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A Note on CLU

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Introduction

Our work on quality software concerns the development of tools and techniques which aid in the production of software that is correct, modifiable, understandable, and transferable. A major research effort of the previous year has been the design of CLU, a language system to support structured programming, by a group of students and faculty led by Professor Liskov. This work is motivated as follows: We believe that a significant improvement in software quality will result from the use of programming methodologies which aid the programmer in discovering correct and understandable problem solutions. Two promising methodologies have been described in the literature: structured programming [1] and modularity [2, 3].

Unfortunately, it is not easy to apply the methodologies to practical software problems. The methodologies are described by means of some "rules of thumb" illustrated by examples of "toy" problems. It is difficult to extrapolate from such descriptions to real situations, and conscientious attempts to apply the methodologies may fail [4]. In addition, even if the programmer succeeds in producing a design, the task of mapping the design into a program can be difficult and often introduces errors.

We believe the best approach to developing a methodology that will serve as a practical tool for program construction is through the design of a programming language such that problem solutions developed using the methodology are programs in the language. Several benefits accrue from this approach. First, since designs produced using the methodology are actual programs, the problems of mapping designs into programs do not require independent treatment. Second, completeness and precision of the language will be

reflected in a methodology that is similarly complete and precise. Finally, the language provides a good vehicle for explaining the methodology to others.

Our research in the area of programming methodology led to a methodology [3] which combines structured programming with modularity. The fundamental activity taking place in structured programming is, in our opinion, the recognition of abstractions. Structured programs are developed by repeated analysis of a problem into subproblems to be solved by program modules. Each module is a program written to run on an abstract machine providing just those abstractions (data objects and operations) suitable for the problem being solved. The abstractions in this machine, if not already present in the programming language being used, are then realized by means of further modules. The result of this process is a program structure in which each element is a module developed to support an abstraction. The simplicity of this structure, and hence the understandability and provability of the structured program, is directly dependent on a wise choice of suitable abstractions.

We have studied what kinds of abstraction are useful in writing programs, and how such abstractions may be represented in programs. Two kinds of abstraction are recognized at present: abstract operations and abstract data types. Abstract operations are naturally represented by subroutines or procedures, which permits them to be used abstractly (without knowledge of details of implementation). However, a program representation for abstract data types is not so obvious; the ordinary representation, a description of the way the objects of the type will occupy storage, forces the user of the type to be aware of implementation information.

We believe that the user of an abstract data type is interested in how the type's objects behave, and that the behavior is best described in terms

of a set of operations [5]. We developed a set of criteria about the way abstract data types should be handled:

1. A data type definition must include definitions of all operations applicable to objects of that type.
2. A user of an abstract data type need not know how objects of the type are represented in storage.
3. A user of an abstract data type may manipulate the objects only through the type's operations, and not through direct manipulation of the storage representation.

This last criterion insures that the operations provide a complete description of the behavior of the type, and enhances the modifiability and provability of programs.

Analysis of Existing Languages

J. Aiello studied a number of existing languages to determine whether they could meet the data abstraction needs of structured programming [6]. The criteria used were those described in the preceding paragraph. Programs were written in the selected languages to define selected data type examples.

The first language analyzed was PL/I. PL/I is described by IBM as an all-purpose language, but like many conventional languages (FORTRAN, ALGOL), fails to provide the user with a means for constructing data types. Analysis of PL/I revealed alternative mechanisms, for example, the multiple-entry procedure, which could be used for type definitions, and abstractions were programmed using these mechanisms. None of the programs satisfied all the criteria. Criterion 3 proved especially difficult, and attempts to satisfy it led to programs whose complexity greatly exceeded that of the abstraction being programmed.

The next language, Pascal [7], was chosen because it provides numerous data structuring facilities. Pascal does support data type definitions, but

not in sufficiently abstract form. A Pascal type definition merely specifies the storage representation of the new type in terms of existing data types. There is no provision for connecting the new type and the meaningful operations on objects of that type. So criterion 3 is not met.

