Objected Oriented program examples for High Energy Physics reconstruction

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Abstract

A number of Object Oriented example programs based on High Energy Physics event reconstruction are worked out.


1 Introduction

This report presents a set of Object-Oriented (OO) programs that should help the reader to design OO programs for High Energy Physics reconstruction. The writing of these examples seems appropriate at a moment that a large group of people is leaving the FORTRAN language and embrace the OO concepts [Boo94]. Talking with people shows that the step from FORTRAN to C++ [Str97] is easily made. Positive comments on C++ usually concern the pointer handling in C++. Most people that start with OO design are looking for a guide for choosing the appropriate classes. The creation of a class specification that later hides many implementation details is not easily understood. It is difficult to give reasons why one design is better than another (motivation of the design).

Apart from the performance and functional aspects of the software product other aspects can be important as well. OO languages and techniques are generally recognised to be a better vehicle to guarantee several non-functional aspects (e.g. adaptability, modularity).

OO languages facilitate the modelling of real-world objects. This makes it easier to verify that specifications meet the requirements. The step from loose requirements to specification is smaller. However, the accompanying design needs more thought to meet the more detailed and complex specification.

OO languages help to hide tedious implementation details. The resulting software can therefore, with less side effects, be modified at a few well defined places. Extension of the software is more easily possible because the language helps in creating objects with small interfaces thus limiting the number of places where code must be adapted or extended.

A method needs to be found to bridge the gap between the C++ programmer and the OO designer. The first knows how to make a working C++ program, the second knows how to create a set of classes and objects that meet several non functional constraints (such as: different implementations are supported, classes can be reused in other programs). The courses by Kunz are well appreciated by most and give a manual for the language. They provide a limited insight in the design process. The CERN recommended books on software design comprise the most up to date and yet accepted reading material. However, the existing literature does not seem to be convincing to the physicist. A reason can be that the cited examples and constraints are not felt to be significant to the physicist’s problems. It was therefore thought advisable to create a set of examples that are recognised as relevant examples. Several implementations should be provided for these examples. Disadvantages and advantages of the different designs should be pointed out. The elaboration of examples that refer to the patterns in the book Design Patterns [GHJV94] seemed reasonable. The use of the STL library [MS96] was recommended.

The method adopted here is to start with a simple example, provide a simple solution and then complicate the problem or extend the boundary conditions. Examples were found by listening to presentations by persons from different projects within CMS.

The following examples are worked out in this report:

1. **SiBT [ea96] calibration** Good opportunities for layering and abstraction are introduced by looking at aspects of the detector that need to be hidden to the different software components.

2. **Detector layers** A complex set of complex objects with a structure that should support efficient track recognition can be proposed. The opportunity for using STL is exploited.

3. **Local pattern recognition (in progress)** An application of the open-closed principle as elaborated for CMS reconstruction.

4. **Reconstruction algorithm versions (not done)** The Ecole Polytechnique people introduced the concept of sheets to cater for different versions of the algorithms. The introduction of a pattern from [GHJV94] seems advisable.

The readers are assumed to be familiar with the Object Methodology Tool (OMT) notation used for the Rational/Rose tool. Explanations of the meaning of class diagrams and scenario diagrams are not provided. The reader is assumed to have read the Booch book on the subject.

The software described in the examples is available. Exercises are specified to assist the reader in trying different design issues. The best way to learn handling a new technique is by applying the rules and see what they do for you.

The number of comments in the code have been kept low. Quite a lot of the code is described in the text and the comments in the code only help to focus the attention of the reader. In principle every method should have a header
that describes the purpose of the method and its pre- and post- conditions. This is not done for the same reasons. Entry assumptions are usually described in the text and the end results of the method as well.

The main purpose of these examples is to show possible class structures. No emphasis is placed on finding fast track fitting algorithms or complex detector structures. Therefore, the examples only use simple straight line fits and detectors with a simple geometry.

Layering is a well known and important technique to structure the software. The software is divided in layers. Each layer uses the facilities of the layer immediately below. A layer does not see the implementation of this layer or the facilities of the layers that are lower. Each layer delivers higher level abstractions than the layer below. Layering is one of the issues in the presented examples.
2 SiBT example

The first example is based on the work associated with the Silicon Beam Telescope (SiBT) that is developed by the Helsinki Institute of Physics. At the time of writing, SiBT is installed at CMS/H2 testbeam at CERN. It was chosen because at that time the conversion from Geant3 to Geant4 was undertaken and the design issues related with the associated SiBTOO software are also met in the context of CMS reconstruction software.

