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Fall 1999

A Model for Memory, Names, and Types*

1 Programming Models

One way to find your way around a programming language is to learn individual answers to numerous questions of the form "How do I get it to do X?". One can gain a certain amount of proficiency by mastering the answers to a very large body of such questions, but it is far better to find a more efficient way, preferably one that will serve to help you find your way around numerous other programming languages as well.

When I started programming, I first learned a couple of machine languages (for the IBM 1620 and the IBM 1401, and later for the IBM/360, if you are curious). This approach had various advantages. I could understand constructs in higher-level programming languages (which to me at the time meant FORTRAN, Basic, and Algol 60) by informally translating them into corresponding machine code. The reasons for certain peculiarities in the design of programming languages (such as why integers had limited range) became apparent. The relative speeds of alternative codings of a program fragment became more easily predictable. The weird effects of certain bugs in my programs became less surprising. In short, I adopted a *model* for the execution of programs and used it to explain, understand, and predict my programs' behavior. This model was by no means precise—I didn't actually view my FORTRAN programs as assembly language programs—but it gave me conceptual signposts to guide my understanding.

Unfortunately, this machine model of programs has its drawbacks. It's a pretty substantial jump from some of the constructs used in modern programming languages to their machine-code realizations. Many of the details of how a computer does things are largely irrelevant to understanding a program. For example, one usually makes no use of the fact that a pointer to a pair in Scheme is actually a number. Another example is that most machines have a finite set of variables known as *registers,* which must be used for certain operations, but which are typically invisible in high-level programming languages. Accordingly, nowadays I usually find myself using a more abstract conceptual model for most purposes. In this Note, I will present a model suitable for Scheme, Java, C, C++, and, in fact, most modern programming languages. You will find many similarities to what you learned in CS 61A (especially the environment models discussed there), and you may wish to review the textbook and handouts for that course.

2 Overview of the Model

The model presented here consists of the following components:

Values are "what data are made of." They include, among other things, integers, characters, booleans (true and false), and pointers (see below). Values, as I use the term, are *immutable;* they never change.

Containers contain values and other containers. Their contents (or *state*) can vary over time as a result of the execution of a program. Among other things, I use the term to include what are elsewhere called *variables* and *objects.* Containers may be *simple,* meaning that they contain a single value, or *structured,* meaning that they contain other containers, which are identified by names or indices. A container is *named* if there is some label or identifier a program can use to refer to it; otherwise it is *anonymous.* In Java, for example, local variables, parameters, and fields are named, while objects created by **new** are anonymous.

Types are, in effect, tags that are stuck on values and containers like Post-it$^{\text{tm}}$ notes. Every value has such a type, and in Java, so does every container. Types on containers determine the sorts of values they may contain.

Environments are special containers used by the programming language for its local and global variables.

The rest of this Note provides detail.

3 Values

One of the first things you'll find in an official specification of a programming language is a description of the primitive values supported by that language. In Java, for example, you'll find seven kinds of number (types `byte`, `char`, `short`, `int`, `long`, `float`, and `double`), booleans, and pointers. In C and C++, you will also find functions (there are functions in Java, too, but the language doesn't treat them as it does other values), and in Scheme, you will find rational numbers and symbols.

Values vs. containers. The common features of all values in our model are that they have types (see §5) and they are immutable; that is, they are changeless quantities. We may loosely speak of "changing the value of `x`" when we do an assignment such as '`x = 42`' (or '`(set! x 42)`') but under our model what really happens here is that `x` denotes a *container,* and these assignments remove the previous value from the container and deposit a new one. At first, this may seem to be a confusing, pedantic distinction, but you should come to see its importance, especially when dealing with pointers.