EL1 [8], the next language examined, is an extensible language; that is, EL1 provides the user with a number of facilities for defining extensions so that the programmer can shape the language to the problem at hand. Using some of these facilities we were able to construct data abstractions -- but only in a limited sense in accordance with our criteria. The main problem is that EL1 only permits four operations, preselected by the language designer, to be associated with a type definition. The preselection and limited number of operations restricts abstraction power: abstractions are forced to fit into the four-operation mold provided by the language designer. One result is that the EL1 code produced did not necessarily reflect the simplicity of the conceptual solution to the given problem. In addition EL1 provides a facility which converts an abstract type to the representing type. This facility does permit additional operations to be programmed, although they have no special connection to the type, but it violates criterion 3.

The final language examined was SIMULA 67 [9], designed as a general purpose simulation language. This language provides the closest match to abstract data types in its class construct. A Simula class may be viewed as a type-definition, and as part of that definition, the programmer may include all the operations which make sense for the objects of the new type. Unfortunately SIMULA does not constrain access to the objects to occur only through the operations, and thus violates Criterion 3.

Since Simula came so close to satisfying our criteria, we investigated the possibility that some simple changes to the semantics of the language would result in acceptability. However, we found that this augmented SIMULA 67 failed in other respects (for example, representing operations that take more than one argument of abstract type).

As a result of this study, we concluded that existing languages, even with minor modifications, do not support abstract data types, and therefore that a new language must be developed for this purpose.

The Structured Programming Language, CLU

We are designing a structured programming language, called CLU, to permit the abstractions introduced during program design to be easily defined via CLU modules. Two kinds of modules are supported by CLU: procedures, which support abstract operations, and clusters, which support abstract data types in a way which satisfies the three criteria discussed earlier. An abstract data type is defined to be a set of operations. The cluster supporting the type contains definitions of the operations.

Important features of CLU are:

1. CLU is a modular programming language/system. Each CLU module is an independent entity and is accepted by the system by itself. The separateness of modules is a consequence of the view that modules support abstractions. The purpose of abstraction is to separate use from implementation; therefore, the implementation of an abstraction (a module) should be treated separately from its use (in another module or modules).
2. Although each module is developed and submitted to the system independently, a means must be provided to permit modules to refer to each other (so that one module can make use of the abstraction provided by another module). To provide this facility, the CLU system

maintains a data base containing a description unit for each module that has been submitted to it. Whenever a new module is submitted to the system, it must be accompanied by an association list identifying for each data or functional abstraction used in this module, the description unit of the module which the programmer wishes to have implement the abstraction.

3. The only free variables which a module can contain are those which identify other modules (via the association list mentioned above). These variables are bound at compile-time to the appropriate modules. No free variables remain to be bound in the translated module at run time.

4. The language is strongly typed and type-checking occurs at translation time. This means that every use of a data object is checked by the translator to be sure its type matches exactly with the expected type. A very important part of the type checking (and one which is often neglected) is the checking of interfaces between modules. The CLU translator checks such interfaces completely; it is able to do so because the association list tells what module is being called, and the description unit for that module contains complete information about the type requirements of the module. The fact that modules are bound together at translation time insures that the translator's assumptions about what module is being called, and hence what the type requirements are, are valid at execution time.

Example of a definition of an abstract data type

An example of an abstract data type definition is presented to illustrate those features of CLU which are most novel. The type to be defined is that of integer sets; a reasonable set of meaningful operations for integer sets are:

create	creates an empty set
insert	inserts an integer in a set
remove	removes an integer from a set
has	tests whether a set contains a particular integer
equal	tests whether two sets are the same
similar	tests whether two sets contain the same integers
copy	copies a set

Ordinary set behavior is desired: a set does not behave as if it contains multiple copies of the same integer.

