Project Report

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Abstract

This is the project report for my final project for Parallel Functional Programming class 2019. My project was Othello played by two AIs and with minimax of depth 3 and 4. To finish a game with depth > 3 with single core takes really long time, but with parallelism and 4 cores it is quite fast.

The program does a little simple rendering of the game, one snapshot of the final board looks like:

```
    0   1   2   3   4   5   6   7
  +---+---+---+---+---+---+---+---+
0 | O | O | O | O | O | O | O | X |
  +---+---+---+---+---+---+---+---+
1 | X | O | O | O | X | O | X | X |
  +---+---+---+---+---+---+---+---+
2 | X | O | O | O | O | X | X | X |
  +---+---+---+---+---+---+---+---+
3 | X | X | O | O | X | X | X | X |
  +---+---+---+---+---+---+---+---+
4 |   | X | X | X | X | O | X | X |
  +---+---+---+---+---+---+---+---+
5 | O | X | X | X | X | X | X | X |
  +---+---+---+---+---+---+---+---+
6 | O | X | X | X | X | X | X | X |
  +---+---+---+---+---+---+---+---+
7 | O | X | X | X | X | X | X | X |
  +---+---+---+---+---+---+---+---+
```

Compile & Run

- Prerequisites: stack/cabal ghc, threadscope
- To compile, run `stack ghc -- -O2 -threaded -rtsopts -eventlog othello.hs`
- To run with single core and display time analytics, run `./othello +RTS -N1 -s`

- To run with four cores and display time analytics, run `./othello +RTS -N4 -s`
- To run and output a eventlog for threadscope to inspect, run `./othello +RTS -N1 -l`, this outputs **othello.eventlog**
- To inspect with threadscrope, run `threadscope othello.eventlog`

Performance Enhancement with Strategy

Parts of Program Parallelized

The major place for the program to be parallelled at was inside the minimax algorithm. When a player A using minimax tries to maximize its advantage over the opponent, it evaluates multiple branches (depends on games, in this case the possible legal moves) down to a certain depth, and then choose the one with maximum advantage.

Haskell tool used for Parallelism

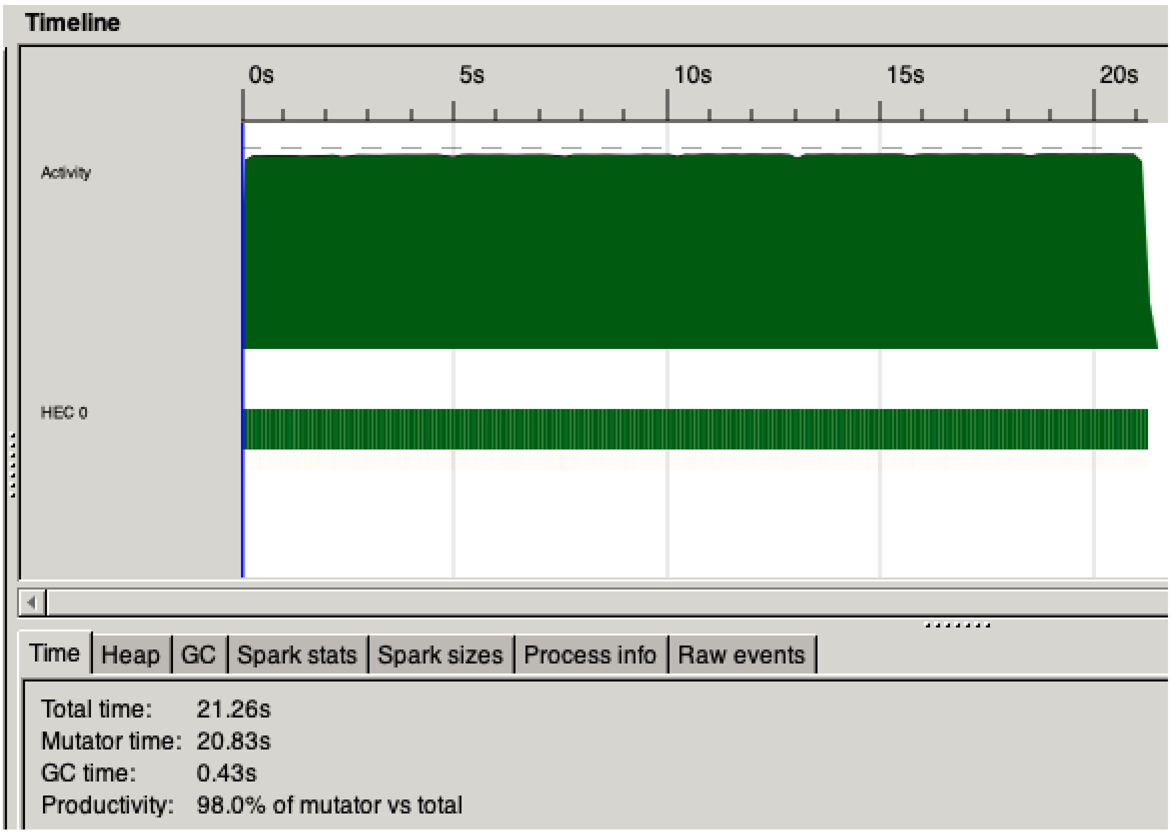
I choose to use the Strategy package (parList, parWith, rdeepSeek, etc.) because they provide very easily usable parallel strategies on top of different datastructures, also I really like how it separates the algorithm from the parallism using keywords like `using`. They make the code easy to understand. The exact strategy I used is `using parList rseq` when I called `map`.

