;
}
long factorial(int n) {
  if (n == 0)
    return 1;
  else
    return(n * factorial(n-1));
}
```

In `long factorial(int n) ..`, `n` is called the *parameter* (or *formal argument*, also *dummy argument*) of the function. The result of a function is called its *return value* and the data type of the return value is called the function's *return type*. The return type of `main()` is int (integer), whereas the one of factorial is `long` (long integer). A *function call* allows us to use a function in an expression. In

```
f = factorial(n);
```

the function on the right-hand-side executes and the value that it returns is assigned to the variable `f` on the left-hand-side. We refer to `n` as the *actual argument* (or just *argument* if the distinction is clear from the context). Obviously the actual argument(s) to a function

would normally vary from one call to another. The values of the actual arguments are copied into the formal parameters, with a correspondence in number and type.

Let us execute the program:

```
Enter an non-negative integer: 5
5! = 120
```

Example 15.2. In this example we are writing a program whose main function requests and receives the value of the fahrenheit temperature to be converted to celsius and proceeds to call function `f2c()` to perform this conversion. The function `f2c()` will apply the conversion formula and return its result to the caller (function `main()`).

```
#include <stdio.h>
int f2c (int fahrenheit);
int main (void) {
  int fahrenheit;
  printf(                                                    );
  scanf(     , &fahrenheit);
  printf (                                                      ,
           f2c(fahrenheit));
  return 0;
}
int f2c (int fahrenheit) {
  int celsius;
  celsius = (5.0/9.0) * (fahrenheit-32);
  return celsius;
}
```

Let us execute the program:

```
Enter the temperature in degrees fahrenheit: 30
The corresponding temperature in celsius is -1
```

15.3 Global and local variables

We distinguish between global and local variables. A global variable is defined at the top of the program file and can be accessed by all functions. A local variable is accessed only within the function which it is declared, called the scope of the variable. Though not a good programming practice, in the case where the same name is used for a global and local variable then the local variable takes preference within its scope. This is referred to as *shadowing*. Global variables have default initializations, whereas local variables do not.

Consider the following program that contains a global and a local variable with the same name. Within function `func(..)` the global variable `a` is not visible as the local variable `a` takes precedence.

```
#include<stdio.h>
int a = 3;
int func() {
  int a = 5;
  return a;
}
int main() {
  printf(                    , a);
  printf(                    , func());
  printf(                    , a);
}
```

The output is:

```
From main: 3
From func: 5
From main: 3
```

15.4 Variable and function modifiers

Two modifiers are used to explicitly indicate the visibility of a variable or function: The `extern` modifier indicates that a variable or function is defined outside the current file, whereas the `static` modifier indicates that the variable or function is visible only from within the file it is defined in. The default (i.e. no modifier) indicates that the variable or function is defined in the current file and it is visible in other files. A summary is given below:

MODIFIER	DESCRIPTION
`extern`	Variable/function is defined outside of current file.
`<blank>`	Variable/function is defined in current file and visible outside.
`static`	Variable/function is visible only in current file.

Consider a program that reads in a collection of elements and proceeds to sort them by calling a function `bubbleSort()` that is defined outside the current file and thus must be declared `extern`.

```
#include <stdio.h>
extern void bubbleSort(int[], int);
int main() {
  int array[10], numberOfElements;
  printf(                              );
  scanf(     , &numberOfElements);
  printf(                        , numberOfElements);
  for (int i = 0; i < numberOfElements; i++)
    scanf(     , &array[i]);
  bubbleSort(array, numberOfElements);
  printf(                                    );
  for (int i = 0 ; i < numberOfElements ; i++)
    printf(      , array[i]);
  return 0;
}
```

Function `bubbleSort()`, defined in some other file, makes use of function `swap()` that swaps two elements. As function `swap()` need not be visible outside the file in which it is defined, it is declared `static`:

```
static void swap(int *a, int *b) {
  int temp = *a;
  *a = *b;
  *b = temp;
}

void bubbleSort(int numbers[], int array_size) {
  int i, j;
  for (i = (array_size - 1); i > 0; i--) {
    for (j = 1; j <= i; j++) {
      if (numbers[j-1] > numbers[j])
        swap(&numbers[j-1], &numbers[j]);
    }
  }
}
```

The output of the program is as follows:

```
Enter number of elements: 10
Enter 10 integers: 4 6 8 12 45 66 23 43 11 2
Sorted list (ascending order): 2 4 6 8 11 12 23 43 45 66
```

15.5 The C standard library

An *application programming interface* (API) is a protocol that constitutes the interface of software components. In the C language this is a collection of functions grouped together according to their domain. We can access this API (called the *C standard library*) by adding the `#include` directive at the top of our program file. Perhaps the most common is the

group of functions that support input-output and are accessed by `<stdio.h>`. This and other common header files are listed in the table below:

HEADER	DESCRIPTION
`<math.h>`	Defines common mathematical functions.
`<stdio>.h`	Defines core input and output functions.
`<stdlib.h>`	Defines numeric conversion functions, pseudo-random number generation functions, memory allocation, process control functions.
`<string.h>`	Defines string manipulation functions.

15.6 Formatted output

You may be surprised to know that the C language defines no input/ouput functionality. The `printf` function is part of the standard library. The following is a list of format specifiers:

SPECIFIER	DISPLAYS	EXAMPLE
`%i` or `%d`	int	`%3d` displays as a decimal integer with a width of at least 3 wide.
`%c`	char	
`%f`	float	`%4f` displays as a floating point with a width of at least 4 wide. `%.1f` displays as a floating point with a precision of one character after the decimal point. `%2.2f` displays as a floating point at least 2 wide and a precision of 2 characters after the decimal point.
`%lf`	double	
`%s`	string	

The `\n` we used in some `printf` statements is called an *escape sequence* and it represents a newline character. The following are common escape sequences:

ESCAPE SEQUENCE	DESCRIPTION
\n	newline
\t	tab
\v	vertical tab
\f	new page
\b	backspace
\r	carriage return
\n	newline

Example 15.3. The following program demonstrates some of the formatting rules:

```
#include<stdio.h>
main() {
  int a, b;
  float c, d;
  a = 7;
  b = a / 2;
  c = 10.5;
  d = c / 2;
  printf(      , b);
  printf(       , b);
  printf(         , c);
  printf(         ,d);
  return 0;
}
```

The output is:

```
3
  3
10.50
5.250
```

Chapter 16

Data types

A program is composed by *constructs*, such as functions and variables. A *data type* (or simply a *type*) is a description of the possible values that a construct can store or compute to, together with a collection of operations that manipulate that type, e.g. the set of integers together with operations such as addition, subtraction, and multiplication. Common types among most programming languages include booleans, numerals, characters and strings.

16.1 Classes of data types

The *Boolean type* contains the values `true` and `false`. The *numeral type* includes integers that represent whole numbers and floating points that represent real numbers. The *character type* is a member of a given set (ASCII) and, finally, strings are sequences of alphanumeric characters. We can distinguish between *simple types* and *composite* (or *aggregate*) types based on whether or not the values of a type can contain subparts. As an example, we can say that integer is a simple type, whereas record is composite. A *data item* is an instance (also: a *member*) of a type.

16.2 Primitive data types

With respect to a given programming language, a *primitive* type is one that is built in (provided by the language). The C language supports two different classes of data types, namely numerals and characters, which are divided into four type identifiers (int, float, double, char), together with four optional specifiers (signed, unsigned, short, long):

IDENTIFIER	TYPE	RANGE
int	integer	$-32,768$ to $32,767$
float	real	1.2×10^{-38} to 3.4×10^{38}
double	real	2.2×10^{-308} to 1.8×10^{308}
char	character	ASCII

16.2.1 Optional specifiers: Short, long, signed and unsigned

The four specifiers define the amount of storage allocated to the variable. We distinguish between *short* and *long* numeral data types that differ in their range. The amount of storage is not specified, but ANSI places the following rules:

$$short\ int \leq int \leq long\ int$$

and

$$float \leq double \leq long\ double$$

Further, we can distinguish between *signed* and *unsigned* numeral data types. Signed variables can be either positive or negative. On the other hand unsigned variables can only be positive, thus covering a larger range.

OPTIONAL SPECIFIER	RANGE
short int	$-32,768$ to $32,767$
unsigned short int	0 to $65,535$
unsigned int	0 to $4,294,967,295$
long int	$-2,147,483,648$ to $2,147,483,647$

16.2.2 Type conversion

Type conversion is the transformation of one type into another. In C, implicit type conversion (or *coercion*) is the automatic type conversion done by the compiler. In the following example, the value of a float variable is assigned to an integer variable which in turn is assigned to another float variable.

```
#include <stdio.h>
int main() {
  int intvar;
  float floatvar = 3.14;
  float floatvar2;
  intvar = floatvar;
  floatvar2 = intvar;
  printf(                    , intvar, floatvar, floatvar2);
  return 0;
}
```

The output of the program is as follows:

```
3 : 3.14 : 3.000
```

16.2.3 Defining constants

A *constant* defines a data type whose value cannot be modified. We can define a constant either with the `const` keyword as in

```
float const pi = 3.14
```

or with `#define` as in

```
#define TRUE    1
#define FALSE   0
```

16.2.4 Constant declarations in function parameters

A constant declaration in a function parameter states that the function is not going to change the value of the parameter.

16.3 Composite data types

A *composite type* is one that is composed by primitive types or other composite types. Normally a composite type is called a *data structure*: a way to organize and store data so that it can be accessed and manipulated efficiently. Common composite types include arrays and records.

16.4 Arrays

An *array* is a collection of values (called its elements), all of the same type, held in a specific order (and in fact stored contiguously in memory). Arrays can be either static (i.e,. fixed-length) or dynamic (i.e. expandable). An array of size n is indexed by integers from 0 up to and including $n-1$. The composition of primitive (and possibly other composite) types into a composite type results in a new type. For example, integers can be composed to construct an array of integers.

Example 16.1. In the following program, we declare and initialize an array, `numbers`, and then pass it as an argument, together with its size, to function `getAverage()` that will compute and return the average of the elements of the array.

```
#include<stdio.h>
float getAverage(float[], int);
int main() {
  float numbers[5] = {1, 2.5, 9, 11.5, 23.5};
  printf(                          , getAverage(numbers, 5));
  return 0;
}
float getAverage(float list[], int size) {
  int i;
  float sum = 0.0;
  float average = 0.0;
  for (i=0; i<size; i++)
    sum = sum + list[i];
  average = (sum/size);
  return average;
}
```

The output is:

```
Array average: 9.5.
```

16.5 Pointers

A *pointer* is a type that references (*"points to"*) another value by storing that other value's address. A *pointer variable* (also called an *address variable*) is declared by putting an asterisk * in front of its name, as in the following statement that declares a pointer to an integer.

```
int *ptr;
```

There are two operators that are used with pointers, namely "dereferencing" and "obtaining the address of."

* The "dereference" operator: Given a pointer, obtain the value of the object referenced (pointed at).

& The "address of" operator: Given an object, use & to point to it. The & operator returns the address of the object pointed to.

Example 16.2. The following code segment declares an integer variable `a` which is assigned to 42 (line 3), and a pointer `p` that points to an integer object (line 4). In line 5, the pointer `p` is assigned the address of variable `a`, and in line 6 we display the contents of the object pointed to by `p`. Accessing the object being pointed at is called *dereferencing* the pointer. An illustration of this is shown in Figure 16.1.

```
1  #include <stdio.h>
2  int main() {
3    int a = 42;
4    int *p;
5    p = &a;
6    printf(          , *p);
7    return 0;
8  }
```

The output of the program is `p:  42`.

Example 16.3. In this example an integer pointer `ptr` points to an integer variable `my_var`. We then proceed to modify the contents of `my_var` through `ptr` and finally we verify that the value of `my_var` has indeed been modified. An illustration of this is shown in Figure 16.2.

```
#include<stdio.h>
int main() {
  int my_var = 13;
  int *ptr = &my_var;
  *ptr = 17;
  printf(               , my_var);
}
```

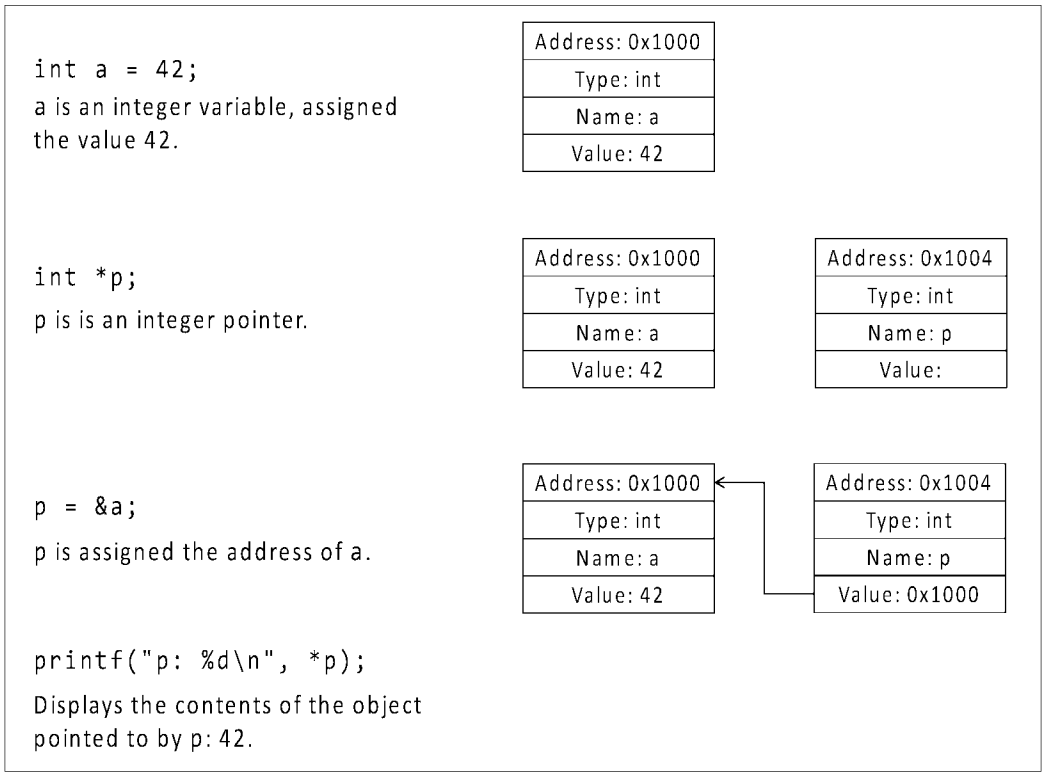

Figure 16.1: An initial illustration of pointers.

Note that a statement such as `*my_var` would have been illegal as it asks C to obtain the object pointed to by `my_var`. However, `my_var` is not a pointer. Similarly, a statement such as `&ptr` though legal is rather strange as it asks C to obtain the address of `ptr`. The result is a pointer to a pointer (i.e. the address of an object that contains the address of another object).

16.5.1 Aliasing

Aliasing is a situation where a single memory location can be accessed through different variables. Modifying the data through one name implicitly modifies the values associated to all aliased names. Consider the program below:

```
#include<stdio.h>
int main() {
  int a = 7;
  int *ptr;
```

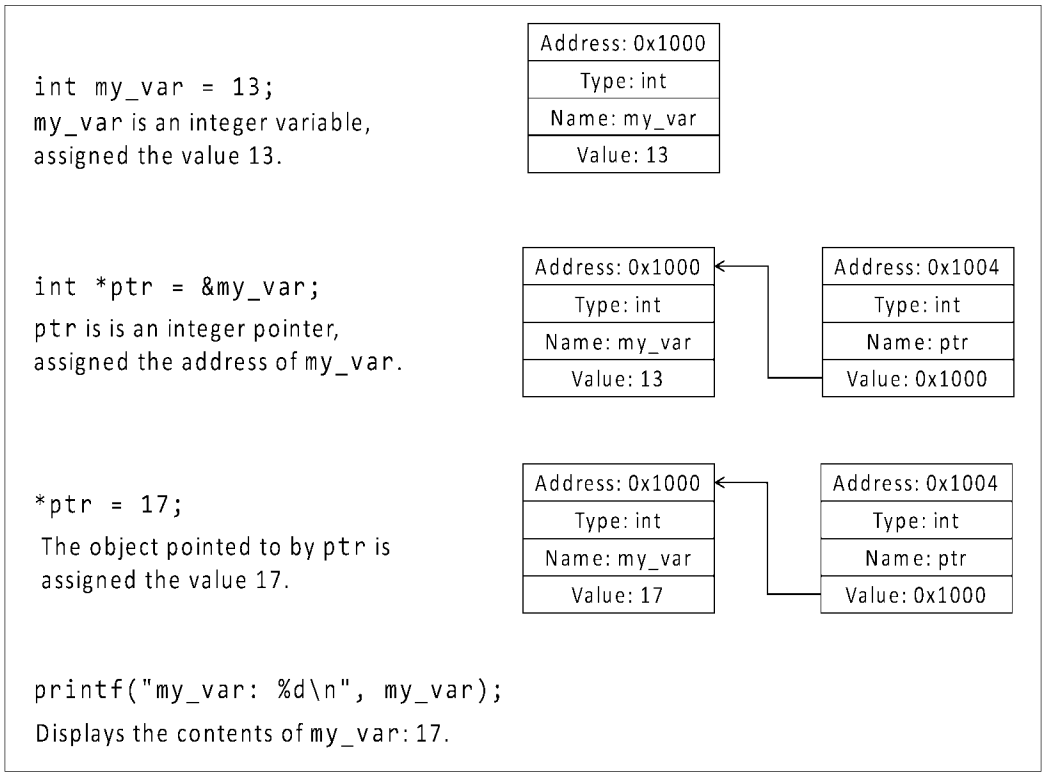

Figure 16.2: Illustration of pointers.

```
ptr = &a;
printf(          , a);
printf(          , *ptr);
a = 9;
printf(          , a);
printf(          , *ptr);
*ptr = 11;
printf(          , a);
printf(          , *ptr);
return 0; }
```

In this example, we create an integer variable `a` and an integer pointer `ptr` that points to `a`. We then verify that the two variables contain the same value:

```
int a = 7;
int *ptr;
ptr = &a;
```

```
printf(          , a);
printf(          , *ptr);
```

This will display

```
a: 7
a: 7
```

We then proceed to modify the value of a, first directly

```
a = 9;
printf(          , a);
printf(          , *ptr);
```

and then through the pointer

```
*ptr = 11;
printf(          , a);
printf(          , *ptr);
```

This will display

```
a: 9
a: 9
a: 11
a: 11
```

16.5.2 Constant pointers and pointers to constants

In this subsection we will discuss three things: Constant pointers, pointers to constants and constant pointers to constants. Consider the statements below

```
int a = 3;
int const b = 5;
int c = 7;
int * const ptr1 = &a;
```

where `ptr1` is a *constant pointer* of integer type, initialized to the address of variable `a`. As its name suggests, the content of a constant pointer once assigned cannot change. In other words, the pointer cannot change the address it holds. If we attempted to do that, as for example with

```
ptr1 = &c;
```

we would get an error from the compiler:

```
error: Assignment to const identifier 'ptr1'.
```

The statement

```
int const * ptr2 = &b;
```

declares and initializes a pointer of constant integer type. This implies that we cannot modify the value of the object pointed to by the pointer. If we attempted to do that as for example with

```
*ptr2 = 7;
```

we would get an error from the compiler:

```
error: Assignment to const location.
```

We can change the content of this pointer but we cannot modify the value of the object pointer to. In the statements below

```
ptr2 = &a;
*ptr2 = 11;
```

we first point the pointer to variable `a` which is accepted, but when we attempt to modify the value of `a` we get an error from the compiler:

```
error: Assignment to const location.
```

The statement

```
int const * const ptr3 = &b;
```

declares and initializes a constant pointer of constant integer type. We can change neither the address the pointer holds nor the value of the object it is pointed at. The following statements result in errors:

```
ptr3 = &a;    >>>error: Assignment to const identifier 'ptr3'.
*ptr3 = 9;    >>>error: Assignment to const location.
```

Let us put everything together:

```
#include <stdio.h>
int main() {
  int a = 3;
  int const b = 5;
  int c = 7;
  int * const ptr1 = &a;    /* a constant pointer of integer type */
  int const * ptr2 = &b;    /* a pointer of constant integer type */
  /* a constant pointer of constant integer type */
  int const * const ptr3 = &b;
  printf(                                          ,
         *ptr1, *ptr2, *ptr3);
  return 0;
}
```

The output of the program is

```
Pointers: ptr1: 3, ptr2: 5, ptr3: 5.
```

16.5.3 Pointers and arrays

The elements of an array are assigned consecutive addresses. We can use a pointer to an array in order to iterate through the array's elements. Suppose we have the following:

```
int arr[5];
int *ptr;
```

In the following statement, we assign the first element of the array as the value of the pointer:

```
ptr = &arr[0];
```

Pointer arithmetic makes `*(ptr + 1)` the same as `arr[1]`.

Example 16.4. In this example we explore pointer arithmetic to assign an array to a pointer, and then use the pointer to display the values of the first three elements of the array. We say that we are displaying the contents of the array by *dereferencing the pointer.*

```
#include <stdio.h>
int main() {
  int arr[5] = {1, 3, 5, 7, 11};
  int *ptr;
  ptr = &arr[0];
  printf(                                          ,
         *ptr, *(ptr + 1), *(ptr + 2));
  return 0;
}
```

The output is:

```
arr[0]: 1, arr[1]: 3, arr[2]: 5
```

Note that `*(ptr + 1)` is not the same as `*(ptr) + 1`. In the latter expression the addition of `1` occurs after the dereference, and it would be the same as `arr[0] + 1`. In the above program, the statement

```
printf(                , *(ptr) + 1);
```

will display

```
arr[1]: 2
```

16.5.4 Pointers as function parameters

In the program that follows, we deploy function `swap` that defines two integer formal parameters, and with the help of a temporary variable it swaps their values:

```
#include <stdio.h>
void swap(int a, int b) {
  int temp = a;
  a = b;
  b = temp;
}
int main() {
  int first, second;
  printf(                          );
  scanf(       , &first, &second);
  printf(                              , first, second);
  printf(                           );
  swap(first, second);
  printf(                              , first, second);
  return 0;
}
```

Let us execute the program:

```
Enter two integers: 5 7
First: 5, Second: 7.
Swap in progress...
First: 5, Second: 7.
```

What is wrong with the program? In C, arguments are passed *by value*, i.e. a copy of the value of each argument is passed to the function. As a result, a function cannot modify the actual argument(s) that it receives. To make the function swap the actual arguments we must pass the arguments *by reference*, i.e. pass the addresses of the actual arguments.

The correct program is shown below:

```
#include <stdio.h>
void swap(int *a, int *b) {
  int temp = *a;
  *a = *b;
  *b = temp;
}
int main() {
  int first, second;
  printf(                        );
  scanf(       , &first, &second);
  printf(                             , first, second);
  printf(                          );
  swap(&first, &second);
  printf(                             , first, second);
  return 0;
}
```

We can execute the program as follows:

```
Enter two integers: 5 7
First: 5, Second: 7.
Swap in progress...
First: 7, Second: 5.
```

16.5.5 Function pointers

Pointers to variables and arrays are examples where a pointer refers to data values. A pointer can also refer to a function, since functions have addresses. We refer to these as *function pointers*. Consider the following (rather cryptic) declaration:

```
long (*ptr)(int);
```

This declares a function pointer; It points to a function that takes an integer argument and returning a long integer. We could now initialize the pointer by making it point to an actual function as follows:

```
ptr = &factorial;
```

This makes `ptr` point to function `factorial(..)`. The function can be invoked by dereferencing the pointer while passing arguments as any regular function call, only in this case we refer to this as an *indirect call*. We can put everything together as follows:

```
#include <stdio.h>
long factorial(int);
int main() {
  int n;
  long f;
  long (*ptr)(int);
  ptr = &factorial;
  printf(                                    );
  scanf(     , &n);
  if (n < 0)
    printf(                                          );
  else
    f = ptr(n);
  printf(              , n, f);
  return 0;
}
long factorial(int n) {
  if (n == 0)
    return 1;
  else
    return(n * factorial(n-1));
}
```

We can execute the program as follows:

```
Enter a non-negative integer: 5
5! = 120
```

16.6 Records

A *record*, or *structure*, is a collection of elements, *fields* (or *members*), which can possibly of different types. The syntax of declaring a structure in C is

```
struct <name> {
  field declarations
};
```

Record initialization and assignment

To create a structure to represent a coordinate on the Cartesian plane, we can say:

```
struct coordinate {
  float x;
  float y;
};
```

To create a `coordinate` variable we can now say

```
struct coordinate p;
```

We can eliminate the word `struct` every time we declare a `coordinate` variable by declaring `coordinate` as a new type with `typedef`.

```
typedef struct {
  float x;
  float y;
} coordinate;
```

We can now create a `coordinate` variable with

```
coordinate p;
```

In the following program we define a new type `coordinate` to be a record (struct) with two float members. We declare and initialize four variables of type `coordinate`. Members of the `coordinate` type can be initialized during declaration either inline as in

```
coordinate p1 = {0, 0};
```

or by designated initializers, as in

```
coordinate p2 = {.x = 1, .y = 3};
```

Members of a record can also be assigned values as in

```
p3.x = 2;
p3.y = 7;
```

or by assigning the value of one record to another, as in

```
p4 = p3;
```

that copies the member values from p3 into p4.

```
#include<stdio.h>
typedef struct {
  float x;
  float y; } coordinate;
int main() {
  coordinate p1 = {0, 0};
  coordinate p2 = {.x = 1, .y = 3};
  coordinate p3;
  coordinate p4;
  p3.x = 2;
  p3.y = 7;
  p4 = p3;
  printf(                    , p1.x, p1.y);
  printf(                    , p2.x, p2.y);
  printf(                    , p3.x, p3.y);
  printf(                    , p4.x, p4.y);
  return 0; }
```

The output of the program is

```
p1 = (0, 0)
p2 = (1, 3)
p3 = (2, 7)
p4 = (2, 7)
```

16.6.1 Records and pointers

A pointer can be deployed to point to a record as in

```
coordinate p = {0, 0};
coordinate *ptr = &p;
```

The pointer can subsequently be dereferenced using the * operator as in

```
(*ptr).x = 3;
```

An alternative binary operator exists (->): The left operand dereferences the pointer, where the right operand accesses the value of a member of the record:

```
ptr->y = 3;
```

Let us put everything together in the program below and an illustration of this is shown in Figure 16.3.

```
#include<stdio.h>
typedef struct {
  float x;
  float y;
} coordinate;
int main() {
  coordinate p = {0, 0};
  printf(                    , p.x, p.y);
  coordinate *ptr = &p;
  (*ptr).x = 3;
  ptr->y = 3;
```

```
  printf(                          , p.x, p.y);
  return 0;
}
```

The output of the program is

```
p = (0, 0)
p = (3, 3)
```

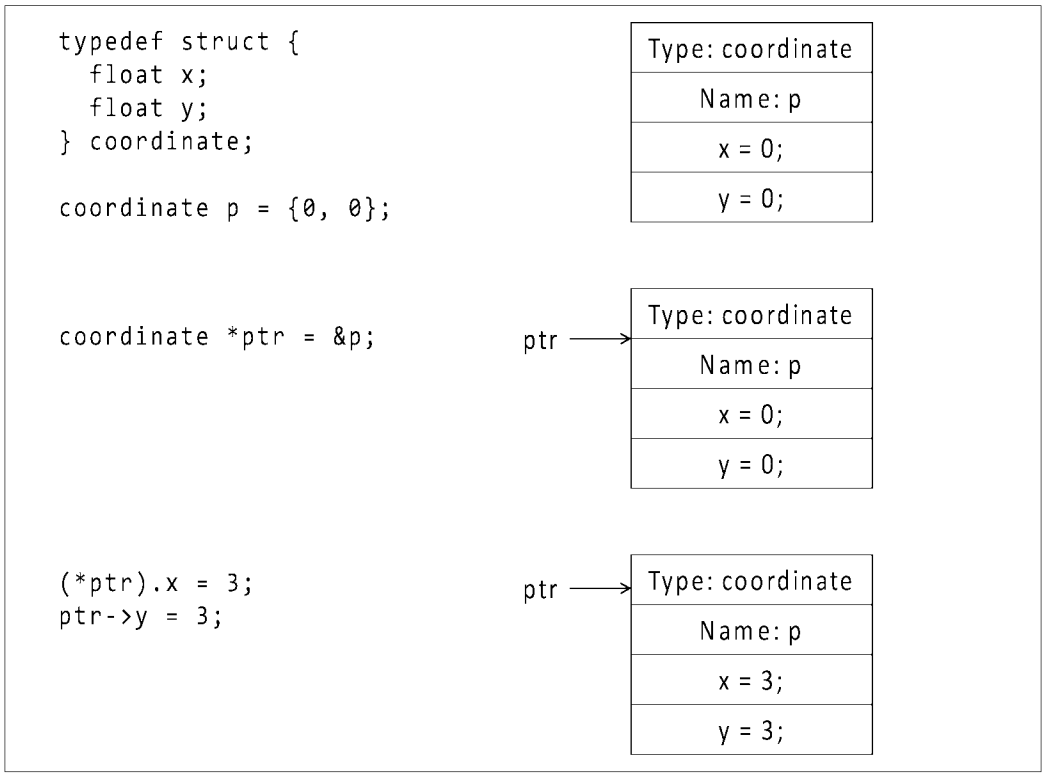

Figure 16.3: A pointer to a record.

Example 16.5. Consider the following program:

```
#include<stdio.h>
  /* Declare 'coordinate', a data type that */
  /* can hold a cartesian point */
  typedef struct {
    float x;
    float y;
  } coordinate;
  int main() {
  /* We will create three points of type coordinate, and */
  /* use three alternative ways to assign them to values */
  /* Inline declaration and initialization */
  coordinate point1 = {0, 0};
  /* Declaration with designated initializers */
  coordinate point2 = {.x = 1, .y = 0};
  /* Declare 'point3' */
  coordinate point3;
  /* Assign 'point3' to (1,5) */
  point3.x = 1;
  point3.y = 5;
  /* Declare 'collection', an array of coordinates */
  coordinate collection[3];
  /* Enter the three points into the array */
  collection[0] = point1;
  collection[1] = point2;
  collection[2] = point3;
  /* Declare 'ptr', a pointer to type coordinate */
  coordinate *ptr;
  /* Point ptr to array 'collection' */
  ptr = &collection[0];
```

```
  /* We will use two alternative ways to display the three points.
     The exact output should be:
     Point1: (0, 0)
     Point2: (1, 0)
     Point3: (1, 5)
  */
  /* Display the first coordinate by dereferencing the pointer */
  printf(                          , (*ptr).x, (*ptr).y);
  /* Display the second coordinate by dereferencing the pointer */
  printf(                          , (*(ptr+1)).x, (*(ptr+1)).y);
  /* Display the third coordinate using the binary operator -> */
  printf(                          , (ptr + 2)->x, (ptr + 2)->y);
  return 0;
}
```

16.6.2 Records and arrays

In the program below we make use of an array of records. More specifically, `line[]` is an array of type `coordinate`, itself defined as a record. The elements of the array are initialized at the time of declaration. We use the dot (.) operator to access fields of individual records. For example `line[0].x` accesses the `x` field of the first element (record) of `line`.

```
#include<stdio.h>
typedef struct {
  float x;
  float y;
} coordinate;
int main() {
  coordinate line[2] = {
    {0, 0},
    {11, 19}
  };
```

```
  printf(                                                    ,
          line[0].x, line[0].y, line[1].x, line[1].y );
}
```

The output of the program is

```
Line points: (0, 0), and (11, 19).
```

16.7 Unions

A union is a variant of a record (structure). Unlike a record where there exists a separate memory location for each of its fields, the union associates all of its fields to a single memory location. In other words, union fields share the same space. This implies that only one field of a union can be accessed at a time, and modifying trhe value of one field results in the modification of the values of the rest of the fields.

Example 16.6. In this example we declare a union type called `package` that contains two fields: `int_label` is of type integer and `char_label` is of type char.

