Parallel and Concurrent Programming in Haskell

version 1.1

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Contents

1 Introduction

While most programming languages nowadays provide some form of concurrent or parallel programming facilities, very few provide as wide a range as Haskell. The Haskell language is fertile ground on which to build abstractions, and concurrency and parallelism are no exception here. In the world of concurrency and parallelism, there is good reason to believe that no *one size fits all* programming model for concurrency and parallelism exists, and so prematurely committing to one particular paradigm is likely to tilt the language towards favouring certain kinds of problem. Hence in Haskell we focus on providing a wide range of abstractions and libraries, so that for any given problem it should be possible to find a tool that suits the task at hand.

In this tutorial I will introduce the main programming models available for concurrent and parallel programming in Haskell. The tutorial is woefully incomplete — there is simply too much ground to cover, but it is my hope that future revisions of this document will expand its coverage. In the meantime it should serve as an introduction to the fundamental concepts through the use of practical examples, together with pointers to further reading for those who wish to find out more.

This tutorial takes a deliberately practical approach: most of the examples are real Haskell programs that you can compile, run, measure, modify and experiment with. For information on how to obtain the code samples, see Section 1.1.1. There is also a set of accompanying exercises.

In order to follow this tutorial you should have a basic knowledge of Haskell, including programming with monads.

Briefly, the topics covered in this tutorial are as follows:

- Parallel programming with the `Eval` monad (Section 2.1)
- Evaluation Strategies (Section 2.2)
- Dataflow parallelism with the `Par` monad (Section 2.3)
- Basic Concurrent Haskell (Section 3)
- Asynchronous exceptions (Section 3.3)

- Software Transactional Memory (Section 3.4)
- Concurrency and the FFI (Section 3.5)
- High-speed concurrent servers (Section 3.6)

One useful aspect of this tutorial as compared to previous tutorials covering similar ground ((Peyton Jones 2002; Peyton Jones and Singh 2009)) is that I have been able to take into account recent changes to the APIs. In particular, the `Eval` monad has replaced `par` and `pseq` (thankfully), and in asynchronous exceptions `mask` has replaced the old `block` and `unblock`.

1.1 Tools and resources

To try out Parallel and Concurrent Haskell, and to run the sample programs that accompany this article, you will need to install the Haskell Platform[1]. The Haskell Platform includes the GHC compiler and all the important libraries, including the parallel and concurrent libraries we shall be using. This version of the tutorial was tested with the Haskell Platform version 2011.2.0.1, and we expect to update this tutorial as necessary to cover future changes in the platform.

Section 2.3 requires the `monad-par` package, which is not currently part of the Haskell Platform. To install it, use the `cabal` command:

```
$ cabal install monad-par
```

(The examples in this tutorial were tested with `monad-par` version 0.1.0.1).

Additionally, we recommend installing ThreadScope[2]. ThreadScope is a tool for visualising the execution of Haskell programs, and is particularly useful for gaining insight into the behaviour of parallel and concurrent Haskell code. ThreadScope can be installed with a simple `cabal install threadscope` on some systems (mainly Linux), but for other systems refer to the ThreadScope documentation at the aforementioned URL.

While reading the article we recommend you have the following documentation to hand:

- The GHC User's Guide[3],
- The Haskell Platform library documentation, which can be found on the main Haskell Platform site[4]. Any types or functions that we use in this article that are not explicitly described can be found documented there.

[1] `http://hackage.haskell.org/platform/`

[2] `http://research.microsoft.com/en-us/projects/threadscope/`

[3] `http://www.haskell.org/ghc/docs/latest/html/users_guide/`

[4] `http://hackage.haskell.org/platform/`

It should be noted that none of the APIs described in this tutorial are *standard* in the sense of being part of the Haskell specification. That may change in the future.

1.1.1 Sample Code

The repository containing the source for both this document and the code samples can be found at `https://github.com/simonmar/par-tutorial`. The current version can be downloaded from `http://community.haskell.org/~simonmar/par-tutorial-1.1.zip`.

1.2 Terminology: Parallelism and Concurrency

In many fields, the words *parallel* and *concurrent* are synonyms; not so in programming, where they are used to describe fundamentally different concepts.

A *parallel* program is one that uses a multiplicity of computational hardware (e.g. multiple processor cores) in order to perform computation more quickly. Different parts of the computation are delegated to different processors that execute at the same time (in *parallel*), so that results may be delivered earlier than if the computation had been performed sequentially.

In contrast, *concurrency* is a program-structuring technique in which there are multiple *threads of control*. Notionally the threads of control execute "at the same time"; that is, the user sees their effects interleaved. Whether they actually execute at the same time or not is an implementation detail; a concurrent program can execute on a single processor through interleaved execution, or on multiple physical processors.

While parallel programming is concerned only with efficiency, Concurrent programming is concerned with structuring a program that needs to interact with multiple independent external agents (for example the user, a database server, and some external clients). Concurrency allows such programs to be *modular*; the thread that interacts with the user is distinct from the thread that talks to the database. In the absence of concurrency, such programs have to be written with event loops and callbacks—indeed, event loops and callbacks are often used even when concurrency is available, because in many languages concurrency is either too expensive, or too difficult, to use.

The notion of "threads of control" does not make sense in a purely functional program, because there are no effects to observe, and the evaluation order is irrelevant. So concurrency is a structuring technique for effectful code; in Haskell, that means code in the `IO` monad.

A related distinction is between *deterministic* and *nondeterministic* programming models. A deterministic programming model is one in which each program can give only one result, whereas a nondeterministic programming model admits programs that may have different results, depending on some aspect of the execution. Concurrent programming models are necessarily nondeterministic, because they must interact with external agents that cause events at unpredictable times. Nondeterminism has some notable drawbacks, however: programs become significantly harder to test and reason about.

For parallel programming we would like to use deterministic programming models if at all possible. Since the goal is just to arrive at the answer more quickly, we would rather not make our program harder to debug in the process. Deterministic parallel programming is the best of both worlds: testing, debugging and reasoning can be performed on the sequential program, but the program runs faster when processors are added. Indeed, most computer processors themselves implement deterministic parallelism in the form of pipelining and multiple execution units.

While it is possible to do parallel programming using concurrency, that is often a poor choice, because concurrency sacrifices determinism. In Haskell, the parallel programming models are deterministic. However, it is important to note that deterministic programming models are not sufficient to express all kinds of parallel algorithms; there are algorithms that depend on internal nondeterminism, particularly problems that involve searching a solution space. In Haskell, this class of algorithms is expressible only using concurrency.

Finally, it is entirely reasonable to want to mix parallelism and concurrency in the same program. Most interactive programs will need to use concurrency to maintain a responsive user interface while the compute intensive tasks are being performed.

2 Parallel Haskell

Parallel Haskell is all about making Haskell programs run *faster* by dividing the work to be done between multiple processors. Now that processor manufacturers have largely given up trying to squeeze more performance out of individual processors and have refocussed their attention on providing us with more processors instead, the biggest gains in performance are to be had by using parallel techniques in our programs so as to make use of these extra cores.

We might wonder whether the compiler could automatically parallelise programs for us. After all, it should be easier to do this in a pure functional language where the only dependencies between computations are data dependencies, and those are mostly perspicuous and thus readily analysed. In contrast, when effects are unrestricted, analysis of dependencies tends to be much harder, leading to greater approximation and a large degree of false dependencies. However, even in a language with only data dependencies, automatic parallelisation still suffers from an age-old problem: managing parallel tasks requires some bookkeeping relative to sequential execution and thus has an inherent overhead, so the size of the parallel tasks must be large enough to overcome the overhead. Analysing costs at compile time is hard, so one approach is to use runtime profiling to find tasks that are costly enough and can also be run in parallel, and feed this information back into the compiler. Even this, however, has not been terribly successful in practice (Harris and Singh 2007).

Fully automatic parallelisation is still a pipe dream. However, the parallel programming models provided by Haskell do succeed in eliminating some mundane or error-prone aspects traditionally associated with parallel programming:

- Parallel programming in Haskell is *deterministic*: the parallel program always produces the same answer, regardless how many processors are used to run it, so parallel programs can be debugged without actually running them in parallel.

- Parallel Haskell programs do not explicitly deal with *synchronisation* or *communication*. Synchronisation is the act of waiting for other tasks to complete, perhaps due to data dependencies. Communication involves the transmission of results between tasks running on different processors. Synchronisation is handled automatically by the GHC runtime system and/or the parallelism libraries. Communication is implicit in GHC since all tasks share the same heap, and can share objects without restriction. In this setting, although there is no explicit communication at the program level or even the runtime level, at the hardware level communication re-emerges as the transmission of data between the caches of the different cores. Excessive communication can cause contention for the main memory bus, and such overheads can be difficult to diagnose.

Parallel Haskell does require the programmer to think about **Partitioning**. The programmer's job is to subdivide the work into tasks that can execute in parallel. Ideally, we want to have enough tasks that we can keep all the processors busy for the entire runtime. However, our efforts may be thwarted:

- **Granularity**. If we make our tasks too small, then the overhead of managing the tasks outweighs any benefit we might get from running them in parallel. So granularity should be large enough to dwarf the overheads, but not too large, because then we risk not having enough work to keep all the processors busy, especially towards the end of the execution when there are fewer tasks left.

- **Data dependencies** between tasks enforce sequentialisation. GHC's two parallel programming models take different approaches to data dependencies: in *Strategies* (Section 2.2), data dependencies are entirely implicit, whereas in the *Par monad* (Section 2.3), they are explicit. This makes programming with Strategies somewhat more concise, at the expense of the possibility that hidden dependencies could cause sequentialisation at runtime.

In this tutorial we will describe two parallel programming models provided by GHC. The first, *Evaluation Strategies* (Marlow et al. 2010) (Strategies for short), is well-established and there are many good examples of using Strategies to write parallel Haskell programs. The second is a dataflow programming model based around a `Par` monad (Marlow et al.). This is a newer programming model in which it is possible to express parallel coordination more explicitly than with Strategies, though at the expense of some of the conciseness and modularity of Strategies.

2.1 Basic parallelism: the `Eval` monad

In this section we will demonstrate how to use the basic parallelism abstractions in Haskell to perform some computations in parallel. As a running example that you can actually test yourself, we use a Sudoku solver[5]. The Sudoku solver is very fast, and can solve all 49,000 of the known puzzles with 17 clues[6] in about 2 minutes.

We start with some ordinary sequential code to solve a set of Sudoku problems read from a file:

```
import Sudoku
import Control.Exception
import System.Environment

main :: IO ()
main = do
    [f] <- getArgs
    grids <- fmap lines $ readFile f
    mapM_ (evaluate . solve) grids
```

The module `Sudoku` provides us with a function `solve` with type

```
solve :: String -> Maybe Grid
```

where the `String` represents a single Sudoku problem, and `Grid` is a representation of the solution. The function returns `Nothing` if the problem has no solution. For the purposes of this example we are not interested in the solution itself, so our `main` function simply calls `evaluate . solve` on

[5] The Sudoku solver code can be found in the module `Sudoku.hs` in the samples that accompany this tutorial.

[6] `http://mapleta.maths.uwa.edu.au/~gordon/sudokumin.php`

each line of the file (the file will contain one Sudoku problem per line). The `evaluate` funciton comes from `Control.Exception` and has type

```
evaluate :: a -> IO a
```

it evaluates its argument to *weak-head normal form*. Weak-head normal form just means that the expression is evaluated as far as the first constructor; for example, if the expression is a list, then `evaluate` would perform enough evaluation to determine whether the list is empty (`[]`) or non-empty (`_:_`), but it would do not evaluate the head or tail of the list. The `evaluate` function returns its result in the `IO` monad, so it is useful for forcing evaluation at a particular time.

Compile the program as follows:

```
$ ghc -O2 sudoku1.hs -rtsopts
[1 of 2] Compiling Sudoku           ( Sudoku.hs, Sudoku.o )
[2 of 2] Compiling Main             ( sudoku1.hs, sudoku1.o )
Linking sudoku1 ...
```

and run it on 1000 sample problems:

```
$ ./sudoku1 sudoku17.1000.txt +RTS -s
./sudoku1 sudoku17.1000.txt +RTS -s
   2,392,127,440 bytes allocated in the heap
      36,829,592 bytes copied during GC
         191,168 bytes maximum residency (11 sample(s))
          82,256 bytes maximum slop
               2 MB total memory in use (0 MB lost due to fragmentation)

  Generation 0:  4570 collections,     0 parallel,  0.14s,  0.13s elapsed
  Generation 1:    11 collections,     0 parallel,  0.00s,  0.00s elapsed

  Parallel GC work balance: -nan (0 / 0, ideal 1)

                        MUT time (elapsed)       GC time  (elapsed)
  Task  0 (worker) :    0.00s    (  0.00s)       0.00s    (  0.00s)
  Task  1 (worker) :    0.00s    (  2.92s)       0.00s    (  0.00s)
  Task  2 (bound)  :    2.92s    (  2.92s)       0.14s    (  0.14s)

  SPARKS: 0 (0 converted, 0 pruned)

  INIT  time    0.00s  (  0.00s elapsed)
  MUT   time    2.92s  (  2.92s elapsed)
  GC    time    0.14s  (  0.14s elapsed)
  EXIT  time    0.00s  (  0.00s elapsed)
  Total time    3.06s  (  3.06s elapsed)

  %GC time       4.6%  (4.6% elapsed)

  Alloc rate    818,892,766 bytes per MUT second
```

```
Productivity  95.4% of total user, 95.3% of total elapsed
```

The argument `+RTS -s` instructs the GHC runtime system to emit the statistics you see above. These are particularly helpful as a first step in analysing parallel performance. The output is explained in detail in the GHC User's Guide, but for our purposes we are interested in one particular metric: `Total time`. This figure is given in two forms: the first is the total CPU time used by the program, and the second figure is the *elapsed*, or wall-clock, time. Since we are running on a single processor, these times are identical (sometimes the elapsed time might be slightly larger due to other activity on the system).

This program should parallelise quite easily; after all, each problem can be solved completely independently of the others. First, we will need some basic functionality for expressing parallelism, which is provided by the module `Control.Parallel.Strategies`:

```haskell
data Eval a
instance Monad Eval

runEval :: Eval a -> a

rpar :: a -> Eval a
rseq :: a -> Eval a
```

Parallel coordination will be performed in a monad, namely the `Eval` monad. The reason for this is that parallel programming fundamentally involves *ordering* things: start evaluating `a` in parallel, *and then* evaluate `b`. Monads are good for expressing ordering relationships in a compositional way.

The `Eval` monad provides a `runEval` operation that lets us extract the value from `Eval`. Note that `runEval` is completely pure - there's no need to be in the `IO` monad here.

The `Eval` monad comes with two basic operations, `rpar` and `rseq`. The `rpar` combinator is used for creating parallelism; it says "my argument could be evaluated in parallel", while `rseq` is used for forcing sequential evaluation: it says "evaluate my argument now" (to weak-head normal form). These two operations are typicaly used together - for example, to evaluate `A` and `B` in parallel, we could apply `rpar` on `A`, followed by `rseq` on `B`.

Returning to our Sudoku example, let us add some parallelism to make use of two processors. We have a list of problems to solve, so it should suffice to divide the list in two and solve the problems in each half of the list in parallel. Here is some code to do just that[7]:

```haskell
    let (as,bs) = splitAt (length grids `div` 2) grids

    evaluate $ runEval $ do
```

[7] full code in sample `sudoku2.hs`

```
4         a <- rpar (deep (map solve as))
5         b <- rpar (deep (map solve bs))
6         rseq a
7         rseq b
8         return ()
```

line 1 divides the list into two equal (or nearly-equal) sub-lists, `as` and `bs`. The next part needs more explanation:

3 We are going to `evaluate` an application of `runEval`

4 Create a parallel task to compute the solutions to the problems in the sub-list `as`. The solutions are represented by the expression `map solve as`; however, just evaluating this expression to weak-head normal form will not actually compute any of the solutions, since it will only evaluate as far as the first `(:)` cell of the list. We need to fully evaluate the whole list, including the elements. This is why we added an application of the `deep` funciton, which is defined as follows:

```
deep :: NFData a => a -> a
deep a = deepseq a a
```

`deep` evaluates the entire structure of its argument, before returning the argument itself. It is defined in terms of the function `deepseq`, which is available from the `Control.DeepSeq` module.