2.1 SiBT description

The telescope is built on an optical precision bench. The telescope consists of 8 assemblies of silicon detector strips called planes. The planes are placed in pairs such that one plane of a pair is aligned horizontally and the other plane is aligned vertically. The plane pairs are evenly spaced and the distance between the first and the last plane is approximately 50 cm.

Silicon Beam Telescope (SiBT)

Fig. 1 (not on scale) explains the basic SiBT properties. A particle passing SiBT from front to end excites the silicon strips through which it passes, thus provoking an electronic signal from the crossed strip and some of its neighbours depending on the particle energy and momentum. In Fig. 1 the first plane is vertically aligned and the second plane is horizontally aligned. The signals recorded in the vertically (horizontally) aligned planes with horizontal (vertical) strips inform about the y- (x-) coordinate of the intersection of the particle trajectory with the plane.

A strip provides two digital numbers: a noise and a signal number. The noise relates to the signal level when no particles pass. The signal is a measure for the excitation of the strip by a particle. The decision whether a particle has excited a strip is based on the signal/noise ratio that should be larger than a plane dependent constant. The criterion for the passage of a particle is given by: at least two neighbouring strips have the required signal/noise ratio. The track of a particle is determined by the measured excitations of the silicon strips. A sequence of three to four horizontal measurements is called a horizontal projection and a sequence of three to four vertical measurements is called a vertical projection.

The planes are carefully aligned. However, small misalignments may subsist. These are measured during a calibration session. A set of measurements of well defined particle tracks is used. Through each set of track measurements a straight line is fitted. For each plane the difference between the measured interaction coordinate and the point where the fitted line crosses the plane is determined. Statistics on the differences are done to establish the realign-
ment coordinates of the individual planes.

## 2.2 Analysis

![Class diagram based on SiBT analysis](image)

SiBTOO is the model of the SiBT detector written in an object oriented language (C++). SiBTOO has a certain configuration. A number of planes (8) at given positions are composed of a number of strips (1024). A plane has a horizontal or vertical orientation determined by the orientation of the strips. Above, a class diagram based on the analysis of the problem domain is presented. The analysis is based on the physical lay-out of SiBT and the following two use-cases: Find tracks and Calibrate SiBT.

1. **Find tracks** An event consists of a set of acquisition values generated by SiBTOO or read from disk (off-line case, simulation) or recorded by SiBT (on-line case). All acquisition values are associated with strips that can be activated by the passage of one or more particles. Activated strips are recognised by the acquisition values. A hit is represented by a strip of which the value satisfies a number of criteria. Neighbouring hits of the same plane are combined to a Cluster. Clusters from planes with the same orientation are combined to a candidate projection. A projection is a candidate projection of three to four clusters through which a straight line can be fitted. A track is the combination of two projections, one from each orientation. Per event one or zero tracks are returned. Difficult to solve ambiguities arise when more than one track is created. For simplicity reasons this is not addressed.

2. **Calibrate SiBT** A set of tracks is used to determine the best alignment constants for the eight planes of SiBTOO. A number of times the following calibration procedure is done. A straight line is fitted through all tracks of the set. For every track from the set for every plane the difference between the cluster coordinate and the straight line coordinate is calculated. The mean and the deviation of the offsets of a given plane over all tracks are calculated. From these values an improved set of alignment constants is calculated.
The above two use-cases and the structure of SiBTOO lead to the identification of a certain number of classes and their associations shown in Fig. 2.

While defining the classes, one should keep in mind that some boundary conditions exist: the configuration of SiBTOO can change, the calculation of projections can change, the track finding and line fitting can change. The calibration can change. Instead of at most one track, several tracks can be returned. The off-line treatment of SiBTOO should resemble the on-line SiBTOO as much as possible.

2.3 Design

The scenario diagrams are used to show where the responsibilities are put for the different classes identified above. The objective is to hide as much as possible unnecessary details concerning a given class from the other classes. *Main* is the actor for the use-cases mentioned above. A first design decision is to hide the structure of SiBTOO from *Main* that provides the acquisition values received from the equipment. The SiBTOO class is made responsible for the calculation and assignment of values to the strips as defined by the acquisition values stored in Event. In this way modifications in the SiBTOO hardware are hidden to *Main*.

**Track fitting** To have close resemblance with the on-line case, SiBTOO is modelled to receive one event at the time and find the tracks corresponding with the event. In the off-line case a set of events can be calculated or fetched from a storage medium after which SiBTOO is invoked once for every event from the set.