```
#include <stdio.h>
typedef union {
  int int_label;
  char char_label;
} package;
int main() {
  package p;
  p.int_label = 12;
  printf(       , p.int_label);
  p.char_label =     ;
  printf(       , p.char_label);
  printf(       , p.int_label);
  return 0;
}
```

The following segment

```
p.int_label = 12;
printf(      , p.int_label);
```

will display 12. We subsequently assign a value to `char_label` and then proceed to display the values of both fields. The following segment

```
p.char_label =    ;
printf(      , p.char_label);
printf(      , p.int_label);
```

will display

```
c
99
```

the second line of which is the value of `int_label` which corresponds to an unexpected result. 99 is the ASCII number for the character 'c.'

16.8 Enumerated data types

Consider the case where a variable contains only a limited set of values which are referenced by name. For example, *week* takes the values *Monday, Tuesday, ..., Sunday,* or *boolean* takes the values *true, false.* The enumerated data type supports such variables, where the compiler assigns each name (called a *tag*) an internal integer value. For example,

```
enum boolean { TRUE, FALSE};
enum boolean bool;              /* a variable of type boolean */
```

The general form of an enumeration statement is

```
enum  enum-name { tag-1, tag-2, ... }
```

where the tags are normally in uppercase. It is important to note that even though tags look like strings, they are not. Tags constitute keywords that we define for our program.

Chapter 17

Memory management

We have already seen that when declaring an array, we have to specify not just the type of its elements but also the size of the array. This allows the system to allocate the appropriate amount of memory. Once specified, we cannot change the size of the array dynamically, i.e. during the execution of the program. Through one of its standard libraries, the C language offers a number of functions that allow us to circumvent this problem and manage memory dynamically. Consider the program below:

```
#include<stdio.h>
#include <stdlib.h>
int main() {
  int *array = malloc(3 * sizeof(int));
  if (array == NULL) {
    printf(                          );
    return 1;
  }
  *array = 1;
  *(array + 1) = 3;
  *(array + 2) = 5;
  printf(      , *array);
  printf(      , *(array + 1));
  printf(      , *(array + 2));
```

```
  free(array);
  return 0;
}
```

In the first statement

```
int *array = malloc(3 * sizeof(int));
```

we request the allocation of enough memory for an array of three elements of type `int`. We stress the fact that this is merely a request and the allocation of memory is not guaranteed to succeed. If successfull, function `malloc` returns a pointer to a block of memory. If not successfull, `malloc` will return the special value `NULL` to indicate that for some reason the memory has not been allocated. As a result, to indicate success we now have to verify that our `array` pointer is not `NULL`.

```
if (array == NULL) {...}
```

We then proceed to assign values to the elements of the array and subsequently display them. Once we no longer need the array, we have to release the allocated memory back to the system. We do this with function `free`:

```
free(array);
```

Memory that is no more needed but it is not deallocated cannot be reused by the system. This waste of resources can accumulate and can lead to allocation failures when resources are needed but have been exhausted. Even though memory not released with `free` is automatically released once the program terminates, it is a good practice to ensure that we explicitly release memory once it is not needed. The output of the program is

```
1
3
5
```

All memory management functions are listed in Table 17.1.

FUNCTION	DESCRIPTION
`malloc`	Allocates the specified number of bytes.
`realloc`	Increases or decreases the size of the specified block of memory.
`calloc`	Allocates the specified number of bytes and initializes them to zero.
`free`	Releases the specified block of memory back to the system.

Table 17.1: Memory management functions and their corresponding descriptions.

Chapter 18

Data structures and abstract data types I

18.1 ADTs vs. data structures

An *abstract data type (ADT)* is a definition for a data type solely in terms of the set of values and a set of operations on that data type. The behavior of each operation is determined by its inputs and outputs. This implies that an ADT is implementation-independent.

A *data structure* is a specific implementation of an ADT. The implementation details are hidden from the clients of the ADT. This is referred to as *information hiding*. Clients of the ADT are unaffected by any changes to the implementation as long as they conform to the interface of the ADT. The choice of a data structure for the implementation of a particular ADT involves benefits and costs. Because of these trade-offs, rarely (if at all) one data structure is better than another in all situations. In identifying the trade-offs for a data structure to implement a particular ADT, we need to consider the following requirements:

- The space for each data item it stores.
- The time to perform each basic operation.
- The programming effort involved.

18.2 Data structures vs. data types

In a previous chapter we discussed data types and we distinguished between primitive and composite. We can view composite data types as data structures. As an example, arrays and records are both composite data types as well as data structures, whereas integers and characters are primitive data types and not data structures.

18.3 The linked list data structure

The linked list is among the most common data structures. It can be used to implement several common abstract data types, including stacks, and queues. Among the different variants, the singly linked list is the simplest: It represents a chain of elements, called *nodes*, where each node contains a minimum of two *fields*: the *data field* (or *value field*) and the *next link* (or *next pointer*) that points to the next node in the chain. Additionally, the *head* of a list is the list's first node and the *tail* either points to the rest of the list (thus following the corresponding mathematical structure), or it can sometimes point to the last node in the list.

Example 18.1. In this example, we will construct a linked list with two nodes. A node is represented as a record:

```
struct node {
  int data;
  struct node *next;
};
```

Initially the list is empty, thus the head of the list points to `NULL`:

```
struct node *head = NULL;
```

We are now ready to request memory for the head of the list:

```
head = malloc(sizeof(struct node));
if (head == NULL) {
  printf(                          );
  return 1;}
```

Once memory has been allocated we need to a) have the head's next field point to null and b) assign some value to the data field:

```
head->data = 5;
head->next = NULL;
```

We follow the same procedure with the second node of the list, but at the end we need to make sure that a) the next field of the new item points to the node currently pointed to by head and b) the new item becomes the new head, i.e. the head pointer is updated to point to the new node:

```
new->next = head;
head = new;
```

An illustration of this is shown in Figure 18.1.

```
#include<stdio.h>
#include <stdlib.h>
struct node {
  int data;
  struct node *next;
};
int main() {
  struct node *head = NULL;
  struct node *new;
  head = malloc(sizeof(struct node));
  if (head == NULL) {
    printf(                          );
    return 1;
  }
  head->data = 5;
  head->next = NULL;
  new = malloc(sizeof(struct node));
```

```
  if (new == NULL) {
    printf(                              );
    return 1;
  }
  new->data = 11;
  new->next = head;
  head = new;
  printf(      , head->data);
  printf(      , (head->next)->data);
  return 0;
}
```

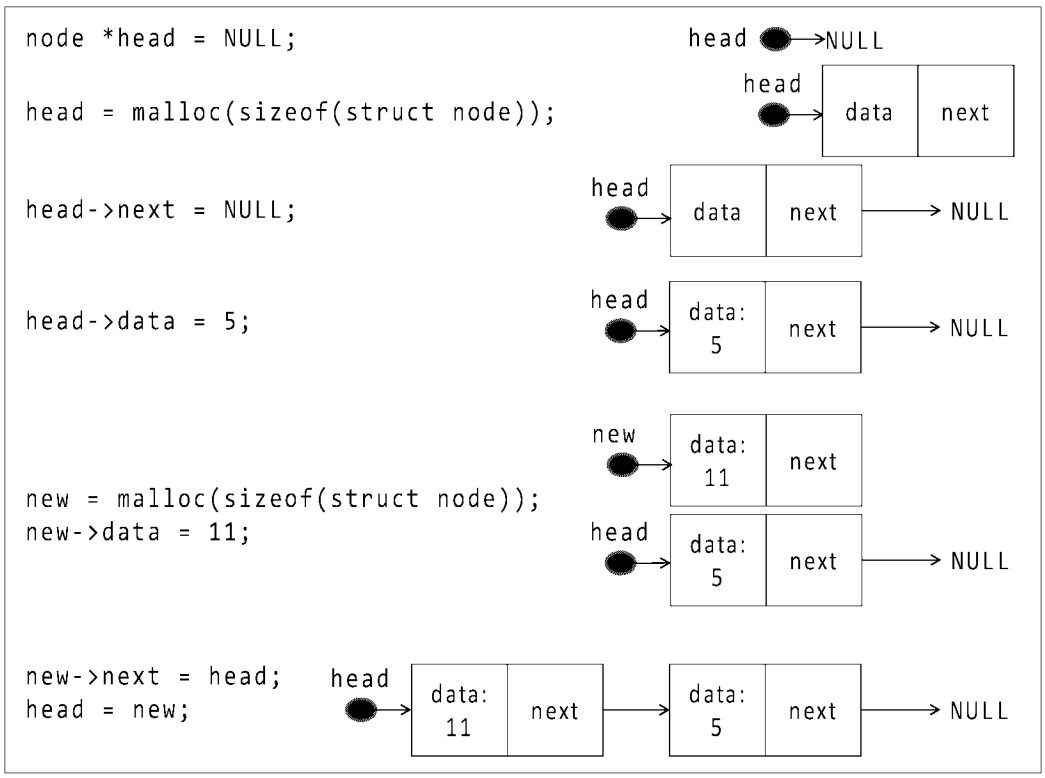

Figure 18.1: The creation of a linked list.

Example 18.2. In this example we will construct a linked list of several items. Once the list has been created, we start at the head

```
current = head;
```

and as long as we do not encounter the NULL value, we iterate through the list, displaying the value of each node's data field:

```
current = head;
while(current) {
  printf(     , current->data);
  current = current->next;
}
```

```
#include<stdio.h>
#include <stdlib.h>
struct node {
  int data;
  struct node *next;
};
int main() {
  struct node *head = NULL;
  struct node *current;
  int counter;
  for (counter=1; counter<=10; counter++) {
    current = malloc(sizeof(struct node));
    if (current == NULL) {
      printf(                          );
      return 1;
    }
    current->data = counter;
    current->next = head;
    head = current;
  }
  current = head;
```

```
  while(current) {
    printf(     , current->data);
    current = current->next;
  }
  return 0;
}
```

The output of the program is

```
10 9 8 7 6 5 4 3 2 1
```

Chapter 19

File I/O

The general form to access a file is

```
file-pointer = file-I/O-function (file-name, mode);
```

Assume that we need to specify that we want to open a file, `out.txt`, in order to write. We can do this as follows:

```
FILE *fp;
fp = fopen(          ,     );
```

where `fp` is a pointer that will keep track of this file, `fopen()` is a function to open a file (from the `stdio` library), and `w` is the writing mode.

Function `fopen()` returns a pointer. It would return `NULL` if for some reason the system has been unable in creating the file. No matter how unlikely this may be, it is a good practice to handle abnormal conditions:

```
if (fp==NULL) {
  printf(                              );
  return 1;
}
```

In order to write to a file, we use the function `fprintf()` (part of `stdio`) where the first argument is the file pointer, `fp`.

```
fprintf(fp,     ,                );
```

We should not forget to close the file upon completion of our task. Function `fclose()` takes as argument a file pointer and closes the file referenced by the pointer:

```
fclose(fp);
```

Putting everything together, we have the following example program that writes the sentence *Sample text.* into file `out.txt`.

```
#include <stdio.h>
int main() {
  FILE *fp;
  fp = fopen(          ,    );
  if (fp==NULL) {
    printf(                          );
    return 1;
  }
  fprintf(fp,     ,              );
  fclose(fp);
  return 0;
}
```

A list of file I/O functions is shown in Table 19.1 and a list of the different file opening modes is shown in Table 19.2.

FUNCTION	DESCRIPTION
fopen	opens a text file.
fclose	closes a text file.
feof	detects end-of-file marker in a file.
fscanf	reads formatted input from a file.
fprintf	prints formatted output to a file.
fgets	reads a string from a file.
fputs	prints a string to a file.
fgetc	reads a character from a file.
fputc	prints a character to a file.

Table 19.1: File functions and their corresponding descriptions.

STRING LITERAL	MODE
w	open for writing (file need not exist)
r	open for reading (file must exist)
a	open for appending (file need not exist)
r+	open for reading and writing, start at beginning
w+	open for reading and writing (overwrite file)
a+	open for reading and writing (append if file exists)

Table 19.2: String literals and their corresponding modes.

Part IV

Object-oriented programming with Java

Chapter 20

Object-oriented programming with message passing I

20.1 Object creation and initialization

A class is both a *type* and a *factory*. As a type, it defines the kind of data any element of this type can hold. As a factory, it provides facilities for its clients to instantiate it. Consider the class definition below:

```
public class Book {
  private String author;
  private String title;
  private String year;
  public Book (String author, String title, String year) {
    this.author = author;
    this.title = title;
    this.year = year;
  }
  public void display () {
    System.out.println (           + author +      +
                                  + title +      +
                                 + year +     ); }...}
```

A *constructor* is a special method which automatically initializes an object immediately upon creation. A Java constructor has the exact same name as the class in which it resides and it has no return type (not even void).

20.1.1 Order of initialization

We will use the terms *attribute*, *(data) field* and *variable* interchangeably. The distinction between instance vs. class scope attributes (see later) and between local vs. non-local variables will be made clear from the context and only mentioned explicitly when it would be necessary. The set of attributes and methods is referred to as the set of *features* of a class.

During instantiation, all attributes are set to their default values (integers to *zero*, booleans to *false* and objects to *null*). The attributes with initializers are set in the order in which they appear in the class definition. Following that, the constructor body is executed.

20.2 Field shadowing

The assignment statement `this.author = author;` in the constructor of the class, distinguishes between the attribute `author` (on the left-hand side of the statement) and the argument with the same name (on the right-hand side). Assume that we had the statement `String author = author;` in the constructor. This would not compile since the left-hand side would define a local variable `author`, and the compiler would have no way of distinguishing it with the attribute of the same name.

Now, assume that we have the following class definition:

```
public class Book {
  private String author;
  private String title;
  private String year;
  public Book (String author1, String title, String year) {
```

```
    this.author = author1;
    String author =      ;
    this.title = title;
    this.year = year;
    System.out.println(           + author);
  }
  public void displayAuthor () {
    System.out.println (           + author);
  }
}
```

The statement `String author = "Jill";` defines a local variable which *shadows* the attribute of the same name. We have changed the name of the first parameter to `author1` to avoid duplication with the local variable of the same name and allow the code to compile. Hence, the output of the print statement in the constructor is `Author:  Jill`. However, once the body of the constructor terminates, the local variable `author` is discarded and the attribute `author` is `Budd`. The main method will display `Author:  Budd`.

20.3 Parameter passing

Objects are passed *by reference*, whereas primitive types are passed *by value* i.e. modifications are made on copies of the actual parameters. Note, however, that not all classes are equal: wrapper classes are immutable (they have no mutator methods).

Example 20.1. In the following example, an instance of the wrapper class `Integer` is passed as an argument to method `inc()` and its value is incremented by one. This, however, has no effect on the actual object. The output of the program will be 7.

```
public class WrapperClassTest {
  public static void inc(Integer in) {
    in = in + 1;
  }
  public static void main(String[] args) {
    Integer i = 7;
    inc(i);
    System.out.println(i);
  }
}
```

20.4 Type signature

The *type signature* of a method (or a constructor) is a sequence that consists of the types of its parameters. Note that the return type, parameter names, and possible final designations of parameters are not part of the type signature.

In class `Book`, the type signature of the constructor is `(String, String, String)` whereas the type signature of method `display` is `()`.

20.5 Static features

Instance features (parameters and methods) can be accessed only through an object reference. *Static features* are used outside of the context of any instances and they may be accessed through either the class name (preferred method) or an object reference.

```
ClassName.staticMethod(parameterList)
ClassName.staticVariable
objectReference.staticMethod(parameterList)
objectReference.staticVariable
```

Example 20.2. In the following example, each time a `Counter` object is created, the static variable `numberOfInstances` is incremented by one. Unlike instance attributes which can have a different value for each instance of `Counter`, the static attribute `numberOfInstances` is universal to the class.

```
public class Counter {
  private int value;
  private static int numberOfInstances = 0;
  public Counter() {
    numberOfInstances++;
  }
  public void reset() {
    value = 0;
  }
  public int getValue() {
    return value;
  }
  public void click() {
    value++;
  }
  public static int howMany() {
    return numberOfInstances;
  }
}
```

```
Counter c1 = new Counter();
Counter c2 = new Counter();
c1.click();
c1.click();
c2.click();
System.out.println(              + c1.getValue());
System.out.println(              + c2.getValue());
System.out.println(                              + Counter.howMany());
```

The output will be as follows:

```
c1 value = 2
c2 value = 1
Number of Counter objects: 2
```

20.5.1 Static blocks

Static blocks run once as soon as the class is loaded and before the `main()` method executes.

Example 20.3. Consider the following program:

```
public class StaticBlockTest {
  static int a = 2;
  static int b;
  static void method (int x) {
    System.out.println(                    + x);
  }
  static {
    System.out.println(                );
    b = a * 3;
    System.out.println(b);
  }
  public static void main (String[] args) {
    method(13); }}
```

The output will be as follows:

```
Static block.
6
Static method: x = 13
```

20.5.2 Initialization of static attributes

Static attributes can be initialized in three ways:

1. With their default values as in `private static int numberOfInstances;`
2. With an explicit initializer as in `private static int globalMoveCount = 0;`
3. By the static initialization block:

```
private static int numberOfInstances;
static {
  numberOfInstances = 0;
}
```

Chapter 21

Inheritance

Inheritance is a mechanism under which one abstraction can be defined in terms of another. Inheritance supports the reuse of implementation and interface, normally to model an *is-a* relationship. With inheritance defined, we can now define *Object-Oriented Programming* (OOP) as:

$$\boxed{\textbf{OOP} = \textbf{ADTs} + \textbf{Inheritance}}$$

We can define a new class from other classes (called its *superclasses* or *component classes*). The newly defined class is called a *subclass*[1] of its superclasses. A subclass inherits both structure and behavior from its superclasses. The immediate superclass(-es) of a class is called its *direct superclass(-es)*, or *parent class(-es)*, (as opposed to other component classes which are *indirect superclasses*). The newly defined class is a *direct subclass* of its direct superclass. Note that inheritance is transitive, i.e. a class can inherit features from superclasses many levels away. This implies that a class is built not only from its direct superclass(-es), but also from each of their direct superclasses, and so on.

21.1 Single vs. multiple inheritance

In *single inheritance* all classes considered have only one direct superclass. The collection of classes extending from a common superclass is called an *inheritance hierarchy*. The path

[1] Some authors use the term *extended*, which is not always true for subclasses.

from a particular class to its ancestors in the inheritance hierarchy is called its *inheritance chain*. In *multiple inheritance* a class has more than one direct superclass. In Java, all public and protected features of a superclass are accessible in all subclasses.

Example 21.1. Consider the following class definitions which specify an inheritance hierarchy:

```
class Person {...}
class Student extends Person {...}
class Professor extends Person {...}
class UndergraduateStudent extends Student {...}
class GraduateStudent extends Student {...}
class TeachingAssistant extends GraduateStudent {...}
```

If we start from `TeachingAssistant`, the inheritance chain includes: `TeachingAssistant`, `GraduateStudent`, `Student`, `Person`, `Object` (the latter is implicitly included).

21.2 Subclass initialization

The initialization of a subclass consists of two phases:

1. The initialization of the attributes inherited from the superclass (one of the constructors of the superclass must be invoked).

2. The initialization of the attributes declared in the subclass.

21.3 Modifiers

Classes, class features, interface features, method parameters, and local variables can be qualified with *modifiers*.

A *public* class is visible to all classes everywhere. If a class has no modifier (the default, also known as *package-private*), then it is visible only within its own package. Class features

that are package-private are not accessible to classes defined outside the package, including subclasses of the class.

21.3.1 Modifiers and inheritance

What happens to inherited features? Based on the types of modifiers attached to features, we can distinguish between the following cases:

Public features can be accessed outside the class definition including outside the package in which they are declared. This is the default modifier for all features declared in an interface.

Protected features can be accessed within the class definition in which they appear, or within other classes in the same package, or within the definitions of subclasses.

Private features can be accessed only within the class definition in which they appear.

21.3.2 Preventing inheritance: Final classes

We can use the `final` modifier in a class definition to prevent a class from being subclassified. We can also make a specific method in a class final in which case no subclass can modify the behavior of this method (see later on *overriding*).

21.3.3 Enforcing inheritance: Abstract classes

An *abstract* class (as opposed to *concrete*) cannot be directly instantiated. An abstract class defines a specification and possibly partial implementation to be inherited. Any class that contains an abstract method must itself be declared abstract. Any concrete subclass of an abstract class must implement all of the abstract methods defined in the superclass. Alternatively, if a subclass implements some (but not all) of the inherited abstract functionality, or if it additionally defines its own abstract functionality, then that subclass must itself be declared abstract.

21.4 Method overloading

If two methods or constructors in the same class or in related classes i.e. in a superclass-subclass pair have different type signatures, then they may share the same name. We say that they are *overloaded* on the same name with multiple implementations. When an overloaded method is called, the number and the types of the arguments are used to determine the signature of the method that will be invoked. Overloading is resolved at compile time. In an inheritance hierarchy, we can overload a superclass method to provide additional functionality.

21.5 Method overriding

A subclass can modify the behavior inherited from a superclass. This is done through a mechanism called *overriding* which refers to the introduction of an instance method in a subclass that has the same name, same type signature and same return type of an inherited method, but a different implementation. The implementation of the method in the subclass replaces the implementation of the inherited method from the superclass.

21.6 Overriding vs. hiding

When a subclass declares an attribute or a static feature that is already declared in a superclass, it is not overridden; it is *hidden*. When a hidden feature is invoked or accessed, the copy that will be used is determined at compile time. In other words, hidden features are *statically bound*, based on their declared type.

In comparing hiding to overriding, we note that instance methods can only be overridden. When an overridden method is invoked, the implementation that will be executed is chosen at run time.

21.7 Static and dynamic type of an object

Consider an assignment statement of the form

```
type variable = expression;
```

The type that is explicitly mentioned in the assignment statement next to the variable is the variable's *declared* or *static* type. On the right-hand side of an assignment statement, a variable may be assigned an object of a type different to its static type. We call this the *run time* or *dynamic* type of the variable. Consider the following class definitions:

```
public class Dog {
  public static void describe() {
    System.out.println(              );
  }
  public void whatIdo() {
    System.out.println(                        );
  }
}
```

```
public class Collie extends Dog {
  public static void describe() {
    System.out.println(                    );
  }
  public void whatIdo() {
    System.out.println(                                    );
  }
}
```

In the code segment that follows, the declared (static) type of `lassie` is `Dog`, and its run time (dynamic) type is `Collie`.

```
Dog lassie = new Collie();
lassie.describe();
lassie.whatIdo();
```

21.8 Subtype relationships

Classes and interfaces define types and all instances of a class constitute legitimate values of that type. The inheritance relationship among classes (and between classes and interfaces) creates a related set of types (*subtype relationship*). Type $T1$ is a subtype of type $T2$ if every legitimate value of $T1$ is also a legitimate value of $T2$. In this case, $T2$ is the supertype of $T1$. This implies that every instance of a subclass is also an instance of a superclass, but not vice-versa. A value of a subtype $T1$ can appear wherever a value of the supertype $T2$ is expected. This implies that an instance of a subclass can appear wherever an instance of a superclass is expected. The type defined by a subclass is a subset of the type defined by its superclass(-es) as the set of all instances of a subclass is included in the set of all instances of its superclass(-es). For example, the pair *(shape, triangle)* defines a subtype relationship as every triangle is a shape (but not vice versa) and thus the set of shapes is a superset of the set of triangles. Furthermore, instances of class `Triangle` can appear in any place where an instance of class *Shape* is expected.

Example 21.2. The relationship between *square* and *quadrilateral* in geometry defines a subtype relationship, since a square is a special type of quadrilateral. On the other hand, the relationship between *stack* and *vector* does not define a subtype relationship even though it may be practical to deploy inheritance and define the former in terms of the latter.

21.9 Compiler and run time system responsibilities

We are now ready to explicitly define the responsibilities of the compiler and of the run time system[2].

The compiler has the following responsibilities:

Check the validity of assignment statements The type of the expression on the right-hand side (RHS) of an assignment statement must the same or a subtype of that of

[2]Note that these responsibilities are laid in the absence of explicit casting. In § 21.14 we amend them in the presence of explicit casting.

the variable on the left-hand side (LHS). In other words, the validity of an assignment statement is based on the static type of a variable. This is referred to as *static type checking*. In the previous example, the compiler asks "Is `Collie` a subtype of `Dog`?"

Check the validity of messages (method calls) The compiler needs to verify that the static type of the object (this includes its declared type and all its supertypes) contains a method with a name and signature that can match the message (method call). In the previous example the compiler asks "Is there a method `whatIdo()` with signature `()` in the static type of `lassie`?"

The run time system has the following responsibilities:

Choice of method invocation A method invocation is determined based on the run time type of the object, where the run time system will try to match the message with a method. The run time system will start a lookup from the class definition of the run time type of the object. If such method exists it will be invoked. Otherwise, the run time system searches for a match along the inheritance chain until it finds a matching method. This procedure is called *dynamic binding* (or *dynamic dispatch*). In the above example, the run time system will start looking for a method to match `whatIdo()` from the definition of class `Collie`, the run time type of `lassie`.

Example 21.3. Let us trace the code of the main method in the previous example:

`Dog lassie = new Collie();` The assignment statement is valid as `Collie` is a subclass of `Dog`.

`lassie.describe();` The declared type of `lassie` is `Dog`. The call to the static method `describe()` is resolved statically, i.e. based on the declared type of the variable, hence the call to `describe()` invokes method `describe()` in class `Dog` which will display `I am a dog.`

`lassie.whatIdo();` The compiler needs to check whether the declared type of `lassie` contains a method to match the message `whatIdo()`. The declared type indeed contains

such a method and thus compilation is successful. The run time system will perform a lookup starting from the run time type of `lassie` to locate a method that can match the message. Recall that the `whatIdo()` method in class `Collie` overrides the behavior of the inherited method of the same name and signature from class `Dog`. The run time system locates method `whatIdo()` in class `Collie` and invokes it, displaying `I save people who are in danger.`

Example 21.4. In this example, class `Point` contains two overloaded constructors. The one with no arguments is called the *default* constructor. The keyword `this` is used inside instance methods (or constructors) to refer to the receiving object, i.e. the instance of the class through which the method is invoked. In this example, the default constructor calls the constructor `Point(double, double)` by passing the arguments `(0, 0)` as the initial (default) coordinates for any point instance. Note that `this` cannot be invoked inside static methods.

```
public class Point {
  protected double x, y;
  public final String description =                ;
  public Point(double x, double y) {
    this.x = x;
    this.y = y;
  }
  public Point() {
    this(0, 0);
  }
  public String toString() {
    return        + x +      +         + y;
  }
}
```

Class `Point3D` extends class `Point` and it also contains two overloaded constructors. During the execution of its default constructor, the instance variable `z` is initialized, and the default constructor of its parent class will be invoked. If the parent class contained no default con-

structor, an error would occur.

The constructor `Point3D (double, double, double)`, initializes the instance variable `z`. Instance variables `(x, y)` are initialized through the constructor of the parent class which is called by the keyword `super`. This keyword must be the first statement in the constructor of the subclass.

```
public class Point3D extends Point {
  private double z;
  public final String description =                    ;
  public Point3D (double x, double y, double z) {
    super (x, y);
    this.z = z;
  }
  public Point3D() {
    this.z = 0;
  }
  public String toString() {
    return       + x +     +       + y +     +       + z; }}
```

The code segment that follows simulates the creation and initialization of several objects.

```
Point p1 = new Point();
Point p2 = new Point (1, 1);
Point3D p3 = new Point3D();
Point3D p4 = new Point3D(1, 1, 2);
Point p5 = new Point3D();
System.out.println(p1.toString());
System.out.println(p2.toString());
System.out.println(p3.toString());
System.out.println(p4.toString());
System.out.println(p5.toString());
System.out.println(p3.description);
System.out.println(p5.description);
```

Variables `p3` and `p5` both contain `Point3D` objects. The statement `System.out.println(p3.description)` will display `Class Point3D`. Consider the statement `System.out.println(p5.description)`. As fields are statically bound, the variable `description` refers to the one in the declared type of `p5`, which is type `Point`. Hence the output will be `Class Point`.

The output of the program is shown below:

```
x: 0.0 y: 0.0
x: 1.0 y: 1.0
x: 0.0 y: 0.0 z: 0.0
x: 1.0 y: 1.0 z: 2.0
x: 0.0 y: 0.0 z: 0.0
Class Point3D
Class Point
```

21.10 Design recommendations for inheritance

You may consider the following design recommendations for inheritance:

1. First and foremost, use inheritance to model an *is-a* relationship. For example, a linked list is a list, but neither a stack nor a queue are vectors.

2. Place common variables and methods in the superclass.

21.11 Types of inheritance

Based on the objective for its deployment, we can identify the following types of inheritance:

Specialization This is the most common use of inheritance. The subclass is a specialized version of the parent class, and thus satisfies the specification (interface) of the parent class in all relevant aspects, adding any particular behavior through overriding. Subclasses are subtypes.

Specification This type of inheritance is deployed to enforce a specification (interface) on a subclass. The subclass implements the abstract specification of the parent class. There are two ways to perform this type of inheritance: through interfaces, and through the inheritance of abstract classes. Subclasses are subtypes.

Construction There is no logical relationship between the two classes. A subclass inherits functionality to be reused for practical reasons. Subclasses are not necessarily subtypes.

Extension A subclass merely adds new behavior and does not modify or alter any of the inherited features. Subclasses are subtypes.

Limitation The behavior in the subclass is smaller or more restrictive than the behavior of the parent class. Subclasses are not subtypes.

Combination A subclass is formed by combining features from more than one type. In Java, we can subclassify from a single class but we can implement one or more interfaces.

21.12 Inheritance vs. delegation

What happens when a subclass uses only part of a superclass' interface or does not need to inherit data? What do we do when it is very practical to use inheritance, but an *is-a* relationship does not hold? Can we just adopt this scheme? Consider class `Stack` in the `java.util` library which inherits class `Vector` (which in turn implements interface `List`) by extending its functionality with operations that would allow a vector to be treated as a stack. In the following example, we create a stack instance and place some items in the collection.

```
Stack<String> s = new Stack<String>();
s.push(        );
s.push(         );
s.push(        );
System.out.println(s.elementAt(0));
```

Note that we have managed to violate the Stack ADT protocol by calling method `elementAt()` inherited from `Vector`. The output of the program is `first`. In order to avoid this problem, it is more advisable to deploy delegation where we create a new class `Stack` with a variable of a type such as a `Vector` which will hold the collection of objects to be held in the stack.

```
import java.util.Vector;
public class Stack {
  Vector<String> container = new Vector<String>();
  int index;
  public void push(String element) {
    container.addElement(element);
    index++;
  }
  public Object pop() {
    return container.elementAt(index-1);
  }
}
```

```
Stack stack = new Stack();
stack.push(       );
stack.push(        );
stack.push(       );
System.out.println((String)stack.pop());
```

Note that methods in class `Stack` delegate to the vector variable. The Stack ADT protocol is now enforced. The output of the program is `third`.

Classes formed with inheritance are assumed to be subtypes of their superclasses. No assumption of substitutability is present during delegation. The interface of a subclass is (usually) a superset of that defined in the superclass. Delegation more clearly indicates exactly the interface of the subclass. Furthermore, inheritance does not prevent users from sending inappropriate messages to the subclass (invoking operations from the superclass). With delegation this is not possible.

In the delegation example, the fact that class `Vector` is used is an implementation detail. It would be easy to reimplement class `Stack` to make use of a different technique (such as a linked list) with minimal or no impact on the users of the stack abstraction. If users counted on the fact that a stack is merely is specialized form of vector, such changes would be more difficult to implement.

21.13 Interfaces

An *interface* defines a type and it provides an encapsulation of (abstract) methods and constants. The general form of an interface is:

```
interface interfaceName
        {
        returnType  method1(parameterList);
        ...
        type  final variableName = value;
        ...
        }
```

Interface methods cannot be static and they have a default public visibility as opposed to methods in classes which have a default package-private visibility. An interface can extend other interfaces (but not classes).

A class may implement one or more interfaces and classes that implement an interface should provide implementation for all methods declared in that interface. A class that implements an interface has the following general form:

class *className* [extends *superclassName*]

[implements $interface_1$ [, $interface_2$ ...]]

{

class body

}

Example 21.5. In the following example, we have two classes: class `Counter` and its subclass `LockableCounter`. The subclass implements the interface `LockIF`. Class `LockableCounter` inherits all methods from `Counter` and implements all methods declared in `LockIF`.

