Maze Generation: Recursive Division

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1 Introduction

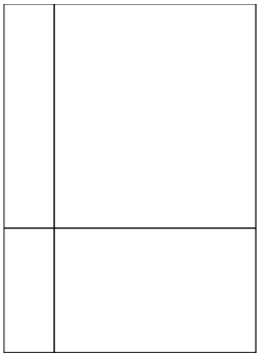
This paper presents a parallelized maze generator implemented in Haskell. There are several algorithms to generate a maze, such as depth-first search, Kruskal's algorithm, Prim's algorithm. However, most of the algorithms are hard to run in parallel. In order to demonstrate the parallelization techniques in Haskell, we decided to use another algorithm, which is known as the Recursive Division algorithm. It is the fastest maze generation algorithm without directional biases thanks to its parallelism, each sub-maze could be processed at finer and finer levels of detail. However, compared to other more convoluted maze generation algorithms, the output maze usually contains long straight walls crossing the space and looks less complicated.

2 Recursive Division Algorithm

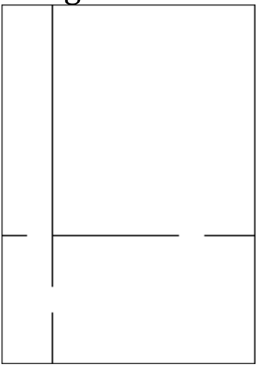
The Recursive Division works as follows:

1. Initialize the maze with no walls inside, i.e. only a frame.

2. Divide the frame into four separate spaces by adding two randomly positioned walls, one vertically and one horizontally.



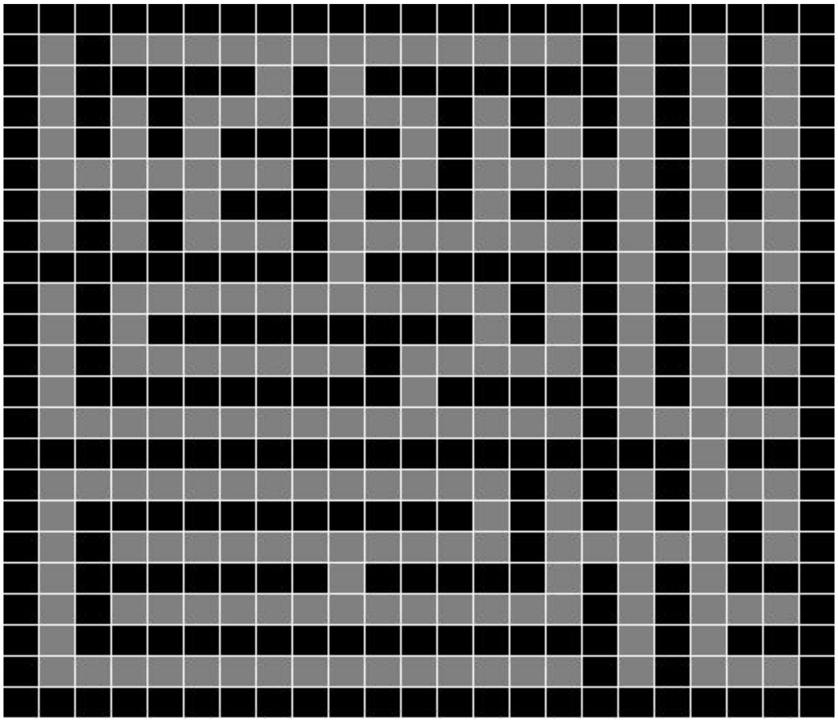
3. Randomly selected three from the four spaces and connected them together by opening three randomly positioned passages on the walls.



4. Recursively repeat the process on the sub maze until all sub maze can't be divided anymore.

2.1 Data Types

Maze could be abstracted as a grid, each passage in the maze could be seen as a cell in the grid, but there are usually two ways to represent the walls in the maze. One is using lines in the grid to represent the walls, whereas the other way represents walls also as cells. In our implementation, we represent both passage and wall using the cells.



We defined two main data types for our implementation, Maze and Wall.
The Maze type is the abstract of the generated maze, with the property width and height represented by m and n. It also contains a set of Wall types, representing the walls in the maze.

```
data Maze = Maze {
  m :: Int, -- number of matrix rows
  n :: Int, -- number of matrix cols
  walls :: Set W.Wall
}

instance Show Maze where
  show (Maze m' n' walls') =
    unlines maze
    where
      maze = [rowToStrng r| r <- [0 .. m'-1]]
      rowToStrng r = [if isWall r c then '#' else ' '| c <- [0 .. n'-
1]]
      isWall r c = W.Wall r c `elem` walls'

instance NFData Maze where
  rnf (Maze m' n' walls') = rnf m' `seq` rnf n' `seq` rnf walls'
```

The data type Wall has the properties r and c representing the row and column number of this wall block respectively.

```
data Wall = Wall {
  r :: Int,
  c :: Int
} deriving (Show, Eq, Ord)

instance NFData Wall where
  rnf (Wall r c) = rnf r `seq` rnf c
```

2.2 Implementation

The entry point of the algorithm is the function **generateWalls,** which generates walls in the area defined by four integers (x0, y0), (x1, y1) representing the top left and bottom right corners.

