Adding Real-time Capabilities to a SML Compiler

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ABSTRACT

There has been much recent interest in adopting functional and reactive programming for use in real-time system design. Moving toward a more declarative methodology for developing real-time systems purports to improve the fidelity of software. To study the benefits of functional and reactive programming for real-time systems, real-time aware functional compilers and language runtimes are required. In this paper we examine the necessary changes to a modern Standard ML compiler, MLton, to provide basic support for real-time execution. We detail our current progress in modifying MLton with a threading model that supports priorities, a chunked object model to support real-time garbage collection, and low level modification to execute on top of a real-time operating system. We present preliminary numbers and our work in progress prototype, which is able to boot ML programs compiled with MLton on x86 machines.

1. INTRODUCTION

Recent work on functional reactive programming has once again spurred interest in examining the usage of functional and declarative languages for main stream real-time system design and programming [2, 6, 17, 20]. Functional programming, much like the mantra of real-time Java, provides a type-safe vehicle for real-time system implementation that by nature of the language structure itself prevents common errors and bugs, like buffer under/over flow and null pointer dereference, from being expressed. Programmers can thus produce higher fidelity code with lower programmer effort. Additionally, functional programming languages are typically easier to analyze statically than their object oriented counter parts, and significantly easier than C. As such, they purport to reduce time and effort from a validation and verification perspective.

As the research community explores new programming models that leverage the benefits of functional and reactive programming, there is an increasing need to examine the addition of real-time capabilities to functional language runtimes. Additionally, classic optimization strategies that most compilers for functional programming languages leverage to achieve performance need to be revisited and adapted for *predictable* execution.

In this paper we present a work in progress system that examines what mechanisms must be in the language runtime to facilitate the development of functional, real-time systems. Specifically we investigate what changes need to be made to MLton [8], a modern SML compiler, in order to add real-time capabilities. This includes an overhaul of the threading system to support fixed priority based scheduling, a new chunked object model for predictable allocation and non moving real-time garbage collection, as well as bindings for a real-time OS for embedded deployment. We leverage our previous experience with Multi-MLton [15, 16] and the Fiji real-time virtual machine [9] in guiding our modifications to MLton. Our changes sit below the MLton library level, providing building blocks to explore new programming models. We present preliminary performance numbers, indicating the viability of our prototype. Our prototype supports embedded execution on x86 architectures and is publicly available for download at: `https://github.com/UBMLtonGroup`.

2. MLTON OVERVIEW

MLton [8, 21] is a whole-program optimizing compiler for SML 97. MLton's leverages whole-program optimization using a simply-typed first-order intermediate language. There are numerous issues that arise when translating SML into a simply-typed IL. First, how does one represent SML modules and functors, since these typically require much more complicated type systems? MLton's answer: defunctorize the program [12]. This transformation turns an SML program with modules into an equivalent one without modules by duplicating each functor at every application and eliminating structures by renaming variables. Second, how does one represent SML's polymorphic types and polymorphic functions? MLton's answer: monomorphise the program [19]. This transformation eliminates polymorphism from an SML program by duplicating each polymorphic datatype and function at every type at which it is instantiated. Third, how does one represent SML's higher-order functions? MLton's answer: defunctionalize the program. This transformation replaces higher-order functions with data structures to represent them and first-order functions to apply them; the resulting IL is Static Single Assignment form. Because each of the above transformations requires matching a functor, function definition, or type definition with all possible uses, MLton must be a whole-program compiler. MLton's whole-program compilation strategy has a number of implications. Most importantly, MLton's use of defunctorization means that the placement of code in modules has no effect on performance. In fact, it has no effect on the generated code whatsoever. Modules are purely for the benefit of the programmer in structuring code. Also, because MLton duplicates functors at each use, no run-time penalty is incurred for abstracting a module into a functor. The benefits of monomorphisation are similar. Thus, with MLton, a programmer does not suffer the time and space penalties from an extra level of indirection in a list of doubles just because the compiler needs a uniform representation of lists.