```
public class Counter {
  private static String description =                                    ;
  int value;
  public void reset() {
    value = 0;
  }
  public int getValue() {
    return value;
  }
  public void click() {
    value++;
  }
}
```

```
public interface LockIF {
  void lock();
  void unlock();
  boolean isLocked();
}
```

```
public class LockableCounter extends Counter implements LockIF {
  static String description =                          ;
  private boolean lock;
  public void lock() {
    this.lock = true;
  }
  public void unlock() {
    this.lock = false;
  }
  public boolean isLocked() {
    return this.lock;
  }
  public void click() {
    this.value = this.value + 2;
  }
}
```

Consider the following code segment:

```
Counter c1 = new LockableCounter();
LockableCounter c2 = new LockableCounter();
LockIF c3 = new LockableCounter();
c1.click();
System.out.println(c1.getValue());
System.out.println(c1.description);
c2.click();
System.out.println(c2.getValue());
c2.unlock();
System.out.println(c2.isLocked());
System.out.println(c2.description);
c3.click();
c3.unlock();
```

```
System.out.println(c3.isLocked());
System.out.println(c3.description);
```

Let us dissect the code segment by considering its statements one by one. In each case, we will describe and distinguish between the responsibilities of the compiler and those of the run time system.

The statement `Counter c1 = new LockableCounter();` will be checked (statically) by the compiler. Class `LockableCounter` is a subclass and therefore a subtype of class `Counter`.

Similarly, the statements

```
LockableCounter c2 = new LockableCounter();
LockIF c3 = new LockableCounter();
```

are valid and type checking will be successful.

For the statement `c1.click();` the compiler will check to see if a matching method to message `click()` is defined in the declared type of the object, namely `Counter`. As a result, method invocation is valid. In the case such as this example where the subclass overrides the method being called, the run time system will make a decision which method to call based on the dynamic type of the variable. In the example, the dynamic type of the variable is `LockableCounter` and the run time system will invoke the overriding method `click()`.

The statement `System.out.println(c1.getValue());` is statically valid because method `getValue()` is defined in the declared type of the variable, namely class `Counter`. The statement will display 2 because the overriding method `click()` increments the variable `value` by 2.

The statement `System.out.println(c1.description);` accesses a static variable. The binding is based on the declared type of the variable and this will display "The foundation of all counters."

The statement `c2.click();` will be successfully statically checked as there is a method match to the message `click()` in the declared type of the variable, namely `LockableCounter`. The run time system will call the method of the dynamic type, namely the one in `LockableCounter`.

The statement `System.out.println(c2.getValue());` will be successfully statically checked and display 2.

The statement `c2.unlock();` will be successfully statically checked as there exists a matched method to `unlock()` in the declared type of the variable, namely the interface `LockIF`.

Similarly the statement `System.out.println(c2.isLocked());` will display *false*.

The statement `System.out.println(c2.description);` is an example of hiding. As the binding of a static variable is done on the declared type of the variable, the statement accesses and displays the value of `description` variable in class `LockableCounter`.

The statement `c3.click();` will fail type checking because there is no matching method in the declared type of the variable `c3`, namely the interface `LockIF`.

The statement `c3.unlock();` will be successfully statically checked as there is a matching method to the message `unlock()` in the declared type of the variable `c3`.

The statement `System.out.println(c3.isLocked());` will be successfully statically checked and it will display *false*.

The statement `System.out.println(c3.description);` will fail.

Resolving name collisions of interface features

To avoid problems associated with multiple inheritance, Java allows only single inheritance for class extension but allows multiple inheritance for interface implementation. This does not guarantee that no potential problems may show up, as name collisions may exist between features of different interfaces or between features of interfaces and classes.

If two inherited methods have the same name, then:

- If they have different signatures, they are overloaded.
- If they have the same signature and the same return type, they are considered to be the same method.
- If they have the same signature but different return types, then a compilation error will occur.
- If they have the same signature and the same return type but throw different exceptions, they are considered to be the same method, and the resulting throws list is the union of the two throws lists.

If two constants have the same name, then they are considered two separate constants and a distinction is made by using the interface name with dot (.) operator.

Example 21.6. Consider the two interfaces `IF1` and `IF2` below:

```
public interface IF1 {
  void method1(int i);
  void method2 (int i);
  void method3 (int i);
}
```

```
public interface IF2 {
  void method1(double d);
  void method2 (int i);
  double method3 (int i);
}
```

The method `void method3(int i)` from interface `IF1` and the method `double method3(int i)` have the same name and signature but different return types, hence a compilation error occurs.

Consider a class `C` which implements both interfaces:

```
public class C implements IF1, IF2 {
  public void method1(int i) {
    System.out.println(                    );
  }
  public void method1(double i) {
    System.out.println(                      );
  }
  public void method2(int i) {
    System.out.println(                    ); }}
```

The two implementations of `method1()` are inherited from interfaces `IF1` and `IF2`. They have the same name but different signatures, hence they are overloaded. Furthermore, `method2` is inherited from both interfaces with the same name, signature and return type, hence the two interfaces essentially declare the same method. Consider the following program:

```
C c = new C();
c.method1(3);
c.method1(5.0);
c.method2(5);
```

The output of the program is as follows:

```
Signature: method1(int)
Signature: method1(double)
Signature: method2(int)
```

21.14 Casting

We can convert between types as follows: the conversion of a subtype to one of its supertypes is called *widening* and it is carried out implicitly whenever necessary. In other words, a reference to an object of class `C` can be implicitly converted to a reference to an object of one of the superclasses of `C`.

On the other hand, the conversion of a supertype to one of its subtypes is called *narrowing*. Narrowing of reference types requires explicit casts. As an example, consider class `Parent`, being the superclass of `Child` and object `p` being an instance of `Parent`. Let `Child` define method `calculate()`. In the following statement

```
((Child)p).calculate();
```

both the compiler and the run time system are involved in validating the explicit casting as follows:

The compiler will obtain the static type of `p`, namely `Parent`. Next, the compiler needs to ensure that the object is (in the case of downcasting) casted downwards in its inheritance chain which is indeed the case in this example. In other words, one cannot cast an object to a non-related type. If, in our example, we had class `Friend` that contained method `calculate()` and we attempted to do

```
((Friend)p).calculate();
```

the compiler will issue an error.

Back to our initial example, the compiler will proceed to check if a method signature exists that matches the message `calculate()` in the static type of the object, that includes the now "forced" type, namely `Child` and all its supertypes. Compilation is successful in this example.

The run time system must ensure that the dynamic type of object `p` is `Child` (or one of its subtypes). Once this validation is successful, the run time system will invoke method `calculate()` in the class that corresponds to the dynamic type, in this case class `Child`. If not successful, the run time system will throw an exception.

What is the motivation for narrowing? Recall that the functionality of a superclass is available to all subclasses and that the subclasses normally contain extended functionality. Narrowing allows us to temporarily achieve the opposite: to extend the functionality of a superclass with that of a subclass.

Example 21.7. Consider the class definitions below:

```
public class Parent { }
public class Child extends Parent {
  public String greet () {return                ;}
}
public class Grandchild extends Child {
  public String greet () {return                    ;}
}
public class Friend {
  public String greet () {return                ;}
}
```

Scenario	Compilation	Run time and output
`Parent p = new Child();` `System.out.println(((Friend)p).greet());`	Not successful.	
`Parent p = new Child();` `System.out.println(((Child)p).greet());`	Successful.	Good morning!

`Parent p = new Parent();`
 	
`System.out.println(((Child)p).greet());`
	Successful.	Exception thrown: Parent cannot be cast to Child.

`Grandchild p = new Child();` `System.out.println(((Child)p).greet());`	Not successful.	
`Parent p = new Grandchild();` `System.out.println(((Child)p).greet());`	Successful.	I want ice cream.

`Parent p = new Child();`
 	
`System.out.println(((Grandchild)p).greet());`
	Successful.	Exception thrown: Child cannot be cast to Grandchild.

Table 21.1: Demonstrating explicit casting.

In Table 21.1 we demonstrate various scenarios where explicit casting is used, and list the result of the compilation and the run time processes, together with any possible output.

Example 21.8. In the Java built-in hierarchy, class `LinkedList` is an ordered list, and it is a subclass of `List`, offering more functionality such as `removeFirst()`. Other subclasses of `List` include `ArrayList` and `Vector`. Consider method `trim()` which takes a parameter of type `List` (or any of its subclasses) and proceeds to delete its first element by downcasting it to `LinkedList` and calling `removeFirst()`. In the main method we instantiate a `LinkedList` object and add two elements to it. We then pass it to method `trim()`. To verify whether `trim()` performed as expected, we proceed to check whether our linked list object contains either element.

```
import java.util.*;
public class CastingTest {
  public static void trim(List lst) {
    ((LinkedList)lst).removeFirst();
  }
  public static void main(String[] args) {
    LinkedList<String> list = new LinkedList<String>();
    list.add(   );
    list.add(   );
    trim(list);
    System.out.println(list.contains(   ));
    System.out.println(list.contains(   ));
  }
}
```

The output of the program is as follows:

```
false
true
```

We indeed did not expect to see element `"a"` in the list.

Example 21.9. What would happen if in the previous example we replaced the `LinkedList` type with an `ArrayList`?

```
public static void main(String[] args) {
  ArrayList<String> list = new ArrayList<String>();
  list.add(   );
  list.add(   );
  trim(list);
  System.out.println(list.contains(   ));
  System.out.println(list.contains(   ));
}
```

Recall that the validity of explicit casting is checked not at compile time but at run time. The program will successfully compile. However, the explicit casting in method `trim()` is not valid since types `LinkedList` and `ArrayList` are siblings, and thus incompatible for type conversion. As a result, the run time system will throw an exception:

```
Exception in thread "main" java.lang.ClassCastException:
java.util.ArrayList cannot be cast to java.util.LinkedList
```

21.15 Additional examples

Example 21.10. Consider the definitions of the following classes. We will use the code in method `main()` to describe all explicit responsibilities of the compiler and the run time system. If a statement does not compile, we will provide a brief explanation why and we will consider it as being commented out.

```
public interface MyIF {
  public void callback();
}
```

```
public class C1 {
  public void call(int i) {System.out.println(      +i);}
  public void callme(String s) {System.out.println(s);}
}
```

```
public class C2 extends C1 implements MyIF {
  public void call(int i) {System.out.println(      +i);}
  public void callback() {System.out.println(     );}
}
```

```
public class C3 extends C2 {
  public void callme(String s) {System.out.println(     + s);}
}
```

```
public class Test {
  public static void main(String args[]) {
    C1 obj1 = new C1();
    C2 obj2 = new C2();
    C2 obj3 = new C3();
    MyIF obj4 = new C3();
    obj1.call(0);
    obj2.call(1);
    obj3.call(2);
    obj4.call(3);
    obj4.callback();
    ((C2)obj4).call(4);
    ((C2)obj1).callback();
  }
}
```

`C1 obj1 = new C1();` Compilation successful: The right-hand side (RHS) and the left-hand side (LHS) are of same type, namely `C1`.

`C2 obj2 = new C2();` Compilation successful: RHS and LHS are of same type, namely `C2`.

`MyIF obj4 = new C3();` Compilation successful: The RHS (`C3`) is a subtype of the LHS (`MyIF`).

`C2 obj3 = new C3();` Compilation successful: The RHS (`C3`) is a subtype of the LHS (`C2`).

`obj1.call(0);` Compilation successful: Method `call(int)` is defined in the static type of `obj1`, namely `C1`. The run time system executes successfully method `call(int)` in class `C1` (the dynamic type of `obj1`) and the output is: `i1: 0`.

`obj2.call(1);` Compilation successful: Method `call(int)` is defined in the static type of `obj2`, namely `C2`. The run time system executes successfully method `call(int)` in class `C2` (the dynamic type of `obj2`) and the output is: `i2: 1`.

`obj3.call(2);` Compilation successful: Method `call(int)` is defined in the static type of `obj3`, namely `C2`. The run time system checks if the dynamic type of `obj3`, namely `C3` has method `call(int)` but fails to locate it. Consequently, a check is performed to the parent class, namely `C2`. Since the method exists, it is executed and provides the following output: `i2: 2`.

`obj4.call(3);` Compilation error: The declared type of `obj4` namely `MyIF` does not contain a definition for method `call(int)`.

`obj4.callback();` Compilation successful: Method `callback()` is defined in the static type of `obj4` namely `MyIF`. The run time system checks if the dynamic type of `obj4` namely `C3` has method `callback()` but fails to locate it. Consequently, a check is performed to the parent class namely `C2`. Since the method exists, it is executed and provides the following output: `bbb`.

`((C2)obj4).call(4);` Compilation successful: The static type of `obj4`, namely `MyIF`, is a supertype of the class to which the object is casted (`C2`) and class `C2` contains a definition for method `call(int)`. The run time system checks if the actual reference of `obj4` is of type (or subtype of) `C2` (i.e. the type to which the object is casted). The check is successful. Next, the run time system checks if the dynamic type of `obj4`, namely `C3` includes method `call(int)` but fails to locate it. Consequently, a check is performed to the parent class, namely `C2`. Since the method exists, it is executed and provides the following output: `i2: 4`.

`((C2)obj1).callback();` Compilation successful: The static type of `obj1`, namely `C1`, is a supertype of the class to which the object is casted (`C2`) and class `C2` contains a definition for method `callback()`. The run time system throws a `ClassCastException` exception, since the dynamic type of `obj1` is `C1` but `C1` is not of type (or a subtype of) `C2` as expected from the cast.

Example 21.11. Consider the class definitions below:

```
interface MyIF {
  public static String name=           ;
  public String call(int x);
}
```

```
class C1 {
  private static String name=          ;
  public Object callme() {
    return                     ;
  }
}
```

```
class C2 extends C1 implements MyIF{
  public String callme() {
    return                     ;
 }
}
```

```
public class Dispatch {
  public static void main(String args[]) {
    MyIF i = new C2();
    C1 c1 = new C2();
    C2 c2=(C2)new C1();
    System.out.println(i.callme());
    System.out.println(c1.callme());
    System.out.println(i.name);
    System.out.println(c1.name);
  }
}
```

1. There are possibly multiple compilation errors in class `C2`. Provide a description of them and modify only class `C2` in a way that compilation can be successful.

2. For each subsequent method, describe 1) Whether this introduction can be characterized by overloading or overriding and 2) Whether this introduction will result in an error. Justify your answers.

```
public Object call(int x) {
  return      ;
}
String call(int x) {
  return      ;
}
public int call(double d) {
  return Math.floor(d)*5;
}
public String callme(String str) {
  return                  + str;
}
```

1. Class `C2` must implement the inherited method `MyIF.call(int)`. There is no such method in `C2`. We must add the following method in `C2`:

```
public String call (int x) {
  return "C2.call called";
}
```

2. Consider the following:

```
public Object call(int x) {
  return      ;
}
```

The attempt to override `MyIF.call(int)` will fail because `Object` is not a subtype of `String`.

```
String call(int x) {
  return      ; }
```

The attempt to override `MyIF.call(int)` will fail since the visibility is reduced from public to package-private (default).

```
public int call(double d) {
  return Math.floor(d)*5;
}
```

Overloading `MyIF.call(int)`.

```
public String callme(String str) {
  return                    + str;
}
```

Overloading `C2.callme()`.

Example 21.12. The *Observer design pattern* supports a many-to-one dependency from a number of observer objects to one subject object where observers attach themselves to a subject. The objective is for observers to maintain the same state as the subject. Upon a change of state in the subject, the subject must deploy a notification mechanism for its observers. The pattern can support two models of notification: 1) Pull and 2) Push.

Pull model: In the pull model, upon a change of state in the subject, the subject activates a notification mechanism whereby it sends a message to all observers indicating that a change of state has occurred. The observers will then explicitly request the details of the change.

Push model: In the push model, upon a change of state in the subject, the subject activates a notification mechanism whereby it sends its own state to all observers (whether they want it or not).

Consider the code segment that follows, the computation that it performs, and its output. Provide an implementation of all definitions involved using the *pull model.*

```
Subject subject = new Subject();
Observer observer1 = new Observer(subject);
Observer observer2 = new Observer(subject);
Observer observer3 = new Observer(subject);
// assign state to subject
subject.setState(                          );
// by this point, subject must have notified all observers
System.out.println(observer1.getState());
System.out.println(observer2.getState());
System.out.println(observer3.getState());
subject.setState(                          );
System.out.println(observer1.getState());
System.out.println(observer2.getState());
System.out.println(observer3.getState());
```

The output of the program is as follows:

```
Best band: Pink Floyd
Best band: Pink Floyd
Best band: Pink Floyd
Best band: The Doors
Best band: The Doors
Best band: The Doors
```

The definitions are as follows:

```
public interface SubjectIF {
  public void attach (Observer observer);
  public void detach (Observer observer);
  public void update();
}
```

```
public interface ObserverIF {
  public void update();
}
```

```
import java.util.Vector;
public class Subject implements SubjectIF {
  private int count = 0;
  private Vector<Observer> observers;
  private String subjectState;
  public Subject() {
    observers = new Vector(0);
  }
  public void attach (Observer observer){
    observers.addElement(observer);
  }
  public void detach (Observer observer) {
    observers.removeElement(observer);
  }
  public void update() {
    for (Observer observer: observers) {
      observer.update();
    }
  /*
   * For earlier versions of Java:
   *
   Observer tempObserver;
   for (int i = 0; i < observers.size(); i++) {
     tempObserver = (Observer)observers.elementAt(i);
     tempObserver.update(); }
   */
  }
```

```
  public String getState() {
    return subjectState;
  }
  public void setState(String newState) {
    subjectState = newState;
    this.update();
  }
}
```

```
public class Observer implements ObserverIF {
  private Subject subject;
  private String observerState;
  public Observer(Subject subject) {
    this.subject = subject;
    this.subject.attach(this);
  }
  public void update() {
    observerState = subject.getState();
  }
  public String getState() {
    return observerState;
  }
}
```

Example 21.13. Consider the class definitions below:

```
public class Counter {
  private static String description =              ;
  int element;
  public void click() {
    element++;
  }
  public int getValue() {
    return element;
  }
  public void reset() {
    this.element = 0;
  }
  public static String getDescription() {
    return description;
  }
}
```

```
public interface Lockable {
  void lock();
  void unlock();
  boolean isLocked();
}
```

```
public class LockableCounter extends Counter implements Lockable {
  static String description =                          ;
  private boolean lock;
  public void lock() {
    this.lock = true;
  }
  public void unlock() {
    this.lock = false; }
```

```
  public boolean isLocked() {
    return this.lock;
  }
  public void reset() {
    this.element = this.element % 5;
  }
  public static String getDescription() {
    return description;
  }
}
```

```
public class LockableCounterTest {
  public static void main(String[] args) {
    Counter lock1 = new LockableCounter();
    Lockable lock2 = new LockableCounter();
    System.out.println(lock1.getDescription());
    lock1.click();
    lock2.click();
  }
}
```

---

1. Trace the body of the main method, and for each statement in that method describe the explicit responsibilities of the compiler and the run time system. In case a statement fails compilation, consider it as being commented out.

2. What is the output of the program?

`Counter lock1 = new LockableCounter();` Compilation successful: The type of the expression on the right-hand side of the assignment statement is a subtype of the type of the variable on the left-hand side.

`Lockable lock2 = new LockableCounter();` Compilation successful: The reasoning is similar to the above.

`System.out.println(lock1.getDescription());` This is an example of *hiding*. The choice of static features is resolved based on the declared type of the object. The declared type of `lock1` is `Counter`. The method will display `A counter.`

`lock1.click();` Compilation successful: There exists a method (`click()`) in the declared type of the object (`Counter`) that matches the message. The run time system will start from the dynamic type of the object (the actual reference held) to see if a method exists that can match the message. Such a method does not exist in `LockableCounter`. As a result, the run time system will perform a look-up in the immediate supertype of the object and find a matching method `click()` in class `Counter`.

`lock2.click();` Compilation error: There is no method in the declared type of `lock2` to match the message.

Example 21.14. Consider the class definitions below. For each statement in method `main()` describe the responsibilities and tasks undertaken by the compiler and by the run time system, and describe the outcomes. If you have to refer to a property of some element, make sure you distinguish between static vs. dynamic properties.

```
public interface Behavior {
  public String act();
  public String reason();
}
```

```
public class Human implements Behavior {
  public String type =          ;
  public boolean empathy = true;
  public String act() {
    return                                  ;
  }
  public String reason() {
    return                                    ;
  }
  public boolean hasEmpathy() {return empathy;}}
```

```
public class Bladerunner extends Human {
  public String type =                ;
  public String rank;
  Bladerunner(){}
  Bladerunner (String r) {
    this.rank = r;
    String rank =           ;
    System.out.println(rank);
  }
  public String reason() {
    return                                    ;
  }
}
```

```
public abstract class Machine implements Behavior {
  public static String type =           ;
}
```

```
public class Android extends Machine {
  public int version;
  Android (int version) {
    this.version = version;
  }
  public String whatIhave() {
    return                          ;
  }
  public static String whatIneed() {
    return                     ;
  }
  public String act() {
    return                                  ;
  }
```

```
  public String reason() {
    return                                          ;
  }
}
```

```
public interface Behavior2 {
  public boolean empathy = true;
  public boolean memories = true;
  public boolean hasEmpathy();
  public boolean hasMemories();
}
```

```
public class Android2 extends Android implements Behavior2 {
  Android2 (int version) {
    super(version);
  }
  Android2() {
    super(8);
  }
  public String whatIhave() {
    return                                ;
  }
  public boolean hasEmpathy() {
    return empathy;
  }
  public boolean hasMemories() {
    return memories;
  }
}
```

```
    public static void main(String[] args) {
1     Machine Leon = new Android(7);
2     System.out.println(Leon.whatIneed());
3     Android Roy = new Android2(7);
4     System.out.println(((Android2)Roy).whatIhave());
5     Behavior2 Pris = new Android2(11);
6     System.out.println(Pris.whatIhave());
7     Android2 Zohra = new Android();
8     Behavior2 Hodge = new Android2();
9     System.out.println(Hodge.whatIhave());
10    Android Rachel = new Android(7);
11    System.out.println(((Android2)Rachel).hasMemories());
12    Human Gaff = new Bladerunner();
13    System.out.println(Gaff.type);
14    System.out.println(                          + Gaff.hasEmpathy());
15    System.out.println(Gaff.reason());
16    Bladerunner Harry = new Bladerunner(         ); }
```

Let us trace the program:

1. `Machine Leon = new Android(7);` Compilation successful: Type checking succeeds as the static type of the expression on the RHS is a subtype of the static type of the variable on the LHS.

2. `System.out.println(Leon.whatIneed());` Compilation error: Static features are accessed based on the declared (static) type of the object (`Machine`). Method `whatIneed()` does not exist in the declared type.

3. `Android Roy = new Android2(7);` Compilation successful: Type checking succeeds as the static type of the expression on the RHS is a subtype of the static type of the variable on the LHS.

4. `System.out.println(((Android2)Roy).whatIhave());` Compilation successful: Static type of Roy (`Android`) is a supertype of `Android2`. The run time system will perform

the following: a) it checks the validity of explicit cast. This is successful since the run time type of `Roy` (`Android2`) is the same or a subtype of `Android2`, and b) it will invoke the dynamic dispatcher to call method `whatIhave()` defined in the run time type of the object, namely `Android2`, and it will display "I have an infinite time."

5. `Behavior2 Pris = new Android2(11);` Compilation successful: Type checking succeeds as the static type of the expression on the RHS is a subtype of the static type of the variable on the LHS.

6. `System.out.println(Pris.whatIhave());` Compilation error: Method `whatIhave()` does not exist in declared type (Behavior2).

7. `Android2 Zohra = new Android();` Compilation error: Static type checking fails: Static type of expression on RHS is not a subtype as the static type of variable on LHS.

8. `Behavior2 Hodge = new Android2();` Compilation successful: Type checking succeeds as the static type of the expression on the RHS is a subtype of the static type of the variable on the LHS.

9. `System.out.println(Hodge.whatIhave());` Compilation error: Method `whatIhave()` does not exist in the declared type of `Hodge` (`Behavior2`).

10. `Android Rachel = new Android(7);` Compilation successful: Type checking succeeds as the static type of the expression on the RHS is the same as the static type of the variable on the LHS.

11. `System.out.println(((Android2)Rachel).hasMemories());` Compilation successful: The static type of `Rachel`, namely `Android`, is a supertype of `Android2`. However, the run time system will not verify the explicit cast since the dynamic type of `Rachel`, namely `Android` is not a subtype of `Android2`.

12. `Human Gaff = new Bladerunner();` Compilation successful: Type checking succeeds as the static type of the expression on the RHS is a subtype of the static type of the variable on the LHS.

13. `System.out.println(Gaff.type);` Variables are accessed based on the declared (static) type of the object (Human). It will display `HUMAN`.

14. `System.out.println("Gaff has empathy?:  " + Gaff.hasEmpathy());` Compilation successful: Type checking succeeds as method `hasEmpathy()` exists in the declared type or one of its supertypes (`Human`). The run time system invokes the dynamic dispatcher and performs a search for a method to match the message starting from the definition of `Bladerunner`. An appropriate method is not found. The dispatcher continues its search and finds a matching method in the superclass. The method returns true and the statement displays `Gaff has empathy?:  true`

15. `System.out.println(Gaff.reason());` Compilation successful: Type checking succeeds as method `reason()` exists in the declared type of the object (`Human`). The run time system invokes the dynamic dispatcher and performs a search for a method to match the message starting from the definition of `Bladerunner` and it is successful. It will display `I am bladerunner and I can reason.`

16. `Bladerunner Harry = new Bladerunner("CHIEF.");` Compilation successful: Type checking succeeds as the static type of the expression on the RHS is the same as the static type of the variable on the LHS. The class constructor displays the value of its local variable ("OFFICER") because of shadowing.

Let us provide the definition of class `Bladerunner2` who is an `Android2` but also behaves exactly like a `Bladerunner` and can be instantiated as follows:

```
Bladerunner2 Deckard = new Bladerunner2();
```

We can model this requirement with a combination of inheritance (of class `Android2`) and delegation (to class `Bladerunner`).

```
public class Bladerunner2 extends Android2 {
  Bladerunner b = new Bladerunner();
  public String act() {
    return b.act(); }
```

```
  public String reason() {
    return b.reason();
  }
  public boolean hasEmpathy() {
    return b.hasEmpathy();
  }
}
```

What is the output of the code below and why?

```
System.out.println(Deckard.reason());
```

The output is `I am bladerunner and I can reason.` since message `reason()` sent to object `Deckard` was captured and delegated to class `Bladerunner`.

Let us provide a statement to verify whether object `Deckard` is human. The statement is `System.out.println(Deckard.type);` and it will display `MACHINE`.

Last, let us identify 1) a pair of overloaded features, 2) a pair of overriding features, 3) a pair of shadowed features, and 4) a pair of hidden features.

Overloaded features: Constructors of class `Bladerunner`, or method `whatIhave()` in in classes `Android` and `Android2`.

Overriding features: Methods `reason()` in classes `Human` and `Bladerunner`.

Shadowed features: Instance variable `rank` and local variable of the same name in the constructor of `Bladerunner`.

Hidden features: String variable `type` in classes `Human` and `Bladerunner`.

Example 21.15. Provide brief answers to the following:

1. In the context of Java, compare *inheritance* to *delegation* in terms of type substitutability, interface, and security.

2. Many OOP textbooks, refer to subclasses as *extended classes* where an is-a relationship holds between subclass and superclass. Does this provide a full description of inheritance? Justify your answer.

3. In OOP, what type of reuse is provided by *inheritance*?

1. Type substitutability: Classes formed with inheritance are assumed to be subtypes of their parent class. No assumption of substitutability is present during delegation. Interface: Delegation more clearly indicates exactly the interface of the subclass. Security: the protocol of the subclass can be violated with inheritance in case where the subclass is not a subtype of the superclass. With delegation this is normally not possible.

2. Not every form of inheritance is for extension and not all forms create subtype relationships. For example, in *inheritance by construction*, There is no logical relationship between the two classes. A subclass inherits functionality to be reused for practical reasons. Subclasses are not necessarily subtypes.

3. With inheritance we can reuse a) implementation and b) specification.

Example 21.16. Consider the following classes:

```
public interface Hunter {
  String goAfter(String str);
}
```

```
public interface Guide {
  void navigate();
  void work();
}
```

```
public class Animal {
  String name;
  public Animal () {}
  public Animal (String name) {this.name = name;}
```

```
  public String toString() {
   return this.name;
  }
}
```

```
public class Cat extends Animal implements Hunter {
  String description =                                    ;
  protected int lifeSpan = 14;
  public Cat () {
    this(      );
  }
  public Cat (String name) {
    super(name);
  }
  public void describe() {
    System.out.println(description);
  }
  public void whatIdo() {
    System.out.println(                                          );
  }
  public String goAfter(String str) {
    return str;
  }
}
```

```
public class Dog extends Animal implements Hunter {
  String description =                                          ;
  static int lifeSpan = 12;
  public Dog () {}
  public Dog (String name) {
    super(name);
  }
```

```
  public void describe() {
    System.out.println(description);
  }
  public String whatIdo(String str) {
    return              + str +     ;
  }
  public String goAfter(String str) {
    return str;
  }
}
```

```
public class Labrador extends Dog implements Guide {
  String description =                              ;
  static int lifeSpan = 14;
  public Labrador () {}
  public Labrador (String name) {
    super(name);
  }
  public void describe() {
    System.out.println(                                    +
                       super.description);}
  public void whatIdo() {
    System.out.println(                                 );
  }
  public void navigate() {
    System.out.println(                                    +
                                          );}
  public void work() {
    System.out.println(                                    +
                                                 );}
  public String goAfter() {
    return          ; }}
```

For each of the statements below, let us describe in detail the explicit responsibilities of the compiler and the run-time system as well as the outcome of each of their tasks. Whenever applicable we will write down and underline the exact output. Additionally, we will indicate any other event such as hiding, overloading, overriding, or shadowing.

