Comparing implementations of stacks and continuations

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Motivation

- Compilers for concurrent and parallel languages can benefit from having an *Intermediate Representation* (IR) that supports operations on lightweight user-space threads.
- Such an IR can then represent the runtime-system mechanisms for concurrency/parallelism.
- Inlining of runtime-system code into the application code then enables cross-layer optimizations.
- We have followed this approach in our *Parallel ML* (PML) compiler, which is part of the Manticore project.
- We are exploring the tradeoffs between several different runtime representations of threads in our compiler using LLVM.

Representing threads in an IR

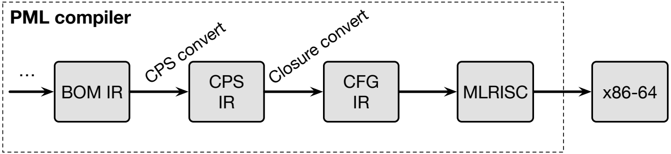
- How should thread state and operations on threads be represented in an IR for a concurrent or parallel language?
- One principled approach is to represent a suspended thread as a **continuation**.
- There is a long history of using surface-language continuations (`callcc`) to implement multithreading.

There are a number of different approaches to incorporating continuations in a compiler's IR.

- Appel-style CPS representation — all continuations are explicit
- Kelsey-style CPS representation – explicit continuations with annotations
- ANF with continuation binders – select continuations are reified

Continuations in an IR

- ANF+Continuations works well for writing runtime code and can be easily converted to the other representations or directly compiled to target code.
- Our PML compiler uses an ANF-style IR extended with continuation operations called BOM.



Representing threads in the BOM IR *(continued ...)*

$$\begin{array}{rcl} \langle exp \rangle & ::= & \texttt{let}\ (x_1, ..., x_n) = \langle prim \rangle\ \texttt{in}\ \langle exp \rangle \\ & | & \texttt{fun}\ f\ (x_1, ..., x_n) = \langle exp \rangle\ \texttt{in}\ \langle exp \rangle \\ & | & \texttt{cont}\ k\ (x_1, ..., x_n) = \langle exp \rangle\ \texttt{in}\ \langle exp \rangle \\ & | & \texttt{if}\ x\ \texttt{then}\ \langle exp \rangle\ \texttt{else}\ \langle exp \rangle \\ & | & \texttt{apply}\ f\ (x_1, ..., x_n) \\ & | & \texttt{throw}\ k\ (x_1, ..., x_n) \end{array}$$

$$\begin{array}{rcl} \langle prim \rangle & ::= & \texttt{create\_thread}\ (f) \\ & | & \textit{other primitive operations and values} \end{array}$$

Three forms for continuations:

- `cont` bindings
- `throw` expressions
- `create_thread` operator

Representing threads in the BOM IR *(continued ...)*

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Example: thread creation

Thread creation

```
fun fork f =
      fun f' () = (
            apply f ();
            throw (Sched.dequeue ()) ())
      let childK = thread_create f'
      in
        apply Sched.enqueue childK
```

We can also run the child thread first

```
fun fork f = cont parentK = ()
      in
        fun f' () = (
              apply f ();
              throw (Sched.dequeue ()) ())
        let childK = thread_create f'
        in
          apply Sched.enqueue parentK;
          throw childK ()
```

Example: context switch

Coroutine style explicit context switch.

```
fun yield () = cont k() = ()
      in
        Sched.enqueue k;
        throw (Sched.dequeue ()) ()
```

We can build all kinds of concurrency and parallelism mechanisms with this IR:

- locks and condition variables
- message-passing mechanisms
- work-stealing fork-join
- futures

Implementing continuations

Given an IR with continuations; we have to decide on a semantics for continuations and a supporting runtime model.

- first-class continuations
- one-shot continuations (may only be thrown to once)
- escape-continuations (essentially `setjmp`/`longjmp`)

First-class continuations are the most expressive and do not require any restrictions on their use in the IR

For example, we do not need to define **create_thread** as a primitive.

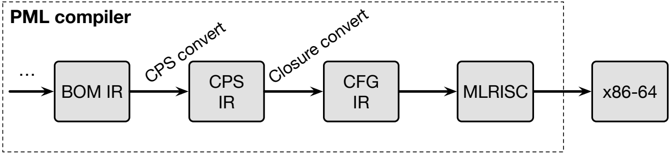
```
fun create_thread f =
      cont thdK () = (
            apply f ();
            throw (Sched.dequeue ()) ())
      in
        thdK
```

Implementing continuations *(continued ...)*

- Implementing first-class continuations on a traditional stack, however, is quite challenging.
- Early Scheme compilers used environment analysis to map continuations to stack-allocated frames (*e.g.*, Rabbit and Orbit). Note that Kelsey's IR encodes this analysis.
- Stack copying would be used to implement captured continuations.
- Segmented stacks were introduced (Chez Scheme) as a way to implement **`callcc`** more efficiently.
- Heap-allocated continuations (SML/NJ) provided a very simple implementation that abandoned the stack.

Choosing an approach

- Heap-allocated continuations provide a simple implementation of CPS, but giving up the stack has potentially significant performance costs.
- Previous empirical comparisons of runtime models are controversial [Appel-Shao ’96] or dated [Clinger *et al.* ’88 & ’99].
- We are comparing five different runtime representations for continuations techniques using the LLVM code generator framework.



