Sussing Merger Trees: A proposed Merger Tree data format

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ABSTRACT
We propose a common terminology for use in describing both temporal merger trees and spatial structure trees for dark-matter halos. We specify a unified data format in HDF5 and provide example I/O routines in C, FORTRAN and PYTHON.

Key words: methods: N-body simulations – galaxies: haloes – galaxies: evolution – cosmology: theory – dark matter

1 INTRODUCTION
The Sussing MERGER TREES Workshop held in Midhurst, Sussex on 7-12 Jul 2013 brought together tree-code builders from 10 distinct groups: CONSISTENT TREES (Behroozi et al. 2013); D-TREES (Jiang et al. 2014); HBT (Han et al. 2012); JMERGE (Julian Onions, unpublished); LHALOTREE (Springel et al. 2005); MERGER TREE (Knebe et al. 2010); SUBLINK (Rodriguez-Gomez et al. 2015); TREEMAKER (Hatton et al. 2003); Tweed et al. 2009); VELOCIRAPTOR (Pascal Elahi, unpublished); YSAMTM (Intae Jung etal, in preparation). Unpublished algorithms are briefly outlined in Srisawat et al. (2013).

During that meeting, it was agreed that a common structure was required for recording merger trees, and that it should include both spatial and temporal information. This paper summarises the results of that discussion and sets out the agreed data format. It also presents an HDF5 implementation of that format and describes some example I/O routines that are available to download.

2 THE ANATOMY OF A MERGER TREE
We use and extend the terminology defined in Srisawat et al. (2013). For ease of reference, we repeat that here with appropriate extensions.

- A halo is a dark-matter condensation as returned by a halo finder. This is a deliberately vague statement as we do not want to be too prescriptive. Halos will usually be identified in the output of a simulation at a fixed time, or snapshot. Halos may be identified at a variety of different overdensities and may be nested within one another (however, we do not allow halos to partially overlap). As the simulation progresses in time, it is natural to associate halos at one snapshot with those in subsequent ones, though that association is

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Figure 1. An example of a nested group of halos. The numbering corresponds to that in the spatial structure tree representation shown in Figure 2.

not always obvious and its investigation was the main purpose of the SUSING MERGER TREES Workshop.

2.1 Spatial structure

An example of a complex set of nested haloes is shown in Figure 1. The numbering of the halos is the same as that in Figure 2 that shows a representation in the form a tree showing the spatial nesting of halos.

During the SUSING MERGER TREES Workshop it became apparent that the current output structure of halo finders can give difficulties in tree-building. It is common practice to choose one of the haloes in a group and designate it as the ‘main halo’ (also know as the ‘background halo’, e.g. [Springel et al. 2001]). This is fine for undisturbed groups that have a relatively smooth structure with an obvious central halo. However, it does not make sense for the coming together of two (or more) roughly equally-sized haloes for which neither is at the dynamical centre of the group. Instead we propose that all subhaloes be recorded separately, together with an enclosing host halo. Optionally, one of the subhaloes can then be designated a main subhalo of the host. The main halo is then an entity in its own right, rather than being associated with any particular subhalo.

We propose the following nomenclature:

- **A spatial structure graph** is a set of ordered halo pairs, \((H_A, H_B)\), where \(H_A\) is nested within \(H_B\). It is the purpose of the halo-finding codes to produce a graph that best represents the spatial structure of halos. The halo definition may occur at discrete steps in overdensity, but this is not a requirement.
- Recursively, \(H_A\) itself and subhaloes of \(H_A\) are **subhaloes** of \(H_B\). Where it is necessary to distinguish \(H_A\) from subhaloes that are more deeply nested, the term **direct subhalo** should be used.
- Recursively, \(H_B\) itself and hosts of \(H_B\) are **hosts** of \(H_A\). Where it is necessary to distinguish \(H_B\) from larger hosts, the term **direct host** should be used.
- Optionally, one direct subhalo may be designated the **main subhalo** to indicate that it is at the dynamical centre of the halo.
- The longest continuous sequence of main subhaloes extending (to higher overdensity) from a given halo is known as the **main root**.

Figure 2. A representation of a spatial structure tree corresponding to the halos shown in Figure 1. The density (size) of haloes decreases (increases) as one moves from top to bottom on the plot. The grey lines show the links of the tree. The A and B labels indicate the ordered pairs that are associated with Halo 14. For that halo, the solid, black arrows show required links in the data structure; the designation of a FirstSubhalo as Main, or otherwise, and the links shown by the dashed, black arrows are optional. Halos 15-24 are subhaloes of Halo 14; Halos 15 & 21 are direct subhaloes.

- A halo that has no host halo is known as a **main halo**.
- A **spatial structure tree** is a spatial structure graph in which there is precisely one direct host for every halo, except for a single main halo.

In Figure 2, halos are represented as circles with IDs as indicated by the number contained within them. The density (size) of halos decreases (increases) from top to bottom on the plot.