We believe that the MLton approach is beneficial for real-time programming as it yields very efficient code, both in time and space. MLton's whole program optimization strategy provides us with precise low-level information about object layouts and sizes, which can be leveraged to optimize existing real-time garbage collection approaches proposed for real-time Java. MLton is easily adaptable to an embedded workflow, by having MLton emit ANSI-C code and then cross compiling using specialized C cross-compilers provided by most real-time OS vendors. Unfortunately, MLton was not designed with real-time applications in mind. Specifically, MLton's threading model and GCs are neither priority aware nor predictable. In the following sub-sections we discuss MLton's internals and their implication on real-time execution.

2.1 Threading

MLton provides a concurrent, but not parallel, threading model. As such, 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 [11]. 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 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. Threading libraries build on top of the MLton thread primitives typically leverage a thread queue data structure (*e.g.* CML).

One of the main prerequisites of a real-time programming language is a threading model consisting of an analyzable scheduling mechanism as well as a scheduling algorithm. MLton's implementation of threading does involve the underlying operating system in any way. The absence of direct relation between a MLton green thread and an OS level thread, results in the operating system seeing only one MLton thread and schedules it for execution along with other non-MLton threads in the system. All MLton green threads are considered equal and the existing model preempts threads either after a fixed interval of time (preemptive) or when the currently executing thread decides to yield (cooperative). The absence of the notion of priority is quite crucial to the use of MLton for real-time systems as the criticality of computations are ignored. Such a case can be explicitly observed when any MLton thread makes a blocking IO call. Since all the green threads are mapped onto a single OS thread, this blocks all other MLton green threads as well until the OS finishes the execution of the IO operation and the blocking green thread can be descheduled to allow another thread to execute.

MLton's execution model places the SML call stack on the heap during the compilation, when it maps SML functions to C code. MLton requires the intervention of the GC when a thread has to grow its stack during execution. The GC clears up space on the heap and then allocates a bigger stack and copies the existing stack into the new location. This process requires the execution of the current thread to pause until the GC exits, thus introducing a point of non deterministic overhead that is undesirable in a real-time system. These properties of MLton make it unsuitable for use as a real-time system out of the box.

2.2 Garbage Collection

MLton adopts a hybrid model of Cheney Copy GC and Mark-Compact. The garbage collector dynamically switches between the two schemes back and forth based on runtime memory utilization. Its heap layout is depicted in Fig. 1.

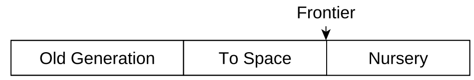


Figure 1: Heap layout in MLton

The default GC scheme is Cheney Copy GC, in which the new objects are allocated in Nursery. When there is insufficient space, a minor Cheney Copy is used to move objects from the nursery to "to space". If a minor GC fails to collect enough heap space for the new object, a major Cheney Copy GC is used, in which a secondary heap is allocated and the GC will attempt to copy objects from current heap to secondary heap. When the total memory usage exceeds 50%, the GC falls back to a 2-generation Mark-Compact GC where the objects are moved to the old generation if the live ratio is low.

MLton has 4 types of objects: normal object, arrays, weak object and stack. These objects are treated differently in GC allocation. Arrays and stacks are typically allocated in Old Generation, since they tend to persist over the lifetime of the program. MLton makes bump-pointer allocation at the frontier for normal and weak objects. However, weak objects are not common – they are typically created by programmers explicitly via primitive calls.

MLton's GC scheme moves objects to achieve compaction, which can be a source of unpredictability. Fig. 2 depicts such unpredictability. We preform a micro benchmark on MLton by allocating `int array option` objects, in which we randomly choose between allocating `NONE` or `SOME array` of 10 million elements. MLton first tries to allocate object by following a Cheney Copy scheme. Then it compacts the heap by copying the object to To Space, which introduces non-predictable behavior. In this benchmark, the time to move objects randomly goes up to 2x with no obvious pattern.

