A Handy Tool for History Keeping of Geant4 Tracks
– J4HistoryKeeper –

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Abstract

The Particle Flow Analysis (PFA) is currently under intense studies as the most promising way to achieve precision jet energy measurements required at the future linear $e^+e^-$ collider. In order to optimize detector configurations and to tune up the PFA it is crucial to identify factors that limit the PFA performance and clarify the fundamental limits on the jet energy resolution that remain even with the perfect PFA and an infinitely granular calorimeter. This necessitates a tool to connect each calorimeter hit in particle showers to its parent charged track, if any, and eventually all the way back to its corresponding primary particle, while identifying possible interactions and decays along the way. In order to realize this with a realistic memory space, we have developed a set of C++ classes that facilitates history keeping of particle tracks within the framework of Geant4. This software tool, hereafter called J4HistoryKeeper, comes in handy in particular when one needs to stop this history keeping for memory space economy at multiple geometrical boundaries beyond which a particle shower is expected to start. In this paper this software tool is described and applied to a generic detector model to demonstrate its functionality.

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1 Introduction

The experiments at the International Linear Collider[1] will open up a novel possibility to reconstruct all the final states in terms of fundamental particles (leptons, quarks, and gauge bosons) as viewing their underlying Feynman diagrams. This involves identification of heavy unstable particles such as $W$, $Z$, $t$, and even yet undiscovered new particles such as $H$ through jet invariant-mass measurements. The goal is thus to achieve an jet invariant-mass resolution comparable to the natural width of $W$ or $Z$[2]. High resolution jet energy measurements will thus be crucial, necessitating high resolution tracking and calorimetry as well as an algorithm to make full use of available information from them. With a currently envisaged tracking system[1] that aims at a momentum resolution of $\sigma_{p_T}/p_T = 5 \times 10^{-5} p_T[\text{GeV}/c]$ or better, tracker information will be much more accurate than that from calorimetry for charged particles. This implies that the best attainable jet energy resolution should be achieved when we use the tracker information for charged particles and the calorimeter information only for neutral particles. This requires separation of calorimeter clusters due to individual particles and, in the case of charged particle clusters, their one-to-one matching to the corresponding tracks detected in the tracking system. This is the so-called Particle Flow Analysis (PFA) currently under intense studies[3].

For the PFA, it is hence desirable to have a highly granular calorimeter that allows separation of clusters due to a densely packed jet of particles. In practice the performance of the PFA depends not only on the hardware design of the detector system consisting of the tracker and the calorimeter but also on a particular algorithm one employs to separate calorimeter signals due to neutral particles from those due to charged particles. Various realistic algorithms are currently being tested by various groups[3].

For the optimization of detector configurations and the PFA algorithm, it is crucial to identify factors that limit the PFA performance and clarify the fundamental limits on the jet energy resolution that remain even with an infinitely granular calorimeter and an ideal algorithm to achieve perfect track-to-cluster matching. We hence need a tool to connect each calorimeter hit in particle showers to its parent charged track, if any, and eventually all the way back to its corresponding primary particle, while identifying possible interactions and decays that might have taken place along the way. In order to achieve this history keeping with a reasonable memory size, we need an algorithm to effectively achieve infinite calorimeter segmentation independently of the physical size of its readout cells as well as a mechanism to stop history keeping at various geometrical boundaries beyond which particle showering is expected.

We have developed a set of C++ classes that realize such a functionality within the framework of Geant4. We call this software tool J4HistoryKeeper hereafter, since it is the name of the central class of the package. Although J4HistoryKeeper was designed primarily for PFA studies, it has wider applications. It comes in handy in particular when one needs to stop history keeping for memory space economy at multiple user-registered geometrical boundaries. The software tool was implemented in a Geant4[6] based Monte Carlo simulator called JUPITER[4,5] and has been used successfully for PFA studies, together with a smearing and reconstruction package called SATELLITES[5], running under a modular analysis framework called JSF[7], both of which are based on ROOT[8]. The source code of a demo package of J4HistoryKeeper with slimmed up versions of JUPITER and SATELLITES is available from our ”J4HistoryKeeper Sample Code Page”[9].
In the following sections, we first elucidate the concept of Cheated PFA, which can be considered as the primary application that J4HistoryKeeper is designed for. We then describe the software tool to keep history of particle tracks (Geant4 tracks) traced through a detector in Geant4 with emphasis put on its design philosophy. The subsequent section is devoted to its usage with a sample application to a generic ILC detector model to demonstrate its functionality.

