Seq no more: Better Strategies for Parallel Haskell

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Abstract

We present a complete redesign of evaluation strategies, a key abstraction for specifying pure, deterministic parallelism in Haskell. Our new formulation preserves the compositionality and modularity benefits of the original, while providing significant new benefits. First, we introduce an evaluation-order monad to provide clearer, more generic, and more efficient specification of parallel evaluation. Secondly, the new formulation resolves a subtle space management issue with the original strategies, allowing parallelism (sparks) to be preserved while reclaiming heap associated with superfluous parallelism. Related to this, the new formulation provides far better support for speculative parallelism as the garbage collector now prunes unneeded speculation. Finally, the new formulation provides improved compositionality: we can directly express parallelism embedded within lazy data structures, producing more compositional strategies, and our basic strategies are parametric in the coordination combinator, facilitating a richer set of parallelism combinators.

We give measurements over a range of benchmarks demonstrating that the runtime overheads of the new formulation relative to the original are low, and the new strategies even yield slightly better speedups on average than the original strategies.

Categories and Subject Descriptors D.1.1 [Programming Techniques]: Applicative (Functional) Programming; D.1.3 [Programming Techniques]: Concurrent Programming

General Terms Performance, Measurement

Keywords Parallel Functional Programming, Strategies

1. Introduction

Evaluation strategies [Trinder et al. 1998], or “strategies” for short, are a key abstraction for adding pure, deterministic parallelism to Haskell programs. Using strategies, parallel specifications can be built up in a compositional way, and the parallelism can be specified independently of the main computation. Despite the apparent conflict between lazy evaluation and the eagerness implied by parallelism, evaluation strategies show that non-strictness and parallelism can co-exist in a coherent programming model, and non-strictness even has some advantages for parallel languages [Loidl et al. 1999]. Strategies have been used for some 15 years in a number of parallel variants of Haskell [Harris et al. 2005; Loogen et al. 2005; Trinder et al. 1998].

This paper presents a complete redesign of the strategy abstraction. Our reformulation preserves the key compositionality and modularity benefits of the original strategies (Section 4), together with their low time and space overheads (Section 6), and the formal semantics [Baker-Finch et al. 2000] is unchanged. The new formulation provides the following additional benefits:

- Clearer, more generic and more efficient specification of parallel evaluation. Describing a parallel algorithm requires specifying an order of evaluation, something which the Haskell language deliberately, and rightly, leaves unspecified. In the new strategies we introduce an evaluation-order monad, allowing the ordering of a set of evaluations to be specified in a perspicuous and compositional way (Section 4). Moreover, by using Applicative functors and the Traversable class [McBride and Paterson 2008], we can define generic regular strategies over data structures (Section 5). Our framework also supports fusion, which allows the intermediate lists introduced by modular strategies to be eliminated by the compiler (Section 4.5).

- The new strategies resolve a subtle space management issue where the original strategies retain heap unnecessarily (Section 4.6). The crux of the space management challenge is to preserve parallelism (sparks), while being able to reclaim the heap associated with superfluous parallelism. Our measurements demonstrate improved space behaviour for existing parallel programs simply by switching to the new strategies (Section 6). Furthermore, the new strategies support speculative parallelism with unnecessary speculative tasks being pruned automatically by the garbage collector, something which was not possible with the original strategies.

- There is a class of important parallel coordination abstractions that cannot be expressed as original strategies, but can be expressed in the new formulation. The feature that this class of abstractions has in common is that they all embed parallelism within lazy components of a data structure, a technique that is essential for parallelising stream-processing pipelines. In the original strategies we could write these functions, but they were not instances of the strategy abstraction and so could not be used compositionally. These drawbacks are resolved by the new framework (Section 5.1).
• Motivated by wanting to have different versions of \texttt{par} to control locality in large architectures, the new formulation allows for abstracting over the coordination combinator used (Section 5.4).

Sadly, however, we must all pay for our lunch, and the new formulation raises three issues.

• There is some extra complexity in the implementation of strategies. However, many casual users of the library are insulated from the changes: using and composing strategies works exactly as before, modulo some renaming. Only users who need to define their own strategies will have to become familiar with the new idioms, and there should now be fewer such users given that we provide generic strategies over any \texttt{Traversable} data type.

• The original strategies provided a strong identity safety property, namely that (\texttt{‘using’ a}) is always an identity function for any strategy \texttt{a}. The new strategies cannot provide the same guarantee, although the library strategies are identities, and the combiners preserve the property. Safety can be regained at the expense of expressiveness by making the strategy type abstract, giving the programmer a choice of expressiveness/safety levels (Section 5.4).

• To express control parallelism an original strategy may freely spark expressions. The corresponding new strategy must carefully preserve any sparked expressions (Section 4.6).

The new strategies are incorporated in the Haskell \texttt{parallel} package (Version 3.1).\footnote{http://hackage.haskell.org/package/parallel} All the code for our benchmarks is available online (Section 6), and the results were obtained with a recent GHC development snapshot (6.13 as of 20.5.2010). The latest official release, GHC 6.12.3, achieves similar speedups.

2. Original Strategies

Pure parallelism in Haskell is achieved using only two primitives, \texttt{par} and \texttt{pseq}, with the following types:\footnote{The original presentation used \texttt{seq} rather than \texttt{pseq} [Trinder et al. 1998]; however, Haskell later adopted a \texttt{seq} operator but without the order-of-evaluation property required for parallel execution [Marlow et al. 2009]. Hence, to avoid confusion with Haskell’s \texttt{seq}, we now use \texttt{pseq} for expressing sequential ordering of evaluation.}

\begin{verbatim}
par :: a -> b -> b
pseq :: a -> b -> b
\end{verbatim}

The \texttt{par} combinator introduces a potential for parallel evaluation. When \texttt{par} is applied to two arguments, it returns the value of its second argument, while its first argument is possibly evaluated in parallel. We say "possibly", because as far as the program is concerned, the result of \texttt{par a b} is always \texttt{b}; it makes no difference to the meaning of the program whether \texttt{a} is evaluated in parallel or not. We should think of \texttt{par} as an \texttt{annotation}; it merely hints to the Haskell implementation that it might be beneficial to evaluate the first argument in parallel.

What if the computation evaluated in parallel has the value \bot, or an error? Surely then it makes a difference to the meaning of the program whether it is evaluated, or not? In fact it does not — the system is required to ensure that the semantics of \texttt{par a b} is always \texttt{b}, regardless of the value of \texttt{a}. \bot, or otherwise. In practice, this isn’t a problem for typical Haskell implementations, as a lazy computation can already have value \bot.

It is not enough to provide \texttt{par} alone, because generally when suggesting that something is to be evaluated in parallel, it is useful to be able to say what it is to be evaluated in parallel \emph{with}. Haskell neither specifies nor requires a particular order of evaluation, so normally the programmer has no control over this aspect of their program’s execution. In particular, the programmer has no control over when a particular call to \texttt{par} will be evaluated, or what will be evaluated before or after it (or indeed in parallel with it). This is the reason for \texttt{pseq}: a call \texttt{pseq a b} introduces an order-of-evaluation requirement that \texttt{a} be evaluated before \texttt{b}. The denotational semantics of \texttt{pseq} is

\[
pseq a b = \bot \text{ if } a = \bot \\
= b \text{ otherwise}
\]

and the operational semantics is that \texttt{a} must be evaluated to weak head normal form before returning \texttt{b} [Baker-Pinch et al. 2000].

An example to illustrate the usage of \texttt{par} and \texttt{pseq} follows, using the traditional \texttt{nfib} function. More examples can be found in the literature [Jones Jr. et al. 2009] [Trinder et al. 1998].

\begin{verbatim}
nfib :: Int -> Int
nfib n | n <= 1 = 1
| otherwise = let
  x = nfib (n-1)
  y = nfib (n-2)
in x ‘par’ (y ‘pseq’ x + y + 1)
\end{verbatim}

The computation is shaped like a binary tree. At each node of the computation we combine \texttt{par} and \texttt{pseq} to evaluate one branch in parallel with the other branch. The pattern here is a common one: in \texttt{x ‘par’ (y ‘pseq’ e)}, typically \texttt{e} involves both \texttt{x} and \texttt{y}. The effect of this pattern is to cause \texttt{x} to be evaluated in parallel with \texttt{y}, When the evaluation of \texttt{y} is complete, computation proceeds by evaluating \texttt{e}. Here the \texttt{pseq} is used to control \texttt{evaluation order}.

