Abstract. Objective Caml is a famous dialect of the ML family languages. It is well-known for its performance as a compiled programming language, notably thanks to its incremental generational automatic memory collection. However, for historical reasons, the latter was built for monocore processors. One consequence is the runtime library assumes there is effectively no more than one thread running at a time, which allows many optimisations for monocore architectures: very few thread mutexes are sufficient to prevent more than a single thread to run at a time. This makes memory allocation and collection quite easier. The way it was built makes it not possible to take advantage of now widespread multicore CPU architectures. This paper presents our feedback on removing Objective Caml’s garbage collector and designing a “Stop-The-World Stop&Copy” garbage collector to permit threads to take advantage of multicore architectures.

Key words: Objective Caml, Garbage Collector, Parallel Threads, Multicore

1 Introduction

History shows Caml dialects are generally designed for monoprocessor architectures. This is actual for Caml (the ancestor), Caml-Light (on the Zinc machine), Caml-Special-Light and Objective Caml (O’Caml) (1). For the last 25 years, the gain had been more important by optimizing the sequential runtime libraries or compiler schemes than by modifying them to target multiprocessors (2). One of the main success factors of O’Caml was its efficient implementation from Inria[7].

Currently, O’Caml’s implementation of threads is only a way to express concurrent algorithms in the language since threads cannot actually be executed in parallel. But the recent rise of cheap multicore architectures – an average machine can run two or more threads in parallel – has created the need to use them. The O’Caml community would like concurrent programs to compute faster on these architectures, as it is already the case for many other languages.
One way to achieve this goal is to add POSIX-like threads, which can actually run in parallel, to Objective Caml. Since the current runtime library has not been designed with this model in mind, we need to provide a compatible alternative runtime library, in particular a new garbage collector, a new allocator and a new thread library.

The idea of modifying O’Caml’s runtime library has already been used to certify safety-critical software development tools by the French company Esterel Technologies for its new SCADE SUITE 6™ qualifiable code generator (KCG) on O’Caml [9]. An O’Caml program such as KCG uses two kinds of library code: the O’Caml standard library, written mainly in O’Caml, and the runtime library, written in C and assembly language. Both are shipped with the O’Caml compiler and linked with the final executable. The difficulty of specifying and testing such low-level library code led to adapt and simplify it. The bulk of the modifications of the runtime library was to remove unessential features according to the coding standard of KCG. Most of the work consisted in simplifying the efficient but complex memory management subsystem. Esterel Technologies successfully replaced it by a plain Stop&Copy collector with a reasonable loss of performance [8].

One difficulty of this replacement was due to the tight coupling of the garbage collector with the O’Caml compiler (in-memory representation of values and entry points of the memory manager).

In this paper we propose to follow this way to exchange the garbage collection runtime library and thread library to be compliant with POSIX threads that allow to use parallel threads in a shared-memory concurrency model. One main constraint is to modify the least possible the O’Caml code generator and to focus modifications only for the runtime library. For that, we design a simple garbage collector with a unique copying, stop-the-world, compacting algorithm. In this case, the garbage collector is sequential and threads can be parallel with a synchronized mechanism when a garbage collector is called. This step allows to emphasize improved performances for real parallel programs in O’Caml. Once the garbage collector interface and thread library are defined using this assumption, it is possible to implement other garbage collector algorithms[6] (3).

We have completely experimented this way, and the modifications of the Inria distribution are available as a patch called OC4MC (4)

1 We use the notation (n) to reference external links; see section Links at the end of the document for full URLs.
tion 5 describes the synchronization mechanism of our garbage collector. Section 6 details the implementation of our garbage collector algorithm. Section 7 presents some O'Caml benchmarks for multicore and comments results. Section 8 discusses related works while section 9 outlines our future work.

2 O'Caml's runtime library

O'Caml's high performance is partially due to its runtime library, which is written in C, plus a per-architecture assembly file that allows O'Caml calls and C calls to live together. Its original garbage collector allows a very fast allocation.

