Values and their Representation

<table>
<thead>
<tr>
<th>Data Type</th>
<th>Representation</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>integer</td>
<td>64 bits, untagged. Unboxed (i.e., not region allocated). One bit is used for tagging when GC is enabled.</td>
<td></td>
</tr>
<tr>
<td>real</td>
<td>64 bits, untagged. Boxed (i.e., allocated in region)</td>
<td></td>
</tr>
<tr>
<td>string</td>
<td>Unbounded size. Allocated in region.</td>
<td></td>
</tr>
<tr>
<td>bool</td>
<td>one 64-bit word. Unboxed.</td>
<td></td>
</tr>
<tr>
<td>α list</td>
<td>nil and :: cells unboxed (i.e., not region allocated). Auxiliary pairs in one region; elements in zero or more regions. Size of auxiliary pairs: two 64-bit words (three when GC is enabled).</td>
<td></td>
</tr>
<tr>
<td>exn</td>
<td>Exception values are boxed and are always stored in a global region.</td>
<td></td>
</tr>
<tr>
<td>fn pat</td>
<td>An anonymous function is represented by a boxed, untagged closure.</td>
<td></td>
</tr>
<tr>
<td>=&gt; exp</td>
<td>Its size is one 64-bit word plus one word for each free variable of the function. Free region variables also count as variables. One extra word is used when GC is enabled.</td>
<td></td>
</tr>
<tr>
<td>fun f ...</td>
<td>Mutually recursive region-polymorphic functions share the same closure, which is region-allocated, untagged, and whose size (in words) is the number of variables that occur free in the recursive declaration. One extra word is used when GC is enabled.</td>
<td></td>
</tr>
</tbody>
</table>

Regions and their Representation

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finite</td>
<td>Region whose size can be determined at compile time. During compilation, a finite region size is given as a non-negative integer. After multiplicity inference, this integer indicates the number of times a value (of the appropriate type) is written into the region. Later, after physical size inference, the integer indicates the physical region size in words. At runtime, a finite region is allocated on the runtime stack.</td>
</tr>
<tr>
<td>Infinite</td>
<td>All other regions. At runtime, an infinite region consists of a stack allocated region descriptor, which contains pointers to the beginning and the end of a linked list of fixed size region pages.</td>
</tr>
</tbody>
</table>

Storage Modes (only significant for infinite regions)

<table>
<thead>
<tr>
<th>Mode</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>atbot</td>
<td>Reset region, then store value.</td>
</tr>
<tr>
<td>sat</td>
<td>Determine actual storage mode (attop/atbot) at runtime.</td>
</tr>
<tr>
<td>attop</td>
<td>Store at top of region, without destroying any values already in the region.</td>
</tr>
</tbody>
</table>
Contents

I Overview 15

1 Region-Based Memory Management 17
   1.1 Dynamic Memory Management .................................. 17
   1.2 Checked De-Allocation of Memory .............................. 18
   1.3 Example: the Game of Life .................................... 23
   1.4 Try it! .............................................................. 29

2 Making Regions Concrete 31
   2.1 Finite and Infinite Regions .................................... 31
   2.2 Runtime Types of Regions .................................... 32
   2.3 Allocation and De-Allocation of Regions ...................... 32
   2.4 Two Backends .................................................... 33
   2.5 Boxed and Unboxed Values .................................... 34
   2.6 Intermediate Languages ...................................... 34
   2.7 The Runtime System .......................................... 35
   2.8 Compiling Programs with the MLKit .......................... 36
   2.9 Compiling with the MLKit Compiler ........................... 36
   2.10 Running Compiled Programs .................................. 37

II The Language Constructs of SML 39

3 Records and Tuples 41
   3.1 Syntax ............................................................. 41
   3.2 Example: Basic Record Operations ............................. 42
   3.3 Region-Annotated Types ...................................... 42
   3.4 Effects and let region ......................................... 43
   3.5 Runtime Representation ....................................... 45
### 4 Basic Values

- **4.1 Integers and Words** .......................................................... 47
- **4.2 Reals** ............................................................................. 48
- **4.3 Characters and Strings** ..................................................... 49
- **4.4 Booleans** ..................................................................... 50

### 5 Lists

- **5.1 Syntax** ........................................................................ 51
- **5.2 Physical Representation** ................................................. 52
- **5.3 Region-Annotated List Types** .......................................... 53
- **5.4 Example: Basic List Operations** ....................................... 54

### 6 First-Order Functions

- **6.1 Region-Polymorphic Functions** ........................................ 57
- **6.2 Region-Annotated Type Schemes** ....................................... 59
- **6.3 Endomorphisms and Exomorphisms** ............................... 60
- **6.4 Polymorphic Recursion** ................................................ 63

### 7 Value Declarations

- **7.1 Syntax** ........................................................................ 69
- **7.2 Scope Versus Lifetime** ................................................... 70
- **7.3 Shortening Lifetime** ..................................................... 73

### 8 Static Detection of Space Leaks

- **8.1 Warnings About Space Leaks** ......................................... 76
- **8.2 Fixing Space Leaks** ....................................................... 76

### 9 References

- **9.1 References in Standard ML** .............................................. 79
- **9.2 Runtime Representation of References** .............................. 80
- **9.3 Region-Annotated Reference Types** ............................... 81
- **9.4 Local References** .......................................................... 83
- **9.5 Hints on Programming with References** ........................... 84

### 10 Recursive Data Types

- **10.1 Spreading Data Types** .................................................. 85
- **10.2 Example: Balanced Trees** ............................................. 87
## CONTENTS

### 11 Exceptions
- 11.1 Exception Names ........................................ 91
- 11.2 Exception Values ....................................... 92
- 11.3 Raising Exceptions ...................................... 92
- 11.4 Handling Exceptions .................................... 93
- 11.5 Example: Prudent Use of Exceptions .................. 94

### 12 Resetting Regions
- 12.1 Storage Modes ........................................... 96
- 12.2 Storage Mode Analysis .................................. 98
- 12.3 Example: Computing the Length of Lists .......... 103
- 12.4 resetRegions and forceResetting ...................... 109
- 12.5 Example: Improved Mergesort ......................... 110
- 12.6 Example: Scanning Text Files ......................... 112

### 13 Higher-Order Functions
- 13.1 Lambda Abstractions (fn) ............................ 121
- 13.2 Region-Annotated Function Types .................. 122
- 13.3 Arrow Effects .......................................... 124
- 13.4 On the Lack of Region Polymorphism ................ 126
- 13.5 Examples: map and foldl ............................. 128

### 14 The Function Call
- 14.1 Parameter Passing ...................................... 134
- 14.2 Tail Calls and Non-Tail Calls ......................... 134
- 14.3 Tail Call to Known Function (jmp) .................. 135
- 14.4 Non-Tail Call to Known Function (funcall) ....... 136
- 14.5 Tail Call to Unknown Function (fnjmp) ............ 137
- 14.6 Non-Tail Call to Unknown Function (fn call) ..... 138
- 14.7 Example: Function Composition ...................... 138
- 14.8 Example: foldl Revisited ............................ 139

### 15 ML Basis Files and Modules
- 15.1 ML Basis Files .......................................... 143
- 15.2 Structures ............................................... 147
- 15.3 Signatures ............................................... 148
- 15.4 Functors ................................................ 149
# CONTENTS

## 16 Garbage Collection
- 16.1 Dangling Pointers ................................................. 153
- 16.2 Scanning Text Files with Stream IO and Garbage Collection 155
- 16.3 Instrumenting the Executable ................................. 155

## III System Reference

### 17 Region Profiling
- 17.1 Example: Scanning Text Files Again ....................... 164
- 17.2 Compile-Time Profiling Strategy ............................ 169
- 17.3 The Log File .................................................. 170
- 17.4 Runtime Profiling Strategy ................................... 172
- 17.5 Regions Statistics ............................................ 173
- 17.6 Processing the Profile Data File ........................... 175
- 17.7 Advanced Graphs with \texttt{rp2ps} ......................... 176

### 18 Controlling MLKit Compilation
- 18.1 Printing of Intermediate Forms .............................. 181
- 18.2 Layout of Intermediate Forms ............................... 183

### 19 Calling C Functions
- 19.1 Declaring Primitives and C Functions ..................... 186
- 19.2 Conversion Macros and Functions .......................... 188
  - 19.2.1 Integers .................................................. 189
  - 19.2.2 Units ....................................................... 189
  - 19.2.3 Reals ...................................................... 190
  - 19.2.4 Booleans .................................................. 190
  - 19.2.5 Records ................................................... 191
  - 19.2.6 Strings ................................................... 192
  - 19.2.7 Lists ....................................................... 192
- 19.3 Exceptions ..................................................... 195
- 19.4 Program Points for Profiling ............................... 196
- 19.5 Storage Modes ................................................ 197
- 19.6 Endomorphisms by Polymorphism ........................... 198
- 19.7 Compiling and Linking ...................................... 199
- 19.8 Dynamic Linking ............................................ 200
- 19.9 Auto Conversion ............................................. 200
CONTENTS

19.10 Examples ......................................................... 202

20 Summary of Changes ............................................. 205
  20.1 Changes Since Version 4.6.1 ............................... 205
  20.2 Changes Since Version 4.3.0 ............................... 205
  20.3 Changes Since Version 4 ..................................... 207
  20.4 Changes Since Version 3 ..................................... 208
  20.5 Changes Since Version 2 ..................................... 209

A Command-Line Options ............................................ 215
The MLKit is a compiler infrastructure for the Standard ML programming language [MTHM97]. The MLKit supports all of Standard ML, including Modules and most parts of the SML Basis Library [GR04]. The MLKit features a region-based native backend that generates efficient x64 machine code. This version of the compiler is also named MLKit with Regions. The MLKit also features a JavaScript backend, which generates code for execution in web browsers. The MLKit with Regions, which this report is about, is intended for the development of stand-alone applications that must be reliable, fast, and space efficient.

There has always been a tension between high-level features in programming languages and the programmer’s legitimate need to understand programs at the operational level. Very likely, if a resource conscious programmer is forced to make a choice between the two, he will choose the latter.

The MLKit with Regions is the result of a research and development effort, which was initiated at the University of Copenhagen in 1992. The goal of the project has been to develop implementation technology that combines the advantages of using a high-level programming language, in this case Standard ML, with a model of computation that allows programmers to reason about how much space and time their programs use.

In most call-by-value languages, it is not terribly hard to give a model of time usage that is good enough for elementary reasoning.

For space, however, the situation is much less satisfactory. Part of the reason is that many programs must recycle memory while running. For all such programs, the mechanisms that reclaim memory inevitably become part of the reasoning. This is true irrespective of whether memory recycling is done by a stack mechanism or by pointer tracing garbage collection.

In the stack discipline, every point of allocation is matched by a point of deallocation and these points are obvious from the program. By contrast,
garbage collection techniques usually separate allocation, which is done by
the programmer, from deallocation, which is done by a garbage collector. The
advantage of using reference tracing garbage collection techniques is that they
apply to a wide range of high-level concepts now found in programming lan-
guages, for example recursive data types, higher-order functions, exceptions,
references, and objects. The disadvantage is that it is becoming increasingly
difficult for the programmer to reason about lifetimes. Lifetimes may depend
on subtle details in the compiler and in the garbage collector. Thus, it is hard
to model memory in a way that is useful to programmers. Also, compilers
offer little assistance for reasoning about lifetimes.

In this report, we describe how Standard ML can be equipped with a dif-
fferent memory management discipline, namely a region-based memory model.
Like the stack discipline, the region discipline is, in essence, simple and
platform-independent. Unlike the traditional stack discipline, however, the
region discipline also applies to recursive data types, references, and higher-
order functions, for which one has hitherto mostly used reference tracing
garbage collection techniques.

The reader we have in mind is a person with a Computer Science back-
ground who is interested in developing reliable and efficient applications writ-
ten in Standard ML. Also, the report may be of interest to researchers of
programming languages, since the MLKit with Regions is a fairly bold exer-
cise in program analysis. We should emphasize, however, that this report is
very much intended as a user’s guide, not a scientific publication.

This report consists of three parts:

**Part I, Overview:** This part gives an overview of the ideas that underlie
programming with regions in the MLKit.

**Part II, Understanding Regions:** The second part of the report system-
atically presents the language constructs of the Standard ML Language,
showing for each construct how it can be used when programming with
regions.

**Part III, System Reference:** In this part, we explain how to interact with
the system, how to use the region profiler and how to call C functions
from the MLKit.

The present report describes the MLKit Version 4.7.2. This version of the
MLKit extends, and differs from, the MLKit Version 4.3.0 by the following
features:
1. Type variables are no longer associated with region variables, which simplifies region types significantly and eases the implementation.

2. The machinery for ensuring that no dangling pointers are dereferenced during a garbage collection has been fixed.

3. A move to machine code generation for the x86-64 architecture. The port also features register allocation for floating point registers, holding intra-procedural values of type real.

4. Additional Standard ML Basis Library features, including support for socket programming (e.g., structure Socket) and general Unix programming (structure Unix).

5. Support for generational garbage collection as a generalisation of the ordinary pointer-tracing garbage collector that can be used as an add-on to region-based memory management.

6. A large number of bug-fixes, performance improvements, and general new features, such as colorful region profile graphs...

Further, Version 4.3.0 extends Version 4 with the following features:

1. Support for compiling ML Basis Files. ML Basis Files allows for expressing source dependencies, exactly (as a directed acyclic graph). ML Basis Files thus provides a mechanism for programming “in the very large”.

2. File-based separate compilation, based on ML Basis Files.

3. An updated Standard ML Basis Library conforming to the specification published in [GR04].

4. Untagged representation of heap-allocated pairs, triples, and Standard ML references, even when garbage collection is enabled.

MLKit Version 4 extends MLKit Version 3 with the following features:

1. Support for pointer tracing garbage collection. Pointer tracing garbage collection works well together with the region memory model. While most de-allocations can be efficiently performed by region de-allocation, there are some uses of memory for which life time prediction is difficult.
In these cases pointer tracing garbage collection does a good job in collaboration with region memory management [Hal99, HET02].

2. An x86 native backend. The backend support has switched from HP PA-RISC to Linux on x86 architectures.

3. A backend. To improve portability of programs, MLKit Version 4 featured a bytecode backend, which generated code for execution on a stack machine with region primitives. The stack machine closely resembles the stack machine used in the OCaml and Moscow ML compilers.

The MLKit Version 3 extends the MLKit Version 2 with support for the Standard ML Modules language. The MLKit Version 2 is a further development of the MLKit Version 1, which was developed at Edinburgh University and University of Copenhagen [BRTT93]. We hope you will enjoy using the MLKit as much as we have enjoyed developing it. If your experience with the MLKit gives rise to comments and suggestions, specifically with relation to the goals and visions expressed here, please feel free to write. Further information is available at the MLKit Github web site:

https://github.com/melsman/mlkit

September, 2001

Mads Tofte, Lars Birkedal, Martin Elsman, Niels Hallenberg, Tommy Højfeldt Olesen, and Peter Sestoft

Contributions

Many people have contributed to the development of the MLKit, including Peter Bertelsen, Lars Birkedal, Martin Elsman, Niels Hallenberg, Tommy Højfeld Olesen, Nick Rothwell, Mads Tofte, David N. Turner, Peter Sestoft, and Carsten Varming.

People who have contributed with bug reports and patches include, but are not limited to (in alphabetical order) Johnny Andersen, Troels Henriksen, Koshy A Joseph, Ken Friis Larsen, Philip Munksgaard, Henning Niss, Daniel Wang, and Stephen Weeks.

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Part I

Overview
Chapter 1

Region-Based Memory Management

Region-Based Memory Management is a technique for managing memory for programs that use dynamic data structures, such as lists, trees, pointers, and function closures.

1.1 Dynamic Memory Management

Many programming languages rely on a memory model consisting of a stack and a heap. Typically, the stack holds temporary values, activation records, arrays, and in general, values whose lifetime is closely connected to procedure activations and whose size can be determined at the latest when creation of the value begins. The heap is what holds all the other values. In particular, the heap holds values whose size can grow dynamically, such as lists and trees. The heap also holds values whose lifetime does not follow procedure activations closely (for example lists and, in functional languages, function closures and suspensions).

The beauty of the stack discipline (apart from the fact that it is often very efficient in practice) is that it couples allocation points and de-allocation points in a manner that is intelligible to the programmer. C programmers appreciate that whatever memory is allocated for local variables in a procedure ceases to exist (and take up memory) when the procedure returns. C programmers also know that counting from one to some large number, \( N \), is not best done by making \( N \) recursive C procedure calls, because that would
use stack space proportional to $N$.

By contrast, programmers have much less help when it comes to managing the heap. Two approaches prevail. The first approach is that the programmer manages memory herself, using explicit allocation and de-allocation instructions (e.g., `malloc` and `free` in C). For non-trivial programs this can be a very significant burden, because it is, in general, very hard to make sure that none of the values that reside in the memory that one wishes to de-allocate are not needed for the rest of the computation. This puts the programmer in a difficult position. If one is too eager to reclaim memory in the heap, the program might crash under some peculiar circumstances, which might be hard to find during debugging. If one is too conservative reclaiming memory, the program might leak space, that is, it might use more memory than expected, perhaps eventually, exhaust the memory of the machine.

The other prevailing approach is to use automatic garbage collection in the heap. Some implementors of some languages even dispense with the stack entirely, relying only on a heap with garbage collection. Garbage collection techniques separate allocation, which is done by the programmer, from de-allocation, which is done by the garbage collector. At first, this might seem like the perfect solution: no longer does the programmer have to worry about whether memory that is being reclaimed really is dead, for the garbage collector only reclaims memory that cannot be reached by the rest of the computation. However, reality is less perfect. Garbage collectors are typically based on the idea that if data is reachable via pointers (starting from the stack and other root data) then those data must be kept. Consequently, programs have to be written with care to avoid hanging on to too many pointers. Space conscious programmers (and language implementors) can work their way around these problems, for example by assigning `nil` to pointers that are no longer used. However, such tricks often rely on assumptions about the code that cannot be checked by the compiler and that are likely to be invalidated as the program evolves.

### 1.2 Checked De-Allocation of Memory

Regions offer an alternative to the two approaches to memory management discussed in the previous section. The runtime model is very simple, at least in principle. The store consists of a stack of *regions*, see Figure 1.1. Regions hold values, for example tuples, records, function closures, references, and
1.2. CHECKED DE-ALLOCATION OF MEMORY

Figure 1.1: The store is a stack of regions; every region is depicted by a box in the picture.

values of recursive types (such as lists and trees). All values, except those that fit within one machine word (for example integers), are stored in regions. The size of a region is not necessarily known when the region is allocated. Thus a region can grow gradually (and many regions can grow at the same time) so one might think of the region stack as a stack of heaps. However, the region stack really is a stack in the sense that (a) if region $r_1$ is allocated before region $r_2$ then $r_2$ is de-allocated before $r_1$ and (b) when a region is de-allocated, all the memory occupied by that region is reclaimed in one constant time operation.

Values that reside in one region are often, but not always, of the same type. A region can contain pointers to values that reside in the same region or in other regions. Both forward pointers (i.e., pointers from a region into a region closer to the stack top) and backwards pointers (i.e., pointers to an older region) occur.

As mentioned in the preface, the present version of the MLKit supports reference-tracing garbage collection in combination with region memory management [Hal99]. While most de-allocations can be efficiently performed by region de-allocation, there are some uses of memory for which it is difficult to predict when memory can be de-allocated. In these cases reference-tracing garbage collection does a good job in combination with region de-allocation.

In many cases however, one can do just fine without reference-tracing garbage collection. Without reference-tracing garbage collection the region
CHAPTER 1. REGION-BASED MEMORY MANAGEMENT

stack is the only form of memory management provided. Is the region model really general enough to fit a wide variety of computations?

First notice that the pure stack discipline (a stack, but no heap) is a special case of the region stack. Here the size of a region is known at the latest when the region is allocated. Another special case is when one has just one region in the region stack and that region grows dynamically. This case can be thought of as a heap with no garbage collection, which again would not be sufficient.

But when one has many regions, one obtains the possibility of distinguishing between values according to what region they reside in. The MLKit has operations for allocating, de-allocating, and extending regions. But it also has an explicit operation for resetting an existing region, that is, reclaiming all the memory occupied by the region without eliminating the region from the region stack. This primitive, simple as it is, enables one to cope with most of those situations where lifetimes simply are not nested. Figure 1.2 shows a possible progression of the region stack.

In the MLKit the vast majority of region management is done automatically by the compiler and the runtime system. Indeed, with one exception, source programs are written in Standard ML, with no added syntax or special directives. The exception has to do with resetting of regions. The MLKit provides two built-in functions (resetRegions and forceResetting), which instruct the program to reset regions. Here resetRegions is a safe form of resetting where the compiler only inserts region resetting instructions if it can prove that they are safe; it prints thorough explanations of why it thinks resetting might be unsafe otherwise. The function forceResetting is for potentially unsafe resetting of regions, which is useful in cases where the programmer jolly well knows that resetting is safe even if the compiler cannot prove it. The function forceResetting is the only way we allow users to make decisions that can make the program crash; many programs do not need forceResetting and hence cannot crash (unless we have bugs in our system).

All other region directives, including directives for allocation and de-allocation of regions, are inferred automatically by the compiler. This happens through a series of fairly complex program analyses and transformations (in the excess of twenty-five passes involving three typed intermediate languages). These analyses are formally defined and the central one, called region inference, has been proved correct for a skeletal language. Although the formal rules that govern region inference and the other program analyses
1.2. CHECKED DE-ALLOCATION OF MEMORY

Figure 1.2: Further development of the region stack: (a) after allocation of $r_4$; (b) after growth of $r_1$ and $r_4$, resetting of $r_3$ and allocation of $r_5$; (c) after popping of $r_4$ and $r_5$ but extension of $r_1$ and $r_3$. 
are complex, we have on purpose restricted attention to program analyses that we feel capture natural programming intuitions. Moreover, the MLKit implementation is such that, with one exception\(^1\), every region directive takes constant time and constant space to execute. The fact that we avoid interrupting program execution for unbounded lengths of time gives a nice smooth experience when programs are run and should make the scheme attractive for real-time programming.

To help programmers get used to the idea of programming with regions, the MLKit can print region-annotated programs, that is, source programs it has annotated with region directives. Also, it provides a region profiler for examining run-time behavior. The region profiler gives a graphical representation of region sizes as a function of time. This tool makes it possible to see what regions use the most space and even to relate memory consumption back to individual allocation points in the (annotated) source program.

To sum up, the key advantages obtained by using regions compared to more traditional memory management schemes are

1. safety of de-allocation is checked by the compiler
2. the compiler can in many cases spot potential space leaks
3. region management is under the control of the user, provided one understands the principles of region inference
4. each of the region operations that are inserted use constant time and constant space at runtime
5. it is possible to relate runtime space consumption to allocation points in the source program; we have found region profiling to be a powerful tool for eliminating space leaks

Regions are not a magic wand to solve all memory management problems. Rather, the region scheme encourages a particular discipline of programming. The purpose of this report is to lay out this discipline.

\(^1\)The exception has to do with exceptions. When an exception is raised, a search down the stack for a handler takes place; this search is not constant time and it involves popping of regions on the way. However, the number of region operations is bounded by the number of handlers that appear on the stack.
1.3 Example: the Game of Life

To illustrate the general flavor of region-based memory management, let us consider the problem of implementing the game of Life. The game takes place on a board that resembles a chess board, except that the size of the board can grow as the game evolves. Thus every position has eight neighboring positions (perhaps after extension of the board). At any point in time, every position is either alive or dead. A snapshot of the game consisting of the board together with an indication of which positions are alive is called a generation. The rules of the game specify how to progress from one generation to the next. Consider generation $n$ from which we want to create generation $n + 1$ ($n \geq 0$). Let $(i, j)$ be a position on the board, relative to some fixed point $(0, 0)$ in the plane. Assume $(i, j)$ is alive in generation $n$. Then $(i, j)$ stays alive in generation $n + 1$ if and only if it has two or three live neighbors in generation $n$. Assume $(i, j)$ is dead at generation $n$. Then it is born in generation $n + 1$ if and only if it has precisely three live neighbors at generation $n$. We assume that only finitely many positions are alive initially. An example of two generations of Life is shown below:

\[
\begin{array}{cccccccc}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{array}
\]
To represent the game board, we need a data structure that can grow dynamically (so a two-dimensional array of fixed size is not sufficient). A simple solution is to represent a generation by a list of integer pairs, namely the positions that are alive. Since we want to give all pairs belonging to one generation the same lifetime (in the computer memory, that is!) it is natural to store all the integer pairs belonging to one generation in the same region. Indeed region inference forces this decision upon us, as it happens, since it requires that all elements belonging to the same list lie in the same region. (Different lists can lie in different regions, however.)

Thus, after having built the initial generation, we expect the region stack to look like this

\[ l_n: \text{list of integer pairs representing generation } n. \]

The computation of the next generation involves a considerable amount of list computation. Chris Reade has expressed the key part of the computation as shown in Figure 1.3. Despite the extensive use of higher-order functions here, there is a great deal of stack structure in this computation. For example, the \texttt{survivors} list can be allocated in a local region which can be de-allocated after the list has been appended (\texttt{@}) to the \texttt{newborn} list. The computation of \texttt{survivors}, in turn, involves the creation of a closure for \texttt{(twothree o liveneighbours)} and additional creation of closures as part of the computation of the application of \texttt{filter}. Each time \texttt{liveneighbours} is called (by \texttt{filter}) additional temporary values are created. All of this data should live shorter than \texttt{survivors} itself. The details of these lifetimes are determined automatically by the region inference algorithm, which ensures that when the above expression terminates it will simply have created a list containing the live positions of the new generation.

But now we have a design choice. Should we put the new generation in the same region as the previous region or should we arrange that it is put in a separate region? Piling all generations on top of each other in the same region would clearly be a waste of space: only the most recent generation
let val living = alive gen
  fun isalive x = member eq_int_pair_curry living x
  fun liveneighbours x = length(filter isalive (neighbours x))
  fun twoorthree n = n=2 orelse n=3
  val survivors = filter (twoorthree o liveneighbours) living
  val newnbrlist =
    collect (fn z => filter (fn x => not(isalive x))
      (neighbours z)
    ) living
  val newborn = occurs3 newnbrlist
in
 mkgen (survivors @ newborn)
end

Figure 1.3: An excerpt of (a modified version of) Chris Reade’s Game of Life program.

is ever needed. Similarly, giving each generation a separate region on the
region stack is no good either, because it would make the stack grow infinitely
(although this could be alleviated somewhat by resetting all regions except
the topmost one). The solution is simple, however: use two regions, one
for the current generation and one for the new generation. When the new
generation has been created, reset the region of the old region and copy the
contents of the new region into the old region. This effect is achieved by
organizing the main loop of the program as follows:

local
  (*1*) fun nthgen'(p as(0,g)) = p
  (*2*) | nthgen'(p as(i,g)) =
  (*3*)   nthgen' (i-1, let val g' = nextgen  g
  (*4*)     in  show g;
  (*5*)     resetRegions g;
  (*6*)     copy g'
  (*7*)   end)
  in
  (*8*) fun iter n = #2(nthgen'(n,gun()))
  end
Here `nthgen'` is the main loop of the program. It takes a pair as argument; the first component of the pair indicates the number of iterations desired, while the second, `g`, is the current generation. The use of the `as` pattern in line 1 forces the argument and the result of `nthgen'` to be in the same regions. Such a function is called a region endomorphism. In line 3, we compute a fresh generation, which lies in fresh regions, as it happens. Having printed the generation (line 4) we then reset the regions containing `g`. The compiler checks that this is safe. Then, in line 6 we copy `g'` and the target of this copy must be the regions of `g`, because `nthgen'` is a region endomorphism (see Figure 1.4). All in all, we have achieved that at most two generations are live at the same time (a fact that can be checked by inspecting the region-annotated code, if one feels passionately about it).

The above device, which we refer to as double copying, can be seen as a much expanded version of what is often called “tail recursion optimisation”. In the case of regions, not just the stack space, but also region space, is re-used. Indeed, double copying is similar to invoking a copying garbage collector on specific regions that are known not to have live pointers into them. But by doing the copying ourselves, we have full control over when it happens, we know that the cost of copying will be proportional to the size of the generation under consideration and that all other memory management is done automatically by the region mechanism. Because each of the region management directives that the compiler inserts in the code are constant time and space operations, we have now avoided unpredictable interruptions due to memory management. This avoidance of unpredictable interruptions might not be terribly important for the purpose of the game of Life, but if we were writing control software for the ABS brakes of a car, having control over all costs, including memory management, would be crucial!

Region profiles for two hundred generations of life starting from the configuration shown earlier appear in Figures 1.5 and 1.6. The highest amount of memory used for regions during the computation is 45KiB. Figure 1.6 which has data collected from 200 snapshots of the computation, clearly shows that most of the 45KiB are reclaimed between every two generations of the game. It turns out that the game essentially stabilizes with a small number of live positions on the board after roughly 150 generations. This stabilisation is

---

2The source file for the life program is `kitdemo/life.sml`. Running programs is described in Section 2.8. When run with n=10000 under Linux on an x64 box, the memory consumption (resident memory, measured using `top`) quickly reaches 500Kb and stays there for the remaining generations.
1.3. EXAMPLE: THE GAME OF LIFE

\[ l_n: \text{list of integer pairs representing generation } n. \]

\( r_0 \)

(a)

\[ l_{n+1}: \text{list of integer pairs representing generation } n+1. \]

\( r_0 \)

\( r_1 \)

(b)

Figure 1.4: Using double-copying in the game of Life: (a) generation number \( n \) resides in region \( r_0 \); (b) generation \( (n + 1) \) has been built in \( r_1 \); (c) region \( r_0 \) has been reset, the new generation copied into \( r_0 \) and \( r_1 \) has been deallocated.
Figure 1.5: A region profile of two hundred generations of the “Game of Life”, showing region sizes as a function of time (80 snapshots).
1.4. Try it!

This section tells you how to repeat the profiling experiment shown above.

Compile the SML program kitdemo/life.sml as follows. First, make a personal copy of the kit/kitdemo directory, place yourself in it, and execute the command:

```
mlkit
```

We assume that the MLKit compiler command `mlkit` is somehow available through your `PATH` environment variable.

---

Figure 1.6: Region profile of two hundred generations of the “Game of Life”, showing region sizes as a function of time (200 snapshots).

clearly reflected in the region profile.

Figure 1.5 is from the same computation, but it only includes data from 80 snapshots. In the figures, we can see that the largest region is `r154413`. To find out what this region contains, however, one needs to know about the methods described in Part II.
$ mlkit -no_gc -prof life.sml

The option -prof enables region profiling and the option -no_gc disables reference tracing garbage collection. After the MLKit has compiled the program life.sml, the executable life program is available as kitdemo/run.

Next, you may execute run, as follows:

$ ./run -microsec 500

This command will make a profiling snapshot every 500 microseconds (i.e., every half millisecond). If you are satisfied with less fine-grained information, choose a larger number; it will speed up execution. If you just type

./run

there will be one snapshot per second.

Finally, you create a PostScript file and convert it into a pdf-file as follows:\footnote{The program rp2ps can be found in the kit/bin directory.}

$ rp2ps -region -name 'Game of life - 200 snapshots' -sampleMax 80
$ ps2pdf region.ps region.pdf

The option -sampleMax $N$ instructs rp2ps to show at most $N$ snapshots (evenly distributed over the duration of the computation).
Chapter 2

Making Regions Concrete

In this chapter, we give a brief overview of how the abstract memory model presented in the last chapter is mapped down to conventional memory. In doing so, we shall introduce notation and concepts that will be used extensively in what follows.

2.1 Finite and Infinite Regions

Not every region has the property that its size is known at compile-time, or even when the region is first allocated at runtime. As we have seen, one typical use of a region is to hold a list, and in general there is no way of knowing how long a given list is going to be.

For efficiency reasons, however, the MLKit distinguishes between two kinds of regions: those regions whose size it can determine at compile-time and those it cannot. These regions are referred to as finite and infinite regions, respectively.¹ Finite regions are always allocated on the runtime stack. An infinite region is represented as a linked list of fixed-size pages. The runtime system maintains a free list of such pages. An infinite region is represented by a region descriptor, which is a record kept on the runtime stack. The region descriptor contains two pointers: one to the first and one to the last region page in the linked list that represents the region. Allocating an infinite region involves getting a page from the free list and pushing a region descriptor onto the runtime stack. Popping a region is done by appending

¹“finite” and “unbounded” would have been better terms, but it is too late to change that.
the region pages of the region and the free list (this is done in constant time) and then popping the region descriptor off the runtime stack.

At runtime, every region is represented by a 64-bit entity, called a region name. If the region is finite, the region name is a pointer into the stack, namely to the beginning of the region. If the region is infinite, the region name is a pointer to the region descriptor of the region.

The multiplicity of a region is a statically determined upper bound on the number of times a value is put into the region. The MLKit operates with three multiplicities: 0, 1 and $\infty$, ordered by $0 < 1 < \infty$. Multiplicities annotate binding occurrences of region variables. An expression of the form

$$\text{let region } \rho : m \text{ in } e \text{ end}$$

where $m$ is a multiplicity, gives rise to an allocation of a region, which is finite if $m < \infty$, and infinite otherwise.

### 2.2 Runtime Types of Regions

Every region has a runtime types exist: PAIR_RT, ARRAY_RT, REF_RT, TRIPLE_RT, STRING_RT, TOP_RT, and BOT_RT. Not surprisingly, regions of runtime type STRING_RT contain values of ML type string. Regions of runtime type PAIR_RT, ARRAY_RT, REF_RT, and TRIPLE_RT contain pairs, arrays, references, and triples, respectively. Regions with runtime type TOP_RT can contain all other forms of allocated values, that is, constructed values, such as tuples (that are not pairs or triples), records (that do not contain two or three fields), and function closures. Regions of runtime type BOT_RT are not present at runtime and are associated only with so-called explicit region variables, which we shall not discuss in this document.

It is often, but not always, the case that all values that reside in the same region have the same type (considered as representations of ML values).

### 2.3 Allocation and De-Allocation of Regions

The analysis that decides when regions should be allocated and de-allocated is called region inference. Region inference inserts several forms of memory management directives as directives into the program. The target language of region inference is called RegionExp.
In RegionExp, region allocation and de-allocation are explicit, they are always paired, and they follow the syntactical structure of the source program. If \( e \) is an expression in RegionExp, then so is

\[
\text{let region } \rho \text{ in } e \text{ end}
\]

Here \( \rho \) is a region variable. At runtime, first a region is allocated and bound to \( \rho \). Then \( e \) is evaluated, presumably using the region bound to \( \rho \) for storing values. Upon reaching end, the program pops the region.