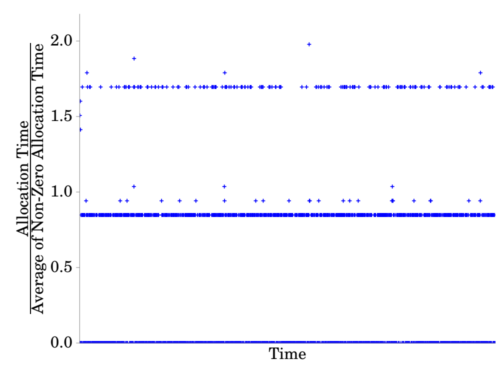


Figure 2: Unpredictable object allocation time in MLton

3. THREADING MODEL

In order to adapt MLton for use in real-time systems, we propose exposing the POSIX threading API within MLton. This will allow us to propagate priority information from the ML thread tracking structure to the RTOS and to leverage the RTOS scheduler. Additionally, this model allows for the use of the established MLton green threading models within each POSIX thread providing a many-to-one mapping of green-to-OS threads. This model also allows for the grouping of threads by activity, for example IO versus computation, which in turn helps isolate long-blocking activities such as IO into their own threads. Fig. 3 shows threads being isolated by priority as well as migrating between priorities, but alternate models bucketing threads by activity are also possible.

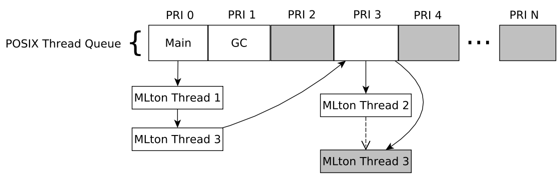


Figure 3: Priority-based Thread Queue

Our base scheduling mechanism is a fixed priority scheduler, mapping one MLton thread of a given priority to a single RTOS thread of the same priority. The maximum number of threads is specified by the programer in a configuration parameter, which allows for static preallocation of threads. We note that this mirrors the approach taken by many RTOSes. We are currently investigating a tiered scheduling mechanism, which allows multiple MLton threads of the same priority to execute on top of a single RTOS thread with user defined schedulers to dictate their scheduling policy. In order to handle priority inversion,we are looking into the use of Priority Inheritance Protocol locks [13].

In order to facilitate the use of OS level threads, several things must change within MLton. For example, the GC must first be moved to a separate thread and made concurrent. For slack based RTGC support this also includes making the GC the lowest priority thread in the system and supporting a concurrent GC that is interruptible at any point [10]. Secondly, the MLton model of a thread requesting GC needs to be changed so that computation is never stalled on GC.

4. HYBRID FRAGMENTING GC

The design of a real-time garbage collector should ensure predictability. To eliminate GC pauses induced by defragmentation and compacting the heap, we make sure that objects are allocated as fixed-size chunks so that objects will never need to be moved for defragmentation through the use of a hybrid fragmenting GC [10]. Small (normal and weak) objects, arrays and stacks are allocated on 3 separate regions of the heap. We maintain the array region and the normal object region by 2 free lists, whereas the stacks are allocated in bump-pointer manner.

Normal and weak objects are represented as linked lists. Since object sizes in MLton are typically small, we achieve constant access time when allocating these objects. Arrays are represented as trees, in which each node is fixed-size. Internal nodes have a large number of branches (32 in our implementation), which keeps access time $log_{32}(n)$ and is close to constant. MLton constantly allocates small sized arrays and even zero sized arrays. We represent such arrays as a single leaf to eliminate the overhead of finding the immediate child of the root. During collection, the GC first marks all fixed-size chunks that are currently live. Then it sweeps the heap and returns all unmarked chunks to the two free lists.

Heap Layout: In MLton, the size of normal objects, arrays and stacks vary significantly. To minimize the overhead induced by object chunking, we partition the heap into three regions for normal / weak objects, arrays and stacks.

Object Layout: MLton tries to pack small objects into larger ones. In our empirical study, most MLton objects are around 24 bytes. We choose 32 bytes as the chunk payload that carries MLton object along with extra 12 bytes overhead associated with chunk management. Objects that are larger than 32 bytes are split into multiple chunks. In our current implementation, we limit object to two chunks each since we haven't noticed objects that are greater than 64 bytes. The object layout is depicted in Fig. 4.