In this function, we split the given area into four sub mazes and solved each of them individually. In the end, we return the result by combining the four solutions.

```
-- Given an frame, generate walls inside the frame
-- top left wall cell: (tr, tc)
-- bottom right wall cell: (br, bc)
generateWalls :: RandomGen g => Int -> Int -> Int -> Int -> g ->
Set W.Wall
generateWalls tr tc br bc g
    | bc - tc < 4 || br - tr < 4 = empty
    | otherwise = walls
      `union` topLeft
      `union` topRight
      `union` bottomLeft
      `union` bottomRight
  where
    (g1, g2) = split g
    (g3, g4) = split g1
    (g5, g6) = split g2
    (g7, g8) = split g3
    (randomRow, _) = pickRandom [(tr + 2), (tr + 4)..(br - 2)]
g1
    (randomCol, _) = pickRandom [(tc + 2), (tc + 4)..(bc - 2)]
g2
    walls = verticalWalls `union` horizontalWalls `difference`
holes
```

```
    verticalWalls = fromList [W.Wall {W.r = r, W.c = randomCol}
| r <- [(tr + 1)..(br - 1)]]
    horizontalWalls = fromList [W.Wall {W.r = randomRow, W.c =
c} | c <- [(tc + 1)..(bc - 1)]]
    topLeft = generateWalls tr tc randomRow randomCol g3
    topRight = generateWalls tr randomCol randomRow bc g4
    bottomLeft = generateWalls randomRow tc br randomCol g5
    bottomRight = generateWalls randomRow randomCol br bc g6
    (holes, _) = getHoles tr tc br bc randomRow randomCol g7
```

2.3 Results

Below are the screenshots of the visualization of the generated maze, the program also accepts the third parameter, which is a seed integer provided by users. The idea is when the given seed is the same, the maze generated will be the same as well.

```
$ stack run 20 20 1337
# #######################################
#     #         #           #     #     #
# ########### ############# ##### ### ###
#                           # # # # # # #
######### ################### # # # # # #
#               #   # #     # # #   # # #
# ### # ### ### ### # # ### # # # # # # #
#   # # #     # #   # # #   # #   #   # #
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# # # # #     # # # # # # # # # # # # # #
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#     # # # # #   # # # #   #   # # # # #
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#               #     #     #   # #     #
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#   # #                     # #     # # #
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# # # # #   #       #     #   #       # #