Because planes differ in orientation, offsets and possibly the number and quality of strips can differ, SiBTOO distributes the unmodified acquisition values of the events over the planes. Acquisition values contain encoded results of SiBTOO. Per strip, the noise and signal values are stored. At some time in the future the event contents can be changed. For example, instead of returning the acquisition values of all strips, only activated strips are returned by the hardware and the acquisition values must contain the strip and plane identifier. The planes calculate the individual strip values and assign them to the strips. Differences between planes are localised to the plane and not visible to SiBTOO as a whole.

![Scenario for track fitting](image)

Figure 3: Scenario for track fitting

A scenario for track fitting is shown in Fig. 3. This represents one of a set of possible scenarios. This one is chosen as a first possibility based on some design criteria explained below. Design decisions concern the choice of classes that contain cluster recognition code. Clusters could be recognised by the plane or by SiBTOO. In favour of SiBTOO is: clusters from different planes need to be visible to the whole of SiBTOO to later create projections. In favour of the plane is: each plane has a specific orientation and delivers either a horizontally or vertically projected cluster; consequently, there are two types of clusters as there are two types of planes (horizontally and vertically aligned). We choose the plane for the location of the cluster calculation code. This implies that the Cluster class must be defined such that they contain sufficient information to construct a track. In this design, alignment and conversion factors are hidden in the planes responsible for creating the clusters. The location of identified clusters
Clusters are calculated from the plane- and strip-characteristics and represent a point in space. The cluster contents is based on the needs for projection and track recognition in a Cartesian coordinate system independent of SiBTOO geometry. The appropriate geometry of a track, line, circle or helix can be chosen independent of the SiBTOO properties. Information about the size of the cluster and the intensity of the signal must be foreseen for later extensions when more than one track may pass through a plane and a cluster can represent the passage of one or more particles.

The SiBTOO object takes all clusters from either the horizontal or the vertical planes and creates horizontal and vertical projections. All possible combinations of clusters from four or three different planes with the same orientation are tried. Two possibilities are immediately obvious: (1) the projection finds the appropriate (vertical or horizontal) planes and selects a given cluster from each plane and (2) SiBTOO selects all possible clusters combinations from the planes and creates a projection with as parameter the selected cluster set. During the development of the program a third possibility was implemented. A projection-list is created with as parameter the set of horizontal or vertical planes. The projection-list creates as many projections as there are combinations of three or four clusters belonging to different planes with the same orientation. This choice allows to encapsulate the cluster selection for projection finding into one class and makes the cluster independent of the plane layout or plane characteristics.

The Valid method of the projection returns True if it can fit a line through the clusters.

To create a projection from the clusters stored inside the planes, the following design is proposed. The location of the cluster can be fixed inside the planes. The clusters in the plane are ordered in a list. By asking a plane for the current or next cluster, all possible combinations of clusters, one from each plane can be stored into projections (lists of clusters). SiBTOO creates a projection-list. The projection list creates projections to which clusters from different planes are added. Each projection tests whether the proposed cluster list is a valid one by fitting a line through them.

All valid projections are combined to all possible tracks by selecting all possible pairs of horizontal and vertical projections. One single track is returned to Main if one vertical and one horizontal projection is found, otherwise a set of zero tracks is returned to Main. Extensions for the return of more tracks will be considered for the design but are not actually implemented.

The track finding algorithm is hidden from Main. Cluster determination is hidden from SiBTOO thus catering for plane dependent cluster calculations.

The current design has consequences for the initialisation. When SiBTOO is activated with new acquisition values and new strip values, references to formerly calculated clusters, projections and tracks must be removed.

Figure 4: Scenario for calibration
Calibration  A scenario for calibration is shown in Fig. 4. Main asks SiBTOO to calibrate itself with a set of tracks. The decision is taken to store statistics on differences between fitted lines and the measured clusters within the associated plane. This enables the use of plane dependent weight factors or to execute plane dependent calculations. Before calibration starts, statistics calculated during a former calibration round must be removed. For each track in the set of tracks, each projection is asked to calculate the difference between the fitted line and the clusters of which the projection is composed. The plane that corresponds with a cluster is found and the deviation is added to the plane statistics.

Once all tracks are done, SiBTOO acquires the statistic results, calculates alignment improvements and communicates them to the planes. After the calibration, Main stores the returned calibration constants in a database.

