Functions

```
1 public static int fib(int x) {
2   if (x<=0)
3     return 0;
4   else if (x==1)
5     return 1;
6   else
7     return fib(x-2) + fib(x-1);
8 }
```

```
1 fib :: Int -> Int
2 fib x
3   | x <= 0 = 0
4   | x == 1 = 0
5   | otherwise =
6     (fib (x - 2))
7       + (fib (x - 1))
```

- Functional programming equally powerful as imperative programming
- focused on the "what?" instead of the "how?"
  $\Rightarrow$ more concise $\Rightarrow$ easier to reason about
- based on Lambda Calculus

Arrow Definition (1)

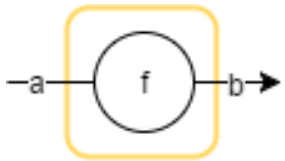
Another way to think about computations:

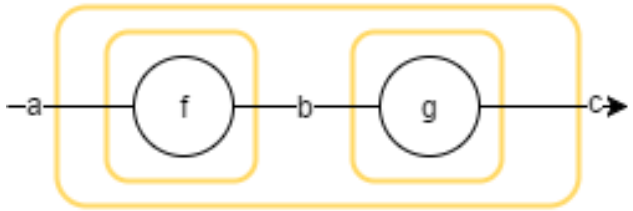
Arrow Definition (2)

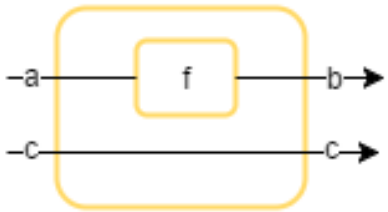
```
class Arrow arr where
  arr  ::  (a -> b) -> arr a b

  (>>>) :: arr a b -> arr b c -> arr a c

  first  ::  arr a b -> arr (a,c) (b,c)
```







Functions ∈ Arrows

Functions (->) are arrows:

```
1 instance Arrow (->) where
2   arr f = f
3   f >>> g = g . f
4   first f = \(a, c) -> (f a, c)
```

The Kleisli Type

The Kleisli type

```
1 data Kleisli m a b = Kleisli { run :: a -> m b }
```

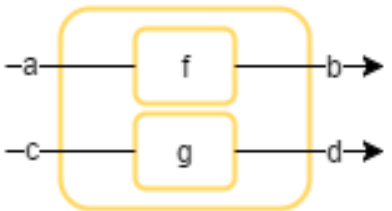
is also an arrow:

```
1 instance Monad m => Arrow (Kleisli m) where
2   arr f = Kleisli $ return . f
3   f >>> g = Kleisli $ \a -> f a >>= g
4   first f = Kleisli $ \(a,c) -> f a >>= \b -> return (b,c)
```

Combinators (1)

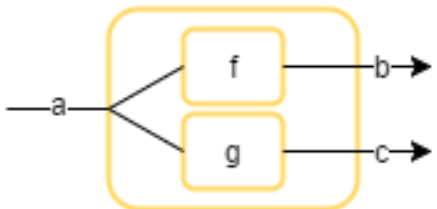
```
1 second :: arr a b -> arr (c, a) (c, b)
2 second f = arr swap >>>
3     first f >>> arr swap
4   where swap (x, y) = (y, x)
```


```
1 (***) :: arr a b -> arr c d -> arr (a, c) (b, d)
2 f *** g = first f >>> second g
```



Combinators (2)

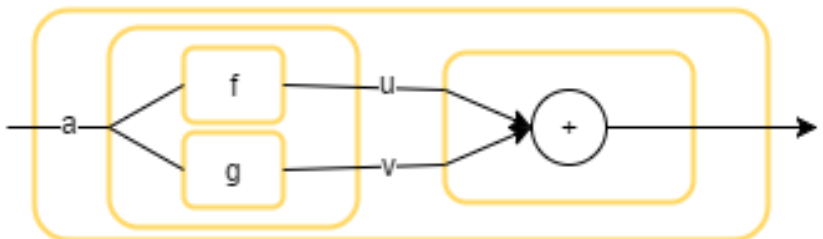
```
1 (&&&) :: arr a b -> arr a c -> arr a (b, c)
2 f &&& g = arr (\a -> (a, a)) >>> (f *** g)
```



Arrow Example

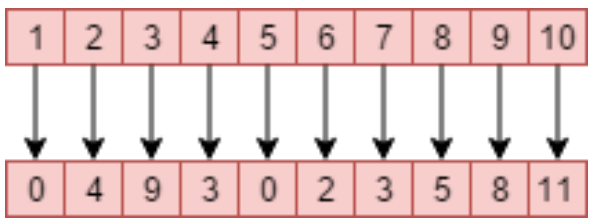
Arrow usage example:

```
1 add :: Arrow arr => arr a Int -> arr a Int -> arr a Int
2 add f g = (f &&& g) >>> arr (\(u, v) -> u + v)
```



In general, Parallelism can be looked at as:

```
1 parEvalN :: [a -> b] -> [a] -> [b]
```



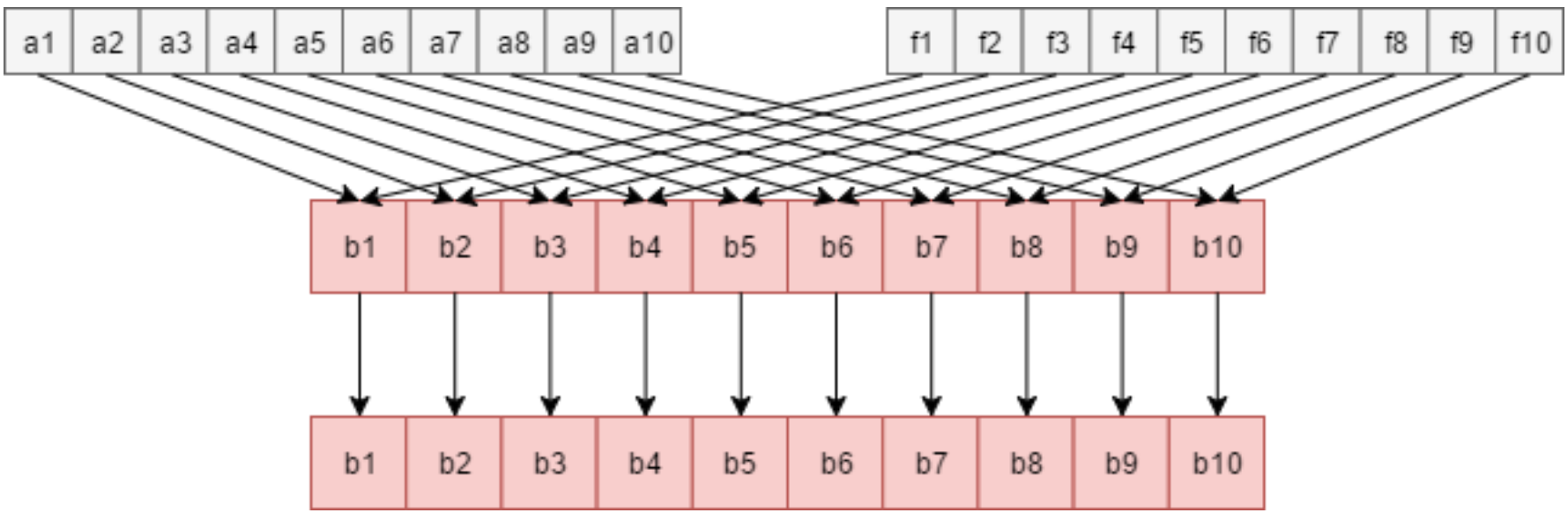
```
1 parEvalN :: [a -> b] -> [a] -> [b]
```