A cluster implementing integer sets is shown in Figure 1. A cluster definition consists of three parts:

1. interface description
2. object description
3. operation definitions

The interface description of a cluster definition provides a very brief description of the interface which the cluster presents to its users. It consists of the name of the cluster and a list of the operations defining the type which the cluster implements: e.g.,

intset = cluster is create, insert remove, has, equal, similar, copy

The use of the reserved word is underlines the idea of a data type being equivalent to a group of operations; the group of operations following is is called the is-list.

```
intset = cluster is create, insert, remove, has, equal, similar, copy;

    rep = array of int;

    create = oper( ) returns (cvt);
        r: rep := rep $ create(0);
        return (r);
    end create;

   insert = oper(s: cvt, i: int);
         if search(s, i) ≤ rep $ high(s) then return;
         rep $ extendh(s, i);
         return;
    end insert;

    search = oper(s: rep, i:int) returns (int);
        for j: int := rep $ low(s) to rep $ high(s) by 1 do
            if i = s[j] then return (j);
        return (rep $ high(s) + 1);
    end search;

    remove = oper(s: cvt, i:int);
        j: int := search(s, i);
        if j ≤ rep $ high(s) then
            begin
                s[j] := s[rep $ high(s)];
                rep $ retracth(s)
            end;
       return;
   end remove;

    has = oper(s: cvt, i:int) returns (boolean);
        if search(s, i) ≤ rep $ high(s)
            then return (true)
            else return (false);
    end has;
```

Figure 1. The intset cluster.

```
    equal = oper(s, t: cvt) returns (boolean);
        return (rep $ equal(s, t));
    end equal;

    similar = oper(s, t: cvt) returns (boolean);
        if rep $ size(s) ~= rep $ size(t) then return (false);
        for i: int := rep $ low(s) to rep $ high(s) by 1 do
            if search(t, s[i]) > rep $ high(t) then return (false);
        return (true);
    end similar;

    copy = oper(s: cvt) returns (cvt);
        return (rep $ copy(s));
    end copy;

end intset
```

Figure 1. The intset cluster (continued).

Users of the abstract data type view objects of that type as indivisible, non-decomposable entities. Inside the cluster, however, objects are viewed as decomposable into elements of more primitive type. The object description defines the way objects are viewed within the cluster, by defining a template which permits objects of that type to be built and decomposed. For example, the representation chosen for integer sets is merely an array of integers:

rep = array of int

This simple representation is possible because CLU provides a powerful kind of array of unbounded size. Although CLU arrays are primitive in the sense that they are supported by the CLU translator, they may be viewed just like any data type as a group of operations, and a description of the array operations is sufficient to provide a programmer with a thorough understanding of the array abstraction. A subset of the array operations is described in Figure 2.

The rep description is actually a type definition: rep is defined to be equal to the type specified on the right hand side of the equal sign. Whenever the word rep appears later in the cluster, it means this type.

The body of the cluster consists of operation definitions, which provide implementations of the permissible operations on the data type. An operation definition must be given for every operation named in the is-list. Operation definitions are like ordinary procedure definitions except the bodies of operations have access to the rep of the cluster, which permits them to decompose objects of the cluster type. Operations are not modules; they may be written only as part of a cluster.

1. array limits. Each array has an upper and a lower bound and a size. All array elements between the bounds are defined (have values); no array elements are defined outside the bounds. Three operations give limit information:

   low(a) returns the index of the lowest defined element, or the initially defined lower bound if the array is empty.

   high(a) returns the index of the highest defined element, or low(a)-1 if the array is empty.

   size(a) returns high(a) - low(a) + 1.

2. growing arrays. Arrays are empty when initially created. They may grow in either direction one element at a time:

   create(i) returns a new empty array a with lower bound i. low(a) = i, high(a) = i - 1, size(a) = 0.

   extendh(a, v) a grows in the high direction by one element, and v is stored in that element. high(a) and size(a) increase by 1.

   extendl(a, v) like extendh, but growth is in low direction.

3. accessing arrays. Arrays may be accessed and updated in the usual way, but only elements between the bounds may be referenced. The index is interpreted absolutely (not relative to low(a))

   fetch(a, i) returns the value in the ith element of a if low(a) ≤ i ≤ high(a), else error. Syntactic "sugar" is provided: fetch(a, i) may be written a[i].

   store(a, i, v) stores v in the ith element of a if low(a) ≤ i ≤ high(i), else error. Syntactic sugar is provided: store (a, i, v) may be written a[i] :== v

Figure 2. CLU arrays.

4. shrinking arrays. Arrays may shrink from either end, one element at a time.

retracth(a)	if a is non-empty, returns the value in high(a) and reduces high(a) and size(a) by 1, else error.
retractl(a)	like retracth, but for low end of array.