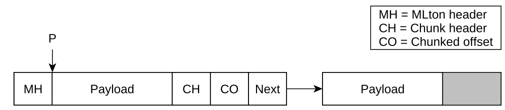


Figure 4: Chunked object layout

When an object fits into one chunk, the object field is calculated by:

```
objectField(p, offset) = p - HEADER_SIZE +
     offset
```

If an object is chunked, the `CO` field records the smallest offset that causes the chunk. The object field is then retrieved by:

```
objectField(p, offset) = (p - HEADER_SIZE)
    ->next + offset - CO
```

Arrays are represented as trees. In MLton, arrays are typically passed around using a pointer to its payload. The header and length of an array are retrieved by subtracting the header size and array length size from current pointer. We stick to this representation as much as possible. Array nodes are represented in Fig. 5. Internal nodes carry 32 pointers to their children. We pass an array around via a pointer to its first leaf. A root pointer and a next pointer is embedded in the leaf node. The leaf pointer connects all leaves that actually carry payloads for potential linear traversal optimization. For an array that is 128 bytes or less, we can fit it into 1 leaf chunk. For arrays that span multiple chunks, we construct trees. When accessing an element of an array, we first follow the root pointer to retrieve the root node and then access the array in a top down manner, in which we determine the branch in current node by `index % CO`, then we follow the branch to an alternative internal node. The process is repeated until we finally arrive at a leaf.

In our current implementation, we leave the stack allocated by bump pointer. The rationale is that, stacks never need to be moved in our implementation. Stacks grow and shrink by pushing and popping stack frames which results in chunks being added and removed as necessary. They are self-managed and do not need GC intervention to grow as they do in the MLton GC model.

Flattening refers to the multiple optimization passes in MLton that reduces the overhead for accessing nested objects. Flattening in MLton changes our array access scheme. The following code creates an array of tuples of `int` and `bool` shown in Fig. 6. Then it reads the second part of the 4^{th} element.

```
val arr = Array.tabulate (5, fn i => (i,
    true))
val a = #2 (Array.sub (arr, 4))
```

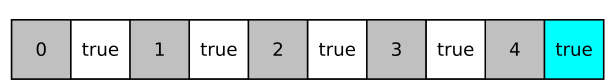


Figure 6: Accessing array of tuples

Without flattening, the read is translated into:

```
tup = arrayOffset(arr, elemSize=8, index=4)
a = objectOffset(tup, elemSize=4, index=1)
```

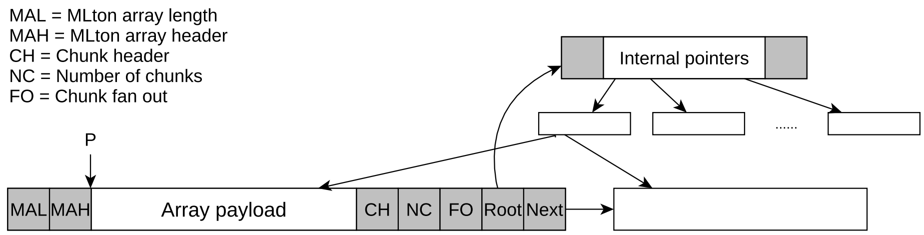


Figure 5: Chunked array layout

and with flattening, the read consists only a single element:

```
a = arrayOffset(arr, elemSize=4, index=9)
```

Unfortunately, it is difficult to reliably decide on an array element size after flattening that can be used at the time of allocation, since tuples can carry elements that differ in size. Our tree-structured array has no information about flattening and the access scheme generated from MLton after flattening cannot work with our chunked array model. Hence, we need to disable some of the flattening optimization passes. We first tried disabling all the flattening passes including local flatten and deep flatten. But in our later investigation, only deep flatten will try to flatten objects in arrays. The local flatten passes are totally compatible with our implementation. The effects of disabling / enabling flatten passes are detailed in Section 6.