# # # # # # # ####### ##### # # # # # # #
#   # #   # #               # # # # # # #
# # # ### ################# # ####### # #
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# # # ### # ### ####### # # # ###########
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# # # # # # ############# # ####### ### #
# #   #   # #     #   #     # # #     # #
# # # # # # ##### ### # # # # # # ##### #
# # # # # # #           # # #   #     # #
##### ####### ############### # ### ### #
#     # #                   # # #       #
# ### # ############### ##### # # ### # #
# #   #                     # #   #   # #
####################################### #
```

```
$ stack run 20 20 1525
# #######################################
# #                   # # #   #     # # #
# # ################### # # # ##### # # #
# #       #         # # # # # #     #   #
# ### ##### ######### # # # ### # # # ###
# # # #   #     # # # #   #     # #     #
# # # ### # # ### # # # # # # # ##### ###
# # # # # # #   #   # # # # # #     #   #
# # # # # # # ### # # # # # # # # ### # #
# # # #   # #     #   # # # # # #   # # #
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#       # # # # # # #   # #   #         #
# ### # # ########### ### # #############
# #   # #             #   #           # #
# ####### ############# # ########### # #
# #                   # # #         # # #
# # ### ############# # ### ######### # #
# # #     #           #                 #
##### ########################### #######
#   #               # # # #   # # # # # #
# # ##### ######### # # # # # # # # # # #
# #               # # #     # # #   # # #
############### ### # ####### # # ### # #
# # #             # # #       # # # #   #
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#                   # # # # # #   #   # #
### ############### # # # # # # # # # # #
#                 # # # # # # # # # # # #
# # ############### # # # # # # # # ### #
# #           #   #   # # # #   #     # #
# ### ##### ### ### # # # # # # # ##### #
# #       #       # # #     # # # #   # #
##################### ### ### # # # ### #
#                   # #     # # #     # #
####### ######### ### ############# #####
#               #     # #       #       #
############### # ### # ##### ##### #####
#               #   # #                 #
####################################### #
```
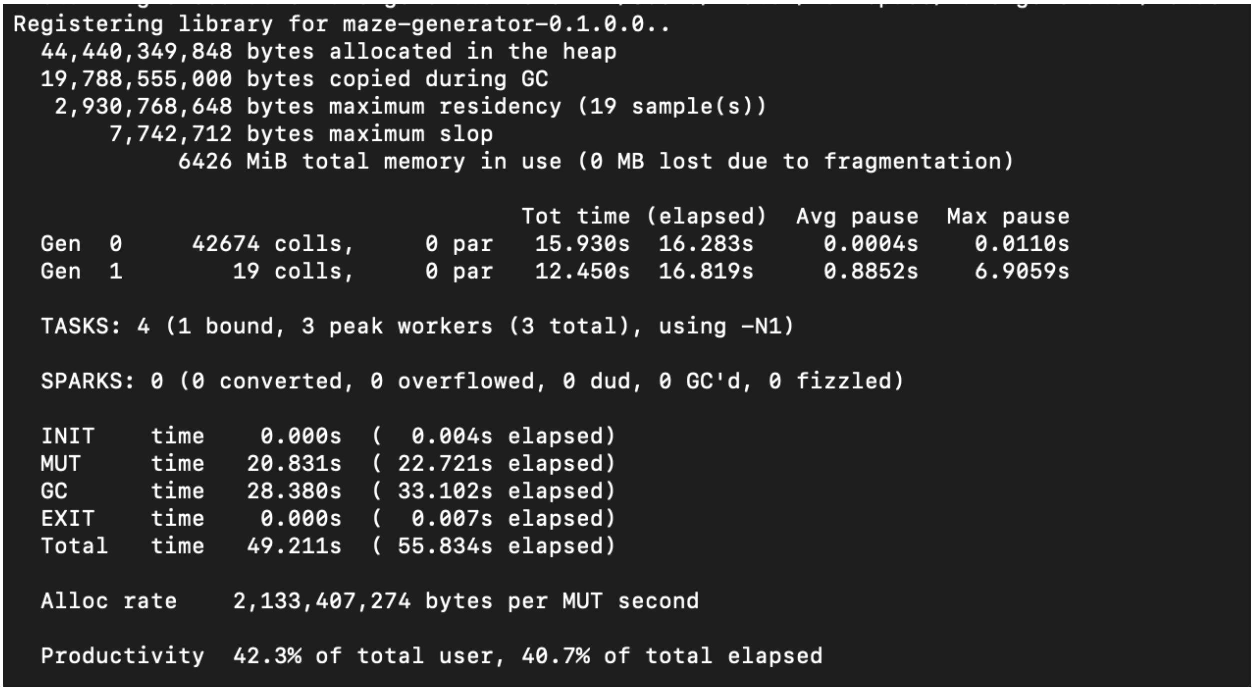
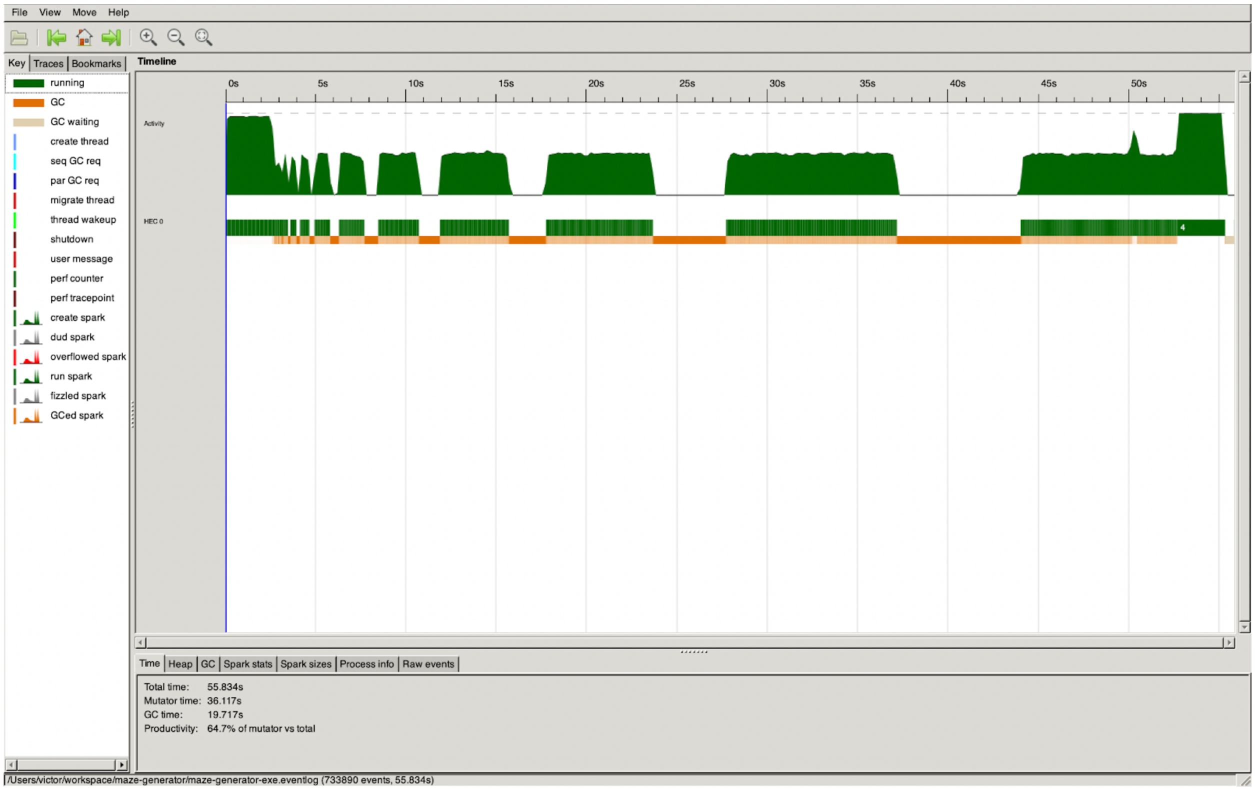

