COMP 212 Fall 2024
Homework 08

In this homework you will implement n-body simulation using the Barnes-Hut algorithm. Two important notes:

- **See the instructions in Section 2.3 for how to compile and run your code: because the project consists of many files, you will need to use `CM.make` rather than `use`.**
- The testing code requires SMLNJ 110.99.6.1 (or SMLNJ 110.99.4 or earlier). You likely installed SMLNJ 110.99.5 at the beginning of the semster, and this will not work. If you installed SMLNJ using Homebrew, you can run `brew install smlnj` to install the latest version. Otherwise download it again from `https://smlnj.org/`.

1 Sequence Library

For this assignment, you will use the implementation of sequences that you downloaded in lab. It is important that you unzip the homework code so the `src` directory from sequences and `hw08-handout` are next to each other. You can find the signature for sequences in the files `src/sequence/sequencecore-sig.sml` and `src/sequence/sequence-sig.sml`. For your reference, we describe the functions you can use here:

- `Seq.length : 'a Seq.seq -> int`
  `Seq.length s` evaluates to the number of items in `s`.
- `Seq.empty : unit -> 'a Seq.seq`
  `Seq.empty ()` evaluates to the sequence of length zero.
- `Seq.cons : 'a * 'a Seq.seq -> 'a Seq.seq`
  If the length of `xs` is `l`, `Seq.cons (x, xs)` evaluates to a sequence of length `l+1` whose first item is `x` and whose remaining `l` items are exactly the sequence `xs`.
- `Seq.singleton : 'a -> 'a Seq.seq`
  `Seq.singleton x` evaluates to a sequence of length 1 where the only item is `x`.
- `Seq.append : 'a Seq.seq -> 'a Seq.seq -> 'a Seq.seq`
  If `s1` has length l_1 and `s2` has length l_2, `Seq.append` evaluates to a sequence with length $l_1 + l_2$ whose first l_1 items are the sequence `s1` and whose last l_2 items are the sequence `s2`.

- `Seq.tabulate : (int -> 'a) * int -> 'a Seq.seq`
  `Seq.tabulate (f, n)` evaluates to a sequence `s` with length `n` where the i^{th} item of `s` is the result of evaluating `(f i)`. `Seq.tabulate (f, i)` raises `Range` if `n` is less than zero.

- `Seq.nth : int * 'a Seq.seq -> 'a`
  `nth i s` evaluates to the i^{th} item in `s`. This is zero-indexed. `Seq.nth (i, s)` will raise `Range` if `i` is negative or greater than `(Seq.length s)-1`.

- `Seq.filter : ('a -> bool) * 'a Seq.seq -> 'a Seq.seq`
  `Seq.filter (p, s)` returns the longest subsequence `ss` of `s` such that `p` evaluates to `true` for every item in `ss`.[1]

- `Seq.map : ('a -> 'b) * 'a Seq.seq -> 'b Seq.seq`
  `Seq.map (f, s)` maps `f` over the sequence `s`. That is to say, it evaluates to a sequence `s'` such that `s` and `s'` have the same length and the i^{th} item in `s'` is the result of applying `f` to the i^{th} item of `s`.

- `Seq.reduce : (('a * 'a) -> 'a) * 'a * 'a Seq.seq -> 'a`
  `Seq.reduce(c, b, s)` combines all of the items in `s` pairwise with `c` using `b` as the base case. `c` must be associative, with `b` as its identity.

- `Seq.mapreduce : ('a -> 'b) * 'b * ('b * 'b -> 'b) * 'a Seq.seq -> 'b`
  `Seq.mapreduce( l, e, n, s)` is equivalent to `Seq.reduce(n, e, Seq.map (l, s))`.

- `Seq.toString : ('a -> string) * 'a Seq.seq -> string`
  `Seq.toString (ts, s)` evaluates to a string representation of `s` by using `ts` to convert each item in `s` to a `string`.

- `Seq.repeat : int * a -> 'a Seq.seq`
  `Seq.repeat (n, x)` evaluates to a sequence consisting of exactly `n`-many copies of `x`.