Another way (not shown here) to perform calibration is to split the invocation of SiBTOO in three parts. In the first part SiBTOO is initialised for calibration and all former statistics are removed. In the second part, Main invokes SiBTOO with Calibrate for every single track. In the third part, Main must invoke SiBTOO to determine the deviations. Based on their values, Main can restart the calibration for the set of tracks or store the values in the database. There are no good arguments on the basis of the available knowledge to determine whether one of the two designs is superior to the other.

2.3.1 Tentative class definitions

The above analysis and responsibility allocation permits us to do a more detailed design of the classes. In fig. 2 classes and associations are shown but no suggestion about the realization of these associations is done. From the scenarios above the association between some classes can be designed with the appropriate language facilities. During the realization of the classes, improvements and modifications are needed. The design in this section represents a first effort not hindered by implementation details. The classes of the final design presented in section 2.4 differ slightly from the here presented classes.

Within SiBTOO an array of 4 horizontal and 4 vertical Plane objects can be defined. Within a Plane an array of 1024 Strip objects can be defined. Planes are not visible outside SiBTOO and strips are not visible outside a Plane object. Arrays are chosen because the number of planes and strips is relatively fixed and changes only after elaborate hardware modifications. The cluster is a number of contiguous strips that have a value higher than a given threshold. Although shown in the analysis (see Fig. 2), no need for the introduction of a Hit class exists. A Cluster class contains a variable number (> 1) of strips. The actual strips are not important to the cluster. The position of the strips associated with a cluster contains enough information for the track calculation.

In Fig. 5 the classes with their methods and attributes as needed so far are shown.

SiBTOO  The SiBTOO class has an interface that is the interface between all classes defined within SiBTOO and the SiBTOO invoking classes (in this case Main). Three public methods are defined Create, FindTracks and Calibrate. Apart from Create, the interface is completely determined by the two scenarios. Create initialises SiBTOO and determines all hardware determined numbers within SiBTOO. Private attributes are the set of horizontal and vertical planes and the set of horizontal and vertical projections. The set of reconstructed tracks is returned as a parameter by FindTracks.

Plane  The Plane is clearly the most complex class. It contains information about its position (Coordinates), the deviations calculated during the calibration efforts (Statistics), conversion factors (Alignments), equipment (StripArray) and measurement results (ClusterSet). All these attributes are hidden. A set of public methods is delivered to manipulate the Plane contents. The Create routine sets all hardware and position parameters that do not change. The alignments are set to zero and are later determined by doing a calibration. The orientation of the plane is determined at the creation of SiBTOO by assigning a plane to either the set of horizontal or the set of vertical planes. The Assign method is used to assign a set of values to the Strips based on the measurements contained in the ChannelSet parameter. As shown in the track fitting scenario once the strip values are determined the new clusters can be calculated. It is possible that more than one cluster is measured. The clusters are stored in a certain order. The method First returns the first cluster and the method Next returns the consecutive Cluster or null when no more clusters follow the last returned one. The method Current returns the last Cluster returned from SiBTOO by former invocations to Next and First. Projections are made of all possible cluster combinations of three or four horizontal or vertical planes.
Figure 5: Association realizations

The calibrate scenario necessitates some additional methods. Statistics are gathered within the plane about the deviations calculated over a set of tracks. The routine \texttt{ClearStatistics} is needed to clear the results of a former calibration. The method \texttt{AddDeviation} adds a new deviation to the plane as calculated from the track fit. The method \texttt{Get} returns the result of all gathered statistics. The method \texttt{StoreAlignment} specifies the alignment that is calculated for this plane.

\textbf{Strip} \hspace{1em} The Strip class is intimately linked with the Plane class. The noise level, the value and the coordinates are implemented as public attributes for fast access within Plane. When, in a later stage, the event contents are modified, these attributes can be replaced with methods that calculate the corresponding values. A Strip needs to be created with the \texttt{Create} method. The \texttt{Assign} method takes the encoded value given as parameter, computes noise and signal value and stores them into the Strip attributes.

\textbf{Event, ChannelSet} \hspace{1em} Both classes are composed of arrays of integers in which strip- and noise values of the Strips are encoded. Each has a public routine \texttt{Get}. \texttt{Event.Get(index)} returns the ChannelSet belonging to the Plane identified by the index parameter. \texttt{ChannelSet.Get(index)} returns the encoded value belonging to the strip identified by the index of the earlier specified Plane.