Region inference also decides, for each value-producing expression, into which region (identified by a region variable) the value will be put.

We emphasize that region variables and region bindings are not present in source programs. The source language is unadulterated Standard ML, so programs that run on the MLKit should be easy to port to any other Standard ML implementation.

### 2.4 Two Backends

The MLKit provides two different backends, one that generates native code for the x64 architecture (running Linux or macOS), the native backend and one that generates JavaScript [Els11].

Whereas the native x64 backend makes use of regions as its basic memory management discipline, SMLtoJs compiles Standard ML programs to JavaScript and makes use of JavaScript’s garbage collection mechanisms for allocating and deallocating memory. In this report, we shall only be concerned about the native backend, for which the linear address space is partitioned into a stack and a heap, which holds region pages, all of the same size.

For the x64 native backend, programs compile into a sequence of instructions, for example for moving word-size data between two registers or between a register and a memory location. More complex operations, such as function application, are expressed by sequences of more detailed instructions.

---

2Previous versions of the MLKit also supported a bytecode backend that allowed for generated bytecode to be executed by a region based abstract machine [EH02] and which was used in the context of a web-server plugin for Standard ML code [EH03, EHV07]; support for this backend has terminated, however.

3With the exception that objects that do not fit into a page are allocated using malloc and freed with free.
native backend implements Iterated Register Allocation [GA96] for assigning machine registers to temporary variables, using the runtime stack for spilling. Although register allocation as well as other issues, such as the interaction between hardware cache strategies and code selection, are important for generating efficient code on modern architectures, we do not want to go to that level of detail here. Our primary concern is with establishing a model that the user can safely use as a worst-case model of what happens at runtime.

2.5 Boxed and Unboxed Values

As is common with implementations of programming languages, we distinguish between boxed and unboxed representation of values. An unboxed value is one that is stored in a register or a machine word. A boxed value is one that is represented by a word-size pointer to the value itself, which is stored in one or more regions.

The MLKit uses unboxed representation for integers, booleans, words, the unit value, and characters. The MLKit uses boxed representation for pairs, records (with at least one element), reals, exception values, function closures, and constructed values (i.e., data types, except lists and booleans).

A boxed value may reside in a finite or an infinite region. Unboxed values are not stored in regions, except when they are part of a boxed value. For example, the integer 3 by itself is stored as the (binary representation) of the value 3 in a register or in a machine word. However, the pair (3,4) is represented as a pointer to two consecutive words in a region, the first of which contains the binary representation of 3 and the second of which contains the binary representation of 4.

2.6 Intermediate Languages

The MLKit native compiler compiles Standard ML programs via a sequence of typed intermediate languages into x64 machine code.

The intermediate languages that we shall refer to in the following are (in the order in which they are used in the compilation process):

Lambda: A lambda-calculus like intermediate language. The main difference between the Standard ML Core Language and Lambda is that
2.7. THE RUNTIME SYSTEM

Lambda only has trivial patterns and allows functions to take multiple arguments.

RegionExp: Same as Lambda, but with explicit region annotations (such as the region bindings mentioned in Section 2.3). Region variables have their runtime type (Section 2.2) as an attribute, although, for brevity, the pretty printer omits runtime types when printing expressions, unless instructed otherwise.

MulExp: Same as RegionExp, but now every binding region variable occurrence is also annotated with a multiplicity (Section 2.1) in addition to a runtime type. Again, the default is that the runtime type is not printed. The terms of MulExp are polymorphic in the information that annotate the nodes of the terms. That way, MulExp can be used as a common intermediate language for a number of the internal analyses of the compiler, which add more and more information on the syntax tree. The analysis that computes multiplicities is called the multiplicity analysis.

The MLKit contains a Lambda optimiser, which will happily rewrite Lambda terms when it is clear that this rewrite results in faster programs (as long as the rewrite cannot lead to increased space usage).

Region inference takes Lambda to be the source language. Region inference happens after the Lambda optimiser has had a go at the Lambda term. Therefore, it was not really true when we said that region inference simply annotates source programs; we ignored the translation from SML to Lambda and the Lambda optimiser. Thus, one has to get used to (mostly minor) differences between the source language and the intermediate languages of the compiler if one wants to read programs in their intermediate forms. Moreover, Modules Language constructs are eliminated during compilation from the intermediate languages (see Chapter 15 for details of compiling with Modules in the MLKit).

When we want to show the result of the analyses, we usually show a MulExp expression.

2.7 The Runtime System

The runtime system is written in C. It is small (less than 30Kb of code when compiled). It contains operations for allocating and de-allocating regions,
extending regions, obtaining more space from the operating system, recording region profiling information, and performing low-level operations for use by the Standard ML Basis Library.

It is possible to call C functions from MLKit code if you use the native backend. The MLKit takes care of the memory allocation, by allocating regions for the result of the call before the call and de-allocating the regions at some point after the call. The C functions can build ML data structures such as lists through abstract operations provided by the MLKit runtime system. See Chapter 19 for further details.

2.8 Compiling Programs with the MLKit

The MLKit is a batch compiler. Thus, executing a program consists of first compiling the program and then running the generated target program. Because the MLKit stores files in the directories where your source files are located, you should make a personal copy of these directories. Before you try any of the examples below, make a personal copy of the kitdemo directory, which is part of the distribution, and run the MLKit on your own copy.

2.9 Compiling with the MLKit Compiler

The mechanism the MLKit provides for compiling programs is to give the program source(s) as argument to the MLKit command mlkit. Together with the sources, a series of options may be passed to the mlkit command. Let us assume that the UNIX command mlkit is available on your system.

Compiling an MLB-file (which may list several SML source files) is similar to compiling a single SML source file. However, we shall postpone the in-depth discussion of how to compile MLB-files to Chapter 15.

As an example, to compile the file projection.sml located in the kitdemo directory, first go to this directory and execute the following command:

```
$ mlkit -no_gc projection.sml
```

Execution of this command will result in an executable file run, placed in the kitdemo directory.

---

4The README file in the distribution tells you how to install the MLKit.
To see some internal representations of the `projection.sml` program, as produced during compilation, try pass the command-line options `--print_types` and `--print_drop_regions_expression` to the `mlkit` command, as follows:

```
$ rm -rf MLB
$ mlkit -no_gc \n    -print_types \n    -print_drop_regions_expression \n    projection.sml
```

Removing the `MLB` directory is necessary to avoid the MLKit to recognise that it can reuse the previous result of compiling the `projection.sml` program. A shorter version of the compilation command is

```
$ mlkit -no_gc -Ptypes -Pdre projection.sml
```

To get more information about which options you can pass to the MLKit at the command-line, try executing `mlkit -help`. The output of executing this command is shown in Appendix A.

## 2.10 Running Compiled Programs

If no errors were found during compilation, the MLKit produces a *target program* in the form of an executable file, called `run`. The MLKit places `run` in the working directory.

Running the target program is done from the UNIX shell by typing

```
$ ./run
```

For small programs, the file will probably be around 50Kb large, even for the trivial examples considered in this chapter. This is because it contains the MLKit runtime system and compiled code for the parts of the SML Basis Library that are needed for linking.

Running the programs presented in this chapter is not particularly exciting, because none of them produce output! However, as an exercise, try compile and execute the `helloworld.sml` program, which, like all other example files in this document, is located in the `kitdemo` directory.
Part II

The Language Constructs of SML
Chapter 3

Records and Tuples

In this chapter we describe construction of records and selection of record components. We also use records to introduce region-annotated types and effects, which are crucial for understanding when regions are allocated and de-allocated.

3.1 Syntax

As part of the SML to Lambda translation, all SML records and SML tuples are compiled into Lambda tuples. The components of Lambda tuples are numbered from left to right, starting from 0. Selection is a primitive operation, both in Lambda and in the other intermediate languages. This primitive is printed using SML notation \#i. Components are numbered from 0: the ith components of a tuple of type \( \tau_1 \ast \ldots \ast \tau_n \) is accessed by \#i, for \( 0 \leq i \leq n - 1 \).

The tuple constructor in Lambda is written as in SML:

\[
(e_1, \ldots, e_n)
\]

However, the corresponding expression in RegionExp and MulExp takes the form

\[
(e_1, \ldots, e_n \at \rho)
\]

where \( \rho \) is a region variable indicating where the tuple should be put. In the case \( n = 0 \), the \( \at \rho \) is not printed, because the empty tuple is not allocated; it is just a constant that fits in a register at runtime.

Records are evaluated left to right.
3.2 Example: Basic Record Operations

Consider the source program

\[
\text{val xy = ((),())}
\]

\[
\text{val x = #1 xy;}
\]

Here is the resulting MulExp program:\footnote{Program kitdemo/projection.sml. Running programs is described in Section 2.8.}

\[
\text{let val xy = ((),()) at r4;}
\]

\[
\text{val x = #0 xy}
\]

\[
in \{|xy: (_,r4), x: _|\}
\]

end

There are several things to notice from this example.

1. The MulExp program contains a free region variable, r4. Notice that the construction of the pair xy has been annotated by “at r4”, indicating where the pair should be put;

2. The expression \{|xy: (_,r4), x: _|\} is an example of a frame expression. A frame enumerates the components that are exported from a compilation unit. A frame is similar to a record, except that its components are variables, each annotated with a type scheme and a region variable, if the value is boxed. (In records, the components can only have types, not general type schemes.) In the example, the type of the frame is \{|xy: (unit*unit, r4), x: unit|\}. The type shows that, after the program unit has been evaluated, xy will reside in r4. In the the above example, printing of types was suppressed. Thus types were abbreviated to _.

3.3 Region-Annotated Types

ML type inference infers a type for every expression in the program. Region inference extends this idea by inferring for each expression a \textit{(region-annotated) type with place}. We use \(\mu\) to range over types with places

\[
\mu ::= (\tau, \rho) \mid \tau
\]
where \( \tau \) is a *region-annotated type*, which again can contain other region-annotated types with places. The region-annotated type with place of an expression is the ML type of the expression decorated with extra region information; every type constructor that represents boxed values (e.g., pairs and strings) is paired with a region variable, indicating where the value is to be put at runtime. Type constructors that represents unboxed values (e.g., integers and booleans) are not paired with a region.

Here are some examples of region-annotated types with places:

- \([\text{unit}]\) The type of 0-tuples. Integers, booleans, and 0-tuples are represented unboxed at runtime (rather than being stored in regions), see Section \(2.5\).
- \([\text{string}, \rho]\) The type of strings in region \( \rho \).
- \([\text{int} \times (\text{string}, \rho_1), \rho_2]\) The type of pairs in \( \rho_2 \) whose first component is an integer and whose second component is a string in region \( \rho_1 \).

One can get the MLKit to print the region-annotated types with places that it infers for binding occurrences of variables. The above example then becomes

```plaintext
let val xy:(unit*unit,r4) = ((), ()) at r4;
val x:unit = #0 xy
in {|xy: (unit*unit,r4), x: unit|}
end
```

### 3.4 Effects and let region

We now describe the general principle that the MLKit uses to decide when it is safe to put *region* binding around an expression.

Here is an example of an SML program that first creates a pair and then selects a component of the pair, after which the pair is garbage\(^2\).

```plaintext
val n = let
    val pair = if true then (3+4, 4+5)
    else (4, 5)
```

\(^2\)Program kitdemo/elimpair.sml.
let val n =
  let region r13:1;
  val pair = case true of
    true => (3 + 4, 4 + 5)at r13
  | _ => (4, 5)at r13
  in #0 pair
  end
in {ln: _}
end

Figure 3.1: Region inference decides that the pair is to be allocated in a local, finite region; the region will be de-allocated as soon as the pair becomes garbage.

in
  #1 pair
end

The MLKit compiles the declaration into the MulExp program shown in Figure 3.1. The compiler compiles the program as it is, without reducing the conditional to its then branch. During evaluation, a region (denoted by r13) is introduced before the pair is allocated; it remains on the region stack until the projection of the pair is evaluated, after which the region is de-allocated.

The “:1” on the binding occurrences of r13 is a multiplicity indicating that there is only one store operation into the region. (The multiplicity analysis has discovered that there is at most one store from the then branch and at most one store from the else branch and that at most one of the branches will be chosen.) Thus, the pair will be allocated in a little region on the runtime stack.

But how does the MLKit know that it is safe to de-allocate r13 when the region goes out of scope?

The answer lies in the fact that the MLKit infers for every expression not just a region-annotated type with place, but also a so-called effect. An effect is a finite set of atomic effects. Two forms of atomic effect are put(ρ) and get(ρ), where ρ as usual ranges over region variables. The atomic effect put(ρ) indicates that a value is being stored in region ρ and get(ρ) indicates that a value is being read from region ρ. In our example, the region inference
algorithm considers the sub-expression \((e_0 =)\)

```ml
let val pair = case true of
  true => (3 + 4, 4 + 5) at r13
  _ => (4, 5) at r13
in #0 pair
end
```

and finds that it has region-annotated type `int` and effect `{\text{put}(r13), \text{get}(r13)}`.

Whenever a region variable occurs free in the effect of an expression but occurs free neither in the region-annotated type with place of the expression nor in the type of any program variable that occurs free in the expression then that region variable denotes a region that is used only locally within the expression. That this is true is of course far from trivial, but it has been proved for a skeletal version of RegionExp. Consequently, when this condition is met, the region inference algorithm wraps a region binding of the region variable around that expression.

In our example, there are no free variables in \(e_0\); moreover, \(r13\) occurs in the effect of \(e_0\) but not in the region-annotated type with place of \(e_0\). Thus, the region inference algorithm inserts a region binding of \(r13\) around \(e_0\).

### 3.5 Runtime Representation

A record with 0 components (the value of type `unit`) is represented unboxed. A record with \(n\) components \((n \geq 1)\) is represented boxed, as a pointer to precisely \(n\) words in a region.

Notice that records are not tagged. Avoiding tags is possible when the reference tracing garbage collector is disabled, because polymorphic equality is compiled into monomorphic equality functions that do not have to examine the type of objects at runtime [Els98].

Lambda, RegionExp, and MulExp allow one to express unboxed tuples, also in the case of function calls and returns. For functions that take a tuple as parameter, the MLKit passes the argument tuple unboxed if it can see that the boxed representation of the tuple is not needed by the function. The MLKit does not at present unbox records returned from functions. See Section 6.1 on page 57 for details about unboxed function arguments.

A tuple is not allocated until its components have been evaluated.

---

3When garbage collection (GC) is enabled, \(n + 1\) words are used to hold a record with \(n\) components.
CHAPTER 3. RECORDS AND TUPLES

When reference-tracing garbage collections is enabled, records and tuples are tagged unless they are of size two or three (pairs or triples), in which case they will reside in regions of runtime type PAIR_RT or TRIPLE_RT, respectively. Such regions are treated specially by the reference-tracing garbage collector.
Chapter 4

Basic Values

In this chapter we describe how basic values such as integers, reals, strings, and booleans are represented in the MLKit. The MLKit complies to the Definition of Standard ML (Revised) and to large parts of the Standard ML Basis Library\footnote{See the MLKit web site for a link to the Standard ML Basis Library.} that is, as a programmer, you can refer to components of the Standard ML Basis Library through the \textit{initial basis}, in which all programs are compiled. Throughout this chapter, we introduce some of the top-level bindings that are provided by the initial basis.

4.1 Integers and Words

Values of type \texttt{int} are represented as unboxed 64-bit signed integers. When reference tracing garbage collection is enabled in the MLKit, one bit is used for tagging, thus in this case values of type \texttt{int} are really 63-bit signed integers; Chapter \ref{chapter:garbage_collection} describes how to compile programs with garbage collection enabled. The structure \texttt{Int} provides many useful operations on integers of type \texttt{int}\footnote{To see what operations are available in the \texttt{Int} structure, consult the file \texttt{basis/INTEGER.sml}.} The MLKit also defines the structures \texttt{Int31}, \texttt{Int32}, \texttt{Int63}, and \texttt{Int64} for operations on 31-bit, 32-bit integers, 63-bit, and 64-bit integers. When garbage collection is enabled, values of type \texttt{Int64.int} and \texttt{Int32.int} (for historical reasons) are represented boxed, whereas values of type \texttt{Int31.int} and \texttt{Int63.int} are represented unboxed. When garbage collection is enabled, the structure \texttt{Int} is identical to the structure \texttt{Int63}. 

47
When garbage collection is disabled, the structure `Int` is identical to the structure `Int64`.

The following operations on integers are pre-defined at top level:

```ocaml
infix 4 = <> < > <= >=
infix 6 + -
infix 7 div mod *
val ~ : int -> int
val abs: int -> int
```

In fact, these operations are overloaded and will work on values of other integer types as well, even on values of type `IntInf.int`, which denotes arbitrarily-sized integers.

Operations on 8-bit, 31-bit, 32-bit, 63-bit, and 64-bit unsigned words are available in the structures `Word8`, `Word31`, `Word32`, `Word63`, and `Word64`.

Similarly as for integers, when garbage collection is enabled, the structure `Word` is identical to the structure `Word63` and values of type `Word64.word` are represented boxed. Contrary, when garbage collection is disabled, the structure `Word` is identical to the structure `Word64` and values of type `Word64.word` are represented unboxed.

### 4.2 Reals

The initial basis provides the following top-level operations on reals:

```ocaml
infix 4 < > <= >=
infix 6 + -
infix 7 * /
val ~ : real -> real
val abs: real -> real
val real: int -> real
val trunc : real -> int
val floor : real -> int
val ceil : real -> int
val round : real -> int
```

Values of type `real` are implemented as 64-bit floating point numbers. They are always boxed when they appear in data structures, that is, they are each
4.3. CHARACTERS AND STRINGS

Characters and Strings

The initial basis provides the following top-level operations on characters and strings:

```
infixed  4 =
infixed  6 ^
val ord: char -> int
val chr: int -> char
val str: char -> string
val size: string -> int
val explode: string -> char list
val implode: char list -> string
val ^ : string * string -> string
val concat: string list -> string
val substring: string * int * int -> string
```

Characters are represented as 64-bit words, although only 8 bits are used to store the character. Characters are always unboxed, also when garbage collection is enabled.

A string is represented by a 64-bit pointer into an infinite region. A string is stored in a region page if it fits in the page; otherwise, it is allocated using `malloc` and linked with the region so that it can be `free`ed when the region is deallocated. The internal string representation is completely transparent to the programmer, who does not have to worry about the actual size of region pages. Characters of a string takes up only 8 bits of memory each. The size of a string is kept along with the characters that make up the

---

\(^3\)Consult the files `basis/REAL.sml` and `basis/MATH.sml`. 
string. For compatibility with many C routines, the character sequence is null-terminated.

Calls of \texttt{ord}, \texttt{chr}, \texttt{str}, and \texttt{size} take constant time and space. Calls of \texttt{explode}, \texttt{implode}, \texttt{concat}, \texttt{substring}, and \^ take time and space proportional to the sum of the size of their input and their output.

The string and character operations can raise exceptions, as detailed in the Standard ML Basis Library documentation.

The structures \texttt{Char}, \texttt{String}, \texttt{CharVector}, \texttt{Byte}, and \texttt{StringCvt} provide other useful operations on characters and strings.\footnote{Consult \texttt{basis/CHAR.sml}, \texttt{basis/STRING.sml}, \texttt{basis/MONO_VECTOR.sml}, \texttt{basis/BYTE.sig} and \texttt{basis/STRING_CVT.sml}.}

\section{4.4 Booleans}

The boolean values \texttt{true} and \texttt{false} are represented as 64-bit words, although only one bit is used to denote the value. Booleans are unboxed. The initial basis provides the following top-level operations on booleans:

\begin{verbatim}
infix 4 =
val not: bool -> bool
\end{verbatim}

The structure \texttt{Bool} provides other useful operations on booleans.\footnote{Consult the file \texttt{basis/BOOL.sig}.}
Chapter 5

Lists

Section 5.1 gives a summary of the list concept in Standard ML, introduces the notion of the auxiliary pairs of a list and presents the syntax of constructors and de-constructors in the intermediate languages. Section 5.3 introduces region-annotated list types and show how they correspond to the layout of lists in memory. Section 5.4 gives a small example.

5.1 Syntax

In Standard ML, all lists are constructed from the two constructors :: (read: cons) and nil. As a shorthand, one can write \([exp_1, \cdots, exp_n]\) for

\[
\text{\texttt{exp}_1 :: \cdots :: \text{\texttt{exp}}_n :: \text{\texttt{nil}}}
\]

which in turn is short for

\[
\text{\texttt{op} :: (exp_1, \cdots, \text{\texttt{op} :: (exp}_n, \text{\texttt{nil})}}\cdots)
\]

where \texttt{exp} ranges over expressions. The type schemes of \texttt{nil} and \texttt{cons} are

\[
\text{\texttt{nil} \mapsto \forall \alpha. \alpha \text{ list}} \quad :: \mapsto \forall \alpha. \alpha \ast \alpha \text{ list} \rightarrow \alpha \text{ list}
\]

Notice that :: is always applied to a pair. The construction of the pair and the application of :: should, in principle, not be confused: the pair and the constructed value are in principle separate values inasmuch as they have different type. For example, the declaration
val p = (2, nil)
val mylist = (op ::) p
val n = #1 p

is legal in Standard ML. We refer to the pairs to which :: is applied as
auxiliary pairs (of the list data type).

Decomposition of list values in Standard ML is done by pattern matching.
A pattern can extract the pair to which :: is applied. Pattern matching on
pairs can then give access to the components of the pair.

val abc = ["a", "b", "c"]
val op :: p = abc (* binds p to the pair ("a", ["b","c"] *))
val (x::y::_) = abc (* binds x to "a" and y to "b" *)

In the last declaration, the pattern (x::y::_) is short for the pattern

    (op ::(x, op ::(y, _)))

which combines decomposition of constructed values with decomposition of
pairs.

The intermediate languages Lambda, RegionExp, and MulExp have SML-
like constructs for applying constructors, but they decompose constructed
values by applying a de-constructor primitive, not by pattern matching.

<table>
<thead>
<tr>
<th>Lambda, RegionExp, or MulExp</th>
<th>nil</th>
<th>::(e)</th>
<th>decon ::(e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>create nil value</td>
<td>create :: (cons) value</td>
<td>cons decomposition</td>
<td></td>
</tr>
</tbody>
</table>

In Lambda, which has essentially the same type system as SML, decon ::,
the decomposition function for ::, has type ∀α.α list → α * α list. In
addition, Lambda, RegionExp, and MulExp have a simple case construct:

    (case e of :: => e1 | _ => e2)

where e must have list type.

5.2 Physical Representation

The empty list is represented by an odd, unboxed integer. A non-empty list
is represented as a pointer to a pair of two words in a region, the first of which
contains the head of the list and the second of which contains the representation of the tail of the list. In other words, the physical representation does not distinguish a \texttt{:} cell from the auxiliary pair to which \texttt{:} is applied. Since \texttt{nil} is represented by an odd number and since word addresses are always even, \texttt{nil} can be distinguished from the representation of a non-empty list.

As a consequence, there is no cost involved in applying \texttt{:} to an auxiliary pair or in applying the decomposition operator \texttt{decon\_} to a non-empty list.

### 5.3 Region-Annnotated List Types

In Standard ML, all elements of a given list must have the same type. We extend this constraint to region inference by saying that all element values in the same list must reside in the same region(s) and that all auxiliary pairs of the same list must reside in the same region.

Thus, region inference does not distinguish between a list and its tail. Indeed, a typical use of an infinite region is to hold all the auxiliary pairs of a list. For an example, Figure 5.1 shows how the list \texttt{["a","b","c"]} is laid out in memory.

In general, the region-annotted type of a list takes the form

\[(\mu, [\rho])\text{list}\]

where \(\mu\) is the region-annotated type with place of the members of the list and where \(\rho\) is the region where the auxiliary pairs of the list are stored. For
example, the region-annotated type

\[(\text{string}, \rho_1), [\rho_2])\text{list}\]

classifies lists that have their auxiliary pairs in a region \(\rho_2\) and strings in a region \(\rho_1\).

Notice that the \texttt{list} type constructor is not paired with a region variable. The reason is that the physical representation of lists treats the constructors as unboxed in the sense described in Section 5.2.

Very importantly, not all lists need to live in the same regions. Formally, \texttt{nil} and :: have the following region-annotated type schemes:

\[
\text{nil} \mapsto \forall \alpha. (\alpha, [\rho])\text{list}
\]

\[
:: \mapsto \forall \alpha \epsilon. (\alpha * (\alpha, [\rho])\text{list}, \rho) \rightarrow \epsilon (\alpha, [\rho])\text{list}
\]

Despite its verbosity, the type scheme for :: deserves careful study. It is polymorphic not just in types (signified by the bound type variable \(\alpha\)) but also in the region signified by the bound region variables \(\rho\), and, in the case of ::, in the effect signified by the \textit{effect variable} \(\epsilon\). The \(\epsilon.\emptyset\) appearing on the function arrow is called an \textit{arrow effect}. Occurring in a function type, an arrow effect describes the effect of applying the function. In this case, the effect is empty, as only unboxed values are manipulated by ::. The effect variable \(\epsilon\) is used for expressing dependencies between effects (examples follow in Chapter 13). Due to the fact that the variables are universally quantified, every occurrence of a list can, potentially, be in its own regions. But notice that the type of :: forces the element, which is consed onto the list, to be in the same regions as the already existing elements of the list. Similarly, the type forces the auxiliary pairs to be in one region (\(\rho\)).

### 5.4 Example: Basic List Operations

The MLKit compiles the program\(^1\)

\[
\text{let val l = [1, 2, 3];}
\]

\[
\text{val (x::_) = l}
\]

\[
\text{in x end}
\]

into the RegionExp program shown in Figure 5.2.

\(^1\)Program kitdemo(onetwothree.sml.
let val it =
    let region r9:INF;
    val l = [1,2,3] at r9
    in case l of :: => let val v91 = decon_:: l
        in #0 v91
        end
    | _ => raise Bind
    end
    in {|it: _|}
end

Figure 5.2: Example showing construction and de-construction of a small list. Layout of the list l is analogous to Figure 5.1. The infinite region r9 holds the auxiliary pairs of the list.
Chapter 6

First-Order Functions

In this chapter, we shall treat functions that are declared with \texttt{fun} and that are first-order (i.e., that neither take functions as arguments nor produce functions as results). Higher-order functions are treated in Chapter 13. Region polymorphism works uniformly over all types; we use lists as an example of the general scheme.

6.1 Region-Polymorphic Functions

It would be a serious limitation if all lists produced by a series of calls to a function were stored in the same region, for then all those lists would have to be kept alive till the last time one of them were used. The solution that the MLKit offers to this problem is \textit{region-polymorphic functions}, that is, functions that are passed regions at runtime.

When one declares a function that, when called, produces a fresh list, then the region inference algorithm will automatically insert extra formal region parameters in the function declaration. At every place one refers to the function, for example because one calls the function, the region inference algorithm inserts actual region parameters that tell the function where to put its result. This is all done automatically; the user does not have to introduce region parameters or pass them as arguments. Even so, it is useful to understand the general principle, so that one can make good use of region polymorphism.

The syntax of a (single) function declaration in MulExp is:

\[
\texttt{fun \ f \ at} \rho_0 \ [\rho_1, \cdots, \rho_k] \ (x_1, \cdots, x_n) = e
\]
Here $\rho_0$ denotes the region in which the closure for $f$ is stored, $\rho_1, \ldots, \rho_k$ are the formal region parameters, $x_1, \ldots, x_n$ are value parameters, and $e$ is the body of the function. A call to $f$ takes the form

$$f \ [\rho'_1, \ldots, \rho'_k] <e'_1, \ldots, e'_n>$$

where $[\rho'_1, \ldots, \rho'_k]$ are actual region parameters and $e'_1, \ldots, e'_n$ are expressions denoting the arguments to the call. Notice that region parameters are enclosed in brackets ([ ]); this should not cause confusion with ML lists, because RegionExp and MulExp do not use brackets for lists. In the special case $k = 0$, no region parameters are passed to the function, and we shall often omit the brackets in this case.

Also notice that, unlike for Standard ML, functions are allowed to be passed multiple value arguments; see below. In the case $n = 1$, we often omit the surrounding brackets $<\ldots>$. In the special case $k = 0$, no region parameters are passed to the function, and we shall often omit the brackets in this case.

Different calls of $f$ can use different actual regions; this feature is essential for obtaining good separation of lifetimes. For an example, consider the following program:

```ml
fun fromto(a, b) = if a>b then []
    else a :: fromto(a+1, b)

val l = #1(fromto(1,10), fromto(100,110));
```

The corresponding MulExp program is shown in Figure 6.1.

There are several things to notice about the region annotated program. First, notice that the function `fromto` represents its argument $(a,b)$ unboxed; the MLKit figures out that the function does not use the boxed representation of the argument and transforms all calls to the function to pass the argument unboxed (on the runtime stack and in registers if possible).

Second, notice that $r14$ is a formal region parameter of `fromto` and that $r14$ is passed along in the recursive call `fromto[r14] <v93 + 1, v94>`. Here the notation $<v93 + 1, v94>$ denotes the passing of the unboxed record to the function `fromto`.

Finally, notice that the regions that hold the two lists generated by this program are distinct. The list that escapes to top level is stored in the global region $r4$, whereas the list that does not escape is stored in the local region $r24$. 


6.2 Region-Annotated Type Schemes

A (region-annotated) type scheme takes the form

\[ \sigma ::= \forall \alpha_1 \cdots \alpha_n \rho_1 \cdots \rho_k \epsilon_1 \cdots \epsilon_m . \tau \]

where \( \alpha_1, \ldots, \alpha_n \) are type variables, \( \rho_1, \ldots, \rho_k \) are region variables, \( \epsilon_1, \ldots, \epsilon_m \) are effect variables, and \( \tau \) is a region-annotated type.

The types of \texttt{nil} and \texttt{::} in Section 5.3 are examples of region-annotated type schemes.

There is a close connection between, on the one hand, the formal and actual region parameters found in RegionExp (and MulExp) programs, and, on the other hand, the region-annotated type schemes that the region inference algorithm assigns to recursively declared functions. The formal region parameters of a function stem from the bound region variables of the region-annotated type scheme of that function. The actual region parameters which annotate a call of the function are the region variables to which the bound region variables are instantiated at that particular application.

For example, the region-annotated type scheme of \texttt{fromto} from Figure 6.1 is

\[ \forall \rho_{14} \epsilon_{\text{int}, \text{int}} . \texttt{\{put(\rho_{14})\} \to (\text{int}, [\rho_{14}]) list} \]
where we use the syntax \([\tau_1, \ldots, \tau_n], n \geq 1\) to denote an unboxed tuple of types \(\tau_1, \ldots, \tau_n\). This syntax is not to be confused with the auxiliary region variables of type constructors (e.g., the list \([\rho_{14}]\) in the region-annotated type scheme of \texttt{fromto}.)

At the last call of \texttt{fromto} in Figure 6.1 the type scheme is instantiated to the region-annotated type

\[
[\text{int}, \text{int}] \mapsto \{\text{\texttt{put}(\rho_{24})}\mapsto (\text{\texttt{int}}, [\rho_{24}])\} \text{\texttt{list}}
\]

The instantiation of bound variables of the type scheme that yields this region-annotated type is

\[
\{\rho_{14} \mapsto \rho_{24}, \epsilon \mapsto \epsilon'\}
\]

In general, the actual region parameters that annotate a call of a region-polymorphic function are obtained from the range of the substitution by which the type scheme of the function is instantiated at that application.

Region-polymorphic functions also have to be allocated somewhere. Therefore, the region information associated with a region-polymorphic function is a \textit{(region-annotated) type scheme with place}, that is, a pair \((\sigma, \rho)\). Indeed, every binding of a variable to a boxed value (whether the binding is done by \texttt{fun}, \texttt{let}, or \texttt{fn}) associates a region-annotated type scheme with place to the binding occurrence. (In the case of \texttt{let}, the type scheme will have no quantified region and effect variables, however, and in the case of \texttt{fn}, the type scheme will have no quantified variables at all.) In the following, when we refer to “the region-annotated type (scheme) with place” of some variable, we mean the region-annotated type (scheme) with place that is associated with the binding occurrence of the variable. The region type scheme should be clearly distinguished from instances of the type scheme, which decorate non-binding occurrences of the variable.

The region-annotated type scheme with place of a variable bound to an unboxed value is always on the form \(\sigma\) (no specified place), where \(\sigma\) is the region-annotated type scheme associated with the variable (see Section 3.3).

### 6.3 Endomorphisms and Exomorphisms

The \texttt{fromto} function from Section 6.2 has the property that it can put its result in regions that are separate from the regions where its argument lies.
This is not surprising, if one looks at the declaration of the function; it creates a brand new list that does not share with the argument \((a,b)\), except for the integers \(a\) and \(b\), which may end up in the list. The freshness of the generated list is evident from the region type scheme of the function; the region variable in the result type does not appear in the argument type.

Not all region-polymorphic functions create brand new values. Very often, a region-polymorphic function simply adds values to regions that are determined by the argument to the function. A good example is the list append function from the initial basis:\footnote{File kitdemo/append.sml.}

```
infixr 5 @
fun [] @ ys = ys
| (x::xs) @ ys = x :: (xs @ ys)
val l = [1] @ [2,3]
```

Append successively conses the elements of the first list onto the second list. Thus, \(ys\) and \(xs @ ys\) must be in the same regions. However, the auxiliary pairs of \(xs\) and \(ys\) need not be in the same regions, although the elements of \(xs\) and \(ys\) clearly must be in the same regions, because they end up in the same list. These properties of the append function @ are summarized in its inferred region-annotated type scheme:

\[
\forall \alpha \rho_{15} \rho_{16} \epsilon. ((\alpha, [\rho_{16}])\text{list}, (\alpha, [\rho_{15}])\text{list}) \xrightarrow{\epsilon\{\text{get}(\rho_{16}), \text{put}(\rho_{12})\}} (\alpha, [\rho_{15}])\text{list}
\]

When one writes a function it is a good idea to consider whether one wants the function to create values in fresh regions or whether one wants it to add values to existing regions. Adding to existing regions can of course make these regions too large and long-lived, because the entire region will be alive for as long as one of the values in the region may be needed in the future.