Roadmap:

- Implement using existing Haskells
  - Multicore
  - ParMonad
  - Eden
- Generalize to Arrows
- Adapt Implementations
- Profit

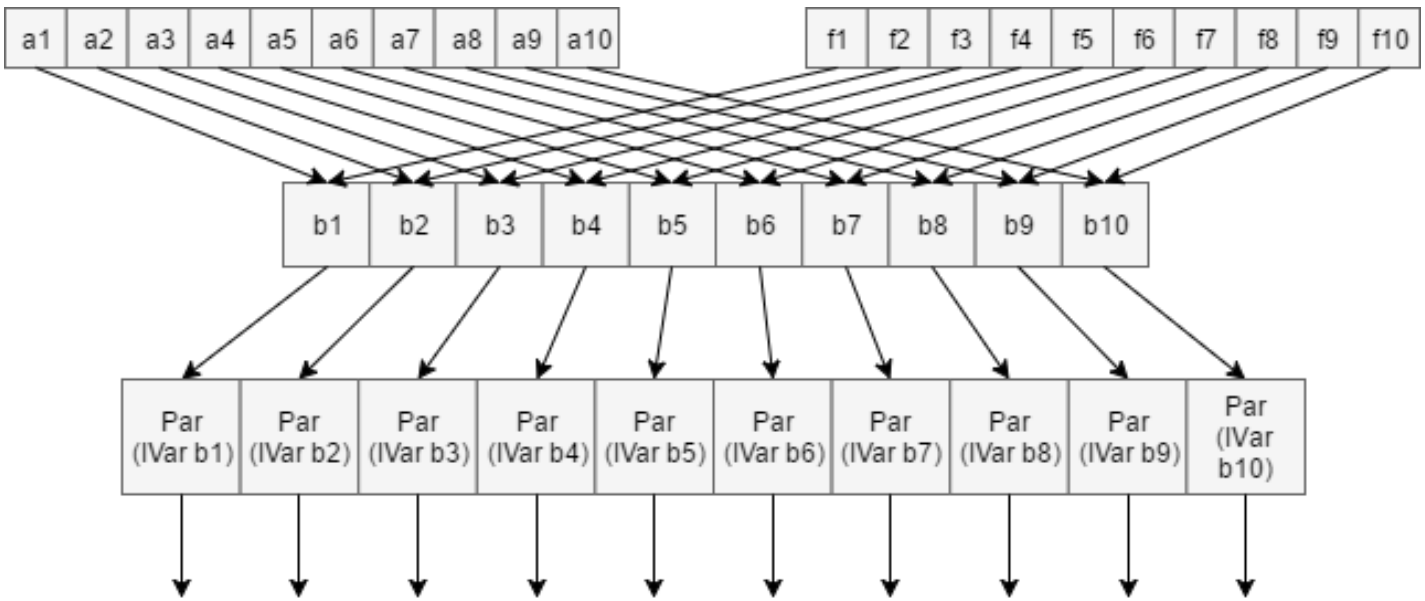
Multicore Haskell

```
1 parEvalN :: (NFData b) => [a -> b] -> [a] -> [b]
2 parEvalN fs as = zipWith ($) fs as `using` parList rdeepseq
```



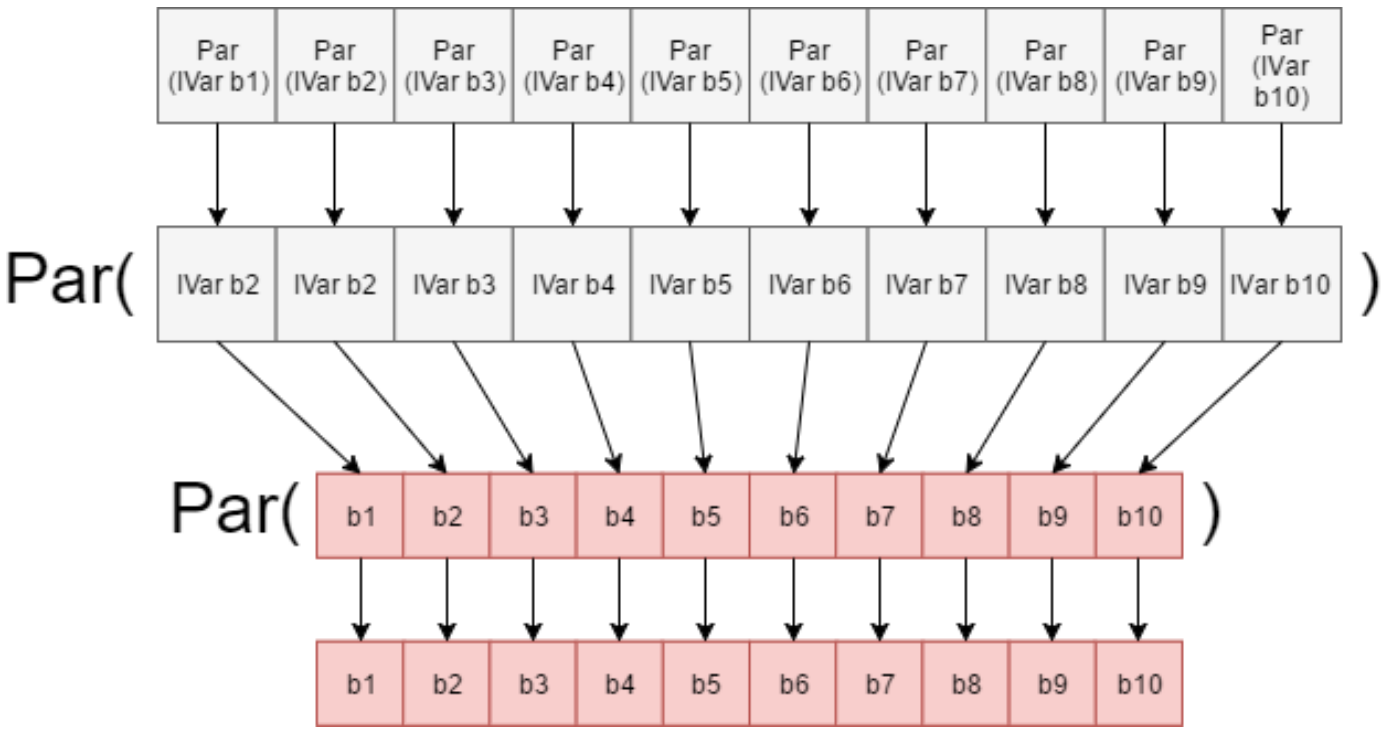
ParMonad

```
1 parEvalN :: (NFData b) => [a -> b] -> [a] -> [b]
2 parEvalN fs as = runPar $
3    (sequence $ map (spawnP) $ zipWith ($) fs as) >>= mapM get
```

