A literate, executable, denotational semantics of simple C++ declarations

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Abstract

Denotational semantics are developed for simple C++ declarations and are implemented in a functional language using a literate programming style.

1 Introduction

Computer languages are difficult to learn and understand. Part of the problem is that there is (usually) no formal statement of what various language constructs mean. Denotational semantics [Sch86] provides a formal framework for developing this meaning. Yet there is no denotational semantics for C++.

This paper provides a denotational semantics for some simple C++ declarations.

1.1 Audience

This paper is intended for a general computer science audience interested in denotational semantics and C++ declarations. A familiarity with C++ and and SML is assumed.

Serious students of C++ can see how memory and environments are used. Students of denotational semantics can use this as an example of a semantics of a "real" language. Designers of C++-like languages can use this to guide how new features will work. Finally, C++ implementors and designers of C++ specification languages can use this as a formal definition of C++.

1.2 C++ declarations

The semantics given here model a small but usable subset of C++'s variable and class declarations. Currently they model variable declarations involving primitive types, pointers, arrays, and classes. No modifiers or initializers can
be specified. Class declarations are limited to public members only, and members must be objects. Nested class definitions are not allowed, although class members may be class types.

Another restriction is that variables and classes must have unique names. E.g., you cannot say class foo {} foo; because then foo would denote both a variable and a class.

1.3 Denotational Semantics

In denotational semantics, programs are mapped directly to their meanings as in [Sch86]. In practice this means a pre-digested tree is mapped onto well-understood environment and memory operations. It is the particular mapping that defines the language and provides the semantics.

1.4 Using SML to implement semantics

The semantics in this paper are implemented in Standard ML (SML) [Pau91]. (ML was originally the name of a meta language for a theorem prover system [GMWT91].) This language is secure from type subversion and corruption of the run-time environment [Pau91, Section 1.5]. These features should be considered essential in any implementation of a formal system.

SML signatures are used to describe the semantic domains. They provide a natural way to modularize the code and separate the system’s functionality from implementation details.

Also, many of these signatures contain an SML datatype. By putting the datatype in the signature, clients can use the type’s constructors and observers without additional effort on the ML programmer’s part. For example, in the following we advertise that clients can create values of Foo_Type using constructors Bar and Baz, and can observe the result of fooey using SML’s pattern matching facilities.

\[
\text{(Example using a SML datatype)}
\]

\[
\text{signature Foo_Sig =}
\]

\[
\begin{align*}
\text{sig} & \\
\text{datatype Foo_Type =} & \\
\text{Bar of Int} & | \text{Baz of Int} & \\
\text{val fooey: Foo_Type * Foo_Type -> Foo_Type} &
\end{align*}
\]

\[
\text{end}
\]

Root module (not used in this document).

We say that a function mutates a value when that value is an input to the function and a similar value of the same type is an output of the function. For instance, consider the signature of a typical memory update function:
update: Location * Value * Memory -> Memory. We say that update mutates memory when, in fact, no SML value is mutated. Memory is mutated only in the sense that the new value is (usually) similar to the old value and the previous value is never again referred to. SML's imperative capability is not used in these semantics because of the well-known difficulty in understanding the scope of the effect of an assignment.

1.5 Literate Programming

The program described here is written using a literate programming technique. This technique combines documentation and source code into one coherent document. In this way, you are assured that the documentation is up to date.

The literate programming tool used here is noweb [Ram92]. With this tool, a text file contains the literate program which looks very much like the \TeX input that created this paper. The file can be processed by nowave to produce this file. And it can be processed by notangle to produce the source code.

Noweb sees this paper as a series of "chunks" embedded in the text of the paper. Each chunk begins with an identifier consisting of a short description in angle braces. Noweb also supplies the page number where the chunk is defined. The body of the chunk is typeset in a monospaced font and may contain references to other chunks by giving those chunks' identifiers.

Noweb forms the completed program by pasting the chunks together hierarchically beginning with the special chunk whose name is simply an asterisk. By recursively following the chunks referred to in that chunk and substituting the text literally, noweb pieces together the entire program.

Noweb chunks in this document are given descriptive names. Pieces of types, typedefs, functions, values, signatures, and structures are identified by chunks that have the appropriate keyword in their name. Chunks that contain complete SML declarations have names that end with the word "declaration" or "definition." Other chunks contain smaller syntactic units, not top-level declarations, and are used to break up the code into manageable pieces.

1.6 Organization

The rest of this paper is organized around the presentation of the semantics. First, the syntactic and semantic domains are described. Next the semantic domains are implemented. Then the valuation functions are given. These are followed by a short section on testing, related work, conclusions, and acknowledgements.

The overall structure of the SML source code is given by the following. Note here that this follows the order given in this paper — this will not always be the case for other sections. (Recall that the asterisk tells noweb this is the root chunk, i.e., noweb starts here when pasting together the code.)
2 Syntactic Domains

We begin with a discussion of the syntactic domains. There are two. The first allows creation of types. The second allows the C++ programmer to declare variables.

C++ declarations are given using an abstract syntax [Sch86, Section 1.1]. For example, the C++ declaration `int i;` is represented by the SML expression `var_decl ("i", IntType)`. A list of such declarations is represented by an ordinary SML list.

2.1 Declaration Syntax

The declarations considered here are either simple variable declarations or simple class definitions. By simple class definitions, we mean classes that do not contain protected or private members, member functions, or type definitions. This corresponds to the Classic C notion of a `struct`.

The following SML datatype defines the type of C++ declarations. For a variable, we need only its name and type. For a structure, we need its name and a list of its field names and what types they store: essentially a list of declarations. Note that this definition allows nested class definitions.

The actual data type is broken out here and given separately so that it can be used in the `Data_Type` signature and also in the `Data_Type` structure to be given later. This is an example of where the literate programming technique facilitates code re-use not present in the target language.
2.2 Data Types

This section gives the abstract syntax for C++ data types—the types for C++ variables. Note that the type is implemented as a SML datatype which provides the clients with constructors and observers. The only operation is `sizeof` which implements the C++ operator of the same name.

Note that the `ClassOf` constructor takes the `name` of a class, not a description of the class itself. Anonymous classes are not allowed in these semantics. This also means that the environment is needed in the `sizeof` function.

For example `var_decl("i", IntType)` represents `int i;`:

\[
\langle Data-Type type declaration \rangle \equiv \\
\text{datatype Data_Type} = \\
\quad \text{CharType} \\
\quad | \text{IntType} \\
\quad | \text{FloatType} \\
\quad | \text{DoubleType} \\
\quad | \text{PtrToType of Data_Type} \\
\quad | \text{ArrayOfType of Nat * Data_Type} \\
\quad | \text{ClassOfType of Identifier}
\]

This code is used on page 4.

\[
\langle Data-Type signature declaration \rangle \equiv \\
\text{signature Data_Type_Sig} = \\
\quad \text{sig} \\
\quad \quad \text{type Environment} \\
\quad \quad \text{type Data_Type} \\
\quad \quad \text{val sizeof: Data_Type * Environment} \to \text{int}
\]

This code is used on page 4.

3 Semantic Domains

We now turn our attention to the semantic domains. The mundane domains of truth values, identifiers, and numbers are modeled with the built-in capabilities of SML. The environment and denotable values provide the usual sort of environment capabilities [Sch86]. Finally, memory and storable values provide the rich set of capabilities in C++ data structures. These last set of capabilities are most interesting.
This section presents the capabilities only—the interfaces for users of the system. The implementations are given later.