2.1 Garbage Collection

O'Caml has a two-generation garbage collector, derived from [3]. To allocate a value in the young generation heap, there are two possibilities: whether there is enough space, in which case a pointer is decremented by the size of the allocation, or there is not enough space, in which case the Stop&Copy garbage collector is triggered. The Stop&Copy part of O'Caml's garbage collection consists of copying the useful values of the young heap to the old heap. The latter is cleaned with an incremental Mark&Sweep&Compact algorithm, which consists of marking the values to sweep the useless ones, and sometimes compact the heap to take back the empty wholes left after value sweeping.

Thence O'Caml provides a particularly efficient allocation, with a Stop&Copy part that is fast because the young heap is small. We also have the possibility to program acceptable user interfaces as the old generation is cleaned incrementally so that we should never wait too long for the garbage collection.

2.2 Foreign function interface

For each supported architecture, there is an assembly interface to allow C function calls and O'Caml function calls to live together. Those files also contain fast memory allocation code and exception mechanism code. One should not ignore those files when modifying the runtime library design.

2.3 Thread library

O'Caml supports concurrency through:

- A POSIX threads-like low-level shared memory model, including mutexes and conditions.
- A higher level model based on Concurrent ML [10], implemented over the low-level thread library.

We focus on the low-level thread library, in particular its implementation and interaction with the runtime library.
2.4 Thread library implementation

or how threads are scheduled to run sequentially

POSIX model threads, the simple case Current thread library is useful to write concurrent programs. It provides a set of functions which match POSIX thread library functions for the C language. But will not allow threads to run simultaneously. Indeed, they share a mutex that prevents parallel memory allocations. Then to start the Stop&Copy garbage collection, there is only a single thread to stop. As functional programs tend to allocate a lot (of small values), it is generally reliable to schedule the threads on allocation, which is the mechanism that is used in O'Caml. However, scheduling at each and every allocation may cost too much, so a tick-counting thread is launched to measure the time the current thread has been running.

Blocking operation case Operations such as I/O operations (e.g. listen on a socket) or locking operations (e.g. Mutex.lock) may block a thread for a long time. During this, the thread cannot access the heap anyway as it is blocked, so it should be safe to allow other threads to run. A mechanism allows to declare such operations (“enter/leave blocking section”) so that when they occur, the scheduler will detach the thread during the time of its blocking operation and allow another thread to run. At the end of a blocking operation, the thread is attached back to the scheduler.

Non allocating threads A thread that never allocates memory, without ever invoking a blocking operation, may prevent the scheduler to trigger, and may block the whole program. It is assumed that such programs do not occur in practice, and if it ever might occur then the programmer should use Thread.yield.

3 Replacing O’Caml’s garbage collector: The Esterel Technologies experiment

Civil avionics software certification authorities assess standard software engineering rules for safety-critical software development. Such software dysfunction may have lethal consequences to their users (flight commands, railway traffic lights, etc). The DO-178B standard defines all the constraints ruling the aircraft software development. Code development as it is recognized by certification authorities follows the traditional V-Model dear to the software engineering industry. Traceability during each step of the development process is mandatory.

For Scade 6, Esterel Technologies decided to use O'Caml [8], which is very well suited for writing compilers, but quite outstanding in a very conservative domain such as civil avionics, even though DO-178B encourage the use of the best language for a given project. Classical language in this field is C, or subsets of C++ or Ada. Taking a new path meant demonstrating the compatibility
between DO-178B and O’Caml, by showing the process was under control (e.g. generated code is as expected, runtime library is predictable). To do so, Esterel Technologies decided not to use the object layer nor experimental features of O’Caml. While the standard library was welcome as fully documented and unit tested, the runtime library was not usable as such. Indeed, to make it more understandable, it was partially rewritten, in particular the garbage collection. The incremental two-generation garbage collector was much too complex to certify, and so was replaced by a simple one-generation Stop&Copy garbage collector. This allowed to dramatically decrease the number of lines of code and to make it easy to document (125 lines of C instead of 1200, for the garbage collector).