Not evaluating deeply enough is a common mistake when using the `rpar` monad, so it is a good idea to get into the habit of thinking, for each `rpar`, "how much of this structure do I want to evaluate in the parallel task?". (indeed, it is such a common problem that in the `Par` monad to be introduced later, we went so far as to make `deepseq` the default behaviour).

5 Create a parallel task to compute the solutions to `bs`, exactly as for `as`.

6-7 Using `rseq`, we wait for both parallel tasks to complete.

8 Finally, return (for this example we aren't interested in the results themselves, only in the act of computing them).

In order to use parallelism with GHC, we have to add the `-threaded` option, like so:

```
$ ghc -O2 sudoku2.hs -rtsopts -threaded
[2 of 2] Compiling Main             ( sudoku2.hs, sudoku2.o )
Linking sudoku2 ...
```

Now, we can run the program using 2 processors:

```
$ ./sudoku2 sudoku17.1000.txt +RTS -N2 -s
./sudoku2 sudoku17.1000.txt +RTS -N2 -s
   2,400,125,664 bytes allocated in the heap
      48,845,008 bytes copied during GC
       2,617,120 bytes maximum residency (7 sample(s))
         313,496 bytes maximum slop
               9 MB total memory in use (0 MB lost due to fragmentation)

  Generation 0:  2975 collections,  2974 parallel,  1.04s,  0.15s elapsed
  Generation 1:     7 collections,     7 parallel,  0.05s,  0.02s elapsed

  Parallel GC work balance: 1.52 (6087267 / 3999565, ideal 2)

                        MUT time (elapsed)       GC time  (elapsed)
  Task  0 (worker) :    1.27s    (  1.80s)       0.69s    (  0.10s)
  Task  1 (worker) :    0.00s    (  1.80s)       0.00s    (  0.00s)
  Task  2 (bound)  :    0.88s    (  1.80s)       0.39s    (  0.07s)
  Task  3 (worker) :    0.05s    (  1.80s)       0.00s    (  0.00s)

  SPARKS: 2 (1 converted, 0 pruned)

  INIT  time    0.00s  (  0.00s elapsed)
  MUT   time    2.21s  (  1.80s elapsed)
  GC    time    1.08s  (  0.17s elapsed)
  EXIT  time    0.00s  (  0.00s elapsed)
  Total time    3.29s  (  1.97s elapsed)

  %GC time      32.9%  (8.8% elapsed)

  Alloc rate    1,087,049,866 bytes per MUT second

  Productivity  67.0% of total user, 111.9% of total elapsed
```

Note that the `Total time` now shows a marked difference between the CPU time (3.29s) and the elapsed time (1.97s). Previously the elapsed time was 3.06s, so we can calculate the *speedup* on 2 processors as $3.06/1.97 = 1.55$. Speedups are always calculated as a ratio of wall-clock times. The CPU time is a helpful metric for telling us how busy our processors are, but as you can see here, the CPU time when running on multiple processors is often greater than the wall-clock time for a single processor, so it would be misleading to calculate the speedup as the ratio of CPU time to wall-clock time (1.67 here).

Why is the speedup only 1.55, and not 2? In general there could be a host of reasons for this, not all of which are under the control of the Haskell programmer. However, in this case the problem is partly of our doing, and we can diagnose it using the ThreadScope tool. To profile the program using ThreadScope we need to first recompile it with the `-eventlog` flag, run it with `+RTS -ls`, and then invoke ThreadScope on the generated

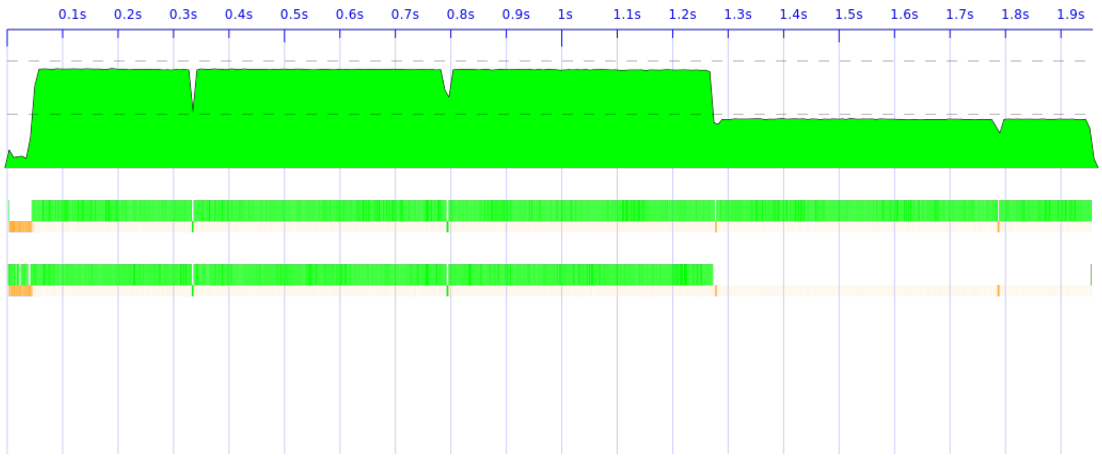


Figure 1: Sudoku2 ThreadScope profile

`sudoku2.eventlog` file:

```
$ rm sudoku2; ghc -O2 sudoku2.hs -threaded -rtsopts -eventlog
[2 of 2] Compiling Main             ( sudoku2.hs, sudoku2.o )
Linking sudoku2 ...
$ ./sudoku2 sudoku17.1000.txt +RTS -N2 -ls
$ threadscope sudoku2.eventlog
```

The ThreadScope profile is shown in Figure 1; this graph was generated by selecting "export to PNG" from ThreadScope, so it includes the timeline graph only, and not the rest of the ThreadScope GUI. The x axis of the graph is time, and there are three horizontal bars showing how the program executed over time. The topmost bar is known as the "activity" profile, and it shows how many processors were executing Haskell code (as opposed to being idle or garbage collecting) at a given point in time. Then there is one bar per processor, showing green when the processor is executing Haskell code, and orange when it is garbage collecting.

As we can see from the graph, there is a period at the end of the run where just one processor is executing, and the other one is idle (except for participating in regular garbage collections, which is necessary for GHC's parallel garbage collector). This indicates that our two parallel tasks are uneven: one takes much longer to execute than the other, and so we are not making full use of our 2 processors, which results in less than perfect speedup.

Why should the workloads be uneven? After all, we divided the list in two, and we know the sample input has an even number of problems. The reason for the unevenness is that each problem does not take the same amount of time to solve, it all depends on the searching strategy used by the Sudoku solver[8]. This illustrates an important distinction between two partitioning strategies:

- **Static Partitioning**, which is the technique we used to partition the Sudoku problems here, consists of dividing the work according to some pre-defined policy (here, dividing the list equally in two).
- **Dynamic Partitioning** instead tries to distribute the work more evenly, by dividing the work into smaller tasks and only assigning tasks to processors when they are idle.

The GHC runtime system supports automatic distribution of the parallel tasks; all we have to do to achieve dynamic partitioning is divide the problem into small enough tasks and the runtime will do the rest for us.

The argument to `rpar` is called a *spark*. The runtime collects sparks in a pool and uses this as a source of work to do when there are spare processors available, using a technique called *work stealing* (Marlow et al. 2009). Sparks may be evaluated at some point in the future, or they might not — it all depends on whether there is spare processor capacity available. Sparks are very cheap to create (`rpar` essentially just adds a reference to the expression to an array).

So, let's try using dynamic partitioning with the Sudoku problem. First we define an abstraction that will let us apply a function to a list in parallel, `parMap`:

```
parMap :: (a -> b) -> [a] -> Eval [b]
parMap f [] = return []
parMap f (a:as) = do
   b <- rpar (f a)
   bs <- parMap f as
   return (b:bs)
```

This is rather like a monadic version of `map`, except that we have used `rpar` to lift the application of the function `f` to the element `a` into the `Eval` monad. Hence, `parMap` runs down the whole list, eagerly creating sparks for the application of `f` to each element, and finally returns the new list. When `parMap` returns, it will have created one spark for each element of the list.

We still need to evaluate the result list itself, and that is a straightforward with `deep`:

```
    evaluate $ deep $ runEval $ parMap solve grids
```

Running this new version[9] yields more speedup:

```
  Total time    3.55s  (  1.79s elapsed)
```

[8]in fact, we ordered the problems in the sample input so as to clearly demonstrate the problem.

[9]code sample `sudoku3.hs`

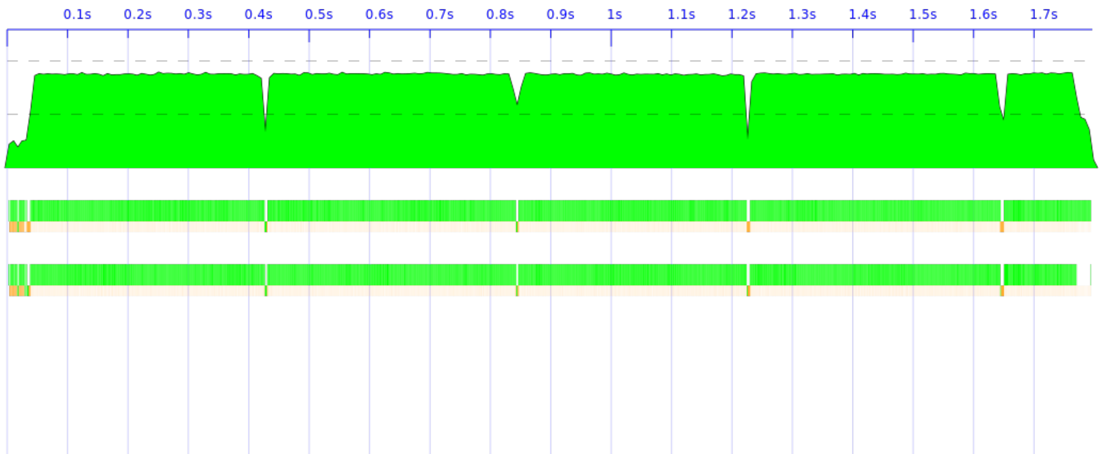


Figure 2: Sudoku3 ThreadScope profile

which we can calculate is equivalent to a speedup of 3.06/1.79 = 1.7, approaching the ideal speedup of 2. Furthermore, the GHC runtime system tells us how many sparks were created:

```
SPARKS: 1000 (1000 converted, 0 pruned)
```

we created exactly 1000 sparks, and they were all *converted* (that is, turned into real parallelism at runtime). Sparks that are *pruned* have been removed from the spark pool by the runtime system, either because they were found to be already evaluated, or because they were found to be not referenced by the rest of the program, and so are deemed to be not useful. We will discuss the latter requirement in more detail in Section 2.2.1.

The ThreadScope profile looks much better (Figure 2). Furthermore, now that the runtime is managing the work distribution for us, the program will automatically scale to more processors. On an 8 processor machine, for example:

```
Total time    4.46s  (  0.59s elapsed)
```

which equates to a speedup of 5.2 over the sequential version.

If we look closely at the 2-processor profile there appears to be a short section near the beginning where not much work is happening. In fact, zooming in on this section in ThreadScope (Figure 3) reveals that both processors are working, but most of the activity is garbage collection, and only one processor is performing most of the garbage collection work. In fact, what we are seeing here is the program reading the input file (lazily) and dividing it into lines, driven by the demand of `parMap` which traverses the whole list of lines.

Figure 3: Sudoku3 (zoomed) ThreadScope profile

Since reading the file and dividing it into lines is a sequential activity anyway, we could force it to happen all at once before we start the main computation, by adding

```
    evaluate (length grids)
```

(see code sample `sudoku4.hs`). This makes no difference to the overall runtime, but it divides the execution into sequential and parallel parts, as we can see in ThreadScope (Figure 4).

Now, we can read off the portion of the runtime that is sequential: 33ms. When we have a sequential portion of our program, this affects the maximum parallel speedup that is achievable, which we can calculate using Amdahl's law. Amdahl's law gives the maximum achievable speedup as the ratio

$$\frac{1}{(1 - P) + \frac{P}{N}}$$

where P is the portion of the runtime that can be parallelised, and N is the number of processors available. In our case, P is $(3.06 - 0.033)/3.06 = 0.9892$, and the maximum speedup is hence 1.98. The sequential fraction here is too small to make a significant impact on the theoretical maximum speedup with 2 processors, but when we have more processors, say 64, it becomes much more important: $1/((1 - 0.989) + 0.989/64) = 38.1$. So no matter what we do, this tiny sequential part of our program will limit the maximum speedup we can obtain with 64 processors to 38.1. In fact, even with 1024 cores we could only achieve around 84 speedup, and it is impossible to achieve a speedup of 91 no matter how many cores we have. Amdahl's law tells us that not only does parallel speedup become harder to achieve the more processors we add, in practice most programs have a theoretical maximum amount of parallelism.

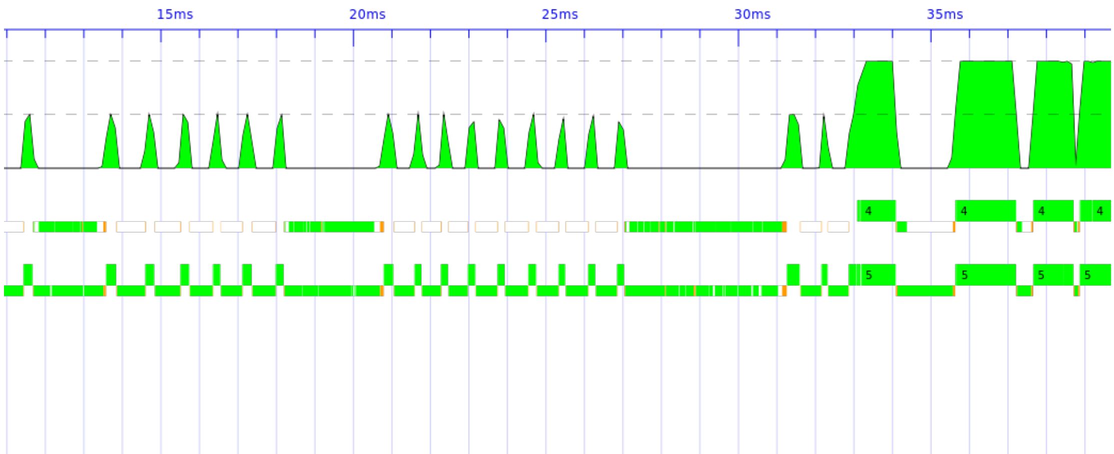


Figure 4: Sudoku4 ThreadScope profile

2.2 Evaluation Strategies

Evaluation Strategies (Trinder et al. 1998; Marlow et al. 2010) is an abstraction layer built on top of the `Eval` monad that allows larger parallel specifications to be built in a compositional way. Furthermore Strategies allow parallel coordination to be described in a modular way, separating parallelism from the algorithm to be parallelised.

A Strategy is merely a function in the `Eval` monad that takes a value of type `a` and returns the same value:

```
type Strategy a = a -> Eval a
```

Strategies are identity functions; that is, the value returned by a `Strategy` is observably equivalent to the value it was passed. Unfortunately the library cannot statically guarantee this property for user-defined `Strategy` functions, but it holds for the `Strategy` functions and combinators provided by the `Control.Parallel.Strategies` module.

We have already seen some simple Strategies, `rpar` and `rseq`, although we can now give their types in terms of `Strategy`:

```
rseq :: Strategy a
rpar :: Strategy a
```

There are two further members of this family:

```
r0 :: Strategy a
r0 x = return x

rdeepseq :: NFData a => Strategy a
rdeepseq x = rseq (deep x)
```

`r0` is the `Strategy` that evaluates nothing, and `rdeepseq` is the `Strategy` that evaluates the entire structure of its argument (it can be defined in terms of `deep` that we saw earlier).