The MulExp version of the append function is listed in Figure \[6.2\]. At the application of @, the region annotated type scheme for @ is instantiated to the region annotated type

\[
[(\text{int}, [\rho_{27}])\text{list}, (\text{int}, [\rho_{4}])\text{list}] \xrightarrow{\epsilon\{\text{get}(\rho_{27}), \text{put}(\rho_{4})\}} (\text{int}, [\rho_{4}])\text{list}
\]

To avoid passing regions that are never used, the MLKit introduces only formal region variables for those bound region variables in the type scheme for which there appears at least one put effect in the type of the function.
let fun $\oplus$ at $r_1$ [$r_{15}^{\text{INF}}$] ($v_{96}$, $v_{129}$) =
\[
\text{case } v_{96} \text{ of}
\]
\[
\text{nil } \Rightarrow v_{129}
\]
\[
| \_ \Rightarrow
\]
\[
\text{let val } v_{98} = \text{decon}_\_ :: v_{96};
\]
\[
\text{val } v_{99} = \#0 v_{98};
\]
\[
\text{val } v_{100} = \#1 v_{98}
\]
\[
in :: (v_{99}, \oplus[r_{15}] <v_{100}, v_{129}> )\text{at } r_{15}
\]
\[
\text{end;}
\]
\[
\text{val } l = \text{let region } r_{27}^{\text{INF}}
\]
\[
in \oplus[r_{4}] <[1] \text{ at } r_{27}, [2,3] \text{ at } r_{4}>
\]
\[
\text{end}
\]
\[
in \{ |\oplus: (\_, r_{1}), l: \_ | \}
\]
\[
\text{end}
\]

Figure 6.2: The region-annotated version of $\text{append}$.

Reading a value is done simply by following a pointer to the value, irrespective of what region the value resides in, whereas storing a value in a region uses the name (see Section 2.1) of the region. This omitting of region parameters explains why $\rho_{16}$ does not become a formal region parameter of $\oplus$ and why $\rho_{27}$ is not passed to $\oplus$ at the call site. This optimisation, which is called dropping of regions, is the key reason why the MLKit takes the trouble to distinguish between $\text{put}$ and $\text{get}$ effects.

Here are two more examples to highlight the difference between functions that can put values in fresh regions and functions that add values to existing regions:

\[
\text{fun } \text{cp1 } [\_] = [\]
\]
| \text{cp1 } (x::xs) = x :: \text{cp1 } xs
\[
\text{fun } \text{cp2 } (l \text{ as } [\]) = l
\]
| \text{cp2 } (x::xs) = x :: \text{cp2 } xs

Here $\text{cp1}$ can copy the auxiliary pairs of a list into a fresh region, whereas $\text{cp2}$ always copies the auxiliary pairs of a list into the same region:

\[
\text{cp1 } \mapsto \forall \alpha \rho \rho'. (\alpha, [\rho ])\text{list} \xleftarrow{\langle \text{get}(\rho), \text{put}(\rho') \rangle} (\alpha, [\rho'])\text{list}
\]
\[
\text{cp2 } \mapsto \forall \alpha \rho \epsilon. (\alpha, [\rho ])\text{list} \xleftarrow{\langle \text{get}(\rho), \text{put}(\rho) \rangle} (\alpha, [\rho ])\text{list}
\]
As we saw in Section 1.3, there are cases where it is useful to copy a list from one region into another region, so as to make it possible to de-allocate the old region. This copying can be used as a kind of programmer-controlled garbage collection in cases where garbage has accumulated in the original region.

Because it is often useful to distinguish between functions that can put their result into fresh regions and functions that simply add to regions determined by their value argument, we shall refer informally to the former functions as region exomorphisms and the latter as region endomorphisms. Notice that this is not a clear-cut distinction, however. Often, functions have both an endomorphic and an exomorphic side to them. Also notice that even a region exomorphic function can be forced to act as an endomorphism by the calling context. As an example, consider the expression

\[
\text{if true then } \text{cp1 } l \text{ else } l
\]

Because the two branches of the conditional are required to have the same region-annotated type with place, \( l \) and \( \text{cp1 } l \) are forced to be in the same regions.

### 6.4 Polymorphic Recursion

A recursive region-polymorphic function

\[
\text{fun } f \text{ at } \rho_0 [\rho_1, \ldots, \rho_k] (x_1, \ldots, x_n) = e
\]

may call itself inside its own body \((e)\) with regions that are different from its own formal region parameter \(([\rho_1, \ldots, \rho_k])\). This feature is called polymorphic recursion in regions, named after polymorphic recursion, the analogous concept for types. Polymorphic recursion in regions is vital for achieving good memory management in connection with recursion. Unfortunately, it is also makes the region inference problem considerably more challenging, but that is a different story [TB98].

We now show a typical use of polymorphic recursion in regions, namely merge sorting of lists. The basic idea of merge sort is simple: first split the input list into two lists \( l \) and \( r \) of roughly equal length. Then sort \( l \) and \( r \) recursively and merge the results into a single sorted list. When programming with regions, we need to plan which of these lists we want to reside in the
same regions. We do not want to waste space. In particular, if $n$ is the length of the list, it would be quite irresponsible to use $O(n \log n)$ space, say. Let us aim at arranging that the sorting function is a region exomorphism that does not produce any values in its result regions except the sorted list. To sort $n$ elements, we shall need $n$ list cells (to hold the input list) plus roughly $2 \times (n/2)$ list cells to hold $l$ and $r$, the two lists that arise from splitting the input list. To sort $l$ recursively, we need space for the two lists obtained by splitting $l$ and so on. The space consumption grows to a maximum of $3n$ list cells (including the $n$ cells to hold the input), before any merging is done. By the time all of $l$ is sorted, that is, just before $r$ is sorted recursively, we have the following lists: the input ($n$ cells), $l$ ($n/2$ cells), $l$ sorted ($n/2$ cells), $r$ ($n/2$ cells). Continuing this way, at the rightmost merge of two lists of length at most one, approximately $4n$ list cells are live. Then a series of final merges occur. Code that uses these ideas is listed in Figure 6.3.

The exomorphic merge function is a bit inefficient in that it copies one argument when the other is empty, but the exomorphism ensures that $\text{msort } 1$ and $\text{msort } r$ are not forced into the same regions. The polymorphic recursion in regions makes it possible for $\text{xs, l, r, msort } 1$, and $\text{msort } r$ all to be in distinct regions. For example, in the call $\text{msort } 1$, the polymorphic recursion makes it possible for $l$ to be in a region different from $\text{xs}$ and it also makes it possible for the result of the call to be in a region different from the result of $\text{msort } \text{xs}$.

Based on the above analysis we conclude that the space required by $\text{msort } \text{xs}$ is approximately $4nc_1 + c_2 \log_2 n$ plus the extra stack space required for the final merges, where $n$ is the length of $\text{xs}$, $c_1$ is the size of a list cell (2 words in this case) and $c_2$ is the space on the runtime stack used by one recursive call of $\text{msort }$ (probably less than 10 words).

Because $\text{merge}$ is not tail-recursive, a merge requires space both for its two input lists, for its output list, and for temporaries stored on the stack. When one of the lists becomes empty, $\text{merge}$ calls $\text{cp}$, which allocates less for each iterative call than $\text{merge}$ does. Each return from $\text{merge}$ allocates a list cell (two words), so the maximum space usage is reached when the last element of the result of the merge is constructed (which happens when the recursion is deepest). Here the space used is (we show $n = 200,000$ list cells).
fun cp [] = []
    | cp (x::xs) = x :: cp xs

(* exomorphic merge *)
fun merge(xs, []) : int list = cp xs
    | merge([], ys) = cp ys
    | merge(l1 as x::xs, l2 as y::ys) = 
        if x<y then x :: merge(xs, l2)
        else y :: merge(l1, ys)

(* splitting a list *)
fun split(x::y::zs, l, r) = split(zs, x::l, y::r)
    | split([x], l, r) = (x::l, r)
    | split([], l, r) = (l, r)

(* exomorphic merge sort *)
fun msort [] = []
    | msort [x] = [x]
    | msort xs = let val (l, r) = split(xs, [], [])
        in merge(msort l, msort r)
        end;

Figure 6.3: Merge sorting of lists.

It turns out that each iterative call of merge pushes three registers on
the stack, so that stack size will be approximately $3 \times 8 \times n$ bytes, which for
Figure 6.4: Region profiling of msort sorting 200,000 integers. The high-level mark denotes the maximum amount of memory allocated in regions and on the stack. Notice that the amount of memory used in regions and the amount of memory used on the stack may not top on the same time, which shows by the high-level mark being lower than the sum of the maximum stack usage and the maximum memory used in regions.

\[ n = 200,000 \text{ is } 4,800,000 \text{ bytes, just before the merged list is constructed, bottom-up. The total space consumption for sorting 50,000 integers should therefore be roughly 14,400,000 bytes (i.e., } 12,800,000-3,200,000+4,800,000).\]

To check the above analysis, we sorted 200,000 integers with the region profiler enabled. As one sees in Figures 6.4 and 6.5, the space usage found by region profiling correspond well to the results of our analysis.

In Chapter 12, we shall see how one can use resetting of regions to reduce the space usage drastically, to roughly \(2n c_1\).
Figure 6.5: Stack profiling of msort sorting 200,000 integers.
Chapter 7

Value Declarations

Although region inference is based on types and effects, it is also to some extent syntax dependent. That is, two programs that are equivalent in their input-output behavior can easily have very different memory behavior. In this chapter, we discuss how to write declarations so as to obtain good results with region inference. The region inference rules that underlie the MLKit with Regions are related to the scope rules of ML, so we start by a (very informal) summary of the scope rules of ML declarations.

7.1 Syntax

A Standard ML value declaration binds a value to a value variable. For example, the result of evaluating the value declaration

\[ \text{val } x = 3 + 4 \]

is the environment \( \{ x \mapsto 7 \} \). More generally, evaluation of a value binding \( \text{val } id = exp \) proceeds as follows. Assume the result of evaluating \( exp \) is a value, \( v \). Then the result of evaluating \( \text{val } id = exp \) is the environment \( \{ id \mapsto v \} \).

The value declaration is just one form of Core Language declaration (the others being type and exception declarations). We use \( dec \) to range over declarations. Declarations can be combined in several ways. For example,

\[ dec_1 ; dec_2 \]

is a sequential declaration. The identifiers declared by this declaration are the identifiers that are declared by \( dec_1 \) or \( dec_2 \); moreover, identifiers declared
in $dec_1$ may be referenced in $dec_2$. The semicolon is associative. Thus, in a sequence $dec_1; \ldots ; dec_n$ of declarations, identifiers declared in $dec_i$ may be referenced in $dec_{i+1}, \ldots , dec_n$ ($1 \leq i \leq n$).

The Core Language has two forms of local declarations. The expression

\begin{verbatim}
let dec in exp end
\end{verbatim}

declares identifiers whose scope does not extend beyond $exp$. Similarly, the declaration

\begin{verbatim}
local dec_1 in dec_2 end
\end{verbatim}

first declares identifiers (in $dec_1$) whose scope does not extend beyond $dec_2$ and then uses these declarations to perform the declarations in $dec_2$. An identifier is declared by the entire local construct if and only if it is declared by $dec_2$.

### 7.2 Scope Versus Lifetime

Scope is a syntactic concept: a declaration of an identifier contains a binding occurrence of the identifier; the scope of the declaration is the part of the ensuing program text whose free occurrences of that identifier are bound by that binding occurrence. By contrast, lifetime, as we use the word, is a dynamic concept. A value is “live” if and only if the remainder of the computation uses it (or part of it). The traditional stack discipline couples these two concepts very closely. For example, in the pure stack discipline, the evaluation of

\begin{verbatim}
let dec in exp end
\end{verbatim}

in an environment $E$ proceeds as follows. First evaluate $dec$ to yield an environment, $E_1$. Then evaluate $exp$, in the environment $E$ extended with $E_1$, to yield value $v$. Then $v$ is the result of evaluating the let expression in $E$. In implementation terms: first push an environment $E_1$ onto the stack, use it to evaluate the expression in the scope of the declaration, and then pop the stack. That this idea works in block-structured languages hinges on a number of carefully made language design decisions. In functional and object-oriented languages, memory cannot be managed that simply. The problem is that while environments can be managed in a stack-like manner, the values in the range of the environment cannot (unless one uses regions, that is). For example consider the ML expression:
local
   val private = [2,3,5,7,11,13]
in
   fun smallPrime(n:int): bool = List.member n private
end

Although the scope of the declaration is only the declaration of smallPrime, private is accessed (at runtime) whenever smallPrime is called. Thus, the lifetime of the list of small primes is at least as long as the lifetime of the smallPrime function itself.

The region discipline still has a coupling between scope and lifetimes, but, because we want to be able to handle recursive data types and higher-order functions, the coupling is less tight. The ground rule of region inference is that as long as a value variable is in scope, the value bound to it at runtime will remain allocated. More precisely:

Ground Rule: The region rules forbid transforming an expression exp into let region ρ in exp end if exp is in the scope of an identifier that has ρ free in its region-annotated type scheme with place.

For an example, consider

let
   val list = [1,2,3]
   val n = length list
   val r = sin(real n)
in
   cos(r)
end

At runtime, the list bound to list is not used (i.e., it is not live) after its length has been computed; similarly, the value of n is not live after it has been converted to a floating point number, and so on. In short, at runtime, we have a sequence of short, non-overlapping lifetimes.

With region inference, however, the list bound to list will stay allocated throughout the evaluation of the remainder of the let expression.¹

¹One can force de-allocation of the list by inserting val _ = resetRegions(list) after the declaration of n; but, as we shall see, there are less draconian ways of achieving the same result.
For a more interesting example of the consequences of the Ground Rule, consider the following declarations, taken from a program that computes prime numbers using the Sieve of Eratosthenes:

```haskell
fun cp [] = []
    | cp (x::xs) = x :: cp xs

fun sift (n, []) = []
    | sift (n, (x::xs)) = if x mod n = 0 then sift(n,xs)
                              else x::sift(n,xs)

fun sieve(a as ([], p)) = a
    | sieve(x::xs, p) = let val rest = sift(x,xs)
                              in sieve(cp rest,x::p)
                              end
```

Here `sift(n, l)` produces a list of the numbers from `l` that are not divisible by `n`; `sieve(xs, p)` repeatedly calls `sift`, adding primes to the front of `p`, until the list of numbers remaining in the sieve becomes empty. The programmer has employed the copying technique suggested in Section 1.3 to avoid that the lists that are bound to `rest` during the repeated filtering all are put in the same region. The programmer’s intention is that the `cp rest` should overwrite `x::xs` by a copy of `rest`, so that space consumption would be bounded by a constant times the size of the input. But it does not work as intended; because `rest` is in scope at the recursive application of `sieve`, the list that is bound to `rest` will stay allocated for the duration of that call, which is in fact the remainder of the entire computation!

In many cases, the solution is simply to shorten the scope of the declaration. In the above example, a good solution is to move the application of `sieve` outside the `let`:

```haskell
fun sieve (a as ([], p)) = a
    | sieve (x::xs, p) =
                              sieve let val rest = sift(x,xs)
                              in (cp rest,x::p)
                              end
```

That the copying really overwrites the input list relies, in part, on region resetting (Chapter 12). But it also relies on region polymorphism and on the Ground Rule. Rewriting the application of `sieve` ensures that the
list bound to rest will not live to see the recursive call of sieve. Unless forced by context to do otherwise, sift will create a list using fresh regions. Because cp is also exomorphic, there will be no sharing between rest and the other lists. The region variable that denotes the region that holds the auxiliary pairs of rest appears in the effect of the (revised) let expression. However, this region variable does not occur free in the region-annotated type scheme with place of any value variable in scope at that point, not even in the region-annotated type scheme with place of sieve, which only has the region that contains sieve itself free in its region-annotated type scheme with place. Consequently, region inference wraps the let expression by a region declaration of the region variable in question:

```haskell
fun sieve (a as ([] , p)) = a
  | sieve (x::xs , p) =
      sieve let region r10
        val rest = sift[r10](x,xs)
        in (cp rest,x::p)
      end
```

### 7.3 Shortening Lifetime

Informally, region inference forces the lifetime of an identifier to be at least its scope. Improving memory performance therefore sometimes requires making scopes of identifiers smaller. Useful program transformations include:

**Inwards let floating**

Transform

```haskell
let val id₁ = exp₁ val id₂ = exp₂ in exp end
```

into

```haskell
let val id₂ = let val id₁ = exp₁ in exp₂ end in exp end
```

provided id₁ does not occur free in exp.
Application extrusion:

Transform

\[
\text{let } \text{dec in } f(\text{exp}) \text{ end}
\]

into

\[
f \text{ let } \text{dec in } \text{exp end}
\]

provided \( f \) is an identifier that is not declared by \( \text{dec} \).

Application extrusion is particularly useful in connection with tail recursion; the reader will see it employed several times in what follows.
Chapter 8

Static Detection of Space Leaks

“Space leak” is the informal term used when a program uses much more memory than one would expect, typically because of memory not being recycled as early as it should (or not at all).

If a region-polymorphic function with region-annotated type scheme $\sigma$ has a \textbf{put} effect on a region variable that is not amongst the bound region variables of $\sigma$, then one quite possibly has a space leak; every application of the function may write values into a region that is the same for all calls of the function. For example, consider the source program\footnote{Program kitdemo/escape.sml.}

```ml
fun g () = 
  let val x = [5,7]
     fun f y = (if y>3 then x@x else x;
                 5)
  in f 1; f 4
  end
```

Here $f$ has type $\text{int} \rightarrow \text{int}$; yet, when the expression $y>3$ evaluates to $\text{true}$, an append operation is performed that produces a list in the same region as $x$. The first call of $f$ will not cause the append operation to be called, but the second one will. One can say that $f$ has a space leak in that it can write values into a more global region, namely a region that is allocated at the beginning of the body of $g$. The sequence of calls to $f$ accumulates copies of $x@x$ in that region, although none of these lists are accessible anywhere. In this particular case, the values are not even part of the result type of $f$, \textit{etc.}
so the writing is a side-effect at the implementation level, even though there are no references in the program.

The region-annotated type scheme inferred for \( f \) is

\[
\forall \epsilon. \text{int} \ (\cdot\{\text{put}(\rho_{11})\}) \text{ int}
\]

where the region-annotated type of \( x \) is

\[(\text{int}, [\rho_{11}])\text{list}\]

Here we see that \( \rho_{11} \) is free in the region-annotated type scheme and appears with a \text{put} effect.

### 8.1 Warnings About Space Leaks

The MLKit can be instrumented to issue a warning each time it meets a function that is declared using \texttt{fun} and has a free \texttt{put} effect occurring somewhere in its type scheme. The way to tell the MLKit to issue the warnings is by passing the option \texttt{-warn on escaping puts} to the MLKit compiler. In practice, this warning mechanism is a valuable device for predicting space leaks. The region-annotated version of our example function \( g \) is listed in Figure 8.1. During compilation of \( g \), the MLKit issues the following warning:

\[
*** \text{Warnings} ***
\]

\( f \) has a type scheme with escaping put effects on region(s): \( r_{11} \), which is also free in the type schemes with places of : \( x \)

We are told that the program might space leak in region \( r_{11} \). Looking at the function \( f \), we see that this region is an actual region parameter to \( @ \). It follows that the problem is the call to \( @ \).

### 8.2 Fixing Space Leaks

Often one can fix a space leak by delaying the creation of the value that causes the space leak. In the above example, we can move the construction of the list into \( f \).\footnote{To provoke the warning, one has to disable in-lining in the Lambda optimiser; this is done by passing the option \texttt{-maximum INLINE size 0} to the MLKit compiler together with the option \texttt{-warn on escaping puts}.}

\footnote{Program \texttt{kitdemo/escape1.sml}.}
8.2. FIXING SPACE LEAKS

let fun g at r1 [] (v86) = 
    let region r11:INF;
    val x = [5,7] at r11;
    region r18:1;
    fun f at r18 [] (y) = 
        let val _ = case y > 3 of
            true => @[r11] <x, x>
        | _ => x
        in 5
    end;
    val _ = f[] 1
    in f[] 4
    end
in {\{g: (_,r1)\}}
end

Figure 8.1: The region-annotated version of g.

fun g () = 
    let fun mk_x () = [5,7]
        fun f y = let val x = mk_x()
            in if y>3 then x@x else x; 5
            end
        in f 1; f 4
    end
In f 1; f 4

Of course, this means that the list will be reconstructed upon each application of f. Another solution is to move the creation of the list as close to the calls as possible and then pass the list as an extra argument:

fun g () = 
    let fun f (x,y) = (if y>3 then x@x else x; 5)
        in let val x = [5,7]
            in f(x,1); f(x,4)
            end
        end

Program kitdemo/escape2.sml.

\textsuperscript{4}Program kitdemo/escape2.sml.
Both solutions stop warnings from being printed, but the second solution is better than the first: f still has a put effect on the regions containing x, but the difference is that these are now represented by bound region variables in the type scheme of f. This quantification has the advantages that (1) allocation of space for the list is delayed until the list is actually used and (2), the list can be de-allocated after the calls have been made (whereas in the original version, x occurs free in the declaration of f and will be kept alive as long as f can be called.)

At other times, there is no clean way of avoiding escaping put effects. One example is found in the TextIO structure of the Basis Library:

```plaintext
element CannotOpen
fun raiseIo fcn nam exn =
  raise IO.Io {function = fcn^"", name = nam^"", cause = exn}

fun openIn (f: string) : instream =
  {ic=prim("openInStream", (f,CannotOpen)),
   name=f} handle exn => raiseIo "openIn" f exn

fun openOut(f: string): outstream =
  {oc=prim("openOutStream", (f,CannotOpen)),
   name=f} handle exn => raiseIo "openOut" f exn
```

As explained in Chapter 11, when a unary exception constructor is applied to a value, both the argument value and the resulting constructed value are forced into a particular global region. Thus, the application

```plaintext
IO.Io {function = fcn^"", name = nam^"", cause = exn}
```

has a potential space leak in it; every time we apply the exception constructor, the resulting exception value will be put into a global region. This particular space leak is perhaps not something that would keep one awake at night, because most programs do not make a large number of failed attempts to open files, but it is useful to be warned about this potential problem. Notice, however, that the string arguments to raiseIo are copied inside the body of raiseIo, so that they are not forced to be placed in the global string region.
Chapter 9
References

Section 9.1 gives a brief summary of references in Standard ML; it may be skipped by readers who know SML. Thereafter, we discuss runtime representation of references and region-annotated reference types.

9.1 References in Standard ML

A reference is a memory address (pointer). Standard ML has three built-in operations on references

\[
\begin{align*}
\text{ref} & : \forall \alpha. \alpha \to \alpha\text{ref} & \text{create reference} \\
! & : \forall \alpha. \alpha\text{ref} \to \alpha & \text{de-referencing} \\
:= & : \forall \alpha. \alpha\text{ref} \times \alpha \to \text{unit} & \text{assignment}
\end{align*}
\]

If the type of a reference \( r \) is \( \tau \text{ref} \) then one can store values of type \( \tau \) (only) at address \( r \). A reference is a value and can therefore be bound to a value identifier by a \text{val} declaration. While the value stored at a reference may change, the binding between variable and reference does not change. We show an example, because this point can be confusing to programmers who are familiar with mutable variables in languages like C and Pascal:

```ml
val it = let val x: int ref = ref 3
    val y: bool ref = ref true
    val z: int ref = if !y then x else ref 5
  in z:= 6; !x
end
```

79
Figure 9.1: Creating a reference allocates one word in a region on the region stack. Here, the region is drawn as a finite region, but it could equally well be infinite.

Because \( !y \) evaluates to true, \( z \) becomes bound to the same reference \( (r) \) as \( x \). So, the subsequent assignment to \( z \) changes the contents of the store at address \( r \) to contain 6. Because \( x \) and \( z \) are aliases, the result of the \texttt{let} expression is the contents of the store at address \( r \) (i.e., 6).

### 9.2 Runtime Representation of References

The MLKit translates an SML expression of the form \texttt{ref exp} into an expression of the form (assuming \texttt{exp} translates into \( e \))

\[
\text{ref at } \rho \ e
\]

which is evaluated as follows. First \( e \) is evaluated. Assume that this evaluation yields a value \( v \). Here \( v \) may be a boxed or an unboxed value. Next, a 64-bit word is allocated in the region denoted by \( \rho \); let \( r \) be the address of this word. Then \( v \) is stored at address \( r \) and \( r \) is the result of the evaluation.

The situation is depicted in Figure 9.1. The value \( v \) can be unboxed as shown in Figure 9.2. Or it may be boxed, in which case \( v \) is an address.

Notice that a reference really is a pointer in the implementation. In particular, a reference is not tagged, so the register allocator may choose to store a particular reference in a register. The content of the reference is also always one word, either an unboxed value (e.g., an integer or a boolean) or a pointer (if the content is boxed). So the content of a reference is not tagged either.

De-referencing a reference \( r \) is done by reading the content of the memory location \( r \). Notice that de-referencing does not require knowledge of what region the word with address \( r \) resides in.
Assigning a value \( v \) to a reference \( r \) simply stores \( v \) in the memory at address \( r \). When \( v \) is an unboxed value, the assignment can be regarded as copying \( v \) into the memory cell \( r \); otherwise \( v \) is a pointer, which the assignment stores in the memory cell \( r \). Either way, assignment is a constant-time operation.

### 9.3 Region-Annotated Reference Types

The general form of a region-annotated reference type is:

\[
(\mu \text{ref}, \rho)
\]

Informally, a reference \( r \) has this type if it is the address of a word in the region denoted by \( \rho \) and, moreover, \( \mu \) is the region-annotated type with place of the contents of that word. For example, assume \( \rho \) is bound to some region name, say \( r35 \); then the evaluation of the declaration `val x = ref at \( \rho \) 3` results in the environment \( \{ x \mapsto r \} \), where \( r \) is the address of a word with contents 3 residing in region \( r35 \), see Figure 9.2. The type of \( x \) is \((\text{int ref}, \rho)\).

References are treated like all other values by region inference. The region-annotated type schemes given to the three built-in operations are:

\[
\begin{align*}
\text{ref} & \quad \forall \alpha \rho. \alpha \xrightarrow{\{ \text{put}(\rho) \}} (\alpha \text{ ref}, \rho) \\
! & \quad \forall \alpha \rho. (\alpha \text{ ref}, \rho) \xrightarrow{\{ \text{get}(\rho) \}} \alpha \\
:= & \quad \forall \alpha \rho. [(\alpha \text{ ref}, \rho), \alpha] \xrightarrow{\{ \text{get}(\rho) \}} \text{unit}
\end{align*}
\]

The type scheme for := has in it a get effect on the region holding the reference. Although the operator does not actually read the value, the presence of
let val it =
  let region r9:INF;
  val x = ref at r9 3;
  region r10:1;
  val y = ref at r10 true;
  val z = case !y of true => x | _ => ref at r9 5;
  val _ = (z := 6)
  in !x
  end
end

Figure 9.3: Region-annotated reference creation.

the value is necessary for it to be updated. Assigning a value $v$ to a reference $r$ does not make a copy of $v$ (unless $v$ is unboxed). Instead, := updates the content of the reference $r$ to point to $v$.

The advantage of the chosen scheme for handling references is that reference creation, de-referencing, and assignment all are constant-time operations. The disadvantage is that if two values may be assigned to the same reference, then they are forced to be in the same regions (cf. the region-annotated type schemes given above).

If we compile the example from Section 9.1, we get the program shown in Figure 9.3. The region denoted by $r_9$ contains the memory word whose address is bound to $x$ and $z$, and whose contents is first 3, then 6. The region denoted by $r_{10}$ contains a single boolean. Also notice that the word containing 5 is designated $r_9$, because the then and else branches must be given the same region-annotated type with place. Finally, notice that all references will be reclaimed automatically at the end of the let construct that bind $r_9$ and $r_{10}$.

\footnote{Program kitdemo/refs3.sml.}
9.4 Local References

References that are created locally within a function and that do not escape the function naturally reside in regions that are local to the function body. For example, the declaration:\(^2\)

\[
\text{fun id x = let val r = ref x in !r end;}
\]

is compiled into

\[
\text{let fun id at r1 [] (x) =}
\text{let region r11:1;}
\text{val r = ref at r11 x}
\text{in !r}
\text{end}
\text{in \{id: (_,r1)\}\}
\text{end}
\]

Here \text{r11} will be implemented as one word on the runtime stack. The evaluation of \text{ref at r11 x} moves the argument \text{x} to that word on the stack. At the end of the inner \text{let}-scope, the word (i.e., region \text{r11}) is popped off the stack.

Now, let us turn to an example of a memory cell whose lifetime extends the scope of its declaration, because it is accessible via a function (in Algol terminology, the reference is an \textit{own variable} of the function).\(^3\)

\[
\text{local}
\text{val r = ref (\[]:string list)}
\text{in}
\text{fun memo_id x = (r:= x:: !r; x)}
\text{end}
\text{val y = memo_id "abc"}
\text{val z = memo_id "efg";}
\]

Provided that in-lining by the optimiser is restricted to in-line only those functions that are applied once,\(^4\) this example compiles into

\(^2\)Program \text{kitdemo/refs1.sml.}

\(^3\)Program \text{kitdemo/refs2.sml.}

\(^4\)To restrict the optimiser accordingly, provide the option \text{-maximum_inline_size 0} to the MLKit compiler.
let val r = ref at r6 nil;
  fun memo_id at r1 [] (x) =
    let val _ = (r := :: (x, !r) at r4) in x end;
  val y = memo_id[] "abc" at r3;
  val z = memo_id[] "efg" at r3
  in { |r: (_,r6), memo_id: (_,r1), y: (_,r3), z: (_,r3) | }
end

and the MLKit warns us that there is a possible space leak:\footnote{Warnings are printed only if the option \texttt{-warn_on_escaping_puts} is passed to the MLKit compiler along with the option \texttt{-maximum_inline_size 0}. See Chapter 8.}

*** Warnings ***
memo_id has a type scheme with escaping put effects on region(s):
  r4, which is also free in the type schemes with places of : r

9.5 Hints on Programming with References

There is no need to shy away from using references when programming with regions. However, one needs to be aware of the restriction that values that may be assigned to the same references are forced to live in the same region, and that this region with all its values will be alive for as long as the reference is live. If the contents type is unboxed (e.g., \texttt{int}), there is no problem, for in that case, no region for the contents is allocated. But one should avoid creating long-lived references that are assigned many different large values.
Chapter 10

Recursive Data Types

This chapter describes how the MLKit treats recursive data types. We have already seen how one recursive datatype, namely lists, is handled. This chapter deals with the general case.

10.1 Spreading Data Types

The MLKit performs an analysis called “spreading of data types”. Spreading of datatypes analyses datatype declarations. This analysis of a datatype declaration uses information about the type constructors that appear in the types of the constructors of the data type(s) introduced by the declaration, but it does not use information about the use of the data type.

Spreading determines (a) a so-called arity of every type name that the data type declaration introduces and (b) a region-annotated type scheme for every value constructor introduced by the data type declaration.

In the Definition of Standard ML every type name has an attribute, called its arity [MTHM97, page 15]. The arity of a type name is the number of type arguments it requires. For example, int has arity 0 while the type name introduced by the following declaration of binary trees has arity 1:

```plaintext
datatype 'a tree = Lf | Br of 'a * 'a tree * 'a tree;
```

The MLKit extends the notion of arity (in it’s internal languages) to account for regions and effects. For lists, for example, we need a region for holding the pairs to which :: is applied. For the data type

```plaintext
datatype 'a foo = A | B of ('a * 'a) * ('a * 'a)
```

85
the type of \( \mathbb{B} \) introduces the possibility of three region variables (one for each star). Region variables that are induced by the types of constructors and that do not hold the constructed values themselves are called auxiliary region variables. For example, the list data type:

```
datatype 'a list = nil | op :: of 'a * 'a list
```

has one auxiliary region variable, namely the region variable that describes where the pairs of type \( 'a * 'a \) list \( (i.e., \text{the auxiliary pairs}) \), reside.

Besides auxiliary regions, one sometimes needs auxiliary effects. For an example, consider:

```
datatype V = N of int | F of V -> V
```

Here one needs an arrow effect for the function type \( V \rightarrow V \). We refer to such an arrow effect as an auxiliary arrow effect of the data type in question.

We define the (internal) arity of a type name \( t \) to be a triple \((n, k, m)\) of non-negative integers, where \( n \) is the usual Standard ML arity of the type name, \( k \) is the region arity of \( t \), and \( m \) is the effect arity of \( t \). The region and effect arities indicate the number of auxiliary regions and arrow effects of the data type, respectively.

For efficiency purposes, we have found it prudent to restrict the maximal number of auxiliary regions a data type can have to one for each kind of runtime type of regions and to restrict the maximal number of auxiliary effects to 1. Otherwise, the number of auxiliary regions can grow exponentially in the size of the program:

```
datatype t0 = C
datatype t1 = C1 of t0 * t0
datatype t2 = C2 of t1 * t1
...
```

Here the number of auxiliary region variables would double for each new data type declaration. Furthermore, all type names introduced by a \texttt{datatype} declaration are given the same arity (a \texttt{datatype} declaration can declare several types simultaneously).

Because of the limit on the number of auxiliary region variables, spreading of data type declarations sometimes unifies two auxiliary region variables that would otherwise be distinct; but it only unifies auxiliary region variables that have the same runtime type. The practical consequence of these restrictions
10.2. EXAMPLE: BALANCED TREES

is that applying a constructor to a value $v$ sometimes forces identification of regions of $v$ that hold otherwise unrelated parts of $v$.

The automatic memory management that we have discussed for lists extends to other recursive data types without problems. For example, binary trees are put into regions and are subsequently de-allocated (in a constant time operation) when the region is popped. The next section goes through an example to illustrate the point.

The MLKit attempts to use an unboxed representation for value constructors when possible. We have already seen how cons (i.e., ::) and nil use an unboxed representation (Chapter 5). In general, a value constructor of a type is represented unboxed if (1) the type has at most three unary constructors and (2) each unary constructor takes boxed arguments.