5. equality:

equal(a1, a2)	two arrays are equal if and only if they are the same identical array.
similar(a1, a2)	two arrays are similar if and only if they have the same limits, and they are element by element similar.

6. copy

copy(a)	returns a new array having the same limits as a, and containing a copy of each element of a.

Figure 2. CLU arrays (continued).

Some operations create new objects of the cluster type; create is an example of such an operation. The first thing create does is to bring into existence a variable r of the representing type

r: rep

It then initializes r to an object of the representing type; it creates the object by calling on a creating operation of that type:

rep $ create(0)

This line is an example of an operation call which requires a compound name to be used to specify the operation. The first part of the name identifies the type of the operation, while the second part identifies the operation. Since rep has been defined to be equal to array of int, the above operation call is the same as

array of int $ create(0)

Thus a call on the create operation for arrays is made.

Finally, create returns this object by the statement

return (r)

However, the type of r is the representing type, while the user of intset expects an object of type intset. Therefore, the create operation must cause the type of r to change before r is passed to the user of intset. The heading of the create operation specifies that this conversion is to occur:

create = oper ( ) returns (cvt)

This line states that the create operation expects no input parameters, and returns a single value. The use of the reserved word cvt states that this return value will be of the cluster type (intset in this case), and that the value being returned should be converted to the cluster

type from the rep type just before it is returned.

Other operations manipulate previously existing objects of the cluster type. For example, the insert operation inserts a given integer into a given intset:

```
insert = oper (s: cvt, i: int)
```

insert doesn't return any values, but instead modifies the contents of the intset object passed to it as a parameter. The use of the word cvt in

```
s: cvt
```

again means that outside the intset cluster, s is an object of type intset, and that a conversion is to occur. However, in this case the conversion is from the cluster type to the rep type, so that whenever s is used inside of insert, it denotes an object of the rep type. The conversion occurs immediately after insert is entered.

The first line of insert

```
if search(s, i) ≤ rep $ high(s) then return
```

illustrates the use of an internal cluster operation. The name search does not appear in the is-list and therefore search is not available for use by users of intset. Note that search expects an object of type rep as its first parameter:

```
search = oper(s:rep, i:int) returns (int);
```

The call of search matches the type requirements because s has type rep inside insert. The operation call of search does not require a compound name, intset $ search, because it is an intra-cluster call.

Uses of intset look very similar to the uses of array objects which appear in the intset operations. Variables may be declared of type intset:

```
s: intset
```

and intset objects created and assigned to such variables:

```
s := intset $ create( )
```

Operations may then be applied to intset objects:

```
intset $ insert(s, 3);
if intset $ has (s, 7) then intset $ remove(s, 7);
```

Also intset objects may be passed to procedures and to operations of other clusters. In every case, the CLU translator will check that the called procedure or operation expects an intset object in the position in which s occurs; any other expectation will cause a type error to be detected, and the translation will not complete. Therefore, it is impossible for any procedure or operation to receive an intset object as anything but an intset object.

Access to the rep of an abstract object can occur only within a cluster operation in which a parameter or result is marked by the indicator cvt. This indicator specifies that the argument or result is considered to be of the cluster's abstract type outside the body of the operation, but of type rep inside the operation body. Thus intset objects can only be accessed as objects of type rep inside the bodies of operations of the intset cluster.

As was mentioned earlier, hiding an object's representation (criterion 3) is necessary to ensure that the behavior of the object is completely defined in terms of the type's operations. In addition, it is beneficial to software quality. Programs produced in this way are easy to modify: all changes to the implementation of a particular abstraction are guaranteed to be limited

to the supporting cluster since users of the original cluster were not able to make use of any implementation details. For example, the cluster for intset could be rewritten to store the set elements in sort order. Users of intset would be unaffected by this change (their programs would continue to run correctly) although performance differences would be noticed.

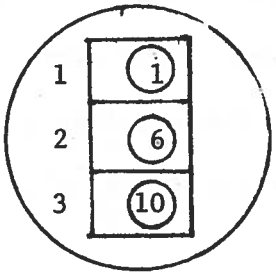
Hiding the representation is also beneficial to proofs of program correctness because it permits the proofs to be modularized along program module boundaries.