3 Parallelization

For the parallelization, we firstly checked our maze generation algorithms. Because we used recursive division, this algorithm keeps dividing the frames with a horizontal wall and a vertical wall. During this process, we find the possibility of parallelization for the algorithm.

The first step we conducted our experiment is that we run the algorithm in a sequential way to generate a 5000 * 5000 maze and check the result.



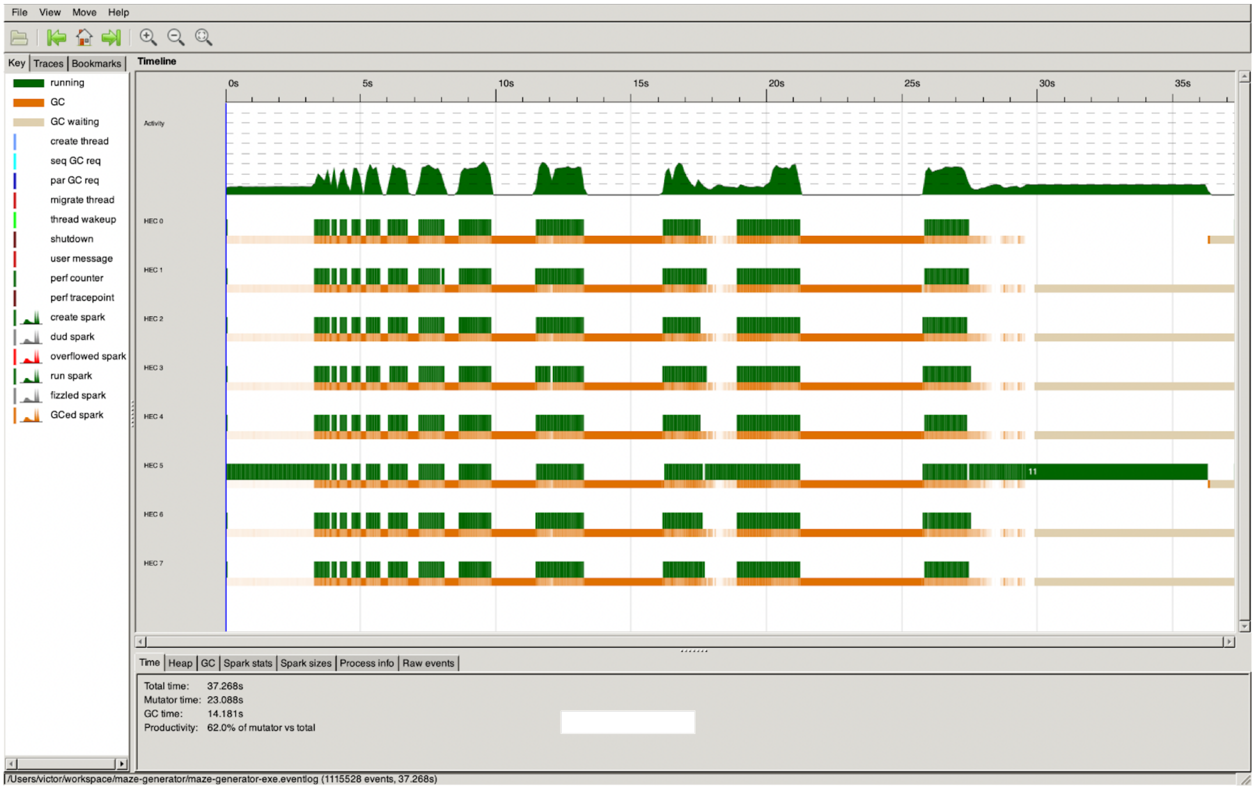
```
Registering library for maze-generator-0.1.0.0..
  44,440,349,848 bytes allocated in the heap
  19,788,555,000 bytes copied during GC
   2,930,768,648 bytes maximum residency (19 sample(s))
       7,742,712 bytes maximum slop
            6426 MiB total memory in use (0 MB lost due to fragmentation)

                                     Tot time (elapsed)  Avg pause  Max pause
  Gen  0     42674 colls,     0 par   15.930s  16.283s     0.0004s    0.0110s
  Gen  1        19 colls,     0 par   12.450s  16.819s     0.8852s    6.9059s

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

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

  INIT    time    0.000s  (  0.004s elapsed)
  MUT     time   20.831s  ( 22.721s elapsed)
  GC      time   28.380s  ( 33.102s elapsed)
  EXIT    time    0.000s  (  0.007s elapsed)
  Total   time   49.211s  ( 55.834s elapsed)

  Alloc rate    2,133,407,274 bytes per MUT second

  Productivity  42.3% of total user, 40.7% of total elapsed
```



```
Total time:     55.834s
Mutator time:   36.117s
GC time:        19.717s
Productivity:   64.7% of mutator vs total
```

```
/Users/victor/workspace/maze-generator/maze-generator-exe.eventlog (733890 events, 55.834s)
```

After finding the total time is about 56s, we tried to use the first method to implement the parallelization. The first method is using par in the Control.Parallel package.

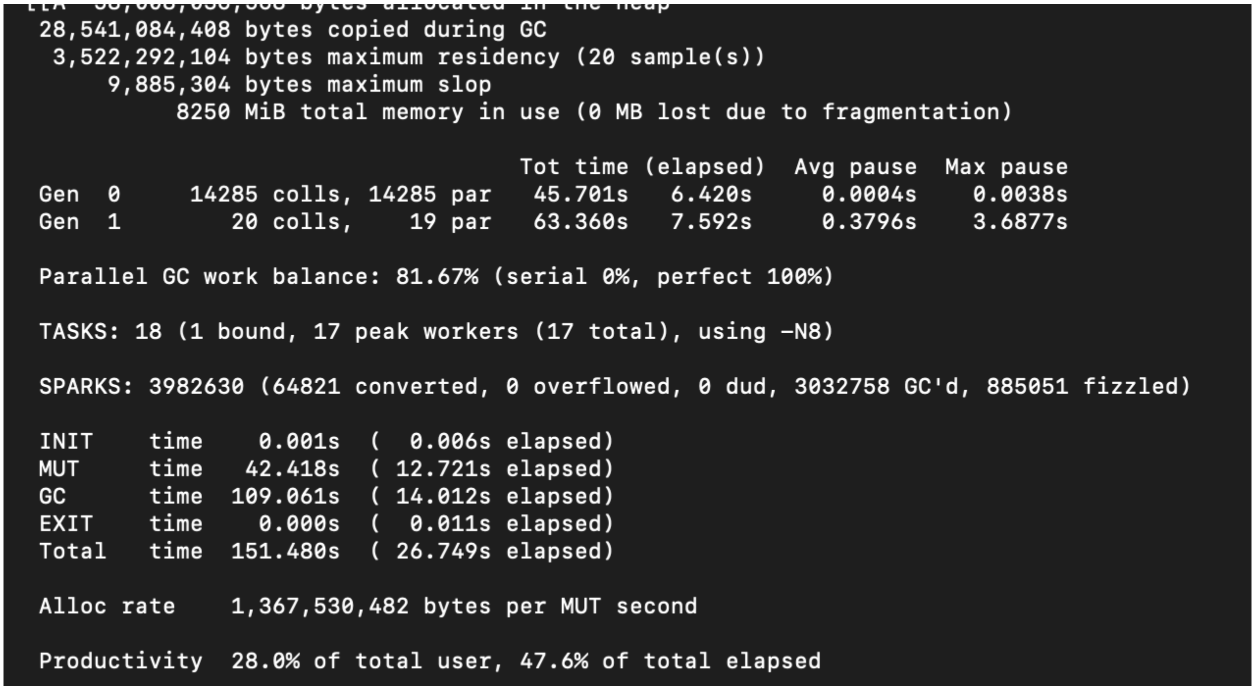


```
Total time:     37.268s
Mutator time:   23.088s
GC time:        14.181s
Productivity:   62.0% of mutator vs total
```