- `Seq.flatten : ('a Seq.seq) Seq.seq -> 'a Seq.seq`
  `Seq.flatten ss` is equivalent to `Seq.reduce(Seq.append, Seq.empty (), ss)`

- `Seq.zip : ('a Seq.seq * 'b Seq.seq) -> ('a * 'b) Seq.seq`
  `Seq.zip (s1,s2)` evaluates to a sequence whose n^{th} item is the pair of the n^{th} item of `s1` and the n^{th} item of `s2`.

- `Seq.split : int * 'a Seq.seq -> 'a Seq.seq * 'a Seq.seq`
  If `s` has at least `i` elements, `Seq.split (i, s)` evaluates to a pair of sequences `(s1,s2)` where `s1` has length `i` and `Seq.append (s1, s2)` is the same as `s`. Otherwise it raises `Range`.

[1] Here we use the term "subsequence" to mean any subsequence of a sequence, not necessecarily one whose elements are consecutive in the original sequence. For example, $\langle\rangle$, $\langle 3\rangle$, and $\langle 2, 4\rangle$ are subsequences of $\langle 1, 2, 3, 4\rangle$.

- `Seq.take : int * 'a Seq.seq -> 'a Seq.seq`
  `Seq.take (i, s)` evaluates to the sequence containing exactly the first `i` elements of `s` if $0 \leq i \leq$ `length s`, and raises `Range` otherwise.

- `Seq.drop : int * 'a Seq.seq -> 'a Seq.seq`
  `Seq.drop (i, s)` evaluates to the sequence containing all but the first `i` elements of `s` if $0 \leq i \leq$ `length s`, and raises `Range` otherwise.

2 n-Body Simulations

The main portion of this programming assignment is modeling movements of bodies through a universe represented by a two-dimensional Euclidian plane. To make this model, we must pick an SML representation of points in the plane that allows us to meaningfully measure the distance between points—that is to say, we must pick a way to measure the universe. We will represent a point in the plane by a pair of floating point numbers, represented by a pair of values of type `real`. The type `Scalar.scalar` is a synonym for `real` (mathematically, a "scalar" is part of the structure of a "vector space", but we won't go into more detail here).

2.1 The Plane

2.1.1 Points and Vectors

We have provided an implementation of the plane, which consists of points and vectors, based on the code from class. These are represent by the types `Plane.point` and `Plane.vec`. In order to write our implementation of the Barnes-Hut algorithm, we need several operations on vectors and points in space, many of which we discussed in lecture. The type `Plane.point` is used to represent a point in space, and the type `Plane.vec` is used to represent vectors of velocity, acceleration, etc. In the implementation, we define the type of points and vectors as in lecture:

```
type Plane.point = Scalar.scalar * Scalar.scalar
type Plane.vec = Scalar.scalar * Scalar.scalar
```

In your implementation, these types are *abstract*, which means you should code only in terms of the provided operations on points and vectors.

You can see the full signature for the plane in `space.sig`. Some operations include:

- `Plane.vecFromPoints : Plane.point * Plane.point -> Plane.vec`
  the vector whose tail is the first point and whose head is the second point
- `Plane.zero : Plane.vec`
  the zero vector
- `Plane.add : Plane.vec * Plane.vec -> Plane.vec`
  add two vectors
- `Plane.scale : Plane.vec * Scalar.scalar -> Plane.vec`
  scale a vector by a constant
- `Plane.origin : Plane.point`
  the origin point of the vector space.
- `Plane.distance : Plane.point * Plane.point -> Scalar.scalar`
  `Plane.distance(p1, p2)` evaluates to the distance between the points `p1` and `p2`.
- `Plane.midpoint : Plane.point * Plane.point -> Plane.point`
  `Plane.midpoint(p1, p2)` evaluates to the midpoint of the points `p1` and `p2`.

- `Plane.head : Plane.vec -> Plane.point`
  `Plane.head v` evaluates to the point that corresponds to the head of `v` if the tail of `v` is at the origin.