Assignment and Parameter Passing

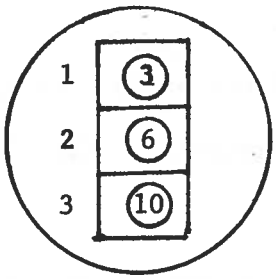
The semantics of CLU is based on a sharp distinction between variables and objects. CLU objects are the values which are manipulated by CLU programs. Each CLU object has a unique type associated with it. CLU objects may be simple, e.g., integer objects

(5) (7)

or complicated, e.g., an array containing integers 1, 6, 10 in elements 1, 2, 3



However, the complicatedness or simplicity of an object can't be observed directly; all that can be done with an object is to manipulate it using the operations defining the object's type. These operations provide the only means for making observations about objects of the type, and the operations completely define the behavior of the objects of the type. The objects of some types exhibit mutable behavior: some operations exist which will change the interior of an object without changing the object's identity. Array objects have mutable behavior; for example, the store operation, if asked to change the first element of the array above to (3), will modify the array object itself, so that at the completion of the operation the object looks like



Objects of type intset, defined in the previous section, have mutable behavior too; operations insert and remove change the state of intset objects. The objects of other types exhibit constant behavior: for such types, no operations exist to change the state of one of the type's objects. For example, integers, characters and strings have constant behavior.

CLU objects have an existence independent of particular CLU programs. They reside in the CLU universe which is like an Algol 68 heap. CLU variables, on the other hand, only exist in programs. They merely provide a convenient way for programs to reference objects. CLU provides a primitive assignment operator which permits a variable to be associated with an object. Thus execution of

```
x := 3
```

results in the variable x denoting the object (3) . CLU variables have type, defined when the variable is declared, and an assignment is only legal when the type of the variable and the type of the object are compatible. Compatible means either the types are equal, or the variable's type is a union of several types including the object's type.

CLU follows the ordinary conventions about coercing a variable to the object it denotes whenever the variable appears anywhere but on the left hand side of := . CLU is unusual in not viewing an array reference or record selector as a left hand side; as explained in Figure 2,

```
a[i] := v
```

is merely syntactic sugar for a call on the array operation, store. The symbol a[i] is not considered to be a variable in CLU ; rather it is an operation invocation.

The semantics of parameter passing in CLU is very straightforward but somewhat unusual. The identifiers of the formal input parameters defined in

the procedure or operation heading are considered to be variables; thus

```
f = proc (s: array of int, i: int)
```

contains the declaration of two variables s and i. When a procedure or operation is invoked, the declarations take effect, and the variables are initialized by assigning the actual parameters to them. For example, if t is an array containing 3, 6, and 10 in elements 1, 2, 3 then

```
f(t, 2)
```

is a legal call of f; it causes variables s and i to be created, and assignments

```
s := t
i := 2
```

to be executed. The result of the call of f is illustrated in Figure 3a.

The reason that parameter passing in CLU is unusual is that assignment to the formal parameters of a procedure or operation does not affect the actual parameters. If x is an array containing 4 in element 1, and the assignment

```
s := x
```

occurs inside f, the result is that s now denotes a different object, but t is unaffected. Figure 3b illustrates the effect of s := x.

Because assignment to formal parameters inside of procedures cannot affect the actual parameters, CLU parameter passing is not call by reference, and one kind of side-effect is eliminated in CLU. We call our parameter passing call by sharing, because the object being passed is shared, as illustrated in Figure 3a. Information can be exchanged between calling and called procedures by changing the state of the shared object (if its type exhibits state behavior). Changing the state of an object received as input is the only kind of side effect a CLU procedure can have.