We have some simple ways to build Strategies, but how is a Strategy actually *used*? A `Strategy` is just a function yielding a computation in the `Eval` monad, so we could use `runEval`. For example, applying the strategy `s` to a value `x` would be simply `runEval (s x)`. This is such a common pattern that the Strategies library gives it a name, `using`:

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

`using` takes a value of type `a`, a Strategy for `a`, and applies the Strategy to the value. The identity property for `Strategy` gives us that

```
x `using` s == x
```

which is a significant benefit of Strategies: every occurrence of `` `using` s `` can be deleted without affecting the semantics. Strictly speaking there are two caveats to this property. Firstly, as mentioned earlier, user-defined `Strategy` functions might not satisfy the identity property. Secondly, `` x `using` s `` might be less defined than `x`, because it evaluates more structure of `x` than the context does. So deleting `` `using` s `` might have the effect of making the program terminate with a result when it would previously throw an exception or fail to terminate. Making programs more defined is generally considered to be a somewhat benign change in semantics (indeed, GHC's optimiser can also make programs more defined under certain conditions), but nevertheless it is a change in semantics.

2.2.1 A Strategy for evaluating a list in parallel

In Section 2.1 we defined a function `parMap` that would map a function over a list in parallel. We can think of `parMap` as a composition of two parts:

- The algorithm: `map`
- The parallelism: evaluating the elements of a list in parallel

and indeed with Strategies we can express it exactly this way:

```
parMap f xs = map f xs `using` parList rseq
```

The benefits of this approach are two-fold: not only does it separate the algorithm from the parallelism, but it also *reuses* `map`, rather than re-implementing a parallel version.

The `parList` function is a Strategy on lists, defined as follows:

```haskell
parList :: Strategy a -> Strategy [a]
parList strat []     = return []
parList strat (x:xs) = do
  x'  <- rpar (x `using` strat)
  xs' <- parList strat xs
  return (x':xs')
```

(in fact, `parList` is already provided by `Control.Parallel.Strategies` so you don't have to define it yourself, but we are using its implementation here as an illustration).

The `parList` function is a *parameterised* Strategy, that is, it takes as an argument a Strategy on values of type `a`, and returns a Strategy for lists of `a`. This illustrates another important aspect of Strategies: they are compositional, in the sense that we can build larger strategies by composing smaller reusable components. Here, `parList` describes a family of Strategies on lists that evaluate the list elements in parallel.

On line 4, `parList` calls `rpar` to create a spark to evaluate the current element of the list. Note that the spark evaluates ``(x `using` strat)``: that is, it applies the argument Strategy `strat` to the list element `x`.

As `parList` traverses the list sparking list elements, it remembers each value returned by `rpar` (bound to `x'`), and constructs a new list from these values. Why? After all, this seems to be a lot of trouble to go to, because it means that `parList` is no longer *tail-recursive* — the recursive call to `parList` is not the last operation in the `do` on its right-hand side, and so `parList` will require stack space linear in the length of the input list.

Couldn't we write a tail-recursive version instead? For example:

```haskell
parList :: Strategy a -> Strategy [a]
parList strat xs = do go xs; return xs
  where go [] = return ()
        go (x:xs) = do
           rpar (x `using` strat)
           go xs
```

This typechecks, after all, and seems to call `rpar` on each list element as required.

The difference is subtle but important, and is best understood via a diagram (Figure 5). At the top of the diagram we have the input list `xs`: a linked list of cells, each of which points to a list element (`x1`, `x2`, and so forth). At the bottom of the diagram is the *spark pool*, the runtime system data structure that stores references to sparks in the heap. The other structures in the diagram are built by `parList` (the first version). Each `strat` box represents ``(x `using` strat)`` for an element of the original list `x`, and `xs'` is the linked list of cells in the output list. The spark pool contains pointers to each of the `strat` boxes; these are the pointers created by the `rpar` calls.

Now, the spark pool only retains references to objects that are required by the program. If the runtime finds that the spark pool contains a reference to an object that the program will never use, then the reference is dropped,

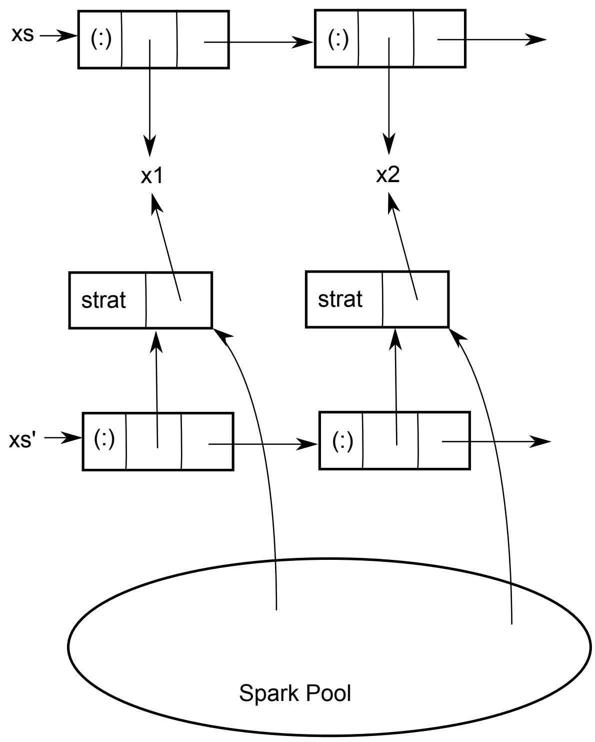


Figure 5: `parList` heap structures

and any potential parallelism it represented is lost. This behaviour is a deliberate policy; if it weren't this way, then the spark pool could retain data indefinitely, causing a space leak (details can be found in Marlow et al. (2010)).

This is the reason for the list `xs'`. Suppose we did not build the new list `xs'`, as in the tail-recursive version of `parList` above. Then, the only reference to each `strat` box in the heap would be from the spark pool, and hence the runtime would automatically sweep all those references from the spark pool, discarding the parallelism. Hence we build a new list `xs'`, so that the program can retain references to the sparks for as long as it needs to.

This behaviour has another benefit: suppose that under some circumstances the program does not need the entire list. If the program simply forgets the unused remainder of the list, the runtime system will clean up the unreferenced sparks from the spark pool, and will not waste any further parallel processing resources on evaluating those sparks. The extra parallelism in this case is termed *speculative*, because it is not necessarily required, and the runtime will automatically discard speculative tasks that it can prove will never be required - a useful property!

While the runtime system's discarding of unreferenced sparks is certainly useful in some cases, it can be tricky to work with, because there is no language-level support for catching mistakes. Fortunately the runtime system will tell us if it garbage collects unreferenced sparks; for example:

```
SPARKS: 144 (0 converted, 144 pruned)
```

A large number of sparks being "pruned" is a good indication that sparks are being removed from the spark pool before they can be used for parallelism. Sparks can be pruned for several reasons:

- The spark was a *dud*: it was already evaluated at the point it was sparked.
- The spark *fizzled*: it was evaluated by some other thread before it could be evaluated in parallel.
- The spark was garbage collected, as described above.

In fact, GHC from version 7.2.1 onwards separates these different classifications in its output from `+RTS -s`:

```
SPARKS: 144 (0 converted, 0 dud, 144 GC'd, 0 fizzled)
```

Unless you are using speculation, then a non-zero figure for GC'd sparks is probably a bad sign.

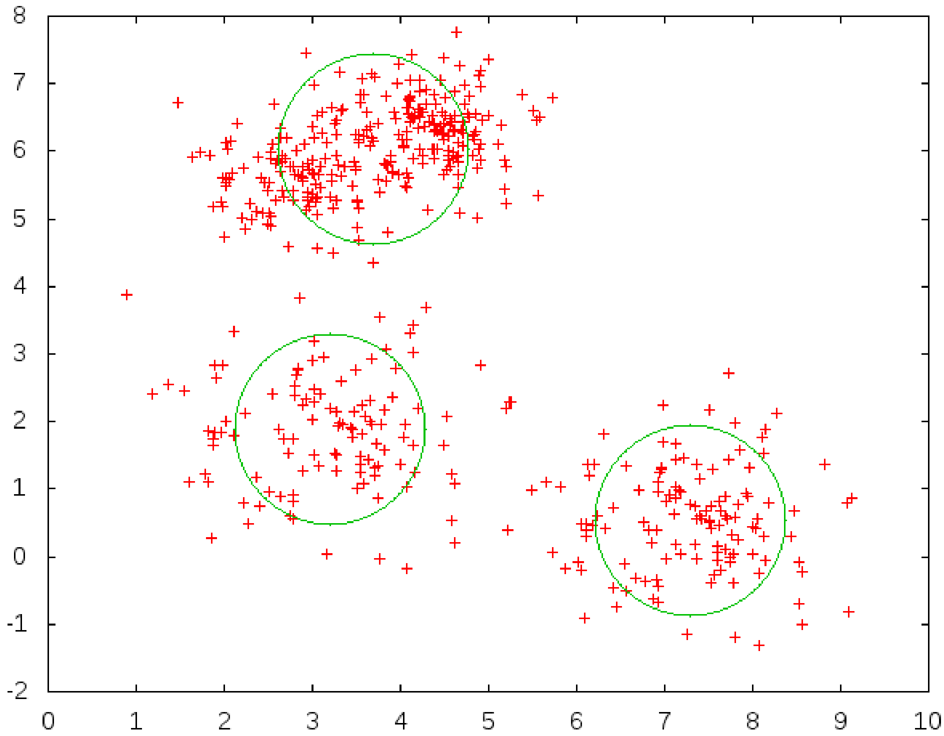


Figure 6: The K-Means problem

All of the combinators in the library `Control.Parallel.Strategies` behave correctly with respect to retaining references to sparks when necessary. So the rules of thumb for not tripping up here are:

- Use `using` to apply strategies: it encourages the right pattern, in which the program uses the results of applying the Strategy.
- When writing your own `Eval`-monad code, remember to bind the result of `rpar`, and use its result.

2.2.2 Using `parList`: the K-Means problem

The `parList` Strategy covers a wide range of uses for parallelism in typical Haskell programs; in many cases, a single `parList` is all that is needed to expose sufficient parallelism.

Returning to our Sudoku solver from Section 2.1 for a moment, instead of our own hand-written `parMap`, we could have used `parList`:

```
    evaluate $ deep $ map solve grids `using` parList rseq
```

Let's look at a slightly more involved example. In the K-Means problem, the goal is to partition a set of data points into clusters. Finding an optimal solution to the problem is NP-hard, but there exist several heuristic techniques that do not guarantee to find an optimal solution, but work well in practice. For example, given the data points shown in Figure 6, the algorithm should discover the clusters indicated by the circles. Here we have only shown the locations of the clusters, partitioning the points is achieved by simply finding the closest cluster to each point.

The most well-known heuristic technique is Lloyd's algorithm, which finds a solution by iteratively improving an initial guess, as follows:

1. Pick an initial set of clusters by randomly assigning each point in the data set to a cluster.
2. Find the centroid of each cluster (the average of all the points in the cluster).
3. Assign each point to the cluster to which it is closest, this gives a new set of clusters.
4. Repeat steps 2–3 until the set of clusters stabilises.

Of course the algorithm works in any number of dimensions, but we will use 2 for ease of visualisation.

A complete Haskell implementation can be found in the directory `kmeans` in the sample code; Figure 7 shows the core of the algorithm.

A data point is represented by the type `Vector`, which is just a pair of `Doubles`. Clusters are represented by the type `Cluster`, which contains its number, the count of points assigned to this cluster, the sum of the `Vectors` in the cluster, and its centre. Everything about the cluster except its number is derivable from the set of points in the cluster; this is expressed by the function `makeCluster`. Essentially `Cluster` caches various information about a cluster, and the reason we need to cache these specific items will become clear shortly.

The function `assign` implements step 2 of the algorithm, assigning points to clusters. The `accumArray` function is particularly useful for this kind of bucket-sorting task. The function `makeNewClusters` implements step 3 of the algorithm, and finally `step` combines `assign` and `makeNewClusters` to implement one complete iteration.

To complete the algorithm we need a driver to repeatedly apply the `step` function until convergence. The function `kmeans_seq`, below, implements this:

```
kmeans_seq :: Int -> [Vector] -> [Cluster] -> IO [Cluster]
kmeans_seq nclusters points clusters = do
  let
```

```haskell
data Vector = Vector Double Double

addVector :: Vector -> Vector -> Vector
addVector (Vector a b) (Vector c d) = Vector (a+c) (b+d)

data Cluster = Cluster
               {
                  clId    :: !Int,
                  clCount :: !Int,
                  clSum   :: !Vector,
                  clCent  :: !Vector
               }

sqDistance :: Vector -> Vector -> Double
sqDistance (Vector x1 y1) (Vector x2 y2)
  = ((x1-x2)^2) + ((y1-y2)^2)

makeCluster :: Int -> [Vector] -> Cluster
makeCluster clid vecs
  = Cluster { clId = clid,
              clCount = count,
              clSum = vecsum,
              clCent = centre }
  where
   vecsum@(Vector a b)  = foldl' addVector (Vector 0 0) vecs
   centre = Vector (a / fromIntegral count)
                   (b / fromIntegral count)
   count = fromIntegral (length vecs)

-- assign each vector to the nearest cluster centre
assign :: Int -> [Cluster] -> [Vector] -> Array Int [Vector]
assign nclusters clusters points =
  accumArray (flip (:)) [] (0, nclusters-1)
     [ (clId (nearest p), p) | p <- points ]
  where
    nearest p = fst $ minimumBy (compare `on` snd)
                        [ (c, sqDistance (clCent c) p)
                        | c <- clusters ]

-- compute clusters from the assignment
makeNewClusters :: Array Int [Vector] -> [Cluster]
makeNewClusters arr =
  filter ((>0) . clCount) $
     [ makeCluster i ps | (i,ps) <- assocs arr ]

step :: Int -> [Cluster] -> [Vector] -> [Cluster]
step nclusters clusters points =
   makeNewClusters (assign nclusters clusters points)
```

Figure 7: Haskell code for K-Means

```
    loop :: Int -> [Cluster] -> IO [Cluster]
    loop n clusters | n > tooMany = return clusters
    loop n clusters = do
      hPrintf stderr "iteration %d\n" n
      hPutStr stderr (unlines (map show clusters))
      let clusters' = step nclusters clusters points
      if clusters' == clusters
         then return clusters
         else loop (n+1) clusters'
--
loop 0 clusters
```

How can this algorithm be parallelised? One place that looks straightforward to parallelise is the `assign` function, since it is essentially just a `map` over the points. However, that doesn't get us very far: we cannot parallelise `accumArray` directly, so we would have to do multiple `accumArrays` and combine the results, and combining elements would mean an extra list append. The `makeNewClusters` operation parallelises easily, but only in so far as each `makeCluster` is independent of the others; typically the number of clusters is much smaller than the number of points (e.g. a few clusters to a few hundred thousand points), so we don't gain much scalability by parallelising `makeNewClusters`.

We would like a way to parallelise the problem at a higher level. That is, we would like to divide the set of points into chunks, and process each chunk in parallel, somehow combining the results. In order to do this, we need a `combine` function, such that

```
points == as ++ bs
  ==>
step n cs points == step n cs as `combine` step n cs bs
```

Fortunately defining `combine` is not difficult. A cluster is a set of points, from which we can compute a centroid. The intermediate values in this calcuation are the sum and the count of the data points. So a combined cluster can be computed from two independent sub-clusters by taking the sum of these two intermediate values, and re-computing the centroid from them. Since addition is associative and commutative, we can compute sub-clusters in any way we wish and then combine them in this way.

Our Haskell code for combining two clusters is as follows:

```
combineClusters c1 c2 =
  Cluster {clId = clId c1,
           clCount = count,
           clSum = vecsum,
           clCent = Vector (a / fromIntegral count)
                           (b / fromIntegral count)}
  where count = clCount c1 + clCount c2
        vecsum@(Vector a b)  = addVector (clSum c1) (clSum c2)
```

In general, however, we will be processing N chunks of the data space independently, each of which returns a set of clusters. So we need to reduce the N sets of sets of clusters to a single set. This is done with another `accumArray`:

```
reduce :: Int -> [[Cluster]] -> [Cluster]
reduce nclusters css =
  concatMap combine $ elems $
    accumArray (flip (:)) [] (0,nclusters)
       [ (clId c, c) | c <- concat css]
 where
  combine [] = []
  combine (c:cs) = [foldr combineClusters c cs]
```

Now, the parallel K-Means implementation can be expressed as an application of `parList` to invoke `step` on each chunk, followed by a call to `reduce` to combine the results from the chunks:

```
1  kmeans_par :: Int -> Int -> [Vector] -> [Cluster]
2             -> IO [Cluster]
3  kmeans_par chunks nclusters points clusters = do
4    let chunks = split chunks points
5    let
6        loop :: Int -> [Cluster] -> IO [Cluster]
7        loop n clusters | n > tooMany = return clusters
8        loop n clusters = do
9          hPrintf stderr "iteration %d\n" n
10         hPutStr stderr (unlines (map show clusters))
11         let
12               new_clusterss =
13                  map (step nclusters clusters) chunks
14                     `using` parList rdeepseq

16               clusters' = reduce nclusters new_clusterss

18         if clusters' == clusters
19            then return clusters
20            else loop (n+1) clusters'
21   --
22   loop 0 clusters
```

the only difference from the sequential implementation is at lines 11–14, where we map `step` over the chunks applying the `parList` strategy, and then call `reduce`.