Consider Halo 14. It has Subhalos 15-24 of which 15 & 21 are direct subhalos. Halo 15 has been deemed a main subhalo of 14, and Halo 16 a main subhalo of 15, but (for the purposes of illustration) Halo 17 is not at the dynamical centre of halo 16 and so is not designated a main subhalo. Then Halos 14-16 are the main root extending back from Halo 14 ![1](1). In a structure tree, each halo has a single direct host, in this case Halo 13. The outermost enclosing main halo (the main halo) is here Halo 7.

Although not shown in Figure 2, it is also useful to have another link, StartMainRootID that shows the largest enclosing halo of which the halo in question lies on the main root. In the figure,

![1](1) We use the term root here to distinguish the spatial tree from the temporal one shown in Figure 3 where the equivalent structure is commonly referred to as the main branch.
Figure 3. A representation of a temporal merger tree. The lookback time of haloes decreases as one moves from top to bottom on the plot. The grey lines show the links of the tree. The A and B labels indicate the ordered pairs that are associated with Halo 14. For that halo, the solid, black arrows show required links in the data structure; the links shown by the dashed, black arrows are optional. Halos 15-24 are progenitors of Halo 14; Halos 15 & 21 are direct progenitors.

Halo 14 is not a main subhalo of 13, and so Halos 14, 15 & 16 will all have Halo 14 as their StartMainRoot. This makes it easy to decide whether a halo should be considered to be the main component of a larger structure, and if so, which one.

2.2 Temporal structure

The term merger tree was first applied to temporal evolution. As shown in Figure 3, the structure of the temporal merger tree is identical to that of the spatial structure tree, but the nomenclature has been changed to distinguish the two. To maintain flexibility, we have modified the usual definition to make the assignment of a main progenitor optional. To complete the analogy we designate the haloes in the final snapshot (i.e. the end of the simulation) as end halos.

- A temporal merger graph is a set of ordered halo pairs, \((H_A, H_B)\), where \(H_A\) is older than \(H_B\). It is the purpose of the merger-tree codes to produce a graph that best represents the growth of structure over cosmic time. \(H_A\) and \(H_B\) are usually taken from adjacent snapshots, but this is not a requirement as there are occasions where haloes lose their identity and then reappear at a later time.
- Recursively, \(H_A\) itself and progenitors of \(H_A\) are progenitors of \(H_B\). Where it is necessary to distinguish \(H_A\) from earlier progenitors, we will use the term direct progenitor.
- Recursively, \(H_B\) itself and descendants of \(H_B\) are descendants of \(H_A\). Where it is necessary to distinguish \(H_B\) from later descendants, we will use the term direct descendant.
- Optionally, one of the direct progenitors may be labelled the main progenitor – this will usually be the most massive, but other choices are permitted. (Note: this deviates from the definition in Srisawat et al. (2013) where the selection of a main progenitor was compulsory.)

- The longest continuous sequence of main progenitors extending back in time from a given halo is known as the main branch.
- A halo that has no descendants is known as an end halo.
- A temporal merger tree is a temporal merger graph in which there is precisely one direct descendant for every halo, except for a single end halo.

2.3 Combined spatial and temporal trees and depth-first ordering

Although our standard does not prescribe it, the trees shown in Figures 2 & 3 are depth-first ordered which means that the subhalos of a given halo are all those with indices between FirstSubhalo and LastSubhalo. Similarly, the progenitors are those halos with indices between FirstProgenitor and LastProgenitor.

Unfortunately, there is no straightforward way to order a combined spatial and temporal tree. Consider the left-hand example in Figure 2; Halo 3 can be reached from Halo 1 in two different ways: it is a subhalo of Halo 4 which is a progenitor of Halo 1; and it is a progenitor of Halo 2 which is a subhalo of Halo 1. It would seem, therefore, that we have a choice of making either time or space the inner loop in any tree traversal. As we describe below, however, only the former will allow us to uniquely traverse the tree starting from end, main halos (i.e. the outermost enclosing halos at the endpoint of the simulation) and visiting each halo precisely once.

As one might conceivably want to examine the structure of a halo without knowing its merger history, it would seem natural to preserve depth-first ordering for the former rather than the latter (i.e. make space the inner loop in any tree-search and time the outer one). Unfortunately, that does not work because the progenitors of a main halo can have a variety of overdensities and may contain halos that are at different levels in the same spatial tree. Consider starting a tree traversal from Halo 5 in the right-hand example of Figure 2:

Such a search would find Halo 6 as a progenitor of Halo 5 and then...
Halo 7 as a subhalo of Halo 6. But it would also find Halo 7 as a progenitor of Halo 5 in its own right and so would appear twice in the tree search.

On the other hand, spatial trees contain halos that are all built from the same snapshot of a simulation and so are coincident in time. So if we search first for subhalos in the final snapshot and then follow all those subhalos back in time, then we will visit each halo precisely once. For that reason, we choose to make space the outer loop and time the inner one within which depth-first ordering is preserved. An example tree-search algorithm (in PYTHON) is given in the Appendix.

3 DATA FORMAT

3.1 Halo indices and pointers

The halos that are returned by a halo finder do not normally have consecutive indices (i.e. with no gaps in the list). However, to allow for efficient data retrieval, the pointer indices that represent the links in the figures need to run in a continuous sequence from HaloIndexOffset to HaloIndexOffset+Nhalo-1, where Nhalo is the total number of halos. We therefore make this a requirement but also store the original HaloID to allow cross-reference back to the halo catalogue.