The parallelism here is independent of the number of processors; every time \texttt{par} is evaluated it creates a new opportunity for some work to be evaluated in parallel (a \texttt{spark}), but the implementation is free to ignore these opportunities. Indeed typical usage of \texttt{par} creates many more sparks than there are processors available to execute them, and the surplus sparks are simply discarded by the runtime system.

2.1 Strategies

The basic programming model described above provides the raw material for expressing parallelism in Haskell. Building on this, a \texttt{Strategies} module affords an abstraction layer over \texttt{par} and \texttt{pseq} to allow larger-scale parallel algorithms to be expressed.

Strategies are a remarkably simple idea. In the original formulation, a strategy is a function of type \texttt{a -> ()} for some \texttt{a}:

\[
type Strategy a = a -> ()
\]

Thus, a Strategy may evaluate its argument either in full or in part, and it may only return () (or diverge). Crucially, using \texttt{par} and \texttt{pseq}, a strategy may specify a recipe for evaluating its argument in parallel.

Some basic strategies can be defined as follows.

\begin{verbatim}
r0 :: Strategy a
r0 x = ()
rwhnf :: Strategy a
rwhnf x = x ‘pseq’ ()
rfn :: NFData a => Strategy a
-- rfn is a method in the class NFData
r0 is a strategy that evaluates nothing of its argument, rwhnf evaluates its argument to weak-head normal form, and rfn eval-
\end{verbatim}
uates its argument completely. The definition of \texttt{rnf} depends on the structure of its argument, so it is defined using a type class \texttt{NFData}, which has to be instantiated separately for each data type (the strategies library provides instances for common types such as Booleans, integers, lists and tuples).

Strategies are applied with the using combinator:

\begin{verbatim}
using :: a \rightarrow Strategy a \rightarrow a
x \text{'using'} s = s x \text{'pseq'} x
\end{verbatim}

So far we haven’t presented any strategies containing actual parallelism. A simple one is \texttt{parList}, which applies a strategy to each element of a list in parallel:

\begin{verbatim}
parList :: Strategy a \rightarrow Strategy [a]
parlist strat [] = ()
parlist strat (x:xs) = strat x \text{'par'} parlist strat xs
\end{verbatim}

The function \texttt{parList} illustrates the compositional nature of the strategies abstraction: it takes as an argument a strategy to apply to each list element, and returns a strategy for the whole list. The strategy argument is typically used to specify the evaluation degree, that is, how much each list element should be evaluated. For instance, \texttt{parList \texttt{rwhnf} causes each spark to evaluate its list element as far as the top-level constructor, whereas \texttt{parList \texttt{rnf} evaluates the elements completely. Various evaluation degrees between these two extremes are possible, such as evaluating the spine of a list (we’ll give examples later in Section 4.7).

The \texttt{parList} function can also be used to illustrate the modular nature of strategies; for example:

\begin{verbatim}
parMap :: Strategy b \rightarrow (a \rightarrow b) \rightarrow [a] \rightarrow [b]
parMap strat f xs = map f xs \text{'using'} \text{'par'} strat
\end{verbatim}

The \texttt{parMap} function takes a strategy \texttt{strat}, a function \texttt{f}, and a list \texttt{x}s as arguments and maps the function \texttt{f} over the list in parallel, applying \texttt{strat} to every element. Note how the construction of the result with \texttt{map}, on the left of \texttt{using}, is separate from the specification of the parallelism, on the right. This is a small-scale example, but the idea also scales to much more elaborate settings [Lodi et al.,1999].

The key to the modularity is lazy evaluation. The argument to a strategy can be a complex data structure with lazy components, or even a lazily-created data structure, and this allows the algorithm that creates the data structure to be separated from the strategy that specifies how to evaluate it. It’s not a panacea: not all algorithms lend themselves to being decomposed in this way, and the intermediate lazy data structure has costs of its own. Nevertheless, in many cases the modularity benefits outweigh the costs, and sometimes the intermediate data structure can be automatically eliminated by the compiler (Section 4.3).

3. Space Management: Preserving Parallelism, not Garbage

In this section we describe the main problem in the original strategies formulation that prompted the redesign described in this paper. The problem we are about to describe only came to light recently [Marlow et al.,2009].

To understand the problem we need to consider how \texttt{par} is implemented. When the Haskell program evaluates the expression \texttt{par a b}, the runtime system saves a pointer to the heap node representing \texttt{a} in a data structure that we call a \texttt{spark pool}. For our purposes, the spark pool is simply a set of pointers to heap objects representing computations that have been sparked by \texttt{par}. The runtime system from time to time removes objects from the pool in order to evaluate them using idle processors, so-called lazy tasks.

In an attempt to retain potential parallelism, the storage manager is retaining memory that should have been released: this is a space leak, and can and does have dramatic performance implications (we’ll tell that story in Section 6.4. Even an innocuous \texttt{parList} or \texttt{parMap} can turn a program that ran in constant space into one that requires linear heap. The adverse effects tend to manifest when running parallel programs on a single processor, because there are no spare processors to evaluate the sparks and hence allow them to be removed from the spark pool. However, effects are felt even when multiple processors are available: the sparks occupy space in the spark pool that could be used for real parallelism, and processors waste time evaluating garbage sparks which erodes the overall speedup achieved.

How should the storage management system, in particular the garbage collector, treat the spark pool? There are two main alternatives, which we call \texttt{ROOT} and \texttt{WEAK} respectively, following the terminology of [Marlow et al.,2009]:

1. \texttt{ROOT}: entries in the spark pool should be considered implicitly live. That is, the spark pool is a source of roots for the garbage collector.

2. \texttt{WEAK}: an entry in the spark pool is only alive if the object to which it points is independently reachable. That is, the spark pool contains \textit{weak pointers} in the usual terminology.

In fact, both of these policies lead to problems with original strategies. First, let us consider \texttt{WEAK}, and examine how it works with the definition of \texttt{parList} in the previous section. The sparks created by \texttt{parList} are all expressions of the form \texttt{strat x} for some strategy \texttt{strat} applied to some list element \texttt{x}. Now, every such expression is uniquely allocated for the sole purpose of being passed to \texttt{par}; the spark pool will contain references to many expressions of the form \texttt{strat x}, and in every case, the \textit{reference from the spark pool is the only reference to that expression in the heap}. So, by definition, if we adopt the \texttt{WEAK} policy then every spark created by \texttt{parList} will be discarded by the garbage collector, and we lose all the parallelism.

Moreover, there is no definition of \texttt{parList} that can avoid this problem. The only value that the \texttt{parList} strategy can return is \texttt{()}, so the only way that \texttt{parList} can create a reachable spark is by sparking part of the structure it was originally given, such as the list elements. For example, we can define a non-compositional variant of \texttt{parList} that works:

\begin{verbatim}
parList\texttt{WHNF} :: Strategy [a]
parList\texttt{WHNF} [] = ()
parList\texttt{WHNF} (x:xs) = x \text{'par'} parList\texttt{WHNF} xs
\end{verbatim}

But unfortunately we lose the compositional nature of strategies that was so appealing about the original formulation.

So what about the alternative garbage collection policy, \texttt{ROOT}, where we treat the spark pool as a source of roots? Considering the \texttt{parList} example again, the spark pool would still contain references to expressions of the form \texttt{strat x} in the heap, but this time all the expressions will be retained by the garbage collector, and no parallelism is lost. However, another problem arises: what happens when there are not enough parallel processors to evaluate all the sparks? The spark pool retains references to all the \texttt{strat x} expressions, perhaps long after each \texttt{x} is no longer required by the program and would otherwise be reclaimed by the garbage collector.