2.1.2 Bounding boxes

The type `BoundingBox.bbox` represents a rectangular region in two-dimensional space. You will want to use the functions whose types and specs are given in `bbox.sig`. These functions are implemented in `bbox.sml`. Here some useful functions:

- `BoundingBox.contained : (bool * bool * bool * bool) * Plane.point * BoundingBox.bbox -> bool`
  `BoundingBox.contained(bs, p, bb)` evaluates to `true` if and only if the point `p` is in the box `b`. The four booleans control whether the left/right/top/bottom edges of the box are included or excluded, where `true` means to exclude an edge.

  For example, `BoundingBox.contains((false,false,false,false),p,b)` returns true if `p` is in the box `b` including all of the edges, while `BoundingBox.contains((true,false,false,false),p,b)` is the same except it will return false if `p` is directly on the left edge of the rectangle. The order of the booleans is

  (exclude left side, exclude right side, exclude top side, exclude bottom side)

  and a corner is excluded if either of the sides containing it are excluded.

- `BoundingBox.diameter : BoundingBox.bbox -> Scalar.scalar`
  Computes the diameter of the box, i.e. the length of the diagonal.

- `BoundingBox.from2Points : Plane.point * Plane.point -> BoundingBox.bbox`
  `BoundingBox.from2Points (p1, p2)` returns the smallest bounding box containing both `p1` and `p2`

- `BoundingBox.fromPoints : Plane.point Seq.seq -> BoundingBox.bbox`
  Computes the minimum bounding box containing every point in a sequence of points, assuming the sequence is non-empty.

- `BoundingBox.center : BoundingBox.bbox -> Plane.point`
  Computes the center point of the bounding box.

- `BoundingBox.corners : BoundingBox.bbox -> Plane.point * Plane.point * Plane.point * Plane.point`
  Returns the four corners of the bounding box in order

  (top left, top right, bottom left, bottom right)

2.2 Barnes-Hut

In lecture, we discussed how to solve the n-body problem in the naïve, quadratic manner. The code for this is given in `mechanics.sml` and `naiveNBody.sml`. Recall that the pieces of information we need about a body in space are its mass, location, and velocity. This is represented by the type definition

```
type body = Plane.scalar * Plane.point * Plane.vec
```

The type `body` is used to represent the different bodies in the n-body simulation. Specifically, in an expression `(m, p, v)` of type `body`, `m` is the mass of the body, `p` is its position, and `v` is the vector representing its velocity.

The naïve, quadratic implementation of an n-body simulation is given by the function

```
accelerations : body Seq.seq -> Plane.vec Seq.seq
```

in `naiveNBody.sml`. This function transforms a sequence of bodies into a sequence in which the element at position `i` represents the acceleration for the element at position `i` of the sequence of bodies.

One of the vital helper functions for this is

```
accOn : body * body -> Plane.vec
```

found in `mechanics.sml`. Recall the specification is that `accOn (b1, b2)` calculates the acceleration on `b1` due to `b2`. Using this function, the calculation is fairly straightforward:

```
fun accelerations (bodies : body Seq.seq) : Plane.vec Seq.seq =
    Seq.map (fn b1 => Plane.sum (fn b2 => accOn (b1, b2), bodies), bodies)
```

where `Plane.sum(f,s)` is `Seq.reduce(Plane.add,Plane.zero,Seq.map(f,s))`

However, on large inputs, this implementation is accurate, but unacceptably slow for an actual simulation. There are many different approximations that have been developed; the one we will look at is called Barnes-Hut.

2.2.1 The algorithm

Barnes-Hut groups bodies into quadrants and uses a fixed threshold value θ (e.g. 0.5) to determine whether each individual body is "far enough" away from a group of other bodies. If a body is far enough away from a quadrant, the algorithm uses a *pseudobody* representing a weighted average of the bodies in that quadrant or the acceleration calculation, instead of using each individual body composing the pseudobody. This results in a loss of accuracy, but a dramatic speedup in terms of runtime—while the old algorithm had work in $O(n^2)$, this algorithm's work is in $O(n \log n)$ if the threshold value is well-chosen.