10.2 Example: Balanced Trees

Consider the program in Figure 10.1. We would hope that the balanced tree produced by balpre is removed after it has been collapsed into a list by preord. And indeed it is. Here is the proof:

```ml
val it =
  let region r257:INF
  in  print[]
  let region r259:INF
  in  implode[r257]
  let region r262:INF, r264:1
  in  preord[r259]
    (let region r267:INF
     in  balpre[r262]
     let region r270:1
     in  explode[r267]
       "Greetings from the Kit\n"at r270
     end
     end,
     nil)
at r264
end
```

1MLB-file: kitdemo/trees.mlb, file kitdemo/trees.sml.
datatype 'a tree = Lf | Br of 'a * 'a tree * 'a tree

(* preorder traversal of tree *)

fun preord (Lf, xs) = xs
| preord (Br(x,t1,t2),xs) =
  x::preord(t1,preord(t2,xs))

(* building a balanced binary tree
 from a list: *)

fun balpre [] = Lf
| balpre(x::xs) =
  let val k = length xs div 2
  in Br(x, balpre(take(xs, k)),
        balpre(drop(xs, k)))
  end

(* preord o balpre is the identity: *)

val it = print(implode(preord(balpre(explode
"Greetings from the MLKit\n"),[]))));

Figure 10.1: Example showing recycling of memory used for an intermediate
data structure. The function \texttt{balpre} builds a balanced binary tree from a list
and \texttt{preord} then flattens the tree to a list (after which the tree is garbage).
The exomorphic behavior of balpre causes the tree to be allocated in region r262, which is de-allocated after the call to preord. This is the kind of certainty about lifetimes we are aiming at. Imagine, for example, that the trees under consideration were terms representing different intermediate forms in a compiler. Then one would like to know that (possibly large) syntax trees are not kept in memory longer than needed.
CHAPTER 10. RECURSIVE DATA TYPES
Chapter 11

Exceptions

Standard ML exception constructors are introduced by exception declarations. The two most basic forms are

\[ \text{exception } \text{excon} \]

and

\[ \text{exception } \text{excon of } \text{ty} \]

for introducing nullary and unary exception constructors, respectively.

Exception declarations need not occur at top level. For example, a function body may contain exception declarations.

11.1 Exception Names

Each evaluation of an exception declaration creates a fresh exception name and binds it to the exception constructor. This is sometimes referred to as the generative nature of Standard ML exceptions.

In the MLKit, an exception name is implemented as a pointer to a pair consisting of an integer and a string pointer; the string pointer points to the name of the exception, which is a global constant in the target program. The string is used for printing the name of the exception if it ever propagates to top level. The memory cost of creating the pair is, as always with pairs, two words.
11.2 Exception Values

Standard ML has a type \texttt{exn} of \textit{exception values}. An exception value is either a \textit{nullary} exception value or a \textit{constructed} exception value. A nullary exception value is a pointer to a word that points to an exception name. A constructed exception value is a pair \((en, v)\) of an exception name \textit{en} and a value \textit{v}; we refer to \textit{v} as the \textit{argument} of \textit{en}. This representation of exception values allows for the exception name of an exception value to be fetched in the same way irrespective of whether the exception value is nullary or constructed.

Referring to a nullary exception constructor allocates no memory. By contrast, applying a unary exception constructor to an argument constructs a constructed exception value. The memory cost of such an application is two words for holding the pair \((en, v)\).

The distinction between nullary and unary exception constructors is important in the MLKit because our region inference analysis takes a simple-minded approach to exceptions:

All exception names and nullary exception values are put into a certain global region and thus never reclaimed automatically. A constructed exception value is put in a region that is live at least as long as the exception constructor is in scope.

We therefore make the following recommendations:

1. Put exception declarations at top level, if possible. That way, the memory required by exception names will be bounded by the program size.

2. Avoid applying unary exception constructors frequently; there is no harm in raising and handling constructed exception values frequently; it is the creation of many different constructed exception values that can lead to space leaks. Nullary constructors may be raised without incurring memory costs.

11.3 Raising Exceptions

An expression of the form

\[ \text{raise } exp \]
is evaluated as follows. First $\text{exp}$, an expression of type `$\text{exn}$', is evaluated to an exception value. Then the runtime stack is scanned from top to bottom in search of a handler that can handle the exception. A register points to the top-most exception handler; the exception handlers are linked together as a linked list interspersed with the other contents of the runtime stack. If a matching handler is found, the runtime stack is popped down to the handler. This popping includes popping of regions that lie between that stack top and the handler. Put differently, consider an expression of the form $\text{let region } \rho \text{ in } e \text{ end}$; if $e$ evaluates to an exception packet, then the region bound to $\rho$ is de-allocated and the packet is also the result of evaluating the $\text{let region}$ expression.

We have not attempted to design an analysis that would estimate how far down the stack a given exception value might propagate. Of course, it would not be a very good idea to allocate a constructed exception value in a region that is popped before the exception is handled! This is why we put all exception names in global regions.

## 11.4 Handling Exceptions

The ML expression form

$$\text{exp}_1 \ \text{handle match}$$

is compiled into a MulExp expression of the form

$$\text{let region } \rho \text{ in}
\text{ let } f = \text{fn at } \rho \text{ match in } e_1 \ \text{handle } f \text{ end}
\text{end}$$

where $f$ is a fresh variable. So first a handler (expressed as a function) is evaluated and stored in some region $\rho$. This region will always have multiplicity one and therefore be a finite region which is put on the stack. Then $e_1$, the result of compiling $\text{exp}_1$, is evaluated. If $e_1$ terminates with a value, the $\text{let region}$ construct will take care of de-allocating the handler. If $e_1$ terminates with an exception, however, $f$ is applied.

Thus the combined cost of raising an exception and searching for the appropriate handler takes time proportional to the depth of the runtime stack in the worst case.
Handling of exceptions is the only operation that takes time that cannot be determined statically, provided one admits arithmetic operations as constant-time operations.

### 11.5 Example: Prudent Use of Exceptions

Here is an example of prudent use of exceptions in the MLKit:

```ml
exception Hd (* recommendation 1 *)
fun hd [] = raise Hd
  | hd (x::_) = x

exception Tl
fun tl [] = raise Tl
  | tl (_, ::xs) = xs

exception Error of string
local
  val error_f = Error "f" (* recommendation 2 *)
in
  fun f(l) = 
      hd(tl(tl l)) handle _ => raise error_f
end

val r = f[1,2,3,4]
```

The application Error "f" has been lifted out from the body of f. No matter how many times f is applied, it will not create additional exception values.

---

\[1\]Program kitdemo/exceptions.sml.
Chapter 12

Resetting Regions

The idea of region resetting was introduced in Section 1.2. This chapter gives an informal explanation of the rules that govern resetting. Knowing these rules is useful, irrespective of whether one makes the MLKit decide on region resetting, or prefers to control resetting explicitly in the program.

Resetting only makes sense for infinite regions. Resetting a region is a constant-time operation. Because the same region variable can be bound sometimes to a finite region and sometimes to an infinite region at runtime, resetting a region can involve a test at runtime.

The MLKit contains an analysis, called the storage mode analysis, which has two purposes:

1. inserting automatic resetting of infinite regions, when possible
2. checking applications of resetRegions (and forceResetting) so as to report on the safety of the resetting requested by the programmer

As a matter of design, one might wonder whether it would not be sufficient to rely on the user to indicate where resetting should be done. However, checking whether resetting is safe at a particular point chosen by the user is of course no easier than checking whether resetting is safe at an arbitrary point in the program, so one might as well let the compiler insert region resetting whenever it can prove that it is safe.

In this chapter, we describe the principles that underlie the storage mode analysis. Even if one is willing to insert resetRegions and forceResetting instructions in the program, one still needs to understand these principles,
so as to be able to act upon the messages that are generated by the system in response to explicit `resetRegions` and `forceResetting` instructions.

### 12.1 Storage Modes

As we have seen in previous chapters, region inference decorates every allocation point with an annotation of the form `at ρ`, indicating into what region the value should be stored.

Now the basic idea is that storing a value into a region can be done in one of two ways, at runtime. One either stores the value at the top of the region, thereby increasing the size of the region; or one stores the value into the bottom of the region, by first resetting the region (so that it contains no values) and then storing the value into the region.

The storage mode analysis transforms an allocation point `at ρ` into `at top ρ` when it estimates that `ρ` contains live values at the allocation point, whereas it transforms it into `at bot ρ` if it can prove that the region will contain no live values at that allocation point. The tokens `at top` and `at bot` are called storage modes.

Region polymorphism introduces several interesting problems. Let `f` be a region-polymporphic function with formal region parameter `ρ` and consider an allocation point `at ρ` in the body of `f`. Whether it is safe for `f` to store the value at bottom in the region depends not only on the body of `f` but also on the context in which `f` is called.

For example, consider the compilation unit

```haskell
fun f [] = []
  | f (x::xs) = x+1 :: f xs

val l1 = [1,2,3]
val l2 = if true then f l1 else l1
val x:_ = l1
```

When `f` creates the empty list, it can potentially reset the auxiliary region intended for the auxiliary pairs of the list. In the above program, however, the conditional forces `f l1` and `l2` to be in the same region as `l1`. Because `l1` is live after the application of `f`, this application must not use `at bot` as storage mode. Indeed, even if we removed the last line of the program, the
application could still not use \texttt{atbot}, for \texttt{l1} is exported from the compilation unit and thus potentially used by subsequent compilation units.

By contrast, consider

\begin{verbatim}
fun f [] = []
  | f (x::xs) = x+1 :: f xs

val n = length(let val l1 = [1,2,3]
               in if true then f l1 else l1
               end)
\end{verbatim}

When \texttt{f} creates the empty list, it is welcome to reset the region that holds \texttt{l1}, for by that time, \texttt{l1} is no longer needed! (\texttt{f} traverses \texttt{l1}, but when it reaches the end of the list, \texttt{l1} is no longer used.) Indeed, the MLKit will replace the list \([1,2,3]\) by \([2,3,4]\). The ability to replace data in regions is crucial in many situations (as we illustrated with the game of Life in Section 1.3).

Because the MLKit allows for separate compilation, it cannot know all the call sites of a region-polymorphic function, when it is declared. Therefore, when considering an allocation point \texttt{at \rho} inside the body of some region-polymorphic function \texttt{f} that has \texttt{\rho} as a formal region parameter, one cannot know at compile time whether to use \texttt{atop} or \texttt{atbot} as storage mode. Instead, the storage mode analysis operates with a third kind of storage mode named \texttt{sat}, read: “somewhere at”. Consider an application of \texttt{f} for which \texttt{\rho} is instantiated to some region variable \texttt{\rho}', say. At runtime, \texttt{\rho}' is bound to some region name (Section 2.1) \texttt{r}'. Then \texttt{r'} is combined with a definite storage mode (i.e., \texttt{atop} or \texttt{atbot}), to yield \texttt{r}, say, which is then bound to \texttt{\rho}. When \texttt{r'} was originally created (by a \texttt{let region expression}), \texttt{r'} was also made to contain an indication of whether it is an infinite region or a finite region. At runtime, an allocation point \texttt{sat \rho} in the body of \texttt{f} will test \texttt{r} to see whether the region is infinite and whether the value should be stored at the top or at the bottom.

\footnote{Program \texttt{kitdemo/sma1.sml}.}
\footnote{On machines that have at least four bytes per word, the two least significant bits of a pointer to a word will always be 00. These two bits hold extra information in the region name. One bit, called the “atbot bit”, holds the current storage mode of the region. Another bit, called the “infinity bit”, indicates whether the region is finite or infinite.}
\footnote{When \texttt{\rho} has multiplicity infinity, \texttt{r'} must be the name of an infinite region, so the runtime check on whether \texttt{r} has its infinity bit set is omitted.}
The relevant parts of the result of compiling the last example are shown in Figure [12.1]. To see the storage modes, pass the option

```
-print_drop_regions_expression_with_storage_modes
```

to the MLKit compiler.

### 12.2 Storage Mode Analysis

For the purpose of the storage mode analysis, actual region parameters to region-polymorphic functions are considered allocation points. Passing a region as an actual argument to a region-polymorphic function involves neither resetting the region nor storing any value in it, but a storage mode has to be determined at that point nonetheless, because it has to be passed into the function together with the region. The storage mode expresses whether, at the call site, there may be any live values in the region after the call. For example, in Figure [12.1] the call to \( f \) at \((\ast 1\ast)\) passes \( r16 \) with storage mode \texttt{atbot} because the only value that exists before the call of \( f \) and is needed after the call of \( f \) is \texttt{length}, which is declared in a different compilation unit and therefore obviously does not reside in \( r16 \).

Within every lambda abstraction, the MLKit performs a backwards flow analysis that determines, for every allocation point, a set of \textit{locally live variables}, that is, a set of variables used by the remainder of the computation in the function up to the syntactic end of the function. (This includes variables that appear in function application expressions.) Prior to the computation of locally live variables, a program transformation, called \textit{K-normalisation}, has made sure that every intermediate result that arises during computation becomes bound to a variable. (This happens by introducing extra \texttt{let} bindings, when necessary.)

The MLKit also computes a set of locally live variables for those allocation points that do not occur inside functions.

We now give an informal explanation of the rules that assign storage modes to allocation points. Let an allocation point

\[ \text{at } \rho \]

\[ (12.1) \]

\(^4\)K-normalisation is transparent to users: although the storage mode analysis and all subsequent phases up to code generation operate on K-normal forms, programs are always simplified to eliminate the extra \texttt{let} bindings before they are presented to the user.
let fun f attop r1 [r14:INF] (var1) = 
  case var1 of 
    nil => nil 
  | _ => 
    let val v94 = decon_:: var1; 
      val v95 = #0 v94; 
      val v96 = #1 v94 
    in :: (v95 + 1, f[sat r14] v96) attop r14 
  end; 
val n = 
  let region r38:INF; 
    val a = let region r27:INF; 
       val l1 = [1,2,3] attop r27 
         (*1*) in f[atbot r38] l1 
    end; 
  region r40:1; 
  fun acc atbot r40 [] (var11, var12) = 
    case var11 of 
      nil => var12 
    | _ => let val v261 = decon_:: var11; 
          val v263 = #1 v261 
        in acc[] <v263, var12 + 1> 
    end 
  in acc[] <a, 0> 
end 
in { |f: (_,r1), n: _ | }
end

Figure 12.1: Storage modes inferred by the storage mode analysis. Notice that the MLKit has inlined the call to the function length.
be given.

**CASE A:** $\rho$ is a global region. Then `attop` is used. There is a deficiency we have to admit here. The MLKit only puts region bindings around expressions, not around declarations. Thus, if one writes

```plaintext
local
  fun f [] = []
  | f (x::xs) = x+1 :: f xs
val l1 = [1,2,3]
in
val n = length(if true then f l1 else l1)
end
```

at top level, then `l1` is put into a global region, although this is really unnecessary. As a consequence, `f` would be called with storage mode `attop` and thus `l1` would not be overwritten.

**CASE B:** The region variable $\rho$ is not a global region and the allocation point (12.1) occurs inside a lambda abstraction, that is, inside an expression of the form `fn pat => e`. Here we regard every expression of the form

```plaintext
let fun f(x) = e in e' end
```

as an abbreviation for

```plaintext
let val rec f = fn(x) => e in e' end
```

Then it makes sense to talk about the *smallest enclosing lambda abstraction (of the allocation point)*.

Now there are the following cases:

**B1** $\rho$ is bound outside the smallest enclosing lambda abstraction (and this lambda abstraction is not the right-hand side of a declaration of a region-polymorphic function that has $\rho$ as formal parameter): use `attop` (see Figure [12.2]).

**B2** $\rho$ is bound by a `let region` expression inside the smallest enclosing function: use `atbot` if no locally live variable at the allocation point has $\rho$ free in its region-annotated type scheme with place (Section [6.2]), and use `attop` otherwise (see Figure [12.3]).
**B3 (first attempt)** \( \rho \) is a formal parameter of a region-polymorphic function whose right-hand side is the smallest enclosing lambda abstraction: use \texttt{sat}, if no locally live variable at the allocation point has \( \rho \) free in its region-annotated type scheme with place, and use \texttt{at\hspace{0.1em}top} otherwise (see Figure 12.4).

```plaintext
let region \( \rho \)
in ... (fn \ pat => ... at \( \rho \)...)
end

fun f at\( \rho \) \[\rho\] =
(fn x => (fn y => ... at \( \rho \)...) at \( \rho \)\_2) at \( \rho \)\_1
```

Figure 12.2: Two typical situations where \texttt{at} \( \rho \) is turned into \texttt{at\hspace{0.1em}top} \( \rho \) by rule B1.

```plaintext
(fn \ pat => ...  
let region \( \rho \)  
in ... at \( \rho \)...l...  
end ...  
)
```

Figure 12.3: The situation considered in B2. If no locally live variable \( l \) has \( \rho \) occurring in its region-annotated type scheme with place, replace \texttt{at} \( \rho \) by \texttt{at\hspace{0.1em}bot} \( \rho \), otherwise by \texttt{at\hspace{0.1em}top} \( \rho \).

The motivation for (B1) is that if \( \rho \) is declared non-locally, then we do not attempt to find out whether \( \rho \) contains live data (this would require a more sophisticated analysis.)

The intuition behind (B2) is as follows. Region inference makes sure that the region-annotated type of a variable always contains free in it region variables for all the regions that the value bound to the variable needs when
fun f at ρ₀ [ρ, ...] =
(fn pat => ... at ρ...l...)

Figure 12.4: The situation considered in B3. If no locally live variable l has in its region-annotated type scheme with place a region variable that may be aliased with ρ, replace at ρ by sat ρ, otherwise by attop ρ.

... used. The lifetime of the region bound to ρ is given by the let region expression, which is in the same function as the allocation point. Thus, if no locally live variable at the allocation point has ρ free in its region-annotated type scheme with place, then ρ really does not contain any live value at that allocation point.

The intuition behind (B3) is the same as behind (B2), but in this case there is a complication: ρ is only a formal parameter so it may be instantiated to different regions; in particular it may be instantiated to a region variable that does occur free in the region-annotated type scheme with place of a locally live variable at the allocation point. If that happens, rule (B3), as stated, is not sound!

We refer to the phenomenon that two different region variables in the program may denote the same region at runtime as region aliasing. To determine whether to use sat or attop in case (B3), the MLKit builds a region flow graph for the entire compilation unit. (This construction happens in a phase prior to the storage mode analysis proper.) The nodes of the region flow graph are region variables and arrow effects that appear in the region-annotated compilation unit. Whenever ρ₁ is a formal region parameter of some function declared in the unit and ρ₂ is a corresponding actual region parameter in the same unit, a directed edge from ρ₁ to ρ₂ is created. Similarly for arrow effects: if ϵ₁.ϕ₁ is a bound arrow effect of a region-polymorphic function declared in the compilation unit and ϵ₂.ϕ₂ is a corresponding actual arrow effect then an edge from ϵ₁ to ϵ₂ is inserted into the graph. Also, edges from ϵ₂ to every region and effect variable occurring in ϕ₂ are inserted. Finally, for every region-polymorphic function f declared in the program and for every formal region parameter ρ of f, if f is exported from the compilation unit, then an edge from ρ to the global region of the same runtime type as ρ is inserted into the graph. (This is necessary, so as to cater for...
applications of \( f \) in subsequent compilation units.)

Let \( G \) be the graph thus constructed. For every node \( \rho \) in the graph, we write \( \langle \rho \rangle \) to denote the set of region variables that can be reached from \( \rho \), including \( \rho \) itself. The rule that replaces (B3) is:

**B3** \( \rho \) is a formal parameter of a region-polymorphic function whose right-hand side is the smallest enclosing lambda abstraction: use \texttt{sat}, if, for every variable \( l \) that is locally live at the allocation point and for every region variable \( \rho' \) that occurs free in the region-annotated type scheme with place of \( l \), it is the case that \( \langle \rho \rangle \cap \langle \rho' \rangle = \emptyset \); use \texttt{attop} otherwise.

**CASE C:** \( \rho \) is bound by a \texttt{let region} expression and the allocation point (12.1) does not occur inside any function abstraction. As in (B2), use \texttt{atbot} if no locally live variable at the allocation point has \( \rho \) free in its region-annotated type scheme with place, and use \texttt{attop} otherwise.

### 12.3 Example: Computing the Length of Lists

We shall now illustrate the storage mode rules of Section 12.2 with some small examples, which also allow us to discuss benefits and drawbacks associated with region resetting.

Consider the functions declared in Figure 12.5; they implement five different ways of finding the length of a list! The first, \texttt{nlength}, is the most straightforward one. It is not tail recursive. Textbooks in functional programming often recommend that functions are written iteratively (i.e., using tail calls) whenever possible. This we have done with \texttt{tlength}. Next, \texttt{klength} is a version that contains a local region endomorphism \texttt{loop} to perform the iteration; \texttt{llength} is similar to \texttt{klength}, except that the region endomorphism is declared outside \texttt{llength}, using \texttt{local}. A region profile resulting from running the program is shown in Figure 12.6. The diagram shows how much space is used in regions (both finite and infinite regions) and on the stack. The \texttt{rDesc} band shows how much space is used on the stack for holding region descriptors. The \texttt{stack} band shows how much space is used on the stack, including neither finite regions nor region descriptors; the \texttt{stack} band mainly consists of registers and return addresses that have been pushed onto the stack.

---

5Program ktdemo/length.sml.
fun upto n = 
  let fun loop(n,acc) = if n=0 then acc 
   else loop(n-1, n::acc) 
  in loop(n,[]) 
end

fun nlength [] = 0 
 | nlength (_::xs) = 1 + nlength xs

fun tlength l = 
  let fun tlength'(nil, acc) = acc 
   | tlength'(_::xs, acc) = tlength'(xs,acc+1) 
  in tlength'(1,0) 
end

fun klength l = 
  let fun loop(p as ([], acc)) = p 
   | loop(_::xs, acc) = loop(xs,acc+1) 
  in #2(loop(l,0))
end

local fun llength'(p as ([], acc)) = p 
 | llength'(_::xs, acc) = llength'(xs,acc+1) 
in fun llength l = #2(llength'(1,0))
end

fun global(p as ([], acc)) = p 
 | global(_::xs, acc) = global(xs, acc+1)
fun glength l = #2(global(l,0))

val k = 5000000
val run = 
nlength(upto k) + tlength(upto k) + klength(upto k) 
+ llength(upto k) + glength(upto k)

Figure 12.5: Five different ways of computing the length of lists.
Figure 12.6: Region profiling of five different ways of computing the length of a list, namely, from left to right: `nlength`, `tlength`, `klength`, `llength`, and `glength`. 
In Figure 12.6, we clearly see the five phases. In each phase, first a list is built—seen as an almost linear growth in a region; then follows a computation of the length of the list. The space behavior of the five ways of computing the length vary. We shall have more to say about the time behavior in what follows.

As one would expect, \texttt{nlength} leads to a peak in stack size; it does not use regions. The peak in stack size is caused by the stacking of a return address.

Next, we see that \texttt{tlength} is an improvement over \texttt{nlength}, the main reason being that the MLKit has figured out that the argument to \texttt{tlength} can be passed unboxed; thus no regions are used to hold the argument pair. However, if we chose to disable the unboxing of arguments that the MLKit performs\(^6\), the function would become region-polymorphic and the polymorphic recursion in regions would allow the pair \((xs, acc+1)\) to be stored in a region different from the argument pair to \texttt{tlength}'\(^7\). In this case, what appeared to be a tail call would in fact not be a tail call, for it would automatically be enclosed in a \texttt{let region} construct, introducing a fresh region for each argument pair \((xs, acc+1)\). This region would be finite, so it would be allocated on the stack. Thus, with unboxing of function arguments disabled, we would see a sharp increase in stack size for \texttt{tlength}'\(^7\). Although unboxing of function arguments saves us in this situation, we cannot always expect it to do so; if we were to collect boxed data in accumulating parameters to the function and this data is not to be returned by the function, there is a danger that the recursive call would not become a tail call due to the introduction of a \texttt{let region} construct being wrapped around the recursive call.\(^7\)

The next function, \texttt{klength}, deserves careful study, because it is a prototype of a particular schema that can be used again and again when programming with regions. Iteration is done by a region endomorphism, \texttt{loop}, which is declared as a local function to the main function. The use of the same variable \(p\) on both the left-hand side and the right-hand side of the declaration of \texttt{loop} forces \texttt{loop} to be a region endomorphism. Because the result of \texttt{loop(xs,acc+1)} is also the result of \texttt{loop}, the result of \texttt{loop(xs,acc+1)} therefore has to be in the same region as \(p\); but because \texttt{loop} is an endo-

\(^6\)Unboxing of function arguments can be disabled by passing the option \texttt{-no_unbox_function_arguments} to the MLKit compiler.

\(^7\)The MLKit features an option \texttt{--preserve_tail_calls}, which ensures that no region binding is wrapped around a tail-call. This option is enabled by default when garbage collection is enabled.
morphism, \((\mathbf{x}s, \mathbf{a}cc+1)\) is forced to be in the same region as \(\mathbf{p}\). Thus, what appears to be a tail call \((\text{loop}(\mathbf{x}s, \mathbf{a}cc+1))\) really will be a tail call; in particular, there will be no fresh region for the argument and no growth of the stack.

Better still, we have carefully arranged that memory consumption will be constant throughout the computation of the length of the list. First, the argument to the initial call of \text{loop} is a pair \((1, 0)\) constructed at that point. Because \text{loop} is a region endomorphism, the result of \text{loop}(1, 0) will be in the same region as \((1, 0)\). Moreover, because we then immediately take the second projection of that pair, that region is clearly local to the body of \text{klength}. Call the region \(\rho\). Because there can be an unbounded number of stores into this region, \(\rho\) is classified as infinite by multiplicity inference.

The storage mode passed along with \(\rho\) in the initial call \text{loop}(1,0) is \text{atbot}, by rule (B2) of Section 12.2. Inside \text{loop}, the storage mode given to the allocation of \((\mathbf{x}s, \mathbf{a}cc+1)\) is \text{sat}, by rule (B3) of Section 12.2: the only locally live variable at the point where the allocation takes place is \text{loop}, which we must not destroy before calling! The region that \text{loop} lies in is clearly different from \(\rho\).

Therefore, every iteration of \text{loop} resets the infinite region \(\rho\) so that it will contain at most one pair. This is seen very clearly in the third hump of Figure 12.6.

Next consider \text{llength}. The difference from \text{klength} is that \text{llength}' is now declared outside \text{llength}. Although the use of \text{local} makes it clear that \text{llength}' is not exported from the compilation unit, \text{llength}' must in fact reside in a global region, because \text{llength}, which is exported, calls \text{llength}'. Nonetheless, the storage mode analysis still achieves constant memory usage. As before, we have arranged that iteration is done by a region endomorphism that is initially applied to a freshly constructed pair. This pair can reside in a region that is local to the body of \text{llength} (once again, the projection \#2(\text{llength}'(1, 0)) makes sure that the pair does not escape the body of \text{llength}). The crucial bit is now what storage mode \text{llength}' uses when it stores \((\mathbf{x}s, \mathbf{a}cc+1)\). The only locally live variable at that point is \text{llength}' itself and, as we noted earlier, \text{llength}' lives in a global region, which is clearly different from the region inside \text{llength} that contains all the pairs. Thus, storage mode \text{sat} will be used, as desired.

Finally, consider \text{glength}, which is similar to \text{llength}, but with the crucial difference that \text{global} is exported from the compilation unit. Because \text{global} may be called from a different compilation unit, then, for all we
know, `global` may be applied to a pair that resides in the same (global) region as `global` itself. Using `sat` when storing `(xs, acc+1)` would then be a big mistake: it would destroy the very function that we are trying to call! Therefore, the storage mode analysis assigns `attop` to that storage operation. Consequently, we get a memory leak, as shown in the final hump of Figure 12.6.

To sum up, here is how one writes a loop without using space proportional to the number of iterations:

1. The iteration should be done by an auxiliary, uncurried function that is declared as local to the function that uses it; we refer (informally) to this auxiliary function as the `iterator`.

2. The iterator should be a region endomorphism and should be tail recursive.

3. Iteration should start from a suitably fresh initial argument; the result of the iteration should be kept clearly separate from the region where the iterator function lies.

Mutual recursion poses no additional complications. All functions in a block of mutually recursive functions are put in the same region.

Finally, the reader may be concerned that the two recommended solutions, `klength` and `llength`, are much slower than the other versions. This is partly an artifact of the profiling software. To get a better picture of the actual cost of the different versions, we compiled the five programs separately (using lists of length 10 million instead of 5 million) and then ran the programs on a Mac Book Pro with 16Gb RAM and a 2.7 GHz Quad-Core Intel Core i7 processor. The results are shown in Figure 12.7. Because `upto` alone takes 0.12 seconds to build the list, the differences in times are clear: the version of the length function that does not use the stack and that takes its argument in registers (i.e., `tlength`) is the fastest. The recommended versions of the length function (i.e., `klength` and `llength`) run as well as

---

8To be precise, `attop` comes about by using rule (B3) of Section 12.2. This example illustrates why we put edges from formal region parameters to global regions for exported functions when constructing the region flow graph. Notice also that storage mode analysis does not take region runtime types into account.

9When profiling is turned on, every resetting of a region involves resetting of values in the first region page of the region.

10For larger lists, the `nlength` program may cause stack overflow.
12.4. **RESETREGIONS AND FORCERESETTING**

<table>
<thead>
<tr>
<th>Program</th>
<th>upto</th>
<th>nlength</th>
<th>tlength</th>
<th>klength</th>
<th>llength</th>
<th>glength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time (s)</td>
<td>0.12</td>
<td>0.25</td>
<td>0.15</td>
<td>0.22</td>
<td>0.23</td>
<td>0.26</td>
</tr>
</tbody>
</table>

Figure 12.7: User time in seconds for building a list of 10 million elements and computing its length, using five different length functions. *upto* builds the list, but does not compute a length. Times are average over three runs.

The versions that make use of the runtime stack (i.e., *nlength* and *glength*), but are scalable and follow general useful approaches to writing recursive functions.

12.4 **resetRegions and forceResetting**

It is often the case that there are only a few places in the program where resetting is really essential, for example in some main loop. Therefore, the MLKit provides two operations that the programmer can use to encourage (or force) the MLKit to perform resetting at particular places in the program. The two operations are

\[ \text{resetRegions } \textit{vid} \]

and

\[ \text{forceResetting } \textit{vid} \]

In both cases, the argument has to be a value identifier. To port programs that contain *resetRegions* and *forceResetting* to other ML systems, simply declare

\begin{verbatim}
fun resetRegions _ = ()
fun forceResetting _ = ()
\end{verbatim}

before compiling the program developed using the MLKit.

Let \( \rho \) be a region variable that occurs free in the region-annotated type scheme with place of \( \textit{vid} \). Let \( m \) be the storage mode determined for \( \rho \) at a program point according to the rules of the previous section. Whether resetting of \( \textit{vid} \) at that program point actually takes place at runtime, depends on \( m \) and on whether resetting is forced, see Figure 12.8.
CHAPTER 12. RESETTING REGIONS

Does resetting take place at runtime?

<table>
<thead>
<tr>
<th>$m = \text{atbot}$</th>
<th>resetRegions</th>
<th>forceResetting</th>
</tr>
</thead>
<tbody>
<tr>
<td>yes</td>
<td>yes</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$m = \text{sat}$</th>
<th>only if runtime storage mode is \text{atbot}</th>
<th>yes*</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m = \text{attop}$</td>
<td>no*</td>
<td>yes*</td>
</tr>
</tbody>
</table>

(*): A compile-time warning is printed in this case.

Figure 12.8: The storage modes that will be used when resetting a region depending on $m$, the storage mode inferred by the storage mode analysis, and depending on whether the resetting is safe (resetRegions) or potentially unsafe (forceResetting).

12.5 Example: Improved Mergesort

We can now improve on the mergesort algorithm (Section 6.4) by taking storage modes into account. Splitting a list can be done by an iterative region endomorphism that is made local to the sorting function. Also, when the input list has been split, it is no longer needed, so the region it resides in can be reset. Similarly, when the two smaller lists have been sorted (into new regions) the regions of the smaller lists can be reset. These three simple observations lead to the variant of \textit{msort} listed in Figure 12.9.

Unfortunately, the storage mode analysis complains:

*** Warnings ***

\texttt{resetRegions(xs)}:

You have suggested resetting the regions that appear free in the type scheme with place of \texttt{’xs’}, i.e., in (int, \{r104\}) list (1)

\texttt{’r104’}: there is a conflict with the locally live variable

\texttt{v187 :(int, \{r113\}) list}

\footnote{MLB-file: kitdemo/msortreset1.mlb, file kitdemo/msortreset1.sml.}
local

fun cp [] = []
  | cp (x::xs) = x :: cp xs

>(* exomorphic merge *)

fun merge(xs, []) : int list = cp xs
  | merge([], ys) = cp ys
  | merge(l1 as x::xs, l2 as y::ys) =
    if x<y then x :: merge(xs, l2)
    else y :: merge(l1, ys)

>(* splitting a list *)

fun split(x::y::zs, l, r) = split(zs, x::l, y::r)
  | split(x::xs, l, r) = (xs, x::l, r)
  | split(p as ([], l, r)) = p

>(* exomorphic merge sort *)

fun msort [] = []
  | msort [x] = [x]
  | msort xs = let val (_, l, r) = split(xs, [], [])
    in resetRegions xs;
      merge(msort l before resetRegions l,
           msort r before resetRegions r)
    end

in
  val runmsort = msort(upto 200000)
  val result = print "Really done\n"
end

Figure 12.9: Variant of msort that uses resetRegions to improve memory usage. The MLKit fails to infer that the region holding the argument list xs can be reset after xs is split.
from which the following region variables can be reached in the region flow graph:
\{r113\}
Amongst these, 'r113' can also be reached from 'r104'. Thus I have given 'r104' storage mode "attop".

There is one complaint concerning the first resetRegions, but none concerning the two remaining ones. By inspecting the region-annotated term one sees that r104 is a formal parameter of msort. Due to the recursive call msort l, the region graph contains an edge from r104 to r113. Thus the analysis decides on attop, using rule (B3). This choice shows a weakness in the analysis, for using sat would really be sound. (The problem is that, unlike polymorphic recursion, the region flow graph does not distinguish between different calls of the same function.) Seeing that this is the problem, we decide to put forceResetting to work, see Figure 12.10\[12\] The region profile of the improved merge sort appears in Figure 12.11. As expected, we have now brought space consumption down from four times to two times the size of the input. Figure 12.11 may be compared to Figure 6.4 on page 66.

12.6 Example: Scanning Text Files

In this section we present a program that can scan a sequence of Standard ML source files and compute what percentage of the source files is made up by comments. Recall that an ML comment begins with the two characters (*), ends with (*), and that comments may be nested but must be balanced (within each file, we require).

The obvious solution to this problem is to implement an automaton with counters to keep track of the level of nesting of parentheses, number of characters read, and number of characters within comments. This solution provides an interesting test for region inference: although designed with the lambda calculus in mind, does the scheme cope with good old-fashioned state computations?