4.1 Allocator Limitations

Relative addressing for arrays: An example of relative addressing is: given `p = &a[5];` then `*(p + 5)` refers to the value stored in `a[10]`. Such addressing is not used in the SML library but is crucial to connect to C via FFI. Our current implementation does not allow relative addressing for arrays. This problem is extremely common when dealing with strings, especially when passing strings around to IO calls such as `printf` since almost all IO calls assume a continuous buffer layout. Our temporary fix is to set an array pointer in the first leaf. However, we note that such an implementation restricts string sizes to 128 bytes or less, which can be annoying when dealing with file IO operations.

Infinite precision integers: MLton implements infinite precision integers with the GMP library. MLton allocates an infinite integer struct by first creating an object header similar to an array header, then it maps the struct to the frontier's position and adjusts frontier accordingly. If the calculated result can fit into a fixed-sized representation, MLton resets frontier and converts the representation of the integer. However, such a scheme is difficult to realize in our model as there is no direct conversion between an array chunk and an object chunk. We plan to look into this issue in the future.

Mapping and reducing over arrays: Operations that span over whole arrays are implemented in terms of array random access in MLton's basis library. Example of `Array.foldl` is implemented in the Fig. 7 (simplified, without boundary check).

```
fun foldl f a arr =
  let
    val l = Array.length arr
    fun loop (i, acc) =
      if i >= l
      then acc
      else loop (i + 1, f (acc, Array.sub (
           arr, i)))
  in
    loop (0, a)
  end
```

Figure 7: MLton Fold Implementation.

In MLton's representation, this implementation is fast – accessing to each element incurs $O(1)$ cost. But this implementation induces unnecessary overhead in our scenario due to $O(log(n))$ accessing time to each element. Since leaf nodes are connected by a next pointer, we could implement these functions in terms of MLton's FFI that maps MLton calls to C runtime. Delivering an efficient array module requires considerable time investment and it is left as our future work.

4.2 GC Limitations

For collection, our GC leverages a traditional mark and sweep scheme. We start with global objects and traverse object pointers to mark all chunks that are live. Then we sweep through the heaps and return the chunks that are not marked. Theoretically, a GC is performed whenever there is insufficient memory to allocate a new object. Yet, MLton only records stack frames prior to current function. Objects in current stack frame are accessed by adding the offset to `stackTop`. In other words, we cannot simply iterate through the stack to mark all objects as the layout of the current stack frame is unknown. An alternative option is to rely on MLton's GC checks.

MLton performs complicated data flow and control flow analysis to insert GC checkpoints to minimize the number of garbage collections needed. However, the data flow and control flow analysis assumes a single heap model and objects are calculated by number of bytes required, which is incompatible with our model. One solution is to patch up each path in the GC check flow, redirecting all GC checks to our GC runtime function and let the C runtime function decide whether a garbage collection is needed. However, as will be discussed in Section 6, such a method introduces high overhead. We currently add an RSSA optimization pass which sums up the allocations in a block and inserts a check to see if there are adequate chunks left. If the block does not allocate objects at all, we ignore it. Such a check only introduces a branch and an inlined integer comparison, which is much faster than the former method. Since arrays are allocated in the C runtime, MLton ensures the stack is completely prepared before jumping into `GC_arrayAllocate`. We can thus safely make GC checks in the array allocation.

To further speed up object allocation, MLton caches the frontier in a register. Yet, we discovered that with our chunked allocation, the frontier is not properly flushed correctly due to changes to the control flow of the program. We currently disable the frontier cache, but expect to be able to infer flush points with a specialized analysis. MLton also uses carding to optimize the GC. Since the card map is not present in our heap layout, we need to disable it to ensure correct behavior.

4.3 Potential Optimizations

Our GC takes about 1.5x the time of MLton with corresponding optimization passes disabled, which is far from optimal. We are currently investigating the following to improve performance:

- **CFG-based GC Checks:** we can perform control flow analysis to track down the object allocation and insert GC checks at the start of a group of blocks and loop entries / exits instead of doing it per block;
- **Improving Object Allocation and Referencing:** Standard ML provides rich type information that we may leverage to increase object allocation and reference efficiency, since we are able to figure out the number of chunks of the object and offset of the reference at compile time;
- **Re-enabling MLton's Optimization Passes:** We will examine those disabled optimization passes to explore the possibility of making them compatible with our object layout.