More details on the implementation of spark pools can be found in [Marlow et al.,2009]. The particular implementation details are not important here.
It is tempting to think that perhaps we can solve the space leak by only retaining sparks that share some data with the main program. This is difficult to achieve, however, and in any case it is not clear that it would be a robust solution to the problem: how much data should be shared before we consider the spark to be alive?

### 3.1 Fizzled Sparks

It is possible that a spark in the spark pool can refer to a computation that has already been evaluated by the program. Perhaps there were not enough processors to evaluate the spark in parallel, and another thread ended up evaluating the computation during the normal course of computing its results.

When a spark in the spark pool refers to a value, rather than an unevaluated computation, we say the spark has fizzled; this potential for parallel execution has expired [Marlow et al. 2009]. The runtime system can, and should, remove fizzled sparks from the spark pool so that the storage manager can release the memory they refer to, to avoid the mutator wasting time evaluating useless sparks, and to make more room for real potential parallelism in the spark pool.

This is all well and good, but note that in the original strategies formulation, most sparks will never fizzles because they are expressions of the form \( \text{strat} \ x \) that are unshared and hence can never be evaluated by the main program. In contrast, the sparks generated by the caller, thus ensuring that the sparked expressions remain reachable as long as the consumer requires it. Furthermore, if the consumer evaluates \( \text{strat} \ x \) before it is evaluated by a parallel thread, then the spark fizzles; superfluous parallelism is discarded by the garbage collector, which is exactly what we need.

Perhaps our strategies should be identity functions. However, the simplest identity type, \( a \rightarrow a \), is not a suitable strategy type candidate. Functions of this type are necessarily strict so we cannot express \( \text{r0} \), the strategy that performs no evaluation of its argument, as a function of this type. To accommodate \( \text{r0} \), the result must be lifted. We use a trivial lifting. \( \text{Eval} \), and provide a way to unlift, \( \text{runEval} \):

\[
\text{runEval} :: \text{Eval} a \rightarrow a
\]

### 3.2 Speculative Parallelism

Sparking ought to support speculative parallelism, by which we mean sparking an expression whose value is not known for certain to be eventually required by the computation as a whole. Ideally, speculative parallelism should be automatically pruned by the system when it can be proven to be never needed.

Speculative parallelism can be created using \( \text{par} \): the question is whether speculative sparks are ever discarded. Under the \( \text{ROOT} \) policy, a speculative spark that is never evaluated will become a space leak, whereas under the \( \text{WEAK} \) policy unreachable speculative sparks will be discarded and their heap reclaimed. In short, only the \( \text{WEAK} \) policy supports speculation.

### 3.3 Summary

For reference, the following table summarises the interaction between the choice of strategy abstraction (original strategies, Section 2), versus new strategies, Section 3, nature of parallelism (speculative or not), and GC policy (\( \text{ROOT} \) versus \( \text{WEAK} \)).

<table>
<thead>
<tr>
<th>Strategies</th>
<th>Parallelism</th>
<th>( \text{ROOT} )</th>
<th>( \text{WEAK} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>original</td>
<td>non-speculative</td>
<td>space leaks</td>
<td>lost parallelism</td>
</tr>
<tr>
<td>new</td>
<td>speculative</td>
<td>space leaks</td>
<td>lost parallelism</td>
</tr>
<tr>
<td>new</td>
<td>non-speculative</td>
<td>OK</td>
<td>OK</td>
</tr>
<tr>
<td>new</td>
<td>speculative</td>
<td>OK</td>
<td>OK</td>
</tr>
</tbody>
</table>

### 4. A New Formulation of Strategies

The difficulties with managing the space behaviour of sparks described in Section 3 are rooted in the choice of the type for strategies: if a strategy is a function returning the unit type \( \bot \), then there is no way for it to spark new expressions and to return them to the caller, thus ensuring that the sparked expressions remain reachable from the caller’s heap.

The key idea in our reformulation is that a strategy returns a new version of its argument, in which the sparked computations have been embedded. For example, when sparking a new parallel task of the form \( \text{strat} \ x \), rather than discarding this expression, the strategy will now build a new version of the original data structure with \( \text{strat} \ x \) in place of \( x \). The caller will consume the new data structure and discard the old, so that the parallel task \( \text{strat} \ x \) remains reachable as long as the consumer requires it. Furthermore, if the consumer evaluates \( \text{strat} \ x \) before it is evaluated by a parallel thread, then the spark fizzles; superfluous parallelism is discarded by the garbage collector, which is exactly what we need.

Perhaps our strategies should be identity functions. However, the simplest identity type, \( a \rightarrow a \), is not a suitable strategy type candidate. Functions of this type are necessarily strict so we cannot express \( \text{r0} \), the strategy that performs no evaluation of its argument, as a function of this type. To accommodate \( \text{r0} \), the result must be lifted. We use a trivial lifting. \( \text{Eval} \), and provide a way to unlift, \( \text{runEval} \):

\[
\text{runEval} :: \text{Eval} a \rightarrow a
\]

The rationale for the names will become clear shortly. Now we can define some basic strategy combinators using the new type:

\[
\text{r0} :: \text{Strategy} a
\]

\[
r0 \ x = \text{Done} \ x
\]

\[
rseq :: \text{Strategy} a
\]

\[
rseq \ x = x \ 'pseq' \ \text{Done} \ x
\]

\[
rpar :: \text{Strategy} a
\]

\[
rpar \ x = x \ 'par' \ \text{Done} \ x
\]

\[
\text{rdeepseq} :: \text{NFData} a \Rightarrow \text{Strategy} a
\]

\[
\text{rdeepseq} \ x = \text{rnf} \ x \ 'pseq' \ \text{Done} \ x
\]

The new basic strategies \( \text{r0} \), \( \text{rseq} \) and \( \text{rdeepseq} \) are analogues to the original strategies \( \text{r0} \), \( \text{rwhnf} \) and \( \text{rnf} \) respectively (in fact, \( \text{rdeepseq} \) uses the original \( \text{rnf} \)).

### 4.1 The Evaluation-order Monad

We can declare \( \text{Eval} \) to be a monad. There are two choices here: either it is the standard identity monad, or it is a strict identity monad. The latter turns out to be a much more useful choice:

\[
\text{instance Monad Eval where}
\]

\[
\text{return} \ x = \text{Done} \ x
\]

\[
\text{Done} \ x \ '>>=' \ k = k \ x
\]

The strict identity monad\(^3\) gives us a convenient and flexible notation for expressing evaluation order, i.e. the ordering between applications of \( \text{rseq} \) and \( \text{rpar} \), which is exactly what we need for expressing basic parallel evaluation. For example, the following fragment of \( \text{nfib} \)

\[
\text{let}
\]

\[
x = \text{nfib} \ (n-1)
\]

\[
y = \text{nfib} \ (n-2)
\]

\[
in \ 'par' \ (y \ 'pseq' \ (x + y + 1))
\]

\(\text{NFData} \) are analogues to the original strategies \( \text{r0} \), \( \text{rwhnf} \) and \( \text{rnf} \) respectively (in fact, \( \text{rdeepseq} \) uses the original \( \text{rnf} \)).