2 Concept of Cheated PFA

In principle Monte Carlo simulations allow us to use so-called Monte-Carlo truth and enable us to unambiguously separate calorimeter hits due to different incident particles, thereby performing perfect clustering. By linking so-formed calorimeter clusters to corresponding charged particle tracks in the tracking system again using Monte-Carlo truth, we can achieve the situation with the perfect PFA. We call this Cheated PFA (CPFA) since it involves cheating by using Monte-Carlo truth, which is impossible in practice. The concept of the CPFA is detailed in this section so as to clarify the philosophy behind the design of the software tool.

2.a Perfect Clustering and Perfect Track-Cluster Matching

For the CPFA, the history of Geant4 tracks should be kept on a track-by-track basis starting from a primary track at the interaction point. The history of all the secondary tracks together with the original one should be recorded until they hit any one of pre-registered boundaries beyond which particles may start showering. At such a boundary we create a virtual hit called PHit. Calorimeter hits by Geant4 tracks in a particle shower will then be tagged with this PHit. By collecting all the calorimeter hits with the same PHit we can hence form a calorimeter cluster without any confusion (see Fig.1).

Since the PHit carries the information of its parent track, one-to-one matching between the calorimeter cluster and its corresponding charged particle track in the tracking system is possible. Once matched, we just lock the calorimeter cluster as linked to a charged track and just use the tracker information. Calorimeter clusters with no matching charged tracks are hereafter called neutral PFOs, while all the charged tracks are called charged PFOs regardless of whether there are corresponding calorimeter clusters or not.

It is also important to record the mother-daughter correspondence for particles decayed in a tracking volume so as to estimate their effects on the PFA performance. The mother-daughter correspondence is book-kept together with the other information on the daughter track such as its particle ID, position, and momentum, in a so-called BreakPoint object which is created at the beginning of each track. The information stored in the BreakPoint objects will be used to follow particle decays observed as kinks or V0's in the tracking volume and to assign correct particle masses to charged PFOs. This bookkeeping comprises the major role of the history keeper.

2.b Infinite Calorimeter Segmentation

For a realistic calorimeter design, the granularity of the calorimeter, or equivalently the cell size, is finite and hence the signals created by shower particles stemming from different parent
particles sometimes merge into a single hit degrading the cluster separation capability. In order to investigate to what extent this limits the PFA performance, we need to know the performance expected for perfect cluster separation. It is, however, impracticable to implement infinitely fine segmentation even in a Monte Carlo detector simulator because of memory space limitation. In order to overcome this drawback, we exploit the following trick.

In each hit cell, say cell $i$, we separately store the energy sum of hits originating from the same PHit:

$$E_i^c = \sum_j E_{i,j}$$

and their center of gravity:

$$x_i^c = \sum_j E_{i,j} x_{i,j} / E_i^c,$$

instead of using the cell center as the hit position. In the above expression $E_{i,j}$ and $x_{i,j}$ are the energy deposit and the position of $j$-th hit in cell $i$ with the same PHit. Denoting the total energy of the cluster originating from the same PHit by

$$E^c = \sum_i E_i^c,$$

we can then calculate its cluster center as

$$x^c = \sum_i E_i^c x_i^c / E^c = \sum_i \sum_j E_{i,j} x_{i,j} / \sum_i \sum_j E_{i,j},$$

showing that the center of gravity calculated this way precisely coincides the one would-be obtained when the segmentation is infinitely fine. It should be also emphasized here that hits from different PHits make multiple centers of gravity in the same cell, which can be later separated even though they are in the same cell, thereby realizing the infinite segmentation in effect.