This experiment showed it was feasible to replace some relatively big parts of the runtime library. We supposed giving parallel-capable concurrent threads to O’Caml was feasible as well. Section 4 details this issue.

How to replace the garbage collector  Basically, to replace O’Caml’s garbage collector, the process consists of the following steps

1. regrouping the garbage collector global variables (essentially heap pointers),
2. providing get and set functions over them and use them,
3. and replacing the allocation functions and the collection code.

However, this works only if the new garbage collector still prevents simultaneous threads. Indeed, some global variables used in the runtime library makes parallel threads unsafe, as they may use the same temporary variable simultaneously. We address this issue in the next sections.

4 Runtime library reentrance and parallel threads

In the current runtime library source code, threading primitives are already separated from core functionality. However, the core assumes that threading primitives allow only one thread to run at a time. In fact, this source code separation has only been made to provide several implementations of threads (over POSIX, Win32, etc.), but does not permit to change the threading model. In this section, we exhibit the main problems preventing the runtime reentrance and how we solved them.

Execution context  A first problem is the program context being stored in global variables in the core module. For this to work in presence of threads, current threading module implementations use

– a global lock preventing threads to run in parallel,
– and a context save/restore mechanism in per-thread context objects when switching between threads.

Our solution for threads to access their execution contexts in parallel is to leave the threading module handle the context. Global variables accesses in the core module are replaced by calls to context accessors from the threading module.
**Global variables** Along with the execution context, other global variables exist. For these, we have to distinguish between three kinds of use:

1. Temporary (i.e. that does not need to be saved on thread switch) thread local data is stored in global variables: we used either the same solution as the one for the execution context or more lightweight solution like adding function parameters
2. Shared data: we use a global lock mechanism provided by the threading module
3. Performance-critical shared data: memory management structures for which we had to implement a new parallel-compliant memory manager.

**Memory management structures** There are three main memory management structures.

1. Heaps which depend on the garbage collection algorithm we will use and will be described later
2. Global roots: we used global locks
3. Local roots which are local to threads and contain pointers to O'Caml stack segment boundaries and to O'Caml values in C stack segments. The local roots are stored in the per-thread structure and as we described earlier can be updated concurrently (foreign function interface is untouched) However, the garbage collector must have access to all roots (globals and locals) which can't be writable by other threads during a collection. We had to implement a synchronisation mechanism to be sure, no thread is able to update its roots during a collection. This mechanism will be detailed in the following section.

**Interface between the core and threads** To sum up, the core and threading modules are now interfaced as follows:

- The threading module defines a way to register thread-local data. When the core accesses such data, it must pass through the associated accessors. In our implementation, these accessors perform direct accesses to per-thread structures. A sequential implementation (like OCaml's current one) could simply use global variables.
- For global data, the threading module defines a global lock mechanism. In our parallel implementation, we use a mutex lock.
- The mechanism is generic, however, for performance reasons, we provide a way to redefine manually some critical functions, possibly in assembly.

5 A garbage collector for parallel threads

5.1 Stopping the World

To run a collection, the garbage collector has to know the exact state of all memory management structures (including the local roots). The heap has to
be inaccessible for every other thread. Before a collection, the collector has to stop every running thread, namely: stop the world. Moreover, this mechanism has to stop the threads while their local roots are updated and exact. One of our main constraints is to keep the O'Caml compiler unchanged. However, due to the current compiler, the only moment where the local roots of a thread are exact is at an allocation. Thus, there is no other choice than to stop the threads during an allocation. Besides, this is the way the current sequential implementation behaves as the collector can only be triggered after a failed allocation while every thread is stopped (every thread being stopped during an allocation by the scheduler).

![Fig. 1. Stop & Copy](image)

- **Running thread**
- **Thread doing GC**
- **Paused thread**
- **Failed allocation**
- **Successful allocation**
- **Suspended allocation**

Fig. 5.1 describes the stop the world mechanism implemented, with three threads.

(a) Each thread may allocate until thread 2 fails an allocation, which means the need of a collection.
(b) Then, every other running thread will stop on the next allocation (ensuring the correctness of its local roots).
(c) Every thread stopped, the garbage collector runs.
(d) Each thread resumes its pre-collection behaviour starting by the allocation which made it stop.