Note that there's no reason the number of chunks has to be related to the number of processors; as we saw earlier, it is better to produce plenty of sparks and let the runtime schedule them automatically, since this should enable the program to scale over a wide range of processors.

Figure 8 shows the speedups obtained by this implementation for a randomly-generated data set consisting of 4 clusters with a total of approximately 170000 points in 2-D space. The data was generated using the Haskell `normaldistribution` package in order to generate realistically clus-

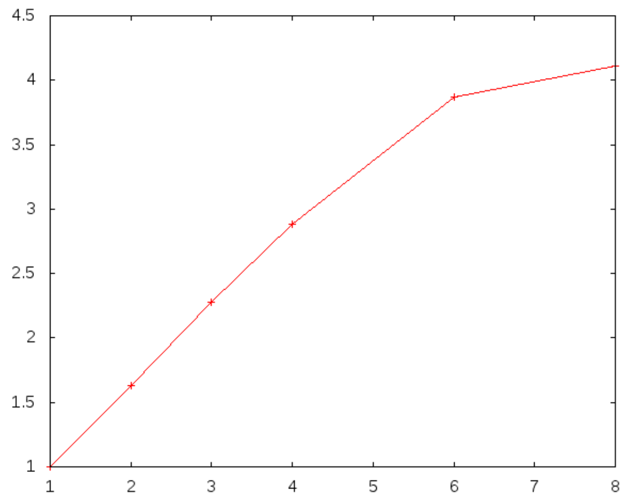


Figure 8: Scaling of parallel K-Means

tered points[10]. For this benchmark we used 1000 for the `chunk` parameter to `kmeans_par`.

The results show the algorithm scaling reasonably well up to 6 cores, with a drop in performance at 8 cores. We leave it as an exercise for the reader to analyse the performance and improve it further!

2.2.3 Further Reading

We have barely scratched the surface of the possibilities with the `Eval` monad and Strategies here. Topics that we have not covered include:

- Sequential strategies, which allow greater control over the specification of *evaluation degree* than is provided by `rseq` and `rdeepseq`. See the documentation for the `Control.Seq` module[11].
- Clustering, which allows greater control over granularity.
- `parBuffer`: a combinator for parallelising lazy streams.

To learn more, we recommend the following resources:

[10] The program used to generate the data is provided as `kmeans/GenSamples.hs` in the sample code distribution, and the sample data we used for this benchmark is provided in the files `kmeans/points.bin` and `kmeans/clusters` (the `GenSamples` program will overwrite these files, so be careful if you run it!)

[11] `http://hackage.haskell.org/packages/archive/parallel/3.1.0.1/doc/html/Control-Seq.html`

- The documentation for the `Control.Parallel.Strategies` module[12].
- Marlow et al. (2010), which explains the motivation behind the design and implementation of `Eval` and Strategies.
- Peyton Jones and Singh (2009), an earlier tutorial covering basic parallelism in Haskell (beware: this dates from before the introduction of the `Eval` monad).
- Trinder et al. (1998), which has a wide range of examples. However beware: this paper is based on the earlier version of Strategies, and some of the examples may no longer work due to the new GC behaviour on sparks; also some the names of functions and types in the library have since changed.

2.3 Dataflow parallelism: the `Par` monad

Sometimes there is a need to be *more explicit* about dependencies and task boundaries than it is possible to be with `Eval` and Strategies. In these cases the usual recourse is to Concurrent Haskell, where we can fork threads and be explicit about which thread does the work. However, that approach throws out the baby with the bathwater: determinism is lost. The programming model we introduce in this section fills the gap between Strategies and Concurrent Haskell: it is explicit about dependencies and task boundaries, but without sacrificing determinism. Furthermore the programming model has some other interesting benefits: for example, it is implemented entirely as a Haskell library and the implementation is readily modified to accommodate alternative scheduling strategies.

As usual, the interface is based around a monad, this time called `Par`:

```
newtype Par a
instance Functor Par
instance Applicative Par
instance Monad Par

runPar :: Par a -> a
```

As with the `Eval` monad, the `Par` monad returns a pure result. However, use `runPar` with care: internally it is much more expensive than `runEval`, because (at least in the current implementation) it will fire up a new scheduler instance consisting of one worker thread per processor. Generally speaking the program should be using `runPar` to schedule large-sale parallel tasks.

The purpose of `Par` is to introduce parallelism, so we need a way to create parallel tasks:

```
fork :: Par () -> Par ()
```

[12] `http://hackage.haskell.org/packages/archive/parallel/3.1.0.1/doc/html/Control-Parallel-Strategies.html`

`fork` does exactly what you would expect: the computation passed as the argument to `fork` (the "child") is executed concurrently with the current computation (the "parent").

Of course, `fork` on its own isn't very useful; we need a way to communicate results from the child of `fork` to the parent, or in general between two parallel `Par` computations. Communication is provided by the `IVar` type[13] and its operations:

```
data IVar a  -- instance Eq

new :: Par (IVar a)
put :: NFData a => IVar a -> a -> Par ()
get :: IVar a -> Par a
```

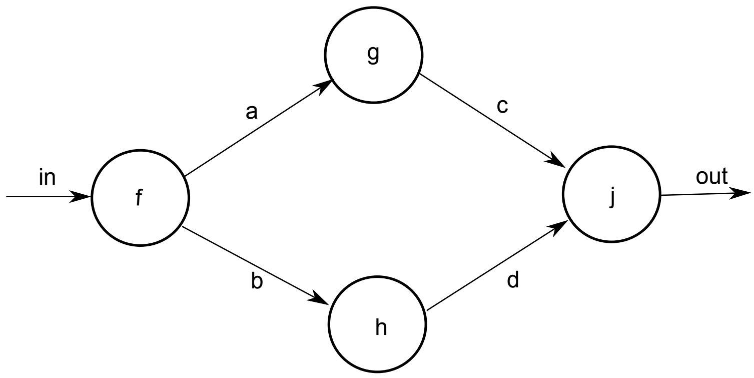
`new` creates a new `IVar`, which is initially empty; `put` fills an `IVar` with a value, and `get` retrieves the value of an `IVar` (waiting until a value has been `put` if necessary). Multiple `put`s to the same `IVar` result in an error.

The `IVar` type is a relative of the `MVar` type that we shall see later in the context of Concurrent Haskell (Section 3.2), the main difference being that an `IVar` can only be written once. An `IVar` is also like a *future* or *promise*, concepts that may be familiar from other parallel or concurrent languages.

Together, `fork` and `IVar`s together allow the construction of *dataflow* networks. The nodes of the network are created by `fork`, and edges connect a `put` with each `get` on that `IVar`. For example, suppose we have the following four functions:

```
f :: In -> A
g :: A -> B
h :: A -> C
j :: (B,C) -> Out
```

Composing these functions forms the following dataflow graph:



There are no sequential dependencies between `g` and `h`, so they could run in parallel. In order to take advantage of the parallelism here, all we need to do is express the graph in the `Par` monad:

[13] `IVar` is so-called because it is an implementation of I-Structures, a concept from the Parallel Haskell variant pH

```haskell
do
   [ia,ib,ic] <- replicateM 4 new

   fork $ do x <- get in
             put ia (f x)

   fork $ do a <- get ia
             put ib (g a)

   fork $ do a <- get ia
             put ic (h a)

   fork $ do b <- get ib
             c <- get ic
             put out (j b c)
```

For each edge in the graph we make an `IVar` (here `ia`, `ib` and so on). For each node in the graph we call `fork`, and the code for each node calls `get` on each input, and `put` on each output of the node. The order of the `fork` calls is irrelevant — the `Par` monad will execute the graph, resolving the dependencies at runtime.

While the `Par` monad is particularly suited to expressing dataflow networks, it can also express other common patterns too. For example, we can build an equivalent of the `parMap` combinator that we saw earlier in Section 2.1. First, we build a simple abstraction for a parallel computation that returns a result:

```haskell
spawn :: NFData a => Par a -> Par (IVar a)
spawn p = do
  i <- new
  fork (do x <- p; put i x)
  return i
```

The `spawn` function forks a computation in parallel, and returns an `IVar` that can be used to wait for the result.

Now, parallel map consists of calling `spawn` to apply the function to each element of the list, and then waiting for all the results:

```haskell
parMapM :: NFData b => (a -> Par b) -> [a] -> Par [b]
parMapM f as = do
  ibs <- mapM (spawn . f) as
  mapM get ibs
```

Note that there are a couple of differences between this and the `Eval` monad `parMap`. First, the function argument returns its result in the `Par` monad; of course it is easy to lift an arbitrary pure function to this type, but the monadic version allows the computation on each element to produce more parallel tasks, or augment the dataflow graph in other ways. Second, `parMapM` waits for all the results. Depending on the context, this may or may not be the most useful behaviour, but of course it is easy to define the other version if necessary.

2.3.1 A parallel type inferencer

In this section we will parallelise a type inference engine using the `Par` monad. Type inference is a natural fit for the dataflow model, because we can consider each binding to be a node in the graph, and the edges of the graph carry inferred types from bindings to usage sites in the program.

For example, consider the following program set of bindings that we want to infer types for:

```
f = ...
g = ... f ...
h = ... f ...
j = ... g ... h ...
```

This pattern gives rise to a dataflow graph with exactly the shape of the example 4-node graph in the previous section: after we have inferred a type for `f`, we can use that type to infer types for `g` and `h` (in parallel), and once we have the types for `g` and `h` we can infer a type for `j`.

Building a dataflow graph for the type inference problem allows the maximum amount of parallelism to be extracted from the type inference process. The actual amount of parallelism present depends on the structure of the input program, however.

The parallel type inferencer can be found in the directory `parinfer` of the code samples, and is derived from a (rather ancient) type inference engine written by Phil Wadler. The types from the inference engine that we will need to work with are as follows:

```haskell
type VarId = String -- variables

data Env -- environment for the type inferencer

-- build environments
makeEnv :: [(VarId,Type)] -> Env

data MonoType -- monomorphic types
data PolyType -- polymorphic types

-- Terms in the input program
data Term = Let VarId Term Term | ...
```

The input to this type inferencer is a single `Term` which may contain `let` bindings, and so to parallelise it we will strip off the outer `let` bindings and typecheck them in parallel. The inner term will be typechecked using the ordinary sequential inference engine. We could have a more general parallel type inference algorithm by always typechecking a `let` binding in parallel with the body, rather than just for the outer `let`s, but that would require threading the `Par` monad through the type inference engine, so for this simple example we are only parallelising inference for the outer bindings.

We need two functions from the inference engine. First, a way to infer a polymorphic type for the right-hand side of a binding:

```
inferTopRhs :: Env -> Term -> PolyType
```

and secondly, a way to run the inference engine on an arbitrary term:

```
inferTopTerm :: Env -> Term -> MonoType
```

The basic idea is that while the sequential inference engine uses an `Env` that maps `VarId`s to `PolyType`s, the parallel part of the inference engine will use an environment that maps `VarId`s to `IVar PolyType`, so that we can `fork` the inference engine for a given binding, and then wait for its result later[14]. The environment for the parallel type inferencer is called `TopEnv`:

```
type TopEnv = Map VarId (IVar PolyType)
```

All that remains is to write the top-level loop. We will write a function `inferTop` with the following type:

```
inferTop :: TopEnv -> Term -> Par MonoType
```

There are two cases to consider. First, when we are looking at a `let` binding:

```
1  inferTop topenv (Let x u v) = do
2      vu <- new

4      fork $ do
5        let fu = Set.toList (freeVars u)
6        tfu <- mapM (get . fromJust . flip Map.lookup topenv) fu
7        let aa = makeEnv (zip fu tfu)
8        put vu (inferTopRhs aa u)

10     inferTop (Map.insert x vu topenv) v
```

On line 2 we create the `IVar` to hold the result, `vu`. Lines 4–8 implement the typechecking for the binding:

4 We `fork` here, so that the binding is typechecked in parallel,

5 Find the `IVar`s corresponding to the free variables of the right-hand side

6 Call `get` for each of these, thus waiting for the typechecking of the binding corresponding to each free variable

7 Make a new `Env` with the types we obtained on line 6

8 Call the type inferencer for the right-hand side, put the result in the `IVar vu`.

[14] We are ignoring the possibility of type errors here; in a real implementation the `IVar` would probably contain an `Either` type representing either the inferred type or an error,

The main computation continues (line 10) by typechecking the body of the `let` in an environment in which the bound variable `x` is mapped to the `IVar vu`.

The other case of `inferTop` handles all other expression constructs:

```
inferTop topenv t = do
    let (vs,ivs) = unzip (Map.toList topenv)
    tvs <- mapM get ivs
    let aa = makeEnv (zip vs tvs)
    return (inferTopTerm aa t)
```

This case is straightforward: just call `get` to obtain the inferred type for for each binding in the `TopEnv`, construct an `Env`, and call the sequential inferencer on the term `t`.

This parallel implementation works quite nicely. For example, the input file below (with some duplicate bindings elided, the full version is in the file `parinfer/example/in`) defines an expression in which there are two parallel branches to infer, one represented by the sequence of `let` bindings for `x` (each successive binding for `x` shadows the previous), and the other branch represented by the sequence of `let` bindings for `y`:

```
let id = \x.x in
    let x = \f.f id id in
    let x = \f . f x x in
    let x = \f . f x x in
    let x = \f . f x x in
    ...
    let x = let f = x in \z . z in
    let y = \f.f id id in
    let y = \f . f y y in
    let y = \f . f y y in
    let y = \f . f y y in
    ...
    let x = let f = y in \z . z in
    \f. let g = \a. a x y in f
```

With one processor:

```
$ ./infer <./example.in +RTS -s
  ...
  Total time    1.13s  (  1.12s elapsed)
```

and with two processors:

```
$ ./infer <./example.in +RTS -s -N2
  ,..
  Total time    1.19s  (  0.60s elapsed)
```

representing a speedup of 1.87.

2.3.2 The `Par` monad compared to Strategies

We have presented two different parallel programming models, each with advantages and disadvantages. Below we summarise the trade-offs so that you can make an informed decision for a given task as to which is likely to be the best choice:

- Using Strategies and the `Eval` monad requires some understanding of the workings of lazy evaluation. Newcomers often find this hard, and diagnosing problems can be difficult. This is part of the motivation for the `Par` monad: it makes all dependencies explicit, effectively replacing lazy evaluation with explicit `put`/`get` on `IVar`s. While this is certainly more verbose, it is less fragile and easier to work with.

  Programming with `rpar` requires being careful about retaining references to sparks to avoid them being garbage collected; this can be subtle and hard to get right in some cases. The `Par` monad has no such requirements, although it does not support speculative parallelism in the sense that `rpar` does: speculative paralelism in the `Par` monad is always executed.

- Strategies allow a separation between algorithm and parallelism, which allows more reuse in some cases.

- The `Par` monad requires threading the monad throughout a computation which is to be parallelised. For example, to parallelise the type inference of all `let` bindings in the example above would have required threading the `Par` monad through the inference engine (or adding `Par` to the existing monad stack), which might be impractical. `Par` is good for localised parallelism, whereas Strategies can be more easily used in cases that require parallelism in multiple parts of the program.

- The `Par` monad has more overhead than the `Eval` monad, although there is no requirement to rebuild data structures as in `Eval`. At the present time, `Eval` tends to perform better at finer granularities, due to the direct runtime system support for sparks. At larger granularities, `Par` and `Eval` perform approximately the same.