Figure 1: Schematics showing the cheated PFA concept. Only two cells in a single sampling layer of the calorimeter are shown to simplify the picture though in practice much more cells are expected to be hit over different sampling layers.
3 Tool Design

Before coding our tool for history keeping, we set the following guideline to fulfill the required functionality discussed in the last section: a) there must be a versatile mechanism to register user-defined physical volumes whose specified boundaries can be used to define a PHit that marks the source point of a particle shower, b) whether a track is allowed to create a PHit or not depends on whether the track originates from any pre-created PHit or not, which should be checked on a track-by-track basis at the beginning of its tracking, c) the history keeping is to be done on the track-by-track basis by creating a BreakPoint object at the beginning of each track if there is no PHit from which the track stems, and d) the history keeping should be realized making maximum use of existing Geant4 facilities within the framework of JUPITER, e) JUPITER should produce Monte-Carlo truths (i.e. exact hits) and their smearing should be done later in SATELLITES as needed.

The following is a sketch of the tool design we adopted according to the guideline:

1. The history keeping is to be done on the track-by-track basis using J4TrackingAction that inherits from G4UserTrackingAction. Its PreUserTrackingAction method is hence called at the beginning of a new track. The PreUserTrackingAction method serially invokes PreTrackDoIt method of each offspring of J4VSubTrackingAction pre-registered to the J4TrackingAction object. Likewise, its Clear method serially invokes Clear method of individual offsprings of J4VSubTrackingAction.

2. J4VSubTrackingAction is an abstract class that serves as a base class for user-defined sub-actions taken by J4TrackingAction thereby extending the G4UserTrackingAction functionality. It has a method called Clear to reset the object state.

3. J4HistoryKeeper is implemented as a derived class from J4VSubTrackingAction and, in its PreTrackDoIt method, scans through a collection of pre-registered J4PHitKeeper objects corresponding to a collection of bounding surfaces. It then creates a J4BreakPoint object if none of them has been hit by any ancestors of the new track.

4. J4PHitKeeper also inherits from J4VSubTrackingAction. Its PreTrackDoIT method checks if this new track is stemming from any pre-created PHit, and, if not, resets its state to allow creation of a new PHit. When its corresponding boundary is hit by the current track, a PHit object is created, if it is allowed, to tag subsequent daughter tracks possibly created in a shower.

The flow of tracking related to J4HistoryKeeper is shown in Fig. 2.

3.a Extension of G4UserTrackingAction

The G4UserTrackingAction class provides one with a handy tool to perform a user-defined action on a track-by-track basis. In its original form, however, it allows only a single action. In order to extend its functionality to accept multiple user-defined actions, we have introduced the concept of SubTrackingAction as sketched above.
Figure 2: The flow diagram for Geant4 tracking related to J4HistoryKeeper.
The abstract base class J4VSubTrackingAction has the following methods:

```cpp
void PreTrackDoIt(const G4Track *aTrack = 0) = 0
```
which is pure virtual and to be implemented by its derived class to take a sub-tracking action for the given track.

```cpp
void Clear()
```
which does nothing, and to be overridden in the derived class as needed.

This class just specifies the interface and requires its users to implement the methods listed above.

**J4TrackingAction**

The J4TrackingAction class is a singleton inheriting from G4UserTrackingAction. It has, among others, an STL vector as a data member to store pointers to objects derived from the J4VSubTrackingAction class. Its major methods include the following:

```cpp
static J4TrackingAction *GetInstance()
```
which returns the pointer to the single instance of J4TrackingAction.

```cpp
void Add(J4VSubTrackingAction *aSta)
```
which registers a user-defined object derived from J4VSubTrackingAction. When *aSta has already been registered, the pre-registered one is erased and the new entry is appended.

```cpp
void PreUserTrackingAction(const G4Track *aTrack)
```
which loops over the registered offsprings of J4VSubTrackingAction and invokes their PreTrackDoIt methods.

```cpp
void Clear()
```
which loops over the registered offsprings of J4VSubTrackingAction and invokes their Clear methods.

