COMS 4995W: Modeling Trees (Parallel Space Colonization Algorithm

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1 Background

For my project, I implemented the space colonization algorithm for modeling trees as outlined in this paper:

http://algorithmicbotany.org/papers/colonization.egwnp2007.html

The algorithm starts off with a set of points which will act as the leaves of the trees and a root. The goal is to grow the branches of the root towards the leaves. The result is hopefully a structure that resembles a tree.

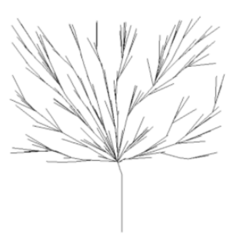
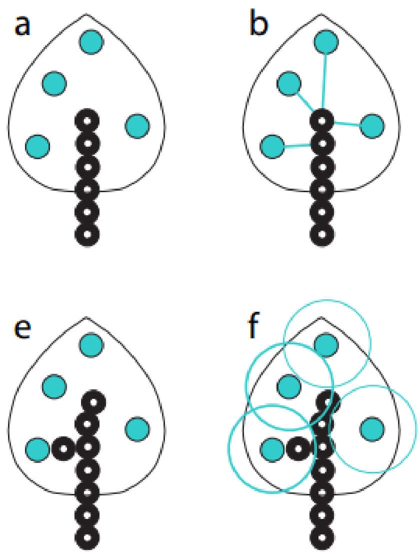


Figure 1: Tree rendered with 200 Leaves

2 Algorithm

For this project, I implemented the algorithm for a 2D tree. In general the algorithm is as follows:



(a) Root extends until within detection range (maxDist) of at least 1 Leaf

(b) Every leaf within detection range finds the closest branch

(c) Direction vectors are calculated from the detected leaves to their respective âclosestâ branch

(d) From each branch determined to be âclosestâ to a leaf, find the average direction vector of every direction from that branch to their leaves

(e) Create a new branch in direction from step d

(f) Check if the new branch enters the kill distance (minDist)

(g) Delete the visited leaves

(h) Loop back to b, until no new branches are found (either because there are no leaves at all, or if there are no leaves within any branchâs detection range

3 Implementation

3.1 Data Types

3.1.1 Leaf

A leaf is represented by a position in a 2D world. It also has a Bool attribute to show that it has been killed.

```
type Point = (Float,Float)
data Leaf = Leaf Point Bool | None
```

3.1.2 Branch

A Branch also has a position, but also includes a parent branch and a direction vector. The length of each branch is the same for every branch.

```
data Branch = Empty | Branch {
                        position :: Point,
                        parent :: Branch,
                        direction :: Point
                        }
```

3.1.3 Leaf

A tree is the overarching data structure that holds the leaves and branches in lists. `max_dist` is the maximum detection radius of each leaf and `min_dist` is the kill radius of each leaf. Both are provided by the user.

```
type Leaves = [Leaf]
type Branches = [Branch]
data Tree = DONE Tree | Tree {
                    leaves :: Leaves,
                    root :: Branch,
                    branches  :: Branches,
                    max_dist :: Float,
                    min_dist :: Float,
                    detected :: Bool
                    }
```

3.1.4 Algorithm

The main computation of the implementation of this algorithm can be summarized with the following pseudo-code:

```
closestBranches = []
For each alive leaf:
 closest = findClosestBranch(leaf,branches)
    new_direction = normalize(calculateDirection(leaf, closest))
    closestBranches.push((closest, new_direction))

groupedBranches = groupByBranch(closestBranches)

newBranches = []
For each group in groupedBranches:
 branch = group.shared_branch()
 sum_direction = sumDir(group) //Point
 average_dir = sum_direction / group.length()
 new_position = add(average_dir, branch.position())
 newBranch = new Branch(position=new_position,
                        direction=average_dir, parent=branch)
 newBranches.push(newBranch)

addBranchesToTree(tree, newBranches)
```

The first loop iterates over the leaves to find the closest branch and calculate a direction vector. The second loops groups and averages the directions to the paired leaves. The full Haskell code can be found in Tree.hs in the code listing at the end of the report.