\(\text{r0} \)

\(\text{rseq} \) and \( \text{rdeepseq} \) are analogues to the original strategies \( \text{r0} \), \( \text{rwhnf} \) and \( \text{rnf} \) respectively (in fact, \( \text{rdeepseq} \) uses the original \( \text{rnf} \)).
type Strategy a = a -> ()

using :: a -> Strategy a -> a
x 'using' s = s x 'pseq' x

r0 :: Strategy a
r0 x = ()

rwhnf :: Strategy a
rwhnf x = x 'pseq' ()

rnf :: NFData a => Strategy a
-- rnf is a method in the class NFData

seqList :: Strategy a -> Strategy [a]
seqList s [] = ()
seqList s (x:xs) = s x 'pseq' (seqList s xs)

parList :: Strategy a -> Strategy [a]
parList s [] = ()
parList s (x:xs) = s x 'par' (parList s xs)

data Eval a = Done a
instance Monad Eval where
  return x = Done x
  Done x >>= k = k x
runEval :: Eval a -> a
runEval (Done a) = a

using :: a -> Strategy a -> a
x 'using' s = runEval (s x)

r0 :: Strategy a
r0 x = return x

rseq :: Strategy a
rseq x = x 'pseq' return x

rdeepseq :: NFData a => Strategy a
rdeepseq x = rnf x 'pseq' return x

rpar :: Strategy a
rpar x = x 'par' return x

evalList :: Strategy a -> Strategy [a]
evalList s [] = return []
evalList s (x:xs) = do x' <- s x
                      xs' <- evalList s xs
                      return (x':xs')

runEval $ append <$> rpar (nfib (n-1)) <*> rseq (nfib (n-2))

which clearly expresses the ordering between rpar and rseq, using a notation that Haskell programmers will find familiar.

Programmers using the new strategies API no longer need to use par and pseq to construct new strategies, instead they use the Eval monad with rpar and rseq. The Eval monad raises the level of abstraction for pseq and par; it makes fragments of evaluation-order first class, and lets us compose them together. We should think of the Eval monad as an Embedded Domain-Specific Language (EDSL) for expressing evaluation order, embedding a little evaluation-order-constrained language inside Haskell, which does not have a strongly-defined evaluation order.

Figure 1 summarises the differences between the API for the original strategies and the new strategies. Note that we have redefined a few combinators using the monadic style consistently, using return in place of Done, for example.

4.2 Eval, applicatively

An evaluation order is often something we want to impose on an existing expression. Since Eval is a monad, it is also an Applicative functor [McBride and Paterson2008]:

can be rewritten as

instance Functor Eval where
  fmap f x = x >>= return . f

instance Applicative Eval where
  pure x = return x
  (<><>)= ap

This means that we can use applicative notation for threading “evaluation order” through an expression. Here's a simple example: in one of our benchmarks (Coins in Section 6.3), a result value is defined as

res = append left right

and we want to spark left in parallel with right. We could use the monadic syntax as we did for the nfib example above, but sometimes even the monadic syntax is too heavy, and obscures the structure of the original code. The Applicative operators <$ and $<> let us rewrite the expression to include the parallelism, without losing its structure:

res = runEval $ append <$> rpar left $<> rseq right

One might object that this is not a modular specification of parallelism, and that would be a fair criticism. However, note that apart from the introduction of rpar and rseq, the translation to applicative style is mechanical, so this is a minimal and yet precise way to add a little parallelism to an existing expression. We will discuss how to recover modularity in cases like this in Section 4.6.

Applicative notation fixes the ordering to be depth-first, so in cases where depth-first is not appropriate the monadic syntax has to be used.
4.3 Using Strategies

As with the original strategies, a strategy application operator is provided:

\[
\text{using} :: \text{a} \rightarrow \text{Strategy a} \rightarrow \text{a}
\]

\[
x \text{ ‘using’ } s = \text{runEval} (s \ x)
\]

The using function is defined to have lowest precedence and associate to the left, that is \(e \text{ ‘using’ } s1 \text{ ‘using’ } s2\) stands for \((e \text{ ‘using’ } s1) \text{ ‘using’ } s2\). This stacking of strategies being similar to the stacking of function applications, there is a strategy composition dot such that

\[
(e \text{ ‘using’ } s1) \text{ ‘using’ } s2 = e \text{ ‘using’ } (s2 \text{ ‘dot’ } s1)
\]

Just like function composition, dot has highest precedence and associates to the right, so the parentheses can be dropped from the above equation.

4.4 Compositional Strategies over Data

We build strategies over data types by first constructing a basic strategy for the data type, parametrised over strategies for the components of the type. The basic strategy traverses the data type in the Eval monad, applies the argument strategies to the components (usually in depth-first order), and builds a new instance of the type.

As an example, consider the Strategy combinator evalList, which walks over a list and applies the argument strategy \(s\) to every element:

\[
evalList :: \text{Strategy a} \rightarrow \text{Strategy} \ [\text{a}]
\]

\[
evalList \ s \ [] = \text{return} \ []
\]

\[
evalList \ s \ (x:xs) = \text{do} \ x' \leftarrow s \ x \quad \text{xs}' \leftarrow \text{evalList} \ s \ xs \quad \text{return} \ (x':xs')
\]

The evalList combinator generalises both parList and seqList of original strategies, and more besides. For example, parList is obtained by composing the element strategy \(s\) with rpar:

\[
\text{parList} :: \text{Strategy a} \rightarrow \text{Strategy} \ [\text{a}]
\]

\[
\text{parList} \ s = \text{evalList} (\text{rpar} \text{ ‘dot’ } s)
\]

The original strategies had a seqList combinator, whereas the new strategies do not provide a seqList. In fact, evalList is the new strategies’ equivalent to seqList, but it is not immediately obvious why this should be so -- seqList is defined in terms of pseq, but there is no pseq to be found in the definition of evalList. The purpose of seqList is to apply the strategy \(s\) to each element of the list in left-to-right order, and it achieves this ordering by using pseq at each step. In evalList, we achieve the same ordering, but by using the Eval monad instead: the Eval monad explicitly sequences the application of the strategy \(s\) to each list element in order — pseq is no more required.

We can specialise evalList in more ways. A number of new parallel primitives are envisioned, for instance, a bounded par that restricts locality, e.g. a spark with a low bound should be executed "nearby". An advantage of the new strategies is that all these primitives can be passed as parameters, thus avoiding code replication.

4.5 Generic Strategies

The Traversable class provides a convenient way to thread any Applicative computation through the components of a data structure in a depth-first manner, performing any effects on the way whilst building a new data structure [McBride and Paterson 2008]. This is exactly what we need for defining strategies over regular data structures such as lists and trees: a means of traversing the data structure using Eval, applying a strategy at the leaves, and building a new structure to return.

The method traverse has the following type:

\[
\text{traverse} :: (\text{Traversable t}, \text{Applicative f}) \rightarrow (\text{a} \rightarrow f \text{ b}) \rightarrow t \text{ a} \rightarrow f (t \text{ b})
\]

This function is so generic it is not immediately obvious how it can be applied in our setting. However, if we specialise \(a \rightarrow f \ b\) to Strategy \(a\) then we get:

\[
\text{evalTraversable} :: \text{Traversable t} \rightarrow \text{Strategy} \ a \rightarrow \text{Strategy} (t \text{ a})
\]

\[
\text{evalTraversable} = \text{traverse}
\]

This is a generic parametrised strategy for any Traversable data type. It has evalList as an instance, and gives us strategies for types like Maybe and Array for free. Adding parallelism to the generic strategy is straightforward:

\[
\text{parTraversable} :: \text{Traversable t} \rightarrow \text{Strategy} \ a \rightarrow \text{Strategy} (t \text{ a})
\]

\[
\text{parTraversable} \ s = \text{evalTraversable} (\text{rpar} \text{ ‘dot’ } s)
\]

4.6 Modularity

The key modularity property we have is that \(e \text{ ‘using’ } s\) is observably equivalent to \(e\), at least in so far as it is defined (the former may be less defined than the latter). The point of this guarantee is that someone who only wants to understand the algorithm can ignore the strategies, i.e. every ‘using’ \(s\).

Of course, this property is only useful in cases where we can actually make use of using. Some of the examples we have already seen are not easily expressed with using; consider for example nfib from Sections [4.4.4.5/6].

\[
\text{runEval} \$ \text{do}
\]

\[
x' \leftarrow \text{rpar} (\text{nfib} (\text{n-1}))
\]

\[
y' \leftarrow \text{rseq} (\text{nfib} (\text{n-2}))
\]

\[
\text{return} \ (x' + y' + 1)
\]

This kind of parallelism is known as control or task parallelism, where the parallelism follows the control structure of the program. However, we cannot consider this a modular specification of parallelism, as it clearly interleaves the algorithm with the coordination.