The class diagram for J4TrackingAction and J4VSubTrackingAction is shown in Fig. 3.

### 3.b P-Hits and P-Hit Keeper

PHit is a generic name for a Pre-Hit or a Post-Hit, which stands for a virtual hit created on a boundary of a G4PhysicalVolume beyond which particle showering is expected. The PHit creation is done in the user-overridden ProcessHits method of a user-defined virtual detector derived from G4SensitiveDetector corresponding to the physical volume. Notice that PHits are created for all kinds of particles, even neutrinos, that pass through the boundary. One PHit class is defined inheriting from the J4VTrackerHit class for each such boundary. The J4VTrackerHit class carries basic track hit information such as track ID, particle ID, position, momentum, TOF, energy deposit, etc. and setters and getters to access them. An individual PHit class has a data member to store PHit ID and a static data member to store the current PHit ID, which can be retrieved by a static method to mark calorimeter hits as needed. The class diagram for J4VTrackerHit, J4PHitKeeper, and related classes is shown in Fig. 4.
**J4PHitKeeper**

The *J4PHitKeeper* class inherits from *J4VSubTrackingAction*. It serves as a base class for a *PHitKeeper* class defined for an individual *PHit* class corresponding to a boundary beyond which particle showering is expected. The *J4PHitKeeper* class has data members to store i) the current incident track ID (*fInTrackID*) that is expected to create or has already created a *PHit*, ii) the track ID (*fTopTrackID*) of the next track to be processed, if any, after the offsprings from the *PHit* are exhausted, and iii) a flag (*fIsPHitCreated*) to tell whether a *PHit* has been created or not. The major methods of *J4PHitKeeper* are listed below:

```cpp
void PreTrackDoIt(const G4Track *)
```

This implements the corresponding base class pure virtual method so as to reset *fInTrackID* and *fTopTrackID* to `std::numeric_limits<int>::max()` and *fIsPHitCreated* to `false` upon encountering a new track which has a track ID smaller than *fTopTrackID*.

```cpp
G4bool IsNext()
```

This returns `false` if a *PHit* has already been created. If not, it updates *fInTrackID* and *fTopTrackID* and returns `true` to tell the caller (the *ProcessHits* method of the sensitive detector defining the virtual boundary) that a new *PHit* is to be created.

```cpp
void Reset(G4int k = std::numeric_limits<int>::max())
```

This resets *fInTrackID* and *fTopTrackID* to `k`.

```cpp
G4bool IsPHitCreated()
```

This returns `fIsPHitCreated`, which is `true` if a *PHit* has been created, and `false` otherwise.

The algorithm of *J4PHitKeeper* heavily depends on Geant4’s default track stacking scheme, which is worth explaining here for readers unfamiliar with it. By default Geant4 uses two types of track stacks, a Primary Stack (*PS*) and a Secondary Stack (*SS*).

At the beginning of each event, primary particles 1, ⋯, *n* are pushed into *PS*. According to the ”last in first out” rule, the top entry, track *n*, is popped out for tracking. Notice that there remains *n* − 1 tracks in *PS* at this point. All the secondary particles produced while track...
\( n \) is being processed are pushed into \( SS \). Let us assume that there will be \( m \) secondary particles stacked into \( SS \) by the time track \( n \) is disposed of. All of these \( m \) secondary particles in \( SS \) are moved to \( PS \) upon the death of track \( n \) and numbered serially as tracks \( n+1, \ldots, n+m \). Notice that there are \( n+m-1 \) tracks in \( PS \) at this point since track \( n \) has been popped out and disposed of.