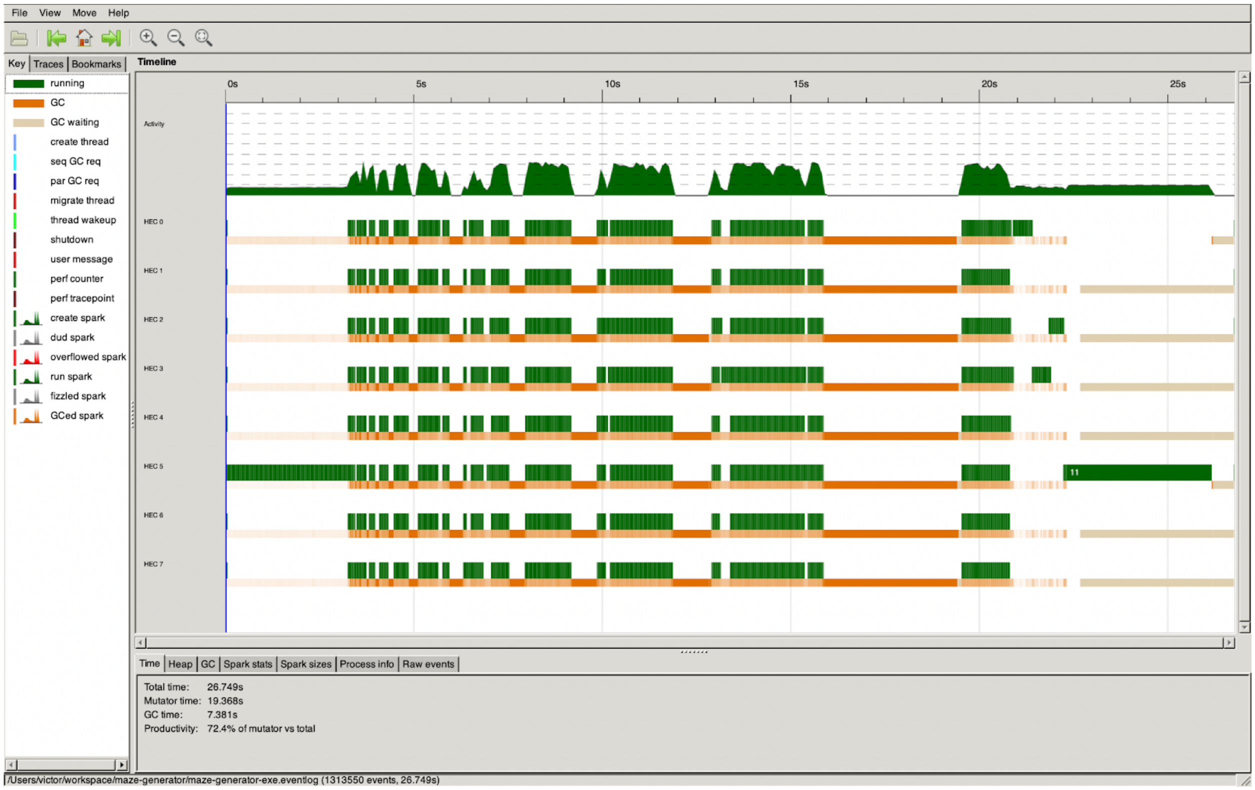
```
/Users/victor/workspace/maze-generator/maze-generator-exe.eventlog (1115528 events, 37.268s)
```

We can find that using par and running the code on 8 cores, that total time decreased to about 37s.

Then, we tried the Strategy and used runEval and rpar to do the parallelization. The result is below.



```
 28,541,084,408 bytes copied during GC
  3,522,292,104 bytes maximum residency (20 sample(s))
      9,885,304 bytes maximum slop
           8250 MiB total memory in use (0 MB lost due to fragmentation)

                                     Tot time (elapsed)  Avg pause  Max pause
 Gen  0     14285 colls, 14285 par   45.701s   6.420s     0.0004s    0.0038s
 Gen  1        20 colls,    19 par   63.360s   7.592s     0.3796s    3.6877s

 Parallel GC work balance: 81.67% (serial 0%, perfect 100%)

 TASKS: 18 (1 bound, 17 peak workers (17 total), using -N8)

 SPARKS: 3982630 (64821 converted, 0 overflowed, 0 dud, 3032758 GC'd, 885051 fizzled)

 INIT    time    0.001s  (  0.006s elapsed)
 MUT     time   42.418s  ( 12.721s elapsed)
 GC      time  109.061s  ( 14.012s elapsed)
 EXIT    time    0.000s  (  0.011s elapsed)
 Total   time  151.480s  ( 26.749s elapsed)

 Alloc rate    1,367,530,482 bytes per MUT second

 Productivity  28.0% of total user, 47.6% of total elapsed
```



Total time: 26.749s
Mutator time: 19.368s
GC time: 7.381s
Productivity: 72.4% of mutator vs total

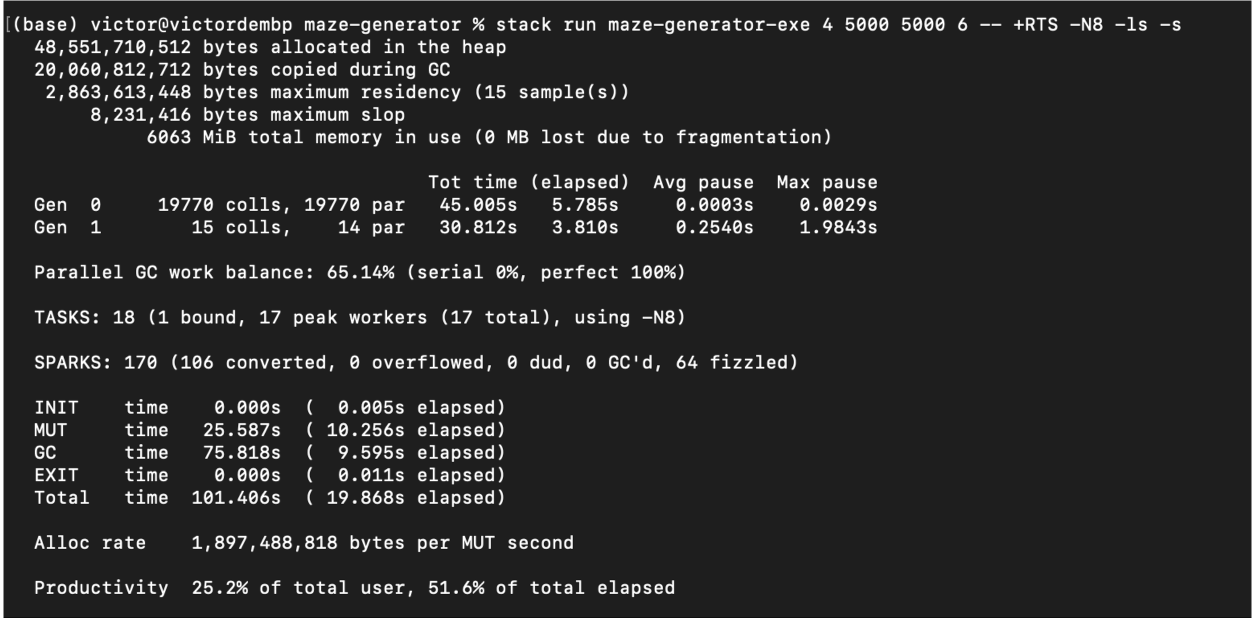
/Users/victor/workspace/maze-generator/maze-generator-exe.eventlog (1313550 events, 26.749s)