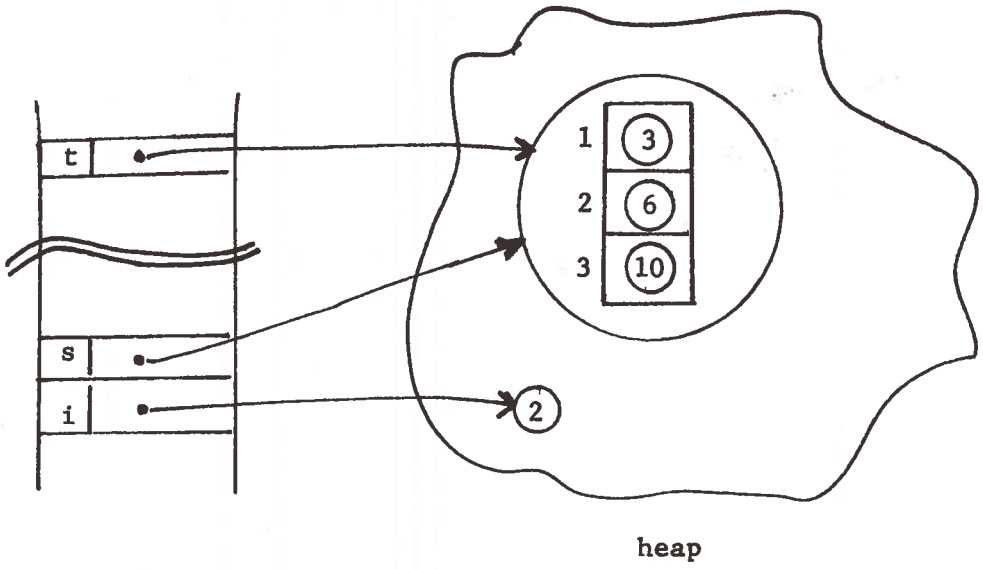


Figure 3a. Situation after f has been called.

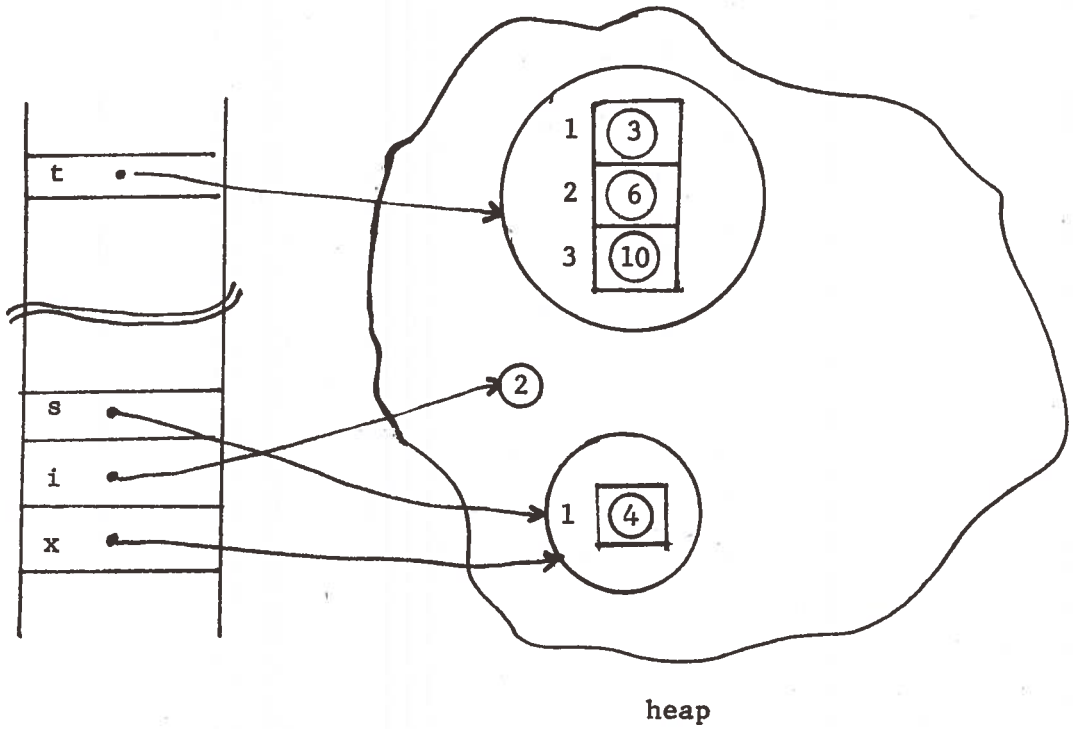


Figure 3b. Situation after s := xx has been executed.