Pointers. A *pointer* (also known as a *reference*[1]) is a value that designates a container. When I draw diagrams of data structures, I will use rectangular boxes to represent containers and arrows to represent pointers. Two pointer values are the same if they point to the same container. For example, all of the arrows in Figure 1a represent equal pointer values. As shown there, we indicate that a container contains a certain pointer value by drawing the pointer's tail inside the container. The operation of following a pointer value to the con-

[1] For some reason, numerous Java enthusiasts are under the impression that there is some well-defined distinction between "references" and "pointers" and actually attempt to write helpful explanations for newcomers in which they assume that sentences like "Java has *references,* not *pointers*" actually convey some useful meaning. They don't. The terms are synonyms.

tainer at its head (i.e., its point) in order to extract or store a value is called *dereferencing* the pointer, and the pointed-to container is the *referent* of the pointer.

Certain pointer values are known as *null pointers*, and point at nothing. In diagrams, I will represent them with the electrical symbol for ground, or use a box with a diagonal line through it to indicate a container whose value is a null pointer. Figure 1b illustrates these conventions with a "free-floating" null pointer value and two containers with a null pointer value. Null pointers have no referents; dereferencing null pointers is undefined, and generally erroneous.

Invisible pointers. I use the term *invisible pointer* to denote special kind of 'pointer' that the programmer never sees. It is typically used to model situations where one name serves as an *alias* for another. I will draw invisible pointers with dashed arrows. The effect of fetching from or storing into a container that contains an invisible pointer is to fetch from or store into the invisibly pointed-to container. Invisible pointers, in other words, are *automatically dereferenced* (therefore, a null invisible pointer is always erroneous). Since any ordinary attempt by the programmer to set a container holding an invisible pointer instead sets the referent of that pointer, containers with invisible pointers tend to be constant once created. The motivation for these beasts may seem obscure to you, since they are not needed to describe Java; however, they are needed for C++ and numerous other languages.

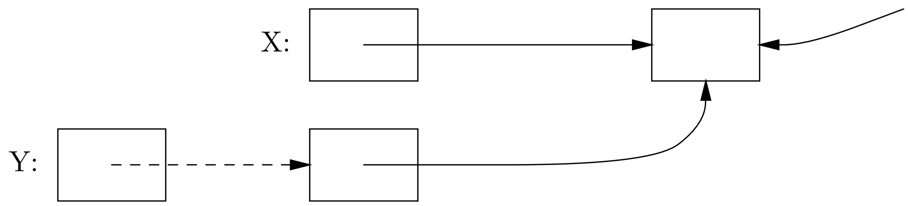
4 Containers and names

A *container* is something that can contain values and other containers. Any container may either be *labeled* (or *named*) – that is, have a some kind of name or label attached to it – or *anonymous.* A container may be simple or structured. A *simple container,* represented in my diagrams as a plain rectangular box, contains a single value. A *structured container* contains other containers, each with some kind of label; it is represented in diagrams by nested boxes, with various abbreviations. The full diagrammatic form of a structured container consists of a large container box containing zero or more smaller containers[2], each with a *label* or *name,* as in Figure 2a. Figures 2b–d show various alternative depictions that I'll also use. The inner containers are known as *components, elements* (chiefly in arrays), *fields,* or *members.*

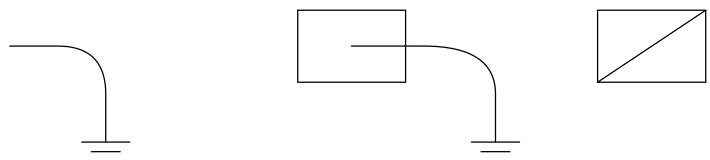
An *array* is a kind of container in which the labels on the elements are themselves values in the programming language—typically integers or tuples of integers. Figure 3 shows various alternative depictions of a sample array whose elements are labeled by integers and whose elements contain numbers.