The following is an outline of all the signatures for the semantic domains. These are discussed later in this section.

\[
\langle\text{semantic domain declarations 6}\rangle \equiv \\
\langle\text{***** semantic domains *****}\rangle \\
\langle\text{environment signature declaration 7}\rangle \\
\langle\text{memory signature declaration 8}\rangle \\
\langle\text{basic value signature declaration 9}\rangle \\
\langle\text{array signature declaration 10}\rangle \\
\langle\text{pointer signature declaration 10}\rangle \\
\langle\text{object signature declaration 11}\rangle \\
\text{This code is used on page 4.}
\]

3.1 Denotable Values

For our purposes, a C++ name is either the name of a variable or the name of a class.

For a variable, we are interested in its type and where its value is stored. Since our model of memory keeps track of the type of data stored at each location, the denotation of a variable is simply the Location of its value. The types for classes are discussed in the next paragraph.

\[
\langle\text{Denotable-Value type declaration 6}\rangle \equiv \\
\text{datatype Denotable\_Value =} \\
\text{ Variable of Location} \\
\text{ Class of class\_info} \\
\text{This code is used on page 12.}
\]

The class\_info type holds information about a class. It consists of the size of a class and a function to construct new objects in memory. These are created when the class is declared and are discussed with the class valuation functions.

\[
\langle\text{Class type declarations 6}\rangle \equiv \\
\text{type object\_constructor\_type = Memory} \rightarrow \text{Location} \ast \text{Memory} \\
\text{type class\_info = int} \ast \text{object\_constructor\_type} \\
\text{This code is used on page 12.}
\]

3.2 Environment

The environment maps from Identifier to Denotable\_Value. For example, the following C++ declarations would add two new mappings to the environment: the name “Coord” to a SML\_Class which represents the equivalent C++
class, and the name “loc” to a SML Variable which represents the equivalent C++ variable.

```c
struct Coord { int x, y; }; Coord loc;
```

Functions `new.add` and `lookup` provide the usual capabilities [Sch86, Chapter 7]. `lookup` raises the exception `symbol_not_found` if the symbol it is looking for is not there.

The operations `enter_block` and `is_local` handle C++'s block structure.

```c
<environment signature declaration?>≡
signature Environment_Sig =
sig
type Environment
  type Denotable_Value
  exception symbol_not_found
  val empty_env: Environment
  val add: Environment * Identifier * Denotable_Value → Environment
  val lookup: Environment * Identifier → Denotable_Value
  val is_in_env: Environment * Identifier → bool
  val in_local_scope: Environment * Identifier → bool
  val enter_block: Environment → Environment
end
```

This code is used on page 6.

### 3.3 Storable Value

The C++ memory stores several different kinds of values: basic values, arrays, pointers, and objects. These are all alternatives of the `Storable_Value` type, discussed in detail below.

These types are all mutually recursively defined with Memory and the specific storable values. The SML keyword `datatype` is given when all these types are all defined together, not here.

```c
<Storable-Value type?>≡
(* datatype *) Storable_Value =
  BV of Basic_Value
  | AV of Array_Value
  | PV of Pointer_Value
  | OV of Object_Value
```

This code is used on page 12.

There are three functions over all kinds of storable values: `alloc`, `sizeof`, and `copy`. Alloc creates a storable value from a data type. Sizeof yields the size, in bytes, of a storable value. And copy copies a storable value into some memory location.
\{alloc function signature 8\} ≜
Data_Type * Memory * Environment → Location * Memory
This code is used on page 16.

\{sizeof function signature 8\} ≜
Storable_Value → int
This code is used on page 16.

\{copy function signature 8\} ≜
Storable_Value * Location * Memory → Memory
This code is used on page 16.

3.4 Memory

Memory provides the usual sort of mapping from Location to Storable_Value [Sch86, Chapter 5]. The value initial and functions alloc and read should be self-explanatory. Function is_same_location provides an equality test for locations. The only wrinkle is that we require clients to make up values when they allocate cells even if they want to consider a cell uninitialized. (We do this so we will have a type for the cell.) The clients must supply either the value initialized or not_initialized when they allocate cells.

The other elements of the memory domain is for the convenience of the rest of the program. The location null_loc provides the null pointer value in C++. Location undef_loc provides the initial value for an uninitialized pointer. The exception read_out_of_bounds is raised only when a read or write operation requests a non-existant memory location. Finally, the exception uninitialized_memory is raised when attempting to read from a location that does not contain a value.

Our memory is primitive in that that deals only with storing and retrieving information, not how that information is aggregated. The array, pointer, and object domains each have to worry about how they aggregate their values.

\{memory signature declaration 8\} ≜
signature Memory_Sig =
sig
type Location
type Storable_Value
type Memory
exception read_out_of_bounds
exception uninitialized_memory
val initialized: bool
val not_initialized: bool
val null_loc: Location
val undef_loc: Location
val is_same_location: Location * Location → bool
val initial: Memory
val alloc: Memory * Storable_Value * bool -> Location * Memory
val write: Memory * Location * Storable_Value -> Memory
val read: Memory * Location -> Storable_Value
end;

This code is used on page 6.

3.5 Basic Value

The Basic_Value domain holds those C++ types that do not refer to other C++ types. It is implemented as an SML datatype. Once again, here, we use noweb to duplicate code. This appears both in the signature and in the structure.

```
⟨Basic-Value datatype declaration 9⟩≡
  datatype Basic_Value =
    IntVal of int
  | CharVal of int
  | FloatVal of real
  | DoubleVal of real
This code is used on pages 9, 12, and 19.
```

```
⟨basic value signature declaration 9⟩≡
  signature Basic_Sig =
    sig
      ⟨Basic-Value datatype declaration 9⟩
    end;
This code is used on page 6.
```

3.6 Array Value

The Array_Value domain models C++ arrays.

Since C++ uses the indirect model of arrays, so do these semantics. An array is a sequence of Locations. This makes it easy to take the address of an element as in &myarray[3]. (Recall that C++ arrays are one dimensional, but elements can themselves be arrays.)

The alloc function takes a memory, the type of array elements, and the array size. It reserves cells for the array and returns a new memory and the location of where the new array was created. Indexing yields one of the reserved locations. Hence reading or writing an array element involves first indexing to get the location, then manipulating memory directly.

The operation is_same_array_value checks if two arrays are the same array. This is used, for instance, to determine if pointer comparison is meaningful.
(Comparing two pointers is meaningful only if the pointers are either both point-
ing to the same location or both pointing into the same array [ES90, Section 5.9].)

```plaintext
{array signature declaration 10}≡
signature Array_Sig =
    sig
    type Array_Value
    type Memory
    type Location
    val alloc: Data_Type * Nat * Memory → Array_Value * Memory
    val index: Array_Value * Nat → Location
    val is_same_array_value: Array_Value * Array_Value → bool
end;
This code is used on page 6.
```

### 3.7 Pointer Value

Pointers refer to other storable values. They can be thought of abstractions on Location.

Function `create`, when given a type, creates an uninitialized pointer. The function `make_ref`, when given a `Location` and `Memory`, mutates a pointer refer to the new location. Its inverse, `deref`, gets back the location from the pointer. The `Memory` is required as an argument to `make_ref` so type checking can be done. If `make_ref` is passed the location of an entire array it silently forms a pointer to the zeroth element of that array.

The `increment` operation traverses the array forward or backward. If it goes past the beginning or more than one past the end of the array, it raises the exception `pointer_escaped_array`. Any attempt to `deref` a pointer one past the end of an array will raise the exception `deref_outside_array`. Using `increment` on a non-array pointer will raise the exception `increment_undefined`.

When two pointers are both pointing into the same array or both at the same non-array value, `difference` returns the pointers’ distance in terms of array elements. Otherwise it raises the exception `ptrdiff_undefined`.

```plaintext
{pointer signature declaration 10}≡
signature Pointer_Sig =
    sig
    type Pointer_Value
    type Memory
    type Location
    exception ptdiff_undefined
    exception pointer_escaped_array
    exception deref_outside_array
```
exception increment_undefined

val create: Data_Type -> Pointer_Value
val make_ref: Pointer_Value * Location * Memory -> Pointer_Value
val deref: Pointer_Value -> Location

val difference: Pointer_Value * Pointer_Value -> int
val increment: Pointer_Value * int -> Pointer_Value
end;

This code is used on page 6.