\textbf{Cluster} \hspace{1em} The Cluster is a class that represents the position of the passage of a particle through a Plane. The criteria whether a certain set of strips represents the activation by a particle are the responsibility of the Plane class. Coordinate is a public attribute to be used by the Projection and Track classes. Coordinate is represented in a coordinate system that is independent of the Planes. Width gives the size of the cluster determined by the number of activated strips and Weight determines the importance of the Cluster. Weight has value 1 or 0. Zero means dummy or not applicable cluster. A public \texttt{Orientation} method returns whether the Cluster originates from a horizontal or vertical Plane.

\textbf{Projection} \hspace{1em} SiBTOO assigns three or four clusters from the same number of different Planes to the projection at the invocation of \texttt{Create}. After termination, the \texttt{Valid} method returns \texttt{True} if the clusters are aligned otherwise it
returns False. The Intersect method determines the coordinate where the line fitted for the projection intersects a plane and adds the deviation between cluster coordinate and line coordinate to the plane statistics. ClusterSet is a public attribute that can be used by the Track.

**Track**  At invocation of Create, two projections, one for each orientation, are assigned to Track. In Create, a line is fitted through them. If no fit can be done, the public Valid method returns False otherwise True. At invocation of Calibrate, the intersection point between each of the eight planes and the fitted line are calculated. The method First returns the cluster coordinate of the first plane. The method Next returns the deviation of the next plane.

**Line**  The line is created from the ClusterSet communicated at invocation of Create. The intersection point with a plane specified by the parameters is returned after invocation of Intersect. To hide the plane code from the Track and vice versa, the cluster contains the plane coordinates from which it originates.

The use of lists is suggested by the above design. There are sets of Clusters in a Plane, sets of Clusters that represent a Projection, sets of Tracks and sets of Projections. The members of the sets are used in a certain order and the number of set members is variable. This observation indicates the storage of the members in a list with a variable number of items. It is not a very encouraging prospect to do all the work for a list of Clusters and then redo the same work for Tracks, etc., The Template facility (or generic Class) offered by C++ makes it possible to specify a class "List" of a not yet known type. Every time a list of a given type is needed a concrete instance of the list is defined. In Fig. 6 the template class list is defined with the possibility to enter and remove items from the list. Three concrete instances of List are shown as well.

The code for a Projection depends on the orientation of the Projection. This means that IF statements are needed to test the orientation and execute the appropriate part of the code. The IF statements can be avoided (thus simplifying the code) by using inheritance. An abstract Cluster and Projection are defined that are specialised to the concrete classes Cluster-H, Cluster-V, Projection-H and Projection-V. This is shown in Fig. 7. Code particular to horizontal and vertical projections are thus assigned to different classes. At this moment it is difficult to decide whether also two classes Plane-H and Plane-V are appropriate.

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2.4 Implementation

In the above we have done a top-down approach. Using the class diagrams and scenarios, a more detailed design and implementation are done in this section. The lowest level classes are implemented first and other classes are built on top, finally ending with a SiBTOO program in which tracks are recognised and calibration can be done. The final code is shown in appendix A.

List  The most basic class is the list that will be used at many places. It is organised in a singly linked list. The variable head points to an object of class Link. Inside link, the attribute val is a pointer to an object of the parameter class T. The attribute next points to the next Link object in the list. The pointer cur is an attribute of list and points to the currently accessed item in list. The attribute number represents the number of items in the list.

```cpp
template<class T> class list{
// parametrised class List
// singly linked list of items
// initialised with zero items, with head and cur initialised to null
protected:
    class Link{
    public:
        Link* next;
        T* val;
        Link(Link* n, T* v) {next = n; val = v; }
    };
    Link* head; // head of singly linked list
    Link* cur; // last selected item
public:
    int number; // number of items in list
    list() {head = null; cur = null; number = 0; }
    list() {
        while (head != null) {
            cur = head;
            delete head->val;
            head = head->next;
            delete cur;
        }
    }

    void enter(T* item) {
        Link* temp = head;
        if (item != null) {
            head = new Link(temp, item);
            number ++;
        }
    }

    T* first() {cur = head;
        if (cur == null) { return null; }
        else { return (cur->val); }
    }

    T* next() {
```
if (cur == null){ return null;}
else {cur = cur->next;
    if (cur == null){return null;}
    else {return (cur->val);}
}
}
T* current() {
    if (cur == null){ return null;}
    else {return (cur->val);}
};
bool sequel(){
    if (cur == null){ return false;}
    else {return cur->next != null;}
};
The invocation of first initialises the value of cur. As long as cur is null, current returns null and sequel returns false. When the last element has been accessed, the invocation of next returns null and cur is set to null. Once the value of cur = null, the method first needs to be reinvoked to access again elements in the list. The use of sequel will become clear at a later stage in the implementation.