We can see that using the rpar and running the code on 8 cores, the total time decreased to about 26s, far from the original sequential time of 56s. But, we still have a problem that the GC time is too much and there are a lot of unnecessary sparks generated during the code running. To solve this problem, we tried to control the depth to parallel to a certain depth. We implemented the depth control like below.

```
generateHWalls 0 tr tc br bc seed = generateWallsOriginial tr tc br bc seed
generateWalls deep tr tc br bc seed
 -- | trace ("generateHWalls for the space: " ++ show (tx, ty, bx, by)) False = undefined
 -- | trace ("holes: " ++ show holes) False = undefined
 | bc - tc < 4 || br - tr < 4 = (empty, seed)
 | otherwise = (walls
   `union` runEval (rpar (topLeft `union` topRight))
   `union` runEval (rpar (bottomLeft `union` bottomRight))
   , newSeed5)
 where
   (randomRow, newRowSeed) = pickRandom [(tr + 2), (tr + 4)..(br - 2)] seed
   (randomCol, newColSeed) = pickRandom [(tc + 2), (tc + 4)..(bc - 2)] newRowSeed
   walls = verticalWalls `union` horizontalWalls `difference` holes
   verticalWalls = fromList [W.Wall {W.r = r, W.c = randomCol} | r <- [(tr + 1)..(br - 1)]]
   horizontalWalls = fromList [W.Wall {W.r = randomRow, W.c = c} | c <- [(tc + 1)..(bc - 1)]]
   (topLeft, newSeed1) = generateWalls (deep - 1) tr tc randomRow randomCol seed
   (topRight, newSeed2) = generateWalls (deep - 1) tr randomCol randomRow bc seed
   (bottomLeft, newSeed3) = generateWalls (deep - 1) randomRow tc br randomCol seed
   (bottomRight, newSeed4) = generateWalls (deep - 1) randomRow randomCol br bc seed
   (holes, newSeed5) = getHoles tr tc br bc randomRow randomCol seed

generateWallsOriginial tr tc br bc seed
 -- | trace ("generateHWalls for the space: " ++ show (tx, ty, bx, by)) False = undefined
 -- | trace ("holes: " ++ show holes) False = undefined
  | bc - tc < 4 || br - tr < 4 = (empty, seed)
 | otherwise = (walls
   `union` runEval (rpar (topLeft `union` topRight))
   `union` runEval (rpar (bottomLeft `union` bottomRight))
   , newSeed5)
 where
   (randomRow, newRowSeed) = pickRandom [(tr + 2), (tr + 4)..(br - 2)] seed
```

```
  (randomCol, newColSeed) = pickRandom [(tc + 2), (tc + 4)..(bc - 2)] newRowSeed
  walls = verticalWalls `union` horizontalWalls `difference` holes
  verticalWalls = fromList [W.Wall {W.r = r, W.c = randomCol} | r <- [(tr + 1)..(br - 1)]]
  horizontalWalls = fromList [W.Wall {W.r = randomRow, W.c = c} | c <- [(tc + 1)..(bc - 1)]]
  (topLeft, newSeed1) = generateWallsOriginial tr tc randomRow randomCol seed
  (topRight, newSeed2) = generateWallsOriginial tr randomCol randomRow bc seed
  (bottomLeft, newSeed3) = generateWallsOriginial randomRow tc br randomCol seed
  (bottomRight, newSeed4) = generateWallsOriginial randomRow randomCol br bc seed
  (holes, newSeed5) = getHoles tr tc br bc randomRow randomCol seed
```

After control the depth of the code, we found that the sparks generated decreased a lot.



```
[(base) victor@victordembp maze-generator % stack run maze-generator-exe 4 5000 5000 6 -- +RTS -N8 -ls -s
  48,551,710,512 bytes allocated in the heap
  20,060,812,712 bytes copied during GC
   2,863,613,448 bytes maximum residency (15 sample(s))
       8,231,416 bytes maximum slop
            6063 MiB total memory in use (0 MB lost due to fragmentation)

                                     Tot time (elapsed)  Avg pause  Max pause
  Gen  0     19770 colls, 19770 par   45.005s   5.785s     0.0003s    0.0029s
  Gen  1        15 colls,    14 par   30.812s   3.810s     0.2540s    1.9843s

  Parallel GC work balance: 65.14% (serial 0%, perfect 100%)

  TASKS: 18 (1 bound, 17 peak workers (17 total), using -N8)

  SPARKS: 170 (106 converted, 0 overflowed, 0 dud, 0 GC'd, 64 fizzled)

  INIT    time    0.000s  (  0.005s elapsed)
  MUT     time   25.587s  ( 10.256s elapsed)
  GC      time   75.818s  (  9.595s elapsed)
  EXIT    time    0.000s  (  0.011s elapsed)
  Total   time  101.406s  ( 19.868s elapsed)

  Alloc rate    1,897,488,818 bytes per MUT second

  Productivity  25.2% of total user, 51.6% of total elapsed
```

5 Code Listing

Main.hs

```
module Main where
import System.Exit(die);
import System.Environment (getArgs, getProgName)
```

```haskell
import System.Random (getStdGen)
import System.CPUTime
import Generator
import Control.DeepSeq

main :: IO Integer
main = do
 args <- getArgs
 seed <- getStdGen
 case args of
   [deep, width, height] -> do
     start <- getCPUTime
     let r = mazeGenerator (read deep) (read width) (read
height) seed
     end <- r `deepseq` getCPUTime
     return (end - start)

   _ -> do
     progName <- getProgName
     die $ "Usage: " ++ progName ++ " <width> <height>"
```