- The `Par` monad is implemented entirely in a Haskell library (the `monad-par` package), and is thus readily modified should you need to.

3 Concurrent Haskell

Concurrent Haskell (Peyton Jones et al. 1996) is an extension to Haskell 2010 (Marlow ed.) adding support for explicitly threaded concurrent programming. The basic interface remains largely unchanged in its current implementation, although a number of embellishments have since been added, which we will cover in later sections:

- Asynchronous exceptions (Marlow et al. 2001) were added as a means for asynchronous cancellation of threads,
- Software Transactional Memory was added (Harris et al. 2005), allowing safe composition of concurrent abstractions, and making it possible to safely build larger concurrent systems.
- The behaviour of Concurrent Haskell in the presence of calls to and from foreign languages was specified (Marlow et al. 2004)

3.1 Forking Threads

The basic requirement of concurrency is to be able to fork a new thread of control. In Concurrent Haskell this is achieved with the `forkIO` operation:

```
forkIO :: IO () -> IO ThreadId
```

`forkIO` takes a computation of type `IO ()` as its argument; that is, a computation in the `IO` monad that eventually delivers a value of type `()`. The computation passed to `forkIO` is executed in a new *thread* that runs concurrently with the other threads in the system. If the thread has effects, those effects will be interleaved in an indeterminate fashion with the effects from other threads.

To illustrate the interleaving of effects, let's try a simple example in which two threads are created, once which continually prints the letter `A` and the other printing `B`[15]:

```
1 import Control.Concurrent
2 import Control.Monad
3 import System.IO

5 main = do
6   hSetBuffering stdout NoBuffering
7   forkIO (forever (putChar 'A'))
8   forkIO (forever (putChar 'B'))
9   threadDelay (10^6)
```

Line 6 puts the output `Handle` into non-buffered mode, so that we can see the interleaving more clearly. Lines 7 and 8 create the two threads, and line 9 tells the main thread to wait for one second (`10^6` milliseconds) and then exit.

When run, this program produces output something like this:

[15]this is sample `fork.hs`

```
AAAAAAAAABABABABABABABABABABABABABABABABABABABABABAB
ABABABABABABABABABABABABABABABABABABABABABABABABABAB
ABABABABABABABABABABABABABABABABABABABABABABABABABAB
ABABABABABABABABABABABABABABABABABABABABABABABABABAB
```

Note that the interleaving is non-deterministic: sometimes we get strings of a single letter, but often the output switches regularly between the two threads. Why does it switch so regularly, and why does each thread only get a chance to output a single letter before switching? The threads in this example are contending for a single resource: the `stdout` Handle, so scheduling is affected by how contention for this resource is handled. In the case of GHC a Handle is protected by a lock implemented as an `MVar` (described in the next section). We shall see shortly how the implementation of `MVar`s causes the `ABABABA` behaviour.

We emphasised earlier that concurrency is a program structuring technique, or an abstraction. Abstractions are practical when they are efficient, and this is where GHC's implementation of threads comes into its own. Threads are extremely lightweight in GHC: a thread typically costs less than a hundred bytes plus the space for its stack, so the runtime can support literally millions of them, limited only by the available memory. Unlike OS threads, the memory used by Haskell threads is movable, so the garbage collector can pack threads together tightly in memory and eliminate fragmentation. Threads can also expand and shrink on demand, according to the stack demands of the program. When using multiple processors, the GHC runtime system automatically migrates threads between cores in order to balance the load.

User-space threading is not unique to Haskell, indeed many other languages, including early Java implementations, have had support for user-space threads (sometimes called "green threads"). It is often thought that user-space threading hinders interoperability with foreign code and libraries that are using OS threads, and this is one reason that OS threads tend to be preferred. However, with some careful design it is possible to overcome these difficulties too, as we shall see in Section 3.5.

3.2 Communication: MVars

The lowest-level communication abstraction in Concurrent Haskell is the `MVar`, whose interface is given below:

```haskell
data MVar a  -- abstract

newEmptyMVar :: IO (MVar a)
takeMVar     :: MVar a -> IO a
putMVar      :: MVar a -> a -> IO ()
```

An `MVar` can be thought of as a box that is either empty or full; `newEmptyMVar` creates a new empty box. The `takeMVar` operation puts a value into the box, but blocks (waits) if the box is already full. Symmetrically, the `putMVar` operation removes the value from a full box but blocks if the box is empty. An `MVar` can also be thought of as a 1-place bounded channel.

`MVar`s generalise several simple concurrency abstractions:

- `MVar ()` is a *lock*; `takeMVar` acquires the lock and `putMVar` releases it again. An `MVar` used in this way can protect shared mutable state or critical sections.

- An `MVar` is a one-place channel, which can be used for asynchronous communication between two threads. In Section 3.2.1 we show how to build unbounded buffered channels from `MVar`s.

- An `MVar` is a useful container for shared mutable state. For example, a common design pattern in Concurrent Haskell when several threads need read and write access to some state, is to represent the state value as an ordinary immutable Haskell data structure stored in an `MVar`. Modifying the state consists of taking the current value with `takeMVar` (which implicitly acquires a lock), and then placing a new value back in the `MVar` with `putMVar` (which implicitly releases the lock again).

We can also use `MVar`s to do some simple asynchronous I/O. Suppose we want to download some web pages concurrently and wait for them all to download before continuing. We are given the following function to download a web page:

```
getURL :: String -> IO String
```

Let's use this to download two URLs concurrently:

```
1  do
2     m1 <- newEmptyMVar
3     m2 <- newEmptyMVar

5     forkIO $ do
6       r <- getURL "http://www.wikipedia.org/wiki/Shovel"
7       putMVar m1 r

9     forkIO $ do
10      r <- getURL "http://www.wikipedia.org/wiki/Spade"
11      putMVar m2 r

13    r1 <- takeMVar m1
14    r2 <- takeMVar m2
15    return (r1,r2)
```

Lines 1–2 create two new empty `MVar`s to hold the results. Lines 5–7 fork a new thread to download the first URL; when the download is complete the result is placed in the `MVar` `m1`, and lines 9–11 do the same for the second URL, placing the result in `m2`. In the main thread, line 13 waits for the result from `m1`, and line 14 waits for the result from `m2` (we could do these in either order), and finally both results are returned.

This code is rather verbose. We could shorten it by using various existing higher-order combinators from the Haskell library, but a better approach would be to extract the common pattern as a new abstraction: we want a way to perform an action *asynchronously*, and later wait for its result. So let's define an interface that does that, using `forkIO` and `MVar`s:

```
1  newtype Async a = Async (MVar a)
2
3  async :: IO a -> IO (Async a)
4  async io = do
5    m <- newEmptyMVar
6    forkIO $ do r <- io; putMVar m r
7    return (Async m)
8
9  wait :: Async a -> IO a
10 wait (Async m) = readMVar m
```

Line 1 defines a datatype `Async` that represents an asynchronous action that has been started. Its implementation is just an `MVar` that will contain the result; creating a new type here might seem like overkill, but later on we will extend the `Async` type to support more operations, such as cancellation.

The `wait` operation uses `readMVar`, defined thus[16]:

```
readMVar :: MVar a -> IO a
readMVar m = do
  a <- takeMVar m
  putMVar m a
  return a
```

that is, it puts back the value into the `MVar` after reading it, the point being that we might want to call `wait` multiple times, or from different threads.

Now, we can use the `Async` interface to clean up our web-page-downloading example:

```
do
   a1 <- async $ getURL "http://www.wikipedia.org/wiki/Shovel"
   a2 <- async $ getURL "http://www.wikipedia.org/wiki/Spade"
   r1 <- wait a1
   r2 <- wait a2
   return (r1,r2)
```

Much nicer! To demonstrate this working, we can make a small wrapper that downloads a URL and reports how much data was downloaded and how long it took[17]:

```
sites = ["http://www.google.com",
         "http://www.bing.com",
         ... ]
```

[16] `readMVar` is a standard operation provided by the `Control.Concurrent` module

[17] the full code can be found in the sample `geturls.hs`

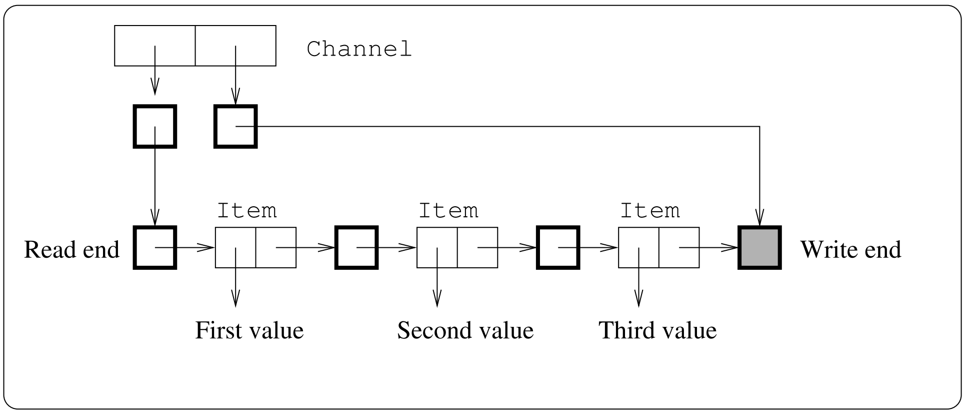


Figure 9: Structure of the buffered channel implementation

```
main = mapM (async.http) sites >>= mapM wait
 where
   http url = do
     (page, time) <- timeit $ getURL url
     printf "downloaded: %s (%d bytes, %.2fs)\n"
        url (B.length page) time
```

which results in something like this:

```
downloaded: http://www.google.com (14524 bytes, 0.17s)
downloaded: http://www.bing.com (24740 bytes, 0.18s)
downloaded: http://www.wikipedia.com/wiki/Spade (62586 bytes, 0.60s)
downloaded: http://www.wikipedia.com/wiki/Shovel (68897 bytes, 0.60s)
downloaded: http://www.yahoo.com (153065 bytes, 1.11s)
```

3.2.1 Channels

One of the strengths of `MVar`s is that they are a useful building block out of which larger abstractions can be constructed. Here we will use `MVar`s to construct a unbounded buffered channel, supporting the following basic interface:

```
data Chan a

newChan   :: IO (Chan a)
writeChan :: Chan a -> a -> IO ()
readChan  :: Chan a -> IO a
```

This channel implementation first appeared in Peyton Jones et al. (1996) (although the names were slightly different), and is available in the Haskell module `Control.Concurrent.Chan`. The structure of the implementation is represented diagrammatically in Figure 3.2, where each bold box represents an MVar and the lighter boxes are ordinary Haskell data structures. The current contents of the channel are represented as a Stream, defined like this:

```
type Stream a = MVar (ChItem a)
data Item a   = Item a (Stream a)
```

The end of the stream is represented by an empty MVar, which we call the “hole”, because it will be filled in when a new element is added. The channel itself is a pair of MVars, one pointing to the first element of the Stream (the read position), and the other pointing to the empty MVar at the end (the write position):

```
data Chan a
 = Chan (MVar (Stream a))
        (MVar (Stream a))
```

To construct a new channel we must first create an empty Stream, which is just a single empty MVar, and then the Chan constructor with MVars for the read and write ends, both pointing to the empty Stream:

```
newChan :: IO (Chan a)
newChan = do
   hole  <- newEmptyMVar
   readVar  <- newMVar hole
   writeVar <- newMVar hole
   return (Chan readVar writeVar)
```

To add a new element to the channel we must make an Item with a new hole, fill in the current hole to point to the new item, and adjust the write-end of the Chan to point to the new hole:

```
writeChan :: Chan a -> a -> IO ()
writeChan (Chan _ writeVar) val = do
  new_hole <- newEmptyMVar
  old_hole <- takeMVar writeVar
  putMVar write new_hole
  putMVar old_hole (Item val new_hole)
```

To remove a value from the channel, we must follow the read end of the Chan to the first MVar of the stream, take that MVar to get the Item, adjust the read end to point to the next MVar in the stream, and finally return the value stored in the Item:

```
1 readChan :: Chan a -> IO a
2 readChan (Chan readVar _) = do
3   stream <- takeMVar readVar
4   Item val new <- takeMVar stream
5   putMVar read new
6   return val
```

Consider what happens if the channel is empty. The first takeMVar (line 3) will succeed, but the second takeMVar (line 4) will find an empty hole, and so will block. When another thread calls `writeChan`, it will fill the hole, allowing the first thread to complete its `takeMVar`, update the read end (line 5) and finally return.

If multiple threads concurrently call `readChan`, the first one will successfully call `takeMVar` on the read end, but the subsequent threads will all block at this point until the first thread completes the operation and updates the read end. If multiple threads call `writeChan`, a similar thing happens: the write end of the `Chan` is the synchronisation point, only allowing one thread at a time to add an item to the channel. However, the read and write ends being separate `MVar`s allows concurrent `readChan` and `writeChan` operations to proceed without interference.

This implementation allows a nice generalisation to *multicast* channels without changing the underlying structure. The idea is to add one more operation:

```
dupChan :: Chan a -> IO (Chan a)
```

which creates a duplicate `Chan` with the following semantics:

- The new `Chan` begins empty,
- Subsequent writes to either `Chan` are read from both; that is, reading an item from one `Chan` does not remove it from the other.

The implementation is straightforward:

```
dupChan :: Chan a -> IO (Chan a)
dupChan (Chan _ writeVar) = do
   hole       <- takeMVar writeVar
   putMVar writeVar hole
   newReadVar <- newMVar hole
   return (Chan newReadVar writeVar)
```

Both channels share a single write-end, but they have independent read-ends. The read end of the new channel is initialised to point to the hole at the end of the current contents.

Sadly, this implementation of `dupChan` does not work! Can you see the problem? The definition of `dupChan` itself is not at fault, but combined with the definition of `readChan` given earlier it does not implement the required semantics. The problem is that `readChan` does not replace the contents of a hole after having read it, so if `readChan` is called to read values from both channels returned by `dupChan`, the second call will block. The fix is to change a `takeMVar` to `readMVar` in the implementation of `readChan`:

```
readChan :: Chan a -> IO a
readChan (Chan readVar _) = do
  stream <- takeMVar readVar
  Item val new <- readMVar stream -- modified
  putMVar read new
  return val
```

Line 4 returns the Item back to the Stream, where it can be read by any duplicate channels created by dupChan.

Before we leave the topic of channels, consider one more extension to the interface that was described as an "easy extension" and left as an exercise by Peyton Jones et al. (1996):

```
unGetChan :: Chan a -> a -> IO ()
```

the operation unGetChan pushes a value back on the read end of the channel. Leaving aside for a moment the fact that the interface does not allow the atomic combination of readChan and unGetChan (which would appear to be an important use case), let us consider how to implement unGetChan. The straightforward implementation is as follows:

```
1 unGetChan :: Chan a -> a -> IO ()
2 unGetChan (Chan readVar _) val = do
3    new_read_end <- newEmptyMVar
4    read_end <- takeMVar readVar
5    putMVar new_read_end (ChItem val read_end)
6    putMVar readVar new_read_end
```

we create a new hole to place at the front of the Stream (line 3), take the current read end (line 4) giving us the current front of the stream, place a new Item in the new hole (line 5), and finally replace the read end with a pointer to our new item.

Simple testing will confirm that the implementation works. However, consider what happens when the channel is empty, there is already a blocked readChan, and another thread calls unGetChan. The desired semantics is that unGetChan succeeds, and readChan should return with the new element. What actually happens in this case is deadlock: the thread blocked in readChan will be holding the read-end MVar, and so unGetChan will also block (line 4) trying to take the read end. As far as we know, there is no implementation of unGetChan that has the desired semantics.

The lesson here is that programming larger structures with MVar can be much trickier than it appears. As we shall see shortly, life gets even more difficult when we consider exceptions. Fortunately there is a solution, that we will describe in Section 3.4.

Despite the difficulties with scaling MVars up to larger abstractions, MVars do have some nice properties, as we shall see in the next section.

3.2.2 Fairness

Fairness is a well-studied and highly technical subject, which we do not attempt to review here. Nevertheless, we wish to highlight one particularly important guarantee provided by MVars with respect to fairness:

> No thread can be blocked indefinitely on an MVar unless another thread holds that MVar indefinitely.