5. PORTING MLTON TO RTEMS

RTEMS API emulates POSIX in many places but it is not 100% compatible. We ported MLton to RTEMS 4.10.2 instead of the latest 4.11, due to an issue when compiling GMP with GCC 4.9.2 provided by RTEMS Source Builder. MLton calls `mmap` to allocate the heap and `munmap` to release it, both of which are missing as of RTEMS 4.10.2. We used `malloc` and `free` to manage the memory directly. MLton determines object alignment based on page size. Due to lack of virtual memory, the page size for RTEMS is rather arbitrary and we have coded it to be 1 MB. `rlimit` is missing in RTEMS, and so we needed to fall back to MLton's compatible implementation originally intended for MinGW. RTEMS' network structure is not compatible in various places, for example, there is no definition for `socket_len`. We had to strip all the POSIX networking primitives from MLton to ensure a successful compilation.

6. RESULTS

We compare our current prototype of RT MLton with various configurations of vanilla MLton. Both versions of MLton are based on MLton Git commit 2a2ebce6d12f7fc40. The evaluation is conducted on a workstation with Intel Core i7-3770 3.4GHz CPU, running Gentoo Linux. Fig. 8 shows our preliminary numbers.

MLton makes exceptional effort to optimize the final program. Unfortunately, we need to disable various optimization passes for correctness as mentioned in Section 4. In Fig. 8a, we demonstrate the effect of disabling optimization passes in MLton and compare our implementation with those configurations. Disabling optimization passes increases code size and slows the performance for MLton by multiple times. Compared to MLton with those optimizations disabled, our current implementation is approximately 3x slower. We are unfortunately very conservative at inserting GC checks at each path, resulting in interrupted control flow through jumps to a (potentially unnecessary) GC checkpoint. This also prevents further optimization passes from taking effect. Table. 1 compares the code size before / after limit check and at the start of machine IL (right after RSSA finished). We add an RSSA optimization pass to insert GC checks block-wise. As shown in Fig. 8a, it improves the performance dramatically. In the Fibonacci and MD5 benchmark, our implementation achieves identical performance to MLton with optimization passes disabled. Array referencing is particularly slow at the moment as demonstrated in the Matrix Multiplication benchmark. Currently, to allocate and iterate through an array of 10,000,000 integers, our array implementation takes 0.3 seconds. The Matrix Multiplication benchmark multiplies matrices heavily based on individual element reference that introduces $O(log(n))$ cost at each access. We believe it could be sped up dramatically if the program is made aware of our architecture and implements matrix multiplications as reduction over continuous sequences and with the delivery of sequential access optimizations discussed in Section 4.2. We envision that to ensure performance in real time setting, a functional program still needs to be aware of the low level object model and optimize algorithm / code towards the model. Fig. 8a also shows the potential benefit of enabling the local flattening passes while leaving deep flattening off. Local flattening ensures smaller object sizes and significantly reduces allocations. In fact, in Mandelbrot and MD5, with local flattening enabled, the GC is never activated. The result in this case is very similar to the vanilla MLton, which proves that the chunked object access adds only little overhead.

	Vanilla MLton	Conservative limit check
Before limit check	57,328 bytes	54,956 bytes
After limit check	77,904 bytes	179,324 bytes
Machine IL	103,028 bytes	216,960 bytes