To calculate the effect of a pseudobody on another body, it is important to know the total mass of all the bodies represented by the pseudobody and also their center of mass or *barycenter*. Therefore, when we form a pseudobody, we will compute a tuple `(m, c)` such that `m : Plane.scalar` is the total mass of the bodies and `c : Plane.point` is the

barycenter. To compute the barycenter, we compute a weighted average of the vectors corresponding to the displacement of each body's position from the origin. For bodies $(m_1, p_1, v_1), (m_2, p_2, v_2), \ldots (m_n, p_n, v_n)$, we compute the following vector:

$$\mathbf{R} = \frac{m_1\mathbf{r}_1 + m_2\mathbf{r}_2 + \ldots m_n\mathbf{r}_n}{m_1 + m_2 + \ldots m_n}$$

where $\mathbf{r}_i$ is the vector from the origin to position p_i. The barycenter is then the head of this vector.

To approximate the acceleration on a body using a pseudobody, we represent the acceleration due to all the bodies in a group as the acceleration due to a single body located at the barycenter with mass equal to the total mass.

2.2.2 Computing the barycenter

Rather than computing the barycenter for each quadrant of space from all of the points in that quadrant, we will approximate the barycenter as an average of the averages of the four subquadrants of a region of space. This means that all we ever need to do is to compute the barycenter of four pairs of masses and points.

Task 2.1 (10 pts). In `barnes-hut.sml`, write the function

```
fun barycenter ((m1,p1) : (Scalar.scalar * Plane.point),
                (m2,p2) : (Scalar.scalar * Plane.point),
                (m3,p3) : (Scalar.scalar * Plane.point),
                (m4,p4) : (Scalar.scalar * Plane.point)) :
               Scalar.scalar * Plane.point = ...
```

that computes the pair `(m, c)` where `m` is the total mass of the four bodies (*i.e.*, the sum of the first components of the pairs) and `c` is the barycenter.

2.2.3 Grouping bodies

We still have not discussed exactly *how* to group bodies. There are many different ways of doing so, but the most straightforward is by grouping things into quadrants (for the 2D case). That is, starting at the center of the area, we divide the field into quadrants, then recursively group the bodies in each quadrant, stopping when a region has either zero or one body in it. This yields a tree-structured division of space, where each node has four subtrees, corresponding to the four quadrants of it. We can represent this tree structure as a datatype in SML:

```
datatype bhtree =
    Empty
  | Single of body
  | Cell of (Scalar.scalar * Plane.point) * BB.bbox
            * bhtree * bhtree * bhtree * bhtree
```

`Empty` represents a region with no bodies in it. `Single b` represents a region with exactly the body `b` in it. `Cell ((m, c), bb, sq)` is somewhat more complicated:

- `m` is the total mass of the bodies contained in the region.
- `c` is the barycenter of the bodies contained in the region.
- `bb` is a bounding box of the region.
- The four subtrees represent the subdivisions of the four quadrants of the region. The four child `bhtree`'s are, in order, the top-left, top-right, bottom-left, and bottom-right quadrants of the region, respectively.

As a first step in constructing this tree, we will write the `quarters` function to split a bounding box into four equally sized quadrants.

Task 2.2 (10 pts). Write the function

```
quarters : BoundingBox.bbox
        -> BoundingBox.bbox * BoundingBox.bbox *
           BoundingBox.bbox * BoundingBox.bbox
```

to compute the four bounding boxes that correspond to the top-left, top-right, bottom-left, and bottom-right quadrants of the argument bounding box. Use the bounding box functions described above.

2.2.4 Growing the tree

We now have the tools we need to compute a `bhtree` from a sequence of points and a bounding box.

Task 2.3 (30 pts). Write the function

```
compute_tree : body Seq.seq * BoundingBox.bbox -> bhtree
```

such that `compute_tree (s, bb)` evaluates to `T`, where `T` is the tree decomposition of `s` in the bounding box `bb`. You may assume that all of the bodies in `s` are within the bounding box `bb` and that no two bodies in `s` occupy the same position (*i.e.*, have equal position components).

In the recursive calls, you will need to divide `s` into four sequences corresponding to those bodies in each of the four quadrants of `bb`. If a body is on the border between two quadrants, it should be placed in the *first* quadrant that it is in, in the following order: top left, top right, bottom left, bottom right.

Note: The barycenter of the bodies in a bounding box should be computed as the barycenter of the four quadrants' barycenters. You can use the helper function `center_of_mass : bhtree -> Plane.scalar * Plane.point` to project the relevant data from the result of a recursive call.