Let us be ambitious and write a program that only ever holds on to one character at a time when it scans a file. In other words, the aim is to use constant space (i.e., space consumption should be independent of the length of the input file).

\[12\]MLB-file: kitdemo/msortreset2.mlb, file kitdemo/msortreset2.sml.
local
  fun cp [] = []
  | cp (x::xs) = x :: cp xs

(* exomorphic merge *)
fun merge(xs, []) : int list = cp xs
  | merge([], ys) = cp ys
  | merge(l1 as x::xs, 12 as y::ys) =
      if x<y then x :: merge(xs, 12)
      else y :: merge(l1, ys)

(* splitting a list *)
fun split(x::y::zs, l, r) = split(zs, x::l, y::r)
  | split(x::xs, l, r) = (xs, x::l, r)
  | split(p as ([], l, r)) = p

(* exomorphic merge sort *)
fun msort [] = []
  | msort [x] = [x]
  | msort xs = let val (_, l, r) = split(xs, [], [])
               in forceResetting xs;
                 merge(msort l before resetRegions l, msort r before resetRegions r)
               end
  in
val runmsort = msort(upto 200000)
val result = print "Really done\n"
end

Figure 12.10: Using forceResetting to reset regions.
Figure 12.11: Region profiling of the improved mergesort. The upper triangle contains unsorted elements, while the lower triangle contains sorted elements. The program was compiled with profiling enabled and then run with the command `run -microsec 1000`. The PostScript picture `region.ps` was generated with the command `rp2ps -region -sampleMax 200` and then converted into `region.pdf` with `ps2pdf`. 
To this end, let us arrange to use a region with infinite multiplicity to hold the current input character and then reset that region before we proceed to the next character. The iteration is done by tail recursion, using region endomorphisms to ensure constant space usage.

The bulk of the program appears below. The scanning of a single file is done by \texttt{scan}, which contains three mutually recursive region endomorphisms (\texttt{count}, \texttt{after_lpar}, and \texttt{after_star}) written in accordance with the guidelines in Section 12.3.

It turns out that the constraints we have put on ourselves with running in constant space does work well with the combination of how \texttt{TextIO} input streams buffers input data. Instead, we shall make use of the lower-level \texttt{Posix} operations for opening and reading files.

The built-in function \texttt{Posix.IO.readVec}, which reads a vector of bytes from an open file descriptor, understands storage modes; if called with storage mode \texttt{atbot}, it will reset the region where the byte vector should be put before reading the bytes from the file descriptor. Consequently, at every call of \texttt{next}, the “input buffer region” will be reset.

The other important loop in the program is \texttt{driver}, a function that repeatedly reads a file name from a given file descriptor, opens the file with that name, and calls \texttt{scan} to process the file. Once again, we want to keep at most one file name in memory at a time, so we would like the region containing the file name to be reset upon each iteration. As it turns out, \texttt{readWord} will always try to store the string it creates at the bottom of the region in question.

In general however, when splitting a program unit into two, one may have to insert explicit \texttt{resetRegions} into the second unit, when operations from the first unit are called. This extra resetting may be necessary because formal region parameters of exported functions are connected to global regions in the region flow graph (cf., rule B3).

\begin{verbatim}
local
    structure F = Posix.FileSys

  exception NotBalanced
  fun scan fd : int * int =
    let

\end{verbatim}

\footnote{MLB-file: kitdemo/scan.mlb, file: kitdemo/scan.sml.}
fun next () = Byte.bytesToString(Posix.IO.readVec(fd,1))
fun up (lev,ins) = if lev > 0 then ins + 1
    else ins

(* n  : characters read from ’fd’
ins : characters inside comments
lev : current (level) number of unmatched (*
s : next input character or empty *) *)

fun count (p as (n,ins,lev,s)) =
    case s of
        "" => (* end of stream: *) p
    | "(" => after_lpar(n+1,ins,lev,next())
    | ")" => after_star(n+1,up(lev,ins),lev,next())
    | _  => count(n+1,up(lev,ins), lev,next())
and after_lpar (p as (n,ins,lev,s)) =
    case s of
        "" => p
    | "*" => count(n+1,ins+2, lev+1,next())
    | "(" => after_lpar(n+1,up(lev,ins),lev,next())
    | _  => count(n+1,up(lev,up(lev,ins)),lev,next())
and after_star (p as (n,ins,lev,s)) =
    case s of
        "" => p
    | ")" => if lev > 0 then
                count(n+1,ins+1,lev-1,next())
            else raise NotBalanced
    | "*" => after_star(n+1,up(lev,ins),lev,next())
    | "(" => after_lpar(n+1,ins,lev,next())
    | _  => count(n+1,up(lev,ins),lev,next())

val (n,ins,lev,_) = count(0,0,0,next())
in if lev=0 then (n,ins) else raise NotBalanced

fun report_file (filename, n, ins) =
    writeln (filename ^ ": size = " ^ Int.toString n
12.6. **EXAMPLE: SCANNING TEXT FILES**

```
^ " comments: " ^ Int.toString ins ^ " (" ^ (Int.toString(percent(ins, n)) handle _ => "") ^ "/")

(* scan_file(filename) scans through the file named filename returning either SOME(size_in_bytes, size_of_comments) or, in case of an error, NONE. In either case a line of information is printed. *)

fun scan_file filename : (int*int) option =
  let val fd = F.openf (filename, F.O_RDONLY, F.O.flags[])
  in let val (n, ins) = scan fd
     in Posix.IO.close fd;
        report_file (filename, n, ins);
        SOME (n, ins)
     end handle NotBalanced =>
        (writeln (filename ^ ": not balanced");
         Posix.IO.close fd;
         NONE)
  end handle IO.Io {name,...} =>
        (writeln (name ^ " failed."); NONE)

fun report_totals (n, ins) =
  writeln ("\nTotal sizes: " ^ Int.toString n ^ " comments: " ^ Int.toString ins ^ " (" ^ (Int.toString (percent (ins, n)) handle _ => "") ^ "/")

(* main(fd) reads a sequence of filenames from fd, one file name pr line (leading spaces are skipped; no spaces allowed in file names). Each file is scanned using scan_file after which a summary report is printed *)

fun main fd : unit =
  let fun driver (p as (NONE, n, ins)) =
         (report_totals(n, ins); p)
    | driver (p as (SOME filename, n, ins)) =
         driver (case scan_file filename of
```
Some(n', ins') =>
  (resetRegions p
   ; (readWord fd, n+n', ins+ins')
   
  | NONE => (resetRegions p
            ; (readWord fd, n, ins)
  )
  )

in driver (readWord fd, 0, 0); ()

in
  val result = main F.stdin

end

The program was compiled both with and without profiling turned on. The output from running the program on 14 of the source files for the MLKit is shown here:

Parsing/Infixing.sml: size = 32156 comments: 5294 (16%)
Parsing/Parse.sml: size = 4537 comments: 726 (16%)
Parsing/Topdec.grm.sml: size = 195869 comments: 4698 (2%)
Parsing/GRAMMAR_UTILS.sml: size = 4818 comments: 701 (14%)
Parsing/INFIX_STACK.sml: size = 487 comments: 321 (65%)
Parsing/Topdec.lex.sml: size = 49968 comments: 1023 (2%)
Parsing/LEX_BASICS.sml: size = 2046 comments: 1289 (63%)
Parsing/LEX_UTILS.sml: size = 1575 comments: 383 (24%)
Parsing/GrammarUtils.sml: size = 17002 comments: 1820 (10%)
Parsing/LexBasics.sml: size = 12649 comments: 3987 (31%)
Parsing/MyBase.sml: size = 33803 comments: 11124 (32%)
Parsing/HOOKS.sml: size = 312 comments: 170 (54%)
Parsing/InfixStack.sml: size = 7404 comments: 2972 (40%)
Parsing/LexUtils.sml: size = 8305 comments: 487 (5%)

Total sizes: 370931 comments: 34995 (9%)

A region profile for that run is shown in Figure [12.12]. The almost-constant space usage is evident. The occasional disturbances are due to the non-iterative functions that read a file name from input by first reading one line and then extracting the name.
Figure 12.12: Region profile of the comment scanner. The occasional increases in memory use is due to the functions that read a file name from a file descriptor. The program was compiled with profiling enabled, then run with the command `run -notimer 1000 < ../kitdemo/scanfiles`. A PostScript file `region.ps` can be generated with the command `rp2ps -region -sampleMax 200` and converted to `region.pdf` using `ps2pdf region.ps region.pdf`. 
Chapter 13

Higher-Order Functions

13.1 Lambda Abstractions (fn)

A lambda abstraction in Standard ML is an expression of the form

\[ \text{fn } pat \Rightarrow exp \]

where \( pat \) is a pattern and \( exp \) an expression. Lambda abstractions denote functions. We refer to the \( exp \) as the body of the function; variable occurrences in \( pat \) are binding occurrences; informally, the variables that occur in \( pat \) are said to be lambda-bound with scope \( exp \).

Lambda abstractions are represented by closures, both in the language definition and in the MLKit. In the MLKit, a closure for a lambda abstraction consists of a code pointer plus one word for each free variable of the lambda abstraction. Closures are not tagged except when garbage collection is enabled, in which case a closure contains one or more words to hold the tag.

At this stage, it will hardly come as a surprise to the reader that closures are stored in regions. Sometimes they reside in finite regions on the stack, other times they live in infinite regions, just like all other boxed values.

Every occurrence of \texttt{fn} in the program is considered an allocation point; the region-annotated version of the lambda abstraction is

\[ \text{fn at } \rho \; pat \Rightarrow exp \]

Standard ML allows functions to be declared using \texttt{val} rather than \texttt{fun}, for example,
val h = g o f

declares the value identifier h to be the composition of g and f. Whereas functions declared with fun automatically become region-polymorphic, functions declared with val do not in general become region-polymorphic. However, in the special case where the right-hand side of the value declaration is a lambda abstraction, the MLKit automatically converts the declaration into a fun declaration, thereby making the function region-polymorphic after all.

ML allows declarations of the form

\[
\text{fun } f \ atpat_1 atpat_2 \cdots atpat_n = \text{exp}
\]
as a shorthand for

\[
\text{fun } f \ atpat_1 = \text{fn } atpat_2 => \cdots \text{fn } atpat_n => \text{exp}
\]

where atpat ranges over atomic patterns. Functions declared using this abbreviation are said to be Curried.

### 13.2 Region-Annotated Function Types

The general form of a region-annotated function type is

\[
([\mu_1, \cdots, \mu_n] \rightarrow_{\epsilon, \varphi} \mu', \rho)
\]

where \(\mu_1, \cdots, \mu_n\) are the type with places of the arguments, \(\mu'\) is the type with place of the result, and \(\rho\) is the region containing the closure for the function. When a function type has only one argument type, we shall often write it on the form \((\mu \rightarrow_{\epsilon, \varphi} \mu', \rho)\), and so shall the MLKit.

As mentioned in Section 5.3, the unusual looking object \(\epsilon, \varphi\) is called an arrow effect. Its first component is an effect variable, whose purpose will be explained shortly. The second component is called the latent effect, and describes the effect of evaluating the body of the function.

The following example illustrates why latent effects are crucial for knowing the lifetimes of closures. Consider

---

\(\text{1}\) The reason for this is that the expression on the right-hand side of the value declaration might have an effect (e.g., print something) before returning the function. It would not be correct to suspend this effect by introducing formal region parameters.

\(\text{2}\) Program kitdemo/lambda.sml.
13.2. REGION-ANNOTATED FUNCTION TYPES

\begin{verbatim}
let val n =
  let region r134:INF, r141:INF, r150:1;
    val f =
      let val xs = [1,2] attop r134
        in fn atbot r150 ys =>
          length[] xs + length[] ys
        end
      in f [7] attop r141
    end
  in {n: _}
end
\end{verbatim}

Figure 13.1: Region-annotated program illustrating that the lifetime of a
closure is at least as long as the lifetime of the values that evaluation of the
function body will require.

\begin{verbatim}
val n = let val f = let val xs = [1,2]
  in fn ys => length xs + length ys
  end
  in f [7]
end
\end{verbatim}

Notice that *xs* has to be kept alive for as long as the function (fn ys => ⋯)
may be called, for this function will access *xs*, when called. The region-
annotated version of the example appears in Figure 13.1\(^3\) We see that *xs*
is put in *r134*, that the function closure for (fn ys => ⋯) is put in *r150*
and indeed, *r134* and *r150* have the same lifetime. To understand how
the region inference system figured that out, let us consider the effect and the
region-annotated types of particular sub-expressions. Looking at the lambda
abstraction, it must have a functional type of the form \(\tau \to \phi \to \tau'\), where
*\phi* is the effect
\[\{\text{get}(r1), \text{get}(r134), \text{get}(r141)\}\]

Notice that *r134* occurs free in the type of the lambda abstraction. But, as
pointed out in Section 3.4 the criterion for putting a region binding of \(\rho\)

\(^3\)To see the output programs discussed in this section, enable the flag
-print_drop_regions_expression.
around an expression $e$ is that $\rho$ occurs free neither in the type with place of $e$ nor in the type scheme with place of any variable in the domain of the type environment. The smallest sub-expression of the program for which $r_{134}$ does not occur free in the type with place of the expression is the right-hand side of the `val` binding of $n$, for that expression simply has type with place `int`. And at that point, the only region variables that occur free in the type environment are global region variables. Hence the placement of the `region` binding of $r_{134}$.

### 13.3 Arrow Effects

In a first-order language, effect variables might not be particularly important. But in a higher-order language like ML, effect variables are useful for tracking dependencies between functions. The following example illustrates the point:

```ml
fun apply f x = f x
val y = apply (fn n => n + 1.0) 5.0
val z = apply (fn m => m) 6
```

Here is the region-annotated type scheme of `apply`:

$$\forall \alpha_0 \alpha_2 \rho_7 \rho_8 \epsilon_{11} \epsilon_{12} \epsilon_{13}. (\alpha_0 \xrightarrow{\epsilon_{11}} \alpha_2, \rho_8) \xrightarrow{\epsilon_{12}} \{\text{put}(\rho_7)\} \xrightarrow{\epsilon_{13}} (\alpha_0 \xrightarrow{\epsilon_{13}} \{\text{get}(\rho_8)\} \epsilon_{11} \xrightarrow{\epsilon_{13}} \alpha_2, \rho_7)$$

The latent effect associated with $\epsilon_{12}$ shows that when `apply` is applied to a function, it may create (in fact: will create) a function closure in $\rho_7$. The latent effect associated with $\epsilon_{11}$ is empty, because the declaration of `apply` does not tell us anything about what effect its formal parameter $f$ must have. Crucially, however, $\epsilon_{11}$ is included as an atomic effect in the latent effect associated with $\epsilon_{13}$; whenever the body of `apply f` is evaluated, the body of $f$ may be (in fact: will be) evaluated.

The polymorphism in effects makes it possible to distinguish between the latent effects of different actual arguments to `apply`. For example, the functions `(fn n => n + 1.0)` and `(fn m => m)` have different latent effects.

---

4Program `kitdemo/apply.sml`. 
13.3. ARROW EFFECTS

Let us take the function \((\text{fn } n \Rightarrow n + 1.0)\) as an example. It has region-annotated type with place

\[
\((\text{real}, \rho_{18}) \xrightarrow{\epsilon_{14}} \text{get}(\rho_{18}), \text{put}(\rho_{5})) \rightarrow (\text{real}, \rho_{5}, \rho_{17})
\]  

(13.1)

Here, the effect variable \(\epsilon_{14}\) and the region variables \(\rho_{18}\) and \(\rho_{5}\) were chosen arbitrarily. (Actually, the region variable \(\rho_{5}\) denotes the global region for reals.) The region inference algorithm discovers that (13.1) can be derived from the argument type

\[
(\alpha_0 \xrightarrow{\epsilon_{11}} \alpha_2, \rho_8)
\]

of the type scheme for \(\text{apply}\) by the instantiating substitution

\[
S = \{(\alpha_0 \mapsto (\text{real}, \rho_{18}), \alpha_2 \mapsto (\text{real}, \rho_{5})), (\rho_8 \mapsto \rho_{17}),
\{\epsilon_{11} \mapsto \epsilon_{14}.\{\text{get}(\rho_{18}), \text{put}(\rho_{5})\}\}\}
\]

Formally, a substitution is a triple \((S^t, S^r, S^e)\), where \(S^t\) is a finite map from type variables to region-annotated types, \(S^r\) is a finite map from region variables to region variables, and \(S^e\) is a finite map from effect variables to arrow effects. Let us explain why substitutions map effect variables to arrow effects. One alternative, one might consider, is to let substitutions map effect variables to effect variables. But then substitutions would not be able to account for the idea that effects can grow, when instantiated. In the \(\text{apply}\) example, for instance, the empty effect associated with \(\epsilon_{11}\) has to grow to \(\{\text{get}(\rho_{18}), \text{put}(\rho_{5})\}\) at the concrete application of \(\text{apply}\). Otherwise, as it is easy to demonstrate, the region inference system would become unsound.

Another alternative would be to let substitutions map effect variables to effects. But nor that would work well together with the idea of using substitutions to express growth of effects. For example, when applying the map \(\{\epsilon \mapsto \{\text{get}(\rho_{0}), \text{put}(\rho_{2})\}\}\) to the effect \(\{\text{get}(\rho_{0}), \epsilon\}\), say, we would presumably yield the effect \(\{\text{get}(\rho_{0}), \text{get}(\rho_{0}), \text{put}(\rho_{2})\}\) in which the fact that the original effect had to be at least as large as whatever \(\epsilon\) stands for, is lost. Instead, we define substitution so that applying the effect substitution \(\{\epsilon \mapsto \epsilon.\{\text{get}(\rho_{2}), \text{put}(\rho)\}\}\) to \(\{\text{get}(\rho_{0}), \epsilon\}\) yields \(\{\text{get}(\rho_{0}), \epsilon, \text{get}(\rho_{2}), \text{put}(\rho)\}\).

We can now give a complete definition of atomic effects. An atomic effect is either an effect variable or a term of the form \(\text{get}(\rho)\) or \(\text{put}(\rho)\), where \(\rho\) as usual ranges over region variables. An effect is a finite set of atomic effects.

One can get the MLKit to print region-annotated type schemes with places of all binding occurrences of value variables. Also, one can choose to
have arrow effects included in the printout by passing the options `print_types` and `print_effects` to the MLKit compiler. Although passing these options gives very verbose output, it is instructive to look at such a term at least once, to see how arrow effects are instantiated. We show the full output for the `apply` example in Figure 13.2.

In reading the output, it is useful to know that the MLKit represents effects and arrow effects as graphs, the nodes of which are region variables, effect variables, `put`, `get`, or `U` (for “union”; `U` by itself means the empty set). Region variables are leaf nodes. A `put` or `get` node has emanating from it precisely one edge; it leads to the region variable in question. An effect variable node (written `e` followed by a sequence number) is always the handle of an arrow effect; there are edges from the effect variable to the atomic effects of that arrow effect, either directly, or via union nodes or other effect variable nodes. For instance, `e13(U(U,get(r8),e11))` in the figure denotes an effect variable with an edge to a union node that has edges to an empty union node, a `get` node, and an effect variable node.

When a term containing arrow effects is printed, shared nodes that have already been printed are marked with a `@`; their children are not printed again. In the figure, the binding occurrence of `apply` has been printed with its region-annotated type scheme. Each non-binding occurrence of `apply` has been printed with four square-bracketed lists. The first list is the actual region arguments; the following three are instantiation lists that show the range of the substitution by which the bound variables of the type scheme was instantiated, in the same order as the bound variables occurred. For example, in the second use of `apply`, `r8` was instantiated to `r25`.

### 13.4 On the Lack of Region Polymorphism

Unlike identifiers bound by `fun`, lambda-bound function identifiers are never region-polymorphic. So in an expression of the form

\[
\text{fn } f \Rightarrow \cdots f \cdots f \cdots
\]

all the uses of `f` use the same regions. Indeed, because `f` occurs free in the type environment while region inference analyses the body of the lambda abstraction, none of the regions that appear in the type of `f` will be deallocated inside the body of the lambda abstraction. Also, such a region must be bound outside the lambda abstraction, so any attempt to reset
fun apply
  :all
  r18,r16,e15,e19,e17,'a0,'a2.
  ('a0-e15->'a2,r16)
  -e19(put(r18))->
  ('a0-e17(U(U,get(r16),e15))->'a2,r18)
  attop r1
  [r18:1]
  [r16:0]
  (f) =
  fn attop r18 x:'a0 => f x;
val y:(real,r1) =
  let region r21:1, r23:1, r24:1
  in apply
  [atbot r24]
  [(real,r21),(real,r1)]
  [r24,r23]
  [e27(get(r21),put(r1)),
    e26(put(r24)),
    e25(e27(get(r21),put(r1)),get(r23))]
  (fn atbot r23 n:(real,r21) =>
    f64_to_real( attop r1, real_to_f64(n) + 1.0f64))
  5.0attop r21
  end;
val z:int =
  let region r42:1, r43:1
  in apply
  [atbot r43]
  [int,int]
  [r43,r42]
  [e46,e45(put(r43)),e44(e46,get(r42))]
  (fn atbot r42 m:int => m)
  6
  end

Figure 13.2: The instantiation of arrow effects keeps different applications of the same function (here apply) apart. The output was obtained by compiling the program kitdemo/apply.sml with options -print_types, -print_effects, -no_uncurry and -maximum_inline_size 0.
such a region inside the body of the abstraction will cause the storage mode analysis to complain (by Rule (B1) of Section \[12.2\]).

Therefore, when a function \( f \) is passed as argument to another function \( g \), as in the expression \( g(f) \), first regions are allocated for the use of \( f \), then \( g \) is called, and finally, the regions are de-allocated (provided they are not global regions). Whether the \texttt{let region} construct thus introduced encloses the call site immediately, as in

\[
\text{let region } \rho_1, \ldots, \rho_n \text{ in } g(f) \text{ end}
\]

or further out, as in

\[
\text{let region } \rho_1, \ldots, \rho_n \text{ in } \ldots g(f) \ldots \text{ end}
\]

depends on the type and effect of the expression \( g(f) \) in the usual way: regions can be de-allocated when they occur free neither in the type with place of the expression nor in the type environment.

### 13.5 Examples: map and fold1

Consider the program\(^5\)

\[
\begin{align*}
\text{fun map } f \emptyset &= \emptyset \\
| \text{map } f (x::xs) &= f(x) :: \text{map } f \text{ } xs
\end{align*}
\]

val \( x = \text{map } (\text{fn } x \Rightarrow x+1) \) \([7,11]\)

This formulation of \texttt{map} is not the most efficient one in the MLKit, because it will create one closure for each element in the list, due to currying\(^6\). However it serves to illustrate the point made in the previous section about allocating regions in connection with higher-order functions. The region-annotated version is listed in Figure \[13.3\]. We see that the region that appears free in the type with place of the successor function (i.e., \( r37 \)) is allocated prior to the

\(^5\)Program \texttt{kitdemo/map.sml}.

\(^6\)When \texttt{map} and the application of \texttt{map} appear in the same compilation unit, the MLKit will automatically specialise \texttt{map} to a recursive function that does not have this defect. This specialisation is the result of a general optimisation of curried functions that are invariant in their first argument. The output we present in this section was obtained by passing to the MLKit compiler the options \texttt{-maximum_specialise_size 0} and \texttt{-no_uncurry}.\n
let fun map attop r1 [r34:1, r20:0] (var1) =
    fn attop r34 var2 =>
        (case var2 of
            nil => nil
        | _ =>
            let val v102 = decon_:: var2;
                val v103 = #0 v102;
                val v104 = #1 v102
            in :: (var1 v103, let region r28:1
                in map[atbot r28, attop r20]
                    var1 v104
                end) attop r20
            end
        );
val x =
    let region r37:1, r38:INF, r40:1
        in map[atbot r40, attop r4]
            (fn atbot r37 x => x + 1) [7,11] attop r38
        end
    in {map: (_, r1), x: _}
end

Figure 13.3: Although this version of `map` creates a closure for each list element, the region-polymorphic recursion (of `map`) ensures that that closure is put in a region local to `map`. Thus, these closures do not pile up in `r37`, the region of the initial argument.
call of \texttt{map} and that it stays alive throughout the evaluation of the body of \texttt{map}. Notice, however, that the closures that are created when \texttt{map} is applied do not pile up in \texttt{r37}, the region of the successor function. Instead, they are put in local regions bound to \texttt{r28}, one closure in each region. Also, if we had given some more complicated argument to \texttt{map}, the body of that function could include local \texttt{region} declarations. For each list element, regions would then be allocated, used, and then de-allocated before proceeding to the next list element.

So it might appear that higher-order functions are nothing to worry about when programming with regions. That is not so, however. The limitation that lambda-bound functions are never region-polymorphic can lead to space leaks. Here is an example:

\begin{verbatim}
fun foldl f acc [] = acc
  | foldl f acc (x::xs) = foldl f (f(x,acc)) xs

val x = foldl (fn (x,acc) => 10*acc+x) 0 [7,2]
\end{verbatim}

Because \texttt{f} is lambda-bound, all the pairs created by the expression \((x,\texttt{acc})\) will pile up in the same region. The storage mode analysis will infer storage mode \texttt{attop} for the allocation of the pair, by rule (B1) of Section 12.2 because \texttt{foldl} is curried, there are several lambdas between the formal region parameter of \texttt{foldl} that indicates where the pair should be put and the allocation point of the pair.

It does not help to uncurry \texttt{foldl} and turn \texttt{foldl} into a region endomorphism:

\begin{verbatim}
fun foldl(p as (f,\[],_)) = p
  | foldl(f,x::xs,acc) = foldl(f,xs,f(x,acc))

val x = #3(foldl(fn(x,acc) => 10*acc+x,[7,2],0))
\end{verbatim}

The storage mode analysis will still give \texttt{attop} for the allocation of the pair \((x,\texttt{acc})\), because the region of the pair is free in the region-annotated type of \texttt{f}, which is locally live at that point.

What if we require that \texttt{f} be curried, so as to avoid the creation of the pair altogether?\footnote{Program \texttt{ktdemo/fold2.sml}.}
fun foldl f b xs = 
  let fun loop(p as ([] , b)) = p 
      | loop(x::xs , b) = loop(xs,f x b) 
  in #2(loop(xs,b)) 
end 

The region-annotated version of this program appears in Figure 14.4 on page 141. This saves the allocation of a pair inside loop, although the saving is lost if the evaluation of \( f \ x \) creates a closure.

In short, folding a function over a list may leak two words of memory for each list element.
Chapter 14

The Function Call

Standard ML allows function applications of the form

\[ \text{exp}_1 \text{exp}_2 \]

where \( \text{exp}_1 \) is the operator and \( \text{exp}_2 \) is the operand. The syntax for function application is overloaded, in that it is used for three different purposes in ML:

1. applications of built-in operations such as +, =, and :=

2. applications of unary value constructors (including ref) and unary exception constructors

3. applications of user-defined functions, that is, functions introduced by fn or fun

This chapter is about the last kind of function applications; in the following, we use the term function application to stand for applications of user-defined functions only.

Function applications are ubiquitous in Standard ML programs; in particular, iteration is often achieved by function calls. Not surprisingly, careful compilation of function calls is essential for obtaining good performance.

The MLKit partitions function calls into four kinds, which are implemented in different ways. At best, a function call is simply realised by a jump in the target code. The resource conscious programmer will want to know the special cases; for example, when doing an iterative computation, it
is important to know whether the space usage is going to be independent of the number of iterations.

The MLKit performs a backwards flow analysis, called call conversion, to determine what function calls are tail calls and, more generally, what function calls fall into the four special cases. We say that expressions produced by this analysis are call-explicit. One can inspect call-explicit programs by passing the option

```
-print_call_explicit_expression
```

to the MLKit compiler, and thus check whether specific function calls in the code turn out as intended. Call-explicit expressions are produced after regions have been dropped (page 62) but before native code generation.

We shall first give a brief description of the parameter passing mechanism in general and then discuss the different kinds of function calls provided, working our way from the most specialised (and most efficient) cases towards the default cases.

14.1 Parameter Passing

Parameters to functions are passed either on the runtime stack or, if possible, in registers. Also region parameters to region-polymorphic functions are passed on the runtime stack or in registers.

14.2 Tail Calls and Non-Tail Calls

A call that is the last action of a function is referred to as a tail call. After region inference, the MLKit performs a tail call analysis (in one backwards scan through the program). It is significant that the tail call analysis happens after region inference; as we saw in Section 12.3, a function call that looks like a tail call in the source program may end up as a non-tail call in the region-annotated program, because the function has to return to free memory. The tail call analysis divides function calls into four different kinds of calls:

- **jmp**: tail calls to known functions
- **funcall**: non-tail calls to known functions
- **fnjmp**: tail calls to unknown functions
- **fncall**: non-tail calls to unknown functions
In the sections to follow, we describe each of these kinds of calls in detail.

14.3 Tail Call to Known Function (jmp)

A call to a region-polymorphic function (i.e., a known function) takes the form

\[ f \left[ \rho_1, \ldots, \rho_n \right] \langle e_1, \ldots, e_m \rangle \]

where \( \rho_1, \ldots, \rho_n \) are actual region parameters to the function, \( f \) is the name of a region-polymorphic function, and \( e_1 \cdots e_m, m \geq 1 \) are value arguments to the function (we often omit the brackets \( \langle \cdots \rangle \) when \( m = 1 \)). The MLKit turns such a function call into the form

\[ \text{jmp } f \left[ \rho_1, \ldots, \rho_n \right] \langle e_1, \ldots, e_m \rangle \]

if the call appears in a tail-call position, that is, if the call is the last thing the current function needs to do. Because the start address of \( f \) is known during compilation (because \( f \) is region-polymorphic), such a call is as efficient as an assembly language jump to a constant label (not taking into account the shuffling of arguments needed to match the calling convention for \( f \)).

The way to avoid that a region binding is wrapped around the function call (and thus causes the call not to be recognized as a tail call) is to turn the calling function into a region endomorphism, when possible.

The following is an example of how one obtains a tail call to a known function:\textsuperscript{1}

```ml
local
  fun f'(p as (0,b)) = p
  | f'(n,b) = f'(n-1,n*b)

in
  fun f(a,b) = #2(f'(a,b))
end
```

The call-explicit version of \( f' \) appears in Figure 14.1.

There is a more efficient version of the function \( f \) that exploits the MLKit’s unboxing of function arguments, but in general, one can rely on unboxing to ensure tail-calls only when the elements of the argument tuple

\textsuperscript{1}Program kitdemo/tail.sml.
fun f’ attop r1 [r13:inf] (var2) = 
let val v96 = #0 var2 
in  case v96 of 
  0 => var2 
| _ => let val v98 = #1 var2 
in  jmp f’[sat r13] (v96 - 1, v96 * v98)sat r13 
end

Figure 14.1: An example where a function call turns into a tail call to a known function.

themselves are unboxed; otherwise there is a risk that, for each invocation, fresh regions are introduced to hold the arguments to the call, and the call would need to return to de-allocate these regions.

The MLKit can transform a call into a jmp tail call even in the case that the call appears in the body of a fn expression. Consider the following two mutually recursive functions g and h:

fun g (n,b) = h (n-1) b 
and h 0 b = b 
| h n b = g(n,n*b)

Here h calls g in a tail position. The call explicit version of the program is listed in Figure [14.2] and indeed, the call to g is recognized as a tail call. Also notice that the MLKit does not try to in-line g in h (or vice-versa), although such an optimisation would certainly improve on the efficiency of the generated code. Another example of a jmp tail call is shown in Section [14.8]

14.4 Non-Tail Call to Known Function (funcall)

In the case that a call to a known function cannot be turned into a tail call, because the call needs to return to do more work, the call is transformed into

funcall f [ρ₁,...,ρₙ] exp

Program kitdemo/tail2.sml.
14.5 Tail Call to Unknown Function (fnjmp)

Consider the case

\[ \text{exp}_1 \text{exp}_2 \]

where (a) the call is a tail call and (b) \text{exp}_1 is not the name of a region-polymorphic function.

Here \text{exp}_1 is evaluated to a closure in memory, pointed to by a standard closure register. Then \text{exp}_2 is evaluated and the result put in a standard argument register. The first word in the closure contains the address of the code of the function. This address is fetched into a third register and a jump to the address is made. Because the call is a tail call, it induces no allocation,
neither on the stack nor in regions. It is thus as efficient as an indirect jump in assembly language.

The mnemonic used in call-explicit expressions for this special case is

\[ \text{fnjmp } exp_1 \ exp_2 \]

14.6 Non-Tail Call to Unknown Function (fncaII)

Consider the case

\[ exp_1 \ exp_2 \]

where (a) the call is not a tail call and (b) \( exp_1 \) is not the name of a region-polymorphic function.

Applications of this form are implemented as follows. First \( exp_1 \) is evaluated and the result, a pointer to a closure, is stored in the standard closure register. Then \( exp_2 \) is evaluated and stored in the standard argument register. Then live registers and a return address are pushed onto the stack and a jump is made to the code address that is stored in the first word of the closure pointed to by the standard closure register. Upon return, registers are restored from the stack.

The mnemonic used in call-explicit expressions for this special case is

\[ \text{fncaII } exp_1 \ exp_2 \]

14.7 Example: Function Composition

The Standard ML Basis Library declares function composition as follows\(^3\)

\[ \text{fun } (f \ o \ g) \ x = f(g \ x) \]

The resulting call-explicit expression produced by the MLKit is

\[ \text{fun } o \ \text{attop } r1 \ [r22;3] \ (v92, v93) = \\
\text{fn } \text{attop } r22 \ x \Rightarrow \text{fnjmp } v92 \ (\text{fncaII } v93 \ x) \]

Notice that \( f \ o \ g \) first creates a closure in \( r22 \) and then returns. The closure is of size three words and contains a pointer to the code for the function and pointers to the closures for \( f \) and \( g \). When called, the created function first performs a non-tail call of \( g \) and then a tail call to \( f \).

\(^3\)Program kitdemo/compose.sml.
14.8 Example: foldl Revisited

Consider the following declaration of folding over lists:

```ml
fun foldl f b xs =
    case xs of
    [] => b
  | x::xs' => foldl f (f x b) xs'
```

The recursive call of foldl is a call of a known function, but not a tail call; foldl returns a closure, which is subsequently applied to the value of (f x b). This too returns a closure, which in turn is applied to xs’. The resulting call-explicit expression is shown in Figure 14.3. Notice that upon each iteration, fresh regions for holding two closures are being allocated for

---

4Program kitdemo/fold1.sml.
the duration of the recursive call. Thus, space usage is linear in the length of the list (4 words for each list cell, to be precise).