3.8 Object Value

Objects are instances of C++ classes. When we say C++ classes, we also mean
C++ structures since the two are so similar. Recall also that our model only
handles the Classic C features of structs.

We model objects using the indirect model: as mappings from field names
to locations. The dot function selects a member of an object. If the field name
is incorrect, the exception not_member is raised.

{object signature declaration 11}≡
signature Object_Sig =
sig
type Object_Value
  type Memory
  type Location
exception not_member
val dot: Object_Value * Identifier -> Location
end;

This code is used on page 6.

The instantiation and copy functions are handled by the object’s class defi-
nition. They are discussed with the Class implementation, not here.

4 Semantic Domain Implementations

In this section we implement the semantic domains. Overall, we have several
semantic domains that need to share types. These are declared first. Next,
Memory and Environment are implemented in terms of these. Finally, the
subdomains and Storable-Values themselves are given.

{domain implementations 11}≡
(***** domain implementations *****)
{semantic domain implementation type declarations 12}
The outline of all semantic types is given below. The details are discussed with each domain. Most of these have to be in the order given here. As is usual in denotational semantics, there are many mutually-recursive types; these are given here with the and \texttt{withtype} keywords.

\begin{verbatim}
\{semantic domain implementation type declarations 12\} ≡
\{Location type declaration 17\}
\{Basic-Value datatype declaration 9\}
datatype \{Pointer-Value type 24\}
        and \{Storable-Value type 7\}
withtype \{Memory type 17\}
        and \{Array-Value type 20\}
        and \{auxiliary object types 31\}
        and \{Object-Value type 27\}
\{Class type declarations 6\}
\{Denotable-Value type declaration 6\}
\{Environment type declaration 13\}
\end{verbatim}

This code is used on page 11.

\section{Data Type Implementation}

The type \texttt{Data_Type} has a simple implementation; the SML \texttt{datatype} did most of the work. We simply use that here and implement the \texttt{sizeof} function.

\begin{verbatim}
\{data type implementation 12\} ≡
structure Data_Type_Struct : Data_Type_Sig =
\{data type sizeof function declaration 13\}
\end{verbatim}

This code is used on page 12.

The \texttt{sizeof} function gives the size of each type. Its second argument, the environment, is necessary to look up a class by name.
\{data type \texttt{sizeof function declaration 13}\} ≡ 
\begin{verbatim}
fun sizeof(IntType, _) = 2
| sizeof(CharType, _) = 1
| sizeof(FloatType, _) = 4
| sizeof(DoubleType, _) = 8
| sizeof(PtrToType(_), _) = 4
| sizeof(ArrayOfType(size, t), env) =
    size * sizeof(t, env)
| sizeof(ClassOfType(name), env) =
    let val Class(size, _) = lookup(env, name) in
    size
end
\end{verbatim}
This code is used on page 12.

4.2 Environment Implementation

Our environment implementation consists of the environment structure opened up so its components can be used easily.

\{Environment implementation 13\} ≡ 
\begin{verbatim}
\{environment structure declaration 13\}
open Environment_Struct;
\end{verbatim}
This code is used on page 12.

We implement environments in the usual way: as functions from identifiers to denotable values.

\{Environment type declaration 13\} ≡ 
\begin{verbatim}
type Environment = Identifier -> Denotable_Value
\end{verbatim}
This code is used on page 12.

To implement scoping, we use an exception, \texttt{end_of_block}. Raising this exception means “the operation could not be carried out within the most local block.” The exception returns the next-most local environment so further work can be done. Clients will never see this exception; they are all handled within environment functions. See \texttt{enter_block} and \texttt{is_local} for details.

\{environment structure declaration 13\} ≡ 
\begin{verbatim}
structure Environment_Struct : Environment_Sig =
structure
    type Denotable_Value = Denotable_Value
type Environment = Environment
exception symbol_not_found
exception end_of_block of Environment
\end{verbatim}
Looking up a symbol amounts to applying the environment to the symbol. If the symbol is not in the top-level block, there will be an end_of_block exception. We handle this by looking up the symbol in the next block down. If the symbol is undefined, the exception symbol_not_found is raised for the client to handle.

\[\text{fun \ lookup(env, id) =} \]
\[\text{handle end_of_block env2 => lookup(env2, id)} \]

Checking if a symbol is defined amounts to looking it up. If found, the function returns true. Otherwise the symbol_not_found exception will be raised and the function returns false.

\[\text{fun \ in\_env(env, id) =} \]
\[\text{let \ val _ = lookup(env, id) in} \]
\[\text{true} \]
\[\text{handle symbol_not_found => false} \]

Checking if a symbol has a local definition is similar to looking it up. If it is in the most local block, then it will be found without raising any exceptions and the function returns true. Otherwise an end_of_block exception will be raised and the function returns false.

\[\text{fun \ in\_local\_scope(env, id) =} \]
\[\text{let \ val info = env(id) in} \]
\[\text{true} \]
\[\text{handle end_of_block _ => false} \]
To enter a new block we create a function which raises the `end_of_block` exception and carries with it the lower-level blocks.

\[\text{environment enter block function declaration 15}\] \begin{align*}
\text{fun enter_block(env) =} \\
\quad \text{fn(id) => raise end_of_block(env)}
\end{align*}

This code is used on page 14.

The empty environment contains one block with no symbols defined.

\[\text{environment empty env val declaration 15}\] \begin{align*}
\text{val empty_env =} \\
\quad \text{fn(id) => raise end_of_block(fn(id) => raise symbol_not_found)}
\end{align*}

This code is used on page 14.

Adding a binding to an environment is done in the usual way. We simply add the mapping to the function.

\[\text{environment add function declaration 15}\] \begin{align*}
\text{fun add(env, id, info) =} \\
\quad \text{update(env, id, info)}
\end{align*}

This code is used on page 14.

The function above uses the “update” function to make incremental changes in the behavior of a function. The implementation is given here although it is not part of the environment domain; so this chunk is pasted into the “miscellaneous” section of the program `noweb` builds.

The general-purpose update function takes three arguments: the function to be updated, an element of the domain of the function, and its new value. It constructs a new function such that \(update(f, x, y)\) is defined as \(f\) updated so that \(x\) maps to \(y\).

\[\text{general-purpose function update declaration 15}\] \begin{align*}
\text{fun update(oldfun, domain_element, new_value) =} \\
\quad \text{fn(x) => if x=domain_element then new_value else oldfun(x)}
\end{align*}

This code is used on page 28.

4.3 Storable Value Implementation

Recall that the `Storable_Value` datatype is nothing more than a collection of other types, each with their own implementations. What is left to do here is to tie the `alloc`, `copy`, and `sizeof` function implementations together. These do little more than shunt the work off to the appropriate functions.
4.4 Memory Implementation

To implement memory, we complete the memory structure and make some shorthand notation.

\(\text{Memory implementation 17} \equiv \)
\(\text{Memory structure declaration 17} \equiv 
\begin{align*}
\text{val allocmem} &= \text{Memory}\_\text{Struct}.\text{alloc} \\
\text{val readmem} &= \text{Memory}\_\text{Struct}.\text{read} \\
\text{val writemem} &= \text{Memory}\_\text{Struct}.\text{write} \\
\text{val initialized} &= \text{Memory}\_\text{Struct}.\text{initialized} \\
\text{val not}\_\text{initialized} &= \text{Memory}\_\text{Struct}.\text{not}\_\text{initialized} \\
\text{val is}_\text{same}\_\text{location} &= \text{Memory}\_\text{Struct}.\text{is}\_\text{same}\_\text{location} \\
\text{val undef\_loc} &= \text{Memory}\_\text{Struct}.\text{undef\_loc} \\
\text{val null\_loc} &= \text{Memory}\_\text{Struct}.\text{null\_loc}
\end{align*}
\)

This code is used on page 12.