To avoid repetition, we describe the structure of the data format here only for the structure tree; that of the merger tree is exactly analogous. To store a basic tree in which there is no main subhalo designation, then all that would be required would be a pointer to the direct host of each halo – this is the HostHaloIndex. However, in order to allow efficient traversal of the tree, we also need an efficient way to locate subhalos of a given halo. That is provided by two pointers: the FirstSubhaloIndex points to the main subhalo, if that exists, or to one of the other direct subhaloes if not (typically that with the lowest halo index). Then each of those subhaloes is also given a NextNeighbourIndex pointer to another of the direct subhaloes (typically the one with the next highest halo index) such that eventually all the direct subhaloes have been visited. If any of the halos described above does not exist, then the corresponding pointer is set to a null value (e.g. −1 for C/PYTHON or 0 for FORTRAN).

If the halo indexing is done in depth-first order, as shown in the figures, then the (optional) inclusion of pointers EndMainRootIndex to indicate the end of the main root, and LastSubhaloIndex to identify the subhalo with the largest index, allows for efficient identification of contiguous blocks of useful data.

The inclusion of MainSubhaloFlag for identification of the first subhalo as a main subhalo (or not) is also optional. For trees in which the first subhalo is always a main subhalo then this could be omitted. Likewise, it is common practice to always require a main progenitor but the (optional) inclusion of a MainProgenitorFlag allows flexibility not to do so, for example in the case of equal-sized mergers in which there is no obvious dominant progenitor on the previous snapshot.

2 The use of HaloIndexOffset allows for an offset in case that the indexing does not start from zero (e.g. the use of FORTRAN-style indexing, or when working with a subset of a larger data-set).

3.2 HDF5 data format

The use of HDF5 allows for efficient data compression and avoids having to worry about the endianness of the data. Table outlines an HDF5-compatible data format to record both spatial and temporal merger trees. Required entries are entered in plain text and optional ones in italics. The required entries specify minimal information to associate halos with particular snapshots and density levels and to allow efficient traversal of the tree. We also include the halo mass as that is a fundamental property that will be required in almost any application.

To increase flexibility, we allow the entries in the MergerTree group to be stored either in a table (one row per halo) or as a set of arrays (one array per property; Nhalo entries per array). Which of these is more efficient in terms of data I/O will depend upon the number of halos and the number of properties that are stored.

Note that the pointers refer to the position of the corresponding halo in this array of halo structures, not to the original halo ID in the halo catalogue (this latter OriginalHaloID may optionally be provided separately to allow cross-reference). The pointers thus have values between HaloIndexOffset and HaloIndexOffset+Nhalo−1, inclusive. A null pointer can be taken as any number that lies outside this range, although the values −1 and 0 are the most common (for C/PYTHON and FORTRAN, respectively).

We give two options for storing the physical properties of halos – in practice users may want to use a mixture of the two. Firstly, for ease of lookup, properties may be specified in the MergerTree group; alternatively, they may be stored by snapshot number in groups Snapshots/Snapshot#. In order to look up the latter a HaloIndex pointer would be needed to identify the appropriate entry in the table.

In general a data-set may contain more than one tree and in that case it may be useful to know the indices of the main (end) halos. Our suggested data structure avoids storing that information as it would be contained in an array of variable length, but we note that it can easily be recovered by searching for haloes for which the HostHaloIndex (DescendantIndex) is the null pointer.

Note that arrays are datasets with a predefined HDF5 datatype. Arrays and attributes can be manipulated using the high-level H5LT routines. Tables have compound datatypes and are manipulated using the high-level H5TB routines.

3.3 Example I/O routines

One of the main advantages of HDF5 and similar formats is that the structure of the file and the nature of its contents can be discerned using utility programs such as hdfview, h5ls and h5dump.

To encourage use of the data format described in this paper, we provide example programs to read and write merger tree data files in C, FORTRAN-95 and PYTHON. For those new to HDF5 we strongly recommend first working with PYTHON as the h5py module greatly simplifies the interface with the underlying HDF5 libraries. In applications handling large data-sets, however, the greater efficiency of C or FORTRAN will be required.

We provide some basic examples of merger tree I/O in PYTHON in the Appendix. These routines, together with their equivalents in C & FORTRAN may be downloaded from https://bitbucket.org/ProfPAThomas/mergertree/. These routines are very much work in progress and we encourage anyone with the interest and time to improve and extend them.
Table 1. An interpretation of the data format in HDF5.