We can write a modular version:

\[
x + y + 1 \ ‘using’ \ strat
\]

\[
\text{where}
\]

\[
x = \text{fib} (\text{n-1})
\]

\[
y = \text{fib} (\text{n-2})
\]

\[
\text{strat} \ v = \text{do} \ \text{rpar} \ x; \ \text{rseq} \ y; \ \text{return} \ v
\]

This strategy looks odd. We aren’t using the result of \text{rpar}, which should raise the red flags: normally the result of \text{rpar} should be embedded in the result returned, otherwise the spark is likely to be discarded by the garbage collector, or become a space leak. However, it is acceptable to discard the result of \text{rpar} if the argument is a variable, and that variable is already shared by the result, as it is in this case.

This is a somewhat subtle rule-of-thumb, and the user may well prefer the original direct definition using \text{runEval}. Note that the same technique was possible with original strategies, although there we had no option to use the more direct \text{runEval} style. This technique will be applied to a more realistic example in Section 5.3.

4.7 Sequential Strategies

An important class of strategies specify only evaluation degree, i.e. do evaluation only, and introduce no parallelism. Since they create no sparks, there is no need for these strategies to rebuild the data
structure that they are passed. For example, if we were to define a
strategy that evaluates a list sequentially as

```haskell
forceList = evalList rseq :: Strategy [a]
```

then the result is a strategy that is not only needlessly inefficient,
but worse, may overflow the stack on long lists because evalList
is not tail-recursive.

Hence we dedicate a separate module Seq to the class of strategies
that do evaluation only. These sequential strategies have type

```haskell
Seq.Strategy a = a -> ()
```

We make Seq.Strategy into a “subtype” of Strategy by providing
an explicit upcast evalSeq, which evaluates a sequential strategy
before returning the evaluated argument into the Eval monad.

```haskell
evalSeq :: Seq.Strategy a -> Strategy a
evalSeq ss x = ss x 'pseq' return x
```

Basic sequential strategies and sequential strategy combinators are
similar to the respective original strategies and combinators; for example:

```haskell
r0 :: Seq.Strategy a
r0 x = ()
```

```haskell
rseq :: Seq.Strategy a
rseq x = x 'seq' ()
```

```haskell
seqList :: Seq.Strategy a -> Seq.Strategy [a]
seqList ss [] = ()
seqList ss (x:xs) = ss x 'seq' seqList ss xs
```

As the order of evaluation of substructures is irrelevant here, these
combinators may use the ordinary Haskell seq operator instead of
pseq, granting the compiler more freedom to optimise the order of
evaluation. In contrast, the upcast evalSeq must use pseq to force
evaluation of the sequential strategy before returning.

Finally, seqFoldable is the sequential strategies’ counterpart to
the generic strategy evalTraversable.

```haskell
seqFoldable :: Foldable t
  => Seq.Strategy a -> Strategy (t a)
seqFoldable ss = foldl' (const ss) ()
```

seqFoldable strictly applies a strategy to all elements of a data
structure. Given the simpler return type of sequential strategies,
seqFoldable is already applicable to all Foldable data structures,
which form a super class of the Traversable data structures.

Sequential strategies are widely used. The example below transposes
a list of matrices mats, each represented as a list of lists, in
parallel without evaluating the matrix elements. The sequential strategy
seqList (seqList r0) evaluates just the shape of a matrix
while the parMap computes the parallel transpose:

```haskell
parMap (evalSeq (seqList (seqList r0))) transpose mats
```

The detailed control of evaluation degree provided by sequential
strategies may also be useful for tuning sequential programs. In
effect the module Seq complements existing abstractions provided by
the module DeepSeq.

### 4.8 Fusion

Using strategies in a modular way often implies that an interme-
diate data structure is generated by the computation, filtered by the
strategy, and finally consumed upstream. Consider once again
parMap:

```haskell
parMap :: Strategy b -> (a -> b) -> [a] -> [b]
parMap s f xs = map f xs 'using' parList s
```

The list produced by map is consumed by parList, which generates
another list to return to the caller of parMap. Furthermore,
there is an extra traversal: both map and parList traverse the complete
list.

Ideally we would like to have this intermediate structure and the
extra traversal eliminated by the compiler. Fortunately, using GHC
it is almost trivial to arrange that this optimisation occurs: GHC
provides user-defined transformation rules, which are used to im-
plement list fusion between many of the standard list-producing
and consuming library functions. Our parList is defined in terms of
parTraverse, which is defined in terms of traverse, and the
list instance of traverse happens to be defined in terms of foldr.
The intermediate list between map and foldr is automatically re-
moved by GHC’s transformation rules, so in fact parMap compiles to
an efficient single-traversal loop.

The measurements we report in Section 6 are without the bene-
fit of fusion. Separate measurements with fusion enabled, which
require an extra annotation in the Data.Traverse library, exhib-
tied a small improvement in speedup of +1.40% across most of the
applications. Since the overhead of data structure traversal in
strategies is fairly small (see Section 6.2) we cannot expect a major
improvement from this conceptually important optimisation.

### 5. Advanced Strategies

This section discusses how advanced features such as clustering,
buffering and parallel patterns, can be expressed in the new strate-
gies. Such features are essential for real parallel applications, and
are used in the kernels measured in Section 6.3

#### 5.1 Embedded Strategies: Rolling Buffers

Some parallel abstractions that are important for parallel perfor-
ance tuning rely on embedding parallelism inside a lazy data
structure, such that opportunities for parallel evaluation are cre-
ated “on demand” by the consumer of the data structure. The most
commonly encountered example is a parallel buffer [Trinder et al.
1998].

```haskell
parBuffer :: Int -> Strategy a -> Strategy [a]
```

Informally the idea is that parBuffer n s xs yields a list in which
evaluation of the ith element induces parallel evaluation of the
(i + n)th element with the first n elements being evaluated in
parallel immediately. The result list must therefore be lazy, at least
beyond the first n elements.

In the original strategies, while the parBuffer functionality could
be defined perfectly well, it could not be expressed as a strategy,
because it returns a new list containing parallelism embedded in
the lazy components. That is, the original type was

```haskell
parBuffer :: Int -> Strategy a -> [a] -> [a]
```

This was an unfortunate wart, because it meant that parBuffer
could not be used as the argument to a strategy combinator and thus
compositionality was diminished.

Fortunately embedded parallelism can be directly expressed in the
new strategy formulation, and so parBuffer and functions like it
are instances of the Strategy type.

A fully compositional implementation of parBuffer can be found
below. It implements a rolling buffer (with amortised constant
overhead) by means of a highly optimised functional queue data
structure provided by module Data.Sequence. The rolling buffer
functionality is provided by roll, which takes a functional queue
(the buffer) and a list of elements yet to go into the buffer, and

---

6 One would typically not use parList on long lists as too many sparks
would be created, instead parBuffer tends to be more practical.
returns a list (via the Eval monad). Whenever the result list is
demanded, roll applies the strategy \( s \) to the first element \( z \) to
go into the buffer and sticks the result to the end of the queue (by
calling \( q \mid z' \)). Then it pulls the first element \( y' \) out at the front of
the queue (by matching \( \text{viewl} (\ldots) \) against \( y' : q' \)) and returns
it as the head of the result list while embedding the recursive call
into the tail of the result list.

evalBuffer :: \( \text{Int} \rightarrow \text{Strategy} \ a \rightarrow \text{Strategy} \ [a] \)
evalBuffer \( n \) \( s \) \( x s \) =
  roll (fromList (ys \( \text{using} \) evalList \( s \))) \( z s \) 
  where \( (ys,zs) = \text{splitAt} \ n \ x s \)
  roll q \( [] \) = return (toList q)
  roll q (z:zs) = do z' <- s z
  let y' : q' = \text{viewl} (q \mid z')
  return \( (y':q') : \text{runEval} \ (\text{roll} \ q' \ zs) \)

parBuffer :: \( \text{Int} \rightarrow \text{Strategy} \ a \rightarrow \text{Strategy} \ [a] \)
parBuffer \( n \) \( s \) = evalBuffer \( n \) (rpar 'dot' \( s \))