Memory is implemented in the usual way [Sch86, Section 5.1]. Locations are represented by integers. Memory is represented by a function from Location to Storable\_Value. We also keep a separate component to generate unique locations, so Memory is a tuple containing the function and an integer which represents the next-free location.

\(\text{Location type declaration 17} \equiv 
\begin{align*}
\text{type Location} &= \text{int} \\
\end{align*}
\)

This code is used on page 12.

\(\text{Memory type 17} \equiv 
\begin{align*}
\text{Memory} &= \text{Location} \times (\text{Location} \to \text{Storable\_Value})
\end{align*}
\)

This code is used on page 12.

Our goal in this section is to implement the memory structure.

\(\text{Memory structure declaration 17} \equiv 
\begin{align*}
\text{structure Memory}\_\text{Struct} : \text{Memory}\_\text{Sig} = 
\text{struct} \\
\text{type Location} &= \text{Location} \\
\text{type Storable\_Value} &= \text{Storable\_Value} \\
\text{type Memory} &= \text{Memory} \\
\text{exception read\_out\_of\_bounds} \\
\text{exception uninitialized\_memory}
\end{align*}
\)

\(\text{initialized and not\_initialized value declarations 18} \equiv 
\text{the null location declaration 18} \equiv 
\text{the undefined location declaration 18} \equiv 
\text{the memory is\_same\_location function definition 18} \equiv 
\)}
(the initial memory value declaration 18)
(the memory alloc function declaration 19)
(the memory write function declaration 19)
(the memory read function declaration 18)
end;

This code is used on page 17.

The following two values provide mnemonics for when memory is allocated. Recall that a storable value is required when allocating memory. Clients must say whether this value initializes memory or not.

(initialized and not-initialized value declarations 18)≡
val initialized = true
val not_initialized = false

This code is used on page 17.

In this model, it is easy to create special locations.

(null location declaration 18)≡
val null_loc = 0

This code is used on page 17.

(undef location declaration 18)≡
val undefined_loc = 1

This code is used on page 17.

The initial memory begins allocating at the location represented by the SML integer 2 and contains the function that rejects every reference.

(initial memory value declaration 18)≡
val initial = (2, fn(loc) => raise read_out_of_bounds)

This code is used on page 18.

Checking if two locations are really the same location is as easy as comparing their integer locations.

(is same-location function definition 18)≡
fun is_same_location(loc1, loc2) = loc1 = loc2

This code is used on page 17.

As a consequence of the memory type, the memory read function is very simple. We have only to apply the location to the memory mapping.

(memory read function declaration 18)≡
fun read(_, mem_fn, loc) = mem_fn(loc)

This code is used on page 18.
Writing to some location involves updating the memory mapping so that the location maps to its new value. The next-free counter is not changed.

\[\text{mem write function declaration 19}\] \equiv
fun write((size,f), loc, new_value) =
  (size, update(f, loc, new_value))
This code is used on page 18.

Allocating a new location is only a bit more involved. Here we must return a pair containing the new location and the new memory. The new location is readily available from the old memory. And the new memory is easily constructed by incrementing the next-free counter and constructing the appropriate function.

\[\text{mem alloc function declaration 19}\] \equiv
fun alloc((size,f), value, is_init) =
  (size,
   (size+1,
    fn(loc) => if loc=size
    then if is_init
    then value
    else raise uninitialized_memory
    else f loc))
This code is used on page 18.

4.5 Basic Value Implementation

To complete the Basic Value Implementation we have only to complete the alloc, sizeof, and copy functions.

As already given in the signature, we model the C++ basic values as SML values. We simply repeat that datatype here.

\[\text{basic value structure declaration 19}\] \equiv
structure Cxx_Basic : Basic_Sig =
  struct
  \{Basic-Value datatype declaration 9\}
  end
This code is used on page 12.

Finding the sizeof a basic value is trivial. Note that the sizes used here are implementation dependent. For instance, some machines have 4 byte integers. The language standard does not specify a size, only that sizeof(char) == 1.

\[\text{Basic-Value sizeof function 19}\] \equiv
  (BV(IntVal(_))) => 2
| (BV(CharVal(_))) => 1 |
| (BV(FloatVal(_))) => 4 |
| (BV(DoubleVal(_))) => 8 |

This code is used on page 16.

Allocating memory for a basic value is as simple as allocating a chunk of memory. We have to make up a dummy value of the correct type to store in the memory. And we tell Memory that the cell is not_initialized. Recall that this code is just part of the unified alloc function.

\[
\text{Basic-Value alloc function 20} \equiv
\]
\[
(* \text{val rec alloc = fn *})
\]
\[
\text{(CharType, mem, env) =>}
\]
\[
\text{allocmem(mem, BV(CharVal(99)), not_initialized)}
\]
| (IntType, mem, env) => |
\[
\text{allocmem(mem, BV(IntVal(99)), not_initialized)}
\]
| (FloatType, mem, env) => |
\[
\text{allocmem(mem, BV(FloatVal(99.0)), not_initialized)}
\]
| (DoubleType, mem, env) => |
\[
\text{allocmem(mem, BV(DoubleVal(99.0)), not_initialized)}
\]

This code is used on page 16.

Copying a basic value to some location is as simple as writing its value there.

\[
\text{Basic-Value copy function 20} \equiv
\]
\[
(BV(x), loc, mem) =>
\]
\[
\text{writemem(mem, loc, BV(x))}
\]

This code is used on page 16.

4.6 Array Value Implementation

Array values are basically mappings from integers to locations. Along with this function we also store the number of elements in the array, the type of the elements, and the sizeof the array.

\[
\text{Array-Value type 20} \equiv
\]
\[
\text{Array Value = Nat} \times (\text{Nat} \rightarrow \text{Location}) \times \text{Data Type} \times \text{Nat}
\]

This code is used on page 12.

Our goal in this section is to complete the Array_Struct and to write the alloc, copy, and sizeof functions for arrays.

\[
\text{array structure declaration 20} \equiv
\]
\[
\text{structure Array_Struct =}
\]
\[
\text{struct}
\]
type Array_Value = Array_Value
    type Memory = Memory
    type Location = Location
except array_range

{array index function declaration 21}
    {is-same-array-value function declaration 21}
end;
This code is used on page 12.

The index function is straightforward given our array types.

{array index function declaration 21} ≡
    fun index((_, index_fn, _,_), index) = index_fn(index)
This code is used on page 21.

The function is_same returns true if and only if its inputs are the same array. This is true exactly when the locations of the zeroth elements coincide. (Recall that the indexing function does not change after the array is created.)

{is-same-array-value function declaration 21} ≡
    fun is_same_array_value((_, index_fnA, _,_), (_, index_fnB, _,_)) =
        is_same_location(index_fnA(0), index_fnB(0))
This code is used on page 21.

Allocating an array involves allocating a location for each element, an additional location for the array value itself, and storing the array value there. This uses the auxiliary function, private_array_alloc, to allocate space for the elements. The environment is used only to pass to the sizeof function. The size of an array is simply the number of elements times the size of each element.

{Array-Value alloc function 21} ≡
    (ArrayOfType(size, elemtype), mem, env) =>
        let val (arr_fn, mem') =
            private_array_alloc(size, 0, fn(_, _) => raise Array_Struct.array_range,
                    elemtype, mem, env)
    in
        let val (location, mem'') =
            allocmem(mem'', BV(IntVal(99)), not_initialized)
            (* any value will do *)
        in
            let val mem''', =
                    writemem(mem''', location,
                    AV(size, arr_fn, elemtype),
                    21
size * Data_Type_Struct.sizeof(elemtype, env))

    in
    (location, mem''')
    end
end
end

This code is used on page 16.

