Programs are built out of components.

Each component:

- has a public interface that defines entities exported by the component
- may depend on the entities defined in the interface of another component (weak external coupling)
- may include other (private) entities that are not exported
- should define a set of logically related entities (strong internal coupling)

We call these components modules.
What is a module?

- different languages use different terms
- different languages have different semantics for this construct (sometimes very different)
- a module is somewhat like a record, but with an important distinction:
  - **record** → consists of a set of names called *fields*, which refer to values in the record
  - **module** → consists of a set of names, which can refer to values, types, routines, other language-specific entities, and possibly other modules
Language constructs for modularity

Issues:
- public interface
- private implementation
- dependencies between modules
- naming conventions of imported entities
- relationship between modules and files
- access control: module controls whether a client can access its contents
- closed module: names must be explicitly imported from outside the module
- open module: outside names are accessible inside module (no explicit import)
Language choices

- **Ada**: package declaration and body, `with` and `use` clauses, renamings
- **C**: header files, `#include` directives
- **C++**: header files, `#include` directives, namespaces, `using` declarations/directives, namespace alias definitions
- **Java**: packages, `import` statements
- **ML**: signature, `structure` and `functor` definitions
package Queues is
  Size: constant Integer := 1000;

type Queue is private; -- information hiding

  procedure Enqueue (Q: in out Queue, Elem: Integer);
  procedure Dequeue (Q: in out Queue; Elem: out Integer);
  function Empty (Q: Queue) return Boolean;
  function Full (Q: Queue) return Boolean;
  function Slack (Q: Queue) return Integer;
  -- overloaded operator "=":
  function "=" (Q1, Q2: Queue) return Boolean;

private
  ... -- concern of implementation, not of package client
end Queues;
package Queues is
  ...  -- visible declarations
private
  type Storage is
    array (Integer range <>) of Integer;
  type Queue is record
    Front: Integer := 0;  -- next elem to remove
    Back: Integer := 0;  -- next available slot
    Contents: Storage (0 .. Size-1);  -- actual contents
    Num: Integer := 0;
  end record;
end Queues;
package body Queues is
    procedure Enqueue (Q: in out Queue;
                        Elem: Integer) is
    begin
        if Full(Q) then
            -- need to signal error: raise exception
        else
            Q.Contents(Q.Back) := Elem;
        end if;
        Q.Num := Q.Num + 1;
        Q.Back := (Q.Back + 1) mod Size;
    end Enqueue;
function Empty (Q: Queue) return Boolean is
begin
    return Q.Num = 0;   -- client cannot access
                      --   Num directly
end Empty;

function Full (Q: Queue) return Boolean is
begin
    return Q.Num = Size;
end Full;

function Slack (Q: Queue) return Integer is
begin
    return Size - Q.Num;
end Slack;
function "=" (Q1, Q2 : Queue) return Boolean is
begin
  if Q1.Num /= Q2.Num then
    return False;
  else
    for J in 1 .. Q1.Num loop
      -- check corresponding elements
      if Q1.Contents((Q1.Front + J - 1) mod Size) /=
         Q2.Contents((Q2.Front + J - 1) mod Size)
      then
        return False;
      end if;
    end loop;
    return True; -- all elements are equal
  end if;
end "="; -- operator "/=" implicitly defined
          -- as negation of "="
with Queues; use Queues; with Text_IO;

procedure Test is
  Q1, Q2: Queue; -- local objects of a private type
  Val : Integer;
begin
  Enqueue(Q1, 200); -- visible operation
  for J in 1 .. 25 loop
    Enqueue(Q1, J);
    Enqueue(Q2, J);
  end loop;
  Dequeue(Q1, Val); -- visible operation
  if Q1 /= Q2 then
    Text_IO.Put_Line("lousy implementation");
  end if;
end Test;
package body holds bodies of subprograms that implement interface

package may not require a body:

```pascal
package Days is
    type Day is (Mon, Tue, Wed, Thu, Fri, Sat, Sun);

    subtype Weekday is Day range Mon .. Fri;

    Tomorrow: constant array (Day) of Day := (Tue, Wed, Thu, Fri, Sat, Sun, Mon);

    Next_Work_Day: constant array (Weekday) of Weekday := (Tue, Wed, Thu, Fri, Mon);
end Days;
```
Visible entities can be denoted with an expanded name:

```plaintext
with Text_IO;
...
Text_IO.Put_Line("hello");
```