The key point is to bookmark the secondary track which is to be created just after the creation of a \( \text{PHit} \) by the track which has been being processed, track \( n \) in the present case. The track ID with the bookmark will be \( f\text{TopTrackID} = n+k' + 1 \) where \( k' (\leq m) \) is the number of secondary particles in \( SS \) at the time of the \( \text{PHit} \) creation. Further \( \text{PHit} \) creation is to be forbidden until it becomes necessary.

The top of the stack, track \( n+m \), is popped out and to be processed as before. Track \( n+m \) will produce further \( m' \) secondary particles to be pushed into \( PS \) upon its death and to be numbered as tracks \( n+m+1, \ldots, n+m+m' \).

This procedure is repeated and after some time all the secondary particles originating from the track created the last \( \text{PHit} \) will be disposed of and the next track to be popped out from \( PS \) will have a track ID that is smaller than that of the last bookmarked one, \( f\text{TopTrackID} \). This signals a new incident track which is allowed to create a new \( \text{PHit} \). By repeating this procedure until all the tracks in \( PS \) are exhausted, we can mark all the calorimeter hits with corresponding \( \text{PHits} \).

### 3.c Break Points and History Keeper

The purpose of the history keeper is to allow us to trace back to kink and \( V^0 \) particles that decay before entering calorimeters so as to correctly link clusters to tracks. As sketched above, the his-
tory keeper is implemented as a `J4VSubTrackingAction` so as to create a `J4BreakPoint` object for each new track until a `PHit` is created on any of the pre-registered boundaries beyond which particle-showering is expected. The class diagram for `J4BreakPoint` and `J4HistoryKeeper` is shown in Fig. 5.

![Class diagram for J4HistoryKeeper and J4BreakPoint.](image)

**J4BreakPoint**

The `J4BreakPoint` class has data members to store the information about a track at its starting position such as track ID (`fTrackID`), parent track ID (`fParentID`), charge, particle ID, time, position, 4-momentum, etc. In addition it has a static data member called `fgBreakPointMap`, which is an STL map that links track ID to a `J4BreakPoint` object. Besides the getters to these data members, `J4BreakPoint` has the methods listed below:

```cpp
static J4BreakPoint *GetBreakPoint(G4int trackID)
    returns the pointer to the J4BreakPoint object corresponding trackID.

static void Clear()
    clears the track-to-break-point map.
```

**J4HistoryKeeper** 


The **J4HistoryKeeper** class is a singleton that inherits from **J4VSubTrackingAction**. It has an STL vector (**fPHitKeepers**) as a data member to store registered **J4PHitKeepers** that correspond to boundaries beyond which particle-showering is expected. As sketched above, it scans through these pre-registered **J4PHitKeeper** objects to make sure that none of them has a **PHit**, and then creates a **J4BreakPoint** object. The major methods of **J4HistoryKeeper** are listed below:

- **static J4HistoryKeeper *GetInstance()**
  returns the pointer to the single instance of **J4HistoryKeeper**.

- **void PreTrackDoIt(const G4Track *)**
  implements the corresponding base class pure virtual method. It scans through the pre-registered **J4PHitKeeper** objects in **fPHitKeepers** to make sure that none of them has a **PHit** by calling their **IsPHitCreated()** method. It then creates a **J4BreakPoint** object.

- **void Clear()**
  calls **J4BreakPoint::Clear()**.

- **void SetPHitKeeperPtr(J4PHitKeeper *aPhk)**
  pushes back the input **J4PHitKeeper** pointer into **fPHitKeepers**.

**S4BreakPoint**

Upon the completion of Monte Carlo truth generation by JUPITER, each **J4BreakPoint** object is copied to its SATELLITE dual, an **S4BreakPoint** object. The **S4BreakPoint** object inherits from ROOT’s **TObjArray** and stores pointers to its daughter **S4BreakPoints**, if any. It has additional methods such as

- **void LockAllDescendants()**
  which flags all of its descendants as locked. This functionality proves handy to avoid double counting of energies.

- **TObject *GetPFOPtr()**
  which returns the pointer to its corresponding Particle Flow Object (PFO), if any.