The function **private_array_alloc** is essentially a **for** loop to allocate successive array locations and collect them in the array indexing function. It is mutually recursive with the other alloc functions. The environment is passed through unchanged.

This function iterates over the array elements. On each iteration it calls **alloc** and builds up the array indexing function with its result, then recurses.

\(<\text{special array alloc stuff 22}\>\)
private_array_alloc :
  \((\text{int} * \text{int} * (\text{Nat} \to \text{Location}) * \text{Data_Type} * \text{Memory} * \text{Environment}) \to \text{fn} \text{ (wanted}_\text{size}, \text{old}_\text{size}, \text{old}_\text{fn}, \text{elemtype}, \text{mem}, \text{env}) \Rightarrow\) 
  if \text{wanted}_\text{size}=\text{old}_\text{size} then \text{old}_\text{fn,mem} 
  else
    let \text{val (new}_\text{loc,new}_\text{mem} = \text{alloc(elemtype,mem,env) in}
    let \text{val new}_\text{fn = fn(index) =>}
      if \text{index}=\text{old}_\text{size} then \text{new}_\text{loc}
      else \text{old}_\text{fn(index) in}
    private_array_alloc(\text{wanted}_\text{size}, \text{old}_\text{size}+1, 
      \text{new}_\text{fn, elemtype, new}_\text{mem, env})
  end
end

This code is used on page 16.

Finding the size of an array value involves simply retrieving it from the array value.

\(<\text{Array-Value } \text{sizeof function 22}\>\)
\((\text{AV (_,_,_, sizeof)}) \Rightarrow\)
\text{sizeof}

This code is used on page 16.

Copying an array involves using a **for** loop to run through all the elements and copy each one individually. The state propagated by the **for** function
includes the memory and the two indexing functions. The update function
given to for simply forms a tuple containing the mutated memory and the
unchanged indexing functions.

\(\langle Array-Value copy function 23 \rangle \equiv\)

\((AV(n1, src_f, t, tsize), loc, mem) \Rightarrow\)

let val AV(n2, dest_f, t2, tsize2) = readmem(mem, loc) in

\(\langle Array-Value copy function 23 \rangle \equiv\)

let val (mem, _, _) =

\(\langle Array-Value copy function 23 \rangle \equiv\)

for(0, n1, (mem, src_f, dest_f),

\(\langle Array-Value copy function 23 \rangle \equiv\)

fn(i, (mem, src_f, dest_f)) =>

\(\langle Array-Value copy function 23 \rangle \equiv\)

(copy(readmem(mem, src_f(i)), dest_f(i), mem),

\(\langle Array-Value copy function 23 \rangle \equiv\)

src_f,

\(\langle Array-Value copy function 23 \rangle \equiv\)

dest_f))

in

\(\langle Array-Value copy function 23 \rangle \equiv\)

mem

end

\(\langle Array-Value copy function 23 \rangle \equiv\)

end

This code is used on page 16.

The functions above use the “for” function to loop through a series of values
like the traditional for loop. The implementation of the for function is given
here. Noweb will paste this into the “miscellaneous” section of the program.

The for function operates much like a C for loop. The index runs from
current to range. On each iteration, the info is updated by the update_fun.

In C++, this would go something like this:

\(\langle the for function declaration 23 \rangle \equiv\)

\(\langle the for function declaration 23 \rangle \equiv\)

for ( ; current<range; current++)

\(\langle the for function declaration 23 \rangle \equiv\)

info = update_fun(current, info);

\(\langle the for function declaration 23 \rangle \equiv\)

\(\langle the for function declaration 23 \rangle \equiv\)

fun for(current, range, info, update_fun) =

\(\langle the for function declaration 23 \rangle \equiv\)

if current = range then info

\(\langle the for function declaration 23 \rangle \equiv\)

else for(current+1, range, update_fun(current, info), update_fun)

This code is used on page 28.

4.7 Pointer Value Implementation

The goal of this section is to complete the pointer structure and implement the
alloc, copy, and sizeof functions for pointer values.

\(\langle pointer structure declaration 23 \rangle \equiv\)

\(\langle pointer structure declaration 23 \rangle \equiv\)

structure Pointer_Struct : Pointer_Sig =

\(\langle pointer structure declaration 23 \rangle \equiv\)

struct

\(\langle pointer structure declaration 23 \rangle \equiv\)

type Pointer_Value = Pointer_Value

\(\langle pointer structure declaration 23 \rangle \equiv\)

type Memory = Memory

\(\langle pointer structure declaration 23 \rangle \equiv\)

type Location = Location

23
type Data_Type = Data_Type
exception ptdiff_undefined
exception pointerescaped_array
exception deref_outside_array
exception increment_undefined

(create function declaration 24)
(make-ref function declaration 25)
(deref function declaration 25)
(difference function declaration 26)
(increment function declaration 26)

end;

This code is used on page 12.

A pointer value is basically a location. We also keep track of the type of value the pointer points at. Finally, if the pointer points into an array, we need to know which element it points at. (Recall that C++ arrays are all one dimensional. To use this for “multi-dimensional” arrays, the client must keep track of the dimensions separately.)

C++ does not make a distinction between pointers that can point to cells and pointers that can point to array elements. At any given time, a C++ pointer may point to either. However, we have to know so we can do pointer arithmetic and array bounds checking.

(Pointer-Value type 24)≡
(* datatype *) Pointer_Value =
cell_ptr of Data_Type * Location
| arr_ptr of Data_Type * Array_Value * Nat
This code is used on page 12.

To allocate memory space for a pointer, we need its type. Then we just store the pointer in a new memory cell.

(Pointer-Value alloc function 24)≡
(PtrToType(t), mem, env) =>
allocmem(mem, FV(Pointer_Struct.create(t)), initialized)
This code is used on page 16.

To create a new pointer, we need only its type. We use the undefined location because the pointer is not yet pointing anywhere.

(create function declaration 24)≡
fun create(t) = cell_ptr(t, undef_loc)
This code is used on page 24.
To copy a pointer value, we assume the pointer types are of compatible types, then we just write the value into the memory cell. The client is responsible for type checking.

\[ \langle \text{Pointer-Value copy function 25} \rangle \equiv \\
(\text{PV}(v), \text{newloc}, \text{mem}) \Rightarrow \\
\text{writemem}(\text{mem}, \text{newloc}, \text{PV}(v)) \]

This code is used on page 16.

The size of all pointers in this implementation is constant, although the standard allows for pointers of various sizes.

\[ \langle \text{Pointer-Value size of function 25} \rangle \equiv \\
(\text{PV}(_)) \Rightarrow 4 \]

This code is used on page 16.

When making a pointer refer to some cell, we require the client to ensure the types are compatible. If they want to make the pointer point to an array, this forms an \texttt{arr_ptr} to the first element. Otherwise, it forms a \texttt{cell_ptr}.

We want it to do this regardless of whether it used to be pointing to an array or not. So once again literate programming gives us a way to name just the body of a function and to use that body in two places.

\[ \langle \text{make-ref function declaration 25} \rangle \equiv \\
\text{fun make_ref(cell_ptr(t,\_), newloc, mem) : Pointer_Value =} \\
\langle \text{make-ref body 25} \rangle \\
| \text{make_ref(arr_ptr(t,\_), newloc, mem) =} \\
\langle \text{make-ref body 25} \rangle \\
\]

This code is used on page 24.

\[ \langle \text{make-ref body 25} \rangle \equiv \\
\text{let val referenced_value = readmem(mem, newloc) in} \\
(\text{case referenced_value of} \\
\text{AV(array_value) => arr_ptr(t, array_value, 0)} \\
| \_ => cell_ptr(t, newloc)) \\
\]

This code is used on page 25.