Equality

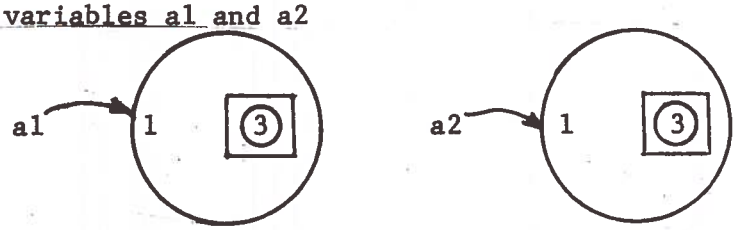
In addition to the primitive notion of assignment, a primitive notion of equality is often required in order to write meaningful programs. However, unlike assignment, which has a type-independent meaning and can be implemented automatically, equality has a type-dependent meaning. Therefore, it is not possible to provide an automatic implementation for equality. Instead, each cluster must include an equal operation (the operation which is named "equal") to provide an implementation of equality which is meaningful for the type being defined.

Although the meaning of equality is type-dependent, some general statements can be made about the meaning of equality which will help the cluster definer provide the correct definition of the equal operation. First, we can state what we expect equality to mean. Intuitively, two objects are equal if, at any time in the future, one can be substituted for the other without any resulting detectable difference in program behavior.

> Suppose T is a type, s1 and s2 are objects of type T, and o1, ..., on are operations of type T. If s1 has been determined to be equal to s2 by an application of the equal operation for T at time t, then at any time t' > t, any application of operation o1, ..., on to object s1 must provide "precisely the same results" as that operation applied to s2, where "precisely the same results" is measured by using the equal operation for the type of the resulting object.

In trying to apply the above criterion when defining a type, it is helpful to distinguish between constant and mutable types. For constant types, two objects are equal if the values inside them are equal insofar as the other operations of the type are able to distinguish. For example, two complex numbers are equal if their real and imaginary components are equal; two strings are equal if they contain the same characters in the same order.

For mutable types, two objects are equal if and only if they are the same identical object. The equal operations for intset (Figure 1) and for arrays (Figure 2) are examples of such a definition. The necessity for such a stringent definition arises directly from the requirement, given above, that one of two equal objects can be freely substituted for the other with the same results. Suppose, for example, that the two distinct array objects, denoted by variables a1 and a2



were considered to be equal. Now consider the program text:

```
array of int $ extendh(a1, 4)
i := array of int $ size(a1)
```

where i is some integer variable. Since a2 can be freely substituted for a1 with no detectable difference in program behavior, the following text should have the same behavior

```
array of int $ extendh(a1, 4)
i := array of int $ size(a2)
```

Clearly there is a difference in behavior; the value of i in the first case is 2 and in the second case, 1. The difference arises because, for mutable types, operations exist which change the state of objects.

Since the equal operation is present in almost every type, and its use is very widespread, CLU provides a short form for calling it. The expression

```
x = y
```

is valid only if x and y are objects of the same type, and if they are, it means

```
typeofx$equal(x,y).
```

For example, in the search operation of intset, the expression

```
i = s[j]
```

means

```
int $ equal(i, s[j])
```

Since the meaning of equality is so constrained for mutuable types, it is useful to have other concepts of equivalence supported by other cluster operations. One such definition is associated with the operation name "similar": two objects are similar if their contents are similar, insofar as the other operations of the type are able to distinguish. Thus, for a1 and a2 above,

```
array of int $ similar(a1, a2) = true
```

Another example is the similar operation of intset (Figure 1); two intset objects are similar if they contain the same integers, regardless of the order in which the integers are stored. Note that for both constant and mutable types, equality of objects implies similarity. The definer of a cluster has no obligation to provide a "similar" operation.