5.2 Clustering

When tuning the performance of parallel programs it is often important
to increase the size of parallel computation, i.e. to use a
cosser granularity, in order to achieve a better ratio of computation
versus coordination costs. Implementations often contain mechanisms
to automatically control granularity on loaded processors. The scenario of
fizzling sparks discussed in Section 5.1 is such an example, because the work of a spark is performed by an
already running computation. However further improvements can be obtained by explicitly controlling thread granularity, and in the
context of the original strategies we developed a range of clustering
methods, as well as a method \( \text{lift} \) that turns an operation over the
original data structure into one over such a clustered data structure.

class \( \text{(Traversable}, \text{Monoid}} a) \Rightarrow \text{Cluster} \ a \ c \ where
  \text{cluster} :: \( \text{Int} \rightarrow a ightarrow c \ a \)
  \text{decluster} :: c \ a \rightarrow a
  \text{lift} :: (a ightarrow b) ightarrow c \ a \rightarrow c \ b

  \text{lift} = \text{fmap}
  \quad \text{-- } c \text{ is a Functor, via Traversable}
  \text{decluster} = \text{fold}
  \quad \text{-- } c \text{ is Foldable, via Traversable}
  \quad \text{-- we require: declusterຮ. cluster} n = \text{id}

By assuming the Traversable and Monoid contexts we get several
operations for free. Through the implicit Functor context, we can use
\text{fmap} to lift an operation over the base type to one in the
cluster type. And through the Monoid and Foldable contexts (the
latter implicit), we can use \text{fold} as the default for \text{decluster} —
provided it is an inverse of \text{cluster}.

As an example we provide an instance for lists, clustered into
lists of lists. Notably, we only have to provide a definition for the
cluster method.

instance Cluster \( [a] \) \[ [] \] where
  \text{cluster} _ [] = []
  \( \text{cluster} \ n \ x s = ys : \text{cluster} \ n \ zs ~ y : zs = \text{splitAt} \ n \ x s \)

We aim to define a strategy combinator

ev\text{alCluster} :: \text{Cluster} \ a \ c
  \Rightarrow \text{Int} ightarrow \text{Strategy} \ a ightarrow \text{Strategy} \ a
  \text{which takes a cluster size parameter and generically transforms a strategy}
  \text{by performing clustering and declustering behind the scenes (using the methods of appropriate Cluster instances). Un-}
  \text{fortunately, the cluster type} \ c \text{ shows up only in the class context, which means it could be ambiguous — in fact, it should: be that there may well be multiple reasonable ways of clustering a given type.}

To disambiguate the cluster type, we need to expose \( c \) in the
signature of evalCluster by passing it as an extra argument
(which requires wrapping it with a fresh type variable \( w \)). This extra
argument serves purely as a “type parameter”, it is never evaluated
and will be optimised away by the compiler.

evalCluster :: \forall a w c \ . \text{Cluster} \ a \ c
  \Rightarrow w c \rightarrow \text{Int} ightarrow \text{Strategy} \ a ightarrow \text{Strategy} \ a
  \text{evalCluster} \ _ n \ s \ x =
    \text{return} \ (\text{decluster} \ (\text{cluster} \ n \ x \ \text{using} \ cs))
  \text{where} \ cs = \text{evalTraversable} \ s :: \text{Strategy} \ (c \ a)

Thanks to the \text{Traversable} context (inherited from \text{Cluster}), we
can lift the strategy \( s \) to a strategy \( cs \) which is applicable to the
clustered input. Note that the type annotation in the \text{where} clause
necessitates the explicit \text{forall} in the signature.

With this infrastructure we can define a generic \text{parMapCluster},
a variant of \text{parMap} performing implicit clustering (based on the
\text{Cluster} class) behind the scenes.

\text{parMapCluster} :: \forall a b w c \ . \text{Cluster} \ [b] \ c
  \Rightarrow w c \rightarrow \text{Int} ightarrow \text{Strategy} \ b 
  \rightarrow (a ightarrow b) ightarrow \text{Strategy} \ a
  \text{parMapCluster} _ n \ s \ f x s = \text{map} \ f \ x s
  \text{‘using’} \ \text{evalCluster} _ {\ldots} : w c \ n \ (\text{rpar} \ ‘dot’ \ \text{evalList} \ s)

\text{Observe how a type annotation is used to emulate passing the}
\text{(wrapped) cluster type} \ c \text{ as a ‘type argument’ to evalCluster: the}
double underscore \( _{\ldots} \) is short for the bottom value \text{undefined}.

To improve readability, instead of wrapping the type argument with
fresh type variables, we can use a properly named phantom type:

\text{data ClusterWith :: \( (\ast \rightarrow \ast) \rightarrow \ast \) \}

Now it is intuitive that \text{parMapCluster} _ {\ldots} : \text{ClusterWith} []
uses lists for clustering.

5.3 A Divide-and-conquer Pattern

One of the main strengths of strategies is the possibility of con-
structing abstractions over patterns of parallel computation. There-
by all code specifying the coordination of the program is confined to
the pattern. Concrete applications can then instantiate the func-
tion parameters to get parallel execution for free. Such patterns are
commonly known as algorithmic skeletons [Cole 1989].

As an example we give the implementation of a divide-and-conquer pattern. It is parametrised by a function that specifies the operation
to be applied on atomic arguments (\( f \)), a function to (potentially)
divide the argument into two smaller values (\( \text{divide} \)), and a func-
tion to combine the results from the recursive calls (\text{conquer}). Ad-
ditionally, we provide a function \text{threshold} that is used to limit
the amount of parallelism, by using a sequential strategy for argu-
ments below the threshold.

\text{divideConq} :: \( a \rightarrow b \)
  \Rightarrow \text{compute the result}
  \rightarrow a
  \text{-- the value}
  \rightarrow (a \rightarrow \text{Bool})
  \text{-- par threshold reached?}
  \rightarrow (b \rightarrow b \rightarrow b)
  \text{-- combine results}
  \rightarrow (a \rightarrow \text{Maybe} \ (a,a))
  \text{-- divide}
  \rightarrow b
All coordination aspects of the function are encoded in the strategy `strat`, which describes how the two subcomputations `l1` and `r1` should be evaluated. The thresholding predicate `threshold` provided by the caller places a bound on the depth of parallelism, and this is used by `strat` to decide whether to spark both `l1` and `r1` or to evaluate them directly. The definition of `divConq` achieves separation between the specifications of algorithm and parallelism, the latter being confined entirely to the definition of `strat`.

5.4 Improving Safety

The original strategy type `a -> ()` embodies the key modularity goal of separating computation and coordination. As any original strategy can only ever return `()`, it can never change the result of a computation, up to divergence. Unfortunately, the new strategy type gives up this type safety. Strategies of the new type `strat` should be identity functions, i.e. only evaluate their argument but never change its value; we term this property identity safety. However, the type system cannot enforce this behaviour and it is all too easy to accidentally write flawed strategies, for instance:

```haskell
x:xs "using" \_ -> parList rdeepseq xs
```

The intention of the programmer is to evaluate the tail of the list in parallel when the list is demanded. The strategy will do that, but then returns only the tail of the list.

We propose a way of trading expressiveness for type checked identity safety. For this purpose, the module `SafeStrategies` clones the functionality and interface of Strategies, except for wrapping the strategy type with a newtype and providing an explicit strategy application operator.

```haskell
newtype Strategy a = MkStrat (a -> Eval a)

($) :: Strategy a -> a -> Eval a
(MkStrat strat) $ x = strat x
```

By hiding the constructor `MkStrat` when importing the module `SafeStrategies`, programmers can choose to treat `Strategy` as an abstract type, thereby restricting themselves to use only strategies constructed by the predefined and trusted (identity safe) strategy combinators (like `evalList` and `evalTraversable`). Since `MkStrat` is not available, the type checker will prevent programmers from “hand-rolling” their own strategies (e.g. the flawed strategy above will be rejected), thereby eliminating the danger of accidentally violating identity safety.