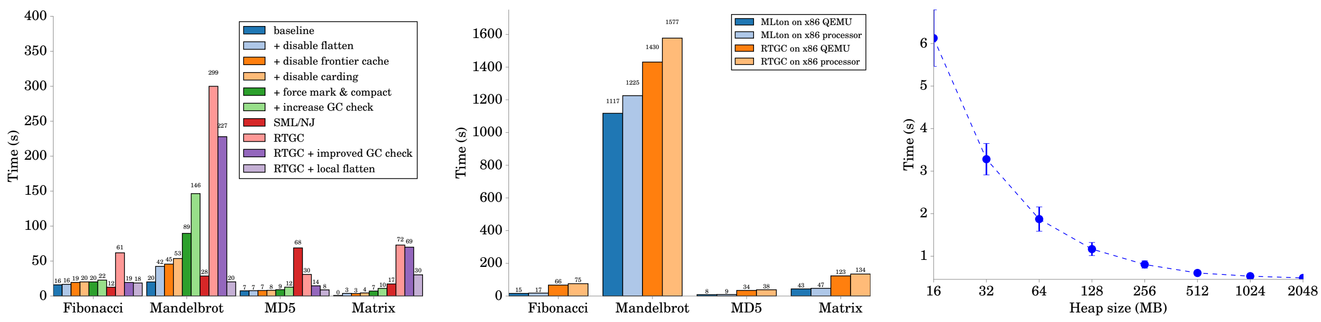
Table 1: Impact of limit check on RSSA optimization

To evaluate the actual performance on a real time system, we have conducted evaluation on RTEMS both in x86 QEMU and real x86 CPU. The workstation has Intel Xeon E3-1230 v2 3.3GHz. QEMU is configured with 4G available memory and KVM enabled. Direct execution on the CPU is enabled by connecting GRUB with the compiled RTEMS executable. Fig. 8b depicts the results. We observe a smaller performance gap between our implementation and vanilla MLton. In both cases, our implementation is at 3 - 5x slower than vanilla MLton. Directly running RTEMS executable on the CPU results in a slightly slower performance, which may due to Linux Kernel's awareness of Turbo Boost of the CPU. We haven't observed as significant performance boost as running on x86 Linux by refining the limit checks – generally, it runs only 1 - 2 s faster than the numbers in Fig. 8b. Note that we make every effort to ensure the comparison is fair but various factors could contribute to the performance results, including of platform specific functions to RTEMS largely based on MinGW platform implementation for MLton, which might not be efficient when used on RTEMS. MLton's lack of knowledge of RTEMS may be a contributing factor to the ineffectiveness of its optimizations. Old version (4.4) of GCC that lacks particular knowledge of certain flow optimization used by RTEMS 4.10 tool-chain might cause inefficient code organization. Targeting i386 instead of i686 in our RTEMS port may disable a few optimizations. We thus consider this result as a preliminary baseline, but expect better performance once we consider optimizations geared toward RTEMS and embedded execution.

Fig. 8c depicts the relation between time taken by garbage collection for our RTGC compared to heap size while running Mandelbrot set benchmark of size 8192.

7. RELATED WORK

Real-Time Garbage Collection: There are roughly three classes of RTGC: (i) *time based* [1] where the GC is scheduled as a task in the system, (ii) *slack based* [10] where the GC is the lowest priority real-time task and executes in the times between release of higher priority tasks, and (iii) *work based* [14] where each allocation triggers an amount of GC work proportional to the allocation request. In each of these RTGC definitions, the overall system designer *must* take into consideration the time requirements to run the RTGC. We currently have adopted a slack based approach in



(a) Baseline Performance Comparison (b) Embedded Performance on RTEMS (c) RTGC time vs heap size

Figure 8: Performance metrics of RT MLton

the context of real-time MLton, though a work based approach is also worth exploring.

Real-Time Java: The real-time specification for Java RTSJ [4] and safety critical Java (SCJ) [7], both provide definitions for scoped memory [5], a region based automatic memory management scheme. We believe it would be interesting to leverage previous work on region inference [3] in the context of ML [18] to eschew RTGC entirely through the use of scoped memory.

8. CONCLUSION AND FUTURE WORK

In this paper we presented our prototype implementation of a real-time capable version of MLton. Our next steps are to investigate necessary changes to the optimization passes we needed to disable to ensure correctness and predictability. We also plan on investigating new optimizations, specifically targeted at reducing the overheads of the hybrid fragmenting GC. Previous experience with the Fiji VM indicates that this is feasible. Lastly, we will consider optimizations specific to RTEMS and revisit the I/O libraries.

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