**use** clause makes name of entity directly usable:

```plaintext
with Text_IO; use Text_IO;
...
Put_Line("hello");
```

**renames** clause makes name of entity more manageable:

```plaintext
with Text_IO;
package T renames Text_IO;
...
T.Put_Line("hello");
```
with Queues;

procedure Test is
  Q1, Q2: Queues.Queue;
begin
  if Q1 = Q2 then ...
    -- error: "=" is not directly visible
    -- must write instead: Queues."=(Q1, Q2)

Two solutions:
- import all entities:
  use Queues;
- import operators only:
  use type Queues.Queue;
late addition to the language
an entity requires one or more declarations and a single definition
a namespace declaration can contain both, but definitions may also be given separately

// in .h file
namespace util {
  int f (int); /* declaration of f */
}

// in .cpp file
namespace util {
  int f (int i) {
    // definition provides body of function
    ...
  }
}
files have semantic significance: `#include` directives means textual substitution of one file in another.

- convention is to use header files for shared interfaces

```cpp
#include <iostream> // import declarations

int main () {
    std::cout << "C++ is really different" << std::endl;
    return 0;
}
```
namespace stack {  // in file stack.h
    void push (char);
    char pop ();
}

#include "stack.h"  // import into client file

void f () {
    stack::push('c');
    if (stack::pop() != 'c') error("impossible");
}
#include "stack.h"  // import declarations

namespace stack {  // the definition
    const unsigned int MaxSize = 200;
    char v[MaxSize];
    unsigned int numElems = 0;

    void push (char c) {
        if (numElems >= MaxSize)
            throw std::out_of_range("stack\noverflow");
        v[numElems++] = c;
    }

    char pop () {
        if (numElems == 0)
            throw std::out_of_range("stack\nunderflow");
        return v[--numElems];
    }
}
namespace queue {  // works on single queue
    void enqueue (int);
    int dequeue ();
}

#include "queue.h"  // in client file
using queue::dequeue;  // selective: a single entity
void f () {
    queue::enqueue(10);  // prefix needed for enqueue
    queue::enqueue(-999);
    if (dequeue() != 10)  // but not for dequeue
        error("buggy implementation");
}
#include "queue.h" // in client file

using namespace queue; // import everything

void f () {
    enqueue(10); // prefix not needed
    enqueue(-999);
    if (dequeue() != 10) // for anything
        error("buggy implementation");
}
Sometimes, we want to qualify names, but with a shorter name.

In Ada:

```ada
package PN renames A.Very_Long.Package_Name;
```

In C++:

```cpp
namespace pn = a::very_long::package_name;
```

We can now use PN as the qualifier instead of the long name.
When an unqualified name is used as the postfix-expression in a function call (\texttt{expr.call}), other namespaces not considered during the usual unqualified look up (\texttt{basic.lookup.unqual}) may be searched; this search depends on the types of the arguments.

For each argument type \(T\) in the function call, there is a set of zero or more associated namespaces to be considered. The set of namespaces is determined entirely by the types of the function arguments. \texttt{typedef} names used to specify the types do not contribute to this set.