```
1    Dog Max = new Labrador(     );
2    Labrador Duke = new Animal(      );
3    Guide Buddy = new Labrador(       );
4    Cat Molly = new Cat(       );
5    Hunter Oscar = new Cat(       );
6    Hunter Bella = new Dog(       );
7    Hunter Rocky = new Labrador(       );
8    Hunter MyCat = new Cat();
9    Labrador Luna = new Labrador(      );
10   Guide Roxy = new Labrador(      );
11   Hunter Zeus = new Labrador(      );
12   Animal Bobby = new Labrador(       );
13   Guide Honey = new Dog(       );
14   System.out.println(Max.lifeSpan);
15   Max.describe();
16   System.out.println(Max.whatIdo(          ));
17   System.out.println(Max.description);
18   Buddy.whatIdo();
19   Buddy.work();
20   ((Labrador)Buddy).whatIdo();
21   ((Labrador)Molly).whatIdo();
22   ((Labrador)Oscar).whatIdo();
23   Bella.goAfter();
24   System.out.println(((Dog)Bella).whatIdo(              ));
25   System.out.println(        + Rocky.toString() +
                                        +
                          ((Labrador)Rocky).goAfter() +     );
```

```
26    System.out.println(MyCat.toString());
27    System.out.println(                + Luna.goAfter(       ) +     );
28    System.out.println(Roxy.goAfter());
29    Zeus.work();
30    ((Labrador)Bobby).whatIdo();
```

1 `Dog Max = new Labrador("Max");` Compilation is successful. The compiler validates the assignment statement as the type of the RHS expression is a subtype of the LHS variable.

2 `Labrador Duke = new Animal("Duke");` Compilation is not successful. The compiler does not validate the assignment statement as the type of the RHS expression is not the same or a subtype of the LHS variable.

For lines 3-12, compilation is successful as all assignment statements are validated.

13 `Guide Honey = new Dog("Honey");` Compilation is not successful. The compiler does not validate the assignment statement

14 `System.out.println(Max.lifeSpan);` The choice of attribute is based on the static type of `Max`, namely `Dog`, and the binding is done at compile-time. This is an example of *hiding*. The statement will display 12.

15 `Max.describe();` Compilation is successful. The compiler validates the method call since there exists a method `describe()` in the static type of `Max`, namely `Dog`. The run-time system has the responsibility to choose the appropriate method to invoke. It will perform a search starting from the run-time type of `Max`, namely `Labrador` where it will locate the overriding method `describe()` which displays
I am athletic and playful and I am the first domesticated animal.

16 `System.out.println(Max.whatIdo("retrieve"));` Compilation is successful. The compiler validates the method call since there exists a method `whatIdo(String)` in the static type of `Max`, namely `Dog`. The run-time system has the responsibility to choose the appropriate method to invoke. It will perform a search starting from the

run-time type of `Max`, namely `Labrador` where it will not locate such method. The run-time system will continue its search up the inheritance chain and it will locate the overloaded method `whatIdo(String)` in `Dog` which displays I like to retrieve.

17 `System.out.println(Max.description);` The choice of attribute is based on the static type of `Max`, namely `Dog`, and the binding is done at compile-time. This is an example of *hiding*. The statement will display I am the first domesticated animal.

18 `Buddy.whatIdo();` Compilation is not successful. The compiler does not validate the method call as there does not exist a method `whatIdo()` in the static type of `Buddy`, namely `Guide`.

19 `Buddy.work();` Compilation is successful. The compiler validates the method call since there exists a method `work()` in the static type of `Buddy`, namely `Guide`. The run-time system has the responsibility to chose the appropriate method to invoke. It will perform a search starting from the run-time type of `Buddy`, namely `Labrador` where it will locate such method which displays I can track, I can detect and I can do therapy work.

20 `((Labrador)Buddy).whatIdo();` Compilation is successful since the static type of `Buddy`, namely `Guide`, can be downcast to `Labrador`. Additionally, the compiler validates the method call since there exists a method `whatIdo()` in the casted type, namely `Labrador`. The run-time system has the responsibility to validate the explicit cast. This will succeed as the run-time type of `Buddy` is `Labrador`. The run-time system also has the responsibility to choose the appropriate method to invoke, performing a search starting from the run-time type of `Buddy`, namely `Labrador` where it will locate the overloaded method `whatIdo()` which displays I retrieve game for a hunter.

21 `((Labrador)Molly).whatIdo();` Compilation is not successful, as the static type of `Molly`, namely `Cat`, cannot be downcasted to `Labrador`.

22 `((Labrador)Oscar).whatIdo();` Compilation is successful as the static type of `Oscar`, namely `Hunter` can be downcasted to `Lambrador`. Additionally, the compiler validates the method call as there exists method `whatIdo()` in the casted type. However, the

run-time system will not validate the explicit cast since the run-time of `Oscar`, namely `Cat`, cannot be casted to `Labrador`.

23 `Bella.goAfter();` Compilation is not successful. The compiler does not validate the method call as there does not exist a method `goAfter()` in the static type of `Bella`, namely `Hunter`.

24 `System.out.println(((Dog)Bella).whatIdo("run in parks"));` Compilation is successful as the static type of `Bella`, namely `Hunter` can be downcasted to `Dog`. Additionally, the compiler validates the method call as there exists method `whatIdo(String)` in the casted type. The run-time system will validate the explicit cast since the run-time of `Bella` is `Dog`. Additionally the run-time system is responsible to chose the appropriate method to call, performing a search starting from the run-time type of `Bella`, namely `Dog` where it will locate the overloaded method `whatIdo(String)` which displays I like to run in parks.

25 `System.out.println("I am " + Rocky.toString() + " and I go after " + ((Labrador)Rocky).goAfter() + ".");` Compilation is successfull. The static type of `Rocky`, namely `Hunter` can be downcasted to `Labrador`. Additionally, the compiler validates both cases of method call: First, method `toString()` exists in the static type of `Rocky`, namely `Animal`, and second, method `goAfter()` exists in the casted type, namely `Labrador`. The run-time system successfully validates the explicit casting as the run-time type of `Rocky` is `Labrador`. Additionally, the run-time system has the responsibility to choose the appropriate method to invoke string from the run-time type of `Rocky`, namely `Labrador` where it locates method `goAfter()`. The statement displays I am Rocky and I go after thieves.

26 `System.out.println(MyCat.toString());` Compilation is successful. The compiler validates the method call as there exists method `toString()` in the static type of `MyCat`, namely `Object` (the root of all classes in the Java system). The run-time system is responsible to chose the appropriate method to call performing a search starting from the run-time type of `MyCat`, namely `Cat` where it invokes method `toString()` which

displays Ella.

27 `System.out.println("I go after " + Luna.goAfter("cats") + ".");` Compilation is successful. The compiler validates the method call as there exists method `goAfter(String)` in the static type of `Luna`, namely `Dog`. The run-time system is responsible to choose the appropriate method to call performing a search starting from the run-time type of `Luna`, namely `Labrador` where it does not locate such method. The run-time system continues its search up in the inheritance chain, locating and invoking the overloaded method `goAfter(String)` in `Dog`. The statement displays I go after cats.

28 `System.out.println(Roxy.goAfter());` Compilation is not successful. The compiler does not validate the method call as there does not exist method `goAfter()` in the static type of `Roxy`, namely `Guide`.

29 `Zeus.work();` Compilation is not successful. The compiler does not validate the method call as there does not exist method `work()` in the static type of `Zeus`, namely `Hunter`.

30 `((Labrador)Bobby).whatIdo();` Compilation is successful. First, the static type of `Bobby`, namely `Animal`, can be casted to `Labrador`. Second, the compiler validates the method call as there is method `whatIdo()` in the casted type. The run-time system has the responsibility to validate the explicit casting. This is successful as the run-time type of `Bobby` is `Labrador`. Additionally, the run-time system has the responsibility to choose the appropriate method to call performing a search starting from the run-time type of `Bobby`, namely `Labrador` where it locates and invokes the overloaded method `whatIdo()` which displays I retrieve game for a hunter.

Example 21.17. Consider the following classes:

```
public abstract class Human {
  String name;
  public static String description =        ;
  public abstract void speak();
```

```
  public static void whatAmI() {System.out.println(        +
                                  description +    );}}
```

```
public class Commoner extends Human {
  public void speak() {
    System.out.println(              );
  }
}
```

```
public class Noble extends Human {
  String house;
  public Noble(String name, String house) {
    this.name = name;
    this.house = house;
  }
  public Noble(String name) {
    this.name = name;
  }
  public void speak() {
    System.out.println(               );
  }
  public String toString() {
    return          + this.name +         + this.house +     ;
  }
}
```

```
public interface Faceless {
  public void declare();
  public String declare(String str);
}
```

```
public class Free extends Noble implements Faceless {
  public Free(String name) {
    super(name,           );
  }
  public void declare() {
    System.out.println(                );
  }
  public String declare(String str) {
    return str;
  }
}
```

```
public class NightsWatch extends Noble {
  public NightsWatch(String name) {
    super(name);
    String house =                ;
    System.out.println(        + name +         + house +    );
  }
  public void speak() {System.out.println(                  );}}
```

Consider the test class below. For each statement in method `main(..)` let us describe the explicit responsibilities of the compiler and the run-time system. Whenever applicable write down the exact output in double quotes. Additionally, we will indicate any other event such as hiding, overloading, overriding, or shadowing.

```
public class Test {
  public static void face(Noble noble) {
    ((Free)noble).declare();
  }
  public static void main(String[] args) {
1    Human Tyrion = new Noble(         ,            );
2    Noble Arya = new Free(      );
3    Faceless Jaqen = new Free(             );
```

```
4     Noble Jon = new NightsWatch(          );
5     Faceless Syrio = new Noble();
6     Tyrion.speak();
7     Tyrion.whatAmI();
8     ((Free)Arya).declare();
9     System.out.println(Jaqen.declare(                  ));
10    Jon.speak();
11    ((Free)Jon).declare();
12    face(Tyrion);
13    System.out.println(Jaqen.toString());
  }
}
```

---

1. `Human Tyrion = new Noble("Tyrion", "Lannister");`

   The compilier must check the validity of the assignment statement. Compilation is successfull as the type of the expression of the right-hand-side is a subtype of that of the variable on the left-hand-side. We have *overloading* of the constructor.

2. `Noble Arya = new Free("Arya");` Compilation successfull as above.

3. `Faceless Jaqen = new Free("Jaqen H'ghar");` Compilation successfull as above.

4. `Noble Jon = new NightsWatch("Jon Snow");`

   Compilation successfull as above. The constructor displays "`I am Jon Snow of The NightsWatch.`" We have *shadowing* of the attribute `house`.

5. `Faceless Syrio = new Noble();` We have compilation failure as the assignment statement is not valid. Type `Noble` is not a subtype of `Faceless`.

6. `Tyrion.speak();`

   The compiler successfully validates the method call as there exists a method in the static type of `Tyrion` (`Human`) to match the call (message). The run-time system must chose which method to invoke starting from the run-time type of the object (`Noble`)

where the lookup is successfull. We have *overriding* of method `speak()`. The output is "`Yes, my lord.`"

7. `Tyrion.whatAmI();`

   The compiler binds the static method `whatAmI()` to the object. The statement will display "`I am human.`"

8. `((Free)Arya).declare();`

   The compiler successfully validates the method call as there exists a method in `Free` to match the call. The run-time system successfully validates the explicit casting since `Arya` has a run-time type `Free`. The output is "`Valar morghulis.`"

9. `System.out.println(Jaqen.declare("Valar dohaeris."));`

   The compiler successfully validates the method call as there exists a method in the static type of `Jaqen` (`Faceless`) to match the call. We have *overloading* of method `declare()`. The output is "`Valar dohaeris.`"

10. `Jon.speak();`

    The compiler successfully validates the method call as there exists a method in the static type of `Jon` (`Noble`) to match the call. The run-time system must chose an appropriate method to invoke, starting from the run-time type of the object (`NightsWatch`) where the lookup is successfull. We have *overriding* of method `speak()`. The output is "`Winter is coming.`"

11. `((Free)Jon).declare();`

    The compiler successfully validates the method call as there exists a method in `Free` to match the call. The run-time system fails to validate the explicit casting since `Jon` has a run-time type `NightsWatch` which cannot be downcasted to `Free`.

12. `face(Tyrion);`

    We have compilation failure as the method expects an argument of static type `Noble` (or any of its subtypes). The static type of `Tyrion` is `Human`.

13. `System.out.println(Jaqen.toString());`

    The compiler successfully validates the method call as method `toString()` is available in Java's root class (`Object`). The run-time system must chose an appropriate method to invoke, starting from the run-time type of the object (`Free`) where the lookup is initially not successfull. The run-time system will go up the inheritance chain where it will locate and subsequently invoke method `toString()` in `Noble`. The output is "`I am Jaqen H'ghar of no house.`"

Part V

Aspect-Oriented Programming with AspectJ

Chapter 22

Aspects

22.1 Introduction

> *"To my taste the main characteristic of intelligent thinking is that one is willing and able to study in depth an aspect of one's subject matter in isolation, for the sake of its own consistency, all the time knowing that one is occupying oneself with only one of the aspects. The other aspects have to wait their turn, because our heads are so small that we cannot deal with them simultaneously without getting confused. I usually refer to it as Separation of Concerns, because one tries to deal with the difficulties, the obligations, the desires, and the constraints one by one."*
>
> (E. W. Dijkstra, A Discipline of Programming, 1976, last chapter, In Retrospect)

The principle of *separation of concerns* refers to the realization of system concepts into separate software units and it is a fundamental principle of software development. The associated benefits include improved readability of code that results in better analysis and understanding of systems, an increased level of reusability and easy adaptability that result in good maintainability. Despite the success of object-orientation in the effort to achieve separation of concerns, certain properties in object-oriented systems cannot be directly mapped in a one-to-one fashion from the problem domain to the solution space, and thus cannot be localized in single modular units. Their implementation ends up cutting across the inheritance hierarchy

of the system. Examples of such crosscutting concerns (or *aspects*) include persistence, authentication, synchronization and contract checking. Aspect-oriented programming (AOP) explicitly addresses those concerns by introducing the notion of an *aspect* as a modular unit of decomposition. Currently there exist many approaches and technologies to support AOP. One such notable technology is AspectJ[1], a general-purpose aspect-oriented language, which has influenced the design dimensions of several other general-purpose aspect-oriented languages, and has provided the community with a common vocabulary based on its linguistic constructs. AspectJ is a superset of Java and as such every valid Java program is also a valid AspectJ program.

22.2 The building blocks: Join points, pointcuts and advices

In this section we will introduce an aspect definition and we will dissect it into its individual elements, by following a bottom-up approach on an example.

Consider the implementation of an unbounded stack as shown below. The stack implements a *last-in-first-out (LIFO)* protocol. Variable `stack` is an `ArrayList` that contains a collection of elements. Variable `top` holds the current size of the stack, initialized to -1 implying that the collection is empty. The interface of class `Stack` contains a number of methods. We can distinguish between those methods that modify the state of an object, referred to as *mutators*, and those that access the state but do not modify it, referred to as *accessors*. Methods `push()` and `pop()` are mutators, whereas methods `top()`, `isEmpty()` and `size()` are accessors.

```
import java.util.*;
public class Stack {
  private ArrayList <String> stack = new ArrayList<String> ();
```

[1]AspectJ Documentation and Resources, on-line repository from `eclipse.org`.
URL: `http://www.eclipse.org/aspectj/doc/released/`

```
  protected int top = -1;
  public void push (String str) {
    stack.add(++top, str);
  }
  public String pop () {
    if (!this.isEmpty()) {
      String result = stack.get(top--);
      return result;
    }
    else
      return null;
  }

  public String top () {
    if (!this.isEmpty()) {
      String result = stack.get(top);
      return result;
    }
    else
      return null;
    }
  protected boolean isEmpty () {
    return top == -1;
  }
  public int size () {
    return top;
  }
}
```

22.2.1 Join points

A *join point* is a point in the execution of the program. We can regard join points as events of interest that can be captured by the underlying language. AspectJ supports a rich set of join points that includes *message sends* and *execution of methods*.

In this example, we want to capture all `push` and `pop` messages[2] sent to an object of type `Stack`. The following join point

```
call(void Stack.push(String))
```

captures a `push` message that includes one argument of type `String`, sent to an object of type `Stack`, where the invoked method is not expected to return any value. Note that in the literature the expression is interpreted in terms of a *call to a method* as follows: The join point captures a call to method `push()` in class `Stack`, taking a `String` argument and returning no value (`void`). The modifier of the method is not specified, implying that it can be of any type.

Similarly the following join point

```
call(String Stack.pop())
```

captures a `pop` message that includes no argument, sent to an object of type `Stack`, where the receiver object is expected to return a value of type `String`.

22.2.2 Pointcuts

Since we want to log both `push` and `pop` messages, we can combine the two join points into a single disjunctive expression. A *pointcut* (or *pointcut designator*) is a logical expression composed by individual join points. Additionally, a pointcut may be given and it can subsequently be referred to by an identifier. Consider pointcut `mutators()` that combines the two individual join points into a logical disjunction as follows:

```
pointcut mutators(): call(void Stack.push(String)) ||
```

[2]A more elaborate explanation is given in § 22.6.1.

```
call(String Stack.pop());
```

Since a join point refers to an event, we say that a join point is *captured* whenever the associated event occurs. Consequently, we say that a pointcut is captured whenever the logical expression made up of individual join points becomes true.

Pointcuts can adopt unary and binary logical operators in their definition as follows:

- The conjunction operator (&&) returns true only if both operands (join points) are captured by the expression. Otherwise it returns false.
- The disjunction operator (||) returns true if either or both operands are captured by the expression. Otherwise it returns false.
- The negation operator (!) returns true if the expression is not captured by the specified join point. Otherwise it returns false.

22.2.3 Advice

In this example once a `push` or `pop` message is sent, and before any corresponding method executes, we want to first display some message. An *advice* is a method-like block, that associates to a pointcut, defining behavior to be executed. However, unlike a method, an advice block is never explicitly called. Instead, it is only implicitly invoked once its associated pointcut is captured. The following advice

```
before(): mutators() {
  System.out.println(                                    );
}
```

is attached to pointcut `mutators()`. Once a `push()` or `pop()` message is sent to an object of type `Stack`, the pointcut `mutators()` is captured. Before the message can proceed, the `before` advice will execute.

AspectJ provides a level of granularity which specifies exactly when an advice block should be executed, such as executing *before*, *after*, or *instead of* the code that is associated with the pointcut. More specifically, an advice block can be:

- `before`: An advice that runs before the code associated with the pointcut expression.
- `after`: An advice that runs after the code associated with the pointcut expression (It may be after normal return, after throwing an exception or after returning either way from a join point).
- `around`: An advice that runs instead of the code associated with the pointcut expression, with the provision for the pointcut to resume normal execution through a `proceed` call (see later).

22.2.4 Named and unnamed pointcuts

In the example above, `mutators()` is a *named pointcut*. As the term suggests, it is an expression bound to an identifier. On the other hand, an *unnamed* (or *anonymous*) *pointcut* is an expression not bound to an identifier but instead it is directly attached to an advice as shown below:

```
before(): call(void Stack.push(String)) ||
          call(String Stack.pop()); {
  System.out.println(                                    );
}
```

The two pointcuts are semantically equivalent. A preference which one to adopt will be based on coding convention and reusability. We would normally prefer unnamed pointcuts for short and trivial pointcuts, such as those that contain an individual join point, particularly when it is highly unlikely that such a pointcut will be reused. However, for long and non-trivial pointcuts, or for pointcuts which we plan to reuse, we would prefer named pointcuts.

22.2.5 Putting everything together: An aspect definition

Much like a class, an *aspect* is a unit of modularity. We can now provide a complete aspect definition as follows:

```
public aspect Logger {
  pointcut mutators(): call(void Stack.push(String)) ||
                       call(String Stack.pop());
  before(): mutators() {
    System.out.println(                                    );
  }
}
```

Consider the following test program:

```
public class Test {
  public static void main(String[] args) {
    Stack myStack = new Stack();
    myStack.push(      );
    myStack.push(      );
    myStack.push(     );
    System.out.println(myStack.pop());
    System.out.println(myStack.pop());
    System.out.println(myStack.pop());
    System.out.println(myStack.top());
  }
}
```

The output of the program is as follows:

```
>Message sent to update stack.
>Message sent to update stack.
>Message sent to update stack.
```

```
>Message sent to update stack.
all
>Message sent to update stack.
your
>Message sent to update stack.
base
null
```

22.3 A closer view of crosscutting

In the previous example, logging is a crosscutting concern which is explicitly captured and implemented as an aspect. Crosscutting imposes two symptoms on software development which are illustrated in Figure 22.1, where the R's represent individual requirements and the C's represent classes as an example of a unit of modularity even though, by principle, crosscutting can manifest in different paradigms.

1. *Code scattering*: The implementation of a concern is not being well modularized but instead it cuts across the decomposition hierarchy of the system.

2. *Code tangling*: A module containing implementation elements (code) for more than one concerns.

Code scattering and code tangling describe two different facets of the same problem.

22.3.1 Implications of crosscutting

As a result of crosscutting, the benefits of object-oriented programming cannot be fully utilized, and developers are faced with a number of implications:

1. Poor traceability of requirements: The mapping from an n-dimensional space to a single dimensional implementation space implies that any changes in the semantics of one crosscutting concern are difficult to trace among various modules that it spans over.

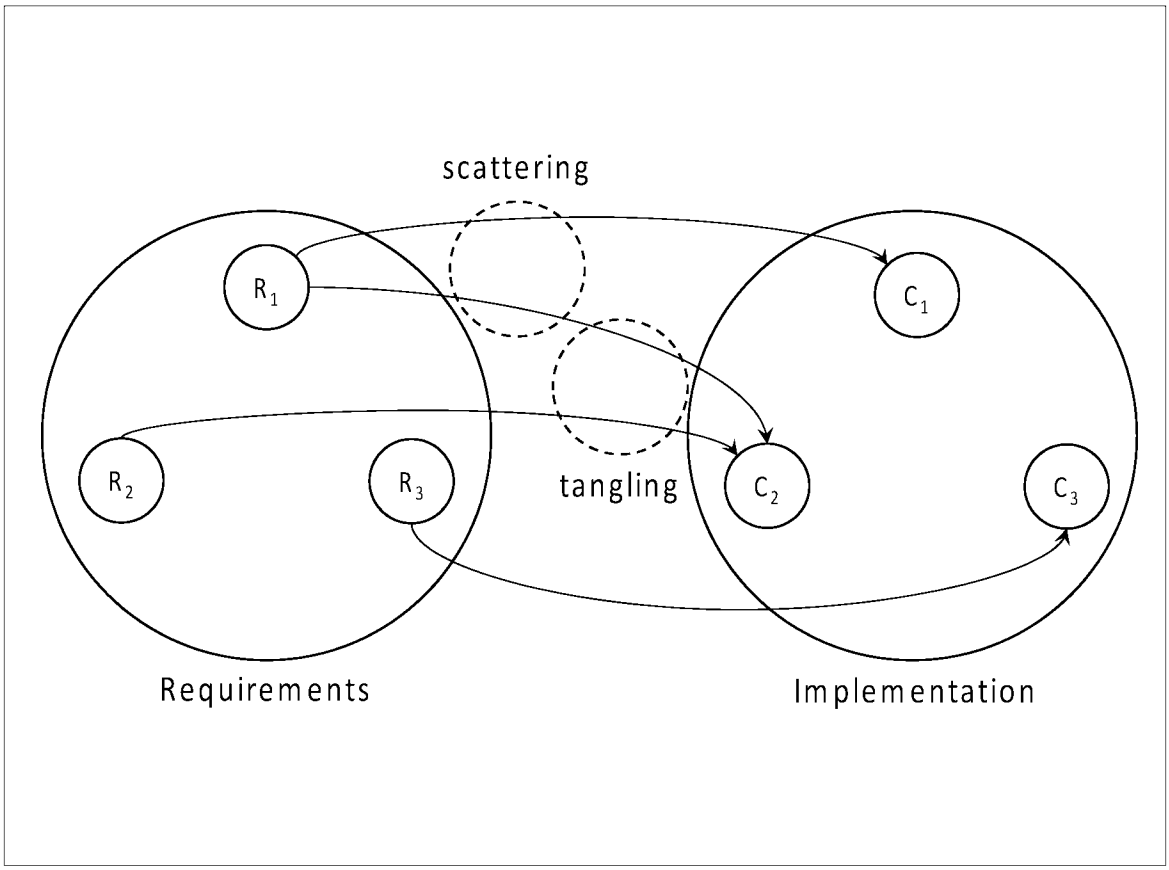

Figure 22.1: Crosscutting: Scattering and tangling.

2. Strong coupling between modular units in classes that are difficult to understand and change.

3. Low degree of code reusability. Core functionality impossible to be reused without related semantics, already embedded in component.

4. Lower productivity: Simultaneous implementation of multiple concerns in one module breaks the focus of developers.

5. Programs are more error prone.

In general, we can say that crosscutting affects the quality of software. In object-oriented programming, the tendency is to find commonality among classes and push them up (vertically) in the inheritance hierarchy. In AOP, we identify scattered concerns and eject them horizontally from the object structure into aspect definitions. It is also important to note that just as object-oriented programming did not discard the idea of block structure and structured programming, AOP does not reject existing technology.

22.4 Quantification and obliviousness

In an article[3] that has received a great popularity, authors Filman and Friedman argue that *quantification* and *obliviousness* are two principles that characterize AOP:

Quantification "In a program P, when condition C occurs, execute action A."

Obliviousness No visibility exists from the components of the core functionality to the aspect definitions.

In Figure 22.2 the points in components `C2` and `C3` constitute join points. Note that even though both components are enhanced by the aspectual behavior defined by `A`, neither of them is aware of this fact (nor have they been implemented to accept such enhancements).

[3]Aspect-Oriented Programming is Quantification and Obliviousness. Robert E. Filman. Daniel P. Friedman. RIACS Technical Report 01.12. May 2001.

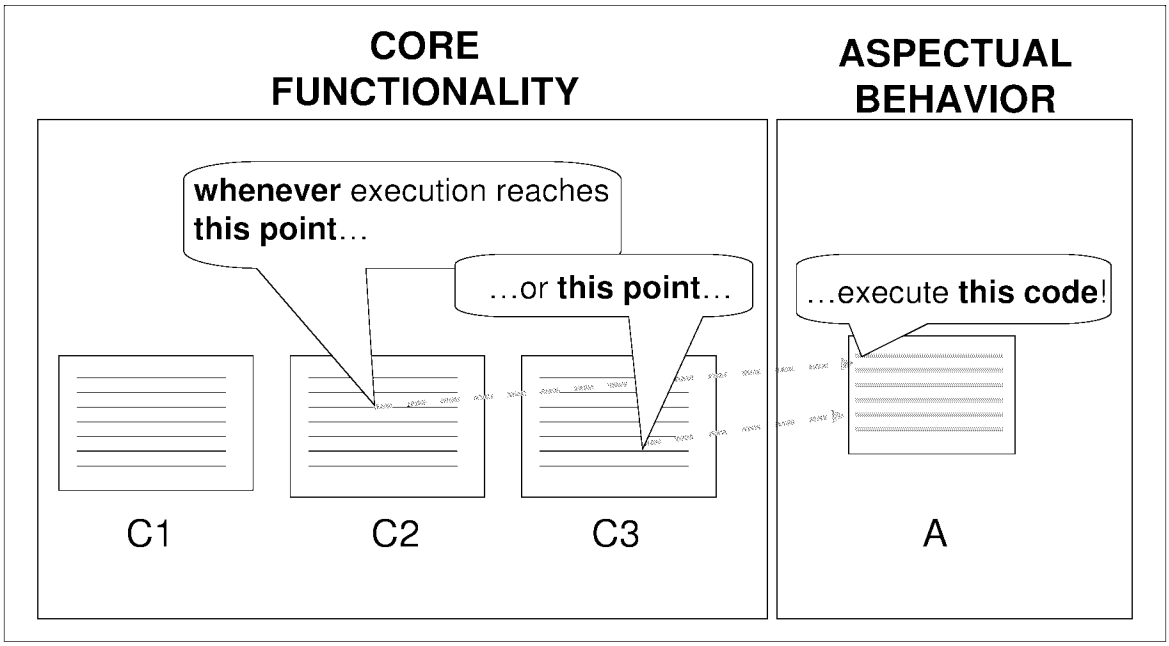

Figure 22.2: Quantification and obliviousness.

22.5 Dissection of a pointcut

In the previous example, we had defined a named pointcut as follows:

```
pointcut mutators(): call(void Stack.push(String)) ||
                     call(String Stack.pop());
```

The format of a named pointcut is

```
pointcut <name> ([<object(s) to be picked up>]) : <join point expression>
```

where a join point expression is any predicate over join points. A join point has the following format:

```
<join point type> (<signature>)
```

In the above example, pointcut `mutators()` was defined as the logical disjunction of two join points, both of type *call*, and picked up no object (see later on context passing). We discuss different join point types in § 22.6.

The dissection of a (named) pointcut is illustrated in Figure 22.3 and a dissection of a call join point is illustrated in Figure 22.4.

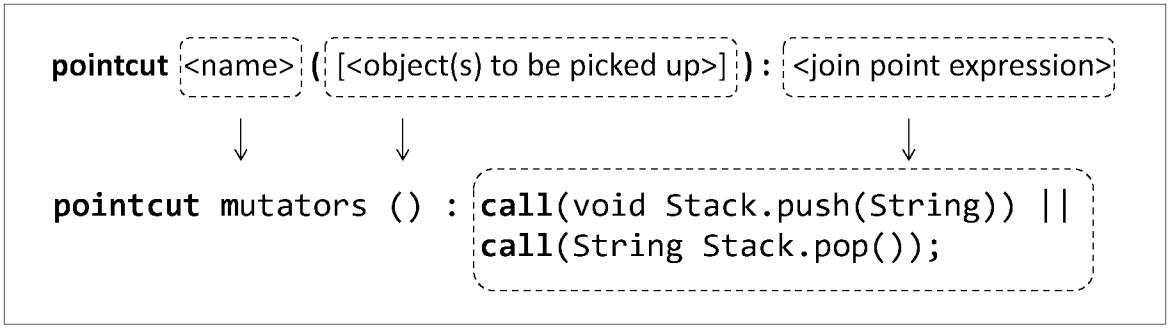

Figure 22.3: A dissection of a pointcut.

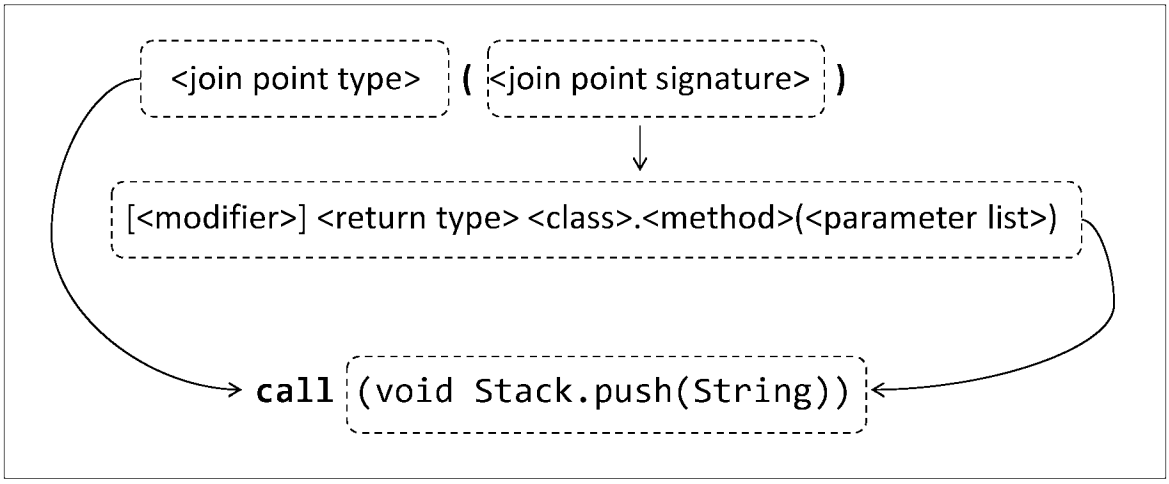

Figure 22.4: A dissection of a call join point.

22.6 The join point model

AspectJ provides a rich expression set through which we can build join points. It is referred to as the language's *join point model*. Even though the specification and level of granularity of the join point model differ from one language to another, join points that capture message passing and those that capture the execution of methods are common in most current languages. The most common join points in AspectJ are the following:

1. Call join points (§ 22.6.1): Capture messages (or "calls to methods").
2. Constructor call join points (§ 22.6.2): Capture calls to constructors.
3. Execution join points (§ 22.6.6): Capture execution of methods.
4. Constructor execution join points (§ 22.6.7): Capture execution of constructors.
5. Exception handling join points (§ 22.6.9).
6. Lexical structure join points (§ 22.6.10).
7. Object initialization join points (§ 22.6.11).
8. Class initialization join points (§ 22.6.12).
9. Control flow join points (§ 22.6.13).
10. Field access join points (§ 22.6.14). Capture read/write access to class attributes.
11. Conditional test join points (§ 22.6.15).
12. Self and target join points (§ 22.10.1). Capture caller and callee objects, executing objects.
13. Argument join points (§ 22.10.3). Capture method arguments.
14. Advice execution join points (§ 22.10.5).

JOIN POINT SIGNATURE	DESCRIPTION
`protected void Vector.removeRange(int, int)`	Captures a `protected void` method `removeRange` in class `Vector`, taking two arguments of type `int`.
`protected void Vector+.removeRange(int, int)`	As above but it also includes subclasses of `Vector`.

Table 22.1: Join point signatures - 1 of 3.

22.6.1 Call join points

A *call join point* captures a message that matches a given signature that is sent to an object with a given static type. For example, the join point `call (void Server.attach(..))` captures message `attach` with any (including zero) arguments sent to an object whose static type is `Server` and where the invoked method is not expected to return any value.

The format of a call join point is

call (*signature*)

where the format of *signature* is

```
[<modifier>] <return type> <class>.<method>(<parameter list>)
```

Join point signatures

In AspectJ, the join point model can adopt wildcards for the definition of expressions. The most common are the asterisk * that has the meaning of *any*, and in the case of the parameter list the double-dot `..` means *any and of any type*. The + next to a class name is interpreted as *this type and all its subtypes*. Tables 22.1, 22.2 and 22.3 illustrate examples of expressions of join point signatures.

Table 22.4 shows examples of expressions of call join points. There is a trade-off in the expressiveness of the join point model language. On one hand, wildcards and other special characters can provide shorter expressions but on the other hand they can make expressions difficult to read. They may also unintentionally capture join points in the program execution. For example, the following join point

JOIN POINT SIGNATURE	DESCRIPTION
`* void Vector.removeRange(int, int)`	Captures a `void` method `removeRange` of any modifier in class `Vector`, taking two arguments of type `int`.
`void Vector.removeRange(int, int)`	As above (modifier is optional and it was omitted).
`* * Vector.removeElement(Object)`	Captures method `removeElement` of any return type and any modifier in class `Vector`, taking one argument of type `Object`.
`* Vector.removeElement(Object)`	As above (modifier is optional and it was omitted).
`* * *.removeElement(Object)`	Captures method `removeElement` of any return type and any modifier in any class, taking one argument of type `Object`.
`* * *.*(Object)`	Captures any method of any return type and any modifier in any class, taking one argument of type `Object`.

Table 22.2: Join point signatures - 2 of 3.

JOIN POINT SIGNATURE	DESCRIPTION
`* * *.*(*, int)`	Captures any method in any class, returning any type, of any modifier, taking two arguments, where the first is of any type and the second is of type `int`.
`* * *.*(int, ..)`	Captures any method in any class, returning any type, of any modifier, taking an argument of type `int`, followed by a sequence of additional arguments (that can also be empty) of any type.
`* * *.*(.., int)`	As above but an argument of type `int` is preceded by a sequence of arguments (that can also be empty) of any type.
`* * *.*(..)`	Captures any method in any class, returning any type, of any modifier, taking any (or zero) arguments.
`* * *.*()`	As above but taking no arguments.
`* * Vector.remove*(..)`	Captures any method whose name starts with the string `remove` followed by zero or more characters, of any return type and any modifier, in class `Vector`, taking any (or zero) arguments.

Table 22.3: Join point signatures - 3 of 3.

```
call (* Stack.*(..))
```

captures any messages with any (including zero) arguments sent to any object of type `Stack`, where the invoked method is expected to return a value of any type (including `void`). If we used this join point (as an anonymous pointcut) in the `Logger` aspect in the `Stack` example, i.e.