4 Parallelization

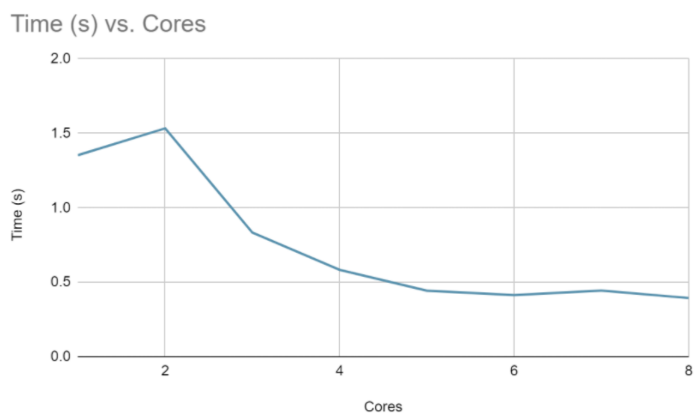
The work in the first loop from the pseudocode is very easy to separate into independent parallel work. This is because each computation to find the closest branch to each leaf do not depend on the other leaves. After testing different variations/strategies to parallelize this first loop, I found that using `parMap rpar` provided the best performance and speed up with increasing cores.

```
parMap rpar (\x -> closestBranch x (branches tree)
        (min_dist tree) (max_dist tree)) unreached
```

Using just this strategy, the algorithm observed just about 3x speedup with 8 cores:

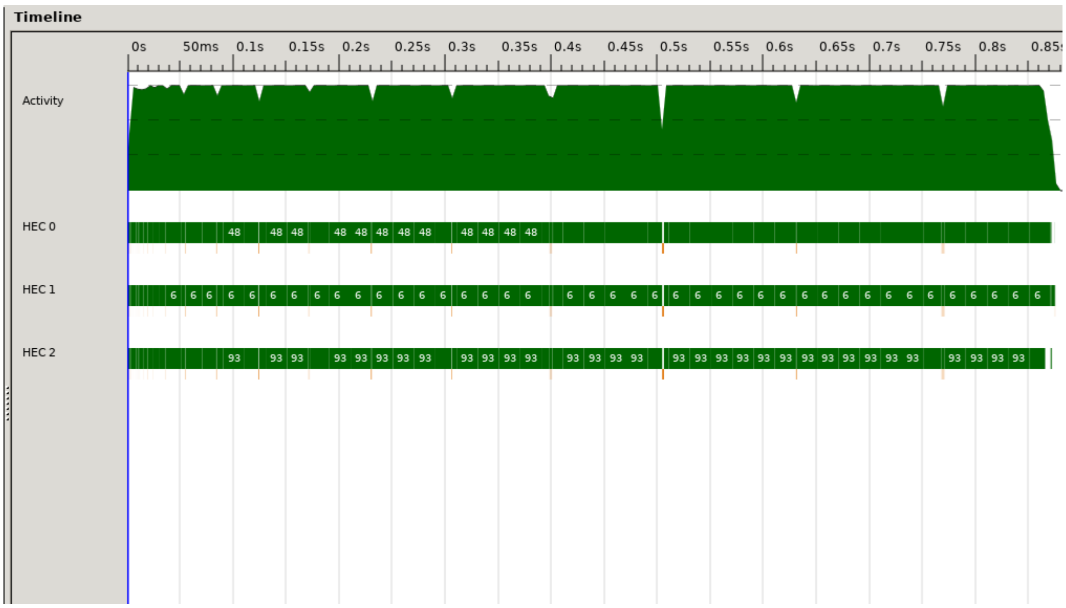
Params: Max-Dist = 70.0, Min-Dist = 30.0, 200 leaves

Cores	Time (s)
1	1.353
2	1.533
3	0.833
4	0.583
5	0.443
6	0.414
7	0.444
8	0.394



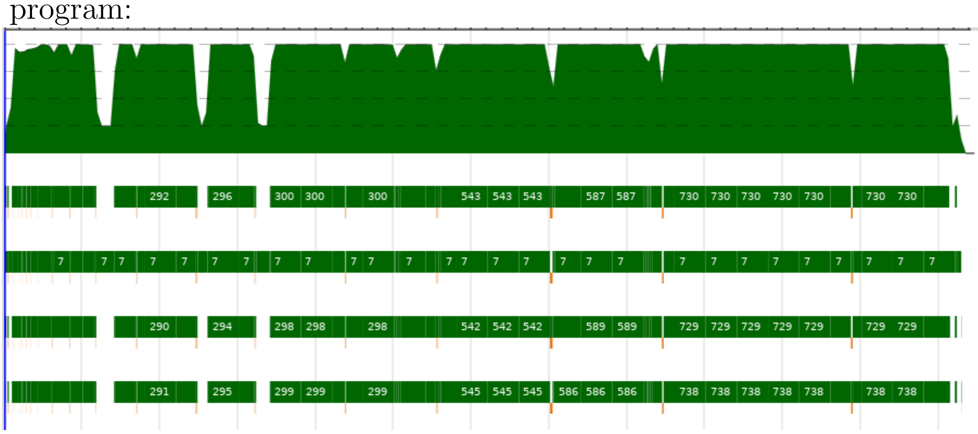
The parallelization provided pretty consistent speed increases with increasing cores. Using 3 cores as an example, the percentage of sparks converted was ~90% as shown log output and threadscope analysis:

```
SPARKS: 127335 (112666 converted, 0 overflowed,
    0 dud, 10604 GC'd, 4065 fizzled)
```