In other words, if a thread T is blocked in `takeMVar`, and there are regular `putMVar` operations on the same `MVar`, then it is guaranteed that at some point thread T's `takeMVar` will return. In GHC this guarantee is implemented by keeping blocked threads in a FIFO queue attached to the `MVar`, so eventually every thread in the queue will get to complete its operation as long as there are other threads performing regular `putMVar` operations (an equivalent guarantee applies to threads blocked in `putMVar` when there are regular `takeMVar`s). Note that it is not enough to merely *wake up* the blocked thread, because another thread might run first and take (respectively put) the `MVar`, causing the newly woken thread to go to the back of the queue again, which would invalidate the fairness guarantee. The implementation must therefore atomically wake up the blocked thread *and* perform the blocked operation, which is exactly what GHC does.

Fairness in practice Recall our example from Section 3.1, where we had two threads, one printing `A`s and the other printing `B`s, and the output was often perfect alternation between the two: `ABABABABABABABAB`. This is an example of the fairness guarantee in practice. The `stdout` handle is represented by an `MVar`, so when both threads attempt to call `takeMVar` to operate on the handle, one of them wins and the other becomes blocked. When the winning thread completes its operation and calls `putMVar`, the scheduler wakes up the blocked thread *and* completes its blocked `takeMVar`, so the original winning thread will immediately block when it tries to re-acquire the handle. Hence this leads to perfect alternation between the two threads. The only way that the alternation pattern can be broken is if one thread is pre-empted while it is not holding the `MVar`; indeed this does happen from time to time, as we see the occasional long string of a single letter in the output.

A consequence of the fairness implementation is that, when multiple threads are blocked, *we only need to wake up a single thread.* This single wakeup property is a particularly important performance characteristic when a large number of threads are contending for a single `MVar`. As we shall see later, it is the fairness guarantee together with the single-wakeup property which means that `MVar`s are not completely subsumed by Software Transactional Memory.

3.3 Cancellation: Asynchronous Exceptions

In an interactive application, it is often important for one thread to be able to *interrupt* the execution of another thread when some particular condition occurs. Some examples of this kind of behaviour in practice include:

- In a web browser, the thread downloading the web page and the thread rendering the page need to be interrupted when the user presses the "stop" button.

- A server application typically wants to give a client a set amount of time to issue a request before closing its connection, so as to avoid dormant connections using up resources.

- An application in which a compute-intensive thread is working (say, rendering a visualisation of some data), and the input data changes due to some user input.

The crucial design decision in supporting cancellation is whether the intended victim should have to poll for the cancellation condition, or whether the thread is immediately cancelled in some way. This is a tradeoff:

1. If the thread has to poll, there is a danger that the programmer may forget to poll regularly enough, and the thread will become unresponsive, perhaps permanently so. Unresponsive threads lead to hangs and deadlocks, which are particularly unpleasant from a user's perspective.

2. If cancellation happens asynchronously, critical sections that modify state need to be protected from cancellation, otherwise cancellation may occur mid-update leaving some data in an inconsistent state.

In fact, the choice is really between doing only (1), or doing both (1) and (2), because if (2) is the default, protecting a critical section amounts to switching to polling behaviour for the duration of the critical section.

In most imperative languages it is unthinkable for (2) to be the default, because so much code is state-modifying. Haskell has a distinct advantage in this area, however: most code is purely functional, so it can be safely aborted or suspended, and later resumed, without affecting correctness. Moreover our hand is forced: purely functional code cannot by definition poll for the cancellation condition, so it must be cancellable by default.

Therefore, fully-asynchronous cancellation is the only sensible default in Haskell, and the design problem reduces to deciding how cancellation appears to code in the `IO` monad.

It makes sense for cancellation to behave like an exception, since exceptions are already a fact of life in the `IO` monad, and the usual idioms for writing `IO` monad code include exception handlers to release resources and clean up in the event of an error. For example, to perform an operation that requires a temporary file, we would use the `bracket` combinator to ensure that the temporary file is always removed, even if the operation raises an exception:

```
bracket (newTempFile "temp")
        (\file -> removeFile file)
        (\file -> ...)
```

where `bracket` is defined thus:

```
bracket :: IO a -> (a -> IO b) -> (a -> IO c) -> IO c
bracket before after during = do
  before
  during `catch` \e -> do after; throw e
  after
```

we want exception handlers to run in the event of cancellation, so cancellation should be an exception. However, there's a fundamental difference between the kind of exception thrown by `openFile` when the file does not exist, for example, and an exception that may arise *at any time* because the user pressed the "stop" button. We call the latter kind an *asynchronous* exception, for obvious reasons. (We do not review the Haskell support for *synchronous* exceptions here; for that see the Haskell 2010 report (Marlow ed.) and the documentation for the `Control.Exception` module).

To initiate an asynchronous exception, Haskell provides the `throwTo` primitive which throws an exception from one thread to another (Marlow et al. 2001):

```
throwTo :: Exception e => ThreadId -> e -> IO ()
```

the `Exception` constraint requires that the exception value being thrown is an instance of the `Exception` class, which implements a simple hierarchy (Marlow 2006). The `ThreadId` is a value previously returned by `forkIO`, and may refer to a thread in any state: running, blocked, or finished (in the latter case, `throwTo` is a no-op).

To illustrate the use of `throwTo`, we now elaborate the earlier example in which we downloaded several web pages concurrently, to allow the user to hit `'q'` at any time to stop the downloads.

First, we will extend our `Async` mini-API to allow cancellation. We add one operation:

```
cancel :: Async a -> IO ()
```

which cancels an existing `Async`. If the operation has already completed, `cancel` has no effect. The `wait` operation cannot just return the result of the `Async` any more, since it may have been cancelled. Therefore, we extend `wait` to return `Either SomeException a`, containing either the exception raised during the operation, or its result:

```
wait :: Async a -> IO (Either SomeException a)
```

(`SomeException` is the root of the exception hierarchy in Haskell.) In order to implement the new interface, we need to extend the `Async` type to include the `ThreadId` of the child thread, and the `MVar` holding the result must now hold `Either SomeException a`.

```
data Async a = Async ThreadId (MVar (Either SomeException a))
```

Given this, the implementation of `cancel` just throws an exception to the thread:

```
cancel :: Async a -> IO ()
cancel (Async t var) = throwTo t ThreadKilled
```

(`ThreadKilled` is an exception provided by the Haskell exception library and is typically used for cancelling threads in this way.) The remaining piece of the implementation is the `async` operation, which must now include an exception handler to catch the exception and store it in the `MVar`:

```
async :: IO a -> IO (Async a)
async action = do
   var <- newEmptyMVar
   t <- forkIO ((do r <- action; putMVar var (Right r))
                  `catch` \e -> putMVar var (Left e))
   return (Async t var)
```

Now, we can change the `main` function of the example to support cancelling the downloads:

```
1  main = do
2    as <- mapM (async.http) sites

4    forkIO $ do
5       hSetBuffering stdin NoBuffering
6       forever $ do
7          c <- getChar
8          when (c == 'q') $ mapM_ cancel as

10   rs <- mapM wait as
11   printf "%d/%d finished\n" (length (rights rs)) (length rs)
```

Line 2 starts the downloads as before. Lines 4–8 fork a new thread that repeatedly reads characters from the standard input, and if a `q` is found, calls `cancel` on all the `Async`s. Line 10 waits for all the results (complete or cancelled), and line 11 emits a summary with a count of how many of the operations completed without being cancelled. If we run the sample[18] and hit `'q'` fast enough, we see something like this:

```
downloaded: http://www.google.com (14538 bytes, 0.17s)
downloaded: http://www.bing.com (24740 bytes, 0.22s)
q2/5 finished
```

Note that this works even though the program is sitting atop a large and complicated HTTP library that provides no direct support for either cancellation or asynchronous I/O. Haskell's support for cancellation is modular in this respect: most library code needs to do nothing to support it, although there are some simple and unintrusive rules that need to be followed when dealing with state, as we shall see in the next section.

[18] full code is in the sample `geturlscancel.hs`

3.3.1 Masking asynchronous exceptions

As we mentioned earlier, the danger with fully asynchronous exceptions is that one might fire while we are in the middle of updating some shared state, leaving the data in an inconsistent state, and with a high probability leading to mayhem later.

Hence, we certainly need a way to control the delivery of asynchronous exceptions during critical sections. But we must tread carefully: it would be easy to provide the programmer with a way to turn off asynchronous exception delivery temporarily, but such a facility is in fact not what we really need.

Consider the following problem: a thread wishes to call `takeMVar`, perform an operation depending on the value of the `MVar`, and finally put the result of the operation in the `MVar`. The code must be responsive to asynchronous exceptions, but it should be safe: if an asynchronous exception arrives after the `takeMVar`, but before the final `putMVar`, the `MVar` should not be left empty, instead the original value should be replaced.

If we code up this problem using the facilities we already seen so far, we might end up with something like this:

```
1 problem m f = do
2   a <- takeMVar m
3   r <- f a `catch` \e -> do putMVar m a; throw e
4   putMVar m r
```

There are at least two points where if an asynchronous exception strikes the invariant will be violated. If an exception strikes between lines 2 and 3, or between lines 3 and 4, the `MVar` will be left empty. In fact, there is no way to shuffle around the exception handlers to ensure the `MVar` is always left full. To fix this problem, Haskell provides the `mask` combinator[19]:

```
mask :: ((IO a -> IO a) -> IO b) -> IO b
```

The type looks a bit confusing, but it isn't really[20]. The `mask` operation defers the delivery of asynchronous exceptions for the duration of its argument, and is used like this:

```
problem m f = mask $ \restore -> do
  a <- takeMVar m
  r <- restore (f a) `catch` \e -> do putMVar m a; throw e
  putMVar m r
```

`mask` is applied to a *function*, that takes as its argument a function `restore`, that can be used to restore the delivery of asynchronous exceptions to its present state. If we imagine shading the entire argument to `mask` except

[19] Historical note: the original presentation of asynchronous exceptions used a pair of combinators `block` and `unblock` here, but `mask` was introduced in GHC 7.0.1 to replace them as it has a more modular behaviour.

[20] for simplicity here we are using a slightly less general version of `mask` than the real one in the `Control.Exception` library.

for the expression `(f a)`, asynchronous exceptions cannot be raised in the shaded portions.

This solves the problem that we had previously, since now an exception can only be raised while `(f a)` is working, and we have an exception handler to catch any exceptions in that case. But a new problem has been introduced: `takeMVar` might block for a long time, but it is inside the `mask` and so the thread will be unresponsive for that time. Furthermore there's no good reason for mask exceptions during `takeMVar`; it would be safe for exceptions to be raised right up until the point where `takeMVar` returns. Hence, this is exactly the behaviour that Haskell defines for `takeMVar`: we designate a small number of operations, including `takeMVar`, as *interruptible*. Interruptible operations may receive asynchronous exceptions even inside `mask`.

What justifies this choice? Think of `mask` as "switching to polling mode" for asynchronous exceptions. Inside a `mask`, asynchronous exceptions are no longer asynchronous, but they can still be raised by certain operations. In other words, asynchronous exceptions become *synchronous* inside `mask`.

All operations which may block indefinitely[21] are designated as interruptible. This turns out to be the ideal behaviour in many situations, as in `problem` above.

In fact, we can provide higher level combinators to insulate programmers from the need to use `mask` directly. For example, the function `problem` above is generally useful when working with `MVar`s, and is provided under the name `modifyMVar_` in the `Control.Concurrent.MVar` library.

3.3.2 Asynchronous-exception safety

All that is necessary for most code to be safe in the presence of asynchronous exceptions is to use operations like `modifyMVar_` instead of `takeMVar` and `putMVar` directly. For example, consider the buffered channels that we defined earlier. As defined, the operations are not asynchronous-exception-safe; for example, `writeChan` was defined like this:

```
writeChan :: Chan a -> a -> IO ()
writeChan (Chan _ writeVar) val = do
  new_hole <- newEmptyMVar
  old_hole <- takeMVar writeVar
  putMVar write new_hole
  putMVar old_hole (Item val new_hole)
```

there are several windows here where if an asynchronous exception occurs, an `MVar` will be left empty, and subsequent users of the `Chan` will deadlock. To make it safe, we use `modifyMVar_`:

```
writeChan (Chan _ writeVar) val = do
  new_hole <- newEmptyMVar
  modifyMVar_ writeVar $ \old_hole -> do
```

[21]except foreign calls, for technical reasons

```haskell
    putMVar old_hole (ChItem val new_hole)
    return new_hole
```

We saw a use of the `bracket` function earlier; in fact, `bracket` is defined with `mask` in order to make it asynchronous-exception-safe:

```haskell
bracket before after during =
  mask $ \restore -> do
    a <- before
    r <- restore (during a) `catch` \e -> after a; throw e
    _ <- after a
    return r
```

3.3.3 Timeouts

A good illustration of programming with asynchronous exceptions is to write a function that can impose a time limit on given action. We want to provide the timeout wrapper as a combinator of the following type:

```haskell
timeout :: Integer -> IO a -> IO (Maybe a)
```

where `timeout` t m has the following behaviour:

1. `timeout` t m behaves exactly like `fmap Just` m if m returns a result or raises an exception (including an asynchronous exception), within t microseconds.

2. otherwise, m is sent an asynchronous exception of the form `Timeout` u. `Timeout` is a new datatype that we define, and u is a unique value of type `Unique`, distinguishing this particular instance of `timeout` from any other. The call to `timeout` then returns `Nothing`.

The implementation is not expected to implement real-time semantics, so in practice the timeout will only be approximately t microseconds. Note that (1) requires that m is executed in the context of the current thread, since m could call `myThreadId`, for example. Also, another thread throwing an exception to the current thread with `throwTo` will expect to interrupt m.

The code for `timeout` is shown in Listing 1; this implementation was taken from the library `System.Timeout` (with some cosmetic changes for presentation here). The implementation is tricky to get right. The basic idea is to fork a new thread that will wait for t seconds and then call `throwTo` to throw the `Timeout` exception back to the original thread; that much seems straightforward enough. However, we must ensure that this thread cannot throw its `Timeout` exception after the call to `timeout` has returned, otherwise the `Timeout` exception will leak out of the call, so `timeout` must kill the thread before returning.

Here is how the implementation works, line by line:

1–2 Handle the easy cases, where the timeout is negative or zero.

Listing 1: implementation of `timeout`

```
1  timeout n m
2      | n <  0     = fmap Just m
3      | n == 0     = return Nothing
4      | otherwise = do
5          pid <- myThreadId
6          u <- newUnique
7          let ex = Timeout u
8          handleJust
9             (\e -> if e == ex then Just () else Nothing)
10            (\_ -> return Nothing)
11            (bracket (forkIO $ do threadDelay n
12                                  throwTo pid ex)
13                     (\t -> throwTo t ThreadKilled)
14                     (\_ -> fmap Just m))
```

5 find the `ThreadId` of the current thread

6–7 make a new `Timeout` exception, by generating a unique value with `newUnique`

8-14 `handleJust` is an exception handler, with the following type:

```
handleJust :: Exception e
           => (e -> Maybe b) -> (b -> IO a) -> IO a
           -> IO a
```

Its first argument (line 9) selects which exceptions to catch: in this case, just the `Timeout` exception we defined on line 7. The second argument (lines 10) is the exception handler, which in this case just returns `Nothing`, since timeout occurred.

Lines 11–14 are the computation to run in the exception handler. `bracket` (Section 3.3) is used here in order to fork the child thread, and ensure that it is killed before returning.

11-12 fork the child thread. In the child thread we wait for t microseconds with `threadDelay`, and then throw the `Timeout` exception to the parent thread with `throwTo`.

13 always kill the child thread before returning.

14 the body of `bracket`: run the computation `m` passed in as the second argument to `timeout`, and wrap the result in `Just`.

The reader is encouraged to verify that the implementation works by thinking through the two cases: either `m` completes and returns `Just x` at line 14, or, the child thread throws its exception while `m` is still working.

There is one tricky case to consider: what happens if *both* the child thread and the parent thread try to call `throwTo` at the same time (lines 12 and 13 respectively)? Who wins?