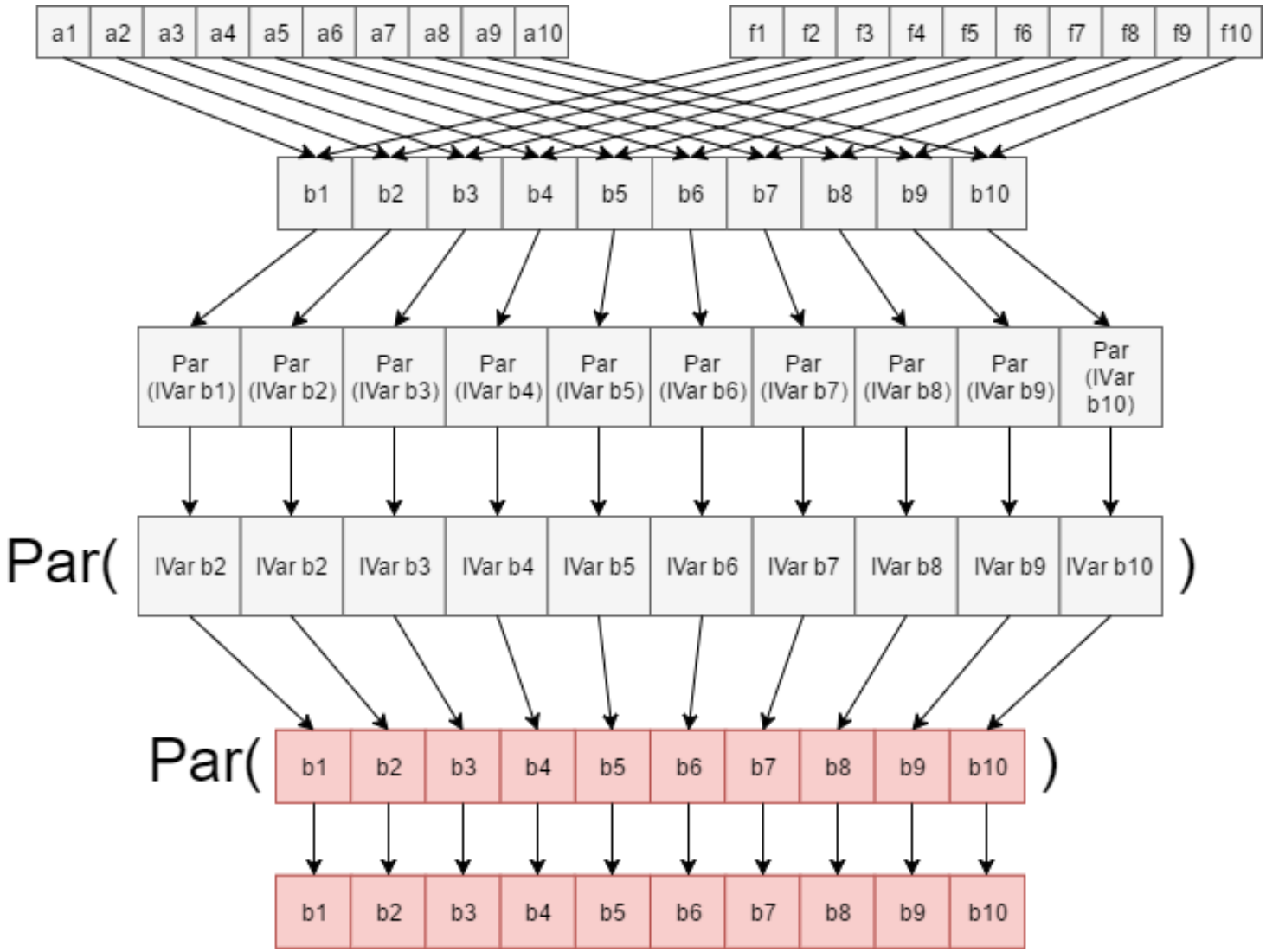


ParMonad

```
1 parEvalN :: (NFData b) => [a -> b] -> [a] -> [b]
2 parEvalN fs as = runPar $
3   (sequence $ map (spawnP) $ zipWith ($) fs as) >>= mapM get
```

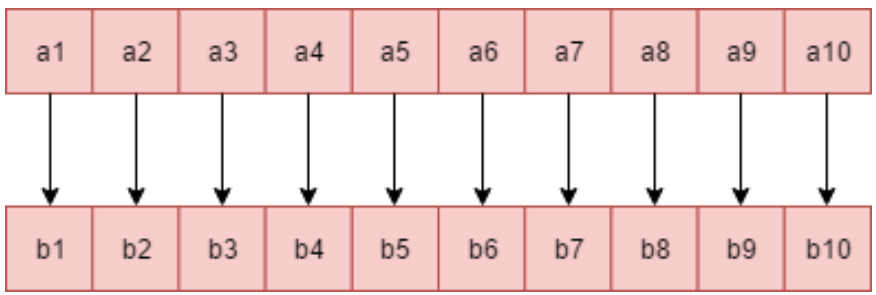


ParMonad


a1 a2 a3 a4 a5 a6 a7 a8 a9 a10
f1 f2 f3 f4 f5 f6 f7 f8 f9 f10
b1 b2 b3 b4 b5 b6 b7 b8 b9 b10
Par (IVar b1) Par (IVar b2) Par (IVar b3) Par (IVar b4) Par (IVar b5) Par (IVar b6) Par (IVar b7) Par (IVar b8) Par (IVar b9) Par (IVar b10)
Par(IVar b2 IVar b2 IVar b3 IVar b4 IVar b5 IVar b6 IVar b7 IVar b8 IVar b9 IVar b10)
Par(b1 b2 b3 b4 b5 b6 b7 b8 b9 b10)
b1 b2 b3 b4 b5 b6 b7 b8 b9 b10