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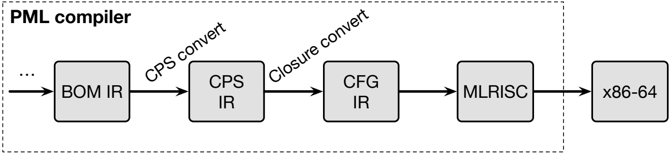

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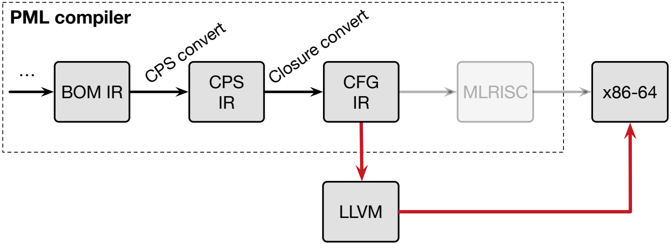


Fixed-size contiguous stacks

Standard calling convention; crash on overflow.

Pros and cons:

+ natural LLVM model
+ good locality across call/return
+ hardware optimized for return branch prediction
- stack overflow is a problem
- GC interface is more complicated and expensive
- potential race conditions when switching stacks
- thread overhead is high
- can run out of stack space

Resizable contiguous stacks

Calling convention checks for overflow; grow stack on overflow by copying to new memory object.

Pros and cons:

+ good locality across call/return
+ hardware optimized for return branch prediction
+ better space overhead than contiguous stacks
• specialized calling convention
- GC interface is more complicated and expensive
- potential race conditions when switching stacks
- thread creation overhead is high

Segmented stacks

Calling convention checks for overflow; switch to new segment on overflow.

Pros and cons:

+ good locality across call/return
+ hardware optimized for return branch prediction
+ more flexible management of space overhead than resizable stacks
• specialized calling convention
- GC interface is more complicated and expensive
- potential race conditions when switching stacks
- thread creation overhead is high
- additional runtime system complexity

Heap-allocated linked stack frames

Stack frames are heap-allocated mutable objects that are organized into a linked list.

Pros and cons:

+ good locality across call/return
+ hardware optimized for return branch prediction
+ better space overhead than contiguous stacks
+ low thread creation overhead
- GC interface is more complicated and expensive
- potential race conditions when switching stacks
- additional calling overhead/complexity

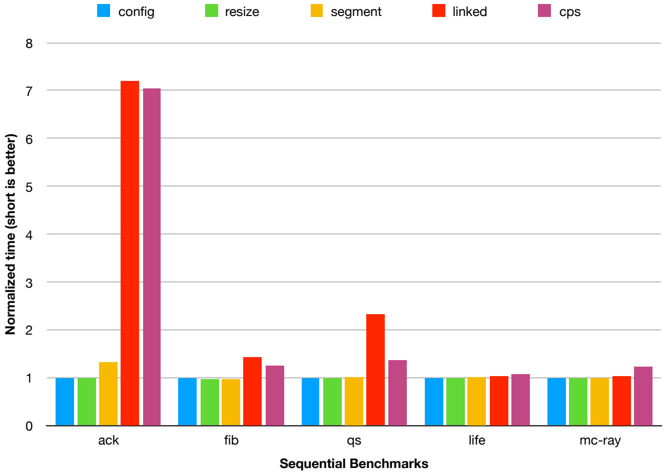
Heap-allocated continuation closures

Return continuation closures are heap-allocated immutable objects.

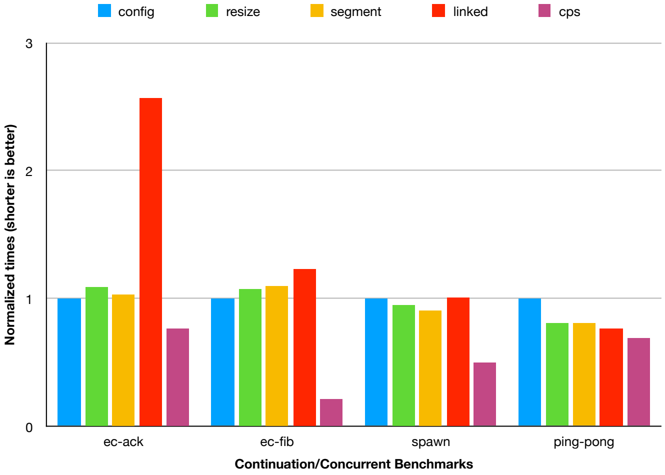
Pros and cons:

+ simple implementation
+ simple GC interface
+ minimal space overhead
+ fast thread creation
+ no race conditions when context switching
- loses locality between calls and returns
- increased allocation rate
- cannot take advantage of return-branch prediction

Sequential costs



Concurrency costs



Future Work

- hybrid schemes may also provide some advantages
- we are exploring a resizable + segmented stack scheme.
- The idea is to start with small resizable stacks, which gives low space overhead for applications with large numbers of threads.
- The stack is resized until it hits the size of a segment at which point the thread switches to the segmented model.
- Unlike resizable stacks, segmented stacks reclaim memory after deep recursions.
- Resizable and segmented stacks use the same function prologue and require similar stack meta data, so the extra implementation overhead is low.

Conclusion

- the overhead of linked frames appears to outweigh the locality benefits of reusing the frame
- For sequential languages, resizable stacks are the best choice.
- segmented stacks are probably the best overall choice if sequential performance is a high priority, but you still want concurrency.
- the cost of heap-allocated continuations is low enough for traditional code that their ease of implementation may make them a good choice. They are even a better choice if you are implementing a concurrent or parallel language.