Copying

Often a user does not wish to have two variables share an object, or to share an object with a procedure he calls. Sharing of objects between two variables is dangerous because a change to the object through one of the variables affects the other variable. For example, starting from the situation in Figure 3b, if

```
s[1] := 5
```

is executed, the result is that x[1] will now return (5) . Copying objects is much safer than sharing because such anomolies don't arise. However, the meaning of copy is not defined by the CLU semantics; instead copy (like equal) is an operation which must be defined for each abstraction by giving an operation definition in the cluster. The reason for this is that the meaning of copy may be abstraction dependent; in fact, some abstractions may not even have a copy operation.

Since copying is frequently desired, definers of clusters are urged (but not required) to provide a copy operation.

A general guideline for the definition of the copy operation, along the lines of the one given for equality in the preceding section, is:

1. for constant types,

```
y := typeofx $ copy(x)
```

   implies

```
x = y
```

2. for mutable types

```
y := typeofx $ copy(x)
```

   implies

```
typeofx $ similar(x, y)
```

Examples of copy definitions satisfying the above guidelines are given for arrays (Figure 2) and for the intset cluster (Figure 1).

Type Generators

The integer set example described earlier does not capture the concept of a set as a general receptacle for values; it only defines one particular kind of set -- a set containing integers. The concept of a generalized set presents a more powerful abstraction, the concept of "setness", than does the concept of integer set. Since the purpose of CLU is to support the use and definition of abstractions, particularly abstractions involving data, we felt it was important that CLU be powerful enough to permit a generalized set abstraction to be defined. The CLU mechanism which supports the programming of such abstractions is called a type-generator.

Type-generators differ from ordinary clusters in that they define a whole class of types, rather than a single type. Conventional programming languages contain one or more built-in type-generators. An example of such a type generator is the array. An array defines an access mechanism which is independent of the type of data which is stored in the array. Whenever an array is to be used, the program must specify what type of data the array is to contain; e.g.,

```
array of int
array of string
```

Type definitions like these can be viewed as selecting a particular array-type from the class of such types which the array type-generator defines.

CLU permits the programming of clusters which define type-generators rather than types. An example of the set type-generator is shown in Figure 4. The set cluster is very similar to the intset cluster shown in Figure 1. The two clusters differ only in that the set cluster makes use of a type parameter to define the type of element in the set, and everywhere the intset cluster used the type int to define the type of set element, the set cluster uses the type parameter.

The interface description for set identifies it as a type-generator by the presence of the cluster parameter

```
set = cluster[etype: type] is create, insert, remove, has, equal, copy
```

All clusters defining type-generators take one or more cluster parameters. The rep for set is now

```
rep = array of etype
```

The rep still makes use of the array type-generator, but it selects the particular array-type using the type parameter of the cluster.

```
set = cluster[etype: type] is create, insert, remove, has, equal, similar, copy;

    rep = array of etype;

    create = oper( ) returns (cvt);
        return (rep $ create(0));
    end create;

    insert = oper(s: cvt, i: etype);
        if search(s, i) ≤ rep $ high(s) then return;
        rep $ extendh(s, i);
        return;
    end insert;

    search = oper(s: rep, i: etype) returns (int);
        for j: int := rep $ low(s) to rep $ high(s) by 1 do
            if etype $ equal(i, s[j]) then return (j);
        return (rep $ high(s) + 1);
    end search;
     .
     .
     .
end set
```

Figure 4. The set cluster.

In addition to appearing in the cluster interface definition and in the rep definition, the cluster parameter is also used to define the types of input and output parameters of operations; for example

```
insert = oper(s: cvt, i: etype)
```

Finally, the set cluster makes use of some of the etype operations. For example, in the search operation, the equal operation of etype is used:

```
etype $ equal(i, s[j])
```

A user-defined type-generator defines a whole class of types just like the built-in type-generator array does, and the rules for using type-generators are the same in either case. First it is necessary to state precisely what type is desired. This is done by using a type definition in which values are specified for the cluster parameters of the type generator; for example

```
intset = set[int]
newset = set[set[int]]
```

As with primitive type generators, such definitions can be viewed as selecting particular set-types from the class of types defined by the set type-generator.

Once a type has been defined, it can be used to declare variables and make operation calls, e.g.,

```
 s: intset :=  intset $ create( );
 t: intset := intset $ copy(s);
ss: newset :=  newset $ create( );
      :
newset $ insert(ss, s);
```

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