```
before(): call (* Stack.*(..)) {
  System.out.println(                                    );
}
```

then the pointcut would also capture messages `isFull()` and `isEmpty()` as well as any other messages sent to a `Stack` object whether existing or introduced in the future, such as `toString()`, `clone()`, etc.

22.6.2 Call to constructor join points

AspectJ distinguishes between regular messages (sent to objects and classes) and messages that are sent to class constructors. A *call to constructor join point* captures a call made to the constructor of a given class. The keyword `new` is used to identify such join point signatures. For example, `call(Stack.new())` captures a call to the default constructor of class `Stack`. Note that signatures of constructor call join points contain no return type. The format of a call to constructor join point is

call (*signature*)

where the format of *signature* is

```
[<modifier>] <class>.new(<parameter list>)
```

Table 22.5 shows expressions for call to constructor join points.

22.6.3 Call join points in the presence of inheritance

A call join point captures a message that is sent to an object of a given static type. This implies that it can capture such message sent to an object of a subtype. We will demonstrate this with an example.

JOIN POINT PATTERN	DESCRIPTION
`call(void Buffer.put(String))`	Matches messages `put` taking one argument of type String, sent to an object of type `Buffer`, where the invoked method is not expected to return any value.
`call(void Buffer.put(..))`	Matches messages `put` taking any (or zero) arguments , sent to an object of type `Buffer`, where the invoked method is not expected to return any value.
`call(* Buffer.put(..))`	Matches messages `put` taking any (or zero) arguments, sent to an object of type `Buffer`, where the invoked method is expected to return a value of any type (or no value).
`call(* Buffer.put*(..))`	Matches any message whose name starts with `put` and followed by zero or more characters, taking any (or zero) arguments, sent to an object of type `Buffer`, where the invoked method is expected to return a value of any type (or no value).
`call(* Buffer.put*(String, ..))`	Matches any message whose name starts with `put` and followed by zero or more characters, taking an argument of type `String` followed by a sequence of additional arguments (that can also be empty) of any type, sent to an object of type `Buffer`, where the invoked method is expected to return a value of any type (or no value).

Table 22.4: Examples of call join points.

JOIN POINT PATTERN	DESCRIPTION
`call(Buffer.new())`	Captures calls to the constructor method of class `Buffer` taking no arguments.
`call(Buffer.new(..))`	Captures calls to the constructor method of class `Buffer` taking any (or zero) arguments.
`call(Buffer+.new(..))`	Captures all calls made to the constructor of class `Buffer`, or any of its subclasses, taking any (or zero) arguments.

Table 22.5: Examples of constructor call join points.

Example: A bounded stack

We now subclassify `Stack` to define class `BStack` that implements a stack of bounded capacity.

```
import java.util.*;
public class BStack extends Stack {
  private int capacity;
  public BStack (int capacity) {
    this.capacity = capacity;
  }
  @Override
  public void push (String str) {
  if (!this.isFull())
    super.push(str);
  }
  private boolean isFull() {
    return top == capacity;
  }
}
```

We need to modify `main` to accommodate for the construction of a bounded stack object with a given capacity:

```
public class Test {
  public static void main(String[] args) {
    BStack myStack = new BStack(2);
    myStack.push(      );
    myStack.push(      );
    myStack.push(     );
    System.out.println(myStack.pop());
    System.out.println(myStack.pop());
```

```
    System.out.println(myStack.pop());
    System.out.println(myStack.top());
  }
}
```

Let us run the program:

```
>Message sent to update stack.
>Message sent to update stack.
>Message sent to update stack.
>Message sent to update stack.
your
>Message sent to update stack.
base
>Message sent to update stack.
null
null
```

We see that pointcut `mutators()` is captured. The reason is that the call join point

```
call(void Stack.push(String))
```

captures calls to `push(String)` declared in class `Stack` or any of its subclasses.

22.6.4 Reflective information on join points with `thisJoinPoint`

AspectJ provides the special variable `thisJoinPoint` that contains reflective information about the current join point. Let us modify aspect `Logger`, in the bounded stack example, to access reflective information on all join points captured by `mutators()`:

```
public aspect Logger {
  pointcut mutators(): call(void Stack.push(String)) ||
                       call(String Stack.pop());
  before(): mutators() {
```

```
    System.out.println(                                    + thisJoinPoint);
  }
}
```

We run the test program on the bounded stack and we see that it has the same behavior as before, but with additional information on each captured join point:

```
>Message sent to update stack: call(void BStack.push(String))
>Message sent to update stack: call(void BStack.push(String))
>Message sent to update stack: call(void BStack.push(String))
>Message sent to update stack: call(String BStack.pop())
your
>Message sent to update stack: call(String BStack.pop())
base
>Message sent to update stack: call(String BStack.pop())
null
null
```

22.6.5 Multiple pointcuts

A pointcut may capture a set of join points. This implies that two (or more) pointcuts may share join points. We will demonstrate this through an example.

Example: Blade Runner

In this example, we define classes `Human` and `Bladerunner` that are related by inheritance (See Figure 22.5).

```
public class Human {
  public String reason() {
    return                                    ;
  }
}
```

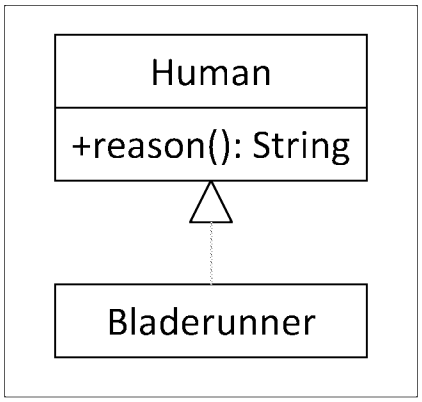

Figure 22.5: Classes `Human` and `Bladerunner`.

```
public class Bladerunner extends Human { }
```

Aspect `Logger` defines two unnamed pointcuts: `call(String Human.reason())` captures messages `reason()` sent to objects of type `Human` and `call(String Bladerunner.reason())` captures messages `reason()` sent to objects of type `Bladerunner`.

```
public aspect Logger {
  before() : call(String Human.reason()) {
    System.out.println(                                    +
                       thisJoinPoint);
  }
  before() : call(String Bladerunner.reason()) {
    System.out.println(                                        +
                       thisJoinPoint);
  }
}
```

Consider the following test program:

```
public class Test {
  public static void main(String[] args) {
    Human sebastian = new Human();
```

```
    Bladerunner deckard = new Bladerunner();
    System.out.println(sebastian.reason());
    System.out.println(deckard.reason());
  }
}
```

The output of the program is as follows:

```
>Captured call to Human.reason(): call(String Human.reason())
I am a human and I can reason.
>Captured call to Human.reason(): call(String Bladerunner.reason())
>Captured call to Bladerunner.reason(): call(String Bladerunner.reason())
I am a human and I can reason.
```

The statement `sebastian.reason()` is captured by pointcut `call(String Human.reason())`. As a result, the body of the associated advice will execute, displaying

```
>Captured call to Human.reason(): call(String Human.reason())
```

On the other hand, the statement `deckard.reason()` will be captured by *both* pointcuts. As a result, both advices will execute, displaying

```
>Captured call to Human.reason(): call(String Bladerunner.reason())
>Captured call to Bladerunner.reason(): call(String Bladerunner.reason())
```

22.6.6 Execution join points

As its name suggests, an *execution join point* captures the execution of a method defined in a given class. The join point signatures in Tables 22.1 and 22.2 are also applicable to execution join points. For example, the join point `execution (void Server.attach(..))` captures the execution of a `void` method `attach` with any (including zero) parameters defined in class `Server`, regardless of its visibility.

The format of an execution join point is

execution (*signature*)

where the format of *signature* is

```
[<modifier>] <return type> <class>.<method>(<parameter list>)
```

Example: Blade Runner revisited

We have slightly modified aspect `Logger`, in the blade runner example, by replacing the call join points by execution join points and adjusting the messages displayed:

```
public aspect Logger {
  before() : execution(String Human.reason()) {
    System.out.println(                                          +
                       thisJoinPoint);
  }
  before() : execution(String Bladerunner.reason()) {
    System.out.println(                                              +
                       thisJoinPoint);
  }
}
```

It is important to see that the pointcut `execution(String Bladerunner.reason())` will never be captured as there exists no method `reason()` defined in class `Bladerunner`. For the test program shown again below

```
public class Test {
  public static void main(String[] args) {
    Human sebastian = new Human();
    Bladerunner deckard = new Bladerunner();
    System.out.println(sebastian.reason());
    System.out.println(deckard.reason());
  }}
```

the run-time system will invoke method `reason()` defined in class `Human` twice. The output of the program is as follows:

```
>Captured execution of Human.reason(): execution(String Human.reason())
I am a human and I can reason.
>Captured execution of Human.reason(): execution(String Human.reason())
I am a human and I can reason.
```

22.6.7 Constructor execution join points

AspectJ distinguishes between executions of regular methods and executions of constructor methods. The latter are identified in join point signatures by the keyword `new`. Note also that join point signatures of constructor executions contain no return type. The format of a constructor execution join point is

execution (*signature*)

where the format of *signature* is

```
[<modifier>] <class>.new(<parameter list>)
```

22.6.8 Call vs. execution join points

With the aid of examples we will demonstrate the difference between call and execution join points.

Example: A client and server

Consider the definitions of classes `Server` and `Client` below:

```
public class Server {
  public String ping() {
    System.out.println(                          );
    return         ; }}
```

```
public class Client {
  Server server;
  public Client(Server server) {
    this.server = server;
  }
  public String testConnection() {
    System.out.println(                                  );
    String str = server.ping();
    System.out.println(                                  );
    return str;
  }
}
```

When we view such a model we can see (statically) when two classes are related through attribute visibility. This implies that an instance of one can send messages to an instance of the other (or to self if this is a reflexive association). Much like classes are instantiated at run-time, a call creates an association (at run-time) between two instances. On the other hand, an execution is an event that takes place within an instance. A summary of these differences is illustrated in Figure 22.6. Aspect `Logger` captures calls to `String Server.ping()` and executions of `String Server.ping()`.

```
public aspect Logger {
  before() : call(String Server.ping()) {
    System.out.println(              + thisJoinPoint);
  }
  after() : call(String Server.ping()) {
    System.out.println(             + thisJoinPoint);
  }
  before() : execution(String Server.ping()) {
    System.out.println(              + thisJoinPoint);
  }
```

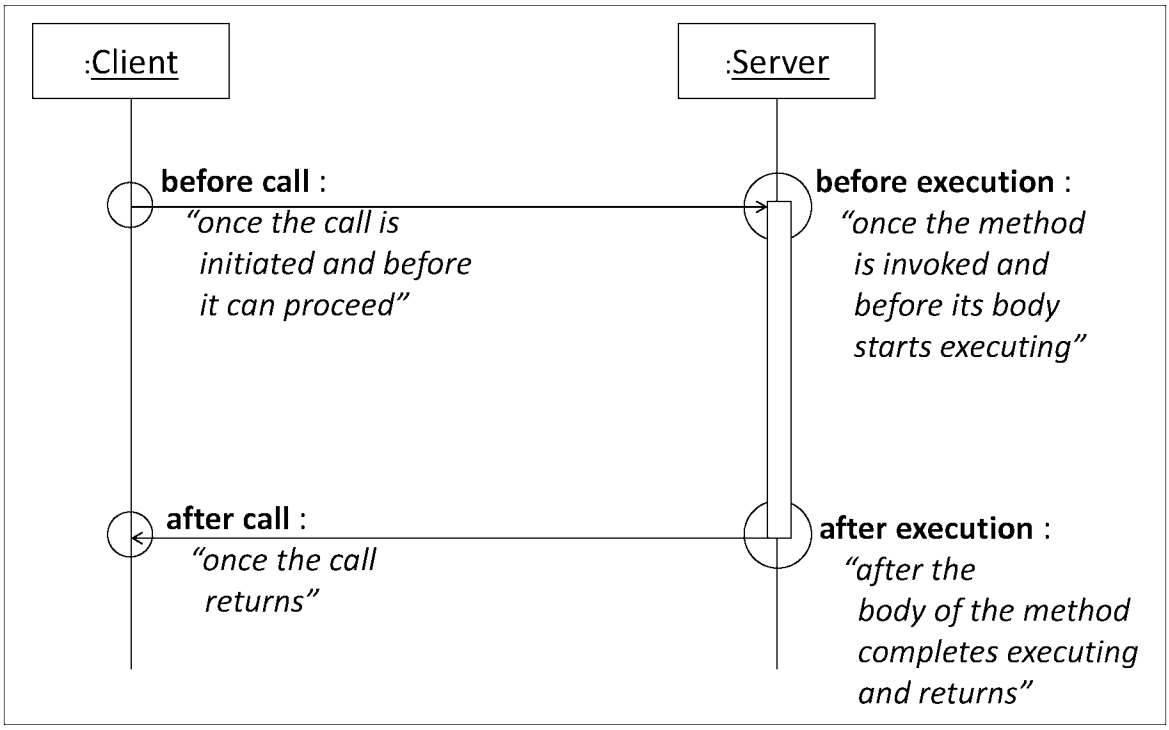

Figure 22.6: Calls and executions.

```
  after() : execution(String Server.ping()) {
    System.out.println(           + thisJoinPoint);
  }
}
```

Consider the following test program:

```
public class Test {
  public static void main(String[] args) {
    Server server = new Server();
    Client client = new Client(server);
    System.out.println(client.testConnection()); }}
```

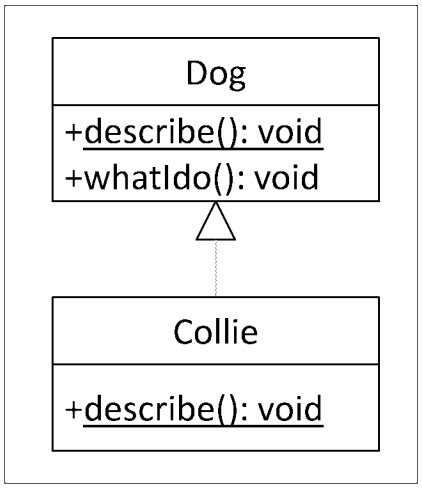

Figure 22.7: Classes `Dog` and `Collie`.

The output of the program is as follows:

```
About to call server.ping()
>Before: call(String Server.ping())
>Before: execution(String Server.ping())
Inside Server.ping().
>After: execution(String Server.ping())
>After: call(String Server.ping())
Just called server.ping()
pong.
```

Example: A dog's life

Consider the following class definitions, the UML class diagram of which is shown in Figure 22.7. Initially we define classes `Dog` and `Collie`.

```
public class Dog {
  public static void describe() {
    System.out.println(      );
  }
```

```
  public void whatIdo() {
    System.out.println(                              );}}
```

```
public class Collie extends Dog {
  public static void describe() {
    System.out.println(          );
  }
}
```

Aspect `Tracer` provides pointcuts that capture all messages sent to objects of either type, as well as any method executions that occur in either class.

```
public aspect Tracer {
  before(): call(* Dog.*()) {
    System.out.println(                                          +
                       thisJoinPoint);
  }
  before(): call(* Collie.*()) {
    System.out.println(                                              +
                       thisJoinPoint);
  }


  after() : execution(* Dog.*()) {
    System.out.println(                                      +
                       thisJoinPoint);
  }
  after() : execution(* Collie.*()) {
    System.out.println(                                        +
                       thisJoinPoint);
  }
}
```

Consider the test program below:

```
public class Test {
  public static void main(String[] args) {
    Dog lassie = new Collie();
    Collie bella = new Collie();
    lassie.describe();
    bella.describe();
    lassie.whatIdo();
    bella.whatIdo();
  }
}
```

Recall that static features are chosen based not on the dynamic (run-time) type of the object but based on its static (declared) type. The statement `lassie.describe()` is captured by the anonymous pointcut `call(* Dog.*())`. The `before` advice will display

```
>Captured message to object of type Dog: call(void Dog.describe())
```

The static method in class `Dog` then executes displaying `Dog`. The execution of the method is captured by the anonymous pointcut `execution(* Dog.*())`. Upon successful termination of the method, the `after` advice will display

```
>Captured execution in class Dog: execution(void Dog.describe())
```

The statement `bella.describe()` is captured by the anonymous pointcut `call(* Collie.*())`. The `before` advice will display

```
>Captured message to object of type Collie: call(void Collie.describe())
```

The static method in class `Collie` then executes displaying `Collie`. The execution of the method is captured by the anonymous pointcut `execution(* Collie.*())`. Upon successful termination of the method, the `after` advice will display

```
>Captured execution in class Collie: execution(void Collie.describe())
```

The statement `lassie.whatIdo()` is captured by the anonymous pointcut `call(* Dog.*())`. The `before` advice will display

```
>Captured message to object of type Dog: call(void Dog.whatIdo())
```

The instance method in class `Dog` then executes displaying `I save people from danger`. The execution of this method is also captured by the anonymous pointcut `execution(* Dog.*())`. Upon successful termination of the method, the `after` advice executes displaying

```
>Captured execution in class Dog: execution(void Dog.whatIdo())
```

The statement `bella.whatIdo()` is captured by two anonymous pointcuts `call(* Dog.*())` and `call(* Collie.*())` since being of type `Collie` implies that `bella` is also of type `Dog`. The two corresponding advices will execute according to their lexical ordering (we discuss advice precedence later) and they will display

```
>Captured message to object of type Dog: call(void Collie.whatIdo())
>Captured message to object of type Collie: call(void Collie.whatIdo())
```

The Java run-time system will attempt to locate a method to match the message starting from the dynamic type of the object, namely class `Collie`. Such a method does not exist, so the run-time system will go up the inheritance chain, locating and invoking such method in class `Dog`. The method will display `I save people from danger`. The execution of this method is captured by the anonymous pointcut `execution(* Dog.*())`. Upon successful termination of the method, the `after` advice executes displaying

```
>Captured execution in class Dog: execution(void Dog.whatIdo())
```

Putting everything together, the output of the program is as follows:

```
>Captured message to object of type Dog: call(void Dog.describe())
Dog.
>Captured execution in class Dog: execution(void Dog.describe())
>Captured message to object of type Collie: call(void Collie.describe())
Collie.
```

```
>Captured execution in class Collie: execution(void Collie.describe())
>Captured message to object of type Dog: call(void Dog.whatIdo())
I save people from danger.
>Captured execution in class Dog: execution(void Dog.whatIdo())
>Captured message to object of type Dog: call(void Collie.whatIdo())
>Captured message to object of type Collie: call(void Collie.whatIdo())
I save people from danger.
>Captured execution in class Dog: execution(void Dog.whatIdo())
```

22.6.9 Exception handling join points

The `after` advice provides the option to execute only when the method throws an exception. The format of such an expression is

`after() throwing`, or

`after() throwing` (*exception type identifier*)

22.6.10 Lexical structure join points

Lexical structure join points capture well-defined points inside the lexical structure of classes or methods. The forms are

`within` (*type pattern*), and

`withincode` (*method signature*)

where *type pattern* may include wildcard characters and must resolve to a class, or a range of different classes, and *method signature* may include wildcard characters and must resolve to a method in a class or to a range of methods. Example patterns of lexical strucure are shown in Table 22.6.

22.6.11 Object initialization join points

Object initialization join points capture the call to a constructor that matches a specified signature. The format is

JOIN POINT PATTERN	DESCRIPTION
`within`(className)	Matches any join point inside the lexical scope of `className`.
`within`(className*)	Matches any join point inside the lexical scope of classes with a name that starts with `className`.
`withincode`(* className.methodName(..))	Matches any join point inside the lexical scope of `methodName` in `className`.

Table 22.6: Examples of lexical structure join points.

`initialization` (*signature*)

where *signature* is defined as

```
[<modifier>] <class>.new(<parameter list>)
```

The *signature* must resolve to a constructor of an object or of a range of objects.

Example: A point hierarchy

In the following example (Figure 22.8), we capture the initialization of two objects of class `ColoredPoint`.

```
public class Point {
  public float x;
  public float y;
  public Point() {
    this(0, 0);
  }
  public Point (float x, float y) {
    this.x = x;
    this.y = y;
  }
}
```

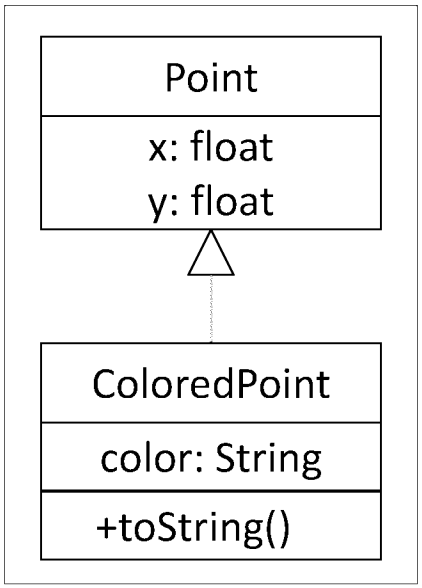

Figure 22.8: Classes `Point` and `ColoredPoint`.

```
public class ColoredPoint extends Point {
  public String color;
  public ColoredPoint () {
    super();
    System.out.println(                                    );
    this.color =        ;
    System.out.println(                                  );}
  public ColoredPoint (float x, float y, String color) {
    super(x, y);
    System.out.println(                                       );
    this.color = color;
    System.out.println(                                     );
  }
  public String toString() {
    return      + this.x +       + this.y +          + this.color;
  }
}
```

Aspect `InitializationMonitor` captures the initialization of `ColoredPoint` instances.

```
public aspect InitializationMonitor {
  before() : initialization(ColoredPoint.new(..)) {
    System.out.println(thisJoinPoint);
  }
}
```

Consider the following test program:

```
public class Test {
  public static void main(String[] args) {
    ColoredPoint p = new ColoredPoint();
    ColoredPoint q = new ColoredPoint(1, 1,      );
    System.out.println(p.toString());
    System.out.println(q.toString());
  }
}
```

The output of the program is shown below. Notice that the `before` advice executes after the super constructor initializes both inherited attributes and before the body of the constructor of the current class executes.

```
initialization(ColoredPoint())
>Entry: Default constructor.
>Exit: Default constructor.
initialization(ColoredPoint(float, float, String))
>Entry: Non-default constructor.
>Exit: Non-default constructor.
(0.0, 0.0) : Black
(1.0, 1.0) : Red
```

If we now changed the type of advice from `before` to `after`, the output of the program is as follows:

```
>Entry: Default constructor.
>Exit: Default constructor.
initialization(ColoredPoint())
>Entry: Non-default constructor.
>Exit: Non-default constructor.
initialization(ColoredPoint(float, float, String))
(0.0, 0.0) : Black
(1.0, 1.0) : Red
```

22.6.12 Class initialization join points

Class initialization join points capture the execution of static initialization blocks of specified types. The format is

`staticinitialization` (*type pattern*)

where *type pattern* may include wildcard characters and must resolve to a class, or a range of different classes.

22.6.13 Control flow join points

The term *control flow* refers to the order in which events, such as messages or method executions, occur. For example, if during $event_1$ the event causes $event_2$ which in turn causes $event_3$, then we say that the sequence $\langle event_2, event_3 \rangle$ lies within the control flow of $event_1$, as well as $\langle event_3 \rangle$ lies within the control flow of $event_2$. Recall that in AspectJ, events are captured by join points and pointcuts. The format of a control flow join point is

`cflow` (*pointcut designator*)

where *pointcut designator* can be any pointcut. Note that `cflow` (*pointcut*) captures *pointcut* itself as well as all subsequent pointcuts in its control flow. If we want to exclude *pointcut* and

JOIN POINT PATTERN	DESCRIPTION
`cflow(call (* Server.attach(..)))`	Matches any join point in the control flow of a message `attach` that includes any (including zero) arguments sent to an object of type `Server`, including the message itself.
`cflowbelow(call (* Server.attach(..)))`	Matches any join point in the control flow of a message `attach` that includes any (including zero) arguments sent to an object of type `Server`, but excluding the message itself.

Table 22.7: Examples of control flow join points.

capture only those pointcuts that occur subsequently, we must use the following alternative notation:

`cflowbelow` (*pointcut designator*)

Example patterns of control flow are shown in Table 22.7.

Example: Blade Runner revisited

Let us now consider the hierarchy in the Bladerunner example, where aspect `Logger` contains two `before` advices on the executions of `Human.reason()` and `Bladerunner.reason()`. The aspect is shown here again.

```
public aspect Logger {
  before() : execution(String Human.reason()) {
    System.out.println(                                          +
                       thisJoinPoint);
  }
  before() : execution(String Bladerunner.reason()) {
    System.out.println(                                                +
                       thisJoinPoint);
  }
}
```

We will proceed to add a new aspect to the project. In `ReflectiveLogger` the unnamed pointcut of the `after` advice captures all method executions made in the program, but not those made from within itself and not those within the control flow of the Java system, i.e. execution of library methods.

```
public aspect ReflectiveLogger {
  after(): execution(* *(..))
    && !within(ReflectiveLogger)
    && !cflow(execution (* java.*.*.*(..))) {
      System.out.println(                + thisJoinPoint);
  }
}
```

The output of the program is as follows:

```
>Captured execution of Human.reason(): execution(String Human.reason())
>Executed: execution(String Human.reason())
I am a human and I can reason.
>Captured execution of Human.reason(): execution(String Human.reason())
>Executed: execution(String Human.reason())
I am a human and I can reason.
>Executed: execution(void Test.main(String[]))
```

22.6.14 Field access join points

Field access join points capture read and write access to the fields declared in a given class. The formats are

`get` (*field signature*), and
`set` (*field signature*)

for read and write access respectively, where a *field signature* is defined as

```
[<modifier>] <return type> <class>.<field>
```

A field signature may contain wildcard characters and it must resolve to an attribute of a given class.

Example: Global Positioning System

In the following example, we define class `GPSCoordinate` that holds a coordinate in the Global Positioning System (GPS).

```
public class GPSCoordinate {
  private Double latitude = 0.;
  private Double longitude = 0.;
  public  GPSCoordinate(Double latitude, Double longitude) {
    this.latitude = latitude;
    this.longitude = longitude;
  }
  public void setLatitude(Double latitude) {
    this.latitude = latitude;
  }

  public Double getLatitude(){
    return this.latitude;
  }
  public void setLongitude(Double longitude) {
    this.longitude = longitude;
  }
  public Double getLongitude() {
    return this.longitude;
  }
  public void moveTo(Double latitude, Double longitude) {
    this.latitude = latitude;
    this.longitude = longitude; }
```

```
  public String toString() {
    return      + latitude +       + longitude +     ;
  }
}
```

Aspect `FieldAccess` defines two unnamed pointcuts to capture read and write access, respectively, to any field of class `GPSCoordinate`. Note that the join points are able to capture access to the fields despite the fact that the fields are declared `private`. It is also important to note that these join points do not capture inherited fields.

```
public aspect FieldAccess {
  before() : get(* GPSCoordinate.*) {
    System.out.println(                    + thisJoinPoint);
  }
  before() : set(* GPSCoordinate.*) {
    System.out.println(                     + thisJoinPoint);
  }
}
```

A test program creates and initializes an instance of `GPSCoordinate`. It then proceeds to move the instance to a new location and finally it displays its latitute and longitute values.

```
public class Test {
  public static void main(String[] args) {
    GPSCoordinate point = new GPSCoordinate(45.220227, -73.564453);
    point.moveTo(46.763321, -71.224365);
    System.out.println(point.getLatitude());
    System.out.println(point.getLongitude());
    System.out.println(point.toString());
  }
}
```

The output of the program is as follows:

```
>Write access: set(Double GPSCoordinate.latitude)
>Write access: set(Double GPSCoordinate.longitude)
>Write access: set(Double GPSCoordinate.latitude)
>Write access: set(Double GPSCoordinate.longitude)
>Write access: set(Double GPSCoordinate.latitude)
>Write access: set(Double GPSCoordinate.longitude)
>Read access: get(Double GPSCoordinate.latitude)
46.763321
>Read access: get(Double GPSCoordinate.longitude)
-71.224365
>Read access: get(Double GPSCoordinate.latitude)
>Read access: get(Double GPSCoordinate.longitude)
(46.763321, -71.224365)
```

Example: Points

Consider the implementation of class `Point`:

```
public class Point {
  protected double x, y;
  public Point(double x, double y) {
    this.x = x;
    this.y = y;
  }
  public Point() {
    this(0, 0);
  }
  public void move(double x, double y) {
    this.x = x;
    this.y = y;
  }
```

```
  public String toString() {
    return        + x +          + y +     ;
  }
}
```

We subclassify `Point` by introducing `ColoredPoint` that adds attribute `color`.

```
public class ColoredPoint extends Point {
  String color;
  public ColoredPoint(double x, double y, String color) {
    super(x, y);
    this.color = color;
  }
  public ColoredPoint() {
    super(0., 0.);
    this.color =         ;
  }

  public String toString() {
    return        + x +          + y +                + color +     ;
  }
}
```

In aspect `FieldAccess`, the two poincuts that are set to capture field access on class `ColoredPoint`:

```
public aspect FieldAccess {
  before() : get(* ColoredPoint.*) {
    System.out.println(                    + thisJoinPoint);
  }
  before() : set(* ColoredPoint.*) {
    System.out.println(                     + thisJoinPoint); }}
```

A test program creates and initializes an instance of `ColoredPoint`. It proceeds to move the object to a new location and finally it displays the object's coordinate and color values.

```
public class Test {
  public static void main(String[] args) {
    ColoredPoint point = new ColoredPoint(3, 5,        );
    point.move(7,  9);
    System.out.println(point.toString());
  }
}
```

The output of the program is as follows:

```
>Write access: set(String ColoredPoint.color)
>Read access: get(String ColoredPoint.color)
x: 7.0, y: 9.0, color: white.
```

We observe that the pointcuts only capture access to atttribute `color`, but do not capture access to the `x` and `y` attributes. Let us modify the two pointcuts, to capture access to fields declared in `Point` and all its subclasses:

```
public aspect FieldAccess {
  before() : get(* Point+.*) {
    System.out.println(                  + thisJoinPoint);
  }
  before() : set(* Point+.*) {
    System.out.println(                   + thisJoinPoint);
  }
}
```

The output of the same test program is now as follows:

```
>Write access: set(double Point.x)
>Write access: set(double Point.y)
```

```
>Write access: set(String ColoredPoint.color)
>Write access: set(double Point.x)
>Write access: set(double Point.y)
>Read access: get(double Point.x)
>Read access: get(double Point.y)
>Read access: get(String ColoredPoint.color)
x: 7.0, y: 9.0, color: white.
```

22.6.15 Conditional test join points

A conditional test join point captures join points based on some conditional check at the join point. The format is

`if` (*Boolean expression*)

22.7 Around advice

The third type of advice allows us to say "Whenever a pointcut is captured, *instead of* running the code associated with the pointcut, execute the body of the advice." An optional mechanism allows us to resume execution of the code associated with the pointcut. Visually, the mechanism of an `around` advice is shown in the UML sequence diagram of Figure 22.9.

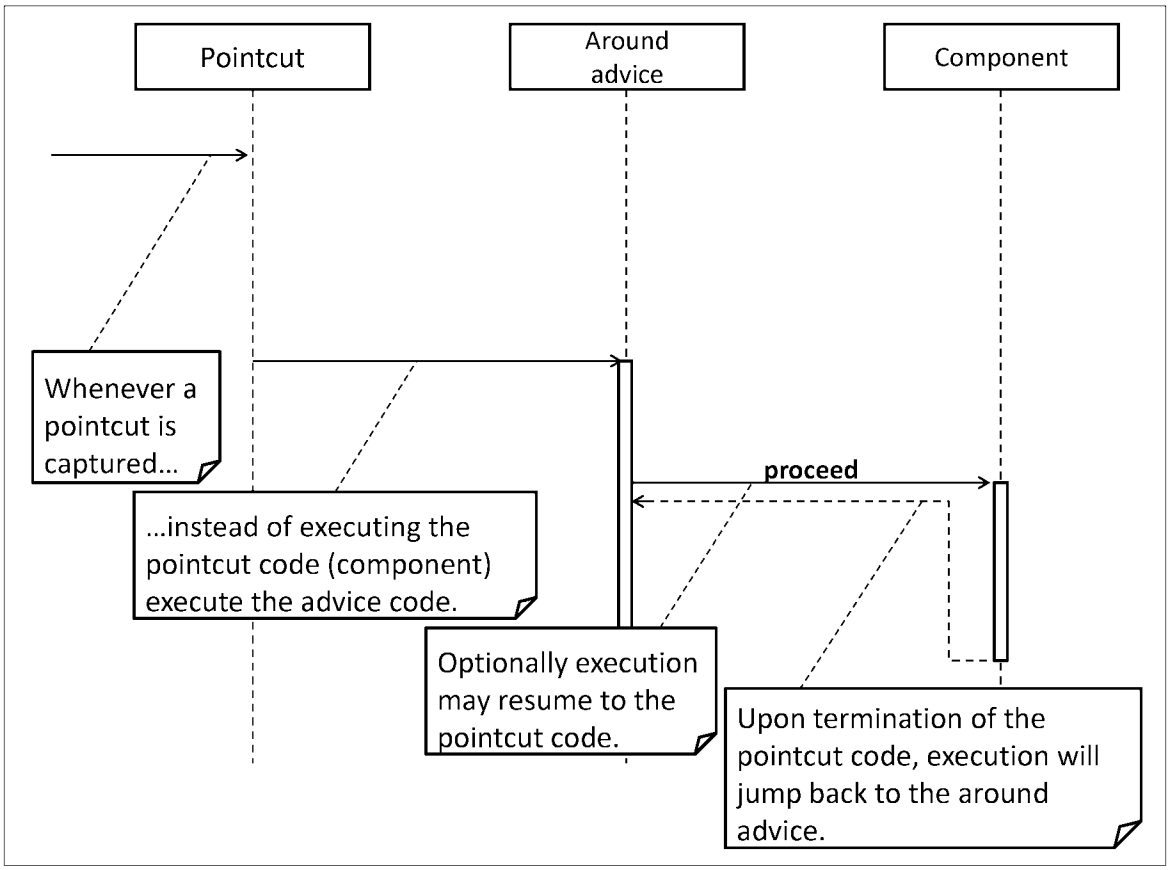

Figure 22.9: Around advice.

Example: History protocol

Consider the implementation of a circular bounded buffer:

```
public class Buffer {
  String[] BUFFER;
  int putPtr;
  int getPtr;
  int counter;
  int capacity;
  String name;
  Buffer (int capacity) {
    BUFFER = new String[capacity];
    this.capacity = capacity; }
  Buffer (int capacity, String name) {
    this(capacity);
    this.name = name; }
  public String getName() {return name;}
  private boolean isEmpty() {return (counter == 0);}
  private boolean isFull() {return (counter == capacity);}
  public void put (String s) {
    if (isFull())
      System.out.println(                    );
    else {
      BUFFER[putPtr++ % (capacity)] = s;
      counter++; }}
  public String get() {
    if (isEmpty())
      return                       ;
    else {
      counter--;
      return BUFFER[getPtr++ % (capacity)]; }}}
```

Consider now the definition of class `Buffer2` which introduces method `gget()`. This method behaves exactly like `get()`, but it can only execute after a `get()`. To implement this requirement in Java would imply that `Buffer2` would have to re-define methods `put()` and `get()` to implement a history protocol. Instead, we will implement the history protocol in an aspect.