The answer depends on the semantics of `throwTo`. In order for this implementation of `timeout` to work properly, it must not be possible for the call to `bracket` at line 11 to return while the `Timeout` exception can still be thrown, otherwise the exception can leak. Hence, the call to `throwTo` that kills the child thread at line 13 must be synchronous: once this call returns, the child thread cannot throw its exception any more. Indeed, this guarantee is provided by the semantics of `throwTo`: a call to `throwTo` only returns after the exception has been raised in the target thread[22]. Hence, `throwTo` may block if the child thread is currently masking asynchronous exceptions with `mask`, and because `throwTo` may block, it is therefore *interruptible* and may itself receive asynchronous exceptions.

Returning to our "who wins" question above, the answer is "exactly one of them", and that is precisely what we require to ensure the correct behaviour of `timeout`.

3.3.4 Asynchronous exceptions: reflections

Abstractions like `timeout` are certainly difficult to get right, but fortunately they only have to be written once. We find that in practice dealing with asynchronous exceptions is fairly straightforward, following a few simple rules:

- Use `bracket` when acquiring resources that need to be released again.
- Rather than `takeMVar` and `putMVar`, use `modifyMVar_` (and friends) which have built-in asynchronous exception safety.
- If state handling starts getting complicated with multiple layers of exception handlers, then there are two approaches to simplfying things:
  - Switching to polling mode with `mask` can help manage complexity. The GHC I/O library, for example, runs entirely inside `mask`. Note that inside `mask` it is important to remember that asynchronous exceptions can still arise out of interruptible operations; the documentation contains a list of operations that are guaranteed *not* to be interruptible.
  - Using Software Transactional Memory (STM) instead of `MVar`s or other state representations can sweep away all the complexity in one go. We will describe STM in Section 3.4.

[22]Note: a different semantics was originally described in Marlow et al. (2001).

The rules are usually not onerous: remember this only applies to code in the `IO` monad, so the vast swathes of purely-functional library code available for Haskell is all safe by construction. We find that most `IO` monad code is straightforward to make safe, and if things get complicated falling back to either `mask` or STM is a satisfactory solution.

In exchange for following the rules, however, Haskell's approach to asynchronous exceptions confers many benefits.

- Many exceptional conditions map naturally onto asynchronous exceptions. For example, stack overflow and user interrupt (e.g. control-C at the console) are mapped to asynchronous exceptions in Haskell. Hence, control-C not only aborts the program but does so cleanly, running all the exception handlers. Haskell programmers have to do nothing to enable this behaviour.

- Constructs like `timeout` always work, even with third-party library code.

- Threads never just die in Haskell, it is guaranteed that a thread always gets a chance to clean up and run its exception handlers.

3.4 Software Transactional Memory

Software Transactional Memory (STM) is a technique for simplifying concurrent programming by allowing multiple state-changing operations to be grouped together and performed as a single atomic operation. Strictly speaking, "Software Transactional Memory" is an implementation technique, whereas the language construct we are interested in is "atomic blocks". Unfortunately the former term has stuck, and so the language-level facility is called STM.

STM solves a number of problems that arise with conventional concurrency abstractions, that we describe here through a series of examples. For reference throughout the following section, the types and operations of the STM interface are collected in Listing 2.

Imagine the following scenario: a window manager that manages multiple desktops. The user may move windows from one desktop to another, while at the same time, a program may request that its own window moves from its current desktop to another desktop. The window manager uses multiple threads: one to listen for input from the user, one for each existing window to listen for requests from those programs, and one thread that renders the display to the user.

How should the program represent the state of the display? One option is to put it all in a single `MVar`:

```
type Display = MVar (Map Desktop (Set Window))
```

Listing 2: the interface provided by `Control.Concurrent.STM`

```haskell
data STM a -- abstract
instance Monad STM -- amongst other things

atomically :: STM a -> IO a

data TVar a -- abstract
newTVar   :: STM (TVar a)
readTVar  :: TVar a -> STM a
writeTVar :: TVar a -> a -> STM ()

retry     :: STM a
orElse    :: STM a -> STM a -> STM a

throwSTM  :: Exception e => e -> STM a
catchSTM  :: Exception e => STM a -> (e -> STM a) -> STM a
```

and this would work, but the `MVar` is a single point of contention. For example, the rendering thread, which only needs to look at the currently displayed desktop, could be blocked by a window on another desktop moving itself.

So perhaps we can try to allow more concurrency by having a separate `MVar` for each desktop:

```haskell
type Display = Map Desktop (MVar (Set Window)
```

unfortunately this approach quickly runs into problems. Consider an operation to move a window from one desktop to another:

```haskell
moveWindow :: Display -> Window -> Desktop -> Desktop -> IO ()
moveWindow disp win a b = do
  wa <- takeMVar ma
  wb <- takeMVar mb
  putMVar ma (Set.delete win wa)
  putMVar mb (Set.insert win wb)
 where
  ma = fromJust (lookup disp a)
  mb = fromJust (lookup disp b)
```

Note that we must take both `MVar`s before we can put the results: otherwise another thread could potentially observe the display in a state in which the window we are moving does not exist. But this raises a problem: what if there is concurrent call to `moveWindow` trying to move a window in the opposite direction? Both calls would succeed at the first `takeMVar`, but block on the second, and the result is a deadlock. This is an instance of the classic Dining Philosophers problem ().

One solution is to impose an ordering on the `MVar`s, and require that all agents take `MVar`s in the correct order and release them in the opposite order. That is inconvenient and error-prone though, and furthermore we have to extend our ordering to any other state that we might need to access concurrently. Large systems with many locks (e.g. Operating Systems) are often plagued by this problem, and managing the complexity requires building elaborate infrastructure to detect ordering violations.

Transactional memory provides a way to avoid this deadlock problem without imposing a requirement for ordering on the programmer. To solve the problem using STM, we replace `MVar` with `TVar`:

```
type Display = Map Desktop (TVar (Set Window))
```

`TVar` stands for "transactional variable", and it is a mutable variable that can only be read or written within a transaction. To implement `moveWindow`, we simply perform the necessary operations on `TVar`s in the STM monad, and wrap the whole sequence in `atomically`:

```
moveWindow :: Display -> Window -> Desktop -> Desktop -> IO ()
moveWindow disp win a b = atomically $ do
  wa <- readTVar ma
  wb <- readTVar mb
  writeTVar ma (Set.delete win wa)
  writeTVar mb (Set.insert win wb)
 where
  ma = fromJust (Map.lookup a disp)
  mb = fromJust (Map.lookup b disp)
```

The code is almost identical to the `MVar` version, but the behaviour is quite different: the sequence of operations inside `atomically` happens indivisibly as far as the rest of the program is concerned. No other thread can observe an intermediate state; the operation has either completed, or it has not started yet. What's more, there is no requirement that we read both `TVar`s before we write them, this would be fine too:

```
moveWindow :: Display -> Window -> Desktop -> Desktop -> IO ()
moveWindow disp win a b = atomically $ do
  wa <- readTVar ma
  writeTVar ma (Set.delete win wa)
  wb <- readTVar mb
  writeTVar mb (Set.insert win wb)
 where
  ma = fromJust (lookup disp a)
  mb = fromJust (lookup disp b)
```

So STM is far less error-prone here. The approach also scales to any number of `TVar`s, so we could easily write an operation that moves the windows from all other desktops to the current desktop, for example.

Now suppose that we want to swap two windows, moving window W from desktop A to B, and simultaneously V from B to A. With the `MVar` representation we would have to write a special-purpose operation to do this, because it has to take the `MVar`s for A and B (in the right order), and then put both `MVar`s back with the new contents. With STM, however, we can express this much more neatly as a composition. First we need to expose a version of `moveWindow` without the `atomically` wrapper:

```
moveWindowSTM :: Display -> Window -> Desktop -> Desktop
              -> STM ()
moveWindowSTM disp win a b = do ...
```

and then we can define `swapWindows` by composing two `moveWindowSTM` calls:

```
swapWindows :: Display
            -> Window -> Desktop
            -> Window -> Desktop
            -> IO ()
swapWindows disp w a v b = atomically $ do
  moveWindowSTM disp w a b
  moveWindowSTM disp v b a
```

This demonstrates the *composability* of STM operations: any operation of type `STM a` can be composed with others to form a larger atomic transaction. For this reason, `STM` operations are usually provided without the `atomically` wrapper, so that clients can compose them as necessary, before finally wrapping the entire operation in `atomically`.

So far we have covered the basic facilities of STM, and shown that STM can be used to make atomicity scale in a composable way. STM confers a qualitative improvement in expressibility and robustness when writing concurrent programs. The benefits of STM in Haskell go further, however: in the following sections we show how STM can be used to make blocking abstractions compose, and how STM can be used to manage complexity in the presence of failure and interruption.

3.4.1 Blocking

An important part of concurrent programming is dealing with *blocking*; when we need to wait for some condition to be true, or to acquire a particular resource. STM provides an ingenious way to do this, with a single operation:

```
retry :: STM a
```

the meaning of `retry` is simply "run the current transaction again". That seems bizarre - why would we want to run the current transaction again? Well, for one thing, the contents of some `TVar`s that we have read may have been changed by another thread, so re-running the transaction may yield different results. Indeed, there's no point re-running the transaction *unless* it is possible that something different might happen, and the runtime system knows this, so `retry` waits until a `TVar` that was read in the current transaction has been written to, and then triggers a re-run of the current transaction. Until that happens, the current thread is blocked.

As a concrete example, we can use `retry` to implement the rendering thread in our window-manager example. The behaviour we want is this:

- One desktop is designated as having the *focus*. The focussed desktop is the one displayed by the rendering thread.
- The user may request that the focus be changed at any time.
- Windows may move around and appear or disappear of their own accord, and the rendering thread must update its display accordingly.

We are supplied with a function `render` which handles the business of rendering windows on the display. It should be called whenever the window layout changes[23]:

```
render :: Set Window -> IO ()
```

The currently focussed desktop is a piece of state that is shared by the rendering thread and some other thread that handles user input. Therefore we represent that by a `TVar`:

```
type UserFocus = TVar Desktop
```

Next, we define an auxiliary function `getWindows` that, given the `Display` and the `UserFocus`, returns the set of windows to render, in the `STM` monad. The implementation is straightforward: read the current focus, and look up the contents of the appropriate desktop in the `Display`:

```
getWindows :: Display -> UserFocus -> STM (Set Window)
getWindows disp focus = do
  desktop <- readTVar focus
  readTVar (fromJust (Map.lookup desktop disp))
```

Finally, we can implement the rendering thread. The general plan is to repeatedly read the current state with `getWindows` and call `render` to render it, but use `retry` to avoid calling `render` when nothing has changed. Here is the code:

```
renderThread :: Display -> UserFocus -> IO ()
renderThread disp focus = do
  wins <- atomically $ getWindows disp focus
  loop wins
 where
  loop wins = do
    render wins
    next <- atomically $ do
               wins' <- getWindows disp focus
               if (wins == wins')
                   then retry
                   else return wins'
    loop next
```

[23] we are assuming that the actual window contents are rendered via some separate means, e.g. compositing

First we read the current set of windows to display (line 3) and use this as the initial value for the `loop` (line 4). Lines 6-13 implement the loop. Each iteration calls `render` to display the current state (line 7), and then enters a transaction to read the next state. Inside the transaction we read the current state (line 9), and compare it to the state we just rendered (line 10); if the states are the same, there is no need to do anything, so we call `retry`. If the states are different, then we return the new state, and the loop iterates with the new state (line 13).

The effect of the `retry` is precisely what we need: it waits until the value read by `getWindows` could possibly be different, because another thread has successfully completed a transaction that writes to one of the `TVar`s that is read by `getWindows`. That encompasses both changes to the `focus` (because the user switched to a different desktop), and changes to the contents of the current desktop (because a window moved, appeared, or disappeared). Furthermore, changes to other desktops can take place without the rendering thread being woken up.

If it weren't for STM's `retry` operation, we would have to implement this complex logic ourselves, including implementing the signals between threads that modify the state and the rendering thread. This is anti-modular, because operations that modify the state have to know about the observers that need to act on changes. Furthermore, it gives rise to a common source of concurrency bugs: *lost wakeups*. If we forgot to signal the rendering thread, then the display would not be updated. In this case the effects are somewhat benign, but in a more complex scenario lost wakeups often lead to deadlocks, because the woken thread was supposed to complete some operation on which other threads are waiting.

3.4.2 Implementing channels with STM

As a second concrete example, we shall implement the `Chan` type from Section 3.2.1 using STM. We shall see that using STM to implement `Chan` is rather less tricky than using `MVar`s, and furthermore we are able to add some more complex operations that were hard or impossible using `MVar`s.

The STM version of `Chan` is called `TChan`[24], and the interface we wish to implement is as follows:

```
data TChan a

newTChan   :: IO (TChan a)
writeTChan :: TChan a -> a -> IO ()
readTChan  :: TChan a -> IO a
```

that is, exactly the same as `Chan`, except that we renamed `Chan` to `TChan`. The full code for the implementation is given in Listing 3. The implementa-

[24]the implementation is available in the module `Control.Concurrent.STM.TChan` from the `stm` package.

Listing 3: implementation of `TChan`

```haskell
data TChan a = TChan (TVar (TVarList a))
                     (TVar (TVarList a))

type TVarList a = TVar (TList a)
data TList a = TNil | TCons a (TVarList a)

newTChan :: STM (TChan a)
newTChan = do
  hole <- newTVar TNil
  read <- newTVar hole
  write <- newTVar hole
  return (TChan read write)

readTChan :: TChan a -> STM a
readTChan (TChan read _write) = do
  listhead <- readTVar read
  head <- readTVar listhead
  case head of
    TNil -> retry
    TCons a tail -> do
        writeTVar read tail
        return a

writeTChan :: TChan a -> a -> STM ()
writeTChan (TChan _read write) a = do
  listend <- readTVar write
  new_listend <- newTVar TNil
  writeTVar listend (TCons a new_listend)
  writeTVar write new_listend
```

tion is similar in structure to the MVar version in Section 3.2.1, so we do not describe it line by line, however we shall point out a few important details:

- All the operations are in the STM monad, so to use them they need to be wrapped in atomically (but they can also be composed, more about that later).
- Blocking in readTChan is implemented by the call to retry (line 19).
- Nowhere did we have to worry about what happens when a read executes concurrently with a write, because all the operations are atomic.

Something worth noting, although this is not a direct result of STM, is that the straightforward implementation of dupChan does not suffer from the problem that we had in Section 3.2.1, because readTChan does not remove elements from the list.

We now describe three distinct benefits of the STM implementation compared to using MVars.

More operations are possible. In Section 3.2.1 we mentioned the unGetChan operation, which could not be implemented with the desired semantics using MVars. Here is its implementation with STM:

```
unGetTChan :: TChan a -> a -> STM ()
unGetTChan (TChan read _write) a = do
   listhead <- readTVar read
   newhead <- newTVar (TCons a listhead)
   writeTVar read newhead
```

The obvious implementation does the right thing here. Other operations that were not possible with MVars are straightforward with STM, for example isEmptyTChan, which suffers from the same problem as unGetChan in the MVar version:

```
isEmptyTChan :: TChan a -> STM Bool
isEmptyTChan (TChan read _write) = do
  listhead <- readTVar read
  head <- readTVar listhead
  case head of
    TNil -> return True
    TCons _ _ -> return False
```

Composition of blocking operations. Suppose we wish to implement an operation readEitherTChan that can read an element from either of two channels. If both channels are empty it blocks; if one channel is non-empty it reads the value from that channel, and if both channels are non-empty it chooses which channel to read from non-deterministically. Its type is

```
readEitherTChan :: TChan a -> TChan b -> STM (Either a b)
```

We cannot implement this function with the operations introduced so far, but STM provides one more crucial operation that allows blocking transactions to be composed. The operation is `orElse`:

```
orElse :: STM a -> STM a -> STM a
```

The operation `orElse a b` has the following behaviour:

- First `a` is executed. If `a` returns a result, then that result is immediately returned by the `orElse` call.
- If `a` instead called `retry`, then `a`*'s effects are discarded*, and `b` is executed instead.

We can use `orElse` to compose blocking operations atomically. Returning to our example, `readEitherTChan` could be implemented as follows:

```
readEitherTChan :: TChan a -> TChan b -> STM (Either a b)
readEitherTChan a b =
  fmap Left (readTChan a)
    `orElse`
  fmap Right (readTChan b)
```

This is a straightforward composition of the two `readTChan` calls, the only complication is arranging to tag the result with either `Left` or `Right` depending on which branch succeeds.