- **void SetPFOPtr(TObject *aPfo)**
  which is the setter corresponding to **GetPFOPtr** to be invoked from a PFO maker.

The class diagram for **S4BreakPoint** is shown in Fig. 6.

### 4 Tool Usage

What a tool user has to do for the history keeping is as follows:

- Inheriting **G4SensitiveDetector**, create a sensitive detector class, say **J4XXXSD**, that corresponds to a boundary on which a **PHit** object (**J4XXXPHit**) is to be created for each particle that is expected to produce a shower beyond that boundary.
Inheriting J4PHitKeeper, create a J4XXXPHitKeeper as a singleton to book-keep J4XXXPHits.

In J4XXXSD’s constructor, do

```cpp
J4XXXPHitKeeper *aPhk = J4XXXPHitKeeper::GetInstance();
J4TrackingAction::GetInstance()->Add(aPhk);
J4TrackingAction::GetInstance()->Add(J4HistoryKeeper::GetInstance());
J4HistoryKeeper::GetInstance()->SetPHitKeeperPtr(aPhk);
```

in order to register the J4XXXPHitKeeper to J4TrackingAction and to J4HistoryKeeper.

In J4XXXSD’s ProcessHits(···) method, do

```cpp
if (J4XXXPHitKeeper::GetInstance()->IsNext()) {
    // create and store a J4XXXPHit object
}
```

In ProcessHits(···) of each calorimeter sensitive detector, which usually corresponds to a single calorimeter cell, store the centers of gravity and energy deposits of particles from different PHits as different calorimeter hits even in the same cell and mark them with the current PHit ID obtainable from an appropriate J4PHitKeeper object.

This ensures the history keeping to be continued until any one of the pre-registered boundaries is hit and beyond which the calorimeter hits are marked with the PHit ID put to the PHit created on that boundary.

As an example of J4HistoryKeeper application, a typical multi-particle event detected with a generic $e^+e^-$ collider detector model is shown in Fig. 7. It is an $e^+e^- \rightarrow q\bar{q}$ event at the center of mass energy of 350 GeV. Circles in the figure indicate, from outside to inside, the outer and the inner boundaries of the barrel calorimeter, and the inner wall of the central tracker, a Time Projection Chamber (TPC), respectively. The calorimeter inner radius of 210 cm sets the scale of the detector model. Both the tracker and the calorimeter are placed in a solenoidal magnetic field of 3 Tesla. Using the J4HistoryKeeper package, calorimeter signals are matched to their corresponding track signals and are painted with the same color. With
J4HistoryKeeper, the centers of gravity of the calorimeter signals can be calculated as with infinite segmentation, which proves extremely useful in investigating the ultimate performance of the detector system with infinitely granular calorimetry.

Figure 7: A typical $e^+e^- \rightarrow q\bar{q}$ event with a hard gluon emission at the center of mass energy of 350 GeV, viewed from the beam direction. Matching calorimeter and tracker signals are identified by using the J4HistoryKeeper package and painted with same colors. Three circles indicate, from outside to inside, the outer and the inner boundaries of the calorimeter, and the inner wall of the TPC. Points inside the TPC inner wall are signals by silicon trackers.

5 Conclusion

We have developed a software tool, J4HistoryKeeper, for history keeping of Geant4 tracks. J4HistoryKeeper records history of Geant4 tracks starting from the interaction point until they reach any of user-registered geometrical boundaries. The tool allows us to record their positions, momenta, trackIDs, TOFs, etc. at their birth points as well as at the user-registered boundaries. The flexible registration capability of the user-given boundaries and a mechanism to achieve effectively-infinite segmentation with a finite readout cell size comprise the core features of the package. These features provide J4HistoryKeeper with wider applications though it has been designed primarily for PFA studies. The package comes in handy in any application where history keeping is necessary but particle showering and consequently memory need explosion
are expected beyond multiple boundaries of a complicated detector geometry. The tool has been used for the so-called Cheated PFA to investigate limiting factors and ultimate performance of jet energy measurements at the future linear $e^+e^-$ collider.

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