```
public class Buffer2 extends Buffer {
  Buffer2 (int capacity) {
    super(capacity);
  }
  public String gget() {
    return super.get();
  }
}
```

In defining the aspect, we first need to introduce a variable to serve as a flag that would indicate which operation has been lastly executed:

```
private boolean afterGet;
```

We must update the history flag `afterGet` appropriately after the execution of both `put()` and `get()`. Note that both methods have been inherited to `Buffer2`. Thus, if we say

```
execution(void Buffer2.put(String))
```

then this join point would never be caught, since the method is defined (and therefore executes) from within `Buffer`. We can capture proper behavior as follows:

```
after(): execution(void Buffer.put(String)){
  afterGet = false;
}
after(): execution(String Buffer.get()) {
  afterGet = true;
}
```

We now need to write code to say: "Once there is a message `gget()` sent to an object of type `Buffer2`, instead of running the code that should run, check the history of method

execution and if the previous executed method was a `get()`, then allow execution to go ahead; Otherwise, issue an error." We use the `around` advice for this as shown below:

```
String around() : call (String Buffer2.gget()) {
  if (afterGet == false)
    return                                    ;
  else {
    return proceed();
  }
}
```

The call to `proceed` allows execution to resume at the code associated with the pointcut. One thing to remember is that unlike the two other types of advices, `before` and `after`, the `around` advice must contain a return type which should be the same as the return type of the method of the associated pointcut. In this example, as the pointcut is on `gget()` with a return type `String`, then the same return type must be associated with the advice. If there is more than one method invoved with different return types, then the type of the `around` advice should be `Object`.

We can now put everything together in aspect `HistoryProtocol` as follows:

```
public aspect HistoryProtocol {
  private boolean afterGet;
  after(): execution(void Buffer.put(String)) {
    afterGet = false; }
  after(): execution(String Buffer.get()) {
    afterGet = true;}
  String around() : call (String Buffer2.gget()) {
    if (afterGet == false)
      return                                  ;
    else
      return proceed(); }}
```

Consider the following test program:

```
public class Test {
  public static void main(String[] args) {
    Buffer2 buffer = new Buffer2(5);
    buffer.put(     );
    buffer.put(      );
    buffer.put(      );
    buffer.put(     );
    buffer.put(        );
    System.out.println(buffer.gget());
    System.out.println(buffer.get());
    System.out.println(buffer.gget());
    buffer.put(    );
    buffer.put(    );
    System.out.println(buffer.gget());
    System.out.println(buffer.get());
    System.out.println(buffer.get());
    System.out.println(buffer.gget());
    System.out.println(buffer.get());
    System.out.println(buffer.get()); }}
```

The output of the program is as follows:

```
Error: Cannot execute gget()
all
your
Error: Cannot execute gget()
base
are
belong
to
us
```

Example: A Stack protocol enforcement

What happens when a subclass uses only part of a superclass' interface or does not need to inherit data? What do we do when it is very practical to use inheritance, but an *is-a* relationship does not hold? Can we just adopt this scheme? Consider class `Stack` in the `java.util` library of the Java Application Programming Interface (API) which inherits class `Vector` (which in turn implements interface `List`) by extending its functionality with operations that would allow a vector to be treated as a stack.

Consider the following test program where we create a stack instance and place some items in the collection. We do, however, manage to violate the Stack Abstract Data Type (ADT) protocol by calling method `elementAt()` inherited from `Vector`.

```
import java.util.*;
public class StackAPITest {
  public static void main(String[] args) {
    Stack<String> s = new Stack<String>();
    s.push(       );
    s.push(        );
    s.push(       );
    System.out.println(s.elementAt(0));
  }
}
```

The output of the program is as follows:

```
first
```

In aspect `StackProtocolEnforcer` we intercept and disallow all calls sent to a stack instance except those that are legitimate under the appropriate protocol.

```
public aspect StackProtocolEnforcer {
  pointcut allowedcalls() :
```

```
    call(* java.util.Stack.push(..)) ||
    call(* java.util.Stack.pop()) ||
    call(* java.util.Stack.empty()) ||
    call(* java.util.Stack.peek());
    Object around(): (call(* java.util.Stack.*(..)) ||
                      call(* java.util.Stack.*())) &&
                     !allowedcalls() {
     System.out.println(thisJoinPoint +
                                                          );
     return thisJoinPoint +                    ;
  }
}
```

In the following test program we attempt to call methods inherited from `Vector` which would essentially violate the Stack ADT protocol.

```
import java.util.*;
public class Test {
  public static void main(String[] args) {
    Stack<String> s = new Stack<String>();
    s.push(    );
    s.push(    );
    s.push(        );
    System.out.println(s.elementAt(0));   // illegal for a stack
    s.push(     );
    s.push(      );
    s.push(      );
    s.push(     );
    System.out.println(s.firstElement()); // illegal for a stack
    System.out.println(s.pop());
    System.out.println(s.pop());
    System.out.println(s.pop());
```

```
    s.removeElementAt(3);                    // illegal for a stack
    System.out.println(s.pop());
    System.out.println(s.pop());
    System.out.println(s.pop());
    s.clear();                               // illegal for a stack
    System.out.println(s.pop());
  }
}
```

The output of the program is shown below. We see that all illegal calls are successfully captured by the aspect. We also make the following observation: The `around` advice will not return anything if the captured method is of type void.

```
call(Object java.util.Stack.elementAt(int)) is not allowed for a Stack ADT.
call(Object java.util.Stack.elementAt(int)): Illegal operation.
call(Object java.util.Stack.firstElement()) is not allowed for a Stack ADT.
call(Object java.util.Stack.firstElement()): Illegal operation.
all
your
base
call(void java.util.Stack.removeElementAt(int)) is not allowed for a Stack ADT.
are
belong
to
call(void java.util.Stack.clear()) is not allowed for a Stack ADT.
us
```

22.8 Advice precedence

Several advice blocks may apply to the same join point. In this case the order of execution is determined by a set of rules of *advice precedence* specified by the underlying language.

There are two cases to consider:

1. Precedence rules among advices within the same aspect.

2. Precedence rules among advices from different aspects.

22.8.1 Precedence rules among advices within the same aspect

There are two ways to describe precedence among advices within the same aspect. One way is to answer "[In the case of two like advices] which one executes first?" in which case the answer is "The one defined first executes first."

Another way to describe this is asking a slightly different question: "Which advice has precedence?" To answer the question we first must define "precedence."

- In the case of two or more `before` advices, "precedence" has the meaning of executing *first*.

- In the case of `after` advice, "precedence" has the meaning of executing *last*.

Thus, to answer the question in terms of precedence, in the case of two or more `before` advices, the one that appears earlier in the aspect definition has precedence over the one that appears later. Otherwise, in the case of two or more `after` advices, the one that appears later in the aspect definition has precedence over the one that appears earlier.

Precedence among `before` and `after` advices

We will demonstrate precedence among `before` and `after` advices with the test program below:

```
public class Test {
  public static void main(String[] args) {
    System.out.println(                );
  }
}
```

```
public aspect Monitor {
  pointcut progmonitor(): execution (public static void *.main(..));
  before(): progmonitor() {
    System.out.println(                                                    );
  }
  before(): progmonitor() {
    System.out.println(                          );
  }
  after(): progmonitor() {
    System.out.println(                          );
  }
  after(): progmonitor() {
    System.out.println(                                                  );
  }
}
```

The output of the program is as follows:

```
>before; defined first; should have precedence.
>before; defined last.
Inside main().
>after; defined first.
>after; defined last; should have precedence.
```

Precedence among `around` advices

In the presence of multiple `around` advices from within the same aspect, the one defined first has priority. In the example below, our test program is defined as follows:

```
public class Test {
  public static void greet() {
    System.out.println(            );
  }
```

```
  public static void main(String[] args) {
    greet();
  }
}
```

We have two `around` advices without a `proceed`:

```
public aspect Monitor {
  pointcut progmonitor(): execution (public static void *.greet());
  void around(): progmonitor() {
    System.out.println(                                                    );
  }
  void around(): progmonitor() {
    System.out.println(          );
  }
}
```

The output of the program is as follows:

```
>around; defined first; should have precedence.
```

In the next example, we have two `around` advices with a `proceed` inside the high-priority one:

```
public aspect Monitor {
  pointcut progmonitor(): execution (public static void *.greet());
  void around(): progmonitor() {
    System.out.println(                                                    );
    proceed();
  }
  void around(): progmonitor() {
    System.out.println(          );
  }
}
```

The output of the program is as follows:

```
>around; defined first; should have precedence.
>around.
```

In the last example, we have two `around` advices, both with a `proceed`:

```
public aspect Monitor {
  pointcut progmonitor(): execution (public static void *.greet());
  void around(): progmonitor() {
    System.out.println(                                                    );
    proceed();
  }
  void around(): progmonitor() {
    System.out.println(          );
    proceed();
  }
}
```

The output of the program is as follows:

```
>around; defined first; should have precedence.
>around.
Greetings.
```

Precedence among `before`, `after` and `around` advice

To see how `around` advice fits into precedence among advices within the same aspect, we need to run the following cases:

1. `around` with `before`
   (a) `around` without a `proceed` above `before`.
   (b) `around` with a `proceed` above `before`.

(c) `around` without a `proceed` below `before`.

(d) `around` with a `proceed` below `before`.

2. `around` with `after`

(a) `around` without `proceed` above `after`.

(b) `around` with `proceed` above `after`.

(c) `around` without `proceed` below `after`.

(d) `around` with `proceed` below `after`.

We will demonstrate all cases with the program below:

```
public class Test {
  public static void main(String[] args) {
    System.out.println(                );
  }
}
```

Case 1. `around` **with** `before`

We place the `around` without a `proceed` above `before`:

```
public aspect Monitor {
  pointcut progmonitor(): execution (public static void *.main(..));
  void around(): progmonitor() {
    System.out.println(           );
  }
  before(): progmonitor() {
    System.out.println(           );
  }
}
```

The output of the program is as follows:

```
>around.
```

indicating that the `around` advice shadows the `before` advice (making it inaccessible) as well as the code that corresponds to the pointcut (i.e. the body of the main method).

Consider now the `around` with a `proceed` above `before`:

```
public aspect Monitor {
  pointcut progmonitor(): execution (public static void *.main(..));
  void around(): progmonitor() {
    System.out.println(          );
    proceed();
  }
  before(): progmonitor() {
    System.out.println(          );
  }
}
```

The output of the program is as follows:

```
>around.
>before.
Inside main().
```

indicating that before terminating, the `around` advice relinquished control back to the pointcut at which point the `before` advice executed, followed by the body of the main method.

We now place the `around` without a `proceed` below `before`:

```
public aspect Monitor {
  pointcut progmonitor(): execution (public static void *.main(..));
```

```
  before(): progmonitor() {
    System.out.println(          );
  }
  void around(): progmonitor() {
    System.out.println(          );
  }
}
```

The output of the program is as follows:

```
>before.
>around.
```

indicating that the `before` advice executed first, followed by the `around` advice which shadows the execution of the code associated with the pointcut.

We now place the `around` with a `proceed` below `before`:

```
public aspect Monitor {
  pointcut progmonitor(): execution (public static void *.main(..));
  before(): progmonitor() {
    System.out.println(          );
  }
  void around(): progmonitor() {
    System.out.println(          );
    proceed();
  }
}
```

The output of the program is as follows:

```
>before.
>around.
Inside main().
```

indicating that the `before` advice executed first, followed by the `around` advice which relinquishes control to the code associated with the pointcut.

Case 2. `around` **with** `after`

We place `around` without `proceed` above `after`:

```
public aspect Monitor {
  pointcut progmonitor(): execution (public static void *.main(..));
  void around(): progmonitor() {
    System.out.println(          );
  }
  after(): progmonitor() {
    System.out.println(         ); }}
```

The output of the program is as follows:

```
>around.
>after.
```

indicating that the `around` advice did in fact shadow the code that corresponds to the pointcut (i.e. the body of the main function), even though the `after` advice does execute.

Consider now the `around` with `proceed` above `after`:

```
public aspect Monitor {
  pointcut progmonitor(): execution (public static void *.main(..));
  void around(): progmonitor() {
    System.out.println(          );
    proceed();
  }
  after(): progmonitor() {
    System.out.println(         ); }}
```

The output of the program is as follows:

```
>around.
Inside main().
>after.
```

indicating that before terminating, the `around` advice delegated control back to the pointcut at which point the body of the main method executed, followed by the `after` advice.

We place `around` without `proceed` below `after`:

```
public aspect Monitor {
  pointcut progmonitor(): execution (public static void *.main(..));
  after(): progmonitor() {
    System.out.println(         );
  }
  void around(): progmonitor() {
    System.out.println(          );
  }
}
```

The output of the program is as follows:

```
>around.
```

Why is that? The `after` advice would have precedence and would execute after the code associated with the pointcut. However, the code associated with the pointcut never executes as it is being shadowed by the `around` advice.

We place `around` with `proceed` below `after`:

```
public aspect Monitor {
  pointcut progmonitor(): execution (public static void *.main(..));
```

```
  after(): progmonitor() {
    System.out.println(          );
  }
  void around(): progmonitor() {
    System.out.println(            );
    proceed();
  }
}
```

The output of the program is as follows:

```
>around.
Inside main().
>after.
```

indicating that the `around` advice did in fact relinquish control to the code associated with the pointcut which executed, followed by the execution of the `after` advice.

22.8.2 Precedence rules among advices from different aspects

An aspect definition can include an explicit declaration of precedence over another with the following statement:

`declare precedence` : *type pattern*$_1$, *type pattern*$_2$, ..., *type pattern*$_n$

where a *type pattern* must resolve to an aspect or it may include wildcard characters that must resolve to a set of aspects.

In the above, all advices defined in an aspect (or a set of aspects) that match *type pattern*$_1$ have precedence over all advices defined in an aspect (or a set of aspects) that match *type pattern*$_2$, etc. Consider the following example:

```
public aspect A {
  declare precedence: A, B;
```

```
  pointcut callMain(): execution (public static void *.main(..));
  before(): callMain() {System.out.println(              );}
  after(): callMain() {System.out.println(             );}}
```

```
public aspect B {
  pointcut callMain(): execution(public static void *.main(..));
  before(): callMain() {System.out.println(              );}
  after(): callMain() {System.out.println(             );}}
```

The output of the program is as follows:

```
>A: before.
>B: before.
Inside main().
>B: after.
>A: after.
```

Without an explicit declaration of precedence, if aspect `Child` is a subaspect of aspect `Parent`, then all advices defined in `Child` have precedence over all advices defined in `Parent`. Without an explicit declaration of precedence or a super-subaspect relationship, if two pieces of advice are defined in two different aspects, precedence is undefined.

Precedence rules in the presence of `around` advice

To see how the `around` advice fits into precedence among advices from different aspects, we need to run the following cases:

Case 1. `around` without a `proceed`

```
public aspect A {
  declare precedence: A, B;
  pointcut callMain() : execution (public static void *.main(..));
  void around(): callMain() {System.out.println(              );}
}
```

```
public aspect B {
  pointcut callMain() : execution(public static void *.main(..));
  void around(): callMain() {System.out.println(              );}
}
```

The output of the program is as follows:

```
>A: around.
```

Case 2. around with a proceed

We now modify class A to add a proceed statement:

```
public aspect A {
  declare precedence: A, B;
  pointcut callMain() : execution (public static void *.main(..));
  void around(): callMain() {
    System.out.println(              );
    proceed();
  }
}
```

The output of the program is as follows:

```
>A: around.
>B: around.
```

Let us now add a proceed statement to class B:

```
public aspect B {
  pointcut callMain() : execution(public static void *.main(..));
  void around(): callMain() {
    System.out.println(              );
    proceed(); }}
```

The output of the program is as follows:

```
>A: around.
>B: around.
Inside main().
```

22.9 Introducing state and behavior

The mechanism of *introduction* allows for crosscutting state and behavior to be defined as part of class definitions from within aspect definitions. It also allows one to define a given type (class or interface) as a supertype to a given type, thus modifying the class hierarchy.

22.9.1 Introducing static features

In the simplest case of introductions, we can introduce static state or behavior inside a class definition. We will demonstrate this with an example.

Example: Counting objects

Consider class `Point`:

```
public class Point {
  private double x, y;
  public Point (double x, double y) {
    this.x = x;
    this.y = y;
  }
}
```

We introduce a static integer variable `numberOfInstances` in the class definition of `Point`:

```
public static int Point.numberOfInstances;
```

This variable will have to be increased every time an instance of `Point` is created.

We do this by the following `after` advice:

```
after (): execution (Point.new(..)) {
  Point.numberOfInstances++;
}
```

We also introduce a static integer method `howmany()` in the definition of class `Point` that would allow its client to query on the value of variable `numberOfInstances`:

```
public static int Point.howMany() {
  return numberOfInstances;
}
```

The complete aspect definition is shown below:

```
public aspect Tracer {
  public static int Point.numberOfInstances;
  public static int Point.howMany() {
    return numberOfInstances;
  }
  after (): execution (Point.new(..)) {
    Point.numberOfInstances++;
  }
}
```

Clients of class `Point` may now assume that method `howMany()` forms part of the interface of the class. They remain unaware of its introduction through an aspect. For the program below,

---

```
public static void main(String[] args) {
  Point p1 = new Point(0, 0);
  Point p2 = new Point(1, 3);
  System.out.println(                                    + Point.howMany());
}
```

The output of the program is as follows:

```
Number of Point instances: 2
```

22.9.2 Introducing instance features I

Example: Game of thrones

Consider classes `Human` and `Noble` below:

```
public abstract class Human {
  String name;
  public Human(String name) {
    this.name = name;
  }
  public void speak() {
    System.out.println(                          );
  }
}
```

```
public class Noble extends Human {
  String house;
  public Noble(String name, String house) {
    super(name);
    this.house = house;
  }
  public String toString() {
    return          + this.name +     ;
  }
}
```

Consider the following test program:

```
public class Test {
  public static void main(String[] args) {
    Noble Arya = new Noble(              ,         );
    Arya.speak(); }}
```

The output of the program is as follows:

```
Good morning m'lord.
```

The aspect below adds an overriding method `speak()` to class `Noble`.

```
public aspect Behavior {
  public void Noble.speak() {
    System.out.println(                                  + this.toString());
  }
}
```

The output of the program is as follows:

```
Good morning my lord. I am Arya Stark.
```

Note that the keyword `this` refers to the instance of the executing object. Furthermore, if class `Noble` already had an overriding method `speak()`, the AspectJ compiler would detect a conflict and it would produce an error.

22.9.3 Introducing behavior through an interface implementation

AspectJ allows us to declare that a class implements a given interface and thus being able to introduce behavior, and we will extend the game of thrones example to demonstrate this.

Consider interface `Allegiance`:

```
public interface Allegiance {
  public void declare();
}
```

We can declare that class `Noble` implements `Allegiance` as follows:

```
declare parents: Noble implements Allegiance;
```

Once we make such a declaration, we must subsequently define method `declare()`:

```
public void Noble.declare() {
  System.out.println(this.toString() +              + this.house +    );
}
```

The complete aspect definition is shown below:

```
public aspect Behavior {
  declare parents: Noble implements Allegiance;
  public void Noble.declare() {
    System.out.println(this.toString() +              + this.house +    );
  }
  public void Noble.speak() {
    System.out.println(                          + this.toString());
  }
}
```

Consider the following test program:

```
public class Test {
  public static void main(String[] args) {
    Noble Arya = new Noble(             ,        );
    Arya.declare(); }}
```

The output of the program is as follows:

```
I am Arya Stark. Of House Stark.
```

22.10 Context passing

The mechanism of *context passing* allows a pointcut to expose a binding to the underlying object, thus making the object available to any advice that may need to access it. What do we mean by "underlying object"? This would be the object where an event of interest occurs. For example, in the case of a call join point we may be interested in the caller, the callee, or both.

22.10.1 Self and target join points

Self and target join points can capture the caller and receiver of a call. The join point `this` captures the sender object (caller), whereas `target` captures the receiving object (callee). For method executions, both join points capture the executing object.

22.10.2 Introducing instance features II

In this subsection we revisit introductions by combining them with context passing.

Example: Keeping track of moves

Consider the implementation of class `Point`:

```
public class Point {
  protected double x, y;
  public Point(double x, double y) {
    this.x = x;
    this.y = y;
  }
```

```
  public Point() {
    this(0, 0);
  }

  public void move(double x, double y) {
    this.x = x;
    this.y = y;
  }
  public String toString() {
    return        + x +      +        + y;
  }
}
```

We want to keep track of each move of each point object. In other words, we must be able to distinguish between moves per instance. The statement

```
int Point.numberOfMoves;
```

introduces a private integer variable `numberOfMoves` in the class definition of `Point`. This implies that every instance of `Point` will maintain its own unique integer variable `numberOfMoves`. Additionally, we want to obtain the value of this variable. The following definition

```
public int Point.howMany() {
  return this.numberOfMoves;
}
```

introduces a method into class `Point` that will return the value of variable `numberOfMoves`.

We must capture the executing object upon reception of a `move()` message. Once we have the executing object, we can then access its own unique variable `numberOfMoves`. We can capture the receiving object through context passing, as follows:

```
pointcut counts(Point p) : execution(void Point.move(double, double)) &&
                           this(p);
```

It is important to stress that pointcut `counts` performs two different tasks here:

1. It captures execution of method `move()`. This will cause any associate advice to execute.

2. It captures and exposes a binding to the `Point` instance whose `move()` method is about to execute. This will allow any associated advice to obtain access to the particular object.

We define an advice to increment the variable `numberOfMoves` as follows:

```
after(Point p) : counts(p) {
  p.numberOfMoves++;
}
```

We can now put everything together in one aspect definition as follows:

```
public aspect Logger {
  int Point.numberOfMoves;
  public int Point.howMany() {
    return this.numberOfMoves;
  }
  pointcut counts(Point p) : execution(void Point.move(double, double)) &&
                             this(p);
  after(Point p) : counts(p) {
    p.numberOfMoves++; }}
```

Consider the following test program:

```
public class Test {
  public static void main(String[] args) {
    Point p1 = new Point();
    Point p2 = new Point();
    p1.move(3, 7);
```

```
    p1.move(3, 11);
    p2.move(10, 10);
    System.out.println(p1.howMany());
    System.out.println(p2.howMany()); }}
```

The output of the program is as follows:

```
2
1
```

22.10.3 Argument join points

The join point `args(type)` can capture the arguments passed to a method or constructor. We will demonstrate this with an example.

Example: Bounded stack with contract specifications

Consider aspect `ContractChecker` that performs partial contract checking on the creation of `BStack` objects, imposing the requirement that no object can be created with capacity zero. Recall that `capacity` is required by the constructor of the class.

```
public aspect ContractChecker {
  pointcut invariantChecking (int arg) : execution (BStack.new(int)) &&
                                         args(arg);
  before (int arg): invariantChecking(arg) {
    if (arg <= 0) {
      System.out.println(             + arg);
      System.out.println(                    );
      System.exit(0);
    }
  }
}
```

The pointcut that captures the execution of the constructor exposes the argument passed to the constructor, and the `before` advice checks the value of the argument. Should the argument be a non-positive number, then the advice does not allow the execution to proceed but it will instead display some informative message and exit the program.

For example, should we attempt to create an empty capacity object with

```
Stack myStack = new BStack(0);
```

we will get the following output:

```
Capacity: 0
Error: Invalid size.
```

22.10.4 Combining advice precedence and context passing

We will demonstrate how to combine advice precedence and context passing with an example.

Example: Filtering

Consider class `Container` that stores strings.

```
import java.util.ArrayList;
public class Container {
  private ArrayList <String> elements = new ArrayList<String> ();
  private int capacity;
  public Container(int capacity) {
    this.capacity = capacity;
  }
  public void add(String str) {
    this.elements.add(str);
  }
  public String remove(int position) {
    return this.elements.remove(position); }
```

```
  public void clear() {
    this.elements.clear(); }}
```

Aspect `Filter` contains two `around` advices, both of which intercept the call to `Container.add(String)` and act as filters to the string argument. The first `around` advice will transform the argument into lower case and allow the call to proceed. The call will then be intercepted by the second `around` advice that will add a timestamp to the string and allow the call to proceed.

```
import java.util.*;
import java.text.*;
public aspect Filter {
  DateFormat dateFormat = new SimpleDateFormat(                    );
  Date date;
  void around(Container c, String arg): call(* Container.add(String)) &&
                                        target(c) &&
                                        args(arg) {
    String newstr = arg.toLowerCase();
    proceed(c, newstr); }
  void around(Container c, String arg): call(* Container.add(String)) &&
                                        target(c) &&
                                        args(arg) {
    date = new Date();
    String newstr = arg +      + date +    ;
    proceed(c, newstr); }}
```

The test program instantiates a container class and adds a string to it which is a mixture of upper and lower-case characters.

```
public class Test {
  public static void main(String[] args) {
    Container c = new Container(3);
    c.add(              );
    System.out.println(c.remove(0)); }}
```

The output of the program is as follows:

```
hello world [Wed Apr 23 21:14:36 EDT 2014]
```

22.10.5 Advice execution join points

As the name suggests, advice execution join points capture the execution of advice blocks. We will demonstrate this with an example.

Example: Bounded stack with monitoring of advice execution

In the following example, we add yet another aspect to class `BStack` in order to trace the execution of all advices from `Logger` and `ContractChecker`. The pointcut should capture all advice execution and will expose a binding to the underlying aspect instance:

```
pointcut executions (Object o) : adviceexecution() &&
                                 !within(AdviceTracer) &&
                                 this(o);
```

The join point `!within(AdviceTracer)` is required in order to avoid circular references between this pointcut and the advice from within this aspect definition which would result in an infinite loop. The complete aspect definition is as follows:

```
public aspect AdviceTracer {
  pointcut executions (Object o) : adviceexecution() &&
                                   !within(AdviceTracer) &&
                                   this(o);
```

```
  after(Object o): executions(o) {
    System.out.println(                          +
                           thisJoinPoint.getSignature()); }}
```

Consider the following test program and its output below:

```
public class Test {
  public static void main(String[] args) {
    Stack myStack = new BStack(5);
    myStack.push(       );
    myStack.push(       );
    myStack.push(      );
    System.out.println(myStack.pop());
    System.out.println(myStack.pop());
    System.out.println(myStack.pop()); }}
```

```
>Advice executed: void ContractChecker.before(int)
>Mutator method called: call(void Stack.push(String))
>Advice executed: void Logger.before(JoinPoint)
>Mutator method called: call(void Stack.push(String))
>Advice executed: void Logger.before(JoinPoint)
>Mutator method called: call(void Stack.push(String))
>Advice executed: void Logger.before(JoinPoint)
>Mutator method called: call(String Stack.pop())
>Advice executed: void Logger.before(JoinPoint)
all
>Mutator method called: call(String Stack.pop())
>Advice executed: void Logger.before(JoinPoint)
your
>Mutator method called: call(String Stack.pop())
>Advice executed: void Logger.before(JoinPoint)
base
```

22.11 Privileged aspects

AspectJ allows us to get access to private features of a class. We will demonsrate this in relation to introductions and context passing with a few examples.

22.11.1 Combining context passing and privileged aspect behavior

We will demonstrate this with an example.

Example: A binary semaphore protocol

Consider the implementation of class `Semaphore`:

```
public class Semaphore {
  private int value;
  public void increment() {
    this.value++;
  }
  public void decrement() {
    this.value--;
  }
  public int getValue() {
    return this.value;
  }
  public void reset() {
    this.value = 0;
  }
}
```

We want to impose a binary protocol to class `Semaphore`. This means that we initially must monitor methods `increment()` and `decrement()`. The two pointcuts capture the execution of each method respectively and expose a binding to the underlying semaphore object:

```
pointcut monitoringIncs (Semaphore s):
                                    execution(* Semaphore.increment()) &&
                                    this(s);
pointcut monitoringDecs (Semaphore s):
                                    execution(* Semaphore.decrement()) &&
                                    this(s);
```

Each pointcut will be associated with an advice. The advice for `monitoringIncs` executes instead of the code associated with the pointcut and performs a check on the value of the semaphore. If it is already `1`, then the advice will do nothing. If it is not `1`, then the advice will pass execution to the code associated with the pointcut, therefore allowing the increment.

```
void around(Semaphore s): monitoringIncs(s) {
  if (s.value == 1)
    ;
  else
    proceed(s);
}
```

The advice for `monitoringDecs` executes instead of the code associated with the pointcut and performs a check on the value of the semaphore. If it is already `0`, then the advice will do nothing. If it is not `0`, then the advice will pass execution to the code associated with the pointcut, therefore allowing the decrement.

```
void around (Semaphore s): monitoringDecs(s) {
  if (s.value == 0)
    ;
  else
    proceed(s);
}
```

Putting everything together we have the following aspect definition:

```
public privileged aspect BinaryProtocol {
  pointcut monitoringIncs (Semaphore s):
                                  execution(* Semaphore.increment()) &&
                                  this(s);
  pointcut monitoringDecs (Semaphore s):
                                  execution(* Semaphore.decrement()) &&
                                  this(s);
  void around(Semaphore s): monitoringIncs(s) {
    if (s.value == 1)
      ;
    else
      proceed(s);
  }
  void around (Semaphore s): monitoringDecs(s) {
    if (s.value == 0)
      ;
    else
      proceed(s);
  }
}
```

Consider the following test program:

```
public class Test {
  public static void main(String[] args) {
    Semaphore semaphore = new Semaphore();
    semaphore.increment();
    semaphore.increment();
    semaphore.decrement();
    System.out.println(semaphore.getValue()); }}
```

The output of the program is as follows:

```
0
```

22.11.2 Combining introductions, context passing, and privileged aspect behavior

We will use examples to demonstrate how to combine introductions, context passing and privileged aspect behavior.

Example: A cyclic counter protocol

In the first example, consider the definition of class `Counter`:

```
public class Counter {
  private int value;
  void increment() {
    this.value++;
  }
  public int getValue() {
    return value;
  }
}
```

We want to add cyclic behavior to counter objects, i.e. once the value of a counter object reaches some predefined maximum value, the object should reset its value. The maximum value is held by the constant

```
private final int MAX = 10;
```

Initially we define an interface that all cyclic objects must implement:

```
public interface Cyclic {
  public void reset();
}
```

We introduce the interface implementation of class `Counter` together with the implementation of method `reset()`:

```
declare parents: Counter implements Cyclic;

public void Counter.reset() {
  this.value = 0;
}
```

Finally we need to capture all calls to method `increment()` and check if variable `value` has reached `MAX`, in which case we must reset the counter. Otherwise, we allow the call to proceed. Aspect `CyclicProtocol` is declared `privileged` as it would need to obtain access to private variable `value` in class `Counter`.

