Embedded SML using the MLton compiler

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Abstract
In this extended abstract we present our current work on leveraging Standard ML for developing embedded and real-time systems. Specifically we detail our experiences in modifying MLton, a whole program, optimizing compiler for Standard ML, for use in such contexts. We focus primarily on the language runtime, re-working the threading subsystem and garbage collector, as well as necessary changes for integrating MLton generated programs into a light weight operating system kernel. We compare and contrast these changes to our previous work on extending MLton for multi-core systems, which focused around achieving scalability.

1. Introduction
With the resurgence of popularity of functional programming, practitioners have begun re-examining usage of functional programming languages for embedded and real-time systems. Specifically we detail our experiences in modifying MLton, a whole program, optimizing compiler for Standard ML, for use in such contexts. We focus primarily on the language runtime, re-working the threading subsystem and garbage collector, as well as necessary changes for integrating MLton generated programs into a light weight operating system kernel. We compare and contrast these changes to our previous work on extending MLton for multi-core systems, which focused around achieving scalability.

2. Threaded programming in MLton
MLton is an open-source, whole-program, optimizing SML compiler that generates very efficient executables. MLton has a number of features that are well suited for embedded systems. MLton uses aggressive whole program optimizations for improving both performance as well as memory utilization. MLton provides the capability of generating c-code, making cross compilation for a different architecture other than the host architecture relatively easy. MLton provides a concurrent, but not parallel, threading model with support for communication between threads either over shared memory of through message passing abstractions.

MLton created threads are green threads that are multiplexed over a single OS level thread. MLton’s thread API is well suited for implementing user defined schedulers, including preemptive and cooperative threading models as well as Concurrent ML [14] and Asynchronous CML [20]. A thread in MLton is a lightweight data structure that represents a paused computation. Threads contain the currently saved execution state of the program, namely the call stack. When a thread is paused, a copy of its current stack is saved and when it is switched to, the stack is restored. MLton also provides a logical ready queue from which the next runnable thread is accessed by the scheduler. This is a regular FIFO queue with no notion of priority, however the structure is implicit, relying on continuation chaining and is embedded in the thread switching code itself. This means that there is no single data structure that governs threads nor is there an explicit scheduler. Threading and concurrency libraries (e.g. CML and AML) built on top of the MLton threading primitives, therefore, typically introduce their own threading primitives, scheduler, policy, as well as structures for managing ready, suspended, and blocked threads.

3. Adapting for OS Threads
Most embedded boards today have more than one core and this might make highly scalable implementations like MultiMLton a preferred choice for embedded use. Such systems, more often than not, go with thread local heaps which have additional read/write barriers to deal with and overheads associated with global synchronization for a global GC. Although MultiMLton uses techniques such as procrastination (delaying writes that would cause eviction to the global heap) and cleanliness (copying of mutable state to avoid sharing of state) [15] to reduce some of these overheads, the true potential of these multicore optimizations are evident when the underlying architecture has 16 or more cores. On the contrary systems like MLton are highly optimized to run on single core machines and we would like to utilize this know how to build a shared heap implementation and give it the ability to spread out across more than one core if needed. This model, we feel, is closer to the current state of embedded boards.

The first step to having a threading model that supports OS-level concurrency is to split the single thread of execution over multiple OS-level threads. We need to identify and separate the execution
states of each of the OS-level threads. MLton keeps track of the
state of the system using the GC_STATE structure. This structure
has numerous fields that store the current position of frontier, cur-
current executing green thread, current StackTop/StackBottom among
others and all these values are accessed at any time by offsetting
a pointer to this structure. The decision to use one single struc-
ture for storing all the global state was to make the access really
fast by caching the entire structure on a register. When there is a
single thread of execution, there is no need to worry about con-
current access to the GC_STATE and thus the integrity of the state
is maintained. Introducing multiple threads of execution brings in a
plethora of changes including the necessity to differentiate between
the thread of execution to which the value being stored belongs.
For example, the GC_STATE must now store the StackTop of all the
executing OS threads. Needless to say, threads must also have con-
trolled access to the shared fields in this structure.

As we alluded above, MLton has a concept of green threads,
and we are adding OS threads. The GC_thread structure includes a
pointer to the thread’s stack. When MLton’s thread library wants to
switch to a new thread, it calls into the runtime and the pointer to the
thread structure is copied into GC_STATE->currentThread and the
GC_STATE stack related fields are updated with values derived
from GC_thread->stack. Execution then can resume in the newly
restored green thread.

In MultiMLton, our previous design centered around making
GC_STATE an array, with each array element corresponding to a
POSIX thread pinned to a processor core. Multiple GC_STATEs
are imperative to MultiMLton as each processor core has its own lo-
cal heap, and it would be faster to access the execution state of the
thread pinned to that core if it were cached in a register local to that
core. Any shared state could be relayed using messages between the
threads. In RTMLton, we’ve decided to keep GC_STATE as a single
structure, but implement arrays within it where appropriate. This
allows us to be somewhat more optimal when it comes to mem-
ory utilization – an important consideration when targeting em-


3.1 Concurrent GC

To implement concurrent GC, it is necessary to have the garbage
collector on its own thread so that it can work independently. But
this is a difficult task as in MLton, the GC is very tightly coupled
with the main thread of execution. Not only does MLton insert
pre-calculated GC checkpoints in the compiled code, it also uses
the GC to grow the SML call stack. Multi-core implementations of
SML like Multi-MLton take a different route in handling this
separation. They use a per thread heap and thus have a per thread
GC which stays coupled to the execution thread. Multiple heaps
may pose other complexities (like read/write barrier overheads,
global synchronization) in a multi-threaded system, which is why
we seek to implement this system on a shared heap. A shared heap
implementation is easier but brings us back to the difficult task of
pulling out the GC onto a separate thread. In doing so, we need to
make sure each thread is responsible for growing its own stack and
only invokes the GC when it needs more space on the heap.