As in the original implementation we use the enter/leave blocking section mechanism (described section 2.3) to allow blocking operation without preventing the stop of the world. Stopping the world allows the implementation of a sequential garbage collector.

### 5.2 Interface between thread library and garbage collector

To use various garbage collectors with different thread library implementations, we had to define clearly the interactions between the two.

As the core runtime library, the garbage collector uses accessors provided by the thread library. We also added primitives to iterate over threads so that the garbage collector does not have to know how thread-local data are stored.
On its side, the garbage collector defines primitives that has to be used by the thread library implementation to ensure that the system is in a correct state. For example, the garbage collector has to be notified when a thread has been paused. Indeed, a garbage collector must not wait for paused threads when stopping the world, and has to prevent them to be resumed before the collection has ended.

6 Our garbage collector

For a language as O'Caml, it is very important to have a very low cost allocation mechanism for small objects. O'Caml's current allocator dedicates a small (young) heap to small objects. This heap is a contiguous memory segment with a cursor indicating the end of the used zone, as shown in Fig. 2.

![Allocation in OCaml's small heap](image)

Thus, allocating is simply decreasing the cursor, testing if it has not crossed the limit, and returning the new cursor as the pointer to the newly allocated block. Of course, in presence of concurrent access to the heap variables, this is not possible. Moreover, adding a lock mechanism around the allocation would be too costly.

We will now describe our (fairly simple) memory management solution, which provides fast allocation for small objects, but allows several threads to allocate at the same time.

6.1 Heap structures

We shall first present the structure of our heap. A graphical representation is shown in Fig. 3.

**Local heaps** Each thread has a small heap using the same cursor mechanism as O'Caml's small heap. These small heaps are called pages, in a page table. Hence, threads can allocate small objects in their own pages simultaneously safely. When a thread has filled its page, it takes a new page in the table, in mutual exclusion with others.
Shared heap For bigger objects, a big shared heap is used. Each allocation requires a lock. Its size grows on demand.

6.2 Collection algorithm

Partial collection When no page is available during a page request, a partial collection is triggered. The thread which encountered the allocation failure stops the world and performs itself the collection while other threads are paused. It uses a Stop&Copy algorithm to flush alive values from the entire page table into the shared heap. The pages are then reinitialized and reassigned. This algorithm is graphically represented by Fig. 4.

Full collection When the allocation of a big object fails or when there is not enough space to flush the pages into the shared heap, a full collection is performed. The world is stopped as for the partial collection. A Stop&Copy algo-
rithm is used to copy all alive values in a fresh shared heap. The old shared heap is then dismissed and the pages are reinitialized and reassigned.

6.3 Optimisations and limitations

For performance reasons, we had to use macros (or inline functions) and link statically the three parts described above. This does not hinder the clear separation we have shown at source level, but means that the garbage collector cannot be changed at run or load time. Moreover, to achieve good performance, even if a generic version calling the C function of the garbage collector can be used, writing an assembly version of the allocator using the garbage collector structures was necessary to obtain best performance.

7 Benchmarks

Our performance benchmarks were made on a Parallels (software for virtualization) Virtual Machine running the Guest machine on a Host machine described as follows:

- the Host is a Mac Pro running Mac OS X.5 Leopard. The hardware hosts two quad-core CPUs (Xeon 2.8 GHz, without hyperthreading) which makes a total of 8 cores. The memory speed is 800 MHz and its capacity is $2 \times 2$ GB (4GB in dual channel), and the bus speed is double (1.6 GHz). The number of cores determines the number of possible parallel threads. The memory speed is mandatory since with multicores, it easily becomes too low because it is shared between cores.
- the Guest is a Debian with a 64-bit Linux kernel (2.6.26), with 7 cores activated, which allow 7 threads to actually run in parallel.

Programs on the Guest are tested while Host’s other tasks are idle.