Result and Performance measurement

1. Experiments with minimax of depth 3
    - Since my Mac is quad-core, I tested at most with 4 cores.
    - When I ran with `./othello +RTS -N1 -s`, the result is the following:

```
57,254,026,704 bytes allocated in the heap
   137,107,488 bytes copied during GC
        87,360 bytes maximum residency (28 sample(s))
        29,192 bytes maximum slop
             0 MB total memory in use (0 MB lost due to fragmentation)

                                    Tot time (elapsed)  Avg pause  Max pause
Gen  0     54823 colls,     0 par    0.422s   0.458s     0.0000s    0.0001s
Gen  1        28 colls,     0 par    0.003s   0.003s     0.0001s    0.0002s

TASKS: 4 (1 bound, 3 peak workers (3 total), using -N1)

SPARKS: 368083(0 converted, 0 overflowed, 0 dud, 241450 GC'd, 126633 fizzled)

INIT    time    0.000s  (  0.002s elapsed)
MUT     time   21.105s  ( 21.343s elapsed)
GC      time    0.425s  (  0.462s elapsed)
EXIT    time    0.000s  (  0.008s elapsed)
Total   time   21.530s  ( 21.815s elapsed)

Alloc rate    2,712,810,935 bytes per MUT second

Productivity  98.0% of total user, 97.8% of total elapsed
```

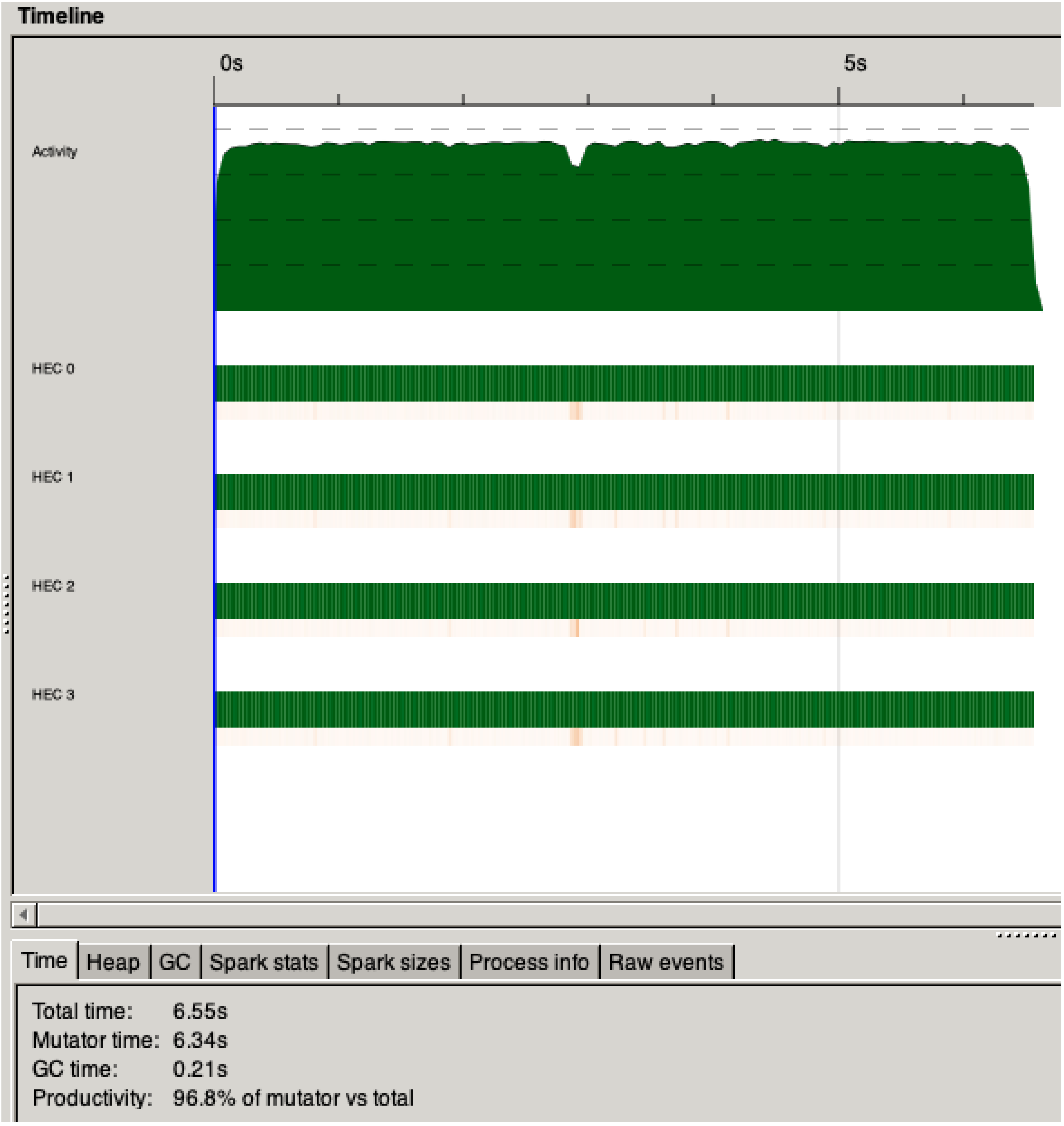
- Threadscope shows the following:



- When I ran with `./othello +RTS -N4 -s`, the result is the following:

```
X won by 4
  60,763,541,784 bytes allocated in the heap
     153,064,880 bytes copied during GC
         367,544 bytes maximum residency (213 sample(s))
          70,528 bytes maximum slop
               0 MB total memory in use (0 MB lost due to fragmentation)

                                     Tot time (elapsed)  Avg pause  Max pause
  Gen  0     15018 colls, 15018 par   14.695s   0.197s     0.0000s    0.0010s
  Gen  1       213 colls,   212 par    0.287s   0.014s     0.0001s    0.0002s

  Parallel GC work balance: 69.96% (serial 0%, perfect 100%)

  TASKS: 10 (1 bound, 9 peak workers (9 total), using -N4)

  SPARKS: 384477(35697 converted, 0 overflowed, 0 dud, 225243 GC'd, 123537 fizzled)

  INIT    time    0.001s  (  0.003s elapsed)
  MUT     time    9.339s  (  6.098s elapsed)
  GC      time   14.982s  (  0.211s elapsed)
  EXIT    time    0.000s  (  0.012s elapsed)
  Total   time   24.323s  (  6.324s elapsed)

  Alloc rate    6,506,094,748 bytes per MUT second

  Productivity  38.4% of total user, 96.4% of total elapsed
```

- Threadscope shows the following:



2. Experiment with minimax of depth 4 (4 core test only).

   - When I ran with `./othello +RTS -N4 -s`, the result is the following:

```
749,645,794,024 bytes allocated in the heap
  1,895,703,872 bytes copied during GC
        464,528 bytes maximum residency (1187 sample(s))
         73,736 bytes maximum slop
              0 MB total memory in use (0 MB lost due to fragmentation)

                                     Tot time (elapsed)  Avg pause  Max pause
  Gen  0     185542 colls, 185542 par   222.273s   2.782s     0.0000s    0.0097s
  Gen  1      1187 colls,  1186 par    1.956s   0.095s     0.0001s    0.0021s

  Parallel GC work balance: 71.96% (serial 0%, perfect 100%)

  TASKS: 10 (1 bound, 9 peak workers (9 total), using -N4)

  SPARKS: 4808723(92883 converted, 0 overflowed, 0 dud, 2883146 GC'd, 1832694 fizzled)

  INIT    time    0.000s  (  0.003s elapsed)
  MUT     time  124.799s  ( 85.510s elapsed)
  GC      time  224.229s  (  2.877s elapsed)
  EXIT    time    0.000s  (  0.008s elapsed)
  Total   time  349.028s  ( 88.398s elapsed)

  Alloc rate    6,006,839,574 bytes per MUT second

  Productivity  35.8% of total user, 96.7% of total elapsed
```

Speedup Analysis

From the above experiment, I was able to achieve a speedup of `(21.815 / 6.324) = 3.45`, which is quite good given we are using 4 times as many cores.