| Group            | Object name     | Object type            | Notes                                                                 |
|------------------|-----------------|------------------------|----------------------------------------------------------------------|
| /                | Version         | Int(32bit) attribute   | Version number                                                        |
|                  | Subversion      | Int(32bit) attribute   | Subversion number                                                     |
|                  | Title           | String attribute       | Title of data-set                                                     |
|                  | Description     | String attribute       | Description of data-set                                               |
|                  | BoxsizeMpc      | Real(32bit) attribute  | Comoving box-size in Mpc (not $h^{-1}\text{Mpc}$)                     |
|                  | OmegaBaryon     | Real(32bit) attribute  | Density parameter of baryons at $z = 0$                               |
|                  | OmegaCDM        | Real(32bit) attribute  | Density parameter of CDM (excluding baryons) at $z = 0$               |
|                  | OmegaLambda     | Real(32bit) attribute  | Density parameter of Cosmological Const. ($w = -1$) at $z = 0$        |
|                  | H100            | Real(32bit) attribute  | Hubble parameter / 100 km s$^{-1}$ Mpc$^{-1}$                         |
|                  | Sigma8          | Real(32bit) attribute  | RMS linear overdensity at $z = 0$ in spheres of radius $8h^{-1}\text{Mpc}$ |
|                  |                 |                        | Optional additional attributes                                        |
|                  | Snapshots       | Group                  | Snapshot info/data                                                    |
|                  | MergerTree      | Group                  | Merger tree info/data                                                 |
|                  | /Snapshots      |                        |                                                                      |
|                  | NSnap           | Int(32bit) attribute   | Number of snapshots                                                   |
|                  | Snap            | Table                  | Table of snapshot properties (a, t, . . .)                            |
|                  | SnapProp        | Table                  | Table of snapshot property names/descriptions/units                   |
|                  | Snapshot1       | Group                  | Snapshot particle and/or halo data                                   |
|                  |                 |                        |                                                                      |
|                  | /Snapshots/Snapshot#       |                        |                                                                      |
|                  | NSnapHalo       | Int(32bit) attribute   | Number of halos in this snapshot                                     |
|                  | SnapHalo        | Table                  | Table of halo properties (Mass, Pos, Vel, AngMom, . . .)             |
|                  | SnapHaloProp    | Table                  | Table of halo property names/descriptions/units                       |
|                  | /MergerTree     |                        |                                                                      |
|                  | NHalo           | Int(32bit)|Int(64bit) attribute | Total number of halos                                                 |
|                  | HaloIndexOffset | Int(32bit)|Int(64bit) attribute | Pointer index value of first halo in the Arrays/Tables               |
|                  | TableFlag       | Int(32bit) attribute   | 0|1 if halos stored in Arrays/Table                                      |
|                  |                 |                        | Optional additional attributes                                        |
|                  | Either (table format): |              |                                                                      |
|                  | Halo            | Table                  | Table of halo properties (Snapshot, Density, Mass, FirstSubhaloIndex, . . .) |
|                  | HaloProp        | Table                  | Table of halo property names/descriptions/units                       |
|                  | or (arrays of size NHalo$^1$): |                  |                                                                      |
|                  | Snapshot        | Int(32bit)             | Snapshot number                                                       |
|                  | Density         | Real(32bit)            | Over-density of halo (units to convert to critical density)           |
|                  | Mass            | Real(32bit)            | Some measure of halo mass                                             |
|                  | FirstSubhaloIndex | Int(32bit)|Int(64bit) attribute | Pointer to FirstSubhalo                                              |
|                  | NeighbourIndex  | Int(32bit)            | Pointer to Neighbour                                                  |
|                  | HostHaloIndex   | Int(32bit)            | Pointer to HostHalo                                                   |
|                  | FirstProgenitorIndex | Int(32bit)|Int(64bit) attribute | Pointer to FirstProgenitor                                            |
|                  | NextSiblingIndex | Int(32bit)            | Pointer to NextSibling                                               |
|                  | DescendantIndex | Int(32bit)            | Pointer to Descendant                                                |
|                  | EndMainRootIndex | Int(32bit)            | Pointer to halo at the end of the main root                          |
|                  | EndMainBranchIndex | Int(32bit)|Int(64bit) attribute | Pointer to halo at the end of the main branch                         |
|                  | LastSubhaloIndex | Int(32bit)            | Pointer to LastSubhalo                                               |
|                  | LastProgenitorIndex | Int(32bit)|Int(64bit) attribute | Pointer to LastProgenitor                                            |
|                  | MainSubhaloFlag | Int(32bit)             | 0|1 if FirstSubhalo is a main subhalo                                   |
|                  | MainProgenitorFlag | Int(32bit)          | 0|1 if FirstProgenitor is a main progenitor                             |
|                  | OriginalHaloID  | Int(32bit)|Int(64bit) attribute | Halo ID in original catalogue                                        |
|                  | HaloIndex       | Int(32bit)|Int(64bit) attribute | Location in Snapshot Halo table                                      |
|                  | Pos             | Real(32bit) array[3]$^3$ | Comoving position of centre of mass                                |
|                  | Vel             | Real(32bit) array[3]$^3$ | Peculiar Velocity of centre of mass                                   |
|                  | AngMom          | Real(32bit) array[3]$^3$ | Angular momentum of halo                                            |
|                  |                 |                        | Other halo properties                                                |

$^1$Each array to come with string Description and Units attributes.