Since there was very little hope of taking advantage of multicore by programming threads in O’Caml, there are very few existing benchmarks. Thus we distinguish two types of programs:

- the classic Caml benchmarks, such as Knuth-Bendix (KB), which are computed several times within threads,
- some programs written for the occasion, such as the sieve of Eratosthenes which is written in two very different paradigms, which are written with concurrency (and possibly parallelism) in mind.

Then, some programs will use a number of concurrent threads lesser or proportional to the available number of cores, and other programs use a great number of concurrent threads.

Our benchmarks consist of the following programs:

- programs with a fixed number of threads
• **sieve**: the sieve of Eratosthenes. It starts with a big allocation of a Boolean matrix. Each cell represents an integer. Then each thread removes all multiples of uncomputed integers. We ran the tests with integers between 2 and 300000.

• **matmult**: a simple matrix multiplication. The main loop is parallelized each thread computing its own lines of the final matrix. Matrix multiplication naive algorithm has a $O(n^3)$ complexity which means that the ratio of computation over allocation is very high. For our benchmarks we multiplied $1000 \times 1000$ matrixes.

• **life**: the classical game of life: a cellular automaton. It’s an imperative object oriented program. It generates a universe (a board) where initially three cells are alive. Each thread manages a section of this universe updating its cells at each step of the program. At the end of a step the main thread awaits for the other threads to end their calculation before allocating a new updated board and discard the old board. For our benchmarks we limited the universe to a $200 \times 200$ board.

– programs with more threads than number of cores

• **sieve in CML-style**: $n$ successive integers are passed through non-prime-number filtering channels. The first filter removes all multiples of 2. For each filter, when the first passing number is found (which is a prime number), a new filter initiates to filter its multiples. At the end, each created filter corresponds to a created thread and to a prime number. We ran the tests with integers between 2 and 9000, which creates about 1100 parallel threads.

<table>
<thead>
<tr>
<th></th>
<th>O’Caml</th>
<th>OC4MC</th>
</tr>
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<tbody>
<tr>
<td><strong>SIEVE</strong> speedup</td>
<td>60s</td>
<td>64s</td>
</tr>
<tr>
<td></td>
<td>1.06</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>6.4</td>
<td>7.11</td>
</tr>
<tr>
<td><strong>MATMULT</strong> speedup</td>
<td>15.5s</td>
<td>18.2s</td>
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<tr>
<td></td>
<td>1.17</td>
<td>1</td>
</tr>
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<td></td>
<td>1.92</td>
<td>3.88</td>
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<td></td>
<td>7.28</td>
<td></td>
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<tr>
<td><strong>LIFE</strong> speedup</td>
<td>24.3</td>
<td>26.5s</td>
</tr>
<tr>
<td></td>
<td>1.09</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>1.82</td>
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**Fig. 5.** Benchmarks for little number of threads

<table>
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<tr>
<th>O’Caml</th>
<th>OC4MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIEVE CML-STYLE</td>
<td>89s</td>
</tr>
</tbody>
</table>

**Fig. 6.** Benchmarks for great number of threads
7.1 Comparison with O’Caml

For most sequential programs, our alternative runtime library will provide predictable yet acceptable loss of performance, because for sequential programs, our garbage collector is particularly naive comparing to O’Caml’s. It is also with no surprise that loss of performance is higher with programs that intensively allocate short-life small data. In this case, multithreading may as much allow a gain of performance as a loss of performance, depending on how memory is used: multithreading may increase or decrease cache miss.

However, as Fig. 5 shows, OC4MC may also provide speedup. Indeed, with sieve and matmult show that the speedup can be close to the number of cores, while life shows that the speedup is actual even though limited, probably due to memory speed limitation as it is a program that allocate a lot of small data.

Fig.6 shows that thread intensive programs may gain speedup thanks to switching-cost limitation, even with heavy structures. Plus, we may gain performance with existing programs written without parallelism but concurrency in mind. However, we shall not forget that shared-memory concurrent programming is hard, and adding parallelism for better performance does not ease the task as computation may actually run in parallel which makes debugging even harder.