n=3

The work on 3 cores is distributed pretty evenly throughout with very little time spend in garbage collection or breaks for sequential computation. However, as the number of cores increase the program has trouble at the start of the program:



n=4

However, because the time spent in garbage collection and the short amount of time it spends in this state, the time saved in the parallelization vastly overshadows the time lost in those steps.

5 Code Listing

5.1 Main.h

```
module Main where
import Graphics.Gloss
import Tree
import Render
import System.Environment(getArgs)
import TestPoints
import System.Exit

maxDistance :: Float
maxDistance = 60.0

minDistance :: Float
minDistance = 5.0;

simulationLoop :: Tree -> IO ()
simulationLoop (DONE _) = putStrLn "Done"
simulationLoop tree = simulationLoop (nextBranch True True tree)


window :: Display
window = InWindow "Tree" (500, 500) (0, 0)

backgroundColor :: Color
backgroundColor = makeColor 255 255 255 255

startTree :: Tree
startTree = initialTree testPoints 500 maxDistance minDistance


main :: IO ()
main = do args <- getArgs
```

```
        case args of
            [maxDist,minDist,speed] -> simulate window backgroundColor (read speed :: Int) ( initialTree  testPoints  500 (read maxDist :: Float) (read minDist :: Float)) treeAsPicture  nextBranch
            [maxDist,minDist] -> simulationLoop ( initialTree  testPoints  500 (read maxDist :: Float) (read minDist :: Float))
            _ -> putStrLn "Usage ./tree-exe maxDist minDist <simulation_display_speed>" >> exitSuccess
```