Value or Object? Sometimes, it is not entirely clear how best to apply the model to a certain programming language. For example, we model a pair in Scheme as an object containing two components (`car` and `cdr`). The components of the pair have values, but does the pair *as a whole* have a value? Likewise, can we talk about the value in the arrays in Figure 3, or only about the values in the individual elements? The answer is a firm "that depends." We are free to say that the container in Figure 3a has the value `<2.7, 0.18, 2.8>`, and that assigning, say, 0 to the first element of the array replaces its *entire* contents with the value `<0, 0.18, 2.8>`. In a programming language with a lot of functions that deal with entire arrays, this would be useful. To describe Java, however, we don't happen to need the

[2] The case of a structured container with no containers inside it is a bit unusual, I admit, but it does occur.



(a) All visible pointers here are equal. Y's value is an invisible pointer, so fetching it also gets the same value as fetching X.



(b) Null pointers.

Figure 1: Diagrammatic representations of pointers.

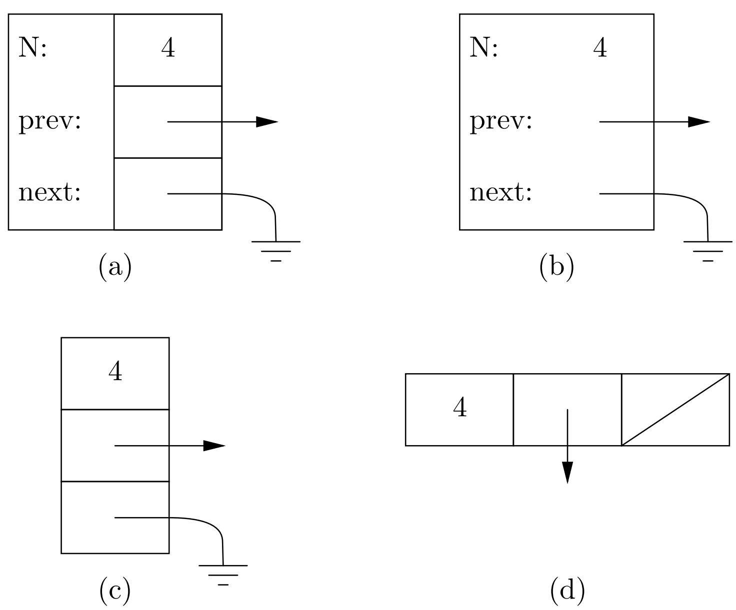


Figure 2: A structured container, depicted in several different ways. Diagrams (c) and (d) assume that the labels are known from context.

