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

Monad Definition

```
1 class Monad m where
2   (>>=) :: m a -> (a -> m b) -> m b
3   return :: a -> m a
```

Similar to Java's Optional, we have **Maybe** a:

```
1 instance Monad Maybe where
2   (Just a) >>= f = f a
3   Nothing >>= _ = Nothing
4   return a = Just a
```

$\Rightarrow$ composable computation descriptions

Monad Usage

With monadic functions like

```
1 func :: Int -> Maybe Int
2 func x
3     | x < 0 = Nothing
4     | otherwise = Just (x * 2)
```

we can compose computations:

```
1 complicatedFunc :: Int -> Maybe Int
2 complicatedFunc x = (return x) >>= func >>= ...
```

Arrow Definition (1)

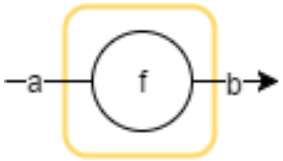
Another way to compose computations are arrows:

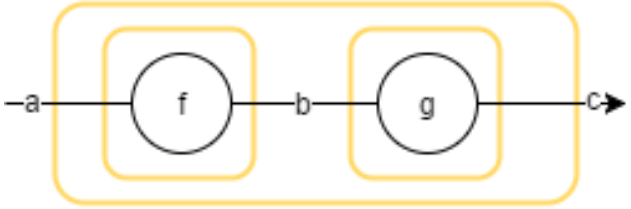
Arrow Definition (2)

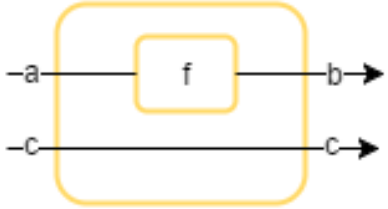
```
class Arrow arr where
  arr   ::  (a -> b) -> arr a b

  (>>>) :: 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 }
```

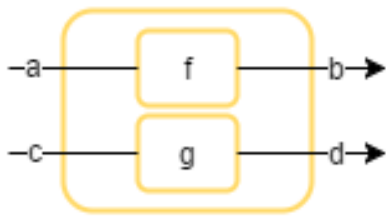
is also an arrow:

```
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)
```

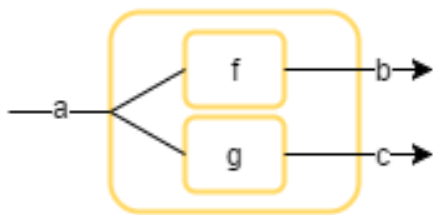
Combinators

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



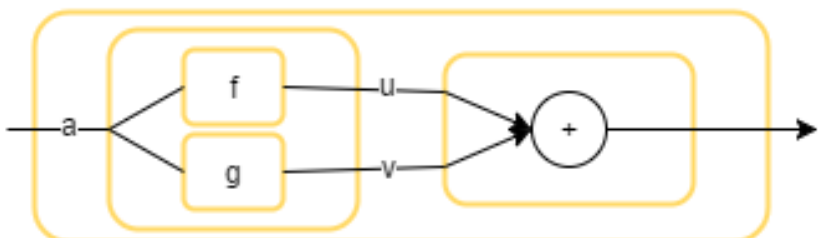

```
1 (&&&) :: arr a b -> arr a c ->
2     arr a (b, c)
3 f &&& g = arr (\a -> (a, a)) >>>
4     (f *** g)
```



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]
```

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
```

with

```
zipWith :: (a -> b -> c) -> [a] -> [b] -> [c]
($) :: (a -> b) -> a -> b
using :: a -> Strategy a -> a
parList :: Strategy a -> Strategy [a]
rdeepseq :: NFData a =>Strategy a
```

ParMonad

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

with

```
runPar :: Par a -> a
($) :: (a -> b) -> a -> b
sequence :: (Monad m) =>[m a] -> m [a]
map :: (a -> b) -> [a] -> [b]
spawnP :: NFData a =>a -> Par (IVar a)
zipWith :: (a -> b -> c) -> [a] -> [b] -> [c]
(>>=) :: m a -> (a -> m b) -> m b
mapM :: Monad m =>(a -> m b) -> [a] -> m [b]
get :: IVar a -> Par a
```

Eden

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

with

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

The ArrowParallel typeclass

Now, let's generalize:

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

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:

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

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

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

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

Multicore

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

with

```
listApp :: (ArrowChoice arr, ArrowApply arr) =>[arr a b] -> arr [a] [b]
(>>>) :: arr a b -> arr b c -> arr a c
arr :: Arrow arr =>(a -> b) -> arr a b
flip :: (a -> b -> c) -> b -> a -> c
using :: a -> Strategy a -> a
($) :: (a -> b) -> a -> b
parList :: Strategy a -> Strategy [a]
rdeepseq :: NFData a =>Strategy a
```

ParMonad

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

with

```
arr :: Arrow arr =>(a -> b) -> arr a b
zipWithArr :: ArrowChoice arr =>arr (a, b) c -> arr ([a], [b]) [c]
app :: ArrowApply arr =>(arr a b, a) b
spawnP :: NFData a =>a -> Par (IVar a)
sequence :: (Monad m) =>[m a] -> m [a]
(>>=) :: m a -> (a -> m b) -> m b
```

Eden (1)

For Eden we need separate implementations, for Functions:

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

with

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

Eden (2)

and 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)
```

with

```
arr  :: (Arrow arr) =>(a -> b) -> arr a b
map :: (a -> b) -> [a] -> [b]
sequence :: (Monad m) =>[m a] -> m [a]
```

Eden (3)

This is because of spawnF's signature:

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

and app's signature:

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

Eden (3)

This is because of spawnF's signature:

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

and app's signature:

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

Hacky alternative:

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

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]
```

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

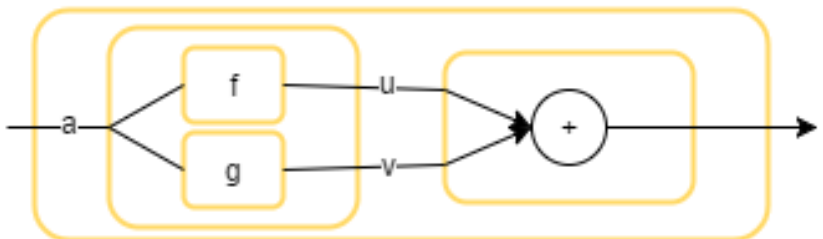
```
1 (|***|) :: (Arrow arr, ...) =>
2   arr a b -> arr c d -> arr (a, c) (b, d)
3 (|***|) = parEval2 ()
```