Generator.hs (using rpar to parallelize)

```haskell
module Generator where

import qualified Maze as M
import qualified Wall as W
import Debug.Trace
import Data.Bifunctor
import Control.Monad
import Data.Array.IO
import Data.Set (Set, fromList, union, empty, difference)
import System.Random
import Control.Parallel.Strategies

-- mazeGenerator :: RandomGen g => Int -> Int -> g -> M.Maze
mazeGenerator deep width height seed =
 M.Maze {
   M.m = m,
   M.n = n,
```

```
   M.walls = initializeFrame m n `union` fst (generateWalls deep
0 0 (m - 1) (n - 1) seed)
   -- M.walls = initializeFrame m n
 }
 where
   m = width * 2 + 1 -- number of matrix rows
   n = height * 2 + 1 -- number of matrix cols

initializeFrame :: Int -> Int -> Set W.Wall
initializeFrame m n = fromList frame


 where
   frame = [ W.Wall {W.r = r, W.c = c} |
     r <- [0..m - 1],
     c <- [0..n - 1],
     r == 0 || r == m - 1 || c == 0 || c == n - 1,
     (r, c) /= (0, 1), -- entrace
     (r, c) /= (m - 1, n - 2)] -- exit

-- Given an frame, generate walls inside the frame
-- top left wall cell: (tr, tc)
-- bottom right wall cell: (br, bc)

generateHWalls 0 tr tc br bc seed = generateWallsOriginial tr tc
br bc seed
generateWalls deep tr tc br bc seed
 -- | trace ("generateHWalls for the space: " ++ show (tx, ty,
bx, by)) False = undefined
 -- | trace ("holes: " ++ show holes) False = undefined
 | bc - tc < 4 || br - tr < 4 = (empty, seed)
 | otherwise = (walls
   `union` runEval (rpar (topLeft `union` topRight))
   `union` runEval (rpar (bottomLeft `union` bottomRight))
   , newSeed5)
 where
   (randomRow, newRowSeed) = pickRandom [(tr + 2), (tr + 4)..(br
- 2)] seed
   (randomCol, newColSeed) = pickRandom [(tc + 2), (tc + 4)..(bc
- 2)] newRowSeed
   walls = verticalWalls `union` horizontalWalls `difference`
holes
```

```
   verticalWalls = fromList [W.Wall {W.r = r, W.c = randomCol} | r <- [(tr + 1)..(br - 1)]]
   horizontalWalls = fromList [W.Wall {W.r = randomRow, W.c = c} | c <- [(tc + 1)..(bc - 1)]]
   (topLeft, newSeed1) = generateWalls (deep - 1) tr tc randomRow randomCol seed
   (topRight, newSeed2) = generateWalls (deep - 1) tr randomCol randomRow bc seed
 (bottomLeft, newSeed3) = generateWalls (deep - 1) randomRow tc br randomCol seed
   (bottomRight, newSeed4) = generateWalls (deep - 1) randomRow randomCol br bc seed
   (holes, newSeed5) = getHoles tr tc br bc randomRow randomCol seed

generateWallsOriginial tr tc br bc seed
 -- | trace ("generateHWalls for the space: " ++ show (tx, ty, bx, by)) False = undefined
 -- | trace ("holes: " ++ show holes) False = undefined
 | bc - tc < 4 || br - tr < 4 = (empty, seed)
 | otherwise = (walls
   `union` runEval (rpar (topLeft `union` topRight))
   `union` runEval (rpar (bottomLeft `union` bottomRight))
   , newSeed5)
 where
   (randomRow, newRowSeed) = pickRandom [(tr + 2), (tr + 4)..(br - 2)] seed
   (randomCol, newColSeed) = pickRandom [(tc + 2), (tc + 4)..(bc - 2)] newRowSeed
   walls = verticalWalls `union` horizontalWalls `difference` holes
   verticalWalls = fromList [W.Wall {W.r = r, W.c = randomCol} | r <- [(tr + 1)..(br - 1)]]
   horizontalWalls = fromList [W.Wall {W.r = randomRow, W.c = c} | c <- [(tc + 1)..(bc - 1)]]
   (topLeft, newSeed1) = generateWallsOriginial tr tc randomRow randomCol seed
   (topRight, newSeed2) = generateWallsOriginial tr randomCol randomRow bc seed
   (bottomLeft, newSeed3) = generateWallsOriginial randomRow tc br randomCol seed
```

```
   (bottomRight, newSeed4) = generateWallsOriginial randomRow
randomCol br bc seed
   (holes, newSeed5) = getHoles tr tc br bc randomRow randomCol
seed


getHoles :: RandomGen g => Int -> Int -> Int -> Int -> Int ->
Int -> g -> (Set W.Wall, g)
getHoles tr tc br bc rr rc seed =
 (fromList $ map (choices !!) $ take 3 $ shuffle seed [0..3],
bottomSeed)
 where
   randomPick l seed = l !! fst (randomR (0, length l - 1) seed)
   choices = [top, left, right, bottom]
   (top, topSeed) = pickRandom [W.Wall {W.r = r, W.c = rc}| r <-
[(tr + 1), (tr + 3)..(rr - 1)]] seed
   (left, leftSeed) = pickRandom [W.Wall {W.r = rr, W.c = c}| c
<- [(tc + 1), (tc + 3)..(rc - 1)]] topSeed
   (right, rightSeed) = pickRandom [W.Wall {W.r = rr, W.c = c}|
c <- [(rc + 1), (rc + 3)..(bc - 1)]] leftSeed
   (bottom, bottomSeed) = pickRandom [W.Wall {W.r = r, W.c =
rc}| r <- [(rr + 1), (rr + 3)..(br - 1)]] rightSeed

pickRandom :: RandomGen g => [a] -> g -> (a, g)
pickRandom l seed = Data.Bifunctor.first (l !!) (randomR (0,
length l - 1) seed)

shuffle :: RandomGen g => g -> [a] -> [a]
shuffle gen [] = []
shuffle gen list = randomElem : shuffle newGen newList
 where
  randomTuple = randomR (0, length list - 1) gen
  randomIndex = fst randomTuple
  newGen      = snd randomTuple
  randomElem  = list !! randomIndex
  newList     = take randomIndex list ++ drop (randomIndex+1)
list
```