Yet, programmers can still use the `Eval` monad freely. For instance, the non-modular example of task parallelism from Section 3.4 can be ported to `SafeStrategies` by inserting `$()` after `rpar` and `rseq`. Of course, careless use of `rpar` may cause space leaks or lost parallelism, depending on the GC policy (Section 3), but that is a lesser concern than identity safety because it does not compromise functional correctness.

Why does `SafeStrategies` export the constructor `MkStrat` at all, rather than making `Strategy` a proper abstract type? The reason is that programmers who do need to “hand-roll” their own strategies may want to wrap them in `MkStrat`. Thus, `MkStrat` marks the pieces of code where programmers incur “proof obligations” to establish identity safety.

6. Evaluation

This section discusses our measurements in detail, but first we summarise the key results:

- For all programs, the speedup and runtime results with original and new strategies are very similar, giving us confidence that they specify the same parallel coordination for a range of programs and parallel paradigms (Figure 2).
- The speedups achieved with the new strategies are slightly better compared to those with the original strategies: a mean of 4.96 versus 4.83 on 7 cores across all applications (columns 3 & 2 of Table 2).
- The new strategies fix the space leak outlined in Section 3, reducing heap residency on a single core by 56.43% across all applications, and better support speculative parallelism (Section 6.4).
- The overheads of the new strategies are low: mean sequential run-time overhead is 3.84% (Table 1), and memory overheads are low for most programs (columns 8 – 11 of Table 2).

6.1 Apparatus

Our measurements are made on an eight-core, 8GB RAM, 6MB L2 cache, HP XW6600 Workstation comprising two Intel Xeon 5410 quad-core processors, each running at 2.33GHz. The benchmarks run under Linux Fedora 7 using a recent GHC development snapshot (6.13 as of 20.5.2010), and parallel packages 1.1.0.1 and 3.1.0.0, for original and new strategies, respectively. The data points reported are the median of 3 executions. We measure up to 7 cores as measurements on the eighth core are known to introduce some variability.

Our benchmarks are 10 parallel applications from a range of application areas; 8 of these have been taken from existing benchmarks suites [Aswad et al. 2009; Loidl et al. 1999; Marlow et al. 2009] and 2 benchmarks, Coins and TransClos, have been developed afresh with the new strategies module. The programs are the computational kernels of realistic applications, cover a variety of parallel paradigms, and employ several important parallel programming techniques, such as thresholding to limit the amount of parallelism generated, and clustering to obtain coarser thread granularity.

**Genetic** aligns RNA sequences, using divide-and-conquer parallelism and nested data parallelism. **MiniMax** performs an alphabeta search in a 2-player game tree, using divide-and-conquer parallelism and exploiting laziness to prune unnecessary subtrees. **Queens** solves the n-queens problem, using divide-and-conquer parallelism with an explicit threshold. **LinSolv** finds an exact solution to a set of linear equations, employing the data parallel multiple homomorphic images approach. **Hidden** performs hidden-line removal in 3D rendering and uses data parallelism via the `parList` strategy. **Maze** searches for a path in a 2D maze and uses speculative data parallelism. **Sphere** is a ray-tracer from the Haskell nofib suite, using nested data parallelism, implemented as `parMaps`. **TransClos** finds all elements that are reachable via a given relation from a given set of seed values, using a `parBuffer` strategy over an infinite list. **Coins** computes the number of ways of paying a given value from a given set of coins, using divide-and-conquer parallelism. **MatMult** performs matrix multiplication using data parallelism with implicit clustering.
6.2 Sequential Overhead

Table 1 shows the sequential runtime overheads. For the new strategies, we encounter a runtime overhead of at most +18.14% for the MatMult program, which is mainly due to the additional work in performing clustering. For all other programs the strategy overhead is significantly lower. Notably, the data parallel programs have a fairly low overhead, despite the additional traversal of a data structure to expose parallelism. Comparing the geometric mean of the runtime overheads imposed by both strategy versions we encounter only a slightly higher overhead for the new strategies: +3.84% compared to +3.21% with the original strategies. This justifies the new strategy approach of high-level generic abstractions.

6.3 Parallel Performance

**Speedups:** Figure 2 compares the absolute speedup curves (i.e. speedup relative to sequential runtime) for the applications with the original and new strategies. Both the runtime curves (not reported here) and speedup curves for the original and new strategies are very similar. The pattern is repeated in more detailed analysis, e.g. in columns 2 and 3 of Table 2. We conclude that the original and new strategies specify the same parallel coordination for a variety of programs representing a range of parallel paradigms, and several tuning techniques.

**Performance:** Table 2 analyses in detail the speedups, number of sparks and memory consumption of all applications, running on 7 cores of an 8 core machine with the original strategies and the new strategies, always using a ROOT garbage collection policy. The number of generated sparks was in all cases virtually identical between original strategies and new strategies, giving us further confidence that the two formulations are expressing the same parallelism. Small differences in the number of generated sparks arise because GHC has a non-deterministic execution model in which a computation close to the root will itself evaluate potential child computations, causing their corresponding sparks to fizzle. Hence the granularity of the generated sparks is automatically made coarser, reducing overheads, as can be seen from the speedups achieved. In general, the new strategies provide more opportunities for sparks to fizzle, as discussed in Section 3. This shows up in a lower number of converted sparks for all divide-and-conquer and nested data parallel programs. For single-level data parallelism as in Sphere, where sparks never share graph structures, there is little or no reduction in the number of converted sparks.

Interestingly, the performance of the new strategies in the Queens and Sphere programs is better than in the original strategies. Examining the heap consumption reveals that with the new strategies the heap residency is significantly reduced: –24.11% for Queens and –14.53% for Sphere. This results in a lower total garbage collection time, which contributes to about half of the reduction in runtime. The reduction in residency is accounted for by the improved space behaviour of the new strategies: the space retained by superfluous sparks is being reclaimed.

**Granularity improvement:** The comparison of generated versus converted sparks in Table 2 demonstrates the runtime system’s effective handling of potential parallelism (sparks). Even when an excessive number of sparks is generated, for example in Coins, the runtime-system converts only a small fraction of these sparks. As with any divide-and-conquer program, a thread generated for a computation close to the root will itself evaluate potential child computations, causing their corresponding sparks to fizzle. Hence the granularity of the generated sparks is automatically made coarser, reducing overheads, as can be seen from the speedups achieved. In general, the new strategies provide more opportunities for sparks to fizzle, as discussed in Section 3. This shows up in a lower number of converted sparks for all divide-and-conquer and nested data parallel programs. For single-level data parallelism as in Sphere, where sparks never share graph structures, there is little or no reduction in the number of converted sparks.

6.4 Memory Management

**Fixing the space leak:** The new strategies fix the space leak outlined in Section 3. For example, for the parallel raytracer that exhibited the space leak with the original strategies, the heap residency drops from 11.6GB to 5.8MB with the new strategies on 1 core, and the runtime correspondingly drops by about a factor of 3. Comparing single core executions for all benchmark programs shows a mean reduction in residency of 56.43% with the new strategies. However, for multiple cores the heap measurements in Table 2 do not show a consistent reduction in residency for the new strategies. There are a number of factors contributing to the observed behaviour here:

- With parallel processors available, garbage sparks tend to be evaluated by other cores and hence fizzle, avoiding the space leak (but wasting some cycles).
- Parallel evaluation itself tends to change the residency profile, in most cases increasing the residency compared to sequential execution.
- Residency is recorded by sampling and hence the measured value is noisy.

**Speculation:** To assess the effectiveness of the garbage collection policies ROOT and WEAK, described in Section 3 for managing speculation we use a program that applies drop to a parallelised list, computing the number of primes up to a given value, thereby rendering the sparks on the dropped list elements speculative:

```haskell
sum $ drop ([(m1-m0) 'quot' 2] $ ([ length (primes n) | n <- [m0..m1] ] 'using' parList rdeepseq)
```

With the WEAK policy almost all sparks of the original strategies are discarded, as expected. With the new strategies 3404 out of 10001 are converted, 32% fewer than with the ROOT policy, although this value changes considerably between executions. Most importantly, the WEAK policy prunes 4796 sparks, almost all of the 5000 speculative sparks. In contrast, the ROOT policy prunes only 3193 sparks, all of them due to fizzling.