An alternative version of \texttt{foldl} assumes that \( f \) is curried:\footnote{Program \texttt{kitdemo/fold2.sml}.}

\[
\text{fun foldl} \ f \ b \ x s = \\
\text{let fun loop}(p \text{ as } ([], b) = p  \\
\text{| loop}(x::xs, b) = \text{loop}(xs, f \ x \ b)  \\
\text{in} \\
\text{#2(loop}(xs, b))  \\
\text{end}
\]

It is compiled into the call-explicit expression in Figure\footnote{Program \texttt{kitdemo/fold2.sml}.}[14.4]. Here the loop is implemented as a jump and there is no new allocation in each iteration, except, of course, for the allocation that \( f \) might make:\footnote{All the allocations made by the calls to \( f \) (one call for each element of the list) are put in the same regions. If the list is very long or the values produced large, it may be a good idea to copy the final result to separate regions.}

As an exercise, consider the following variant of \texttt{foldl}, which assumes that \( f \) takes a pair as an argument:\footnote{Program \texttt{kitdemo/fold3.sml}.}

\[
\text{fun foldl'} \ f \ b \ x s = \\
\text{let fun loop}(p \text{ as } ([], b)) = p  \\
\text{| loop}(x::xs, b) = \text{loop}(xs, f(x,b))  \\
\text{in} \\
\text{#2(loop}(xs, b))  \\
\text{end}
\]

Interestingly, this program contains a potential space leak. Can you detect it? If not, the MLKit will tell you when you compile the program if you pass the compiler the option \texttt{-warn_on_escaping_puts}.
fun foldl attop r1 [r50:3, r48:3] (f) =
  fn attop r50 b =>
    fn attop r48 xs =>
      let region r25:1;
        fun loop atbot r25 [r32:inf] (var2) =
          let val v107 = #0 var2
            in case v107 of
              nil => var2
            | _ =>
              let val v109 = decon_:: v107;
                val v110 = #0 v109;
                val v111 = #1 v109;
                val v112 = #1 var2
              in jmp loop[sat r32]
                (v111,
                  fn call fn call f v110 v112
                )sat r32
              end
            end;
        region r44:inf
        in #1 fn call loop[atbot r44] (xs, b)atbot r44
      end
  end

Figure 14.4: The result of compiling the efficient version of foldl
-kitdemo/fold2.sml) is an iterative function that avoids argument pairs
piling up in one region.
Chapter 15

ML Basis Files and Modules

In Section 2.8 we described how to compile and run single-file programs. In this chapter, we describe how to program in the large with the MLKit, using Standard ML Modules and the possibility of organising source files in ML Basis Files. The MLKit fully supports Standard ML Modules and it has a sophisticated system for avoiding unnecessary recompilation. In the following section, we describe the notion of ML Basis Files. We then turn to show how to program with structures, signatures, and functors. To enable the programmer to write efficient programs using the Modules language, we shall also explain how the MLKit compiles Modules language constructs.

15.1 ML Basis Files

An ML Basis File, in short MLB-file, is a file that lists the SML source files that make up a project or a library. An MLB-file can also reference other MLB-files, so one can organise projects in a hierarchical manner. MLB-files are enforced not to be cyclic.

MLB-files have file extension .mlb. The content of an MLB-file is a basis declaration, for which the grammar is given in Figure 15.1. We assume a denumerable infinite set of basis identifiers Bid, ranged over by bid. We use longbid to range over long basis identifiers, that is, non-empty lists of basis identifiers separated by a punctuation letter (.). Basis identifiers can be used for giving a name to a group of compilation units and allow for expressing source dependencies, exactly, as a directed acyclic graph, within one MLB-file.
Figure 15.1: Grammar for MLB-files, i.e., files with extension .mlb. For some file extension .ext, path.ext denotes either an absolute path or a relative path (relative to the directory in which the MLB-file is located) to a file on the underlying file system.
In an MLB-file, one can reference source files and other MLB-files using absolute or relative paths. Relative paths are relative to the location of the MLB-file. Paths can reference environment variables using the \texttt{$(ENVVAR)$} notation, where \texttt{ENVVAR} is an environment variable.

Until now, we have seen a few examples of MLB-files that reference the Basis Library, using the \texttt{$(SML\_LIB)$} environment variable (see Section 6.4 for such an example). In Section 15.4 we present an example of an MLB-file that reference other MLB-files. In Section 19.7 we shall see an example of how an MLB-file can be compiled and linked with external object files, produced with a C compiler, for instance. MLB-files may contain Standard ML style comments. The declared identifiers of an MLB-file is the union of the identifiers being declared by source files in the MLB-file, excluding source files that are included using \texttt{local}. As an example of the use of basis identifiers and \texttt{local} to limit what identifiers are declared by an MLB-file, consult the MLB-file \texttt{basis/basis.mlb}.

Every source file must contain a Standard ML top-level declaration; the scope of the declaration is all the subsequent source files mentioned in the MLB-file and all other MLB-files that reference this MLB-file. Thus, a source file may depend on source files mentioned earlier in the MLB-file and on other referenced MLB-files. The meaning of an entire MLB-file is the meaning of the top-level declaration that would arise by expanding all referenced MLB-files and then concatenating all the source files listed in the MLB-file (with appropriate renaming of declared identifiers of source files that are included using \texttt{local}), in the order they are listed, except that each MLB-file is executed only the first time it is imported.

The MLKit has a system for managing compilation and recompilation of MLB-files. The system guarantees that the result of first modifying one or more source files and then using the separate compilation system to rebuild the executable is the same as if all source files were recompiled.

Thus, the separate compilation system is a way of avoiding recompiling parts of a (possibly) long sequence of declarations, while ensuring that the result is always the same as if one had compiled the entire program from scratch. As an example, consider the MLB-file (kitdemo/scan.mlb) for the text scanning example of Section 12.6. It contains the following three lines:

\begin{verbatim}
$(SML\_LIB)/basis/basis.mlb
lib.sml
scan.sml
\end{verbatim}
The source files for the project are `lib_posix.sml` and `scan.sml`, which are both located in the directory where `scan.mlb` is located. Whereas each of the source files `lib.sml` and `scan.sml` depends on the Basis Library, the source file `scan.sml` also depends on `lib.sml`.

Compiling an MLB-file is easy; simply give it as an argument to the MLKit executable. When the MLB-file is first compiled, the MLKit detects automatically when a source file has been modified (by checking file modification dates). After a project has been successfully compiled and linked, it can be executed by running the command

```
./run
```
in the working directory.

The MLKit compiles each source file of an MLB-file one at a time, in the order mentioned. A source file is compiled under a given set of assumptions, which provides, for instance, region-annotated type schemes with places for free variables of the source file. Also, compilation of a source file gives rise to exported information about declared identifiers. Exported information may occur in assumptions for source files mentioned later in the MLB-file.

There are two rules that govern when a source file is recompiled. A source file is recompiled if either (1) the user has modified the source file or (2) the assumptions under which the source file was previously compiled have changed. To avoid unnecessary recompilation, assumptions for a source file depend on only its free identifiers. Moreover, if a source file has been compiled earlier, the MLKit seeks to match the new exported information to the old exported information by renaming generated names to names generated when the source file was first compiled. Matching allows the compiler to use fresh names (stamps) for implementing generative data types, for instance, and still achieve that a source file is not necessarily recompiled even though source files, on which it depends, are modified.

Let us assume that we modify the source file `lib.sml` of the text scanning example, after having compiled the MLB-file `kitdemo/scan.mlb` once. When compiling the MLB-file again, the MLKit checks whether the assumptions under which the source file `scan.sml` was compiled have changed, and if so, recompiles `scan.sml`. Modifying only comments or string constants inside `lib.sml` or extending its set of declared identifiers does not trigger recompilation of `scan.sml`.

Some of the information a source file depends on is the ML type schemes of its free variables. It also depends on, for example, the region-annotated type
schemes with places of its free variables. Thus it can happen that a source
file is recompiled even though the ML type assumptions for free variables
are unchanged. For instance, the region-annotated type scheme with place
for a free variable may have changed, even though the underlying ML type
scheme has not.

As an example, consider what happens if we modify the function `readWord`
in the source file `lib.sml` so that it puts its result in a global region. This
modification will trigger recompilation of the source file `scan.sml`, because
the assumptions under which it was previously compiled have changed. Be-
sides changes in region-annotated type schemes with places, changes in mul-
tiplicities and in physical sizes of formal region variables of functions may
also trigger recompilation.

## 15.2 Structures

The support for Modules together with the possibility of dividing top-level
declarations into different source files provide a mechanism for programming
in the large. In the MLKit, structures exist only at compile time. Thus one
need not worry where structures live at runtime.

We illustrate the compile-time nature of structures with the following ex-
ample. Consider the MLB-file `PolySet.mlb`\(^1\) which mentions the source files
`PolySet.sml`, `INT_SET.sml`, and `IntSet.sml`. The source file `PolySet.sml`
contains the following top-level declaration:

```ml
structure PolySet =
    struct
      type 'a set = 'a list
      val empty = []
      fun singleton x = [x]
      fun mem(x,[]) = false
       | mem(x,y::ys) = x=y orelse mem(x,ys)
      fun union(s1,[]) = s1
       | union(s1,x::s2) = if mem(x,s1) then union(s1,s2)
                      else x::union(s1,s2)
    end
```

\(^1\)MLB-file: kitdemo/PolySet.mlb.
The code generated by the MLKit for the PolySet structure is exactly as if the declarations were written outside of a structure. As a consequence, when you refer to a component of a structure using qualified identifiers (e.g., PolySet.mem), no code is generated for fetching the component from the structure. Moreover, when opening a structure, using the open declaration, no code is generated for rebinding the identifiers that become visible.

15.3 Signatures

In the MLKit, signature declarations exist only at compile time. That is, a signature declaration does not result in any code being generated. The source file INT_SET.sml in the MLB-file PolySet.mlb, mentioned earlier, contains the signature declaration

```
signature INT_SET =
  sig
    type 'a set
    val empty : int set
    val singleton : int -> int set
    val mem : int * int set -> bool
    val union : int set * int set -> int set
  end
```

Signatures are used in two contexts; for specifying arguments to functors and for providing restricted views of structures using transparent and opaque signature constraints. We defer the discussion of the use of signatures for specifying arguments to functors to Section 15.4.

Transparent signature constraints may both restrict components from a structure and make polymorphic components less polymorphic. Moreover, opaque signature constraints may also make type components of structures abstract. Consider the structure declarations

```
structure IntSet1 : INT_SET = PolySet
structure IntSet2 :> INT_SET = PolySet
```

located in the source file kitdemo/IntSet.sml. No code is generated for the structure declarations. Instead, the compiler memorises that if you refer to the long identifier IntSet1.mem, for instance, then it is actually PolySet.mem that is applied with type instance int.
15.4 Functionality

As for the second declaration, opaque signature constraints are eliminated at compile time (after elaboration) and transformed into transparent signature constraints.

15.4 Functors

Functors map structures to structures. The MLKit specialises a functor every time it is applied. Thus, types that are abstract for the programmer (inside a functor body) become visible to the compiler. Region-annotated type schemes and other information about identifiers in the actual functor argument are available when the MLKit compiles the functor body.

For practical reasons, it is important that not all functor applications are expanded at once, since this could cause intermediate representations of programs to become as large as (or even much larger than) the entire program. Further, non-restricted in-lining could lead to unnecessary recompilation upon modification of source files. Instead, the largest structure declarations not containing functor applications are compiled into separate chunks of machine object code. Assumptions for compiling these structure declarations are memorised, so that the generated code can be reused upon modification of source files if the assumptions do not change.

Consider the following MLB-file:

```
$(SML_LIB)/basis/basis.mlb
local utils/utils.mlb
in SET.sml Set.sml SetApp.sml
end
```

The MLB-file reference the MLB-file `utils.mlb` from the `utils` directory. This MLB-file provides a structure `ListUtils` that contains the function `pr_list` with type scheme `(‘a -> string) -> ‘a list -> string`. The content of the file `Set.sml` is listed in Figure 15.2. It declares the functor `Set`, which takes as arguments the element type for the set, an ordering function on elements, and a function for providing a string representation of elements.

The source file `SetApp.sml` is listed in Figure 15.3. It constructs a structure `IntSet` by applying the functor `Set` to appropriate arguments including

---

2MLB-file: kitdemo/Set.mlb.
3MLB-file: kitdemo/utils/utils.mlb.
an ordering operation on integers and an operation for giving the string representation of an integer. The \texttt{IntSet} structure is used for constructing a set \{2,5\}, which the program prints using the built-in \texttt{print} function.

The body of the \texttt{Set} functor is instantiated to form the code for the \texttt{IntSet} structure. The result of instantiating the \texttt{Set} functor is first translated into a Lambda program and then translated into a MulExp program. The MulExp call-explicit code for the \texttt{mem} function is shown in Figure 15.4.

Notice that the code for the \texttt{mem} function holds inlined code for the \texttt{lt} function; because the function is sufficiently small, the MLKit propagates its intermediate representation across module boundaries.
functor Set (eqtype elem (*total order*))
  val lt : elem * elem -> bool
  val pr : elem -> string
: SET where type elem = elem =
struct
  type elem = elem
  type set = elem list
  val empty : set = []
  fun singleton e = [e]
  fun mem x l = 
    let fun mem' [] = false
      | mem' (y::ys) = if lt(y,x) then mem' ys
        else not(lt(x,y))
    in mem' l
    end
  fun union(s1,s2) = 
    let fun U (t as ([], [], acc)) = t
      | U ([], y::ys, acc) = U([], ys, y::acc)
      | U (x::xs, [], acc) = U(xs, [], x::acc)
      | U (s1 as x::xs, s2 as y::ys, acc) =
        if lt(x,y) then (xs, s2, x::acc)
        else if lt(y,x) then (s1, ys, y::acc)
        else (xs, ys, y::acc)
    in rev(#3(U(s1, s2, [])))
    end
  val pr = fn s => ListUtils.pr_list pr s
end

Figure 15.2: The source file kitdemo/Set.sml.
structure IntSet = Set(type elem = int
  val lt = op <
  fun pr a = Int.toString a)
open IntSet
val _ = print (pr (union(singleton 2, singleton 5)))

Figure 15.3: The source file kitdemo/SetApp.sml.

fun mem attop r1 [] (x, l) = 
  let region r53:1;
    fun mem' atbot r53 [] (var2) =
      case var2 of
        nil => false
      | _ =>
        let val v193 = decon_:: var2;
            val v194 = #0 v193;
            val v195 = #1 v193
          in case v194 < x of
            true => jmp mem'[] v195
          | _ => (case x < v194 of
                     true => false
                   | _ => true)
        end
      in funcall mem'[] l
    end

Figure 15.4: The MulExp call-explicit code for the mem function resulting from instantiating the Set functor.
Chapter 16

Garbage Collection

The MLKit supports reference tracing garbage collection in combination with the region memory model [Hal99, HET02]. Garbage collection is also possible with region profiling enabled.

The reference-tracing garbage collector is enabled by default and, as we have seen earlier, garbage collection can be disabled by passing the -no.gc option to the MLKit compiler at compile time. As we shall see, it is also possible to disable garbage collection at runtime for a program that has been compiled with garbage collection enabled.

The MLKit also features generational reference-tracing garbage collection (option -gengc), which in some cases is superior to ordinary reference-tracing garbage collection, but which may also cause additional fragmentation [EH21].

16.1 Dangling Pointers

The region type system supports deallocation of memory that is not accessed in the remainder of the execution of the program. Because of this principle, the execution model may lead to dangling pointers, that is, pointers that point into memory that has been discharged. When garbage collection is enabled, the region type system is modified slightly so as to guarantee that no dangling pointers occur during execution [Els03]. The following example illustrates how the enabling of garbage collection changes the way programs are compiled:

```ml
val f = let val x = ref (2, [1])
```

153
When garbage collection is disabled, the program is compiled into the following MulExp program:

```ml
val f = let region r9:inf;
    val x = ref attop r6 (2, [1] attop r9) attop r4
    in fn attop r1 y => (#0 (!x), y) attop r4
end
val r = fn call f 5
```

Notice here that region \( r_9 \), which contains the list \([1]\), is de-allocated before the function \( f \) is applied to the value \( 5 \). If we chose to run this program together with a reference tracing garbage collector, a fatal error could occur: The memory that contains the list \([1]\) could be reused for other purposes at the time the garbage collector tries to trace the dangling pointer.

Figure 16.1 shows the MulExp program produced when garbage collection is enabled. When garbage collection is enabled, the MLKit makes sure that whenever a closure is live all values stored in the closure are kept live as long as the closure itself.

---

1 Compiled with `mlkit -no_gc -maximum_inline_size 0 -Ppse -w 40 dangling.sml` from within the kitdemo directory.
2 Compiled with `mlkit -gc -maximum_inline_size 0 -Ppse -w 50 dangling.sml` from within the kitdemo directory.
as long as the closure is live. Assume that the type with place $\mu$ of the function associated with the closure is on the form $(\mu_1 \xrightarrow{\epsilon, \varphi} \mu_2, \rho_0)$. The MLKit enforces the restriction by requiring that for each region variable $\rho$ that occur free in the type of free variables of the function (those variables for which values are stored in the closure at runtime), $\rho$ occur free in $\mu$. In the implementation, the requirement may lead to extra get effects being added to $\epsilon, \varphi$ when garbage collection is enabled. In the example, an imposed get effect on the arrow effect in the type for $f$ makes it impossible to wrap a region binding around the binding for $f$. (See [TT93, page 50], [Els03], and [Els22] for more information about this requirement.)

### 16.2 Scanning Text Files with Stream IO and Garbage Collection

In Section 12.6, we saw how we could use basic non-buffered Posix IO operations for scanning text files in constant space. The Standard ML Basis library, however, also features a stream-based TextIO structure that supports arbitrary look-ahead, buffering, stream-redirection, and many other features [GR04]. Unfortunately, as mentioned in Section 12.6 this functionality does not work well together with MLKit’s region based memory management, unless combined with a mechanism for dynamically garbage collecting regions. We now consider a modified version of the text scanning program listed in Section 12.6 that uses the TextIO.inputN function for file reading, instead of using Posix buffered IO.

Figure 16.2 shows two region profiles for the modified text scanning program.

We see that the reference-tracing garbage collector periodically cleans up the global regions r1 and r4, which tends to grow steadily without garbage collection.

### 16.3 Instrumenting the Executable

Executables produced by the MLKit with garbage collection enabled can be instrumented by use of command-line options. For instance, if the MLKit has produced a file run, one can pass the option `-verbose gc` to run to enable the printing of garbage collection information at runtime. An overview of

---

3MLB-file: scan_stream.mlb.
Figure 16.2: Two region profiles of text scanning using buffered stream-based IO operations. The top region profile is with reference-tracing garbage collection disabled and the bottom region profile is with reference-tracing garbage collection enabled.
available command-line options is shown by passing the option `-help` to the generated executable:

**Usage:**

```
./run
[-help, -h]
[-disable_gc | -verbose_gc] [-heap_to_live_ratio d]
```

**where**

- `-help, -h` Print this help screen and exit.
- `-disable_gc` Disable garbage collector.
- `-verbose_gc` Show info after each collection.
- `-heap_to_live_ratio d` Use heap to live ratio d, ex. 3.0.
Part III

System Reference
Chapter 17

Region Profiling

We have already seen several examples of the use of the profiler. We shall now explain in more detail how to profile programs. For example, we shall see how one can find out precisely what allocation points in the program contribute to allocation in a particular region.

The profiler consists of several tools that can be used to analyse the dynamic memory behavior of a program. First of all, the profiler lets you create graphs of the dynamic memory usage of the program. Three different kinds of graphs may be created:

- A region profile is a graph that gives a global view of the memory usage by showing the total number of bytes allocated in regions and on the stack as a function of time. In the graph, regions that arise from the same region \( \rho \) construct are collected into one colored band, labelled \( \rho \). The region variables that label bands are always global or region-bound, never formal region parameters.

- An object profile is a graph that, for a particular region, shows the objects allocated in the region, with one coloured band for each allocation point in the region-annotated program\(^1\). Each allocation point is annotated with a program point, which is a unique number that identifies

\(^1\) Every occurrence of an at in the region-annotated program is an allocation point.
the allocation. To inspect region-annotated programs with program points, pass the MLKit compiler the option `-print_program_points` in addition to the option `-print_call_explicit_expression`, say.

If you have an object profile showing that program point `pp42`, say, contributes with allocation, you can search for `pp42` in the region-annotated program and thus find the construct that caused the allocation.

- A *stack profile* is a graph that shows the stack memory usage, as a function of time.

In addition to the possibility of generating programs with program points, it is also possible, during compilation, to generate a *region flow graph*, which shows how regions may be passed around at runtime when region-polymorphic functions are applied. The region flow graph comes in handy when profiling large programs and when one wants to find out why a formal region variable is instantiated to a certain region-bound region variable.

The following example clarifies the use of a region flow graph. Suppose the region profile shows that `r5` is responsible for most of the memory usage. Further, suppose an object profile of `r5` shows that program point `pp345` is responsible for most of the allocation. Searching for `pp345` in the region-annotated program, you may find that the allocation at `pp345` is into some other region variable, `r34`, say. Here `r34` will be a formal region parameter of a region-polymorphic function that at runtime has been instantiated to `r5` by one or more calls of region-polymorphic functions. You can now use the region flow graph to find the cascade of region polymorphic applications that ends up instantiating `r34` to `r5`.

The profiling process is sketched in Figure 17.1.

We will now show an example on how to profile a concrete program that contains a space leak and then show how the profiler can be used to improve the program. We then explain in more detail how to specify the profiling strategies and how the profiles are generated.

\(^2\)Program points are unique. In particular, for a project with two program units, the program points in the region-annotated programs for the two units will be distinct.

\(^3\)Program points are annotated during physical size inference.
Choose compile-time profiling strategy and compile

Generate profile with rp2ps

Choose runtime profiling strategy and execute

Region profile, object profile, or stack profile

Program annotated with program points

Region flow graph

data file profile.rp

Figure 17.1: Overview of the profile process. The process sometimes requires the programmer to refine the runtime profiling strategy, or even the compile-time profiling strategy. Dotted boxes represent output from the compiler, from executing the program, and from using the tool rp2ps, which generates PostScript graphs from the exported data file.
17.1 Example: Scanning Text Files Again

In this section, we concentrate on the general principles of profiling. As an example, we investigate a revised version of the project kitdemo/scan.mlb (see Section 12.6). Instead of asking for a list of input files to scan (as project scan.mlb does), the revised version of the scan project asks for only one input file, which it then scans 50 times.

The first thing to do is to get an overview of the memory usage of the program. A region profile of the program gives you just that. See Figure 17.2.

The graph shows that region r154248 accumulates more memory for each time it scans the file life.sml.

To see what happens in region r154248, we make an object profile of that region, see Figure 17.3. The object profile shows that program point pp120 continually allocates memory that is first freed when the program terminates. We now search for pp120 in the generated log files and in the log file located in the basis library folder $(SML_LIB)/basis). Among other places, we find that the program point pp120 appears in the following fragment in the file basis/Int.sml.log:

```
fun conv attop r1T pp65 [r58484s:inf] (rad, radix, i) =
  case ... of
      ...
    | _ =>
      let ...
        in $implodeCharsML(sat r58484s pp120, ...)
      end
```

So the space leak is caused by the implodeCharsML primitive function being called with region r154248 instantiated for the formal region variable r58484.

We now search for r154248 in file scan_rev1.sml.log and find the following fragment of the region flow graph:

```
readWord[r153984:inf] --r153984 atbot--> [r154248*]
toString[r59007:inf] --r59007 attop--> LETREGION[r154248:inf]
```

---

4Project kitdemo/scan_rev1.mlb.

5Unfortunately, the MLKit compiler happily resets the program point counter for each compilation of a program unit, thus, there are multiple instances of the program point pp120.
17.1. **EXAMPLE: SCANNING TEXT FILES AGAIN**

Figure 17.2: Memory is accumulated in the top two bands. The global regions r1 and r154248 hold the largest amount of memory. The graph was generated by first compiling the kitdemo/scan_rev1.mlb project with profiling enabled (option `-prof`). We also add the compiler options `-log_to_file`, `-Ppp`, `-Prfg`, and `-Ppp` for enabling printing of region flow graphs, program points, and cell-explicit expressions (redirected to log files). Then by executing `echo life.sml | run -notimer 723` and finally by typing `rp2ps -region -name 'Scanning life.sml 50 times'`.
Figure 17.3: There seems to be a space leak at program point pp120. The graph was generated by typing `rp2ps -object 154248`.
The fragment is read as follows. The formal region variable \$r59007\$ is instantiated to the region-bound region variable \$r154248\$ in a call to \$toString\$. Moreover, also the formal region variable \$r153984\$ (of function \$readWord\$) is instantiated to \$r154248\$. (The asterisks (*) denote that the node has been displayed before.)

Region flow graphs are local to each program fragment in a program. A call to a non-local region-polymorphic function introduces an edge in the region flow graph, but the graph says nothing about in which module the called function is located. Thus, it may be necessary to look in several log files to find the path from a formal region variable to an actual region variable. By inspecting the call-explicit programs found in \texttt{basis/Int.sml.log} and \texttt{kitdemo/lib.sml.log} one finds that both \$toString\$ and \$readWord\$ eventually call \$implode\$. However, \$readWord\$ is called only initially, thus, we conclude that the space leak is caused by function \$toString\$ (from the \texttt{Int} structure) being called with region \$r154248\$ instantiated for the formal region variable \$r59007\$. Indeed, by inspecting the calls to \$toString\$ in the call-explicit program found in \texttt{scan_rev1.sml.log}, we see that \$toString\$ is called with actual region \$154248\$.

The \texttt{concat} function from the initial basis catenates a list of strings. But all the strings in the argument list to \texttt{concat} are required to be in the same region. Thus, whenever a file is reported (see Figure 17.4), strings created by the \texttt{Int.toString} function are put in the region that also holds the file name for the report (which is read using the function \texttt{readWord}); and this region is non-local to the \texttt{do_it} function, which implements the main loop of the program.

One way of solving the space leak is to make a copy of \texttt{filename} at the call to \texttt{report_file} in function \texttt{scan_file}:

```ml
fun scan_file filename : (int*int) option =
    let val fd = F.openf (filename, F.O_RDONLY, F.O.flags[]) in
    let val (n, ins) = scan fd
        in Posix.IO.close fd;
        report_file (filename^"", n, ins);
        SOME (n, ins)
        end handle NotBalanced =>
            (writeln (filename ^ ": not balanced"));
            Posix.IO.close fd;
            NONE)
```
fun report_file (filename, n, ins) = 
    writeln(concat[filename, ": size = ", Int.toString n, ": comments: ", Int.toString ins, " (", 
        (Int.toString(percent(ins, n)) 
          handle _ => "-"), ", \%)\n"
    )

fun scan_file filename : (int*int) option = 
    let val fd = F.openf (filename, F.O_RDONLY, F.O.flags[]) 
    in let val (n, ins) = scan fd 
        in Posix.IO.close fd; 
        report_file (filename, n, ins); 
        SOME (n, ins) 
        end handle NotBalanced => 
            (writeln (filename ^ ": not balanced"); 
             Posix.IO.close fd; 
             NONE) 
    end handle IO.Io {name,...} => 
        (writeln (name ^ " failed."); NONE)

fun main () : unit = 
    case readWord F.stdin of 
        SOME filename => 
            let fun do_it 0 = () 
                | do_it n = (scan_file filename; do_it (n-1)) 
            in do_it 50 
            end
        | NONE => ()

Figure 17.4: Fragments of scan_rev1.sml. All the strings in the argument list to concat are put in the same region.
17.2. Compile-Time Profiling Strategy

Before compiling a program for the purpose of profiling, one must decide on a compile-time profiling strategy; see Figure 17.1. The compile-time profiling strategy directs the embedding of profiling instructions in the generated code and instructs the compiler whether to report a region flow graph.

Region profiling is enabled by passing the option `-region_profiling` (or...
simply -prof) to the MLKit compiler. If you want the MLKit to report region-annotated programs with program points, you should pass the option -print_all_program_points to the MLKit compiler together with one or more of the options -print_physical_size_inference_expression and -print_call_explicit_expression.

To make the compiler report a region flow graph, pass the option

    -print_region_flow_graph

to the MLKit compiler at compile time. The region flow graph is reported in text format.

As a running example, we use the life program. We assume that the options -prof, -print_all_program_points, and -print_region_flow_graph are passed to the MLKit compiler together with the option

    -print_call_explicit_expression

By also passing the option -log_to_file to the MLKit compiler, the MLKit generates several files, of which we have life.log (containing, among other things, the call-explicit region-annotated program with program points and the region flow graph in text layout) and the executable file run.

17.3 The Log File

In the file life.log you find the call-explicit region-annotated program with program points and the region flow graph in text layout for the life.sml source file. The region flow graph is found by searching for REGION FLOW GRAPH FOR PROFILING. The graph contains the following fragment (modified slightly to fit here):

```
cp_list[r211368:inf]
  --r211368 sat--> [*r211368*]
  --r211368 sat--> nthgen'[r211902:inf]
    --r211902 atbot--> LETREGION[r212422:inf]
    --r211902 sat--> [*r211902*]
  --r211368 atbot--> LETREGION[r212384:inf]
```

*Program: kitdemo/life.sml.*
The region flow graph is almost equivalent to the graph used by the storage mode analysis (see page [102]). In the graph, region variables are nodes and there is an edge between two nodes \( \rho \) and \( \rho' \) if \( \rho \) is a formal region parameter of a function that is applied to actual region parameter \( \rho' \). It follows that region-bound region variables are always leaf nodes.

Nodes in the graph are written in square brackets, which are labeled with the token \texttt{LETREGION} or the name of the function for which the region variable is a formal parameter. For example, the notation \texttt{cp_list[r211368:inf]} identifies the node \texttt{r211368}, which is a formal region parameter of the function \texttt{cp_list}. An asterisk inside a square bracket means that the node has been written earlier. Only the node identifier (i.e., the region variable) will then be printed. The size of the region is printed after the region variable; we use \texttt{inf} for infinite regions and \texttt{size} for finite regions of size \texttt{size} words.

Edges are written with the \texttt{from node} identifier annotated on them. The edge points to the \texttt{to node}. The fragment

\[
\texttt{cp_list[r211368:inf]}
\texttt{--r211368 sat--> [*r211368*]}
\]

is read: there is an edge from node \texttt{r211368} to node \texttt{r211368} and node \texttt{r211368} has been written earlier. From the cycle in the graph, one can conclude that \texttt{cp_list} calls itself recursively; if you look in file \texttt{life.sml}, you will find something like

\[
\texttt{fun cp_list[]} = []
| \texttt{cp_list((x,y)::rest) =}
  \texttt{let val l = cp_list rest}
  \texttt{in (x,y):: l}
\texttt{end}
\]

The region flow graph can get very complicated to read due to mutually recursive functions, which give many edges and cycles. If the graphs get too complicated, you may find help in the strongly connected component (scc) version of the graph. The scc graph is found by searching for \texttt{sccNo} in the log file. Each scc is identified by a unique \texttt{scc number}. The region variables contained in each scc is annotated on the scc node.

Consider, for example, the following fragment of the scc version of the region flow graph for the \texttt{life} program:

\[
\texttt{[sccNo 97: r211904,] --sccNo 97--> [sccNo 96: r212427,]}
\]
Here, we have a scc node (id 97) containing region variable r211904 and an edge to scc node (id 96) containing region variable r212427.

17.4 Runtime Profiling Strategy

When the source program has been compiled and linked, you have an executable file, run. Typing ./run at the command prompt will execute the program with a predefined runtime profiling strategy, which is displayed when the program is run with the -verbose option:

```
---------------Profiling-Enabled---------------
The profile timer (unix virtual timer) is turned on.
A profile tick occurs every 1th second.
Profiling data is exported to file profile.rp.
```

You can change the profiling strategy by passing command line arguments directly to the executable. The second line says that a virtual timer is used. There are three possible timers, each of which can be enabled using one of the following options:

- **-realtime** Real time.
- **-virtualtime** The execution time for the process.
- **-profiletime** The execution time for the process together with the time used in the operating system on behalf of the process.

The third line says that a *profile tick* occurs every 1 second. A profile tick is when the program stops normal execution, and memory is traversed to collect profile data. The more often a profile tick occurs the more detailed you profile (and the slower the program will run). The *time slot* (i.e., the time between to succeeding profile ticks) to use is specified by the -sec n and -microsec n options. A time slot of half a second is specified by -microsec 500000 and not by -sec 0.5.

---

7 A complete description can be found in the manual page for `getitimer`.
8 The lowest possible time slot to use is system dependent.
The fourth line says that the collected profile data is exported to the file `profile.rp`. The default file name setting can be changed with the `-file name` option.

There are several other possible command-line options; use the `-h` option or the `-help` option for details. When garbage collection is enabled, options for controlling garbage collection are also available as command-line options (see Section 16).

### 17.5 Regions Statistics

If the executable file `run` is executed with the option `-showStat` then `region statistics` is printed just before the program terminates. Region statistics includes information about the use of regions and does not depend on the specifics of the runtime profiling strategy; in fact, region statistics includes only exact, non-sampled values for the program. Assuming that `run` is the executable file generated by compiling the program `life` with profiling enabled, executing `./run -showStat` yields—just before the program terminates—the region statistics shown in Figure 17.6.

The `MALLOC` part of Figure 17.6 shows how memory is allocated from the operating system.

Each infinite region form a linked list of one or more `region pages` whose size is found in the `REGION PAGES` part. The value

| Max number of allocated pages: 25 |

multiplied by

| Size of one page: 8176 bytes |

gives

| Max space for region pages: 204400 bytes (0.2Mb) |

In the `INFINITE REGIONS` part, we see the number of calls to infinite region operations such as `allocateRegionInf` and `alloc`. The program allocates 95767 infinite regions and de-allocates 95761; the six global regions are not de-allocated before the region statistics is printed and the program terminates. The program allocates 858904 objects in infinite regions. Infinite
CHAPTER 17. REGION PROFILING

**MALLOC**

Number of calls to malloc for regions: 1
Alloc. in each malloc call: 819200 bytes
Total allocation by malloc: 819200 bytes (0.8Mb)

**REGION PAGES**

Size of one page: 8176 bytes
Max number of allocated pages: 25
Number of allocated pages now: 7
Max space for region pages: 204400 bytes (0.2Mb)

**INFINITE REGIONS**

Size of infinite region descriptor: 32 bytes
Number of calls to allocateRegionInf: 95767
Number of calls to deallocateRegionInf: 95761
Number of calls to alloc: 858904
Number of calls to resetRegion: 168758
Number of calls to deallocateRegionsUntil: 0

**ALLOCATION**

Max alloc. space in pages: 39560 bytes (0.0Mb)
  incl. prof. info: 79048 bytes (0.1Mb)
Infinite regions utilisation (79048/204400): 39%
Number of allocated large objects: 0

**STACK**

Number of calls to allocateRegionFin: 711935
Number of calls to deallocateRegionFin: 711935
Max space for finite regions: 10488 bytes (0.0Mb)
Max space for region descs: 608 bytes (0.0Mb)
Max size of stack: 61912 bytes (0.1Mb)
  incl. prof. info: 65744 bytes (0.1Mb)
  in profile tick: 0 bytes (0.0Mb)

Figure 17.6: Region statistics for the *life* program.
regions have been reset 168758 times. The `deallocateRegionsUntil` operation is called whenever an exception is raised, thus, we see that no exceptions were raised by the program.