In the `MVar` implementation of `Chan` there is no way to implement `readEitherChan` without elaborating the representation of `Chan` to support the synchronisation protocol that would be required (more discussion on implementing choice with `MVar`s can be found in Peyton Jones et al. (1996)).

One thing to note is that `orElse` is left-biased; if both `TChan`s are non-empty, then `readEitherChan` will always return an element from first one. Whether this is problematic or not depends on the application: something to be aware of is that the left-biased nature of `orElse` can have implications for fairness in some situations.

Asynchronous exception safety. Up until now we have said nothing about how exceptions in STM behave. The `STM` monad supports exceptions much like the `IO` monad, with two operations:

```
throwSTM  :: Exception e => e -> STM a
catchSTM  :: Exception e => STM a -> (e -> STM a) -> STM a
```

`throwSTM` throws an exception, and `catchSTM` catches exceptions and invokes a handler, just like `catch` in the `IO` monad. However, exceptions in STM are different in one vital way:

- In `catchSTM m h`, if `m` raises an exception, then *all of its effects are discarded*, and then the handler `h` is invoked. As a degenerate case, if there is no enclosing `catchSTM` at all, then all of the effects of the transaction are discarded and the exception is propagated out of `atomically`.

This behaviour of `catchSTM` was introduced in a subsequent amendment of Harris et al. (2005); the original behaviour in which effects were not discarded being generally regarded as much less useful. An example helps to demonstrate the motivation:

```
readCheck :: TChan a -> STM a
readCheck chan = do
  a <- readTChan chan
  checkValue a
```

`checkValue` imposes some extra constraints on the value read from the channel. However, suppose `checkValue` raises an exception (perhaps accidentally, e.g. divide-by-zero). We would prefer it if the `readTChan` had not happened, since an element of the channel would be lost. Furthermore, we would like `readCheck` to have this behaviour regardless of whether there is an enclosing exception handler or not. Hence `catchSTM` discards the effects of its first argument in the event of an exception.

The discarding-effects behaviour is even more useful in the case of *asynchronous* exceptions. If an asynchronous exception occurs during an STM transaction, the entire transaction is aborted (unless the exception is caught and handled, but handling asynchronous exceptions in STM is not something we typically want to do). So in most cases, asynchronous exception safety in STM consists of doing *absolutely nothing at all*. There are no locks to replace, so no need for exception handlers or `bracket`, and no need to worry about which critical sections to protect with `mask`.

The implementation of `TChan` given earlier is entirely safe with respect to asynchronous exceptions as it stands, and moreover any compositions of these operations are also safe.

STM provides a nice way to write code that is automatically safe with respect to asynchronous exceptions, so it can be useful even for state that is not shared between threads. The only catch is that we have to use STM consistently for all our state, but having made that leap, asynchronous exception safety comes for free.

3.4.3 Performance

As with most abstractions, STM has a runtime cost. If we understand the cost model, then we can avoid writing code that hits the bad cases. So in this section we give an informal description of the implementation of STM (at least in GHC), with enough detail that the reader can understand the cost model.

An STM transaction works by accumulating a *log* of `readTVar` and `writeTVar` operations that have happened so far during the transaction. The log is used in three ways:

- By storing `writeTVar` operations in the log rather than applying them to main memory immediately, discarding the effects of a transaction is easy; we just throw away the log. Hence, aborting a transaction has a fixed small cost.

- Each `readTVar` must traverse the log to check whether the `TVar` was written by an earlier `writeTVar`. Hence, `readTVar` is an $O(n)$ operation in the length of the log.

- Because the log contains a record of all the `readTVar` operations, it can be used to discover the full set of `TVar`s read during the transaction, which we need to know in order to implement `retry`.

When a transaction reaches the end, the STM implementation compares the log against the contents of memory using a two-phase locking protocol (details in Harris et al. (2005)). If the current contents of memory matches the values read by `readTVar`, the effects of the transaction are *committed* to memory atomically, and if not, the log is discarded and the transaction runs again from the beginning. The STM implementation in GHC does not use global locks; only the `TVar`s involved in the transaction are locked during commit, so transactions operating on disjoint sets of `TVar`s can proceed without interference.

The general rule of thumb when using STM is never to read an unbounded number of `TVar`s in a single transaction, because the $O(n)$ performance of `readTVar` then gives $O(n^2)$ for the whole transaction. Furthermore, long transactions are much more likely to fail to commit, because another transaction will probably have modified one or more of the same `TVar`s in the meantime, so there is a high probability of re-execution.

It is possible that a future STM implementation may use a different data structure to store the log, reducing the `readTVar` overhead to $O(\log n)$ or better (on average), but the likelihood that a long transaction will fail to commit would still be an issue. To avoid that problem intelligent contention-management is required, which is an area of active research.

3.4.4 Summary

To summarise, STM provides several benefits for concurrent programming:

- **Composable atomicity**. We may construct arbitrarily large atomic operations on shared state, which can simplify the implementation of concurrent data structures with fine-grained locking.

- **Composable blocking**. We can build operations that make a choice between multiple blocking operations; something which is very difficult with `MVar`s and other low-level concurrency abstractions.

- **Robustness in the presence of failure and cancellation**. A transaction in progress is aborted if an exception occurs, so STM makes it easy to maintain invariants on state in the presence of exceptions.

3.4.5 Further reading

To find out more about STM in Haskell:

- Harris et al. (2005), the original paper describing the design of Haskell's STM interface (be sure to get the revised version[25] which has the modified semantics for exceptions).
- "Beautiful Concurrency" a chapter in Wilson (2007).

3.5 Concurrency and the Foreign Function Interface

Haskell has a *foreign function interface* (FFI) that allows Haskell code to call, and be called by, foreign language code (primarily C) (Marlow ed.). Foreign languages also have their own threading models — in C there is POSIX or Win32 threads, for example — so we need to specify how Concurrent Haskell interacts with the threading models of foreign code.

The details of the design can be found in Marlow et al. (2004), in the following sections we summarise the behaviour the Haskell programmer can expect.

All of the following assumes that GHC's `-threaded` option is in use. Without `-threaded`, the Haskell process uses a single OS thread only, and multi-threaded foreign calls are not supported.

3.5.1 Threads and foreign out-calls

An out-call is a call made from Haskell to a foreign language. At the present time the FFI supports only calls to C, so that's all we describe here. In the following we refer to threads in C (i.e. POSIX or Win32 treads) as "OS threads" to distinguish them from Haskell threads.

As an example, consider making the POSIX C function `read()` callable from Haskell:

```
foreign import ccall "read"
   c_read :: CInt        -- file descriptor
          -> Ptr Word8  -- buffer for data
          -> CSize      -- size of buffer
          -> CSSize     -- bytes read, or -1 on error
```

This declares a Haskell function `c_read` that can be used to call the C function `read()`. Full details on the syntax of `foreign` declarations and the relationship between C and Haskell types can be found in the Haskell report (Marlow ed.).

[25] `http://research.microsoft.com/people/simonpj/`

Just as Haskell threads run concurrently with each other, when a Haskell thread makes a foreign call, that foreign call runs concurrently with the other Haskell threads, and indeed with any other active foreign calls. Clearly the only way that two C calls can be running concurrently is if they are running in two separate OS threads, so that is exactly what happens: if several Haskell threads call `c_read` and they all block waiting for data to be read, there will be one OS thread per call blocked in `read()`.

This has to work despite the fact that Haskell threads are not normally mapped one-to-one with OS threads; as we mentioned earlier (Section 3.1), in GHC, Haskell threads are lightweight and managed in user-space by the runtime system. So to handle concurrent foreign calls, the runtime system has to create more OS threads, and in fact it does this on demand. When a Haskell thread makes a foreign call, another OS thread is created (if necessary), and the responsibility for running the remaining Haskell threads is handed over to the new OS thread, meanwhile the current OS thread makes the foreign call.

The implication of this design is that a foreign call may be executed in *any* OS thread, and subsequent calls may even be executed in different OS threads. In most cases this isn't important, but sometimes it is: some foreign code must be called by a *particular* OS thread. There are two instances of this requirement:

- Libraries that only allow one OS thread to use their API. GUI libraries often fall into this category: not only must the library be called by only one OS thread, it must often be one *particular* thread (e.g. the main thread). The Win32 GUI APIs are an example of this.
- APIs that use internal thread-local state. The best-known example of this is OpenGL, which supports multi-threaded use, but stores state between API calls in thread-local storage. Hence, subsequent calls must be made in the same OS thread, otherwise the later call will see the wrong state.

For this reason, the concept of *bound threads* was introduced. A bound thread is a Haskell thread/OS thread pair, such that foreign calls made by the Haskell thread always take place in the associated OS thread. A bound thread is created by `forkOS`:

```
forkOS :: IO () -> IO ThreadId
```

Care should be taken when calling `forkOS`: it creates a complete new OS thread, so it can be quite expensive.

3.5.2 Threads and foreign in-calls

In-calls are calls to Haskell functions that have been exposed to foreign code using `foreign export`. For example, if we have a function `f` of type

`Int -> IO Int`, we could expose it like this:

```
foreign export ccall "f" f :: Int -> IO Int
```

This would create a C function with the following signature:

```
HsInt f(HsInt);
```

here `HsInt` is the C type corresponding to Haskell's `Int` type.

In a multi-threaded program, it is entirely possible that `f` might be called by multiple OS threads concurrently. The GHC runtime system supports this (at least with `-threaded`), with the following behaviour: each call becomes a new *bound thread*. That is, a new Haskell thread is created for each call, and the Haskell thread is bound to the OS thread that made the call. Hence, any further out-calls made by the Haskell thread will take place in the same OS thread that made the original in-call. This turns out to be important for dealing with GUI callbacks: the GUI wants to run in the main OS thread only, so when it makes a callback into Haskell, we need to ensure that GUI calls made by the callback happen in the same OS thread that invoked the callback.

3.5.3 Further reading

- The full specification of the Foreign Function Interface (FFI) can be found in the Haskell 2010 report (Marlow ed.);
- GHC's extensions to the FFI can be found in the GHC User's Guide[26];
- Functions for dealing with bound threads can be found in the documentation for the `Control.Concurrent` module.

3.6 High-speed concurrent server applications

Server-type applications that communicate with many clients simultaneously demand both a high degree of concurrency and high performance from the I/O subsystem. A good web server should be able to handle hundreds of thousands of concurrent connections, and service tens of thousands of requests per second.

Ideally, we would like to write these kinds of applications using threads. A thread is the right abstraction: it allows the developer to focus on programming the interaction with a single client, and then to lift this interaction to multiple clients by simply forking many instances of the single-client interaction in separate threads. To illustrate this idea we will describe a simple network server[27], with the following behaviour:

- The server accepts connections from clients on port 44444.

[26] `http://www.haskell.org/ghc/docs/latest/html/users_guide/`
[27] the full code can be found in sample `server.hs`

- If a client sends an integer n, the service responds with the value of $2n$
- If a client sends the string "end", the server closes the connection.

First, we program the interaction with a single client. The function `talk` defined below takes a `Handle` for communicating with the client. The `Handle` is typically bound to a network socket, so data sent by the client can be read from the `Handle`, and data written to the `Handle` will be sent to the client.

```
1  talk :: Handle -> IO ()
2  talk h = do
3    hSetBuffering h LineBuffering
4    loop
5   where
6    loop = do
7      l <- hGetLine h
8      if l == "end"
9         then hPutStrLn h "Thank you for using the Haskell
              doubling service."
10        else do hPutStrLn h (show (2 * (read l :: Integer)))
11                loop
```

Line 3 sets the buffering mode for the `Handle` to line-buffering; if we don't do that then output sent to the `Handle` will be buffered up by the I/O layer until there is a full block (which is more efficient for large transfers, but not useful for interactive applications). Then we enter a loop to respond to requests from the client. Each iteration of the loop reads a new line of text (line 7), and then checks whether the client sent "end". If so, we emit a polite message and return (line 8). If not, we attempt to interpret the line as an integer and to write the value obtained by doubling it. Finally we call `loop` again to read the next request.

Having dealt with the interaction with a single client, we can now make this into a multi-client server using concurrency. The `main` function for our server is as follows:

```
1  main = do
2    s <- listenOn (PortNumber 44444)
3    forever $ do
4      (h,host,_) <- accept s
5      printf "new client: %s\n" host
6      forkIO (talk h `finally` hClose h)
```

on line 2 we create a network socket to listen on port 44444, and then we enter a loop to accept connections from clients (line 3). Line 4 accepts a new client connection: `accept` blocks until a connection request from a client arrives, and then returns a `Handle` for communicating with the client (here bound to `h`) and some information about the client (here we bind `host` to the client's hostname). Line 5 reports the new connection, and on line

6 we call `forkIO` to create a new thread to handle the request. A little explanation is needed for the expression passed to `forkIO`:

```
   talk h `finally` hClose h
```

`talk` is the single-client interaction that we defined above. The infix operator `finally` is a standard exception-handling abstraction from `Control.Exception` rather like a specialised verison of `bracket`. It has the following type

```
finally :: IO a -> IO b -> IO a
```

with the behaviour that ``a `finally` b`` behaves exactly like `a`, except that `b` is always performed after `a` returns or throws an exception. Here we are using `finally` to ensure that the `Handle` for communicating with the client is always closed, even if `talk` throws an exception. If we didn't do this, the `Handle` would eventually be garbage collected, but in the meantime it would consume resources which might lead to the program failing due to lack of file descriptors. It is always a good idea to close `Handle`s when you're finished with them.

Having forked a thread to handle this client, the main thread then goes back to accepting more connections. All the active client connections and the main thread run concurrently with each other, so the fact that the server is handling multiple clients will be invisible to any individual client (unless the server becomes overloaded).

So, making our concurrent server was simple - we did not have to change the single-client code at all, and the code to lift it to a concurrent server was only a handful of lines. We can verify that it works: in one window we start the server

```
$ ./server
```

in another window we start a client, and try a single request[28]:

```
$ nc localhost 44444
22
44
```

Next we leave this client running, and start another client:

```
$ ghc -e 'mapM_ print [1..]' | nc localhost 44444
2
4
6
...
```

[28]`nc` is the netcat program, which is useful for simple network interaction

this client exercises the server a bit more by sending it a continuous stream of numbers to double. For fun, try starting a few of these. Meanwhile we can switch back to our first client, and observe that it is still being serviced:

```
$ nc localhost 44444
22
44
33
66
```

finally we can end the interaction with a client by typing `end`:

```
end
Thank you for using the Haskell doubling service.
```

This was just a simple example, but the same ideas underly several high-performance web-server implementations in Haskell. Furthermore, with no additional effort at all, the same server code can make use of multiple cores simply by compiling with `-threaded` and running with `+RTS -N`.

There are two technologies that make this structure feasible in Haskell:

- GHC's very lightweight threads mean that having one thread per client is practical.
- The IO manager (O'Sullivan and Tibell 2010) handles outstanding blocked I/O operations using efficient operating-system primitives (e.g. the `epoll` call in Unix), which allows us to have many thousands of threads doing I/O simultaneously with very little overhead.

Were it not for lightweight threads and the IO manager, we would have to resort to collapsing the structure into a single event loop (or worse, multiple event loops to take advantage of multiple cores). The event loops style loses the single-client abstraction, instead all clients have to be dealt with simultaneously, which can be complicated if there are different kinds of client with different behaviours. Furthermore we have to represent the state of each client somehow, rather than just writing the straight-line code as we did in `talk` above. Imagine extending `talk` to implement a more elaborate protocol with several states — it would be reasonably straightforward with the single client abstraction, but representing each state and the transitions explicitly would quickly get complicated.

We have ignored many details that would be necessary in a real server application. The reader is encouraged to think about these and to try implementing any requred changes on top of the provided sample code:

- What should happen if the user interrupts the server with control-C? (control-C is implemented as an asynchronous exception `Interrupted` which is sent to the main thread).

- What happens in `talk` if the line does not parse as a number?
- What happens if the client cuts the connection prematurely, or the network goes down?
- Should there be a limit on the number of clients we serve simultaneously?
- Can we log the activity of the server to a file?

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