Generator.hs (Sequential)

```haskell
module Generator where

import qualified Maze as M
import qualified Wall as W
import Debug.Trace
import Data.Bifunctor
import Control.Monad
import Data.Array.IO
import Data.Set (Set, fromList, union, empty, difference)
import System.Random

mazeGenerator :: RandomGen g => Int -> Int -> g -> M.Maze
mazeGenerator width height seed =
 M.Maze {
   M.m = m,
   M.n = n,
   M.walls = initializeFrame m n `union` fst (generateWalls 0 0
(m - 1) (n - 1) seed)
   -- M.walls = initializeFrame m n
 }
 where
   m = width * 2 + 1 -- number of matrix rows
   n = height * 2 + 1 -- number of matrix cols

initializeFrame :: Int -> Int -> Set W.Wall
initializeFrame m n = fromList frame
 where
   frame = [ W.Wall {W.r = r, W.c = c} |
     r <- [0..m - 1],
     c <- [0..n - 1],
     r == 0 || r == m - 1 || c == 0 || c == n - 1,
     (r, c) /= (0, 1), -- entrace
     (r, c) /= (m - 1, n - 2)] -- exit

-- Given an frame, generate walls inside the frame
-- top left wall cell: (tr, tc)
-- bottom right wall cell: (br, bc)
generateWalls :: RandomGen g => Int -> Int -> Int -> Int -> g ->
(Set W.Wall, g)
generateWalls tr tc br bc seed
 -- | trace ("generateHWalls for the space: " ++ show (tx, ty,
```

```haskell
bx, by)) False = undefined
 -- | trace ("holes: " ++ show holes) False = undefined
 | bc - tc < 4 || br - tr < 4 = (empty, seed)
 | otherwise = (walls
   `union` topLeft
   `union` topRight
   `union` bottomLeft
   `union` bottomRight, newSeed5)
 where
   (randomRow, newRowSeed) = pickRandom [(tr + 2), (tr + 4)..(br
- 2)] seed
   (randomCol, newColSeed) = pickRandom [(tc + 2), (tc + 4)..(bc
- 2)] newRowSeed
   walls = verticalWalls `union` horizontalWalls `difference`
holes
   verticalWalls = fromList [W.Wall {W.r = r, W.c = randomCol} |
r <- [(tr + 1)..(br - 1)]]
   horizontalWalls = fromList [W.Wall {W.r = randomRow, W.c = c}
| c <- [(tc + 1)..(bc - 1)]]
   (topLeft, newSeed1) = generateWalls tr tc randomRow randomCol
seed
   (topRight, newSeed2) = generateWalls tr randomCol randomRow
bc seed
   (bottomLeft, newSeed3) = generateWalls randomRow tc br
randomCol seed
   (bottomRight, newSeed4) = generateWalls randomRow randomCol
br bc seed
   (holes, newSeed5) = getHoles tr tc br bc randomRow randomCol
seed

getHoles :: RandomGen g => Int -> Int -> Int -> Int -> Int ->
Int -> g -> (Set W.Wall, g)
getHoles tr tc br bc rr rc seed =
 (fromList $ map (choices !!) $ take 3 $ shuffle seed [0..3],
bottomSeed)
 where
   randomPick l seed = l !! fst (randomR (0, length l - 1) seed)
   choices = [top, left, right, bottom]
   (top, topSeed) = pickRandom [W.Wall {W.r = r, W.c = rc}| r <-
[(tr + 1), (tr + 3)..(rr - 1)]] seed
   (left, leftSeed) = pickRandom [W.Wall {W.r = rr, W.c = c}| c
```

```
<- [(tc + 1), (tc + 3)..(rc - 1)]] topSeed
   (right, rightSeed) = pickRandom [W.Wall {W.r = rr, W.c = c}|
c <- [(rc + 1), (rc + 3)..(bc - 1)]] leftSeed
   (bottom, bottomSeed) = pickRandom [W.Wall {W.r = r, W.c =
rc}| r <- [(rr + 1), (rr + 3)..(br - 1)]] rightSeed

pickRandom :: RandomGen g => [a] -> g -> (a, g)
pickRandom l seed = Data.Bifunctor.first (l !!) (randomR (0,
length l - 1) seed)

shuffle :: RandomGen g => g -> [a] -> [a]
shuffle gen [] = []
shuffle gen list = randomElem : shuffle newGen newList
 where
  randomTuple = randomR (0, length list - 1) gen
  randomIndex = fst randomTuple
  newGen      = snd randomTuple
  randomElem  = list !! randomIndex
  newList     = take randomIndex list ++ drop (randomIndex+1)
list
```

Maze.hs

```
module Maze where
import qualified Wall as W
import Data.Set (Set)
import Control.DeepSeq

data Maze = Maze {
 m :: Int, -- number of matrix rows
 n :: Int, -- number of matrix cols
 walls :: Set W.Wall
}

instance Show Maze where
 show (Maze m' n' walls') =
   unlines maze
   where
     maze = [rowToStrng r| r <- [0 .. m'-1]]
     rowToStrng r = [if isWall r c then '#' else ' '| c <- [0 ..
```

```
n'-1]]
     isWall r c = W.Wall r c `elem` walls'

instance NFData Maze where
 rnf (Maze m' n' walls') = rnf m' `seq` rnf n' `seq` rnf walls'
```

Wall.hs

```
module Wall where
import Control.DeepSeq

data Wall = Wall {
 r :: Int,
 c :: Int
} deriving (Show, Eq, Ord)

instance NFData Wall where
 rnf (Wall r c) = rnf r `seq` rnf c
```