The set of namespaces are determined in the following way:
If T is a fundamental type, its associated set of namespaces is empty.
If T is a class type, its associated namespaces are the namespaces in which the class and its direct and indirect base classes are defined.
If T is a union or enumeration type, its associated namespace is the namespace in which it is defined.
If T is a pointer to U, a reference to U, or an array of U, its associated namespaces are the namespaces associated with U.
If T is a pointer to function type, its associated namespaces are the namespaces associated with the function parameter types and the namespaces associated with the return type. [recursive]
namespace NS
{
    class A {}
    void f( A *&, int ) {}
}

int main()
{
    NS::A *a;
    f( a, 0 );  // calls NS::f
}
Linking

- an external declaration for a variable indicates that the entity is defined elsewhere
  
  ```c
  extern int x; // will be found later
  ```

- a function declaration indicates that the body is defined elsewhere
- multiple declarations may denote the same entity
  
  ```c
  extern int x; // in some other file
  ```

- an entity can only be defined once
- missing/multiple definitions cannot be detected by the compiler: link-time errors
#include "queue.h"  // as if declaration were  
//  textually present

void f () { ... }

#include "queue.h"  // second declaration in  
//  different client

void g () { ... }

- definitions are legal if textually identical (but compiler can't check!)
- headers are safer than cut-and-paste, but not as good as a proper module system
package structure parallels file system
- a package corresponds to a directory
- a class is compiled into a separate object file
- each class declares the package in which it appears (open structure)

```java
package polynomials;
class poly {
    ...
    // in file .../alg/polynomials/poly.java
}
```

```java
package polynomials;
class iterator {
    ...
    // in file .../alg/polynomials/iterator.java
}
```

Default: anonymous package in current directory.
dependencies indicated with import statements:

```java
import java.awt.Rectangle; // declared in java.awt

import java.awt.*;       // import all classes
                        // in package
```

- no syntactic sugar across packages: use expanded names
- none needed in same package: all classes in package are directly visible to each other
There are three entities:

- **signature**: an interface
- **structure**: an implementation
- **functor**: a parameterized **structure**

A **structure** implements a **signature** if it defines everything mentioned in the **signature** (in the correct way).
An ML \textit{signature} specifies an interface for a module.

\begin{verbatim}
signature STACKS =
sig
  type stack
  exception Underflow
  val empty : stack
  val push : char * stack -> stack
  val pop : stack -> char * stack
  val isEmpty : stack -> bool
end
\end{verbatim}
A structure provides an implementation.

```ml
structure Stacks : STACKS =
struct
    type stack = char list
    exception Underflow
    val empty = []
    val push = op:::
    fun pop (c::cs) = (c, cs)
    | pop [] = raise Underflow
    fun isEmpty [] = true
    | isEmpty _ = false
end
```
A functor creates a structure from a structure.

```ml
signature TOTALORDER = sig
  type element;
  val lt : element * element -> bool;
end;

functor MakeBST(Lt: TOTALORDER):
  sig
    type 'label btree;
    exception EmptyTree;
    val create : Lt.element btree;
    val lookup : Lt.element * Lt.element btree -> bool;
    val insert : Lt.element * Lt.element btree -> Lt.element btree;
  end;
```
val deletemin : Lt.element btree ->
Lt.element * Lt.element btree;
val delete : Lt.element * Lt.element btree
  -> Lt.element btree;
end;
Comparisons

structure String : TOTALORDER =

struct

type element = string;
fun lt(x,y) =
  let
    fun lower(nil) = nil |
        lower(c::cs) =
        (Char.toLower c)::lower(cs);
    in
    implode(lower(explode(x))) <
    implode(lower(explode(y)))
  end;
end;

structure StringBST = MakeBST(String);
## Comparisons

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<td>✔</td>
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<tr>
<td>access control</td>
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<td>is closed</td>
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<td>✗</td>
<td>✗</td>
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</tbody>
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Relation between interface and implementation:

- **Ada** :
  
  one package (interface) $\leftrightarrow$ one package body

- **ML** :
  
  one signature *can be implemented by* many structures
  
  one structure *can implement* many signatures