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

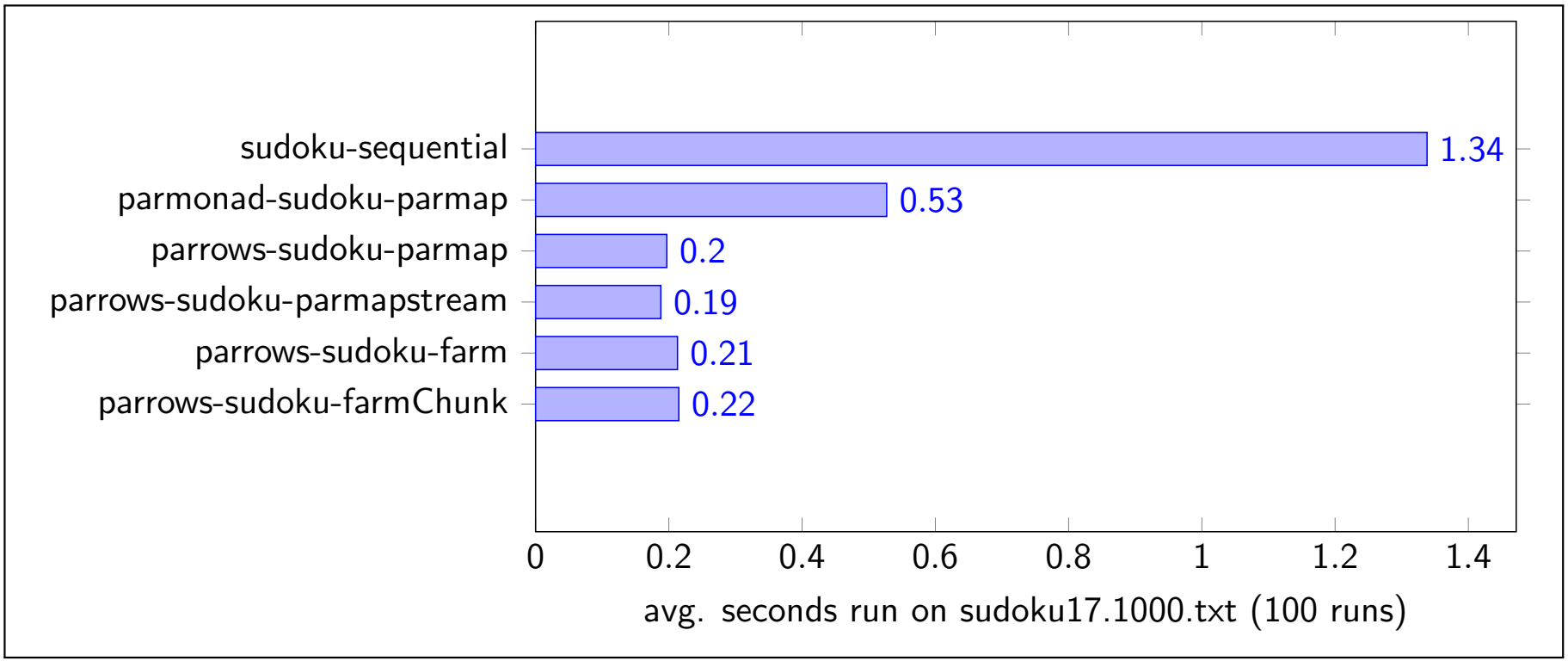
Parallelism as an operator

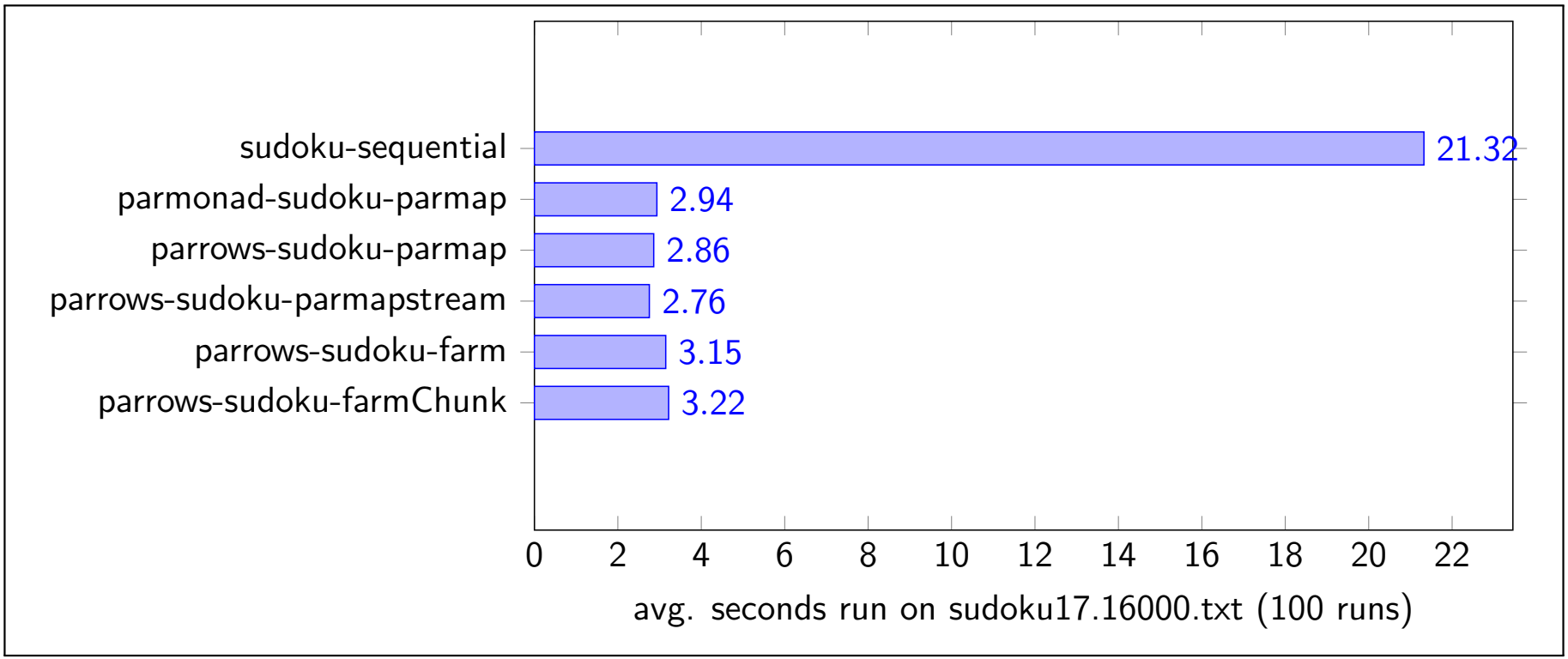
Parallel Evaluation made easy:

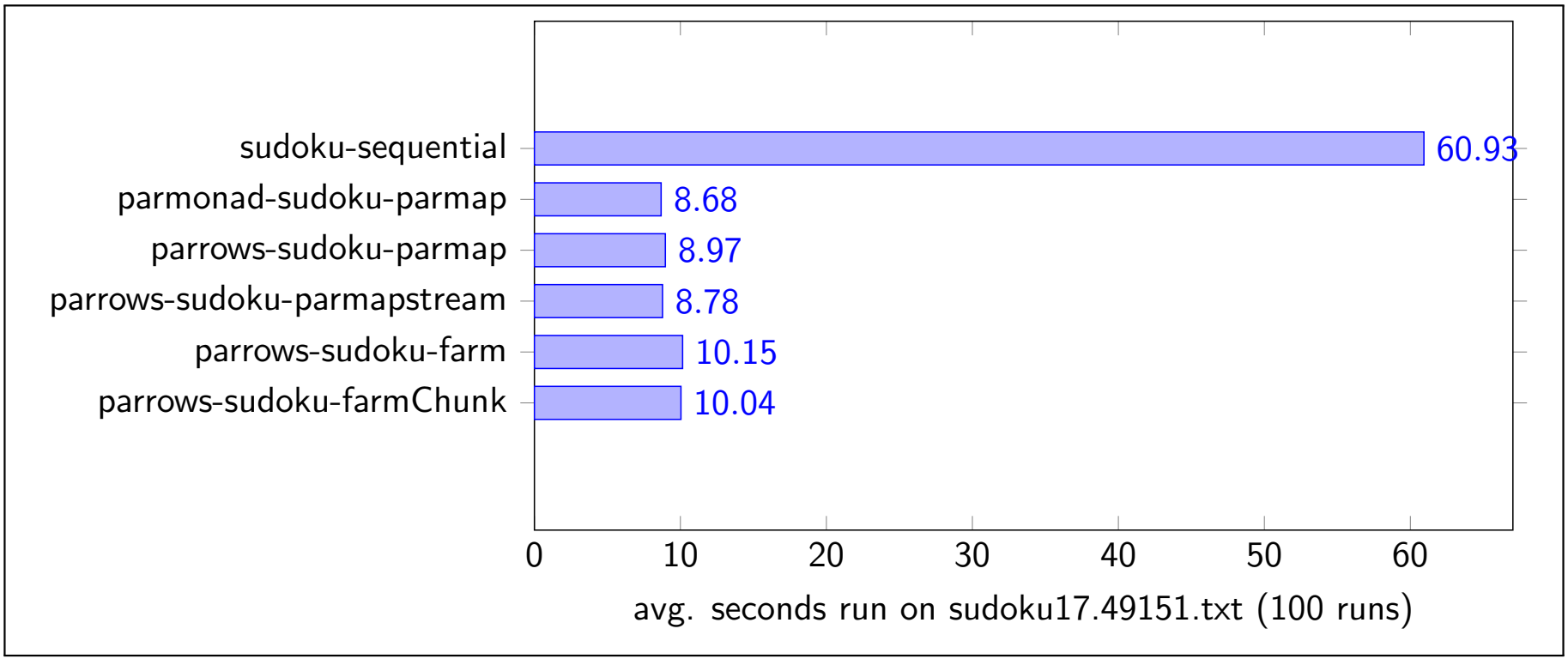
```
1 add :: Arrow arr => arr a Int -> arr a Int -> arr a Int
2 add f g = (f |&&&| g) >>> arr (\(u, v) -> u + v)
```



- 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)