$^2$i.e. arrays of size [NHalo,3] or [3,NHalo] dependent upon the ordering of the data (C-like or FORTRAN-like, respectively).

italic text indicates optional entries.
ACKNOWLEDGEMENTS

The Sussing Merger Trees Workshop was supported by the European Commission’s Framework Programme 7, through the Marie Curie Initial Training Network CosmoComp (PITN-GA-2009-238356). This also provided fellowship support for AS.

KD acknowledges the support by the DFG Cluster of Excellence "Origin and Structure of the Universe”.

PJE is supported by the SSimPL programme and the Sydney Institute for Astronomy(SIfA), and through the ARC via DP130100117.

AK is supported by the Ministerio de Economía y Competitividad (MINECO) in Spain through grant AYA2012-31101 as well as the Consolider-Ingenio 2010 Programme of the Spanish Ministerio de Ciencia e Innovación (MICINN) under grant MultiDark CSD2009-00064. He also acknowledges support from the Australian Research Council (ARC) grants DP130100117 and DP140100198. He further thanks Primal Screem for velocity girl.

HL acknowledges a fellowship from the European Commissions Framework Programme 7, through the Marie Curie Initial Training Network CosmoComp (PITN-GA-2009-238356).

CS is supported by The Development and Promotion of Science and Technology Talents Project (DPST), Thailand.

PAT acknowledges support from the Science and Technology Facilities Council (grant number ST/L000652/1).

The authors contributed in the following ways to this paper: PAT initiated the discussion and wrote the paper. PAT & JO wrote the provided computer code. The other authors participated in the discussion and design of the data format, in particular JO & DT. All authors helped to proof-read the paper.

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APPENDIX A: EXAMPLE PYTHON CODES

In this appendix we present some example PYTHON codes to search merger trees and to read/write them in HDF5 format. These routines can all be downloaded from https://bitbucket.org/ProfPAThomas/mergertree/.

The examples use the tree shown in Figure A1 as recorded in HDF5 format in test.hdf5.

A1 To read a tree written in the default format

We first present an example of how to read in data from an HDF5 file and to dump some properties to the screen. To simply the script, this example makes use of mt.py that defines a MergerTree class and some helper functions, but this is not really necessary and could easily be omitted.

"""readtree.py
   Example of how to read in a merger tree in HDF5 format
   Usage: python readtree.py <tree.hdf>
"""

#--- Imports

# The following imports the python3 print function into python2;
# It seems to be quietly ignored in python3
from __future__ import print_function
import sys
import mt
# The merger tree module contains data structures, methods and global variables
import mt

# Open file
if len(sys.argv) != 2: sys.exit("Usage: " + sys.argv[0] + " filename.hd5")
mtdata=mt.MergerTree(sys.argv[1], "r")
for (name,value) in mtdata.attrs('/'): print(name,value)

# Read in snap table
for (name,value) in mtdata.attrs("Snapshots"): print(name,value)
snap=mtdata.read_snaptable()
print(\'Snap =\')
print(\'{0:>8} {1:>6} {2:>6} {3:>6}\'.format(*snap.dtype.names))
for row in range(len(snap)): print(\'{0:>8} {1:>6.3f} {2:>6.3f} {3:>6.3f}\'.format(*snap[row]))
del snap

# Read merger tree from HDF file
for (name,value) in mtdata.attrs("MergerTree"): print(name,value)
tree=mtdata.read_mergertree()
print(\'Tree =\')
for dset in tree:
    print(dset,end=\'\')
print()
for ntree in range(min(10,len(tree['HaloID']))):
    for prop in tree:
        print(tree[prop][ntree],end=\'\')
    print()
del tree

# Close file
mtdata.close()

A2 Merger tree class and associated methods

Here is file mt.py containing the MergerTree class used in the above example.

"""mt.py
Merger tree class to simplify some i/o functions for merger trees.
It's not entirely obvious that a separate class is needed
- could just put these calls directly into the main program.
"""

#-----------------------------------------------
import h5py

#-----------------------------------------------
class MergerTree:
    def __init__(self, file=None, mode='r'):
        """Initialise the class, opening the file with the mode given"""
        if file:
            self.open(file, mode)
        else:
            """""
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```python
print('mt usage: mt(file, mode=mode)

# Return set of attributes associated with object
def attrs(self, object):
    return self.fid[object].attrs.items()

# Close the HDF5 file
def close(self):
    self.fid.close()

# Open the HDF5 file
def open(self, file, mode):
    self.fid = h5py.File(file, mode)

# Return a handle to the MergerTree group
def read_mergertree(self):
    return self.fid['MergerTree']

# Return a handle to the Snapshot table
def read_snaptable(self):
    return self.fid['Snapshots/Snap']

# Return a handle to the SnapProp table
def read_snapprop(self):
    return self.fid['Snapshots/SnapProp']
```

#---------------------------

A3 Tree-searching

The following example tracetree.py reads in an HDF5 file then shows how to loop over (or 'trace') a tree using a spatial and/or temporal search. It makes use of a Tree class defined in tree.py

```python
"""tracetree.py
Example of how to read in a merger tree in HDF5 format and to use a
specially-defined Tree class to allow spatial and/or temporal searching
of the tree.
Usage: python tracetree.py
"""