```
public privileged aspect CyclicProtocol {
  private final int MAX = 10;
  declare parents: Counter implements Cyclic;
  public void Counter.reset() {
    this.value = 0; }
  void around(Counter c): call(* Counter.increment()) && target(c) {
    if (c.value == MAX)
      c.reset();
    proceed(c); }}
```

Consider the following test program:

```
public class Test {
  public static void main(String[] args) {
    Counter c = new Counter();
    for (int i = 0; i < 15; i++) {
      c.increment();
      System.out.print(c.getValue() +    ); }}}
```

The output of the program is as follows:

```
1 2 3 4 5 6 7 8 9 10 1 2 3 4 5
```

Example: A locking semaphore

We will extend the binary semaphore example by adding locking behavior to a semaphore object. Consider interface `Lockable`:

```
public interface Lockable {
  void lock();
  void unlock();
  boolean isLocked();
}
```

The statement

```
declare parents: Semaphore implements Lockable;
```

introduces interface `Lockable` as a supertype to class `Semaphore`. The statement

```
private boolean Semaphore.lock;
```

introduces a private integer variable `lock` as part of the state of class `Semaphore`. The following segment

```
public void Semaphore.lock() {
  this.lock = true;
}
public void Semaphore.unlock() {
  this.lock = false;
}
public boolean Semaphore.isLocked() {
  return this.lock;
}
```

introduces methods `lock()`, `unlock()`, and `isLocked()` as part of the behavior of class `Semaphore`.

To implement the locking mechanism, we need to intercept calls made to `increment()` or `decrement()` and place a condition that they should only be allowed to run provided that the semaphore is not locked. We do this by first defining a pointcut that would capture any of the two calls and once it is captured it will expose a binding to the underlying semaphore object.

```
pointcut monitoringMods (Semaphore s):
                                    (call (* Semaphore.increment()) ||
                                     call (* Semaphore.decrement())) &&
                                     target(s);
```

An `around` advice executes instead of the code associated with the pointcut and performs a check on the status of the semaphore, only allowing the code associated with the pointcut to run provided the semaphore is not locked.

```
void around (Semaphore s): monitoringMods(s) {
  if (s.isLocked() == true)
    System.out.println(                                          );
  else
    proceed(s);
}
```

Putting everything together, we have the aspect definition shown below. As the aspect definition must access private state of the class `Semaphore` (despite the fact that this is state introduced by the aspect itself), it must be declared `privileged`.

```
public privileged aspect Lock {
  declare parents: Semaphore implements Lockable;
  private boolean Semaphore.lock;
  public void Semaphore.lock() {
    this.lock = true; }
```

```
  public void Semaphore.unlock() {
    this.lock = true;
  }
  public boolean Semaphore.isLocked() {
    return this.lock;
  }
  pointcut monitoringMods (Semaphore s):
                                    (call (* Semaphore.increment()) ||
                                     call (* Semaphore.decrement())) &&
                                     target(s);
  void around (Semaphore s): monitoringMods(s) {
    if (s.isLocked() == false)
      System.out.println(                                          );
    else
      proceed(s);
  }
}
```

Consider the following test program:

```
public class Test {
  public static void main(String[] args) {
    Semaphore semaphore = new Semaphore();
    semaphore.increment();
    semaphore.lock();
    semaphore.increment();
    System.out.println(semaphore.getValue());
    semaphore.unlock();
    semaphore.increment();
    semaphore.lock();
    semaphore.decrement();
    semaphore.unlock();
```

```
    semaphore.decrement();
    System.out.println(semaphore.getValue());
  }
}
```

The output of the program is as follows:

```
Error: Cannot set semaphore value.
1
Error: Cannot set semaphore value.
0
```

22.12 Multiple aspects

Example: A cruise control system

Consider the following class definition:

```
public class Vehicle {
  private double speed;
  public void accelerate(double speedIncrement) {
    this.speed = this.speed + speedIncrement;
  }
  public void decelerate(double speedDecrement){
    this.speed = this.speed - speedDecrement;
  }
}
```

We introduce a privileged aspect, `Logger`, that defines pointcut `monitor` to capture executions of method `accelerate` defined in class `Vehicle` and uses context passing to expose a binding to the executing object. An `after` advice displays the value of variable `speed` once the code associated with the pointcut has successfully terminated.

```
public privileged aspect Logger {
  pointcut monitor (Vehicle v): execution (* Vehicle.accelerate(..)) &&
                                this(v);
  after(Vehicle v): monitor(v) {
    System.out.println(                  + v.speed +          );
  }
}
```

A privileged aspect `CruiseController` implements cruise control by imposing a maximum limit on the speed of the vehicle. Pointcut `accelMonitor` captures execution of method `accelerate()` declared in class `Vehicle`, and proceeds to use context passing to expose two bindings: One to the executing object through `this`, and another to the actual argument passed to the method through `args`. An `around` advice initially checks whether the requested increase is within the allowable limit only in that case it will allow the execution to go ahead through `proceed`. Otherwise, the advice will issue an informative error message.

```
public privileged aspect CruiseController {
  private double speedLimit = 100.0;
  pointcut accelMonitor (Vehicle v, double speedInc):
    execution(* Vehicle.accelerate(..)) &&
    this(v) &&
    args(speedInc);
  void around (Vehicle v, double speedIncrement):
                          accelMonitor (v, speedIncrement) {
    System.out.println(                          +
                       speedIncrement +          );
    if ((v.speed + speedIncrement) <= speedLimit)
      proceed(v, speedIncrement);
    else
      System.out.println(                                  );
  }}
```

The test program below instantiates `Vehicle` and attempts to increase its speed in four consecutive intervals of `30`. Once an attempt would make the speed exceeding its maximum allowable value, the `around` advice will not allow it, thus leaving the speed at `90`. The program subsequently attempts to increase the speed by `10`, which is allowed, thus reaching the maximum allowable limit. Any subsequent attempt for an increase will not be allowed.

```
public class Test {
  public static void main(String[] args) {
    Vehicle car = new Vehicle();
    car.accelerate(30);
    car.accelerate(30);
    car.accelerate(30);
    car.accelerate(30);
    car.accelerate(10);
    car.accelerate(10);
  }
}
```

The output of the program is as follows:

```
About to increase by: 30.0 km/h.
Current speed: 30.0 km/h.
About to increase by: 30.0 km/h.
Current speed: 60.0 km/h.
About to increase by: 30.0 km/h.
Current speed: 90.0 km/h.
About to increase by: 30.0 km/h.
Error: Cannot exceed 100 km/h.
Current speed: 90.0 km/h.
About to increase by: 10.0 km/h.
Current speed: 100.0 km/h.
About to increase by: 10.0 km/h.
```

```
Error: Cannot exceed 100 km/h.
Current speed: 100.0 km/h.
```

22.12.1 Combining context passing, privileged aspect behavior and multiple aspects

Example: Access control

Consider the following application:

```
import java.util.ArrayList;
public class Server {
  private String name;
  private ArrayList<Client> clients = new ArrayList<Client>();
  public Server(String name) {
    this.name = name;
  }
  public void establishConnection (Client client) {
    clients.add(client);
  }
  public void breakConnection (Client client) {
    clients.remove(client);
  }
  public String toString() {
    return name;
  }
}
```

```
public class Client {
  private String name;
  private Server server;
  private Boolean authenticated;
  public Client(String name, Server server) {
```

```
    this.name = name;
    this.server = server;
    this.authenticated = false; }
  public void authenticate() {
    authenticated = true;
  }
  public void connect() {
    server.establishConnection(this);
  }
  public String toString() {
    return name;
  }
}
```

Aspect `AccessController` captures messages sent by clients to a server attempting to establish a connection. The aspect only allows a connection if a client is authenticated. If a connection cannot be established, then the aspect should display an informative message. Additionally, aspect `Logger` displays an informative message once a connection is about to be established between client and server.

```
public privileged aspect AccessController {
  declare precedence: AccessController, Logger;
  pointcut accessMonitor (Server server, Client client):
      call(* Server.establishConnection(Client)) &&
      this(client) &&
      target(server);
  void around (Server server, Client client):
                                    accessMonitor (server, client) {
    if (client.authenticated)
      proceed(server, client);
    else
      System.out.println(                          + client.toString() +
```

```
                                                          +       +
                          server.toString() +    ); }}
```

```
public aspect Logger {
  pointcut accessLog (Server server, Client client):
    call(* Server.establishConnection(Client)) &&
    this(client) &&
    target(server);
  before(Server server, Client client): accessLog (server, client) {
    System.out.println(                                    +
                                        client.toString() +
                                                           +
                                        server.toString() +    );
  }
}
```

Consider the following test program:

```
public class Test {
  public static void main(String[] args) {
    Server server = new Server(                    );
    Client c1 = new Client(      , server);
    Client c2 = new Client(      , server);
    c1.authenticate();
    c1.connect();
    c2.connect();
  }
}
```

The output of the program is as follows:

```
Connection established between Jack and Concordia University.
Authentication error: Jill cannot establish a connection to Concordia University.
```

22.13 Reusing pointcuts: Abstract aspects

Even though the adoption of AOP results in a good separation of concerns, restricting aspect definitions to match class and method names of system core concerns leads to strong binding between aspects and system core concerns. In such cases aspect definitions are not reusable, but they are restricted to be only applicable in one specific application context.

To deploy an aspect definition in different contexts, we first need to answer the following questions: "What needs to be reused?" and "What part of an aspect definition can be bound to the core functionality?" An obvious construct which binds an aspect to the core functionality is the (named or anonymous) pointcut.

In order to support reuse, a level of genericity is supported by AspectJ through the provision of *abstract aspects*. We can distinguish between two cases, discussed in the subsequent subsections.

22.13.1 Reusing concrete pointcuts

A concrete pointcut expression can be reused not only by advices within the aspect where it is being defined, but by advices in all *subaspects*. Much like class features, pointcut declarations can be associated with the access modifiers *public* (the declaration can be visible to all aspects anywhere in the application), no modifier (default; this implies that the declaration is visible to all aspects within the same package), *protected* (declaration is visible to host aspect and all its subaspects) and *private* (declaration is visible only to the host aspect). One restriction imposed by AspectJ is that in order to define a subaspect, the *superaspect* must itself be declared abstract (even in the case where the superaspect contains no abstract feature).

22.13.2 Reusing abstract pointcuts

A pointcut can be declared abstract when we do not want to commit to a particular application in the current aspect definition but we prefer to leave the concrete definition in subaspects. This idea allows the development of aspect libraries, as collections of generic

aspect definitions. Much like a concrete subclass which inherits from an abstract superclass must implement all inherited abstract methods or must itself be declared abstract, a subaspect must provide a definition of all abstract pointcuts inherited from an abstract superaspect, otherwise it must itself be declared abstract.

In the following example, we will build an aspect that will implement a generic tracing facility. The abstract aspect `AbstractLogger` does not implement a pointcut, but it does provide a reflection-based tracing facility upon entering and exiting the code to be defined by some concrete pointcut in a subaspect.

```
public abstract aspect AbstractLogger {
  abstract pointcut monitored();
  before(): monitored() {
    System.out.println(               + thisJoinPoint);
  }
  after(): monitored() {
    System.out.println(              + thisJoinPoint);
  }
}
```

Aspect `ConcreteLogger` inherits from `AbstractLogger` and implements the abstract pointcut `monitored()`.

```
public aspect ConcreteLogger extends AbstractLogger {
  pointcut monitored(): execution(void Stack.push(String)) ||
                        execution(String Stack.pop());
}
```

We include the two aspects in the `Stack` project, whose test program is shown below:

```
public class Test {
  public static void main(String[] args) {
    Stack myStack = new Stack();
    myStack.push(      );
    myStack.push(      );
    myStack.push(     );
    System.out.println(myStack.pop());
    System.out.println(myStack.pop());
    System.out.println(myStack.pop());
  }
}
```

The output of the program is as follows:

```
>Entering: execution(void Stack.push(String))
>Exiting: execution(void Stack.push(String))
>Entering: execution(void Stack.push(String))
>Exiting: execution(void Stack.push(String))
>Entering: execution(void Stack.push(String))
>Exiting: execution(void Stack.push(String))
>Entering: execution(String Stack.pop())
>Exiting: execution(String Stack.pop())
all
>Entering: execution(String Stack.pop())
>Exiting: execution(String Stack.pop())
your
>Entering: execution(String Stack.pop())
>Exiting: execution(String Stack.pop())
base
```

22.14 In retrospect: Final words by E. W. Dijkstra

> *"The purpose of thinking is to reduce the detailed reasoning needed to a doable amount, and a separation of concerns is the way we hope to achieve this reduction. The crucial choice is, of course, what aspects to study in isolation, how to disentangle the original amorphous knot of obligations, constraints and goals into a set of concerns that admit a reasonably effective separation. The knowledge of the goal of separation of concerns is a useful one: we are at least beginning to understand what we are aiming at."*
>
> (E. W. Dijkstra, A Discipline of Programming, 1976, last chapter, In Retrospect)

22.15 The `thisJoinPoint` API

A partial method summary of the `thisJoinPoint` interface is shown in this section for both the call to `Server.connect(..)` and its execution, for the program shown below. A complete summary is provided by the language specification[4].

```
public class Client {
  String name;
  Server server;
  public Client(String name, Server server) {
    this.name = name;
    this.server = server;
  }
  public void openConnection() {
    server.connect(this);
  }
}
```

[4] See `http://eclipse.org/aspectj/doc/next/runtime-api/org/aspectj/lang/JoinPoint.html`

```
import java.util.ArrayList;
public class Server {
  private String name;
  private ArrayList<Client> clients = new ArrayList<Client>();
  public Server(String name) {
    this.name = name;
  }
  public void connect(Client client) {
    clients.add(client);
  }
}
```

```
public class Test {
  public static void main(String[] args) {
    Server host = new Server(      );
    Client client = new Client(        , host);
    client.openConnection();
  }
}
```

22.15.1 thisJoinPoint on call(* Server.connect(..))

thisJoinPoint	call(void Server.connect(Client))
thisJoinPoint.getKind()	method-call
thisJoinPoint.toString()	call(void Server.connect(Client))
thisJoinPoint.toShortString()	call(Server.connect(..))
thisJoinPoint.toLongString()	call(public void Server.connect(Client))
thisJoinPoint.getArgs()	[Ljava.lang.Object;@1f38fc6
thisJoinPoint.hashCode()	23342038
thisJoinPoint.getSourceLocation()	Client.java:10
thisJoinPoint.getStaticPart()	call(void Server.connect(Client))
thisJoinPoint.getSignature()	void Server.connect(Client)

```
thisJoinPoint.getSignature().getName()   connect
thisJoinPoint.getSignature().getDeclaringTypeName()  Server
thisJoinPoint.getSignature().getClass()
                            class org.aspectj.runtime.reflect.MethodSignatureImpl
thisJoinPoint.getSignature().toLongString()
                                         public void Server.connect(Client)
thisJoinPoint.getSignature().toShortString()
                                         Server.connect(..)
thisJoinPoint.getSignature().hashCode()  24769387
thisJoinPoint.getThis()                  Client@15bfdbd
thisJoinPoint.getThis().hashCode()       22805949
thisJoinPoint.getThis().toString()       Client@15bfdbd
thisJoinPoint.getThis().getClass()       class Client
thisJoinPoint.getThis().getClass().getName()  Client
thisJoinPoint.getTarget()                Server@6f8b2b
thisJoinPoint.getTarget().hashCode()     7310123
thisJoinPoint.getTarget().toString()     Server@6f8b2b
thisJoinPoint.getTarget().getClass()     class Server
thisJoinPoint.getTarget().getClass().getName()  Server
```

22.15.2 thisJoinPoint on execution(* Server.connect(..))

```
thisJoinPoint                            execution(void Server.connect(Client))
thisJoinPoint.getKind()                  method-execution
thisJoinPoint.toString()                 execution(void Server.connect(Client))
thisJoinPoint.toShortString()            execution(Server.connect(..))
thisJoinPoint.toLongString()
                                  execution(public void Server.connect(Client))
thisJoinPoint.getArgs()                  [Ljava.lang.Object;@1f38fc6
thisJoinPoint.hashCode()                 23342038
thisJoinPoint.getSourceLocation()        Server.java:8
thisJoinPoint.getStaticPart()            execution(void Server.connect(Client))
```

```
thisJoinPoint.getSignature()              void Server.connect(Client)
thisJoinPoint.getSignature().getName()    connect
thisJoinPoint.getSignature().getDeclaringTypeName()  Server
thisJoinPoint.getSignature().getClass()
                          class org.aspectj.runtime.reflect.MethodSignatureImpl
thisJoinPoint.getSignature().toLongString()  public void Server.connect(Client)
thisJoinPoint.getSignature().toShortString()  Server.connect(..)
thisJoinPoint.getSignature().hashCode()  24769387
thisJoinPoint.getThis()                   Server@15bfdbd
thisJoinPoint.getThis().hashCode()        22805949
thisJoinPoint.getThis().toString()        Server@15bfdbd
thisJoinPoint.getThis().getClass()        class Server
thisJoinPoint.getThis().getClass().getName()  Server
thisJoinPoint.getTarget()                 Server@15bfdbd
thisJoinPoint.getTarget().hashCode()      22805949
thisJoinPoint.getTarget().toString()      Server@15bfdbd
thisJoinPoint.getTarget().getClass()      class Server
thisJoinPoint.getTarget().getClass().getName()  Server
```

Part VI

Multiparadigm Programming with Ruby

Chapter 23

Object-oriented programming with message passing II

In Computer Science, imperative programming is a programming paradigm that describes computation in terms of statements that change a program state. The term *pure object-oriented programming* implies that all of the data types in the language are objects and all operations on those objects can be invoked by message passing. Sending a message to an object invokes a method by the receiver object. A message contains the method's name along with any parameters. In this chapter we will adopt the Ruby language.

```
puts                        .length  #=> 17
puts        .index(    )             #=> 3
puts -7.abs                          #=> 7
puts 10.49.round                     #=> 10
puts 10.51.round                     #=> 11
puts 2.next                          #=> 3
puts 97.chr                          #=> "a"
```

23.1 Variables and aliasing

Multiple variables referencing the same object is called *aliasing*. Consider the following example:

```
person1 =
person2 = person1
```

The assignment of `person1` to `person2` does not create an object. It assigns the object reference of `person1` to `person2`, so that both variables now would refer to the same object.

We can avoid aliasing with `dup`, which creates a new object with identical contents.

```
person3 = person1.dup
person1[0] =
puts person1 #=> Rony
puts person2 #=> Rony
puts person3 #=> Tony
```

23.2 Chain and parallel assignment statements

An assignment statement sets the value of a variable on its left hand side (*lvalue*) to the value of the expression on its right hand side (*rvalue*).

Ruby supports chaining of assignments. It also allows one to perform assignments in some unexpected places. Consider the example below:

```
a = b = 1 + 2 + 3
puts a #=> 6
puts b #=> 6
a = (b = 1 + 2) + 3
puts a #=> 6
puts b #=> 3
```

Ruby supports parallel assignment:

```
a = 1
b = 2
a, b = b, a
puts a #=> 2
```

```
puts b #=> 1
x = 0
a, b, c = x, (x += 1), (x += 1)
puts a #=> 0
puts b #=> 1
puts c #=> 2
puts x #=> 2
```

23.3 Arrays

An array is an ordered collection of elements, where each element is identified by an integer index.

We can create arrays using literals. A literal array is simply a list of objects between square brackets. As everything is an object, this implies that an array can hold objects of different types, as in the example below:

```
a = [          , 1, 2, 3.14 ] # Array with four elements.
puts a[0]       # Access and display the first element. #=> number
a[3] = nil      # Set the last element to nil.
puts a          # Access and display entire array. #=> number 1 2 nil
```

We can also create an array by explicitly creating an Array object. Ruby allows us to specify array ranges, as in the example below:

```
myarray = [ 1, 2, 3, 4, 5, 6 ]
puts myarray[0]       #=> 1
puts myarray[1...3]   # Exclusive range. => 2 3.
puts myarray[1..3]    # Inclusive range. => 2 3 4.
puts myarray[1,3]     # Range between 1st up to 3rd consecutive, inclusive.
                      #=> 2 3 4.
```

Ruby allows a negative index, forcing the array to count from the end.

```
a = [      , 3.14,          , 17 ]
```

```
puts a.class                    #=> Array
puts a.length                   #=> 4
puts a[0]                       #=> pi
puts a[-1]                      #=> 17
puts a[1]                       #=> 3.14
puts a[2]                       #=> prime
puts a[3]                       #=> 17
puts a[4]                       #=> nil
b = Array.new
puts b.class                    #=> Array
puts b.length                   #=> 0
b[0] =
b[1] =
b[2] =
puts b                          #=> a new array
```

23.4 Associative arrays

An *associative array* (or *hash*) is an unordered collection of elements.

An element is a pair of two objects: a *value* and a *key* through which the value can be retrieved. The value can be an object of any type.

To store an element in an associative array, we must supply both objects:

$$hashName = \{ \text{"}key\text{"} \texttt{ => } \text{"}value\text{"},$$
$$\ldots$$
$$\}$$

We can subsequently retrieve the value by supplying the appropriate key:

$$hashName[\text{"}key\text{"}] \texttt{ => } value$$

Example 23.1. Consider the example below which builds and manipulates an associative array.

```
biblio = {                =>        ,
                          =>                  ,
                          =>                   ,
                          =>              ,
                          =>            }
```

We can inquire the collection for its size:

```
puts biblio.length          #=> 5
```

We can access the collection to obtain the value associated with a given key:

```
puts biblio[              ] #=> The master and margarita
```

We can also access the collection in order to modify the value associated with a given key:

```
biblio[             ] =
puts biblio[              ] #=> Lolita
```

We can also add to the collection:

```
biblio[              ] =
puts biblio[               ] #=> Beyond good and evil
puts biblio.length          #=> 6
```

We can delete an element from the collection by supplying the appropriate key:

```
biblio.delete_if {|key, value| key ==          }
puts biblio.length          #=> 5
```

Iterating over an associative array

One of the strengths (and perhaps weaknesses) of Ruby is that it allows us to do the same thing using different ways. We can iterate over the entire collection in a couple of different

ways. In the next example we display all key-value pairs:

```
biblio.each_pair do |key, value|
  puts
end
```

The above will display:

```
nabokov90 : The defense
nietzsche97 : Beyond good and evil
nabokov89a : Lolita
nabokov89b : Invitation to a Beheading
bulgakov96 : The master and margarita
```

We can perform the above iteration as follows:

```
biblio.each do |key, value|
  puts
end
```

There is yet another way to do that:

```
biblio.each {|key, value| puts key +       + value}
```

We can iterate over the collection and access and display each key individually:

```
biblio.each_key {|key| puts key}
```

The above will display:

```
nabokov90
nietzsche97
nabokov89a
nabokov89b
bulgakov96
```

23.5 Classes

We already have seen that a class specifies state and behavior.

What's in a name?

Ruby uses a convention to help it distinguish the usage of a name: the first characters of a name indicate how the name is used. Class names, module names, and constants should start with an uppercase letter. Class variables start with two "at" signs (`@@`). Local variables, method parameters, and method names should all start with a lowercase letter or with an underscore (_). Global variables are prefixed with a dollar sign ($), while instance variables begin with a single "at" sign. Consider the following examples:

```
local_variable
CONSTANT_NAME / ConstantName / Constant_Name
:symbol_name
@instance_variable
@@class_variable
$global_variable
ClassName
method_name
ModuleName
```

23.6 Objects

Instances of classes (objects) contain state and behavior. Each object contains its own unique state. Behavior on the other hand is shared among objects. The state of the object is composed of a set of attributes (or fields), and their current values.

Example 23.2. Consider class `Coordinate` which defines a two-dimensional coordinate.

```
class Coordinate
  @@total = 0
  def initialize (x, y)
    @@total += 1
    @x = x
    @y = y
  end
```

```
  def setx (x)
   @x = x
  end
  def sety (y)
    @y = y
  end
  def getx
    @x
  end
  def gety
   @y
  end
  def to_s
    return
  end
  def Coordinate.total
    return
  end
end
```

- The `class` keyword defines a class.
- By defining a method inside this class, we are associating it with this class.
- The `initialize` method is what actually constructs the data structure. Every class must contain an initialize method.
- `@x` and `@y` are instance (object) variables.
- `puts` and `print` write each of their arguments. `puts` adds a new line, whereas `print` does not add a new line.

A class can be instantiated with `new` as in

```
p1 = Coordinate.new(0, 0)
```

which defines an instance `p1` whose coordinates are $(0, 0)$. We can now interact with object `p1`:

```
puts p1.to_s           #=> (0, 0)
p1.setx(2)
puts p1.getx           #=> 2
p1.sety(3)
puts p1.gety           #=> 3
puts p1.to_s           #=> (2, 3)
p2 = Coordinate.new(1, 1)
puts Coordinate.total  #=> Number of coordinates: 2
```

The following is a refined version of class `Coordinate`:

```
class Coordinate
  attr_accessor :x, :y
  @@total = 0
  def initialize (x, y)
    @@total += 1
    @x = x
    @y = y
  end
  def to_s
     return
  end
  def Coordinate.total
    return
  end
end
```

Let us instantiate class `Coordinate` and interact with an object:

```
p1 = Coordinate.new(0,0)
puts p1.to_s       #=> (0, 0)
p1.x = 2
puts p1.x          #=> 2
p1.y = 3
puts p1.y          #=> 3
puts p1.to_s       #=> (2, 3)
```

23.7 Inheritance

Example 23.3. Consider class `XYZCoordinate` which defines a three-dimensional coordinate.

```
require
class XYZCoordinate < Coordinate
  attr_accessor :z
  @@newtotal = 0
  def initialize (x, y, z)
    super(x, y)
    @z = z
    @@newtotal += 1
  end
  def to_s
    return
  end
  def XYZCoordinate.total
    return
  end
end
```

Let us instantiate class `XYZCoordinate` and interact with its objects:

```
p1 = XYZCoordinate.new(0,0,0)
puts p1.to_s                  #=> (0, 0, 0)
p2 = XYZCoordinate.new(1,5,5)
puts p2.to_s                  #=> (1, 5, 5)
puts XYZCoordinate.total      #=> Number of 3D-coordinates: 2
```

Why have we provided a new class variable, `newtotal`, in the subclass? Ruby does not support hiding and it would not have considered variable `total` in class `XYZCoordinate` as a new variable. As a result, the output on the last statement above would have been 4, not 2.

23.8 Object extensions

Ruby allows us to extend specific instances with new behavior. Consider the example below:

```
def p1.whatIam
  return
end


puts p1.whatIam #=> The origin on the 3D system.
puts p2.whatIam #=> Will cause an error.
```

23.9 Control flow

Ruby provides a rich set of control flow constructs to support *selection* and *repetition*.

23.9.1 Single selection

Consider the sentence "If you are a Computer Science student, then you must take this course." In other words, an action must be taken provided a certain condition holds. To support selection, the `if` statement is perhaps the simplest and it comes in three variations.

Initially to support single selection with the optional alternative to execute a statement if the condition evaluates to false.

```
if boolean-expression [then]
  body
[else
  body]
end
```

The `if` statement also works as a statement modifier which evaluates expression if boolean-expression is true.

```
expression if boolean-expression
```

Finally, the `if` statement can be used as a ternary operator:

```
boolean-expression ? expression1 : expression2
```

which returns $expression_1$ if *booleanExpression* is true and $expression_2$ otherwise.

Consider the sentence: "You must take this course, *unless* you have already taken an equivalent one." In other words, you have to take an action only if a certain condition does *not* hold. The term *unless* works as a negated *if*. In Ruby, a negated form of the `if` statement is also available:

```
unless boolean-expression [then]
  body
[else
  body]
end
```

The `unless` statement can also work as a statement modifier:

```
expression unless boolean-expression
```

which evaluates `expression` only if `boolean-expression` is false.

23.9.2 Multiple selection

To support *multiple selection*, we can use an extended version of the `if` statement:

```
if boolean-expression [then]
  body
elsif boolean-expression [then]
  body
[else
  body]
end
```

We can also use the `case` statement. When a comparison returns *true*, the search stops and the body associated with the comparison is executed. The statement then returns the value of the last expression executed. If no comparison matches and an `else` clause is present, its body will be executed; otherwise, the statement returns `nil`.

```
case target
  when comparison [, comparison ] ... [then]
    body
  when comparison [, comparison ] ... [then]
    body
  [else
    body]
end
```

Example 23.4. Consider the following code segment that deploys multiple selection with the `case` statement:

```
number = 11
case number
  when 1, 3, 5, 7, 9
    puts
  when 0, 2, 4, 6, 8, 10
```

```
    puts
  else
    puts
end
```

23.9.3 Repetition

The `while` loop executes its body zero or more times as long as its condition is true.

```
while boolean-expression [do]
  body
end
```

The `while` loop can also operate as a statement modifier:

```
expression while boolean-expression
```

There is also a negated form that executes the body as long as `boolean-expression` is false (or until the boolean-expression becomes true):

```
until boolean-expression [do]
  body
end
```

The `while` can also work as a statement modifier:

```
expression until boolean-expression
```

Ruby also provides the `do` statement:

```
loop do
  body
  next if boolean-expression  # skip iteration
  break if boolean-expression # exit loop
  redo if boolean-expression  # do it again
end
```

Iterators

The keyword `each` returns successive elements of its collection

```
a = [        ,          ,       ]
a.each { |el| print el +      }                    #=> 3.14 number pi
```

The keyword `collect` takes each element from a collection and passes it to a block. The code below takes each element from the collection and displays its successor.

```
print [    ,     ,     ].collect { |x| x.succ }       #=> IBM
```

The keyword `find` returns the first element from a collection which meets a condition. Otherwise it returns nil. The code below displays the first even number from a collection.

```
print [1, 3, 7, 8, 9, 10].find { |x| x % 2 == 0 } #=> 8
```

Iterator-based loops

```
3.times { |count| puts count}                 #=> 0 1 2

1.upto(10) { |count| puts count }             #=> 1 2 3 4 5 6 7 8 9 10

10.downto(1) { |count| puts count }           #=> 10 9 8 7 6 5 4 3 2 1

0.step(10,2) { |count| puts count }           #=> 0 2 4 6 8 10

for element in [    ,     ,     ]
  puts element                                #=> a b c
end
```

23.10 Regular expressions

A regular expression is a way of specifying a pattern of characters to be matched in a string. In Ruby this is done with `/pattern/`. In Ruby, regular expressions are objects and can thus be manipulated as such. Some common pattern descriptions are shown below:

PATTERN	DESCRIPTION
`/Lisp|Lava/`	Matches a string containing *Lisp*, or *Lava*.
`/L(isp|ava)/`	As above.
`/ab+c/`	Matches a string containing an *a*, followed by one or more *b*s, followed by a *c*.
`/ab*c/`	matches a string containing an *a*, followed by zero or more *b*s, followed by a *c*.
`.`	Matches any character.
`/[Colloqui[um|a]/`	Matches *Colloquium*, or *Colloquia*.

Example 23.5. Consider the lyrics of the song "Welcome to the machine", by Pink Floyd (Lyrics by Roger Waters, 1975).

Welcome my son, welcome to the machine.
Where have you been?
It's alright we know where you've been.
You've been in the pipeline, filling in time,
Provided with toys and 'Scouting for Boys'.
You bought a guitar to punish your ma,
And you didn't like school, and you
know you're nobody's fool,
So welcome to the machine.

Welcome my son, welcome to the machine.
What did you dream?
It's alright we told you what to dream.
You dreamed of a big star,
He played a mean guitar,
He always ate in the Steak Bar.
He loved to drive in his Jaguar.
So welcome to the Machine.

In this example we are looking to extract and display lines which contain the word "punish."