Because objects allocated in infinite regions are not split across different region pages, it is not always possible to fill out a region page entirely. In the `ALLOCATION` part, the value

\textbf{Infinite regions utilisation (79048/204400): 39%}

shows memory utilisation for infinite regions at the moment where the program has allocated the largest amount of memory in infinite regions.

In the `STACK` part, we see that the program allocates and de-allocates the same number of finite regions. We also see that the space used for finite regions is 10488 bytes and that the total use of stack space is 61912 bytes (excluding space used to hold profiling information). The stack size values

\begin{itemize}
  \item[incl. prof. info:] 65744 bytes (0.1Mb)
  \item[in profile tick:] 0 bytes (0.0Mb)
\end{itemize}

can be used to see if it is necessary to profile with a smaller time slot, which will often lower the difference between the two values.

### 17.6 Processing the Profile Data File

The profile data-file `profile.rp` can be processed by the graph generator `rp2ps` (read: RegionProfile2PostScript) found in the `bin` directory. The graph generator is controlled by command line options.

A region profile is produced by typing

\begin{verbatim}
$ rp2ps -region
\end{verbatim}

at the command prompt. The program produces a PostScript file `region.ps` by reading profile information from the Figure 17.1. A region profile for the \texttt{life} program is shown in Figure 1.5 on page 28. The region that occupies the largest area is at the top. If there are more regions than can be shown in different colors, then the smallest regions are collected in an OTHER band at the bottom.

\footnote{The \texttt{rp2ps} program is based on a Haskell profiler written by Colin Runciman, David Wakeling and Niklas Röjemo.}
Each region is identified with a number that matches a region-bound region variable in the region-annotated program. Infinite regions end with \texttt{inf} and finite regions end with \texttt{fin}. There are also a band named \texttt{rDesc} and a band named \texttt{stack}. The \texttt{rDesc} band shows the memory used on region descriptors of infinite regions on the stack. The \texttt{stack} band shows stack usage excluding finite regions and region descriptors for infinite regions.

The vertical line marked “Maximum allocated bytes...” in Figure 1.5 is called the \textit{maximum allocation line}; it shows the maximum number of bytes allocated in regions and on the stack when the program was executed. Notice that this maximum is often lower than the sum of the maximum allocated bytes in regions and the maximum allocated bytes on the stack. The space between the maximum allocation line and the top band shows the inaccuracy of the profiling strategy. To decrease the gap, it often helps to use a smaller time slot.

The largest region shown in Figure 1.5 is \texttt{r155180}. An object profile of region \texttt{r155180} is produced by typing

\begin{verbatim}
$ rp2ps -object 212422
\end{verbatim}

at the command prompt. We obtain the object profile shown in Figure 17.7. We see that allocation point \texttt{pp15} is responsible for the largest amount of allocations in the program. The allocation point may be found in the region-annotated program resulting from compiling the \texttt{life} program (remember to enable printing of program points). In general, program points may also stem from the Basis Library (search the .log files in the directory \texttt{basis}).

The stack profile shown in Figure 17.8 shows memory usage on the stack, excluding space used by finite regions. A stack profile is generated by typing

\begin{verbatim}
$ rp2ps -stack
\end{verbatim}

at the command prompt.

### 17.7 Advanced Graphs with rp2ps

This section gives a quick overview of the more advanced options that can be passed to \texttt{rp2ps}. First of all, it is possible to name the profiles with the \texttt{-name} option. Comments are inserted on the x-axis with the \texttt{-comment} option.
Figure 17.7: The object profile shows all allocation points allocating into region r155180.
CHAPTER 17. REGION PROFILING

Figure 17.8: Memory usage on the stack excluding space for finite regions.
The profile data file may contain a large number of *samples* (the data collected by a profile tick is called a sample). By default, *rp2ps* uses only 64 samples. You can alter the setting with the `-sampleMax` option. The following two possibilities are used to sort out samples:

- `-sortBySize` The *n* (specified by `-sampleMax`) largest samples are shown.
- `-sortByTime` The *n* samples shown are equally distributed over time (default).

The `-sortBySize` option is useful if your profiles have a large gap between the top band and the maximum allocation line. If there is a large gap when using option `-sortBySize`, then it may help to profile with a smaller time slot. You can use the `-stat` option to see the number of samples in the profile data file. It is printed as *Number of ticks*:

Figure 17.9 shows the profile for the following command line:

```bash
$ rp2ps -region -sampleMax 50 -name life -comment 0.06 "A comment at time 0.06" -sortBySize
```

The graph generator recognises several options that are not mentioned here. Help on these options is obtained by typing *rp2ps* `-h` or *rp2ps* `-help` at the command prompt.
Figure 17.9: It is possible to insert comments in profile graphs.
Chapter 18

Controlling MLKit Compilation

We have already described how to compile and run single source files (Section 2.8) and MLB-files (Chapter 15). In the following sections, we give an overview of MLKit options for controlling printing and layout of intermediate forms. One useful command-line option is the \texttt{-help} option; Appendix \textsc{A} shows the output of executing \texttt{mlkit -help}.

18.1 Printing of Intermediate Forms

A series of options may be used to control printing of intermediate forms during compilation. A summary of the major phases that produce printable intermediate forms is shown in Figure 18.1. The phases are listed in the order they take place in the MLKit.

The optimiser, which rewrites a Lambda program, collects statistics about the optimisation. This statistics is printed if the option

\begin{verbatim}
-statistics_after_optimisation
\end{verbatim}

is provided.

Storage mode analysis (see Chapter 12) results in a MulExp expression, which is printed if the option \texttt{-print_storage_mode_expression} is provided. After that, region parameters for which there are only \texttt{get} effects on in the type scheme for a region polymorphic function are removed from the MulExp expression (see page 62). To see the resulting expression, turn on \texttt{-print_drop_regions_expression} or

\begin{verbatim}
-print_drop_regions_expression_with_storage_modes
\end{verbatim}
<table>
<thead>
<tr>
<th>Phase</th>
<th>Result</th>
<th>Flag(s) that Print Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elaboration</td>
<td>Lambda</td>
<td>(*)</td>
</tr>
<tr>
<td>Elim. of Poly. Eq.</td>
<td>Lambda</td>
<td>(*)</td>
</tr>
<tr>
<td>Lambda Optimiser</td>
<td>Lambda</td>
<td>-Pole</td>
</tr>
<tr>
<td>Spreading</td>
<td>RegionExp</td>
<td>(*)</td>
</tr>
<tr>
<td>Region Inference</td>
<td>RegionExp</td>
<td>(*)</td>
</tr>
<tr>
<td>Multiplicity Inference</td>
<td>MulExp</td>
<td>(*)</td>
</tr>
<tr>
<td>K-normalisation</td>
<td>MulExp</td>
<td></td>
</tr>
<tr>
<td>Storage Mode Analysis</td>
<td>MulExp</td>
<td>-Psme</td>
</tr>
<tr>
<td>Dropping of Regions</td>
<td>MulExp</td>
<td>-Pdre</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Pdresm</td>
</tr>
<tr>
<td>Physical Size Inference</td>
<td>MulExp</td>
<td>-Ppse</td>
</tr>
<tr>
<td>Call Conversion</td>
<td>MulExp</td>
<td>-Pcee</td>
</tr>
</tbody>
</table>

Figure 18.1: The table shows how different options correspond to printing different intermediate program representations. The option -debug causes all intermediate forms marked (*) to be printed. Thus, one can select phases individually or ask to have all intermediate forms printed. The phases that follow K-normalisation all work on K-normal forms, but, for readability, terms are printed as if they had not been normalised.
18.2. LAYOUT OF INTERMEDIATE FORMS

The latter flag also prints storage modes.

Physical size inference then determines the size in words of finite region variables. For instance, a finite region that will contain a pair will have physical size two words. To see the expression after physical size inference, provide the option `-print_physical_size_inference_expression`. After that, call conversion converts the MulExp expression to a call-explicit expression (see page 134). To see the result, provide the option

```
-print_call_explicit_expression
```

After that, you can inspect the code at different steps of the transformation into machine code by providing different options (use the `-help` option to see which.

18.2 Layout of Intermediate Forms

While the switches described in the previous section concern which intermediate forms to print, the switches described in this section control how the different forms are printed.

The options `-print_types`, `-print_effects`, and `-print_regions` control the printing of region-annotated types, effects, and region allocation points (e.g., `at ρ`). All eight combinations of these three flags are possible, but if `-print_effects` is turned on, it is best also to turn the two others on so that one can see where the effect variables and region variables that appear in arrow effects are bound.
Chapter 19

Calling C Functions

In this chapter, we describe how the MLKit programmer can call C functions from within Standard ML programs. The MLKit allows ML values to be passed to C functions, which again may return ML values. Not all ML values are represented as if they were C values. For instance, C strings are null-terminated arrays of characters, whereas ML strings in the MLKit are represented as a linked list of bounded sized character arrays. To allow the programmer to conveniently convert between C values and ML values, the MLKit provides conversion functions and macros for commonly used data structures.

When the MLKit calls a C function, data structures returned by the function are stored in regions that are allocated by the MLKit. For dynamically sized objects of the resulting value, such as strings and lists, regions are allocated by the MLKit and passed to the C function as additional arguments; the C function must then itself allocate space in these regions for the dynamically sized data structures. Moreover, for those parts of the resulting value for which the size can be determined statically, pointers to already allocated space are passed to the C function as additional arguments.

In both cases, the MLKit uses region inference to infer the lifetime of regions that are passed to the C function. The region inference algorithm does not analyse C functions. Instead, the MLKit inspects the ML type provided by the programmer. The MLKit assumes that functions with monomorphic types are region exomorphisms; region endomorphic functions may be described using ML polymorphism, see Section 19.6.

For every C function that is called from an ML program, the order of the additional region arguments is uniquely determined by the ML result type
of the function. This type must be constructed from lists, records, booleans, reals, strings, integers, and type variables.

When profiling is enabled, yet another additional argument, a program point, is passed to the C function. This argument provides allocation primitives with information about what points in the program contributes with allocation; see Section 19.4.

Examples of existing libraries that can be accessed from within ML programs include database client drivers (e.g., for Postgresql) and standard UNIX libraries providing functions such as `time`, `cp`, and `fork`. There are limitations to the scheme, however. First, because C and the MLKit do not share value representations, transmitting large data structures between C and ML will often involve significant copying. Second, some C libraries require the user to set up call-back functions to be executed when specific events occur. The MLKit only has very limited functionality for letting a C function call ML code.

19.1 Declaring Primitives and C Functions

The MLKit conforms in large parts to the Standard ML Basis Library. Part of the functionality found in the basis library is programmed in C and linked to the MLKit runtime system. The declarations in system dependent parts of the library use a special built-in identifier called `prim`, which is declared to have type scheme $\forall \alpha \beta. \text{string} * \alpha \to \beta$ in the initial basis. A primitive function is then declared by passing its name to `prim`. For example, the declaration

```ml
fun (s : string) ^ (s' : string) : string = 
    prim ("concatStringML", (s, s'))
```

declares string concatenation. The argument and result types are explicitly stated so as to give the primitive the correct type scheme. The string "concatStringML" denotes a C function identifier. For the example declaration, the MLKit generates a call to the C function `concatStringML` with arguments `s` and `s'`. The C function must then be present at link-time; if not, the MLKit complains.

1 Some primitives (e.g., ":=" and ":=\) are recognised and implemented in assembler by the compiler.

2 When profiling is enabled, the MLKit automatically appends the extension Prof for those functions that take regions (and thus a program point) as argument; see Section 19.4.
is to use the following scheme:

\[
\text{fun } \text{vid} \ (x_1 : \tau_1, \ldots, x_n : \tau_n) : \tau = \text{prim}(c\_func, (x_1, \ldots, x_n))
\]

The result type \( \tau \) must be of the form

\[
\tau ::= \alpha \mid \text{int} \mid \text{bool} \mid \text{unit} \\
\mid \tau_1 \ast \ldots \ast \tau_n \mid \tau \text{ list} \mid \text{real} \mid \text{string}
\]

If the result type is one of \( \alpha \), \text{int}, \text{bool}, or \text{unit} then the result value can be returned in a single register. Contrary, if the result type represents an allocated value, the C function must be told where to store the value. For any type that is either \text{real} or a non-empty tuple type, and does not occur in a list type of the result type \( \tau \), the MLKit allocates space for the value and passes a pointer to the allocated space as an additional argument to the C function. For any type representing an allocated value that is either \text{string} or occurs in a list type of the result type \( \tau \), the MLKit cannot statically determine the amount of space needed to store the value. Instead, regions are passed to the C function as additional arguments and the C function must then explicitly allocate space in these regions as needed, using a C function provided by the runtime system. The order in which these additional arguments are passed to the C function is determined by a pre-order traversal of the result type \( \tau \).

For a list type, regions are given in the order:

1. region for auxiliary pairs
2. regions for elements (if necessary)

We now give an example to show what extra arguments are passed to a C function, given the result type. In the example, we use the following (optional) naming convention: names of arguments holding addresses of pre-allocated space in regions start with \text{vAddr}, while names of arguments holding addresses of region descriptors (to be used for allocation in a region) start with \text{rAddr}.

**Example 1** Given the result type \((\text{int} \ast \text{string}) \text{ list} \ast \text{real}\), the following extra arguments are passed to the C function (in order): \text{vAddrPair}, \text{rAddrLPairs}, \text{rAddrEPairs}, \text{rAddrEStrings} and \text{vAddrReal}, see Figure[19.1].

Here \text{vAddrPair} holds an address pointing to pre-allocated storage in which the tuple of the list and the (pointer to the) real should reside. The
argument \texttt{rAddrLPairs} holds the region address for the auxiliary pairs of the list. Similarly, the arguments \texttt{rAddrEPairs} and \texttt{rAddrEStrings} hold region addresses for element pairs and strings, respectively. The argument \texttt{vAddrReal} holds the address for pre-allocated storage for the real.

Additional arguments holding pointers to pre-allocated space and infinite regions are passed to the C function prior to the ML arguments. Consider again the ML declaration

\begin{verbatim}
fun vid (x_1 : \tau_1, \ldots, x_n : \tau_n) : \tau = prim(c_func, (x_1, \ldots, x_n))
\end{verbatim}

The C function \texttt{c_func} must then be declared as

\begin{verbatim}
int c_func (int addr_1, \ldots, int addr_m, int x_1, \ldots, int x_n)
\end{verbatim}

where \texttt{addr_1}, \ldots, \texttt{addr_m} are pointers to pre-allocated space and infinite regions as described above.

### 19.2 Conversion Macros and Functions

The runtime system provides a small set of conversion macros and functions for use by C functions that need to convert between ML values and C values.
Using these conversion macros and functions for converting between representations protects you against future changes in the representation of ML values. The conversion macros and functions are declared in the header files:

```
src/Runtime/Tagging.h
src/Runtime/String.h
src/Runtime/List.h
```

### 19.2.1 Integers

There are two macros for converting between the ML representation of integers and the C representation of integers:

- `#define convertIntToC(i)`
- `#define convertIntToML(i)`

To convert an ML integer `i_ml` to a C integer (type `long int`) `i_c`, write

```
i_c = convertIntToC(i_ml);
```

To convert a C integer (type `long int`) `i_c` to an ML integer `i_ml`, write

```
i_ml = convertIntToML(i_c);
```

The macros demonstrated here are used in the examples 2, 3, and 6 in Section 19.10.

### 19.2.2 Units

The following constant in the conversion library denotes the ML representation of `()`:

```
#define mlUNIT
```

These macros are the identity maps when garbage collection is disabled.
19.2.3 Reals

An ML real is represented as a pointer into a region containing the real. To convert an ML real to a C real, we dereference the pointer. To convert a C real to an ML real, we update the memory to contain the C real. The following two macros are provided:

\[
\begin{align*}
\text{#define convertRealToC(mlReal)} \\
\text{#define convertRealToML(cReal, mlReal)}
\end{align*}
\]

Converting an ML real \( r_{\_m} \) to a C real \( r_{\_c} \) can be done with the first macro:

\[
r_{\_c} = \text{convertRealToC}(r_{\_m});
\]

Converting from a C real to an ML real (being part of the result value of the C function) is done in one or two steps depending on whether the real is part of a list or not. If the real is not in a list the memory containing the real has been allocated before the C call, see Section 19.1:

\[
\text{convertRealToML}(r_{\_c}, r_{\_m});
\]

If the ML real is part of a list element, then space must be allocated for the real before converting it. If \( r\text{Addr} \) identifies a region for the real, you write:

\[
\begin{align*}
\text{allocReal}(r\text{Addr}, r_{\_m}); \\
\text{convertRealToML}(r_{\_c}, r_{\_m});
\end{align*}
\]

These macros are used in the examples 3, 6 and 8 in Section 19.10.

19.2.4 Booleans

Four constants provide the values of true and false in ML and in C. These constants are defined by the following macros:

\[
\begin{align*}
\text{#define mlTRUE 3} \\
\text{#define mlFALSE 1} \\
\text{#define cTRUE 1} \\
\text{#define cFALSE 0}
\end{align*}
\]

\(^4\text{For historical reasons, booleans in the MLKit are tagged even when garbage collection is disabled.}\)
19.2. CONVERSION MACROS AND FUNCTIONS

Two macros are provided for converting booleans:

```c
#define convertBoolToC(i)
#define convertBoolToML(i)
```

Converting booleans is similar to converting integers:

```c
b_c = convertBoolToC(b_ml);
b_ml = convertBoolToML(b_c);
```

19.2.5 Records

Records are boxed. One macro is provided for storing and retrieving elements:

```c
#define elemRecordML(recAddr, offset)
```

An element can be retrieved from a record `rec_ml` by writing

```c
e_ml = elemRecordML(rec_ml, offset);
```

where the first element has offset 0. An element `e_ml` is stored in an ML record `rec_ml` by writing

```c
elemRecordML(rec_ml, offset) = e_ml;
```

Two specialized versions of the `elemRecordML` macro are provided for pairs:

```c
#define first(x)
#define second(x)
```

If the record is to be part of a list element then it is necessary to allocate the record before storing into it. This allocation is done with the macro

```c
#define allocRecordML(rAddr, size, vAddr)
```

where `rAddr` denotes a region (i.e., a pointer to a region descriptor), `size` is the size of the record (i.e., the number of components), and `vAddr` is a variable in which `allocRecordML` returns a pointer to storage for the record. The record is then stored, component by component, by repeatedly calling `elemRecordML` with the pointer `vAddr` as argument.

The above macros are used in examples 8, 9 and 7 in Section 19.10.
19.2.6 Strings

Strings are boxed and always allocated in infinite regions. It is possible to print an ML string by using the C function

```c
void printStringML(String str);
```

Strings are converted from ML to C and vice versa using the two C functions

```c
void convertStringToC(String mlStr, char *cStr, size_t cStrLen, int exn);
String convertStringToML(Region rAddr, char *cStr);
```

An ML string `str_ml` is converted to a C string `str_c` in already allocated storage of size `size` bytes by writing

```c
convertStringToC(ctx, str_ml, str_c, size, exn);
```

where `exn` is some ML exception value (see Section 19.3) to be raised if the ML string has size greater than `size` and `ctx` is an evaluation context obtained using the `__get_ctx` primitive.

A C string is converted to an ML string in the region denoted by `rAddr` by writing

```c
str_ml = convertStringToML(rAddr, str_c);
```

The following macro returns the size of an ML string:

```c
size_t sizeStringDefine(String str);
```

These macros are used in the examples 7 and 5 in Section 19.10.

19.2.7 Lists

Lists are always allocated in infinite regions. A list uses, as a minimum, one region for the auxiliary pairs of the list, see Figure 5.1 on page 53.

We shall now show three examples of manipulating lists. The first example traverses a list. Consider the following C function template:
19.2. **CONVERSION MACROS AND FUNCTIONS**

```c
void traverse_list(uintptr_t* ls) {
    uintptr_t elemML;
    for ( ; isCONS(ls); ls=tl(ls)) {
        elemML = hd(ls);
        /*do something with the element*/
    }
    return;
}
```

The ML list is passed to the C function in parameter `ls`. The example uses a simple loop to traverse the list. The parameter `ls` points at the first constructor in the list. Each time we have a `CONS` constructor we also have an element, see Figure 5.1. The element can be retrieved with the `hd` macro. One retrieves the tail of the list by using the `tl` macro.

The following four macros are provided in the `src/Runtime/List.h` header file:

```c
#define isNIL(x)
#define isCONS(x)
#define hd(x)
#define tl(x)
```

The next example explains how to construct a list backwards. Consider the following C function template:

```c
uintptr_t mk_list_backwards(Region pairRho) {
    uintptr_t *resList, *pair;
    makeNIL(resList);
    while (/*more elements*/) {
        ml_elem = ...;
        allocRecordML(pairRho, 2, pair);
        first(pair) = (uintptr_t) ml_elem;
        second(pair) = (uintptr_t) resList;
        makeCONS(pair, resList);
    }
    return (uintptr_t)resList;
}
```

First, we create the `NIL` constructor, which marks the end of the list. Then, each time we have an element, we allocate a pair. We store the element in
the first cell of the pair. A pointer to the list constructed so far is put in the second cell of the pair. (In this release of the MLKit, the **makeCONS** macro simply assigns its second argument the value of its first argument.) In the example, we have assumed that the elements are unboxed, thus, no regions are necessary for the elements.

The last example shows how a list can be constructed forwards. It is more clumsy to construct the list forwards because we have to return a pointer to the first element. Consider the following C function template.

```c
uintptr_t mk_list_forwards(Region pairRho) {
    uintptr_t *pair, *cons, *temp_pair, res;

    /* The first element is special because we have to return a pointer to it. */
    ml_elem = ...;
    allocRecordML(pairRho, 2, pair);
    first(pair) = (uintptr_t) ml_elem;
    makeCONS(pair, cons);
    res = (uintptr_t) cons;

    while (/*more elements*/) {
        ml_elem = ...;
        allocRecordML(pairRho, 2, temp_pair);
        first(temp_pair) = (uintptr_t) ml_elem;
        makeCONS(temp_pair, cons);
        second(pair) = (uintptr_t) cons;
        pair = temp_pair;
    }
    makeNIL(cons);
    second(pair) = (uintptr_t) cons;
    return res;
}
```

We create the **CONS** constructor and pair for the first element and return a pointer to the **CONS** constructor (the pair) as the result. We then construct the rest of the list by constructing a **CONS** constructor and a pair for each element. It is necessary to use a temporary variable for the pair (**temp_pair**) because we have to update the pair for the previous element. The second
component of the last pair contains the NIL constructor and thus denotes the end of the list.

The two macros `makeCONS` and `makeNIL` are provided in the `List.h` header file:

```c
#define makeNIL(rAddr, ptr)
#define makeCONS(rAddr, pair, ptr)
```

### 19.3 Exceptions

C functions are allowed to raise exceptions and it is possible for the ML code to handle these exceptions. A C function cannot declare exceptions locally, however. For technical reasons, we must first acquire an evaluation context, which can be obtained using the special built-in primitive `__get_ctx`:

```c
fun getCtx () : foreignptr =
  prim("__get_ctx", ())
```

Now, as an example, consider the following ML declaration:

```ml
exception Exn
fun raiseif0 (arg : int) : unit =
  prim("raiseif0", (getCtx(), arg, Exn))
```

If we want the function `raiseif0` to raise the exception value `Exn` if the argument (`arg`) is 0 then we use the function `raise_exn` provided by the runtime system, by including the header file `src/Runtime/Exception.h`. The C function `raiseif0` may be defined thus:

```c
void raiseif0(Context ctx, long i_ml, uintptr_t exn) {
    long i_c;
    i_c = convertIntToC(i_ml);
    if (i_c == 0) raise_exn(ctx, exn);
    return;
}
```

Notice that the supplied context is passed to the `raise_exn` function, which uses the context to gain access to the region stack and to the current exception handler.
Notice also that there is no need to make the function `raiseif0` return the value `mlUNIT`; in case the type of the return value is `unit` then the MLKit automatically inserts code for returning the ML value `()` after the call to the C function.

Exceptions are used in examples 6 and 7 in Section 19.10.

### 19.4 Program Points for Profiling

To support profiling, the programmer must provide special profiling versions of those C functions that allocate space in regions (i.e., that take regions as additional arguments). If profiling is enabled and at least one pointer to a region is passed to the C function then also a program point that represents the call to the C function is passed. The program point is used by the C function when allocating space in regions, as explained in Section 19.4. The program point is passed as the last argument:

\[
\text{uintptr\_t } c\_funcProf(\text{Region addr}_1, \ldots, \text{Region addr}_m, \text{uintptr\_t } x_1, \ldots, \text{uintptr\_t } x_n, \text{long pPoint})
\]

No special version of the C function is needed if it does not allocate into infinite regions; in this case, the same C function can be used both when profiling is enabled and disabled.

A program point passed to a C function is an integer; it identifies the allocation point that represents the C call in the program, see Chapter 17.

The runtime system provides special versions of various allocation macros and functions presented earlier in this chapter:

```c
#define allocRealProf(realRho, realPtr, pPoint)
#define allocRecordMLProf(rhoRec, ssize, recAddr, pPoint)
String convertStringToMLProf(Region rhoString, char *cStr, long pPoint);
```

Here is the profiling version of the C function `mk_list_backwards`:

```c
uintptr\_t
mk_list_backwardsProf(Region pairRho, long pPoint) {
    uintptr\_t *resList, *pair;
    makeNIL(resList);
```
while (/*more elements */) {
    ml_elem = ...;
    allocRecordMLProf(pairRho, 2, pair, pPoint);
    first(pair) = (uintptr_t) ml_elem;
    second(pair) = (uintptr_t) resList;
    makeCONS(pair, resList);
}
return (uintptr_t) resList;
}

The example shows that it is not difficult to make the profiling version of a
C function; use the Prof versions of the macros and use the extra argument
pPoint, appropriately. The same program point is used for all allocations in
the C function, perceiving the C function as one entity.

19.5 Storage Modes

As described in Chapter 12 on page 97 actual region parameters contain a
storage mode at runtime, if the region is infinite. A C function may check
the storage mode of an infinite region to see whether it is possible to reset the
region before allocating space in it. The header file src/Runtime/Region.h
of the runtime system provides a macro is_inf_and_atbot, which can be
used to test whether resetting is safe, assuming that the arguments to the C
function are dead.

The C function resetRegion, which is also provided by the runtime sys-
tem in the header file src/Runtime/Region.h, can be used to reset a region.
Consider again the mk_list_backwards example. If the atbot bit of the
region for the list is set, then this region can be reset prior to constructing
the list:

    uintptr_t mk_list_backwards(Region pairRho) {
        uintptr_t *resList, *pair;
        if (is_inf_and_atbot(pairRho)) resetRegion(pairRho);
        makeNIL(resList);
        ...
    }

The C programmer should be careful not to reset regions that potentially
contain live values. In particular, the C programmer must be conservative
and take into account possible region aliasing between regions holding arguments and regions holding the result. Clearly, if a region that the C function is supposed to return a result in contains part of the value argument(s) of the function, then the function should not first reset the region and then try to access the argument(s).

19.6 Endomorphisms by Polymorphism

Until now, we have seen examples only of C functions that are region endomorphic, that is, functions that, in general, write their result into regions that are different from those in which the arguments reside.

A region endomorphic function has the property that the result of calling the function is stored in the same regions that hold the arguments to the function. Region endomorphic functions are useful when the result of the function shares with parts of the arguments. Consider the C function

```c
uintptr_t select_second(uintptr_t pair) {
  return second(pair);
}
```

which selects the second component of `pair` (cast to an integer); the identifier `second` is defined in the header file `Tagging.h` by the macro definition

```c
#define second(x) (*((uintptr_t *)(x)+1))
```

Now, for the MLKit to make correct, that is safe, decisions about when to de-allocate regions, the endomorphic properties of a C function must be expressed in the region-annotated type scheme for value identifiers to which the C function is bound. The programmer can tell the MLKit about region endomorphic behavior of a C function by using type variables. For example, here is an ML declaration that binds a value identifier `second` to the C function `select_second`:

```ml
fun second(pair : 'a * 'b) : 'b =
  prim("select_second", pair)
```

---

5MLB-file: `kitdemo/select_second.mlb`. The C file `select_second.c` must be compiled (using `gcc`) to form the object file (archive) `libselect_second.a` before the project can be compiled: `mlkit -no_gc -dirlibs "." -libs "m,d1,c,select_second" select_second.mlb`. 

---
The MLKit associates the following region-annotated type scheme to the value identifier  \textit{second}:

\[
\forall \alpha_1 \alpha_2 \rho \in. (\alpha_1 \ast \alpha_2, \rho) \rightarrow \{\text{get} (\rho_3)\} \rightarrow \alpha_2
\]

Notice that the region-annotated type scheme expresses the region endomorphic behavior of the C function. That is, for any substitution \( S \), mapping \( \alpha_1 \) and \( \alpha_2 \) to region types and places, the type \( S((\alpha_1 \ast \alpha_2, \rho) \rightarrow \{\text{get} (\rho_3)\} \rightarrow \alpha_2) \) will express that the result is located in the same regions as (the second projection) of the argument.

### 19.7 Compiling and Linking

To use a set of C functions in the ML code, one must first compile the C functions into an object file. (Remember to include appropriate header files.)

As an example, the file \texttt{kitdemo/libmylib.c} holds a set of example C functions. This file is compiled into an archive (in the form of a single object file) by typing (from the shell)

\[
\$ \texttt{gcc -o libmylib.a -c libmylib.c}
\]

in the \texttt{kitdemo} directory. Now, to compile the file to work with profiling, type

\[
\$ \texttt{gcc -DPROFILING -o libmylib-p.a -c libmylib.c}
\]

The MLB-file \texttt{mylib.mlb}, which is listed in Figure 19.2, mentions the file \texttt{mylib.sml}, which declares a series of ML functions to be used in the file \texttt{test_mylib.sml}.
Once the archives have been generated, the appropriate archive can be passed to the mlkit compiler, using the options -libs and -libdirs, as follows:

```bash
$ mlkit -no_gc -o mylibtest -libdirs "." \
   -libs "m,c,dl,mylib" mylib mlb
...
$ mlkit -no_gc -prof -o mylibtest-p -libdirs "." \
   -libs "m,c,dl,mylib-p" mylib mlb
...
```

To learn more about the options -libs and -libdirs, type

```bash
$ mlkit --help
```

on the command line.

You may consult the file kitdemo/Makefile to see how one can further automate an appropriate build process.

### 19.8 Dynamic Linking

The MLKit supports dynamic linking at runtime. This is done using the dlopen and dlsym functions from the MLKit library basis/dynlink.mlb. The function dlopen opens a given library and the function dlsym associates a name with a given function in the library. If the name is already linked, the exception Fail is raised.

Using the functions dlopen and dlsym, as shown in Figure 19.3, you can call a dynamically linked library function using a primitive call to `:'.

If `:' is called with a name that has no association, the exception Match is raised.

### 19.9 Auto Conversion

For C functions that are simple, in a sense that we shall soon define, the MLKit can generate code that automatically converts representations of arguments from ML to C and representations of results from C back to ML.

Auto conversion is enabled by prefixing a @-character to the name of the C function, as in the following example:
fun isNullFP(s : foreignptr) : bool = prim("__is_null", s)
val b = Dynlib.dlopen (SOME "libcrack.so", Dynlib.NOW, false)
val _ = Dynlib.dlsym ("testdyn","FascistCheck",b)
fun fascistCheck a : string option =
  let val b : foreignptr =
    prim("@:", ("testdyn", a : string,
      "/usr/lib/cracklib_dict"))
  in if isNullFP b
    then NONE
    else SOME(prim ("fromCtoMLstring", b))
  end

Figure 19.3: Dynamic linking of the function FascistCheck from the library libcrack.so. The ML function fascistCheck calls FascistCheck with the argument (a,/usr/lib/cracklib_dict) and converts the resulting C string into an ML string. This example uses the auto conversion feature as described in the next section.

fun power_auto(base : int, n : int) : int =
  prim (@power_auto, (base, n))

The power function may then be implemented in C as follows:

long power_auto(long base, long n) {
  long p;
  for (p = 1; n > 0; --n) p = p * base;
  return p;
}

No explicit conversion is needed in the C code. Auto conversion is only supported when the arguments of the ML function are of type int or bool and when the result has type unit, int, or bool. It works also when profiling is enabled.

The example shown here is example 4 of Section 19.10; it is part of the mylib.mlb project.
19.10 Examples

Several example C functions are located in the file kitdemo/libmylib.c. The MLB-file kitdemo/mylib.mlb, which is listed in Figure 19.2 makes use of these functions.

The source file mylib.sml, which is part of the mylib.mlb project, contains the following ML declarations:

```sml
fun power(base: int, n: int) : int = 
   prim ("power", (base, n))

fun power_auto(base: int, n: int) : int = 
   prim (@power_auto", (base, n))

fun power_real (base: real, n: int) : real = 
   prim ("power_real", (base, n))

fun print_string_list (ss: string list) : unit = 
   prim ("print_string_list", ss)

exception Power
fun power_exn (base: real, n: int) : real = 
   prim ("power_exn", (base, n, Power))

exception DIR
fun dir (directory: string) : string list = 
   prim ("dir", (directory, DIR))

fun real_list () : real list =
   prim ("real_list", ())

fun change_elem (p : int*string) : string*int =
   prim ("change_elem", p)
```

The C function implementations are summarized below (see the files libmylib.c and mylib.sml in the kitdemo directory for detailed comments.)

**Example 2** The `power` function shows how to convert integers with the macros `convertIntToC` and `convertIntToML.`
Example 3 The `power_real` function shows how to convert reals with the macros `convertRealToC` and `convertRealToML`.

Example 4 The `power_auto` function shows the use of auto conversion, which allows for easy linking to certain C functions.

Example 5 The `print_string_list` example shows how to traverse a list of strings. The technique can easily be adopted to other data structures (e.g., to lists of lists of strings).

Example 6 The `power_exn` function shows how an exception can be raised from a C function.

Example 7 The `dir` function shows how a list can be constructed backwards. We use the UNIX system calls `opendir` and `readdir` to read the contents of the specified directory.

Notice also that we check the infinite regions for resetting at the start of the C function. The checks should be placed at the start of the function, otherwise not inserted at all.