Eden

```
1 parEvalN :: (Trans a, Trans b) => [a -> b] -> [a] -> [b]
2 parEvalN fs as = spawnF fs as
```



The ArrowParallel typeclass

Now, let's generalize:

```
1 parEvalN :: [a -> b] -> [a] -> [b]
```

The ArrowParallel typeclass

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```
1 parEvalN :: [a -> b] -> [a] -> [b]
```

```
1 parEvalN :: (Arrow arr) => [arr a b] -> arr [a] [b]
```

The ArrowParallel typeclass

Now, let's generalize:

```
1 parEvalN :: [a -> b] -> [a] -> [b]
```

```
1 parEvalN :: (Arrow arr) => [arr a b] -> arr [a] [b]
```

```
1 class Arrow arr => ArrowParallel arr a b where
2   parEvalN :: [arr a b] -> arr [a] [b]
```

The ArrowParallel typeclass

Now, let's generalize:

```
1 parEvalN :: [a -> b] -> [a] -> [b]
```

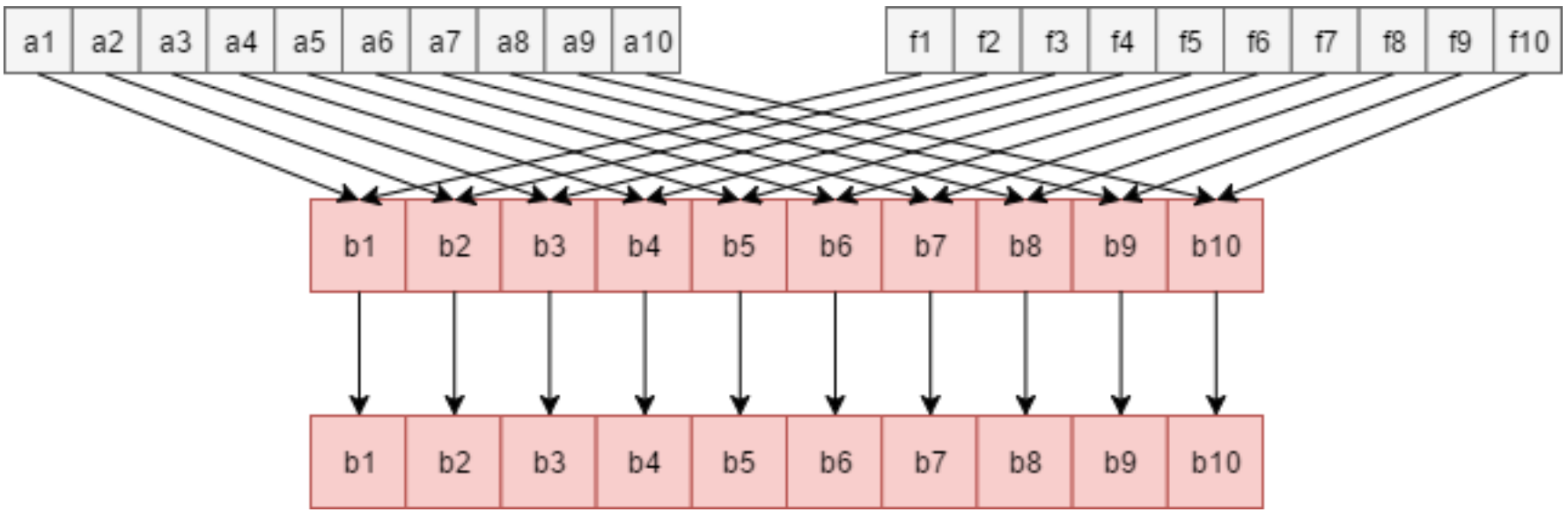
```
1 parEvalN :: (Arrow arr) => [arr a b] -> arr [a] [b]
```

```
1 class Arrow arr => ArrowParallel arr a b where
2   parEvalN :: [arr a b] -> arr [a] [b]
```

```
1 class Arrow arr => ArrowParallel arr a b conf where
2   parEvalN :: conf -> [arr a b] -> arr [a] [b]
```

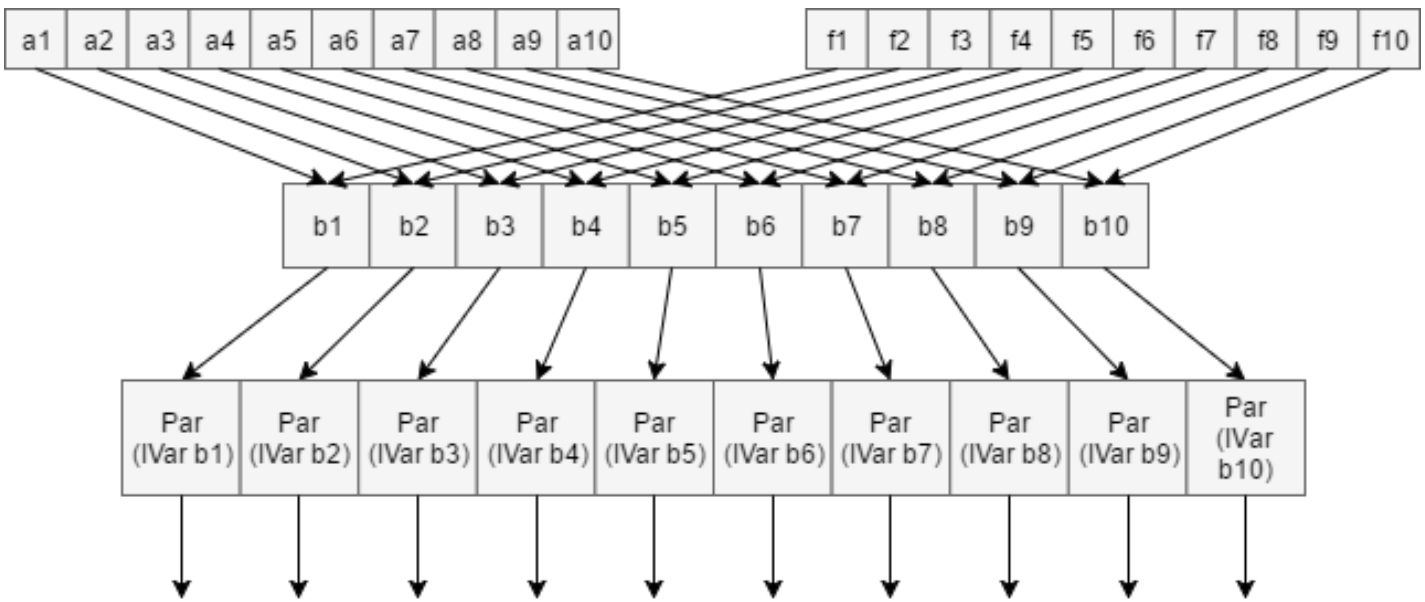
Multicore