Dereferencing a pointer involves pulling out its location. For pointers to arrays, this means indexing the array.

\[ \langle \text{deref function declaration 25} \rangle \equiv \\
\text{fun deref(cell_ptr(\_, loc)) = loc} \\
| \text{deref(arr_ptr(\_, arrval, indx)) = (Array_Struct.index(arrval, indx)} \\
\text{handle array_range => raise deref_outside_array)} \\
\]

This code is used on page 24.
Pointer subtraction is done by cases. We return 0 if the pointers refer to the same cell. If the pointers point into the same array, we perform subtraction. Otherwise, the `ptdiff_undefined` exception is raised. In all cases the result is the C++ type `ptdiff_t`, represented by an ML integer. [ES90, Section 5.7].

```ml
fun difference(cell_ptr(_,loc1), cell_ptr(_,loc2)) = 
    if is_same_location(loc1,loc2) then 0
    else raise ptdiff_undefined 
| difference(arr_ptr(_,arrval1,index1), arr_ptr(_,arrval2,index2)) = 
    if Array_Struct.is_same_array_value(arrval1, arrval2) then 
      index1 - index2
    else raise ptdiff_undefined 
| difference(_, _) = 
    raise ptdiff_undefined
```

This code is used on page 24.

Pointer arithmetic makes sense only when applied to a pointer into an array. For a pointer into an array, simply perform the increment and check if the bounds of the array were violated. If they were, or if the pointer was not pointing into an array, the exception `increment_undefined` is raised.

Note that this section has to be intimately familiar with how array values are represented so it can know if the array bounds are violated.

```ml
(* fun increment: Pointer_Value * int -> Pointer_Value *)
fun increment(arr_ptr(t,(array_size,index,typ,sizeof), old_index), increment) = 
    let val new_index = old_index + increment in 
    if new_index >=0 andalso new_index <= array_size 
    (* Allow pointer to go one past the end *)
    then 
      arr_ptr(t, (array_size,index,typ,sizeof), new_index) 
    else raise increment_undefined 
    end 
| increment(_, _) = 
    raise increment_undefined
```

This code is used on page 24.
4.8 Object Value Implementation

The objective of this section is to finish the object structure and to implement the alloc, copy, and sizeof functions for object values.

\[
\langle \text{object structure declaration 27} \rangle \equiv \\
\text{structure Object_Struct : Object_Sig =} \\
\text{struct} \\
\text{type Object_Value = Object_Value} \\
\text{type Memory = Memory} \\
\text{type Location = Location} \\
\text{exception not_member} \\
\text{fun \{dot fun implementation 27\}} \\
\text{end;}
\]

This code is used on page 12.

An object value contains a mapping from identifier to location. This mapping is used in the C++ dot (.) and arrow (\rightarrow) operators, and is referred to here as the “dot” operator.

\[
\langle \text{dot function signature 27} \rangle \equiv \\
\text{Identifier \rightarrow Location} \\
\text{This code is used on page 31.}
\]

An object value is constructed when an object is created; it is never modified, only the cells it refers to. A “dot” function is created fresh for each new object. The copy and sizeof functions are the same for all objects of the same class. These functions are implemented by the Class functions, described in a later section.

\[
\langle \text{Object-Value type 27} \rangle \equiv \\
\text{Object_Value = dot_type * object_copier_type * int} \\
\text{This code is used on page 12.}
\]

To implement the dot operator, we have only to invoke the “dot” function which maps from identifier to location.

\[
\langle \text{dot fun implementation 27} \rangle \equiv \\
\text{dot((dot_fn, _, _), id) = dot_fn(id)} \\
\text{This code is used on page 27.}
\]

To allocate an object, we need information from its class. Essentially, each class instantiates objects. This function was constructed when the class was declared. We have only to retrieve that function and invoke it.
\{Object-Value alloc function 28\} ≡
(ClassOfType(name), mem, env) =>
  let val Class(size, alloc_fun) = lookup(env, name) in
  alloc_fun(mem)
end

This code is used on page 16.

The function to copy the object is constructed when the object is created. We have only to invoke the result on the current memory and say where we want it copied to.

\{Object-Value copy function 28\} ≡
(OV(dot_fn, copy_fn, size), mem, loc) =>
  copy_fn(loc, mem)

This code is used on page 16.

The size of an object is computed when its class is created and was stored in the object value for easy access. It is used here.

\{Object-Value sizeof function 28\} ≡
(OV(_ , _ , size)) => size

This code is used on page 16.

4.9 Miscellaneous details

And now we have only miscellaneous details to attend to. These include some shorthand types and some general-purpose functions.

\{misc definitions 28\} ≡
  type Identifier = string
  type Nat = int
  \{general-purpose function update declaration 15\}
  \{the for function declaration 23\}

This code is used on page 4.

5 Valuation Functions

The only valuation function, EvalDeclList, accepts a Declaration list and produces a declaration continuation transformer. The function is written in a continuation passing style (CPS) [Sch86, Section 9.1]. Its signature is given here.

\{EvalDeclList signature 28\} ≡
  Declaration list -> DeclCont -> DeclCont

This code is used on page 29.
Our continuations are functions that take an (Environment * Memory) and produce a new (Environment * Memory). This continuation promises to produce a new (Environment * Memory) according to the declaration list used to create it and the (Environment * Memory) it was handed.

\[ \langle \text{DeclCont type definition 29} \rangle \equiv \]

\text{type DeclCont = Environment * Memory -> Environment * Memory}

This code is used on page 29.

The remainder of this section gives the order chunks of code are pasted together. This is different than the order presented in this paper.

\[ \langle \text{Valuation function implementations 29} \rangle \equiv \]

\( \langle \text{DeclCont type definition 29} \rangle \)

\( \langle \text{Class declaration stuff 31} \rangle \)

\( \langle \text{fun EvalDecl definition 29} \rangle \)

\( \langle \text{fun EvalDeclList definition 29} \rangle \)

This code is used on page 4.

5.1 Valuation function definitions

To evaluate a declaration list, we use straightforward CPS recursion. At each element we use EvalDecl to produce a new continuation transformer, then apply this to the continuation which evaluates the rest of the list.

\[ \langle \text{fun EvalDeclList definition 29} \rangle \equiv \]

\text{val rec EvalDeclList : (EvalDeclList signature 28) =}

\text{fn (decl :: decllist) => (fn (declk) =>}

\text{EvalDecl(decl)}

\text{  (EvalDeclList(decllist)}

\text{  declk))}

\text{| (nil) => (fn (declk) =>}

\text{  declk)}

This code is used on page 29.

Function EvalDecl evaluates a single declaration and produces a declaration continuation transformer. Its design is driven by the datatype Declaration given in the section on C++ declarations. There are two types of declarations: variables and classes. The functions which process each of these declarations are given in their respective sections.

\[ \langle \text{fun EvalDecl definition 29} \rangle \equiv \]

\text{fun \langle eval variable-declaration function 30 \rangle}

\text{| \langle eval class-declaration function 30 \rangle}

This code is used on page 29.
5.1.1 Variable Declarations

Here we say how to evaluate a variable declaration. The process involves first making sure the variable was not previously declared, allocating memory for it, and recording the result into the environment. Note that this uses the SML shorthand notation for curried functions.

\[ \text{val variable-declaration function 30} \equiv \]
\[
\begin{align*}
\text{EvalDecl}(&\text{var\_decl}(\text{id}, \text{d\_type})) (\text{declk}) = \\
& \quad (\text{fn} \ (\text{env}, \ \text{mem}) \ => \\
& \quad \quad \text{if is\_in\_env}\text{env} (\text{id}) \\
& \quad \quad \text{then} \ (\text{output} \ (\text{std\_out}, \ \"\text{Identifier "~ id ~ redeclared\n\"});} \\
& \quad \quad \quad \text{declk} (\text{env}, \ \text{mem}) \\
& \quad \quad \text{else} \\
& \quad \quad \quad \text{let val} \ (\text{loc}, \ \text{mem'}) = \text{alloc}(\text{d\_type}, \ \text{mem}, \ \text{env}) \ \text{in} \\
& \quad \quad \quad \quad \text{let val eny'} = \text{add}(\text{env}, \ \text{id}, \ \text{Variable(loc)}) \ \text{in} \\
& \quad \quad \quad \quad \quad \text{declk} (\text{eny'}, \ \text{mem'}) \\
& \quad \quad \quad \text{end} \\
& \quad \text{end}) \\
\end{align*}
\]

This code is used on page 29.