If you compare the C functions `dir` and `dirProf` you may see how the function `dirProf` is modified to work with profiling.

Example 8 Function `real_list` constructs a list of reals forwards. The reals are allocated in an infinite region. It may be more convenient to construct the list backwards in the C function and then apply a list reverse function on the result list in the ML program.

Example 9 Function `change_elem` shows the use of the macro `elemRecordML`. The result type is `string*int`. The function swaps the two elements in the pair. The MLKit passes an address to pre-allocated space for the result pair, and an infinite region for the result string.

At first thought it should be enough to just swap the two arguments, and not copy the string into the string region, that is, one could write the following function:

```c
? uintptr_t
? change_elem(uintptr_t newPair, Region stringRho, uintptr_t pair) {
?     uintptr_t firstElem_ml, secondElem_ml;
?     firstElem_ml = elemRecordML(pair, 0);
```
secondElem_ml = elemRecordML(pair, 1);
elemRecordML(newPair, 0) = secondElem_ml;
elemRecordML(newPair, 1) = firstElem_ml;
return newPair;
}

This function may work sometimes but it is not safe! Region inference expects the result string to be allocated in stringRho, and may therefore de-allocate the region containing the argument string, secondElem_ml, while the string in the returned pair is still live. The safe version of change_elem is found in libmylib.c. See Section 19.6 for inspiration to how a safe non-copying swap function can be implemented.
Chapter 20

Summary of Changes

20.1 Changes Since Version 4.6.1

This section provides an overview of the main changes to the MLKit since version 4.6.1.

Simplification of the Region Type System

To simplify the region type system, region variables are no longer associated with type variables and the concept of word regions has been eliminated entirely. Instead of associating type variables with region variables, type substitutions now map type variables to region type and places.

GC Safety Fixed

A problem with garbage-collection safety was fixed and it is now properly ensured that no dangling pointers appear during evaluation, which is a necessary requirement for combining region inference and reference-tracing garbage collection. Details are described in a technical report [Els22].

20.2 Changes Since Version 4.3.0

This section provides an overview of the main changes to the MLKit since version 4.3.0.
CHAPTER 20. SUMMARY OF CHANGES

**X64 Backend**

The x86 native backend has been replaced with an x64 native backend, which uses the GNU assembler to create native machine code on x86 machines. The new backend also features intra-procedural register allocation for floating-point values. The MLKit now also features `Int64.int` as the default integer and `Word64.word` as the default word type (`Int63.int` and `Word63.word` when garbage collection is enabled).

**Hosted at Github**

The MLKit is now hosted at Github. The repository is

[https://github.com/melsman/mlkit](https://github.com/melsman/mlkit)

Bug reports should be filed by submitting a Github issue. Features and bug fixes can be submitted via Github pull requests. Comprehensive tests are executed using Github actions.

**JavaScript Backend (SMLtoJs)**

SMLtoJs is a standalone version of the MLKit that compiles to JavaScript and makes use of MLKit’s frontend and compilation infrastructure (e.g., re-compilation management). It supports large parts of the Standard ML Basis Library. SMLtoJs does not make use of region-based memory management. SMLtoJs has been used for hosting a Standard ML compiler in a web browser [Els11]. To try Standard ML in a browser, visit the site

[https://diku-dk.github.io/sml-ide/](https://diku-dk.github.io/sml-ide/)

**Generational Garbage Collection**

The non-generational pointer-tracing garbage collection technique has been augmented with a generational version (option `-gengc`), which in some cases is superior to ordinary reference-tracing garbage collection, but which may also cause additional fragmentation [EH21].
20.3. **CHANGES SINCE VERSION 4**

**Improved Basis Library Coverage**

The Standard ML Basis library coverage has been extended to support also the Unix structure, socket programming through the Socket structure, the NetHostDb structure, and the INetSock structure. With the move to the x64 architecture, the MLKit now also supports the structures Word63, Word64, Int63, and Int64.

**20.3 Changes Since Version 4**

This section provides an overview of the main changes to the MLKit since version 4, but before version 4.3.0.

**Support for Compiling ML Basis Files**

ML Basis Files allows for expressing source dependencies, exactly (as a directed acyclic graph). ML Basis Files thus provides a mechanism for programming “in the very large”.

**File-based Separate Compilation**

The MLKit now supports file-based separate compilation, based on dependencies established from ML Basis Files. The compiler serializes symbol table information to disk for each compilation unit, so that this information can be deserialized and used when compiling other compilation units.

**Updated Standard ML Basis Library**

The MLKit implementation of the Standard ML Basis Library now conforms to the specification published in [GR04].

**Untagged Pairs, Triples and References**

The MLKit now support untagged representations of heap-allocated pairs, triples, and Standard ML references, even when garbage collection is enabled.


20.4 Changes Since Version 3

This section provides an overview of the main changes to the MLKit since version 3, but before version 4.

Garbage Collection

The MLKit supports reference tracing garbage collection in combination with the region memory model. Garbage collection is supported only in the native backend version of the MLKit. To enable garbage collection, pass the option `-gc` to the MLKit compiler. Garbage collection is also possible with region profiling enabled. See Chapter 16 for more information about garbage collection with the MLKit.

X86 Backend

The HPPA backend of the MLKit version 3.0 and earlier has been replaced with an x86 native backend, which uses the GNU assembler to create native machine code on x86 machines.

Bytecode Backend

For portability, the MLKit now provides a bytecode backend and a bytecode interpreter. Which backend is used by the MLKit compiler is determined when the MLKit itself is compiled, but it is possible to have both a native version and a bytecode version of the MLKit compiler installed on the same system.

Unboxing of Function Arguments

By default, the MLKit performs a simple local unboxing analysis to figure out if a function taking a tuple as argument can be transformed into a function taking multiple arguments. Only functions that use only the individual elements of the argument tuple undergo transformation. The optimisation can be disabled by passing the option `-no_unbox_function_arguments` to the MLKit compiler.
20.5. CHANGES SINCE VERSION 2

Removal of Region Vectors

In the MLKit version 3.0 and earlier, actual region parameters were passed to a region polymorphic function in a region vector, which itself was allocated in a region. In version 4.0, actual region parameters to region polymorphic functions are passed in registers and on the stack. This simplification improves pretty printing of region annotated terms and on what function calls turn into tail calls (see Section 14.3).

20.5 Changes Since Version 2

This section provides an overview of the main changes to the MLKit since version 2.0 but before version 3.0 of the MLKit.

Modules and Separate Compilation

The most important development since Version 2 is the ability to compile Modules and the discipline of separate compilation. A distinguished feature of the way modules are compiled is that module constructs do not give rise to any code, so there is no runtime overhead in using modules [Els99b, Els99a]. See Chapter 15.

Standard ML Basis Library

The MLKit support a large portion of the Standard ML Basis Library, based on the Moscow ML version of the library. To see exactly what parts of the Standard ML Basis Library are supported, consult the MLB-file basis.mlb located in the directory basis.

Scalability

The MLKit now compiles fairly large programs, including Hafnium’s Annodomi (58,000 lines of SML) and the MLKit itself (around 80,000 lines).

New Match Compiler

The pattern compiler has been rewritten, based on Sestoft’s method [Ses96], which is also the basis of the Moscow ML match compiler.
New StatObject Module

The MLKit contains a module, \texttt{StatObject}, which implements the semantic objects of the static semantics of the Core. Originally, this was a very clean and very inefficient implementation of the Definition. In version 2 of the MLKit, \texttt{StatObject} was replaced by an imperative and efficient, but complicated module. In version 3, \texttt{StatObject} uses a clean, efficient and imperative implementation of \texttt{StatObject}. This is particularly useful for those who want to reuse the front-end of the MLKit for other purposes.

Unboxed Representation of Lists

List constructors are now represented unboxed, that is, the least significant bits of a list value is used to distinguish between \texttt{nil} and a pointer to a pair (::) holding the head and the tail of the list. Thus, a list takes up only one region (for the auxiliary pairs) plus any regions for the elements of the list. Consult Chapter 5 for details.
Bibliography


[EH95] Martin Elsman and Niels Hallenberg. An optimizing backend for the ML Kit using a stack of regions. Student Project 95-7-8, Department of Computer Science, University of Copenhagen (DIKU), July 5 1995.


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of Computer Science, University of Copenhagen (DIKU), June 14 1996.


[TT94] Mads Tofte and Jean-Pierre Talpin. Implementing the call-by-value lambda-calculus using a stack of regions. In Proceedings of

Appendix A

Command-Line Options

This appendix shows the output of executing `mlkit -help`, where mlkit is the version of the MLKit compiler that uses the x64 native backend.

MLKit v4.7.2 ( - ) [X64 Backend]

Usage: mlkit [OPTION]... [file.sml | file.sig | file.mlb]

Options:

--version, -v, -V
    Print version information and exit.

--help
    Print extended help information and exit.

--help S
    Print help information about an option and exit.

--man
    Print man-page and exit.

--SML_LIB S (You_did_not_set_path_to_install_dir)
    Installation directory for the MLKit standard library.
    For normal execution you should not modify this value.
    However, if you wish to use the MLKit with an altered
runtime system you can update this setting and the system will try to link to a runtime system found in the specified install directory.

--aggresive_opt, -aopt (on)
Enable aggressive optimisations, including constant folding and aggressive inlining. These optimisations are not guaranteed to be region safe. Turning off garbage collection automatically turns off this option.

--assembler S, -as S (as -q)
This option specifies the assembler used.
On Linux the default is 'as --64'. On macOS, the default is 'as -q'.

--c_compiler S, -cc S (gcc -Wl,-no_pie,-stack_size,0x10000000,-stack_addr,0xc0000000)
This option specifies which C compiler is used for linking. When linking with c++ libraries, 'g++' is the linker you want.
On Linux the default is 'gcc -no-pie', whereas on macOS, the default is 'gcc -Wl,-no_pie,-stack_size,0x10000000,-stack_addr,0xc0000000'.

--chat, -verbose (off)
Print a message for each compilation step in the compiler.

--comments_in_asmcode (off)
Insert comments in assembler code.

--compile_only, -c (off)
Compile only. Suppresses generation of executable

--compiler_timings, -timings (off)
Show compiler timings for each compilation phase.

--contract (on)
Contract is responsible for inlining, specialization,
elimination of dead code, and much else (Lambda Expression Optimiser).

--contract_regions, -cr (off)
When this option is enabled, identically typed regions bound by the same letregion construct are unified. Moreover, region parameters to non-exported functions are trimmed whenever possible.

--cross_module_opt, -cross_opt (on)
Enable cross-module optimisation including inlining of small functions and specialisation of small recursive functions. Which optimisations are performed across modules is controlled by individual optimisation flags.

--dangling_pointers, -dangle (off)
When this option is disabled, dangling pointers are avoided by forcing values captured in closures to live at-least as long as the closure itself. So as to make garbage collection sound, this option is disabled by default when garbage collection is enabled.

--dangling_pointers_statistics (off)
When enabled, the compiler prints statistics about the number of times strengthening of the region typing rules (to avoid dangling pointers during evaluation) effects the target program. This flag is useful only when the flag -gc or -no_dangle is enabled.

--debug_compiler, -debug (off)
Print intermediate forms of a program during compilation.

--debug_linking (off)
Debug linking of target code by showing which object files are linked together.
APPENDIX A. COMMAND-LINE OPTIONS

--debug_man_enrich
Show information about why a program unit need be recompiled. A program unit (or a functor body) is recompiled if either (a) the program unit is modified, or (b) information about an identifier for which the program unit depends upon has changed.

--debug_which_at
Debug storage mode analysis.

--delete_target_files
Delete assembler files produced by the compiler. If you disable this flag, you can inspect the assembler code produced by the compiler.

--disable_atbot_analysis
Disable storage mode analysis. That is, turn all allocation directives into attop.

--disable_flow_var
Disable optimised compilation of control-flow code, such as conditional expressions.

--eliminate_explicit_records
Eliminate bindings of explicit records only used for selections. Transform

\[
\text{let } r = (e_1, \ldots, e_n) \text{ in ... } \#i \ r \ldots \ #j \ r \ldots
\]

into

\[
\text{let } x_1 = e_1 \text{ in ... let } x_n = e_n \text{ in ... } x_i \ldots x_j \ldots
\]

(Lambda Expression Optimiser).

--explicit_regions, -er
Support programming with explicit regions.

--export_basis_js, -ebjs
When this flag is enabled, SmlToJs writes pickled bases to file.eb.js files to be read by
js-client.

---garbage_collection, -gc
Enable garbage collection. When enabled, regions are garbage collected during execution of the program. When garbage collection is enabled, all values are tagged. Due to region inference, for most programs, the garbage collector is invoked less often than for systems based only on garbage collection. When garbage collection is enabled, introduction of dangling pointers are avoided by forcing values captured in closures to live at-least as long as the closure. Moreover, enabling garbage collection implicitly enables the preservation of tail calls (see the option ‘‘preserve_tail_calls’’.)

---gdb_support, -g
When enabled, the compiler passes the option --g to ‘as’ (The GNU Assembler) and preserves the generated assembler files (.s files). Passing the --g option to ‘as’ makes it possible to step through the generated program using gdb (The GNU Debugger).

---generational_garbage_collection, -gengc
Enable generational garbage collection. Same as option garbage collection except that two generations are used for each region.

---import_basislib, -basislib
Import Basis Library automatically in your projects. If you wish to make use of the Standard ML Basis Library in your projects, this option should be turned on, unless you wish to import the Basis Library manually in your projects.

---inline_names S
Names of functions that should always be inlined if possible, no matter the setting of the flag --maximum_inline_size.
--libdirs S
This option controls where ld looks for archives. The format is a comma-separated list of directories; see the -libs entry. The default is the empty list; thus 'ld' will look for libraries in only the system specific default directories. The directories are passed to 'ld' using the -L option.

--libs S (m,c,dl)
For accessing a foreign function residing in an archive named libNAME.a from Standard ML code (using prim), you need to add 'NAME' to this comma-separated list. Notice that an object file (with extension '.o') is an archive if it is renamed to have extension '.a'. You may need to use the -libdirs option for specifying directories for which ld should look for library archives. The libraries are passed to 'ld' using the -l option.

--link_code S, -link S
Link-files to be linked together to form an executable.

--link_time_dead_code_elimination, -ltdce (on)
Link time dead code elimination.

--load_basis_files S, -load S
Basis files to be loaded before compilation proper.

--log_to_file (off)
Log to files instead of stdout.

--maximum_inline_size N (70)
Functions smaller than this size (counted in abstract
syntax tree nodes) are inlined, even if they are used more than once. Functions that are used only once are always inlined.

`--maximum_specialise_size N` (200)  
Curried functions smaller than this size (counted in abstract syntax tree nodes) are specialised if all applications of the function within its own body are applied to its formal argument, even if they are used more than once. Functions that are used only once are specialised no matter their size. See also the option `--specialize_recursive_functions`.

`--minimize_fixs` (on)  
Minimize fix constructs (Lambda Expression Optimiser).

`--mlb-subdir S`  
For ensuring that the smart recompilation scheme is not reusing target-code compiled with different settings, a string provided with the mlb-subdir option can ensure the use of consistently generated code. This option is useful, in particular, when performing benchmarking.

`--mlb_path_maps S, -mlb-path-map S`  
ML Basis path map files to be used.

`--namebase S` (dummyBase)  
Name base to enforce unique names when compiling mlb-files.

`--no_aggresive_opt, -no_aopt`  
Opposite of `--aggresive_opt, -aopt`.

`--no_contract`  
Opposite of `--contract`.

`--no_cross_module_opt, -no_cross_opt`
APPENDIX A. COMMAND-LINE OPTIONS

Opposite of --cross_module_opt, -cross_opt.

--no_dangling_pointers, -no_dangle
Opposite of --dangling_pointers, -dangle.

--no_delete_target_files
Opposite of --delete_target_files.

--no_eliminate_explicit_records
Opposite of --eliminate_explicit_records.

--no_garbage_collection, -no_gc
Opposite of --garbage_collection, -gc.

--no_generational_garbage_collection, -no_gengc
Opposite of --generational_garbage_collection, -gengc.

--no_import_basislib, -no_basislib
Opposite of --import_basislib, -basislib.

--no_link_time_dead_code_elimination, -no_ltdce
Opposite of --link_time_dead_code_elimination, -ltdce.

--no_minimize_fixs
Opposite of --minimize_fixs.

--no_optimiser, -no_opt
Opposite of --optimiser, -opt.

--no_preserve_tail_calls, -no_ptc
Opposite of --preserve_tail_calls, -ptc.

--no_print_regions, -no_Pregions
Opposite of --print_regions, -Pregions.

--no_raggedRight
Opposite of --raggedRight.
--no_region_inference, -no_ri
   Opposite of --region_inference, -ri.

--no_register_allocation
   Opposite of --register_allocation.

--no_repository, -no_rep
   Opposite of --repository, -rep.

--no_specialize_recursive_functions
   Opposite of --specialize_recursive_functions.

--no_type_check_lambda
   Opposite of --type_check_lambda.

--no_unbox_function_arguments
   Opposite of --unbox_function_arguments.

--no_unbox_reals
   Opposite of --unbox_reals.

--no_uncurrying, -no_uncurry
   Opposite of --uncurrying, -uncurry.

--optimiser, -opt (on)
   Enable optimisation of intermediate language code
   (Lambda Expressions). Which optimisations are performed
   is controlled by individual flags. The optimisations
   include function inlining, function specialisation,
   fix-minimization, unboxing of function arguments, and
   elimination of unnecessary record constructions.

--output S, -o S (run)
   The name of the executable file generated by
   the Kit.

--parallel_compilation N, -j N (1)
   The maximum number of parallel processes used
for compilation.

--parallelism, -par (off)
   When enabled, the runtime system supports parallel threads.

--parallelism_alloc_unprotected, -par0 (off)
   When enabled, allocation into a region is not guaranteed to be atomic.

--preserve_tail_calls, -ptc (on)
   Avoid the wrapping of letregion constructs around tail calls. Turning on garbage collection automatically turns on this option.

--print_K_normal_forms (off)
   Print Region Expressions in K-Normal Form. Applicable, only after storage mode analysis has been applied.

--print_all_program_points, -Ppp (off)
   Print all program points when printing physical size inference expressions.

--print_bit_vectors (off)

--print_calc_offset_program (off)

--print_call_explicit_expression, -Pcee (off)
   Print Region Expression with call annotations.

--print_clos_conv_program, -Pccp (off)
   Print Region Expression after closure conversion.

--print_closed_export_bases, -Pceb (off)
   Controls printing of closed export bases.

--print_drop_regions_expression, -Pdre (off)
   Print Region Expression after dropping word regions and
regions arguments with only get-effects.

--print_drop_regions_expression_with_storage_modes, -Pdresm (off)
Print Region Expression after dropping word regions and
regions arguments with only get-effects. Also print
atbot and attop annotations resulting from storage mode
analysis.

--print_effects, -Peffects (off)
Print effects in region types.

--print_excon_name (off)
Print underlying unique name when printing excons.

--print_export_bases, -Peb (off)
Controls printing of export bases.

--print_fetch_and_flush_program (off)
Print program with instructions for activation
record fetching and flushing.

--print_linearised_program (off)
Print a linearised representation of the
program unit.

--print_lvar_name (off)
Print underlying unique name when printing lvars.

--print_normalized_program (off)
Print Region Expression after K-normalisation.

--print_opt_lambda_expression, -Pole (off)
Print Lambda Expression after optimisation.

--print_physical_size_inference_expression, -Ppse (off)
Print Region Expression after physical size inference.

--print_post_elab_ast, -Ppeast (off)
Print ast after elaboration.

--print_region_flow_graph, -Prfg (off)
   Print a region flow graph for the program fragment
   and generate a .vcg-file, which can be viewed using
   the xvcg program.

--print_region_spreaded_program, -Prsp (off)
   Print region-spreaded program.

--print_region_static_env0, -Prse0 (off)
   Print imported region static environment prior to
   region inference.

--print_regions, -Pregions (on)
   Print region variables in types and expressions.

--print_register_allocated_program (off)

--print_rho_levels (off)
   Print levels of region and effect variables in types and
   intermediate forms. Levels control quantification of
   region and effect variables.

--print_rho_types (off)
   Print region types of region variables in types and
   intermediate forms. Possible region types are:
   p  Type of regions containing pairs.
   a  Type of regions containing arrays.
   r  Type of regions containing references.
   t  Type of regions containing triples.
   s  Type of regions containing strings.
   T  Type of regions containing other than the above
       kinds of values.

--print_simplified_program (off)
   Print simplified program after register
   allocation.
--print_storage_mode_expression, -Psme (off)
  Print Region Expression after storage mode analysis

--print_type_name_stamps, -Ptypestamps (off)
  Print type name stamps and their attributes in types and expressions.

--print_types, -Ptypes (off)
  Print types when printing intermediate forms. For Lambda Expressions, ordinary ML types are printed, whereas for Region Expressions, region types are printed.

--quotation, -quot (off)
  Enable support for quotations and anti-quotations.
  When enabled, the datatype
  
  datatype 'a frag = QUOTE of string 
    | ANTIQUOTE 'a

  is available in the initial environment. Moreover, values of this datatype may be constructed using the quotation/antiquote syntax:
  
  val s = "world"
  val a : string frag list = 'hello ^s - goodbye'

--raggedRight (on)
  Use ragged right margin in pretty-printing of expressions and types.

--recompile BASISLIB, -scratch (off)
  Recompile basis library from scratch. This option is useful together with other options that control code generation.

--region_inference, -ri (on)
  With this flag disabled, all values are allocated in global regions.

--region_profiling, -prof (off)
Enable region profiling. Object code stemming from compiling a program with region profiling enabled is instrumented with profiling information. When a program compiled with region profiling enabled is run, the program produces a profile file run.rp, which can then be read by the profiling tool rp2ps that comes with the MLKit to produce profiling graphs of various forms.

--regionvar N (1)
Uses the provided number as the id of the first generated region variable. When this option is provided together with the -c option, a file f.rv is written in the MLB/ directory with two numbers in it: the id for the first region variable generated and the id for the last region variable generated. The number given must be greater than any id for a top-level region/effect variable (>9).

--register_allocation (on)
Perform register allocation. Without register allocation enabled, programs run somewhat slower—but they run and you save about 15 percent on compile time.

--report_file_sig, -sig (off)
Report signatures for each file read.

--repository, -rep (on)
Use in-memory repository to avoid unnecessary recompilation. This flag should be disabled when compiling mlb-files, which make use of the file system as a repository.

--safeLinkTimeElimination (off)
Treat this module as a library in the sense that the code can be eliminated if it is not used, even if the code has side effects.

--specialize_recursive_functions (on)
Specialise recursive functions. Use the option maximum_specialise_size to control which functions are specialised. If this flag is on, functions that are applied only once are specialised, no matter the setting of maximum_specialise_size (Lambda Expression Optimiser).

--statistics_after_optimisation  (off)
Report optimisation statistics after optimisation of Lambda Expression.

--strip  (off)
If enabled, the Kit strips the generated executable.

--tag_pairs  (off)
Use a tagged representation of pairs for garbage collection. Garbage collection works fine with a tag-free representation of pairs, so this option is here for measurement purposes.

--tag_values, -tag  (on)
Enable tagging of values as used when garbage collection is enabled for implementing pointer traversal.

--type_check_lambda  (on)
Type check lambda expression prior to performing region inference. Type checking is very fast and for normal use you should not disable this option. Type checking intermediate forms is very powerful for eliminating bugs in the compiler.

--unbox_function_arguments  (on)
Unbox arguments to fix-bound functions, for which the argument ‘a’ is used only in contexts ‘#i a’. All call sites are transformed to match the new function (Lambda Expression Optimiser).

--unbox_reals  (on)
Unbox real values and computations on real values inside functions. Real values stored in data structures and passed to functions are still boxed.

--uncurrying, -uncurry (on)
Enable uncurrying of curried functions. The uncurried function takes its arguments unboxed in registers or on the stack. For partial applications and non-application uses of the function, appropriate eta-expansions are applied.

--values_64bit (on)
Support 64-bit values. Should be enabled for backends supporting 64-bit integers and words.

--warn_on_escaping_puts (off)
Enable the compiler to issue a warning whenever a region type scheme contains a put effect on a region that is not quantified.

--warn_on_parallel_puts (off)
Enable the compiler to issue a warning whenever a par-construct is passed functions with intersecting put effects.

--width N, -w N (100)
Column width used when pretty printing intermediate code.
Index

\[\begin{align*}
!, & 79 \\
\mu, & \text{see type and place} \\
* , & 48 \\
+ , & 48 \\
- , & 48 \\
\text{.mlb}, & 143 \\
/, & 48 \\
:: , & 61 \\
:= , & 79 \\
; , & 70 \\
< , & 48 \\
\leq , & 48 \\
\geq , & 48 \\
= , & 48, 50 \\
> , & 48 \\
\geq , & 48 \\
[ ] , & 58 \\
\text{~}, & 49 \\
\text{MLB-file}, & 143 \\
\sim , & 48 \\
\text{abs}, & 48 \\
\text{alignment}, & 49 \\
\text{allocation point}, & 96 \\
\text{allocReal}, & 190 \\
\text{allocRealProf}, & 196 \\
\text{allocRecordML}, & 191 \\
\text{allocRecordMLProf}, & 196 \\
\text{application extrusion}, & 74 \\
\text{arguments} \\
\quad \text{multiple}, & 35, 43, 58, 208 \\
\text{arity}, & 85 \\
\text{arrow effect}, & 54, 122 \\
\quad \text{auxiliary}, & 86 \\
\text{at}, & 41, 49, 52, 96 \\
\text{atbot}, & 96 \\
\text{attop}, & 96, 100 \\
\text{auto conversion}, & 200 \\
\text{auxiliary pairs}, & 53 \\
\text{backend} \\
\quad \text{bytecode}, & 12, 33, 208 \\
\quad \text{hppa}, & 208 \\
\quad \text{native}, & 12, 33 \\
\quad \text{x64}, & 206, 215 \\
\quad \text{x86}, & 206, 208 \\
\text{Basis Library}, & 47, 207 \\
\text{batch compilation}, & 36 \\
\text{block structure}, & 70 \\
\text{bottom of region}, & 96 \\
\text{boxing}, & 34, 43, 80 \\
\text{Br}, & 85 \\
\text{bug report}, & 206 \\
\text{C}, & 17 \\
\quad \text{calling}, & 36, 185 \\
\text{C examples}, & 202 \\
\text{call conversion}, & 134, 183 \\
\text{call-back function}, & 186 \\
\text{ceil}, & 48 \\
\text{cFALSE}, & 190 \\
\text{changeElem}, & 203 \\
\end{align*}\]
INDEX

changes
  since version 2, 209
  since version 3, 208
  since version 4, 207
  since version 4.3.0, 205
  since version 4.6.1, 205

chr, 49
  -comment option, 176
comments
  in MLB-file, 145
concat, 49
convertBoolToC, 191
convertBoolToML, 191
convertIntToC, 189
convertIntToML, 189
convertRealToC, 190
convertRealToML, 190
convertStringToC, 192
convertStringToML, 192
convertStringToMLProf, 196
cp, 64
cTRUE, 190
datatype, 85
description
  local, 70
  sequential, 69
  value, 69
decomp, 52
dir, 203
div, 48
dlopen
dlopen, 200
dlslm
  dlslm, 200
double copying, 26
dynamic linking, 200
effect, 41 44

atomic, 44
  atomic, definition, 125
definition, 125
  latent, 122
effect arity, 86
effect variable, 54 122
  bound, 59
elemRecordML, 191
endomorphism, see region endomorphism
environment, 69
  -eps option, 114
equality
  monomorphic, 45
  polymorphic, 45
evaluation context, 195
example programs, see kitdemo directory
exception, 91
  generative, 91
  handling, 93
  raising, 92
exception, 91
  exception constructor, 91
  exception declaration, 91
  exception name, 91
  exception value, 92
    constructed, 92
    nullary, 92
exn, 92
exomorphism, see region exomorphism
expression
  call-explicit, 183

-file option, 173
first, 191
floor, 48
INDEX

fn, 121
fnjmp, 137
foldl, 139
forceResetting, 20, 95, 109
frame, 42
free, 18
free list, 31
fromto, 58
fun, 122
funcall, 136
function, 57
  Curried, 101, 122
  first-order, 57
  higher-order, 121
  region polymorphic, 209
function arguments
  multiple, 35, 45, 58, 208
function call
  call-explicit, 134
function type
  region-annotated, 122
functor, 149
garbage collection, 10, 19, 207, 208
generational, 206
get, 44, 62
  Github
    issue, 206
    repository, 206
hd, 94, 193
heap, 17, 20
hello world, 37
  -help option, 173, 179
  -help option to mlkit, 181, 215
implode, 49
initial basis, 47, 50
Int31 structure, 47
Int32 structure, 47
Int63 structure, 47
Int64 structure, 47
integer, 47
is_inf_and_atbot, 197
isCONS, 193
isNIL, 193
iterator, 108
JavaScript
  SMLtoJs, 206
  JavaScript backend, 9
K-normalisation, 98
kitdemo directory, 37
Lambda, 34, 41, 181
lambda abstraction, 121, 122
Lambda optimiser, 35
layout control, 183
length of list, 108
let, 70
let floating, 73
let region, 33, 43, 45, 71, 93, 100
Lf, 85
libmylib.c, 202
Life
  game of, 23
  life, 170
lifetime, 70, 73
  shortening, 73
list, 51, 210
  auxiliary pairs, 53
  region-annotated type, 53
tail, 53
live variable analysis, see variable local, 70, 103
makeCONS, 195
INDEX

makeNIL, 195
malloc, 18
matching, 146
merge sort, 64, 110
-microsec option, 172
mk_list_backwards, 193
mk_list_forwards, 194
ML Basis File, 143
ML Basis Files, 11, 207
MLB-file, 36
  comments in, 145
  grammar, 143
MLB-files, 145
mlFALSE, 190
MLKit
  Version 1, 12
  Version 2, 12
  Version 3, 12
  Version 4.7.2, 10
mlkit
  executable, 36
mlTRUE, 190
mlUNIT, 189
mod, 48
msort, 64, 110
MulExp, 35, 181
multiple function arguments, 35, 45, 58, 208
multiplicity, 32
multiplicity analysis, 35, 44
mylib.sml, 202
-name option, 176
nil, 51
not, 50
nthgen, 20
o, 138
-object option, 176
object profile, 161, 176
open declaration, 148
openIn, 78
openOut, 78
optimisation
  statistics, 181
  optimiser, 76
ord, 49
pair
  auxiliary, 52, 86, 96
path
  absolute, 145
  relative, 145
pattern matching, 52
physical size inference, 183
power, 202
power_auto, 203
power_exn, 203
power_real, 203
prim, 186
-print_all_program_points, 170
-print_call_explicit_expression, 134
-print_drop_regions_expression, 181
-print_drop_regions_expression_with_storage_mode, 98
-print_effects, 183
-print_physical_size_inference_expression, 170, 183
-print_region_flow_graph, 170
-print_regions, 183
-print_storage_mode_expression, 181
-print_types, 183
print_string_list, 203
Printing of intermediate forms, 181
printStringML, 192
profile
  object, 161
  region, 161
  stack, 162
profile data file, 175
profile strategy
  compile-time, 169
  options, 172
  runtime, 172
profile tick, 172
-profiletime option, 172
profiling
  time slot, 172
program point, 161
program transformation, 73
projects
  compiling, 64
  running, 64
put, 44, 61
put-effect
  escaping, 76
rDesc, see region descriptor
real, 48
real_list, 203
-realtime option, 172
recompilation, 145
  cut-off, 146
record, 41
  runtime representation of, 45
  unboxed, 45
recursion
  polymorphic, 63
ref, 79
reference, 79
  local, 83
retrieving an MLB-file, 143
RegionExp, 32, 35
region, 18
  auxiliary, 96
  de-allocation, 44, 123
  dropping of, 62
  global, 92, 93
  resetting, 20, 95
-region option, 175
region, 44
  region aliasing, 102
  region arity, 86
  region descriptor, 31, 103
  region endomorphism, 26, 63, 103, 106, 108, 185
  region exomorphism, 63, 73, 185
  region flow graph, 102, 162
  region inference, 20
  ground rule, 71
  region name, 32, 97
  region pages, 31, 173
  region parameter, 59
  actual, 57, 58
  formal, 57, 58, 103
  region polymorphism, 57, 66, 96, 122, 135
  region profile, 161, 175
  region profiling, 22
-region_profiling, 169
region size, 19, 31, 183
  finite, 31
  infinite, 31
region stack, 18
region statistics, 173
region variable, 33, 41
  auxiliary, 86
region vector
  removed, 209
region-annotated type, 42
region-annotated type scheme, 59
INDEX

tl, 94, 193
top of region, 96
traverse_list, 192
tree, 85
trunc, 48
tuple, see record
type
  region-annotated, 41, 53, 81, 122, 125
type scheme
  region-annotated, 59
type scheme with place
  region-annotated, 60
type with place, 42

unit, 45
untagging, 207

val, 122
value
  boxed, 34, 43
  unboxed, 34, 43
value declaration, see declaration
value representation, 207
variable
  lambda-bound, 121
  locally live, 98
  own, 83
  -virtualtime option, 172

web site, 12
Word31 structure, 48
Word32 structure, 48
Word63 structure, 48
Word64 structure, 48
Word8 structure, 48
### Global Regions

<table>
<thead>
<tr>
<th>Region</th>
<th>Type Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>r1</td>
<td>Holds values of type <code>top</code>, that is, records, exceptions, and closures.</td>
</tr>
<tr>
<td>r2</td>
<td>Holds values of type <code>bot</code>. Because no values has type <code>bot</code>, this region contains no values. Region variables with region type <code>bot</code> are used with so-called explicit regions, which are not covered in this report.</td>
</tr>
<tr>
<td>r3</td>
<td>Holds values of type <code>string</code>.</td>
</tr>
<tr>
<td>r4</td>
<td>Holds values of type $\tau_1 \times \tau_2$, for any types $\tau_1$ and $\tau_2$.</td>
</tr>
<tr>
<td>r5</td>
<td>Holds values of type $\tau$ <code>array</code> and $\tau$ <code>vector</code>, for any type $\tau$.</td>
</tr>
<tr>
<td>r6</td>
<td>Holds values of type $\tau$ <code>ref</code>, for any type $\tau$.</td>
</tr>
<tr>
<td>r7</td>
<td>Holds values of $\tau_1 \times \tau_2 \times \tau_3$, for any types $\tau_1$, $\tau_2$, and $\tau_3$.</td>
</tr>
</tbody>
</table>