```
1 instance (NFData b, ArrowApply arr, ArrowChoice arr) =>
2    ArrowParallel  arr  a  b conf where
3      parEvalN _ fs = listApp fs >>>
4         arr (flip using $ parList rdeepseq)
```



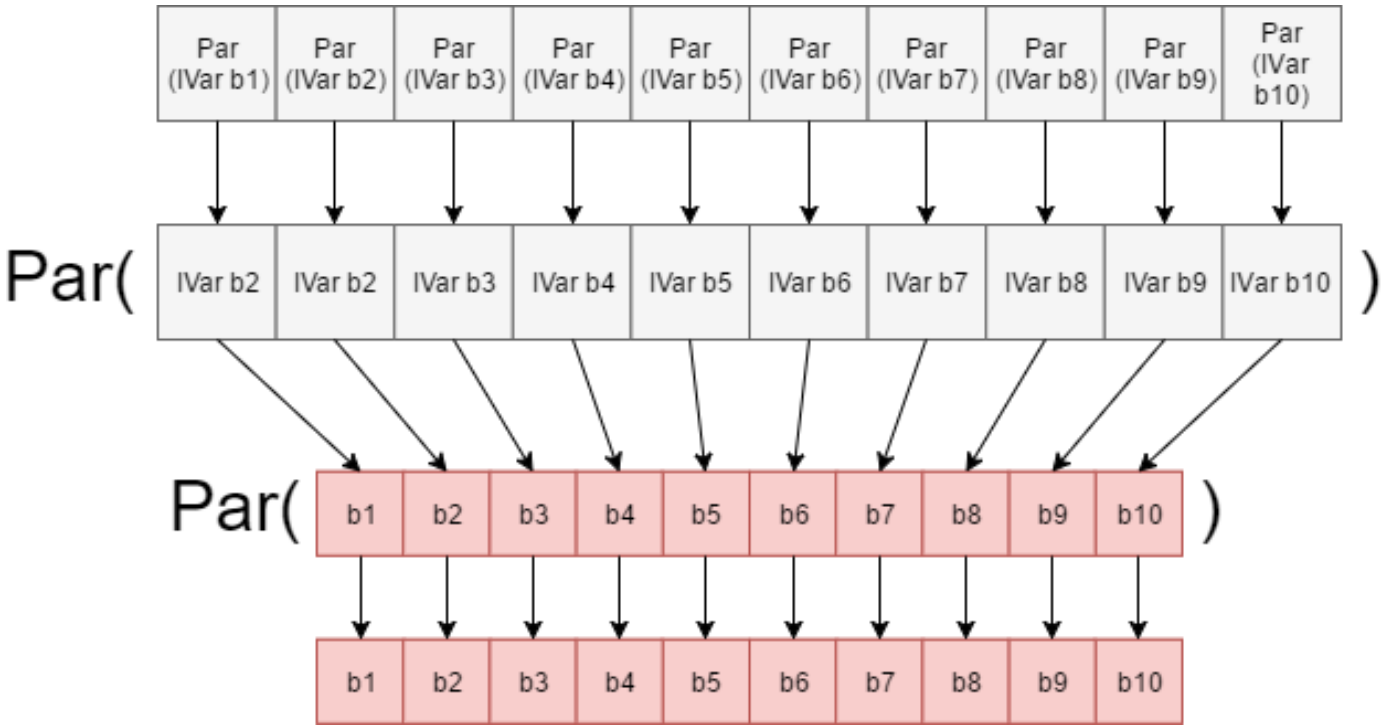
ParMonad

```
instance (NFData b, ArrowApply arr, ArrowChoice arr) =>
  ArrowParallel arr a b conf where
    parEvalN _ fs =
      (arr $ \as -> (fs, as)) >>>
      zipWithArr (app >>> arr spawnP) >>>
       ...
```



ParMonad

```
1   ...
2   arr sequence >>>
3   arr (>>= mapM get) >>>
4   arr runPar
```



Eden (1)

For Eden we need separate implementations.

This is because of spawnF's

```
1 spawnF :: (Trans a, Trans b) => [a -> b] -> [a] -> [b]
```

and app's signature

```
1 app :: (ArrowApply arr) => arr (arr a b, a) b
```

which don't fit together.

Eden (1)

For Eden we need separate implementations.

This is because of spawnF's

```
spawnF :: (Trans a, Trans b) => [a -> b] -> [a] -> [b]
```

and app's signature

```
app :: (ArrowApply arr) => arr (arr a b, a) b
```

which don't fit together.

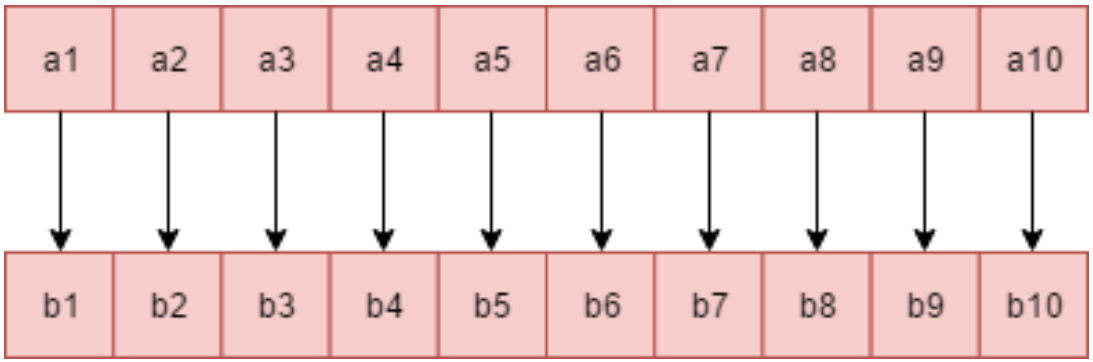
Hacky alternative:

```
class (Arrow arr) => ArrowUnwrap arr where
 arr a b -> (a -> b)
```

Eden (2)

Implementation for Functions

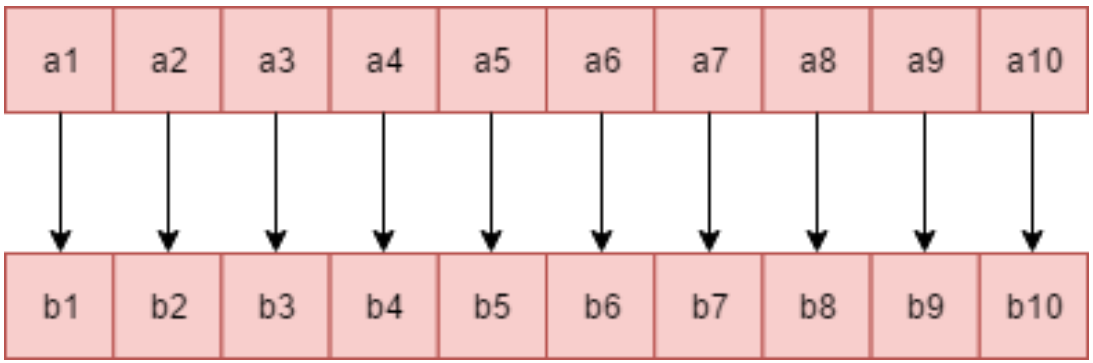
```
1 instance (Trans a, Trans b) => ArrowParallel (->) a b conf where
2   parEvalN _ fs as = spawnF fs as
```



Eden (3)

Implementation for the Kleisli Type:

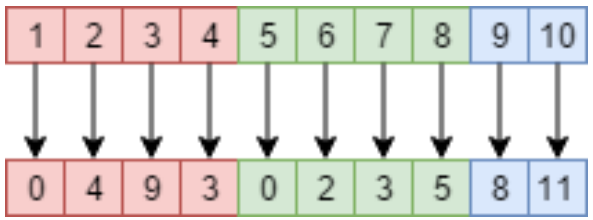
```
instance (Monad m, Trans a, Trans b, Trans (m b)) =>
 ArrowParallel  ( Kleisli  m) a b conf where
parEvalN conf fs =
   (arr $ parEvalN conf (map (\(Kleisli f) -> f) fs)) >>>
   ( Kleisli $ sequence)
```



Skeletons... (1)

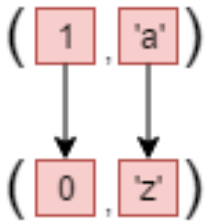
parEvalN, but **chunky**:

```
1 parEvalNLazy :: conf -> ChunkSize -> [arr a b] -> (arr [a] [b])
```



parallel evaluation of **different typed functions**:

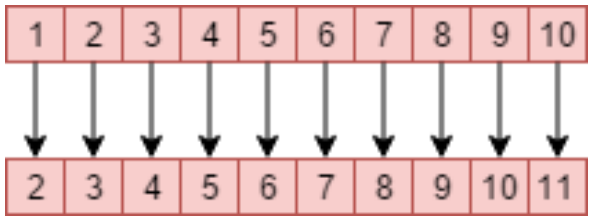
```
1 parEval2 :: conf -> arr a b -> arr c d -> (arr (a, c) (b, d))
```



Skeletons... (2)

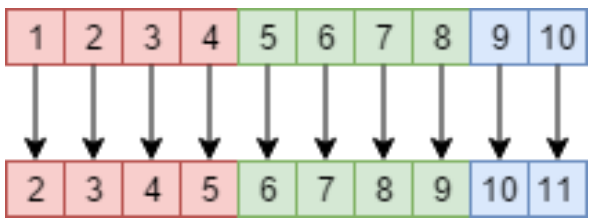
map, but in **parallel**:

```
1 parMap :: conf -> (arr a b) -> (arr [a] [b])
```



parMap, but **chunky**:

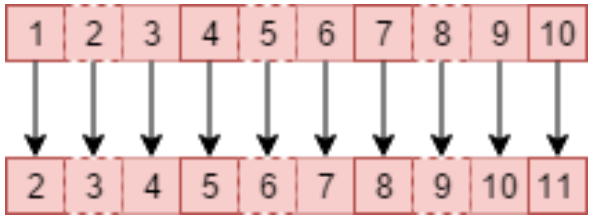
```
1 parMapStream :: conf -> ChunkSize -> arr a b -> arr [a] [b]
```



Skeletons... (3)

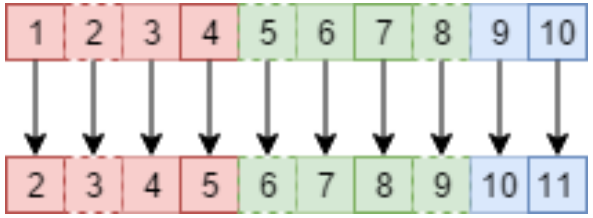
parMap, but with **workload distribution**:

```
1 farm :: conf -> NumCores -> arr a b -> arr [a] [b]
```



farm, but **chunky**:

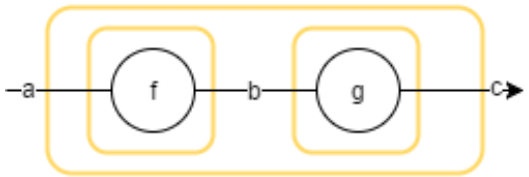
```
1 farmChunk ::
2   conf -> ChunkSize -> NumCores -> arr a b-> arr [a] [b]
```



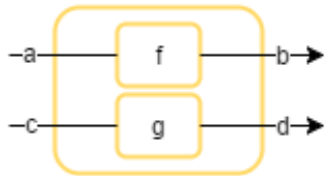
Parallel Operators (1)

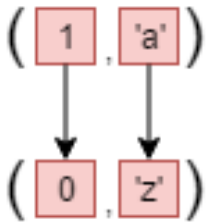
```
1 (|>>>|) :: [arr a b] -> [arr b c] -> [arr a c]
2 (|>>>|) = zipWith (>>>)
```

On all Elements:



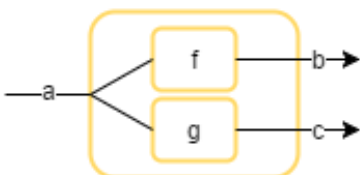