5.1.2 Class Declarations

For a class definition, we process the fields and store that information in the environment. Memory is unchanged.

\[ \text{val class-declaration function 30} \equiv \]
\[
\begin{align*}
\text{EvalDecl}(&\text{class\_decl}(\text{class\_name}, \ \text{fields})) (\text{declk}) = \\
& \quad (\text{fn} \ (\text{env}, \ \text{mem}) \ => \\
& \quad \quad \text{declk}(\text{add}(\text{env}, \ \text{class\_name}, \ \text{make\_class\_info}(\text{fields}, \ \text{env})), \ \text{mem}) \\
\end{align*}
\]

This code is used on page 29.

6 Class Declarations

The implementations of classes and objects are intimately related. The critical relationship is that when a class is declared, we create a function to create objects of that class. When this function is invoked, it allocates memory for the object's members and creates the dot function which maps from member names to the newly allocated locations.

To get started, we will review the types we are dealing with. The information stored for a class has type \text{class\_info} which was defined as part of the denotable values. The information stored for an object has type \text{Object\_Value} which was defined as part of the storable values.

Two types were not defined elsewhere. These are the type of the dot function, and the type of the function to copy an object.
\(\{\text{auxiliary object types 31}\}\) \(\equiv\)
\[
\text{dot_type} = \{\text{dot function signature 27}\}
\]
and object_copier_type = Memory * Location -> Memory
This code is used on page 12.

6.1 Creating class info

We now turn to the function \texttt{make\_class\_info} which transforms a list of fields into a denotable value to represent the class. Its type is given here.

\(\{\text{make-class-info function signature 31}\}\) \(\equiv\)
\[
\text{Declaration list * Environment} \rightarrow \text{Denotable Value}
\]
This code is used on page 31.

The \texttt{make\_class\_info} function is fairly involved and needs some auxiliary definitions. These include the general-purpose field iterator, a function to transform a list of declarations into a list of (Identifier * Type) pairs, and the initial dot function. These are discussed later in this section.

\(\{\text{Class declaration stuff 31}\}\) \(\equiv\)
\[
\{\text{create-field-iterator function definition 33}\}
\{\text{create-field-list function definition 32}\}
\{\text{initial dot function definition 35}\}
\{\text{make-class-info function definition 31}\}
\]
This code is used on page 29.

We now discuss how the \texttt{make\_class\_info} function works. It first creates the list of fields from the list of members, then creates a general-purpose function to iterate over the fields and collect information about them. Next it uses this “field iterator” function to find out the size of the class and objects of that class.

Then it packages its work with the \texttt{Class} constructor which takes the pre-calculated size and the not-yet-calculated instantiation function and produces a \texttt{Denotable Value} which is returned as the value of the function.

The instantiation function takes a memory. When called, this instantiates the fields of an object, creates a function to copy the object, and wraps these up with the size of the object to create the object information.

The details are discussed in the following subsections.

\(\{\text{make-class-info function definition 31}\}\) \(\equiv\)
\[
\text{val make_class_info : (make-class-info function signature 31) =}
\]
\[
\text{fn (members, env) =>}
\]
\[
\text{let val fields = create_field_list(members) in}
\]
\[
\text{let val field_iter = create_field_iterator(fields)}
\]
in
  let val object_size =
    (object size guts 33)
  in
  Class(object_size,
    fn(mem) =>
      let val (mem, dot_fn) =
        (object instantiation guts 33)
      in
      let val copy_fn =
        (object copy guts 33)
      in
      (wrap up object 33)
    end
  end
end

This code is used on page 31.

6.2 Create field list

To create a list of fields from a list of members, we have only to keep “variable” declarations, and ignore nested class declarations. Note that we strip the var_decl constructor and put only the identifier and type into the list. This function performs the usual recursion on lists.

\[
\text{fun create\_field\_list([\ ])} = \\
\text{[\ ]} \\
\text{| create\_field\_list(var\_decl(id, var\_type) :: rest\_of\_list) =} \\
\text{\hspace{1cm} (id, var\_type) :: create\_field\_list(rest\_of\_list)} \\
\text{| create\_field\_list(class\_decl(id, decl\_list) :: rest\_of\_list) =} \\
\text{\hspace{1cm} create\_field\_list(rest\_of\_list)}
\]

This code is used on page 31.

6.3 General purpose field iterator function

This create_field_iterator function creates the field iterator using the usual recursion on lists. The function it produces, the iterator function, takes two arguments: a state, and a function to update the state for each field. This update function takes the current state, the current field, and returns a new state. We will see examples of the field iterator function’s use in the next sections.
Note that the normal use of this function is to supply only the list of fields, i.e., this really is a curried function. Supplying the first argument, the list of fields, produces the iterator. Supplying the second set of arguments, the state and the update function, uses the iterator to do work.

\[
\langle \text{create-field-iterator function definition 33}\rangle \equiv \\
\text{fun create_field_iterator ([]} (\text{state},f) = \\
\quad \text{state} \\
\quad | \text{create_field_iterator (first_field :: other_fields) (state,f)} = \\
\quad \quad \text{let val state’ = f(state,first_field) in} \\
\quad \quad \text{create_field_iterator (other_fields) (state’, f)} \\
\text{end}
\]

This code is used on page 31.

6.4 Object size

To find the size of an object we have only to sum the sizes of the members. This is a straightforward use of the iterator function. The state we keep is the cumulative size of the fields seen so far. The update function has only to add that to the size of the current field. One small wrinkle is that an object with no members has a size greater than zero [ES90, Section 5.3.2, Section 9]; here we arbitrarily choose 4 as the size of such an object.

\[
\langle \text{object size guts 33}\rangle \equiv \\
\text{let val size } = \\
\quad \text{field_iter(0, \text{fn(size_so_far, (field_name, field_type))}} \\
\quad \text{=> size_so_far + Data_Type_Struct.sizeof(field_type, env))} \\
\text{in} \\
\quad \text{if size } = 0 \text{ then 4} \\
\quad \text{else size} \\
\text{end}
\]

This code is used on page 32.

6.5 Object copy

We next turn to the problem of copying objects of this type to memory locations occupied by other objects of this same type. To do this, we create a function that copies arbitrary objects, and arrange to call it with only objects of the correct type. This function takes a memory to mutate and a location to copy the object to.

\[
\langle \text{object copy guts 33}\rangle \equiv \\
\text{fn(mem, dst_loc) =>} \\
\text{\langle ocy’34\rangle}
\]

This code is used on page 32.
We first read the destination object from memory and pull out its dot function. The content of the cell is required to be an object value, otherwise this code will raise the SML match exception. It is the responsibility of the user to make sure this functions is used correctly.

\[
\text{let val OV(dst_dot_fn, _, _) = readmem(mem, dst_loc)} \text{ in}
\]

This code is used on page 33.

Once we have the dot functions of both the source and destination objects, we can iterate over the fields and perform the copy member-by-member using the iterator function. The state includes the two dot functions and the current memory image. The update function simply performs the copy and passes the dot functions to the next iteration unchanged. Afterward, we discard the source and destination dot functions and return only the memory.