As a result of having the garbage collector on a separate thread
and by virtue of this implementation being on a single shared heap,
we need to ensure that the other threads in the system do not
interfere with the GC when it is either scanning or collecting the
heap. Other threads working on the heap must be paused before
allowing the GC to run but we must also ensure that it is safe to
pause these threads when we do so. This is necessary because
MLton stores temporary variables on the stack and if the GC were
to run before the stack frame is fully refilled, the results would be
unpredictable. MLton also will write into a newly created stack
frame before finalizing and recording the size of the frame. Without
the identification of safe points to pause the threads, the heap will
be in an inconsistent state that is not conducive to a GC.

Fortunately, MLton identifies these safe points for us, namely
GC safe points. GC safe points in MLton are points in code where
it is safe for the thread running the code to pause allowing the GC
to run. We can use these safe points in our multi-threaded system
to identify points where it can be safe for us to pause the threads
and thereby allow the GC thread to continue its execution.

Although GC safe points are pre-identified for us, the code gen-
erated by the compiler assumes a single threaded model and so we
found problematic constructs such as global variables and reliance
on caching important pointers in registers for performance. In or-
der to move MLton to a multi-threaded architecture, we needed to
rework these architectural decisions. As discussed above, MLton
tracks a considerable amount of global state using the GC_STATE
structure so we must refactor this structure, in particular, to make
it thread-aware. MLton also uses additional global state, outside of
GC_STATE structure, to implement critical functionality.

For example, MLton caches the frontier pointer in a register.
This naturally leads to unpredictable behavior on multi-core as
multiple threads attempt to move the frontier during allocations.
In terms of global variables, MLton emits C code that mimics
machine code and registers. For example, the C code in Listing[4]
shows MLton comparing a value in the global GC state to the top
of the current stack. The result of that comparison is temporarily
saved to a global C variable (via the G macro) until it can be
operated on by the BNZ macro. Listing[5] shows how the G macro
expands to reference a globally declared array. In a multi-threaded
environment, we must address the use of global variables in these
instances, or the compiler must identify these instructions as a
critical section and place a barrier around them. We elected to
accept the higher memory cost of per-thread global variables versus
the higher performance cost of barriers. Listing[6] shows how we
have the compiler add another dimension to the array, allowing us
to isolate the global to a specific thread (where TID represents a
zero-relative integer ID unique to each thread).

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Listing 1. Use of global variables
G(Word32, 0) = CPointerLit
(O(CPointer, GCState, 40), StackTop);
BNZ(G(Word32, 0), L_8);

Listing 2. Expansion of global variables
GlobalWord32[0] = CPointerLit
(O(CPointer, GCState, 40), StackTop);
BNZ(GlobalWord32[0], L_8);

Listing 3. MT tolerant global variables
GlobalWord32[TID][0] = CPointerLit
(O(CPointer, GCState, 40), StackTop);
BNZ(GlobalWord32[TID][0], L_8);

4. RTEMS support

RTEMS is a real-time operating system that can be run in an
emulator, like QEMU, on commodity hardware such as a laptop, or
on purpose-built hardware such as a LEON3 board. Since MLton is able to emit C code, it was natural to attempt to cross-compile that code using RTEMS.

An interesting feature of RTEMS is that resources such as memory size, maximum stack size, number of threads, device driver support, and so on, are specified at compile time. This is interesting because it directly supports the construction of predictable software by specifying the precise characteristics of the underlying OS. The compiler will then produce a bootable binary file that contains the embedded application as well as the OS. An interesting area of research that we are pursuing is tighter integration of the compiler optimization passes with RTEMS. For example, by enhancing the Static Single Assignment (SSA) optimization pass to recognize things such as maximum thread utilization or worst case memory utilization, we can drive better automation of the RTEMS build process.

Given MLton’s flexible integration with an installed C-compiler, we were able to modify MLton’s build environment to be aware of the availability of the RTEMS cross compiler. We then needed to identify system calls that were not available in RTEMS so that we could eliminate them from the emitted C code or substitute alternatives. This included some memory management calls such as mmemunmap as well as all networking specific functions. Next we needed to deal with MLton’s auto-identification of system constants. Similar to autoconf, MLton will probe the system for various system-specific constants (such as IO constants, POSIX return codes, etc) that can then be referenced from SML code. However, two challenges occurred. First, RTEMS did not provide any networking modules, so the constants related to socket operations need to be suppressed. The second challenge is that the constants identification program needs to be compiled for RTEMS and run within an emulator in order to capture all of the system specific constants which are then used in later stages of the MLton build process. We ran the constants gathering stage of the compilation in QEMU and then stored the output to a file. During the build process, we skip the constants stage and instead copy our RTEMS specific file into the build tree.

Acknowledgments

This research is primarily funded by the National Science Foundation, under grant number CNS-1405614.

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