#---------------------------

# Imports

# The following imports the python3 print function into python2;
# It seems to be quietly ignored in python3
from __future__ import print_function

import sys
import numpy
import h5py

# The tree module contains a class definition for a combined spatial and temporal tree
import tree

#---------------------------

# Parameters
# The following data set contains a simple example with both a spatial and merger trees.
infile='data/test.hdf5'
# We are going to open read only
mode='r'

# Open Merger tree file for reading
fid = h5py.File(infile, mode)

# This shows how easy it is to extract attributes from the file
for (name,value) in fid['/'].attrs.items(): print(name,value)

# Next we are going to construct a tree from the information contained in the HDF5 file

# First let's extract the number of halos
gid = fid['/MergerTree']
nHalo=gid.attrs.get('NHalo')
print('nHalo =',nHalo)

# and now the links that we want. Without the [] we get a pointer to the array.
firstSubhalo=gid.get('FirstSubhaloIndex')[:]
neighbour=gid.get('NeighbourIndex')[:]
firstProgenitor=gid.get('FirstProgenitorIndex')[:]
extSibling=gid.get('NextSiblingIndex')[:]
hostHalo=gid.get('HostHaloIndex')[:]
descendant=gid.get('DescendantIndex')[:]

# Initialise tree nodes...
# Trick: create an extra non-existent node to receive references to index -1 (= last index)
nodes=[tree.Tree(halo) for halo in range(nHalo+1)]
nodes[nHalo]=None

# Now we run through each of the halos extracting those pointers that we need for
# efficient tree traversal
for halo in range(nHalo):
    nodes[halo].load(nodes[firstSubhalo[halo]],
                      nodes[neighbour[halo]],
                      nodes[firstProgenitor[halo]],
                      nodes[nextSibling[halo]],
                      nodes[hostHalo[halo]],
                      nodes[descendant[halo]])

# The end main halos are those that have no Descendants and no HostHalo
# In this simple example there is only one such halo
endMainHalos=numpy.where((descendant==-1) & (hostHalo==-1))[0]
print(endMainHalos)

# Let's trace all the halos in the combined spatial and temporal tree
nodes[0].printheader()
for halo in nodes[0].next():
    print(nodes[halo])

# Here's a trace of just the spatial tree
nodes[0].printheader()
for halo in nodes[0].next('spatial'):
    print(nodes[halo])
# and here are the temporal trees for each end halo
endHalos = numpy.where(descendant == -1)[0]
for endHalo in endHalos:
    nodes[endHalo].printheadern
    for halo in nodes[endHalo].next('temporal'):
        print(nodes[halo])

A4 Tree-search algorithm

We present below an example tree class with methods for generating iterators that can perform a combined (default behaviour), spatial, or temporal tree search.

```python

# The following imports the python3 print function into python2;
# It seems to be quietly ignored in python3
from __future__ import print_function

# In Python 3 the loops of the form
# for __ in self.something():
#     yield __
# can all be replaced by
# yield from self.something()
# which makes for much cleaner code.

class Tree:
    """Tree class for dealing with combined temporal and merger trees"""

    # Constructor: creates an empty tree node.
    def __init__(self, node):
        self.node = node

    # Load pointer arrays.
    def load(self, firstSubhalo, neighbour, firstProgenitor, nextSibling, hostHalo=-1, descendant=-1):
        self.firstSubhalo = firstSubhalo
        self.neighbour = neighbour
        self.firstProgenitor = firstProgenitor
        self.nextSibling = nextSibling
        self.hostHalo = hostHalo
        self.descendant = descendant

    # Default iterator that takes no arguments:
    # Note the asymmetry between spatial and temporal: because there is more
    # than one way to reach a node, can only iterate over one of them.
    # Because of the nature of the trees, space has to be the outer loop.
    def __next__(self):
        yield self.node
        for __ in self.nextSpatial():
            yield __
        for __ in self.nextTemporal('temporal'):
            yield __

```

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# More general iterator method with optional argument specifying tree type:
def next(self, treeType=None):
    yield self.node
    if treeType is None:
        for __ in self.nextSpatial():
            yield __
        for __ in self.nextTemporal('temporal'):
            yield __
    elif treeType=='spatial':
        for __ in self.nextSpatial('spatial'):
            yield __
    elif treeType=='temporal':
        for __ in self.nextTemporal('temporal'):
            yield __
    else:
        raise ValueError('Invalid treeType for tree')

# Spatial tree search
def nextSpatial(self, treeType=None):
    if self.firstSubhalo is not None:
        for __ in self.firstSubhalo.next(treeType):
            yield __
    if self.neighbour is not None:
        for __ in self.neighbour.next(treeType):
            yield __

# Temporal tree search
def nextTemporal(self, treeType=None):
    if self.firstProgenitor is not None:
        for __ in self.firstProgenitor.next(treeType):
            yield __
    if self.nextSibling is not None:
        for __ in self.nextSibling.next(treeType):
            yield __