Here we use the values field_iter and dot_fn from the quadruply nested lets in the section where this code goes.

\[
\text{let val (mem, src, dst) = field_iter}
\]

This code is used on page 34.

### 6.6 Object allocation

We now turn to the problem of allocating object memory. Allocating the memory is a straightforward use of the field-iter function. The state used by the field iterator includes the memory we are mutating and the dot function we are creating. On each iteration we simply allocate memory for the new field and update the dot function to record the new location. The result of all of this is the mutated memory and the dot function.

Here we use the values field_iter and mem from the quadruply nested lets in the section where this code goes.
\{object instantiation guts 35\} ≡ 
field_iter ((mem, initial_dot_fun),
  fn((mem, dot), (field_name, field_type)) =>
  let val (loc, mem') = alloc(field_type, mem, env) in
    (mem', update(dot, field_name, loc))
end)
This code is used on page 32.

The initial dot function does not recognise any member names.

\{initial dot function definition 35\} ≡ 
exception bad_member
val initial_dot_fun = fn(name) => raise bad_member
This code is used on page 31.

6.7 Wrapping up objects

Once we have all the information we need for an object, we wrap it all up and 
store it in memory. This simply fills out an Object_Value and stores that in a 
primitive memory cell.

\{wrap up object 35\} ≡ 
let val object_value = (dot_fn, copy_fn, object_size) 
in
  allocmem(mem, OV(object_value), initialized)
end
This code is used on page 32.

7 Testing

What follows is not part of the semantics itself. This section describes tools 
to examine the environment and memory for testing purposes. These consists 
primarily of a "show-cell" function to describe the contents of memory and a 
"show-id" function to describe the meaning of identifiers.

\{memory examiner 35\} ≡
  \{fun format-Data-Type definition 36\}
  \{Storable-Value printer function definition 36\}
  \{fun show-cell definition 36\}
  \{show-id function definition 37\}
This code is used on page 4.

The primary interface is a function to display the content of one memory 
cell.
(fun show-cell definition 36)≡

fun show_cell(loc, mem) =
    let val item = readmem(mem, loc)
    in
        (print_storable_value(item);
         print "\n ")
    end

handle Memory_Struct.read_out_of_bounds =>
    (print "(read out of bounds)\n "; ();)
| Memory_Struct.uninitialized_memory =>
    (print "(cell does not yet contain a value)\n "; ();)

This code is used on page 35.

The next function formats and prints a Storable-Value; it returns unity.
The design of this function is driven by datatype Storable-Value.

(fun Storable-Value printer function definition 36)≡

fun print_storable_value(BV(IntVal(x))) =
    (print "integer " makestring(x)); ()
| print_storable_value(BV(CharVal(x))) =
    (print "character " makestring(x)); ()
| print_storable_value(BV(FloatVal(x))) =
    (print "float " makestring(x)); ()
| print_storable_value(BV(DoubleVal(x))) =
    (print "double " makestring(x)); ()

| print_storable_value(AV(size:int,index_fn,elem_type,charsize)) =
    (print "array[" makestring(size)"] of " ~ format_Data_Type(elem_type)); ()
| print_storable_value(PV(_)) =
    (print "pointer (not specified)"); ()
| print_storable_value(OV(_)) =
    (print "object (not specified)"); ()

This code is used on page 35.

Finally, format_Data_Type returns a string representing the Data_Type.

(fun format-Data-Type definition 36)≡

fun format_Data_Type(CharType) = "char"
| format_Data_Type(IntType) = "int"
| format_Data_Type(FloatType) = "float"
| format_Data_Type(DoubleType) = "double"
| format_Data_Type(PtrToType(t)) =
    "pointer to " ~ format_Data_Type(t)
| format_Data_Type(ArrayOfType(n,t)) =

36
"array["^ makestring(n) ^ "] of "^ format_Data_Type(t)
| format_Data_Type(ClassOfType(id)) =
"class "^ id
This code is used on page 35.

We next describe a tool for getting information from the environment. Given a C++ symbol it prints everything it can find out about it.

(show-id2 function definition 37)≡
| fun show_id2(Variable(loc), env, mem) =
|   (print ("a variable in cell "^ makestring(loc)" of type ");
|    show_cell(loc, mem);
|    ()
| | show_id2(Class(_,_), env, mem) =
|   (print "the name of a class";
|    ())
This code is used on page 37.

Finally the show-id function looks up the id and passes its value to show-id2 for display.

(show-id function definition 37)≡
| (show-id2 function definition 37)
| fun show_id(id, env, mem) =
|   let val thing = lookup(env, id) in
|   (print (id"" is ");
|    show_id2(thing, env, mem))
| end
| handle symbol_not_found => (print ("Unknown identifier: "^id"\n "); ()
This code is used on page 35.

8 Related Work

Sethi published an article on the denotational semantics of C programs [Set80]. There is a paper on denotational semantics implemented in SML [Mas91]. Compared to these, the techniques used in this paper offers a greater explanation of the denotational semantics technique and a better partitioning of the semantic values into domains. There is work in separating the concerns of the compile-time system from the run-time system [LP87]. This makes compilers derived from a semantic specification much more efficient. The clear separation between the domains in this paper makes it amenable to this type of optimization.
9 Conclusions

We wrap up the paper with a discussion of what was learned and a discussion of possible extensions to this work.

9.1 What was learned

Using literate programming to implement denotational semantics in SML is not commonly done. Here we point out some of the problems and benefits of the combination of techniques.

As programmers, we solve problems and code solutions. The code is there for all to see, but the solutions are usually lost and must be re-created from the code. Literate programming encourages us to document what we were thinking when we solved our coding problem. This, of course, requires extra effort. But this extra effort is rewarded when we have to look back to the code to understand or modify it. It really does.

Another feature of literate programming is that it extends the target language by allowing us to name pieces of our program smaller than the language allows. For instance, this paper defines functions piecemeal (as is normal in denotational semantics), but SML does not allow this. Literate programming gives us the flexibility to do this by naming pieces of the program smaller than the language normally allows. Another example of where literate programming helps is in naming just the body of a function for use in two places. Of course, this can be done with an auxiliary function, but literate programming allows us to both modularize our code and arrange the pieces for efficient execution.

ML is well suited to implementing denotational semantics. ML’s first-class functions provide the expressive power necessary to directly model semantic specifications. ML’s module capability (signatures and structures) provides a convenient implementation of semantic domains. ML’s pattern matching and syntactic support for curried functions makes the implementation look more like a traditional semantic specification.

Despite its advantages, ML is not ideal for implementing denotational semantics. Its typechecking is a blessing and a pain. On the one hand, it catches most errors before programs can be used. On the other hand, it limits the flexibility of functions written in continuation-passing style (CPS). In short, we still have the control advantages of CPS but must use a SML datatype (and explicit injection into a disjoint union) to return an error condition. This is commonly done in a direct semantics.

Finally, ML does not have syntactic sugar for defining a function and giving its complete type. For example, we sometimes give the signature for a function when discussing what it does. Then we give the function itself later and would like to include its signature in the source code to prove that we were not lying about it. The problem is that SML does not allow the complete signature of a function to be given by the fun syntax—only its return type can be specified.
easily. The primitive \texttt{val rec f : TYPE = fn (args) => body} is currently used to document the type.

9.2 Future directions

This work could be extended in several directions. The first and most obvious extension is to remove the restrictions from the declarations it can deal with by adding the usual C++ features. These features include typedefs, private and protected members, nested classes, and inheritance.

Functions and expressions could be added, along with all the other features of C++. A parser could be added to ease testing. Finally, the semantics could be separated more cleanly into compile-time and run-time responsibilities. This would help language implementors and those concerned about execution efficiency.

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