5.2 Tree.hs

```
module Tree where
import Data.List
import Control.DeepSeq
import Data.List.Split
import Control.Parallel.Strategies
type Leaves = [Leaf]
type Branches = [Branch]
data Leaf = Leaf Point Bool | None


type Point = (Float,Float)
data Branch = Empty | Branch {
                              position  :: Point,
                              parent  :: Branch,
                              direction  :: Point -- Vector Representation of direction
                              }

data Tree = DONE Tree | Tree {
                          leaves  :: Leaves,
                          root  :: Branch,
                          branches  :: Branches,
                          max_dist  :: Float,
                          min_dist  :: Float,
                          window_size  :: Float,
                          detected  :: Bool
                          }
{-
  Point Arithmetic Helpers
```

```
-}
add :: Point -> Point -> Point
add (x1, y1) (x2, y2) =
  let
    x = x1 + x2
    y = y1 + y2
  in (x, y)

sub :: Point -> Point -> Point
sub (x1, y1) (x2, y2) =
  let
    x = x1 - x2
    y = y1 - y2
  in (x, y)

vdiv :: Point -> Float -> Point
vdiv (x1, y1) a =
  let
    x = x1 / a
    y = y1 / a
  in (x, y)

vmult :: Point -> Float -> Point
vmult (x1, y1) a =
  let
    x = x1 / a
    y = y1 / a
  in (x, y)

distance :: Point -> Point -> Float
distance (x1,y1) (x2,y2) = let x' = x1 - x2
                               y' = y1 - y2
                           in
                               sqrt (x'*x' + y'*y')

normalize :: Floating b => (b, b) -> (b, b)
normalize (x,y) = let magnitude = sqrt ((x*x) + (y*y))
                  in
                    (x/magnitude, y/magnitude)
```

```
{-
  Tree,Branch,Leaf helpers
-}


-- Convert Array of points to Leaves
pointsToLeaves :: [(Float, Float)] -> [Leaf]
pointsToLeaves arr = (parMap rseq (\(x,y) -> Leaf (x,y) False) arr)


-- Check if Branch is
notEmpty :: Branch -> Bool
notEmpty b = case b of
                Empty -> False
                otherwise -> True

-- Initialize a tree
 initialTree :: [(Float, Float)] -> Float -> Float -> Float -> Tree
 initialTree arr size max min = Tree {
                                        leaves = pointsToLeaves arr,
                                        root = root_init ,
                                        branches = [ root_init ],
                                        max_dist = max,
                                        min_dist = min,
                                        window_size = size,
                                        detected = False
                                        }
                                   where root_init = Branch {position=(0, -size
                                        /2), parent = Empty, direction = (0,1)}

addBranch :: Tree -> Branch -> Tree
addBranch tree branch = tree {branches= branch : (branches tree)}

addBranches :: Tree -> [Branch] -> Tree
addBranches tree b = tree {branches = b ++ (branches tree)}


detectLeaves :: Branch -> [Leaf] -> Float -> Bool
detectLeaves branch lvs maxDist = any (==True) (parMap rseq f lvs)
                                          where f None = False
```

```haskell
                                        f (Leaf (x,y) _) = distance (x,y) (position branch) < maxDist

closestBranch :: Leaf -> [Branch] -> Float -> Float -> (Leaf, Branch)
closestBranch None _ _ _ = (None, Empty)
closestBranch (Leaf (x,y) _) br minDist maxDist = let closest = minimumBy f br
                                                      dis = distance (position closest) (x,y)
                                                      newDir = sub (x,y) (position closest)
                                                      normalized = normalize newDir
                                                  in
                                                      if (dis >= maxDist) then
                                                        ((Leaf (x,y) False), Empty)
                                                      else
                                                        if (dis <= minDist) then
                                                          ((Leaf (x,y) True), closest {parent=closest, direction = normalized})
                                                        else
                                                          ((Leaf (x,y) False), closest {parent=closest, direction = normalized})
                                                  where f a b = compare (distance (position a) (x,y)) (distance (position b) (x,y))
averageDir :: [Branch] -> Branch
averageDir brches = let ref = (head brches)
                        -- sum = foldr1 add $ (parMap rseq (direction) branches)
```

```
                        sumDir = (foldl' (\acc b -> add acc (direction b)) (direction (parent ref)) brches)
                        new_dir = normalize (vdiv sumDir (fromIntegral ((length brches))))
                        new_pos = add (position ref) new_dir
                    in
                        Branch {position=new_pos, parent = (parent ref), direction = new_dir}

calculateNewBranches :: [Branch] -> [Branch]
calculateNewBranches closests = let grouped = groupBy branchPos closests
                                in
                                    map averageDir grouped
                                where branchPos a b = (position a == position b)


step :: Tree -> Tree
step tree = let top = head (branches tree)
            in
              case (detectLeaves top (leaves tree) (max_dist tree)) of
                False -> addBranch tree (Branch {position=(add (position top) (direction top)), parent = top, direction = (direction top)})
                True -> tree {detected = True}

grow :: Tree -> Tree
grow tree = let unreached = filter (\(Leaf (_,_) reached) -> not reached) (leaves tree)
                (newLeaves, closests) = unzip ((parMap rpar (\x -> closestBranch x (branches tree) (min_dist tree) (max_dist tree)) unreached) )
                filteredClosests = filter notEmpty closests
                newBranches = calculateNewBranches filteredClosests
            in
                case newBranches of
                  [] -> DONE tree
                  _ -> addBranches (tree {leaves = newLeaves}) newBranches

nextBranch :: p1 -> p2 -> Tree -> Tree
```

```
nextBranch _ _ (DONE tree) = DONE tree
nextBranch _ _ tree = case (detected tree) of
                        False -> step tree
                        True -> grow tree
```

5.3 Render.hs

```
module Render where
 import Graphics.Gloss
 import Tree

 drawPoint :: Leaf -> Picture
 drawPoint (Leaf (x,y) reached) = case reached of
                                   False -> Color red (Translate x y (
                                        ThickCircle 2 2))
                                   True -> Blank
 drawBranch :: Branch -> Picture
 drawBranch b = case (parent b) of
                  Empty -> Blank
                  otherwise -> let point = position b
                                   parent_point = position (parent b)
                               in
                                   line [point, parent_point]

 treeAsPicture :: Tree -> Picture
 treeAsPicture (DONE tree) = let branchPictures = map drawBranch (branches
     tree)
                                 leafPictures = map drawPoint (leaves tree)
                             in
                                 pictures ( leafPictures ++ branchPictures )
 treeAsPicture tree = let branchPictures = map drawBranch (branches tree)
                          leafPictures = map drawPoint (leaves tree)
                      in
                          pictures (branchPictures ++ leafPictures)
```