2.2.5 Computing acceleration

Now that we can calculate the tree determined by a group of bodies, we can use it to efficiently compute an approximation of the acceleration of all the bodies at this particular timestep. This brings us back to the threshold value θ mentioned above.

The reason Barnes-Hut is more efficient than the naïve approach is that it does not compute the exact acceleration—instead, it uses a parameter θ to determine exactly how precise to be. Whenever your algorithm reaches a region with more than one body in it (that is, a `Cell` in the tree), it checks to see if $\frac{diam}{dist} \leq \theta$, where `diam` is the diameter of the region (the length of the diagonal) and `d` is the distance from the body being checked to the region's barycenter. If it is, then the region is treated as one large body located at its barycenter (which we have conveniently already calculated!). Otherwise, the respective accelerations from the bodies in each quadrant are computed recursively and then summed.

Task 2.4 (5 pts). Write the function

```
val too_far : Plane.point * Plane.point * BoundingBox.bbox * Scalar.scalar -> bool
```

such that given a point `p1` (position of body whose acceleration is being computed), a point `c` (center of a region), and bounding box `bb` (bounding box of that region) and a threshold `t` (θ), `too_far (p1, c, bb, t)` evaluates to `true` if $\frac{diam}{dist} \leq \theta$ and `false` otherwise.

Task 2.5 (25 pts). Write the function

```
bh_acceleration : bhtree * Plane.scalar * body -> vec
```

such that `bh_acceleration (T, threshold, b)` computes the acceleration on `b` from the tree `T` according to the algorithm described above. (**Hint:** Use a function from `mechanics.sig`, which is the mechanics code from lecture.)

Task 2.6 (20 pts). Finally, write a function

```
barnes_hut  : Scalar.scalar * body Seq.seq -> vec Seq.seq
```

that uses your `compute_tree` and `bh_acceleration` functions to form the Barnes-Hut tree for a sequence of bodies and then use it to compute the acceleration on each body in the sequence.

2.3 How to Load the Project

To load your code using the floating point implementation of the plane, in SMLNJ issue the command

```
- CM.make "sources.cm";
```

`CM.make` uses the SMLNJ *compilation manager* to load many different files, including all of our support code and the code that you write. **Every time you edit your file, you should re-run `CM.make` to reload your code—do this in place of "using" the homework file.**

2.4 Testing

Because your solution consists of several functions that build on each other, it is in your interest to test each function in isolation, which will help you figure out where your bugs are. For `barycenter`, `quarters`, and `compute_tree`, we have provided some tests, and you can write more (if you want) using the helper functions and hard-coded points/bounding boxes/bodies in the module `TestData`. You can run `BarnesHut.test_X()` for the `test` functions in `BarnesHut.sml`.

To test the overall behavior, you will generate transcripts describing the position of each body and look at them in a visualizer.

Use the following tests first:

- `Transcripts.run_solar_inner : int * string -> unit`
  `run_solar_inner (days, outfilename)` generates a transcript for running the solar system for that many days and puts the results in the file `data/outfilename`. The transcript file tells the visualizer to show only the planets up to Mars.

  For example:

  ```
  - Transcripts.run_solar_inner (365, "year.txt.sim");
  ```

  will create a file `data/year.txt.sim` that should show the earth (the blue circle) orbiting the sun once and the other planets orbiting as well.

- `Transcripts.run_solar : int * string -> unit` Same as the above, except the visualization radius includes all planets.

Once you have produced a transcript file, you can visualize it by navigating to

`https://dlicata.wescreates.wesleyan.edu/teaching/fp-f24/visualizer/visualizer.html`

You can then load a transcript file in one of two ways: either dragging and dropping the transcript file into the dashed box, or using the file browser to select the file manually. You should refresh the page before running another transcript.