```
File.open(                                    ).each { |line|
    puts line if line =~ /punish/
}
```

This will display: `You bought a guitar to punish your ma,`

23.11 Access control

We can define access rights for features as follows:

Public methods can be called by anyone. Methods are public by default (except for `initialize`, which is always private, see below).

Protected methods can be invoked only by objects of the defining class and its subclasses.

Private methods can be called only in the defining class.

We can specify access control as follows:

```
class MyClass
  def method1    # default is 'public'
    ...
  end
  protected      # subsequent methods will be protected'
  def method2
    ...
  end
  private        # subsequent methods will be 'private'
  def method3
    ...
  end
```

```
  public          # subsequent methods will be 'public'
  def method4
    ...
  end
end
```

Alternatively we can specify access control as follows:

```
class MyClass
  def method1
    ...
  end
  ...
  public :method1, :method4
  protected :method2
  private :method3
end
```

Example 23.6. Consider the following computation:

```
m1 = Movie.new(                ,         )
m2= Movie.new(                    ,         )
m3= Movie.new(                                  ,         )
a = [m1, m2, m3]
puts a.class
puts a.length
puts a[0].to_s
ObjectSpace.each_object(Movie) {|x| puts x.to_s}
puts Movie.total
```

The computation produces the following output:

```
Array
3
Movie: Taxi driver (1976)
```

```
Movie: Once upon a time in America (1984)
Movie: The Deer Hunter (1978)
Movie: Taxi driver (1976)
Number of movies: 3
```

Let us provide a definition of class `Movie`:

```
class Movie
 @@howMany = 0
 def initialize(title, year)
  @title  = title
  @year   = year
  @@howMany += 1
 end
 def Movie.total
  return
 end
 def to_s
  return            + @title +      + @year +
 end
end
```

23.12 The interactive Ruby shell

You can invoke the interactive Ruby shell (irb), shown in Figure 23.1, from the command prompt of the underlying operating system (here: Windows 7). Among other things, irb allows you to enter arithmetic-, relational- or logical expressions.

You can also use the irb to try out snippets of code (see Figure 23.2).

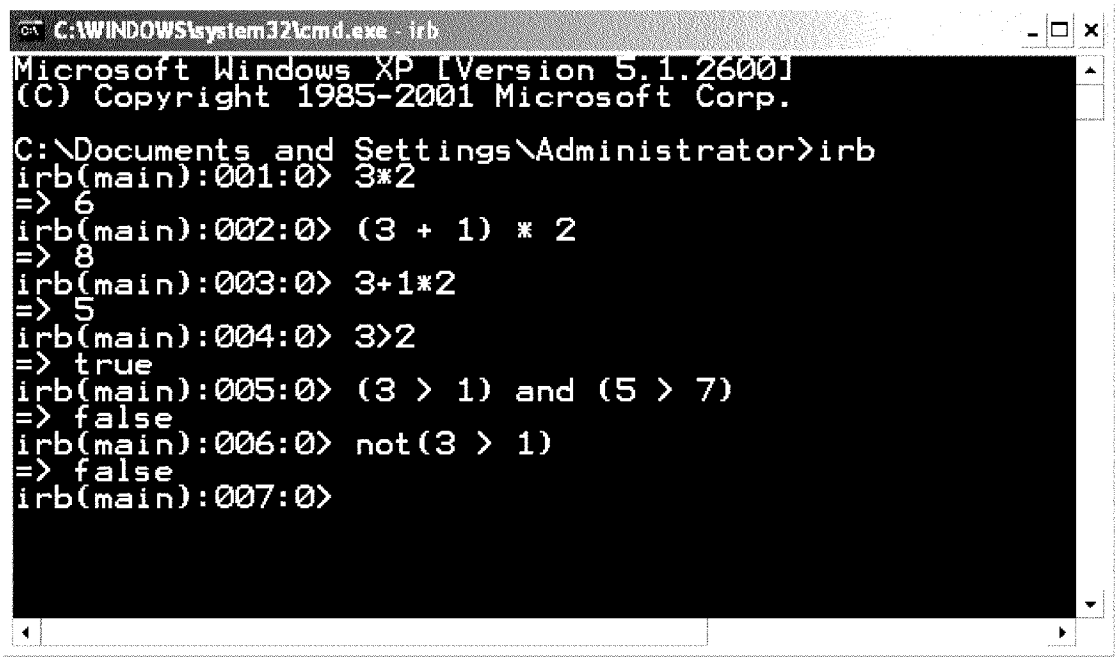

Figure 23.1: The interactive Ruby shell (1).

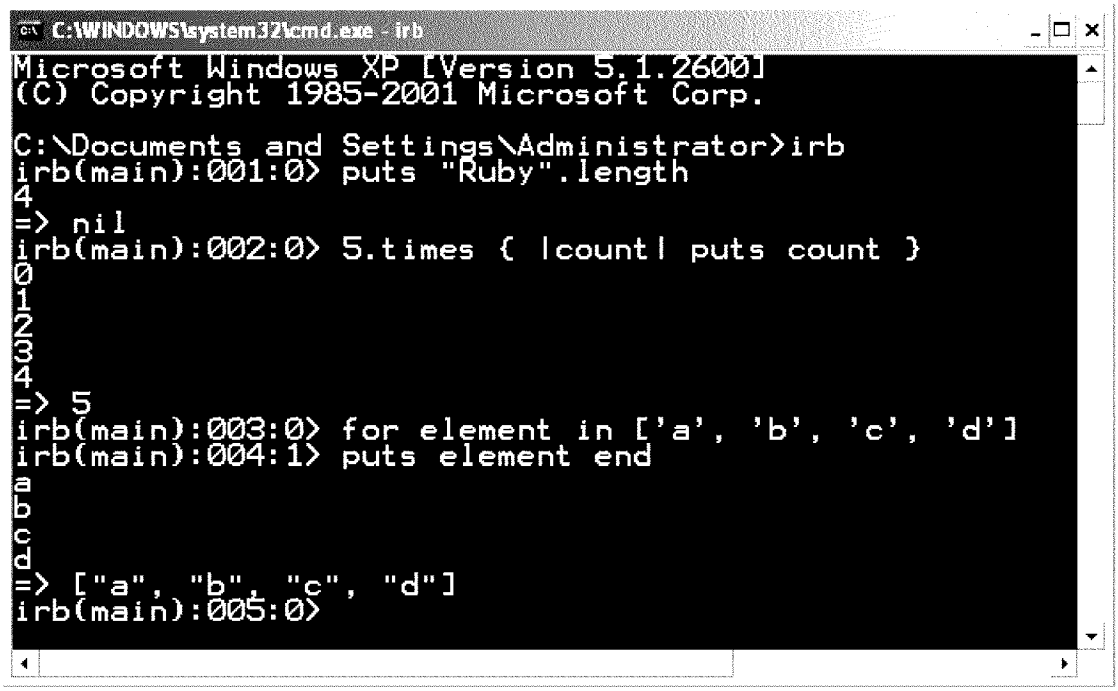

Figure 23.2: The interactive Ruby shell (2).

Chapter 24

Modules

In OOP, the class provides the predominant unit of modularization. Some languages, including Ruby, further support modules. A module in Ruby can encapsulate constants and methods. A module cannot be instantiated and cannot form part of any inheritance hierarchy (i.e. cannot inherit and cannot be subclassified.)

24.1 Modules as namespaces

Example 24.1. Consider module `MathLibrary` which encapsulates mathematical operations for all clients.

```
module MathLibrary
  PI = 3.14159265
  def MathLibrary.factorial(n)
    if n == 0
      1
    else
      n * factorial(n-1)
    end
  end
end
```

We can use the module as follows:

```
puts MathLibrary::PI              #=> 3.14159265
puts MathLibrary.factorial(5)     #=> 120
```

The Math module in Ruby's standard library provides a rich set of methods. As one example:

```
puts Math.sqrt(9)                 #=> 3.0
```

If a class would make heavy usage of a module, then a class can include this module in its definition. This would simplify the calls to the modules functionality as it would not require the module's name as a prefix:

```
include Math
puts sqrt(9)                      #=> 3.0
```

24.2 Modules as mixins

Though Ruby does not support multiple inheritance, classes can import modules as *mixins*. In object-oriented programming languages, a mixin is a class that provides a certain functionality to be inherited by a subclass, but is not meant to be instantiated[1]. Unlike with inheritance, a class cannot claim an `is-a` relationship with a mixin module. Ruby resolves name collision based on the lexical ordering of the inclusion of a module. The last module to be included hides all previous possible name collisions.

In general, mixins are useful for encapsulating behavior that is common to many objects in the class hierarchy, but cannot be factored into a common superclass.

[1]In 1973 Steve Herrell, owner of Steve's ice-cream parlor in Somerville, Massachusetts, began blending his customers' choice of cookie and/or candy morsels into his ice cream and called the item a "mix-in", a copyrighted trademark he sold with the store in 1977.

Example 24.2. Consider class `Coordinate` which includes module `Debugger` which provides a reflective operation.

```
module Debugger
  def reflect


  end
end
```

```
class Coordinate
  include Debugger
  attr_accessor :x, :y
  def initialize (x, y)
    @x = x
    @y = y
  end
  def to_s
     return
  end
end
```

```
p1 = Coordinate.new(0,0)
p2 = Coordinate.new(1,1)
puts p1.reflect          #=> Coordinate (#21114270): (0, 0)
puts p2.reflect          #=> Coordinate (#21114120): (1, 1)
```

Example 24.3. Consider class `DBase` which includes module `Authenticator` which provides an authentication facility.

```
module Authenticator
  def authenticate(passwd)
    if (passwd ==       ) then
      return
    else
```

```
      return
    end
  end
end
```

```
require
class DBase
  include Authenticator
  # ...
end
```

```
db = DBase.new
puts db.authenticate(    ) #=> false
```

24.3 Additional examples

Example 24.4. Describe the axes of decomposition provided by Ruby, and compare and contrast with those of Java.

1. Java provides the notion of class as the primary decomposition axis. Additionally it provides an interface. Ruby's primary decomposition axis is the class and additionally it provides a module.

2. Java's classes can be abstract. Ruby's classes cannot be abstract.

3. Interfaces are a mechanism to reuse specification only; Modules are a way to reuse implementation only.

Example 24.5. In the context of Ruby, compare *delegation* to *module inclusion* in terms of the notion of class interfaces.

With module inclusion, methods defined in modules become part of the interface of classes (and all their subclasses). This is not the case with delegation.

Example 24.6. Briefly provide some rationale for the support of mixins in a language such as Ruby. Is such a construct superfluous?

Mixins are useful for encapsulating behavior that is common to many objects in the class hierarchy, but cannot be factored into a common superclass.

Chapter 25

Introspection

Introspection is the process by which of a program can observe (but not modify) its own properties, including its structure and behavior. A related term, *reflection*, is the process by which a program can observe as well as modify its own properties, including its structure and behavior. In Ruby, we can obtain the following type of knowledge about a program:

- What objects it contains.
- The contents and behaviors of objects.
- The current class hierarchy.

Consider the instantiations below:

```
require
require
p1 = Coordinate.new(0, 0)
p2 = XYZCoordinate.new(0,0,0)
def p2.whatIam
  return
end
```

We can execute a number of different types of reflective queries, discussed in the subsequent sections, to obtain knowledge about the system.

25.1 What objects does the system contain?

We can iterate over all instances of `Coordinate` in the system, posing a reflective query about each one. Let us inspect the system for objects of type `Coordinate`:

```
ObjectSpace.each_object(Coordinate) { |p|
  puts p.inspect
}
```

We obtain the following:

```
#<XYZCoordinate:0x28455d8 @y=0, @z=0, @x=0>
#<Coordinate:0x2846028 @y=0, @x=0>
```

Note that an instance of `XYZCoordinate` is_a `Coordinate`, hence the listing of `p2` in the output.

25.2 Contents and behaviors of objects

We can check whether or not a particular object may respond to a message:

```
puts p1.respond_to?(       )        #=> false
puts p2.respond_to?(          )     #=> true
```

We can also determine the class and unique id of objects, and test their relationship to classes:

```
puts p1.id                          #=> 21113660
puts p1.class                       #=> Coordinate
puts p2.class                       #=> XYZCoordinate
puts p2.instance_variables          #=> @y @z @x
puts p2.kind_of? Coordinate         #=> true
puts p2.kind_of? XYZCoordinate      #=> true
puts p1.kind_of? XYZCoordinate      #=> false
puts p2.instance_of? Coordinate     #=> false
puts p2.instance_of? XYZCoordinate  #=> true
```

25.3 The current class hierarchy

We can inquire about the superclass of a given class:

```
puts XYZCoordinate.superclass       #=> Coordinate
```

We can also inquire about class features:

```
puts XYZCoordinate.private_instance_methods #=>
puts XYZCoordinate.public_instance_methods  #=>
puts XYZCoordinate.class_variables          #=> @@total
```

Part VII

Functional Object-Oriented Programming with Common Lisp Object System (CLOS)

Chapter 26

Object-oriented programming with generic functions

26.1 Classes and objects

We will model classes with CLOS (Common LISP Object System), an object-oriented extension to the LISP language. Consider the CLOS definition of class `semaphore`.

```
(defclass semaphore ()
  ((count :accessor semaphore-count
          :initform 0)
   (name  :reader semaphore-name
          :initarg :name)))
```

All instances of a class have the same structure. This structure is in the form of *slots*. A slot has a name and a value. A value describes the slot's *state* at a given time. This state information can be read and written by accessor methods. CLOS offers two kinds of slots: *local slots* and *shared slots*. Even though all instances of the same class have the same structure, each instance, maintains its own unique state.

We can create an instance of `semaphore` by

```
> (setf s (make-instance 'semaphore))
```

```
#<SEMAPHORE 200D0E93>
```

The `:initform` slot option makes it possible to specify a default value for a slot.

The `:initarg :name` slot option makes it possible to initialize the value of this slot when creating instances. We can, therefore, specify an alternative instantiation for class `semaphore` by providing an argument for the value of slot `name` as

```
> (setf s (make-instance 'semaphore :name 'my-resource))
#<SEMAPHORE 200FEAEF>
```

We can encapsulate the call to `make-instance` in a constructor function to instantiate the class semaphore as follows:

```
(defun make-semaphore(name)
  (make-instance 'semaphore :name name))
```

Now we can instantiate the class as

```
>  (setf s (make-semaphore 'my-resource))
#<SEMAPHORE 20093193>
```

The `:accessor` slot option generates two methods: one for a reader and one for a writer. The term *accessor generic function* is an umbrella term that includes both readers and writers. We can set a new value for the slot `count` as

```
> (setf (semaphore-count s) 1)
1
```

We can read the value of `count` as

```
> (semaphore-count s)
1
```

The `:reader` slot option generates a method for a *reader generic function* only.

```
> (semaphore-name s)
MY-RESOURCE
```

We can provide methods to increment and decrement the value of slot `count` as follows:

```
(defmethod increment ((sem semaphore))
  (setf (semaphore-count sem) (+ 1 (semaphore-count sem))))
(defmethod decrement ((sem semaphore))
  (setf (semaphore-count sem) (- (semaphore-count sem) 1)))
```

```
> (increment s)
1
> (increment s)
2
> (decrement s)
1
```

The complete class definition now looks as follows

```
(defclass semaphore ()
  ((count :accessor semaphore-count
          :initform 0)
   (name  :reader semaphore-name
          :initarg :name)))
(defun make-semaphore(name)
  (make-instance 'semaphore :name name))
(defmethod increment ((sem semaphore))
  (setf (semaphore-count sem) (+ 1 (semaphore-count sem))))
(defmethod decrement ((sem semaphore))
  (setf (semaphore-count sem) (- (semaphore-count sem) 1)))
```

We observe that methods are not encapsulated inside classes, but they are instead defined separately from classes.

26.1.1 Generic functions and methods

A few things are important to note in CLOS: Initially, we see that unlike in message passing systems (like e.g. Java), methods are defined outside of classes. Additionally, all methods that have the same name constitute a *generic function*. In CLOS, a generic function is composed by a number of methods using `defmethod`. Each method provides an implementation of the generic function for a particular class of argument. For example, in

```
(defmethod increment ((sem semaphore))...)
```

the required parameter to method `increment` is specialized by being replaced by a two-element list, the first element being the name of the parameter (`sem`) and the second element (class `semaphore`) being the *specializer*. If a method does not belong to a class definition, where does it belong to? A method belongs to the generic function that is responsible for determining which method to run in response to an invocation.

26.1.2 Auxiliary methods

Regular methods (or *primary methods*) can be augmented by *auxiliary methods* of three kinds:

1. `:before` methods allow us to say "When a primary method is called, before running the code that should run, execute the code of this auxiliary method."

2. `:after` methods allow us to say "When a primary method is called, after running the code that should run, execute the code of this auxiliary method."

3. `:around` methods are called instead of the primary methods. They allow us to say "When a primary method is called, instead of running the code that should run, execute the code of this auxiliary method." An around-method may also choose to invoke its primary method via `call-next-method`.

Example 26.1. In this example we will subclassify `semaphore` to define class `binary-semaphore`.

```
(defclass binary-semaphore (semaphore)() )
(defun make-binary-semaphore(name)
```

```
  (make-instance 'binary-semaphore :name name))
(defmethod increment :around ((binsem binary-semaphore))
 (if (= (semaphore-count binsem) 1)
  nil
  (call-next-method)))
(defmethod decrement :around ((binsem binary-semaphore))
 (if (= (semaphore-count binsem) 0)
  nil
  (call-next-method)))
```

We can instantiate and interact with a binary semaphore object as follows:

```
> (setf bsem (make-binary-semaphore 'my-binary-resource))
#<BINARY-SEMAPHORE 200B8847>
> (increment bsem)
1
> (increment bsem)
NIL
> (semaphore-count bsem)
1
> (decrement bsem)
0
> (decrement bsem)
NIL
> (semaphore-count bsem)
0
```

Example 26.2. Consider the following interaction with an object which acts as an unbounded collection of elements:

```
> (setq c (make-instance 'collection))
#<COLLECTION 200A4347>
```

```
> (insert '(a b) c)
> (insert '(a b) c)
"error: duplicate element."
> (insert '(c d) c)
> (erase '(d e) c)
"error: element does not exist."
> (erase '(c d) c)
> (display c)
((A B))
> (erase '(a b) c)
> (erase '(a b) c)
"error: list empty."
```

The structure of class `collection` is shown below with incomplete definitions of the functions.

```
(defclass collection ()
  ((els  :accessor elements
         :initarg :els
         :initform '())))
;; returns contents of the entire collection c.
(defmethod display ((c collection)) ...)
;; inserts an element el into a collection c.
;; imposes a restriction that el does not already exist;
;; otherwise it returns an error message.
;; calls utility function memberp.
(defmethod insert (el (c collection)) ...)
;; predicate function; tests element for membership in list lst
(defun memberp (element lst) ...)
;; erases el from collection c.
;; returns an error message if collection is empty.
;; returns an error message if el is not found.
;; calls utility function memberp.
```

```
;; calls utility function remove-element.
(defmethod erase (el (c collection)) ...)
;; returns a new list with element el removed from list lst.
(defun remove-element (el lst) ...)
```

Let us complete the definition of the class, by providing the implementation of all functions:

```
(defclass collection ()
  ((els  :accessor elements
         :initarg :els
         :initform '())))
(defmethod display ((c collection))
  (elements c))
(defmethod insert (el (c collection))
   (if (memberp el (elements c))

      (setf (elements c) (cons el (elements c)))))
(defun memberp (element lst)
  (cond
   ((null lst) nil)
   ((equal element (car lst)) t)
   (t (memberp element (cdr lst)))))
(defmethod erase (el (c collection))
   (if (null (elements c))

      (if (memberp el (elements c))
         (setf (elements c) (remove-element el (elements c)))
                                          )))
(defun remove-element (el lst)
   (if (equal el (car lst))
       (cdr lst)
       (cons (car lst) (remove-element el (cdr lst)))))
```

26.2 Inheritance and method combination

As a subclass is a specialization of any component class, it is considered *more specific* (as opposed to the reverse which makes superclasses *less specific* than their subclasses). When

there are methods defined for more than one component class of a given class, we need to have a rule to state how we decide which one to use. CLOS provides a rule that specifies how state and behavior are combined. This rule refers to a total ordering of all the superclasses of a class, from the most specific to the least specific, called *the class precedence list* of a given class.

1. Start from the bottom of the inheritance graph.
2. Walk upward, always taking the left-most unexplored branch.
3. If you are about to enter a node and you notice another path entering the same node from the right, retrace your steps until you get to a node with an unexplored path leading upward. Go to step [2].

The order in which you first enter each node, determines its place in the precedence list.

Example 26.3. Consider the following inheritance hierarchy of Figure 26.1 codified in the segment below:

```
(defclass shape () (...))
(defclass circle (shape) (...))
(defclass colored-object () (...))
(defclass colored-circle (circle colored-object) (...))
```

The precedence list determined by this graph is `colored-circle`, `circle`, `shape`, `colored-object`, `standard-object`.

Example 26.4. Consider the definitions of the following two classes:

```
(defclass person () ())
(defmethod speak ((s person) string)
  (format t      string))
(defmethod speak :before ((s person) string)
  (print         ))
(defmethod speak :after ((s person) string)
  (print                  ))
```

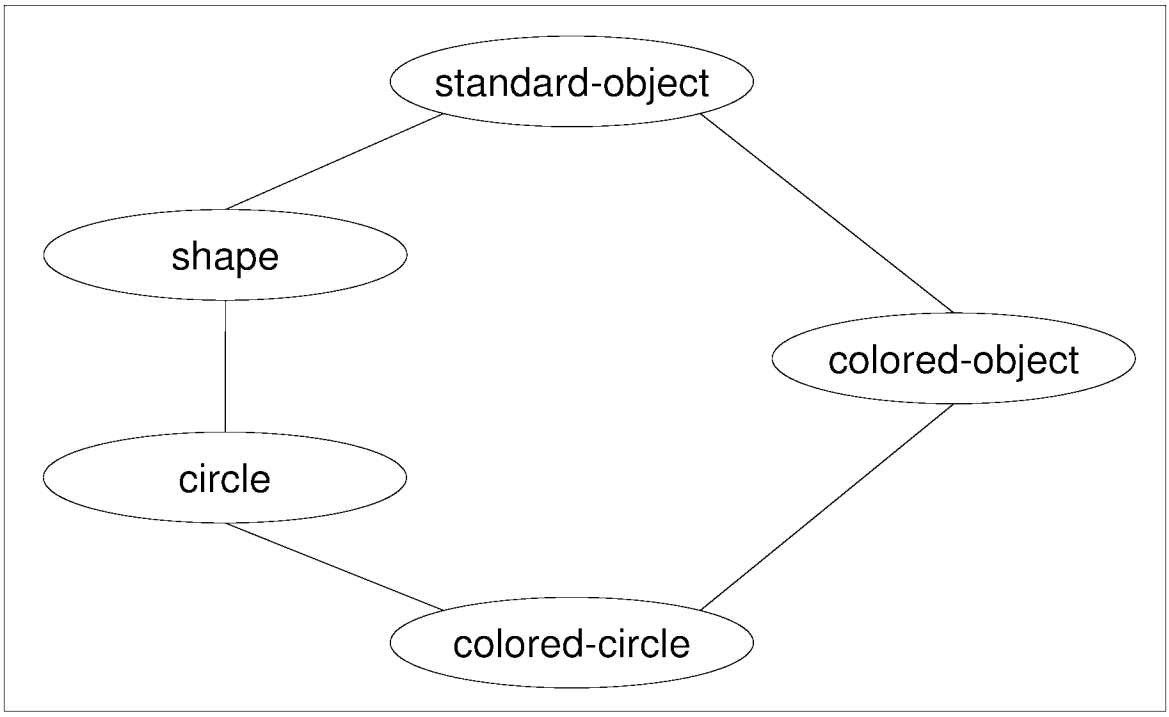

Figure 26.1: Multiple inheritance.

```
(defclass speaker (person) ())
(defmethod speak :before ((i speaker) string)
  (print            ))
(defmethod speak :after ((i speaker) string)
  (print                  ))
```

The code describes two classes `person` and `speaker`, related through inheritance. The latter is a subclass of the former. The superclass defines one regular function, `speak` and two auxiliary functions attached to it which execute before and after the code of the regular function. The subclass only defines auxiliary methods attached to the `speak` function in the superclass. Auxiliary functions in the subclass have priority over the auxiliary functions in the superclass. In the case of `before` auxiliary functions, priority means executing first. In the case of `after` auxiliary functions, priority means executing last.

Consider the following statement:

```
(speak (make-instance 'speaker)                    )
```

The output is as follows:

```
"Bonjour!"
"Hello!" Can I help you?
"Have a nice day!"
"Bonne journee!"
```

The statement creates an instance of `speaker` and sends message `speak` with argument `Can I help you?`. The before auxiliary method of the subclass will run first which will display `"Bonjour!"`, following by the before auxiliary method of the superclass which will display `"Hello!"`. Next comes the body of the regular method `speak` which will display the value of its parameter, `Can I help you?`. The `after` auxiliary method of the superclass will execute first displaying `"Have a nice day!"`, followed by the `after` auxiliary method of the subclass which will display `"Bonne journee!"`.

Chapter 27

Data structures and abstract data types II

27.1 The Stack ADT

The *Stack* ADT is a collection that stores arbitrary objects. Insertions and deletions follow a *last-in first-out* (LIFO) scheme. There are two major stack operations:

`push(stack element)`: inserts `element` onto `stack`.

`pop()`: removes and returns the last inserted element.

Furthermore, there are some auxiliary operations:

`top()`: returns the last inserted element without removing it from the collection.

`size()`: returns the number of elements stored.

`isempty()`: returns a Boolean value indicating whether no elements are stored.

`isfull()`: returns a Boolean value indicating whether the collection has reached its capacity.

In implementing a stack, we need to keep in mind that both major operations access the stack from the same end. The `push(..)` operation would simply create a new list with the

element to be placed on the stack and the current list and set it as the new value of the current list. The `cons` operation is well suited for this as it takes, as its arguments, an atom and a list. We also need to increment the size of the stack by one.

```
(defmethod push ((s stack) element)
  (setf (stack-elements s) (cons element (stack-elements s)))
  (setf (stack-size s) (+ 1 (stack-size s))))
```

The `pop` operation would return the head of the list, as well as create a new list comprised by the tail of the current list, setting it as the new value for the stack. We also need to decrement the size of the stack by one.

```
(defmethod pop ((s stack))
  (let ((top-element  (car (stack-elements s))))
    (setf (stack-elements s) (cdr (stack-elements s)))
    (setf (stack-size s) (- (stack-size s) 1))
    top-element))
```

We can now put everything together as follows:

```
(defclass stack ()
  ((elements :accessor stack-elements
             :initarg :elements
             :initform '())
   (size     :accessor stack-size
             :initarg :size
             :initform 0)
  (capacity  :accessor stack-capacity
             :initform 3
             :allocation :class)))
(defmethod isempty ((s stack))
  (equal (stack-size s) 0))
(defmethod isfull ((s stack))
  (equal (stack-size s) (stack-capacity s)))
```

```
(defmethod push ((s stack) element)
  (setf (stack-elements s) (cons element (stack-elements s)))
  (setf (stack-size s) (+ 1 (stack-size s))))
(defmethod pop ((s stack))
  (let ((top-element  (car (stack-elements s))))
    (setf (stack-elements s) (cdr (stack-elements s)))
    (setf (stack-size s) (- (stack-size s) 1))
    top-element))
(defmethod top ((s stack))
  (car (stack-elements s)))
(defmethod push :around ((s stack) element)
  (if (isfull s)

    (call-next-method s element)))
(defmethod pop :around ((s stack))
  (if (isempty s)

    (call-next-method s)))
(defmethod top :around ((s stack))
  (if (isempty s)

    (call-next-method s)))
```

We can now instantiate `stack` and use it as follows:

```
 > (setq s (make-instance 'stack))
#<STACK 200934B3>
> (push s 3)
> (push s 4)
> (push s 5)
> (top s)
5
```

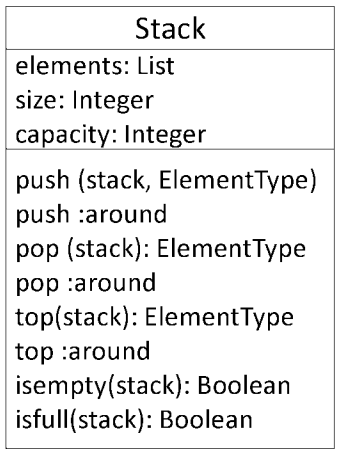

Figure 27.1: UML class diagram representation of class `stack`.

```
> (push s 6)
"The stack is already full."
> (pop s)
5
> (pop s)
4
> (pop s)
3
> (pop s)
"The stack is empty."
> (stack-size s)
0
```

Example 27.1. Consider the definition of class `stack` illustrated in UML in Figure 27.1. Define class `stack2` which extends `stack`. Class `stack2` introduces method `pop2` that behaves exactly like `pop` but can only execute immediately after a `pop`. In the case where `pop2` cannot execute, your program should display an error. You may not redefine `stack` or override behavior from `stack`.

The definition of stack2 is shown below:

```
(defclass stack2 (stack)
  ((popsemaphore   :accessor popsem
                   :initform 0)))
(defmethod pop2 ((s stack2))
  (pop s))
(defmethod push :after ((s stack2) element)
  (setf (popsem s) 0))
(defmethod pop :after ((s stack2))
   (setf (popsem s) 1))
(defmethod pop2 :after ((s stack2))
   (setf (popsem s) 0))
(defmethod pop2 :around ((s stack2))
  (if (= (popsem s) 1)
     (call-next-method s)
                          ))
```

A sample run is shown below:

```
>  (setq s (make-instance 'stack2))
#<STACK2 2009353B>
> (pop2 s)
"Cannot operate: pop2"
> (pop s)
"The stack is empty."
> (push s 1)
1
> (push s 3)
2
> (push s 5)
3
> (push s 7)
```

```
"The stack is already full."
> (pop2 s)
"Cannot operate: pop2"
> (pop s)
5
> (pop2 s)
3
> (pop2 s)
"Cannot operate: pop2"
> (pop s)
1
> (pop s)
"The stack is empty."
> (pop2 s)
"The stack is empty."
> (top s)
"The stack is empty."
> (push s 9)
1
> (pop2 s)
"Cannot operate: pop2"
> (top s)
9
> (pop s)
9
```

27.2 The Queue ADT

The *Queue* ADT is a collection that stores arbitrary objects. Insertions and deletions follow a *first-in first-out* (FIFO) scheme.

There are two major queue operations:

`enqueue(queue element)`: inserts `element` at the rear of `queue`.

`dequeue()`: removes and returns the element at the front of the queue.

Furthermore, there are some auxiliary operations:

`front()`: returns the front element without removing it from the collection.

`size()`: returns the number of elements stored.

`isempty()`: returns a Boolean value indicating whether no elements are stored.

`isfull()`: returns a Boolean value indicating whether the collection has reached its capacity.

In implementing a queue, we need to keep in mind that the two major operations access the queue from two different ends: the front and the rear. Recall that an ADT is an implementation-independent concept. This implies that it is up to us, the implementors of the ADT, to decide which end of the list we will consider as the front or the rear (as long as they are not the same end of the list).

The `enqueue` operation adds an element to the rear and the dequeue operation removes an element from the front. We have two choices for this implementation:

1. To consider the head of the list as the front of the queue. This implies that during enqueue, an element is added to the end of the list and during dequeue the head of the list is removed.

2. To consider the head of the list as the rear of the queue. This implies that during enqueue an element is added to the head of the list and during dequeue the last element of the list is removed.

The first choice is more convenient and we shall follow it here. To enqueue an element, we need to create a new list which is comprised with the current list and the element. How do we attach an element at the end of a current list? Function `cons` takes an element and a list, so that would not work. Function `append` can work, but it takes as arguments two lists. We can transform the element at hand into a list through the `list` function and then provide it as the second argument to `append`. We also need to increment the size of the queue by one.

```
(defmethod enqueue ((s queue) element)
  (setf (queue-elements s) (append (queue-elements s) (list element)))
  (setf (queue-size s) (+ 1 (queue-size s))))
```

To dequeue an element we simply have to return the head of the current list as well as to create a new list without the head element of the current list and set it as the new value to the queue. We also need to decrement the size of the queue by one.

```
(defmethod dequeue ((s queue))
  (let ((top-element  (car (queue-elements s))))
    (setf (queue-elements s) (cdr (queue-elements s)))
    (setf (queue-size s) (- (queue-size s) 1))
    top-element))
```

We can now put everything together as follows:

```
(defclass queue ()
  ((elements :accessor queue-elements
             :initarg :elements
             :initform '())
  (size      :accessor queue-size
             :initarg :size
             :initform 0)
  (capacity  :accessor queue-capacity
             :initform 3
             :allocation :class)))
(defmethod isempty ((s queue))
  (equal (queue-size s) 0))
```

```
(defmethod isfull ((s queue))
  (equal (queue-size s) (queue-capacity s)))
(defmethod enqueue ((s queue) element)
  (setf (queue-elements s) (append (queue-elements s) (list element)))
  (setf (queue-size s) (+ 1 (queue-size s))))
(defmethod dequeue ((s queue))
  (let ((top-element  (car (queue-elements s))))
    (setf (queue-elements s) (cdr (queue-elements s)))
    (setf (queue-size s) (- (queue-size s) 1))
    top-element))
(defmethod enqueue :around ((s queue) element)
  (if (isfull s)

    (call-next-method s element)))
(defmethod dequeue :around ((s queue))
  (if (isempty s)

    (call-next-method s)))
```

We can now instantiate queue and use it as follows:

```
>  (setq q (make-instance 'queue))
#<QUEUE 200BFCD7>
> (enqueue q 3)
> (enqueue q '(a b))
> (enqueue q 7)
> (enqueue q 11)
"The queue is already full."
> (dequeue q)
3
> (dequeue q)
(A B)
```

```
> (dequeue q)
7
> (dequeue q)
"The queue is empty."
```

Chapter 28

Bibliography and online resources

Bibliography

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Online resources

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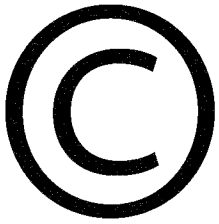

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