# Printing
def printhead(self):
    print ('node,firstSubhalo,neighbour,firstProgenitor,nextSibling,hostHalo,descendant=')
def __str__(self):
    s1='1'
    if self.firstSubhalo: s1=str(self.firstSubhalo.node)
    s2='1'
    if self.neighbour: s2=str(self.neighbour.node)
    s3='1'
    if self.firstProgenitor: s3=str(self.firstProgenitor.node)
    s4='1'
    if self.nextSibling: s4=str(self.nextSibling.node)
    s5='1'
    if self.hostHalo: s5=str(self.hostHalo.node)
    s6='1'
    if self.descendant: s6=str(self.descendant.node)
    return str(self.node)+', '+s1+', '+s2+', '+s3+', '+s4+', '+s5+', '+s6

#-----------------------------------------------------------------------------------
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A5 To extract a tree from an HDF5 file

This example, extracttree.py, reads in an HDF5 file, then extracts some data for a particular tree into a structured numpy array.

```python
# Imports
import sys
import numpy
import h5py

# The tree module contains a class definition for a combined spatial and temporal tree
import tree

# Parameters
infilen='data/test.hdf5'
mode='r'

# Open Merger tree file for reading
fid = h5py.File(infilen, mode)

# Let's extract the data that we want from the HDF5 file.

treedata_dtype=numpy.dtype(
    ('haloID','int64'),
    ('descendant','int32'),
    ('firstProgenitor','int32'),
    ('firstSubhalo','int32'),
    ('hostHalo','int32'),
    ('neighbour','int32'),
)
```
# First let's extract the number of halos

gid = fid['/MergerTree']
nHalo = gid.attrs.get('NHalo')
print('nHalo =', nHalo)

# and now the link that we want. Without the [:] we get a pointer to the array.

haloID = gid.get('HaloID')[:]
descendant = gid.get('DescendantIndex')[:]
firstProgenitor = gid.get('FirstProgenitorIndex')[:]
firstSubhalo = gid.get('FirstSubhaloIndex')[:]
hostHalo = gid.get('HostHaloIndex')[:]
eighbour = gid.get('NeighbourIndex')[:]
nextSibling = gid.get('NextSiblingIndex')[:]
snapNum = gid.get('Snapshot')[:]
density = gid.get('Density')[:]
mass = gid.get('Mass')[:]

# Next we are going to construct a tree from the information contained in the HDF5 file
# This is only needed for trees that are not depth-first ordered, but it's a nice example of how to use iterators in python anyway. It uses the Tree class in the separate tree.py file.

# Initialise tree nodes...

# Trick: create an extra non-existent node to receive references to index -1 (= last index)

nodes = [tree.Tree(halo) for halo in range(nHalo+1)]
nodes[nHalo] = None

# Now we run through each of the halos extracting those pointers that we need for efficient tree traversal

for halo in range(nHalo):
    nodes[halo].load(nodes[firstSubhalo[halo]], nodes[neighbour[halo]], nodes[firstProgenitor[halo]], nodes[nextSibling[halo]], nodes[hostHalo[halo]], nodes[descendant[halo]])

# Let's pick a halo to act as the root of our tree.
# Ideally, we should use a full tree, but we only have one tree in this example.
# However halo 7 has consecutive indices in its subtree, so we'll use that.

root = 7

nodes[root].printheader()
nTreeHalo = 0
nodeMin = nodes[root].node
nodeMax = -1

for halo in nodes[root].next():
    nTreeHalo += 1
    nodeMin = min(halo, nodeMin)
    nodeMax = max(halo, nodeMax)
    print((nTreeHalo == 0, nTreeHalo, nodeMin, nodeMax))

print('nodeMin, nodeMax =', nodeMin, nodeMax)
# Now let's loop over the tree again, recording the data that we want in our table
# Create a numpy structured array to hold the table
# treedata=numpy.empty(nTreeHalo,dtype=treedata_dtype)
# ihalo=-1
# consecutive=True
# firstHalo=nodes[root].node
for halo in nodes[root].next():
    ihalo+=1
    if halo != firstHalo+ihalo: consecutive=False
    treedata[ihalo]=(haloID[halo],descendant[halo],firstProgenitor[halo],firstSubhalo[halo],
                    hostHalo[halo],neighbour[halo],nextSibling[halo],
                    snapNum[halo],density[halo],mass[halo])
print('Consecutive halos = ',consecutive)

# If we have a consecutive list of halos, adjust indices to point to the relevant location
# in our new table.
# Setting the maximum to -1 is not really necessary but helps to make things look tidier.
if consecutive:
    numpy.maximum(treedata['descendant']-nodeMin,-1,treedata['descendant']);
    numpy.maximum(treedata['firstProgenitor']-nodeMin,-1,treedata['firstProgenitor']);
    numpy.maximum(treedata['firstSubhalo']-nodeMin,-1,treedata['firstSubhalo']);
    numpy.maximum(treedata['hostHalo']-nodeMin,-1,treedata['hostHalo']);
    numpy.maximum(treedata['neighbour']-nodeMin,-1,treedata['neighbour']);
    numpy.maximum(treedata['nextSibling']-nodeMin,-1,treedata['nextSibling']);

# We have established that we have a consecutive (depth-first ordered) tree,
# so no need to bother with the Tree class again. Let's just dump the new
# properties in consecutive order as a check.
for ihalo in range(nTreeHalo):
    print(ihalo,treedata[['firstSubhalo','neighbour','firstProgenitor','
                           nextSibling','hostHalo','descendant']][ihalo])

# Or rather more simply, but in a different order
print(treedata)

#-----------------------------------------------

A6 To save a tree in the default format

Finally, we have an example of how to create an HDF5 file in the correct format. Because we need some data to write out, this example also
reads in data from an existing HDF5 file: in practice the data may have come from a mergertree creation algorithm.