Code Listing

```haskell
import Data.List as L
import Data.Maybe
import qualified Data.Map as M
import Control.Parallel.Strategies(using, parList, rseq)

data Color = White | Black | Empty deriving (Eq, Show)
type Pos = (Int, Int)
type Board = M.Map Pos Color

-- Flip the current color to get next color
flipC :: Color -> Color
flipC White = Black
flipC Black = White
flipC _ = Empty

-- All possible legal moves a given current player and board
allMoves :: Color -> Board -> [Pos]
allMoves color board = filter (isLegal color board) [(x, y) | x <- [0..7],
y <- [0..7]]
  where isLegal color board pos = cellsChanged color board pos /= []
```

```
                                  && isNothing (M.lookup pos board)

-- Number of cells changed due to a step
cellsChanged :: Color -> Board -> Pos -> [Pos]
cellsChanged color board pos
  | null flipped = []
  | otherwise    = pos : flipped
  where flipped  = concatMap (rowChange True color board pos)
                [(0, 1), (1, 1), (1, 0), (1, -1), (0, -1), (-1, -1), (-1,
0), (-1, 1)]
        rowChange isFirst color board pos dir
          | nextColor == Just (flipC color) = case restOfRow of
                                               []     -> []
                                               (x:xs) -> if isFirst then
restOfRow
                                                        else pos :
restOfRow
          | nextColor == Just color = [pos | not isFirst]
          | otherwise = []
          where nextPos = (\(x, y) (dx, dy)  -> (x + dx, y + dy)) pos dir
                nextColor = M.lookup nextPos board
                restOfRow = rowChange False color board nextPos dir

-- Calculates advantage of a player/color
advCount :: Color -> Board -> Int
advCount color board = sum $ map (\(_, x) -> advPerCell x) $ M.toList
board
  where
    advPerCell x
      | x == color = 1
      | x == Empty = 0
      | otherwise = -1

-- Heuristic for bottom level miniMax
heuristic :: Color -> Board -> Int
heuristic color board = advCount color board + 20 * optCountAdv color
board
  where
    optCountAdv :: Color -> Board -> Int
    optCountAdv color board = optCounts color board - optCounts (flipC
color) board
    optCounts cl bd = length $ allMoves cl bd

-- Played a move and get a new board
step :: Color -> Board -> Pos -> Board
step color board pos = M.union
  (M.fromList (zip (cellsChanged color board pos) (repeat color))) board

-- Optimal move a player can take
optMove :: Color -> Board -> Pos
optMove color board =
  fst $ maximumBy (\(_, x) (_, y) -> compare x y)
      (map (\pos -> (pos, miniMax 4 color (step color board pos)))
      (allMoves color board))
```

```haskell
-- The minimax algorithm
miniMax :: Int -> Color -> Board -> Int
miniMax depth color board
  | gameOver = if advCount color board > 0
    then 10000000
    else -10000000
  | depth <= 0 = heuristic color board
  | otherwise = if nc /= color
    then -maxAdvOp
    else  maxAdvOp
  where
    opMoves = allMoves (flipC color) board
    moves = allMoves color board
    gameOver = null moves && null opMoves
    nc = if opMoves /= [] then flipC color else color
    ncMoves = if nc /= color then opMoves else moves
    maxAdvOp = maximum (map
               (miniMax (depth - 1) nc . step nc board)
               ncMoves `using` parList rseq)

-- Renders the color pieces or empty cells
colorToChar :: Color -> String
colorToChar Empty = " "
colorToChar White = "O"
colorToChar Black = "X"

-- Renders the entire board
renderBoard :: Board -> String
renderBoard board =
  "\n    0   1   2   3   4   5   6   7 \n  +---+---+---+---+---+---+---+--
-+\n" ++
  intercalate "\n  +---+---+---+---+---+---+---+---+\n" (map (renderRow
board) [0 .. 7])
  ++ "\n  +---+---+---+---+---+---+---+---+\n"
  where renderRow board row = show row ++ " | " ++
          intercalate " | " [helper (x, row) | x <- [0 .. 7]] ++ " | "
        helper position = colorToChar (fromMaybe Empty (M.lookup position
board))

-- Executions after game is over
gameOver :: Color -> Int -> IO ()
gameOver color advCount
  | advCount == 0 = putStr "Game tie\n"
  | advCount > 0 = putStr (colorToChar color ++ " won by " ++
                          show advCount ++ "\n")
  | otherwise = putStr (colorToChar (flipC color) ++ " won by " ++
                          show (-advCount) ++ "\n")

-- Major function of interative gameplay
go :: Color -> Board -> IO ()
go color board =
  if null (allMoves color board) && null (allMoves (flipC color) board)
  then gameOver color $ advCount color board
```

```haskell
  else do
    let oc = flipC color
        move = optMove color board
        nb = step color board move
        nc = if allMoves oc nb /= [] then oc else color
    putStr (renderBoard board)
    go nc nb

main :: IO ()
main = go White newBoard
  where newBoard = M.fromList
                     [((3, 3), White), ((4, 4), White), ((3, 4), Black), ((4,
3), Black)]
```