### Table 1. Sequential runtime overheads.

<table>
<thead>
<tr>
<th>Program</th>
<th>Seq. Runtime (seconds)</th>
<th>Original Strategies</th>
<th>New Strategies</th>
<th>Paradigm</th>
</tr>
</thead>
<tbody>
<tr>
<td>LinSolv</td>
<td>23.40</td>
<td>+0.90</td>
<td>+1.97</td>
<td>Nested Data par</td>
</tr>
<tr>
<td>TransClos</td>
<td>83.12</td>
<td>+0.77</td>
<td>+2.24</td>
<td>Data par</td>
</tr>
<tr>
<td>Sphere</td>
<td>21.11</td>
<td>+4.78</td>
<td>+3.32</td>
<td>Nested Data par</td>
</tr>
<tr>
<td>MiniMax</td>
<td>36.98</td>
<td>+0.87</td>
<td>+3.22</td>
<td>D&amp;C</td>
</tr>
<tr>
<td>Coins</td>
<td>42.49</td>
<td>+1.11</td>
<td>+2.12</td>
<td>D&amp;C</td>
</tr>
<tr>
<td>Queens</td>
<td>25.51</td>
<td>+1.37</td>
<td>+6.12</td>
<td>D&amp;C</td>
</tr>
<tr>
<td>MatMult</td>
<td>18.85</td>
<td>+16.87</td>
<td>+18.14</td>
<td>Data par</td>
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<tr>
<td>Genetic</td>
<td>33.46</td>
<td>+2.96</td>
<td>+3.97</td>
<td>D&amp;C Data par</td>
</tr>
<tr>
<td>Hidden</td>
<td>4.61</td>
<td>+5.86</td>
<td>+2.17</td>
<td>Data par</td>
</tr>
<tr>
<td>Maze</td>
<td>40.93</td>
<td>-2.22</td>
<td>-3.59</td>
<td>Nested Data par</td>
</tr>
<tr>
<td>Geom. Mean</td>
<td></td>
<td>+3.21</td>
<td>+3.84</td>
<td></td>
</tr>
</tbody>
</table>

Only two of our application kernels use speculation: MiniMax and Maze. In the case of MiniMax the WEAK policy significantly reduces the variation of residencies over the number of cores, and in a 7-core execution residency is reduced by 83.4%. In the case of Maze residency remains unchanged. In both cases the speedup improves only slightly when employing a WEAK policy. Of course, the very inability of reclaiming speculative sparks with the ROOT policy discouraged any applications using them on a larger scale.

### 7. Related Work

Parallel functional languages typically embed high level coordination languages into high level computation languages. A range of high level coordination models have been used and this section relates the semi-explicit approach adopted by evaluation strategies to other approaches.

Skeleton based coordination, for instance Loogen et al. [2005] or Scaife et al. [2005], is popular in both imperative and functional languages, and exploits a small set of predefined skeletons. Each skeleton is a polymorphic higher-order function describing a common coordination pattern with an efficient parallel implementation Cole [1989]. As polymorphic higher-order functions, evaluation strategies are similar to skeletons, but there are some key differences. Rather than a fixed set of skeletons, evaluation strategies are readily combined to form new strategies. Moreover, where skeletons are parametrised with computational arguments, a strategy is typically applied to a computation.

Data parallel coordination, as in Blelloch [1996] or implemented in Data Parallel Haskell [Chakravarty et al. 2007], supports the parallel evaluation of every element in a collection. This is a good match with Haskell’s powerful constructs for bulk data types, in particular lists. Data parallelism is often more implicit than evaluation strategies: the programmer simply identifies the collections to be evaluated in parallel. Strategies are more general in that they can express both control parallelism and data parallelism, although in terms of performance Data Parallel Haskell is designed to compile parallel programs down to highly optimised low-level loops over arrays, and hence should achieve significantly better absolute performance on data-parallel programs than would be possible using strategies.

Entirely implicit coordination aims to minimise programmer input, typically using either profiling as in Harris and Singh [2007] or parallel iteration as in Greck and Scholz [2003]. Few entirely implicit approaches other than parallel iteration have delivered acceptable performance Nikhil and Arvind [2001]. Evaluation strategies provide more general parallel coordination than loop parallelism.

Recent work by Prabhu et al. [2010] has shown that parallelism by speculating on future data dependencies can be provided as a safe (correctness-preserving) abstraction to programmers. As one might expect, their approach translates naturally into Haskell using par. This approach to speculation is complementary to the speculative parallelism afforded by strategies.

### Table 2. Speedups, number of sparks and heap consumption on 7 cores.

<table>
<thead>
<tr>
<th>Number of Cores</th>
<th>Speedup</th>
<th>Generated Sparks</th>
<th>Converted Sparks</th>
<th>Allocated Heap</th>
<th>Maximum Residency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orig.</td>
<td>New</td>
<td>Orig.</td>
<td>New</td>
<td>Orig.</td>
<td>New</td>
</tr>
<tr>
<td>LinSolv</td>
<td>6.59</td>
<td>6.44</td>
<td>7562</td>
<td>7562</td>
<td>7562</td>
</tr>
<tr>
<td>TransClos</td>
<td>6.04</td>
<td>5.81</td>
<td>1041</td>
<td>1041</td>
<td>1041</td>
</tr>
<tr>
<td>Sphere</td>
<td>4.95</td>
<td>5.67</td>
<td>160</td>
<td>160</td>
<td>160</td>
</tr>
<tr>
<td>MiniMax</td>
<td>5.61</td>
<td>5.33</td>
<td>145925</td>
<td>146833</td>
<td>2702</td>
</tr>
<tr>
<td>Coins</td>
<td>4.58</td>
<td>5.49</td>
<td>1589</td>
<td>1563</td>
<td>1589</td>
</tr>
<tr>
<td>Queen</td>
<td>5.04</td>
<td>5.39</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>MaliMat</td>
<td>4.95</td>
<td>5.02</td>
<td>659</td>
<td>647</td>
<td>659</td>
</tr>
<tr>
<td>Genetic</td>
<td>4.66</td>
<td>4.66</td>
<td>324</td>
<td>324</td>
<td>324</td>
</tr>
<tr>
<td>Maze</td>
<td>2.05</td>
<td>2.01</td>
<td>2723</td>
<td>2835</td>
<td>2525</td>
</tr>
<tr>
<td>Geom. Mean</td>
<td>4.83</td>
<td>4.96</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 2.** Speedup graphs of the application kernels with original and new strategies.
8. Conclusion

The original strategies were developed in 1996 for Haskell 1.2, i.e. before monads, and using a compiler with relatively tame optimisations. The context for the new strategies is radically different. Monads, supported by rich libraries and syntactic sugar like do-notation, are now the preferred mechanism for sequencing computations, and are familiar to the rapidly growing Haskell user community. Application functors elegantly encode data structure traversals. Finally, the aggressive use of optimisations in mature Haskell implementations like GHC make bespoke efficiency specialisations unnecessary.

The new strategy formulation capitalises on improved Haskell idioms and implementations to provide a modular and compositional notation for specifying pure deterministic parallelism. While it has some minor drawbacks: being relatively complex, providing relatively weak type safety, and requiring care to express control parallelism, the advantages are many and substantial. It provides clear, generic, and efficient specification of parallelism with low runtime overheads. It resolves a subtle space management issue associated with parallelism, better supports speculation, and is able to directly express parallelism embedded within lazy data structures.

The new strategies are available as part of the Haskell parallel package (since Version 3); additional code and benchmarks can be downloaded from http://www.macs.hw.ac.uk/~dsg/gph/papers/abstracts/new-strategies.html

We plan to further enhance and formalise the identity safety of the new strategies, following the direction discussed in Section 5.4. Moreover the genericity of the new strategies could be improved by automatically deriving instances of the NFData class.

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References