"""dumptree.py
Example of how to write a merger tree in HDF5 format.
This example needs some data which it reads in from an existing HDF file,
which makes this whole exercise a bit pointless, but pretend that the data
was created some other way and now needs to be written out.
This is not complete, but it gives the general idea.
"""

#-----------------------------------------------
# Imports
# The following imports the python3 print function into python2;
# It seem to be quietly ignored in python3
from __future__ import print_function
import sys
import numpy as np

# The merger tree module contains data structures, methods and global variables
import mt

# Parameters
infile='data/test.hdf5'
outfile='data/dumptest_Python.hdf5'

# For the purposes of this example, we first have to read in some data.
# Actually, the following creates pointers to the data, to be read below.

mt_in=mt.MergerTree(infile, "r")
attributes = mt_in.attrs('/')

# Read in snap tables
snap_in=mt_in.read_snaptable()
snapprop_in=mt_in.read_snapprop()

# Read merger tree.

mt_in=mt.MergerTree(infile, "r")
attributes = mt_in.attrs('/')

# Read in snap tables
snap_in=mt_in.read_snap_table()
snapprop_in=mt_in.read_snapprop()
snap_attributes=mt_in.attrs("Snapshots")

# Read merger tree.
tree_in=mt_in.read_mergertree()
tree_attributes=mt_in.attrs("MergerTree")

# Now we are going to create a new HDF5 file to write out the data

print('Creating output file')
mt_out=mt.MergerTree(outfile,"w")
print('File =',mt_out.fid)

# Write out the top-level attributes

# Write out the top-level attributes
print('In group',mt_out.fid.name,'attributes are:')
for (name,value) in attributes:
    print('  ',name,value)
    mt_out.fid.attrs.modify(name,value)

# Create MergerTree directory and set attributes

tree=mt_out.fid.create_group("MergerTree")
print('In group',tree.name,'attributes are:')
for (name,value) in tree_attributes:
    print('name, value =',name,value)
    tree.attrs.modify(name,value)

# Write out merger tree datasets

print('MergerTree datasets:')
for dset in tree_in:
    # extract name, dtype and data from input dataset
    name=tree_in[dset].name
dtype=tree_in[dset].dtype
data=tree_in[dset][()]
attrs=tree_in[dset].attrs.items()

    # and now recreate in the output file
    dset=tree.create_dataset(name=name,dtype=dtype,data=data)
    print('  ',name)
print(' ',dset[0:9])
# and set attributes
for (name,value) in attrs:
    print(' ',name,value)
    dset.attrs.modify(name,value)

# Create Snapshot directory and set attributes
snap=mt_out.fid.create_group("Snapshots")
print('In group',snap.name,'attributes are:)
for (name,value) in snap_attributes:
    print(' ',name,value)
    snap.attrs.modify(name,value)

# Write out Snap table
# Tables require use of a complex dtype. Fortunately, that's already set up
# us here in the input file.
# Extract data and dtype from input file
name=snap_in.name
dtype=snap_in.dtype
nsnap=len(snap_in)
data=np.empty(nsnap,dtype=dtype)
for irow in range(nsnap): data[irow]=snap_in[irow]
# and recreate in output file
dset=tree.create_dataset(name=name,dtype=dtype,data=data)
print('Snap table:
print(' name =',dset.name)
print(' dtype =',dset.dtype)
print(' data =',dset[:])

# Write out SnapProp table
# us here in the input file.
# Extract data and dtype from input file
name=snapprop_in.name
dtype=snapprop_in.dtype
nsnapprop=len(snapprop_in)
data=np.empty(nsnapprop,dtype=dtype)
for irow in range(nsnapprop): data[irow]=snapprop_in[irow]
# Rename the Units property to lower case (for consistency).
# Cannot rename in place: have to make a copy of both dtype and data.
temp=dtype.__repr__()[6:-1]
temp=temp.replace("Units","units")
dtypenew=np.dtype(eval(temp))
print('dtypenew=',dtypenew)
datanew=np.empty(nsnapprop,dtype=dtypenew)
for irow in range(nsnapprop): datanew[irow]=data[irow]
# and recreate in output file
dset=tree.create_dataset(name=name,dtype=dtypenew, data=datanew)
print('SnapProp table:
print(' name =',dset.name)
print(' dtype =',dset.dtype)
print(' data =',dset[:])

# The output file is not yet a complete examle of the merger tree data
# format, but hopefully that is enough to illustrate how do do things.

# Close the files
mt_in.close()
mt_out.close()

#---------------------------------------------------------------