Next, you should run some larger simulations. The support code contains initial conditions for the following:

```
N-Body data files
-----------------
galaxy10k.txt       10,000 bodies orbiting in an elliptical galaxy.
galaxy20k.txt       20,000 bodies orbiting in an elliptical galaxy.
galaxy30k.txt       Two 15,000 particle galaxies collide.
saturnrings.txt     Saturn with its 9 rings containing 11,987 particles.
cluster2.5k.txt     A star cluster containing 2,582 particles.
collision1.txt      Two large irregular galaxies collide and mostly pass
                    through each other.
collision2.txt      Collision of two 1000 particle elliptical galaxies.
galaxyform2.5k.txt  A 2,500 particle dust cloud collapses under gravity
```

```
                    and forms into a galaxy.
galaxymerge1.txt    Two 1,000 particle clouds gravitate together and eventually
                    combine into a galaxy.
galaxymerge2.txt    Four 1,000 particle clouds gravitate together and combine
                    into a galaxy.
galaxymerge3.txt    A 900 particle spinning elliptical galaxy collides with a big
                    expanding galaxy and combines with it.
galaxy1.txt         A lighter galaxy is torn apart by a dense galaxy.
galaxy2.txt         A galaxy orbits a heavier one and forms a spiral.
galaxy3.txt         A dense galaxy sucks stars out of a lighter galaxy that orbits it.
galaxy4.txt         Galaxies orbiting each other.
spiralgalaxy.txt    A round galaxy becomes a spiral due to two small galaxies
                    that fly by it.
asteroids1000.txt   Near earth asteroids and the earth in orbit around the sun.
```

To run them:

- `Transcripts.run_file : string * int * real -> unit`

  `run_file (filename, num_iters, timestep)` runs the simulation on an input file specified by `filename`, for `num_iters` steps, with time given by `timestep`. The output is written to `filename.sim`.

  For example:

  ```
  - Transcripts.run_file ("data/galaxy2.txt", 2000, (1.0/10.0));
  ```

  produces a file `data/galaxy2.txt.sim`. See `data/datafiles.txt` for descriptions of the simulations.

  Here are some good timesteps and numbers of iterations.

  ```
  Transcripts.run_file ("data/asteroids1000.txt", 1000, (1.0/10.0)); (* 62 seconds*)
  Transcripts.run_file ("data/cluster2582.txt", 2000, (1.0/10.0)); (* 555 seconds *)
  Transcripts.run_file ("data/galaxy1.txt", 2000, (1.0/10.0)); (* 130 seconds *)
  Transcripts.run_file ("data/galaxy2.txt", 2000, (1.0/10.0)); (* 83 seconds *)
  Transcripts.run_file ("data/galaxy3.txt", 1500, (1.0/10.0)); (* 304 seconds *)
  Transcripts.run_file ("data/galaxy4.txt", 2000, (1.0/10.0)); (* 41 seconds *)
  Transcripts.run_file ("data/spiralgalaxy.txt", 2000, (1.0/10.0)); (* 94 seconds *)
  Transcripts.run_file ("data/galaxymerge1.txt", 5000, (1.0/5.0)); (* 820 seconds *)
  Transcripts.run_file ("data/galaxymerge2.txt", 2500, (1.0/10.0)); (* 626 seconds *)
  Transcripts.run_file ("data/galaxymerge3.txt", 2500, (1.0/10.0)); (* 655 seconds *)
  Transcripts.run_file ("data/galaxyform2500.txt", 2000, (1.0/10.0)); (* 294 seconds
  Transcripts.run_file ("data/collision2.txt", 2500, (1.0/10.0)); (* 330 seconds *)
  Transcripts.run_file ("data/collision1.txt", 1500, (1.0/10.0)); (* 299 seconds *)
  Transcripts.run_file ("data/saturnrings.txt", 100, (1.0/100.0)); (*  112 seconds *)
  Transcripts.run_file ("data/galaxy10k.txt", 100, (1.0/10.0)); (* 93 seconds *)
  Transcripts.run_file ("data/galaxy20k.txt", 50, (1.0/10.0)); (* 188 seconds *)
  Transcripts.run_file ("data/galaxy30k.txt", 800, (1.0/10.0)) (* 1736 seconds *)
  ```

Some of them take a while (the comment is how long they took for me). You don't need to run all of them — you can pick a few to try. Or you can either turn down the number of iterations to see less of the movie, or run them overnight. The total size of all files produced is about 2GB.

- The command

  ```
  - Transcripts.run_files();
  ```

  runs all of the above.