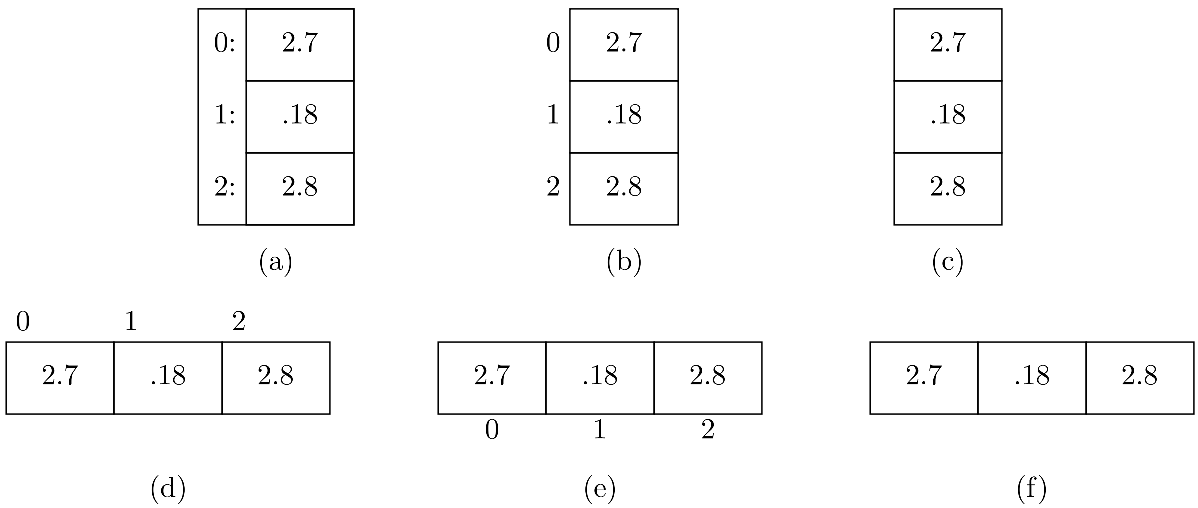


Figure 3: Various depictions of one-dimensional array objects. The full diagram, (a), is included for completeness; it is generally not used for arrays. The diagrams without indices, (c) and (f), assume that the indices are known from context or are unimportant.

concept of "the value of an array object."

5 Types

The term "type" has numerous meanings. One may say that a type is a set of values (e.g., "the type `int` is the set of all values between -2^{31} and $2^{31}-1$, inclusive.") Or we may say that a type is a programming language construct that defines a set of values and the operations on them. For the purposes of this model, however, I'm just going to assume that a type is a sort of "tag" that is attached to values and (possibly) containers. Every value has a unique type. This does *not* necessarily reflect reality directly. For example, in typical Java implementations, the value representing the character `'A'` is indistinguishable from the integer value 65 of type `short`. These implementations actually use other means to distinguish the two than putting some kind of marker on the values. For us programmers, however, this is an invisible detail.

Any given programming language provides some particular set of these type tags. Most provide a way for the programmer to introduce new ones. Few programming languages, however, provide a direct way to look at the tag on a value (for various reasons, among them the fact that it might not really be there!).

When *containers* have tags (they don't have to; in Scheme, for example, they generally don't), these tags generally determine the possible values that may be contained. In the simplest case, a container labeled with type `T` may only contain values of type `T`. In Java (and C, C++, FORTRAN, and numerous other languages), this is the case for all the numeric types. If you want to store a value of type `short` into a container of type `int`, then you must first *coerce* (a technical term, meaning *convert*) the `short` into an `int`. As it happens, that particular operation is often merely notional; it doesn't require any machine instructions to perform, but we can still talk that way.

In more complex cases, the type tag on a container may indicate that the values it contains may be one of a whole set of possible types. In this case, we say that the allowable types on values are *subtypes* of the container's type. In Java, for example, if the definition of class `Q` contains the clause "**extends** `P`," then `Q` is a subtype of `P`; a container tagged to contain pointers to objects of type `P` may contain pointers to objects of type `Q`. As a special case, any type is a subtype of itself; we say that one type is a *proper subtype* of another to mean that it is an unequal subtype.

If type C is a subtype of type P, and V is a value whose type tag is C, we say that "V *is a* P" or "V *is an instance of* P." Unfortunately, this terminology makes it a little difficult to say that V "really is a" a P and not one of its proper subtypes, so in this class I'll say that "the type of V *is exactly* P" when I want to say that.

Important Aside on Java. In Java, all objects created by **new** are anonymous. If `P` is a class, then the declaration

```
P x;
```

does *not* mean that "`x` contains objects of type `P`," but rather that "`x` contains (null or) *pointers to* objects of type `P`." If `Q` is a subtype of `P`, furthermore, then the type "pointer to `Q`" is a subtype of "pointer to `P`." However, because it is extremely burdensome always to be saying "`x` contains a pointer to `P`," the universal practice is just to say "`x` is a `P`." After this section, I'll do that, too, but until it becomes automatic, I suggest that you consciously translate all such shorthand phrases into their full equivalents. **End of Aside.**

All this discussion should make it clear that the tag on a value can differ from the tag on a container that holds that value. This possibility causes endless confusion, because of the rather loose terminology that arose in the days before object-oriented programming (it is object-oriented programming that gives rise to cases where the confusion occurs). For example, the following Java program fragment introduces a variable (container) called `x`; says that the container's type is (pointer to) `P`; and directs that a value of type (pointer to) `Q` be placed in `x`:

```
P x = new Q ();
```

Programmers are accustomed to speak of "the type of `x`." But what does this mean: the type of the value contained in `x` (i.e., pointer to `Q`), or the type of the container itself (i.e., pointer to `P`)?