Eventually, with a relatively simple garbage collector (which offers space for optimizations and improvements), OC4MC brings and shows interesting performance compared to O’Caml when run on multicore architectures, by allowing threads to allocate memory (and compute) in parallel.

8 Related works

There have been many attempts to give multicore support for typed functional languages, whether by adapting runtime libraries or by giving language extensions for parallel programming, or both.

[11] presents runtime support for multicores in parallel Haskell. Parallelism is explicit by using a “par” combinator, allowing the computation of its first parameter by a task (“spark”) manager at anytime while the evaluation continues. This runtime uses a parallel garbage collector and different optimization techniques are presented in the paper.

Manticore [4] is a SML-based functional language providing two new features: CML’s thread mechanism (first-class synchronous communication), and parallel structures (e.g. arrays) for data parallelism. Its two-generation garbage collector works with a per-thread heap without backward pointers and a shared heap. Each thread may collect on its own local heap. If collection fails, then a global garbage collector is triggered to copy from local heaps to shared heap.

Other approaches have introduced basic parallel computation mechanisms. CoThreads (5) for O’Caml introduces communication between processes which may run on different processors, with the same interface as O’Caml thread library. There is currently an attempt to give multicore support for MLton/SML
by implementing low-level threads with additional higher level abstractions. F# (which combines the functional and imperative core of Caml and the object-oriented model of C#, for .NET) provides an interface to .NET CLR's thread system. Two other levels of abstraction complete this low level layer for concurrent programming: message-passing and asynchronous workflow.

In the same vein, OC4MC's low level threading mechanism allows to build higher level abstractions for efficient and expressive parallel programming. For instance, the Event module (O'Caml's module to offer CML features) is built upon that layer. Following this, we can hope to use our work to allow existing parallel programming systems built upon O'Caml to take advantage of multicore architectures. We can cite CamlP3l [2] (skeleton programming: map, pipe, ...), Objective Caml-Flight [1] (data parallelism), and BSML [5] (data parallelism and cost model).

9 Future works and conclusion

The experiment was successful since we effectively produced an adaptation of O'Caml for current multicore architectures showing promising performance results.

However, the strict guidelines we chose to follow, while founded, made this project take a lot of time and restrained our possibilities. For instance, compiler modifications have been kept lightweight for we hope they could be included as options in the standard distribution.

With less limitations, OC4MC would lead to even better results. For instance, we have in mind some more intrusive modifications to the compiler:

- Use of local heaps without backward pointers by exporting at runtime the non-mutability property of constructed types, and thus have local garbage collections without the need to stop everyone.
- Insert checkpoints in the code so that the stop-the-world mechanism could be more responsive and work even for non allocating threads
- or dump more compiling information in the executable about the state of the roots during execution to be able to stop the world at anytime, for example with POSIX signals.

As a result, OC4MC provides a runtime-level experiment platform to develop new threading models or garbage collectors. It also brings the possibility to design language-level concurrency abstractions over its parallel shared memory low-level thread library.

Acknowledgements

We thank Jane Street Capital for choosing this project as an OCaml Summer Project 2008 and for the associated financial participation.
Links

(1) The Caml Language
   http://caml.inria.fr

(2) A brief history of Caml
   http://www.pps.jussieu.fr/~cousinea/Caml/caml%5Fhistory.html

(3) Richard Jones’ Garbage Collection Page
   http://www.cs.kent.ac.uk/people/staff/rej/gc.html

(4) OC4MC distribution
    http://www.orts.com:8480/ocmc/web/

(5) CoThreads
    http://www.pps.jussieu.fr/~li/software/

(6) Multicore MLton
    http://www.cs.cmu.edu/~spoons/parallel/

(7) F#

(8) OCamlP3l
    http://camlp3l.inria.fr/eng.htm

(9) Objective Caml-Flight
    http://www-april.inria.fr/~chaillou/Public/Dev/nocf/

(10) BSML (Bulk Synchronous Parallel ML)
     http://frederic.loulergue.eu/research/bsmlib/bsml-0.4beta.html

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