```
1 (|***|) :: arr a b -> arr c d -> arr (a, c) (b, d)
2 (|***|) = parEval2 ()
```

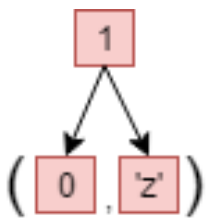




Parallel Operators (2)

```
1 (|&&&|) :: arr a b -> arr a c -> arr a (b, c)
2 (|&&&|) f g = (arr $ \a -> (a, a)) >>> f |***| g
```

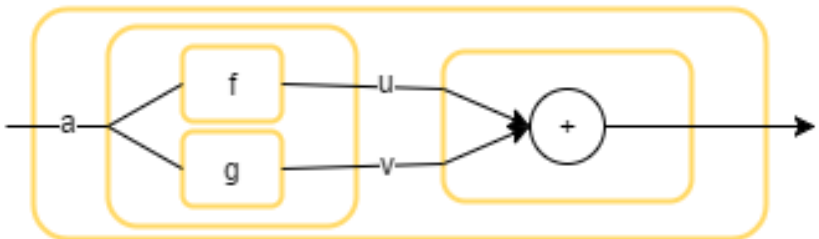


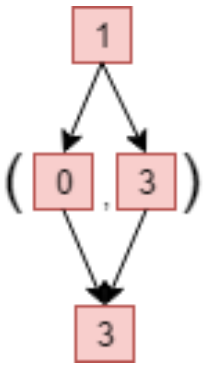


Parallelism made easy

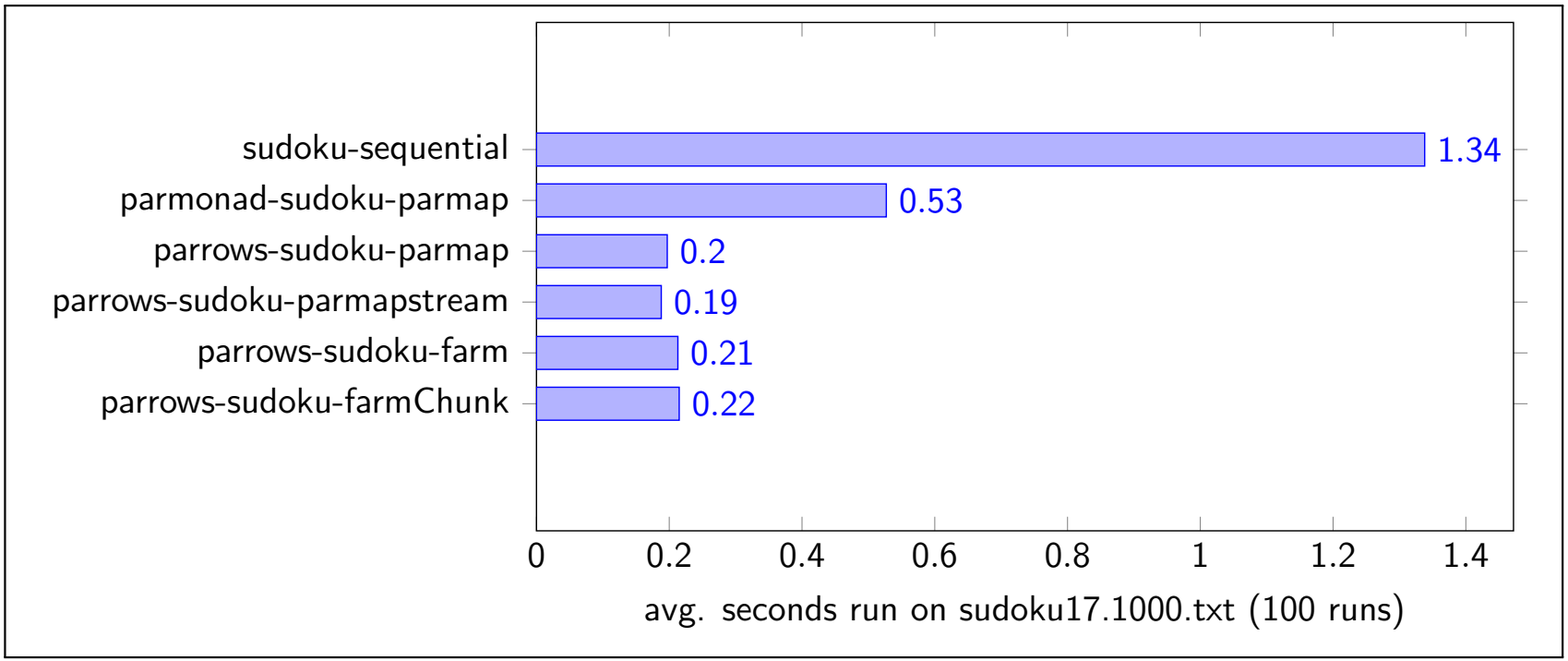
Parallel Evaluation made easy:

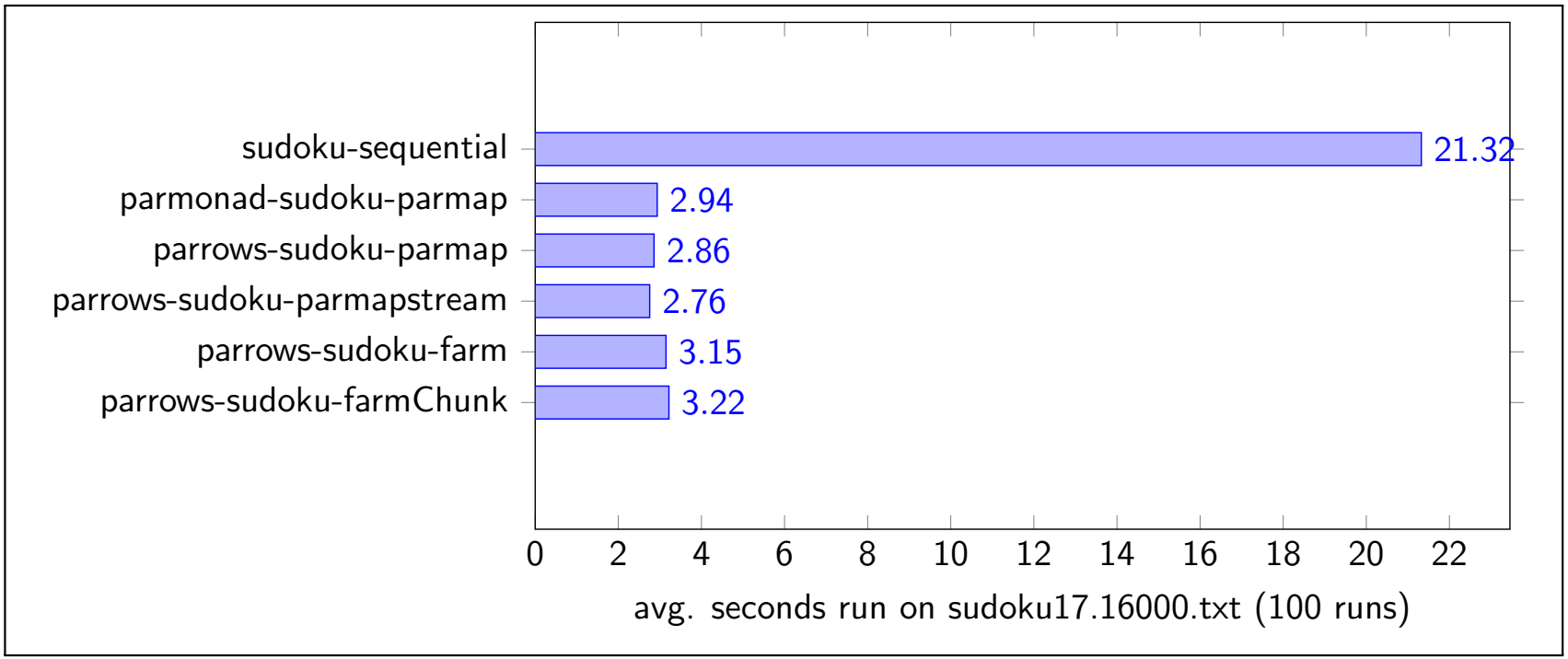
```
1 add :: Arrow arr => arr a Int -> arr a Int -> arr a Int
2 add f g = (f |&&&| g) >>> arr (\(u, v) -> u + v)
```

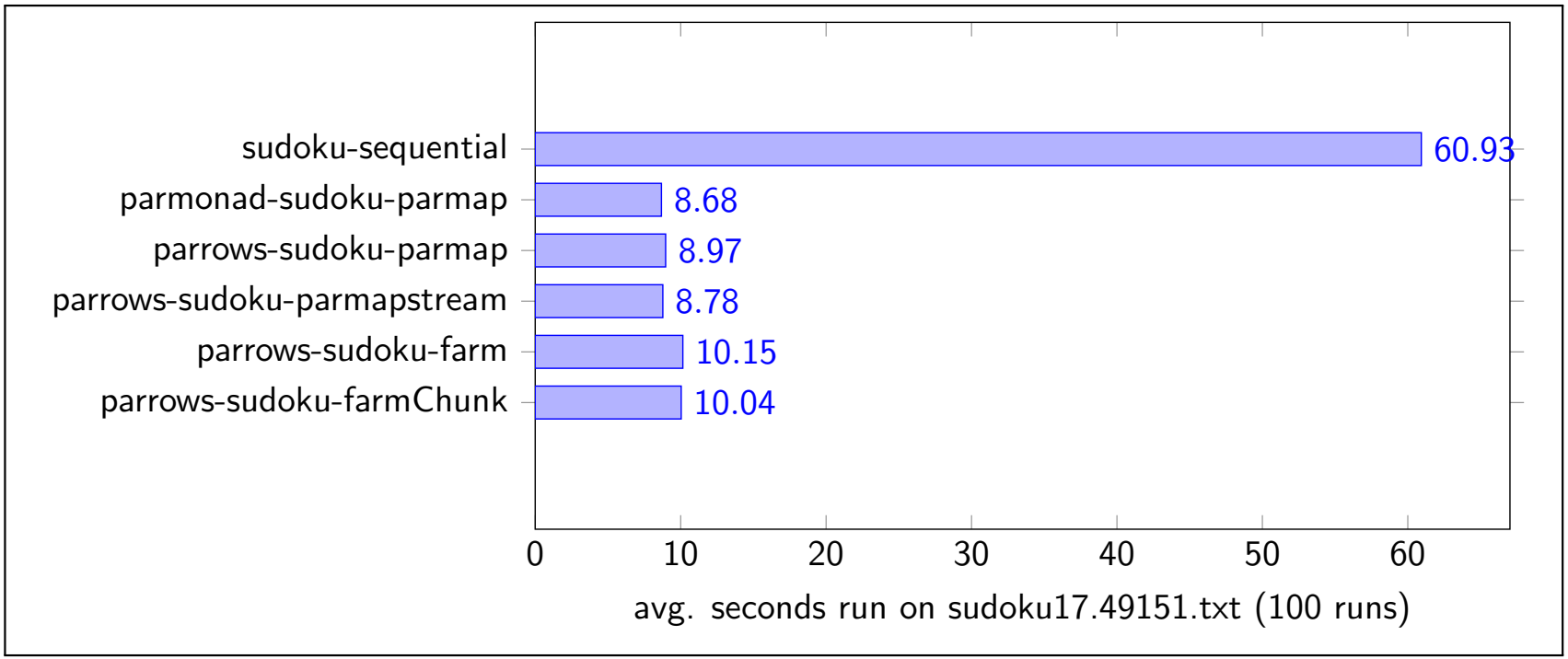




- Run on: Core i7-3970X CPU @ 3.5GHz / 6C/12T
- compiled with ParMonad backend
- used Sudoku Benchmark from ParMonad examples


sudoku-sequential
parmonad-sudoku-parmap
parrows-sudoku-parmap
parrows-sudoku-parmapstream
parrows-sudoku-farm
parrows-sudoku-farmChunk
1.34
0.53
0.2
0.19
0.21
0.22
0
0.2
0.4
0.6
0.8
1
1.2
1.4
avg. seconds run on sudoku17.1000.txt (100 runs)


sudoku-sequential
parmonad-sudoku-parmap
parrows-sudoku-parmap
parrows-sudoku-parmapstream
parrows-sudoku-farm
parrows-sudoku-farmChunk
21.32
2.94
2.86
2.76
3.15
3.22
0
2
4
6
8
10
12
14
16
18
20
22
avg. seconds run on sudoku17.16000.txt (100 runs)


sudoku-sequential
parmonad-sudoku-parmap
parrows-sudoku-parmap
parrows-sudoku-parmapstream
parrows-sudoku-farm
parrows-sudoku-farmChunk
60.93
8.68
8.97
8.78
10.15
10.04
0
10
20
30
40
50
60
avg. seconds run on sudoku17.49151.txt (100 runs)