We will use the phrase "the *static type* of `x`" to mean the type of the container (pointer to `P` in the example above), and the phrase "the *dynamic type* of `x`" to mean the type of the value contained in `x` (pointer to `Q`). This is an extremely important distinction! Object-oriented programming in C++ or Java will be a source of unending confusion to you until you understand it completely.

6 Environments

In order to direct a computer to manipulate something, you have to be able to mention that thing in your program. Programming languages therefore provide various ways to *denote* values (literal constants, such as `42` or `'Q'`) and to denote (or *name*) containers. Within our model, we can imagine that at any given time, there is a set of containers, which I will call the *current environment,* that allows the program to get at anything it is supposed to be able to reach. In Java (and in most other languages as well) the current environment cannot itself be named or manipulated directly by a program; it's just used whenever the program mentions the name of something that is supposed to be a container. The containers in this set are called *frames.* The named component containers inside them are what we usually call local variables, parameters, and so forth. You have already seen this concept in CS 61A, and might want to review the material from that course.

When we have to talk about environments, I'll just use the same container notation used in previous sections. Occasionally, I will make use of "free-floating" labeled containers, such as

X: [42]

to indicate that `X` is a variable, but that it is not important to the discussion what frame it sits in.

7 Applying the model to Java

As modern languages in the Algol family go, Java is fairly simple[3]. Nevertheless, there is quite a bit to explain. Here is a summary of how Java looks, as described in the terminology of our model. We'll get into the details of what it all means in a later note.

- All simple containers contain either numeric values, booleans, or pointers (known as *references* in Java). (There are also functions, but the manipulation of function-valued containers is highly restricted, and not entirely accessible to programmers. We say no more about them here.)

- All simple containers are named and only simple containers are named. The names are either identifiers (variables, parameters, or fields) or non-negative integers (array elements).

- All simple containers have well-defined initial values: 0 for numerics, **false** for booleans, and **null** for pointers.

- The referents of pointers are always anonymous structured containers (called *objects* in Java).

- Aside from environments, objects are created by means of the **new** expression, which returns a pointer (initially the only one) to a new object.

- Each container has a static type, restricting the values it may contain. A container's type may be *primitive* – which in Java terminology means that it may one of the numeric types or **boolean** – or it may be a *reference type,* meaning that it contains pointers to objects (including arrays). If a container's static type is primitive, it is the same as its dynamic type (that is, the type of the container equals the type of the value). If a container has a reference type, then its dynamic type is a subtype of the container's type.

- Named containers comprise local variables, parameters, instance variables, and class variables. Every function call creates a *subprogram frame,* (or *procedure frame,* or *call frame*), which contains parameters and local variables. The **new** operator creates *class objects* and *array objects,* which contain instance variables (also called *fields* in the case of class objects and *elements* in the case of arrays). The type of a class object is called, appropriately enough, a *class.* Each class has associated with it a frame that (for lack of a standard term) I will call a *class frame,* which contains the class variables (also called *static variables*) of the class.

8 Important Concepts

This Note summarizes quite a few rather important concepts. Early on in a programming course, this may all seem rather abstract

[3] Algol 60 (ALGOrithmic Language) was the first widely used language with the kind free-format syntax familiar to C, C++, and Java users. It has, in fact, been called "a marked improvement on its successors."

and vague. Therefore, you will do well to review the concepts in this Note from time to time throughout the semester. See if you can "attach" them to programming languages you already know and look out for their appearance while learning Java. Be particularly sure to understand the following terms and phrases: value, container, simple container, structured container, named and anonymous containers, component (element), pointer (reference), invisible pointer, type, static type, dynamic type, subtype, proper subtype, "V is a T," "type of a value," " type of a container," coercion, environment, and frame.