event, channelset Both classes are added for debugging purposes and are shown in appendix A without further comment.

cluster, strip and plane The class cluster plays a central role in SiBTOO. It uses a class coordinate that represents the cluster coordinates in a Cartesian coordinate system. A cluster represents a longitudinal coordinate ($s_c$) in one plane determined by the s-coordinate along the s-axis of SiBT and a transverse coordinate ($t_c$) that is either the x- or y-value of the cluster. The size attribute is a measure for the number of strips constituting this cluster. Remark that it is assumed that at least two strips constitute a cluster. This is reflected in the code of the plane shown later. A constructor defines the coordinates and size of the cluster. A destructor is not needed as no further structure is defined.

class coord{
public:
    float x,y,z;
};
class cluster{
protected:
    coord cc; //coordinates of cluster
public:
    float size; // number of hits (>1)
    float weight; // weight =0 for dummy cluster
    float s_c; // coordinate along s_axis (z_axis)
    float t_c; // coordinate along transverse axis (x_ or y_ axis)
    cluster(float cx,float cy,float cs,float sz) {
        cc.x = cx; cc.y = cy; cc.z = cs; weight =1.; size = sz;
    }
};
The strip class is shown below and is self-explanatory.

class strip {
public:
    int noise; // noise measurement value
    int value; // value caused by passage of particle
    float dist; // distance from origin along x- or y-axis
    float width; // width of strip along x- or y-axis
    float length; // length of strip over s-axis
};
The plane class is clearly one of the more complex classes. It contains an array of strips, a list of clusters, the coordinates in space of the lower left corner of the plane, and the statistics represented by mean and nr - the number of entries over which mean is calculated-. In the constructor an empty list of clusters is defined and the lower hand coordinates of the plane specified in the constructor parameters. The noise of the strips is initialised to 1 as for cluster calculation the acquired value is divided by the noise and division by zero is not allowed. This way a test on zero is not needed (efficiency). Two virtual methods are defined: storealignment and addcluster that need different implementations dependent on the projection orientation (shown below). The adddeviation method adds a new difference value to the plane and recalculates the mean deviation.

const int nstrip = 1024; // number of strips in plane
class plane {
  protected:
    list<cluster>* clusters; // cluster set
    strip sl[nstrip]; // array of strips
    float x,y,s; // coordinates of lower left corner of plane
    float mean; // statistics
    int nr; // number of entries

  public:
    plane(coord c){
      clusters = new list<cluster>; // empty cluster list to allow
      // access to clusters
      x = c.x; y = c.y; s = c.z; // coordinates of plane
      mean = 0.; nr = 0; // statistics for calibration
      for (int i = 0; i < nstrip; ++i) {
        sl[i].value = 0;
        sl[i].noise = 1; // to prevent division by zero
      }
      return clusters->first();
    }
    cluster* first(){return clusters->first();};
    cluster* get(){return clusters->current();};
    cluster* next(){return clusters->next();};
    bool sequel(){ return clusters->sequel();};
    void assign(channelset s);
    void clearstatistics(){ mean = 0.; nr = 0;};
    float meandev(){ return mean;};
    float scoord() { return s;};
    virtual void storealignment(float cc){ };
    virtual void adddeviation(float dt){
      if (nr == 0) {mean = dt; nr = 1;}
      else { mean = mean*(nr/(nr+1)); nr ++; mean = mean+(dt/nr);}
    }
    virtual void addcluster(float t_c, float s_c, float sz) { };
};

Below, the cluster calculation after assignment of the measured values is shown in the assign method. The parameter, ss, is of type channelset in which the measured values of this plane are defined. First the strip values are initialised and a new empty cluster list is set up. The clusters are calculated by doing a loop over all strips. At the line marked by (==>) a hit has been found and all consecutive strips are inspected to verify whether they also represent a hit. Two values i and k represent the first and last strip associated with the cluster. To test whether the "while loop" must end, a boolean b is used. The end criterium of the while loop is that k<nstrip and sl[k] contains a hit. However, because the test on k must be done first and only when k<nstrip the test on sl[k] can be done, the present construction with a boolean is used. When k>i and at least two consecutive hits have been found, a cluster is added to the attribute clusters -the cluster list of the plane-.

void plane::assign(channelset ss){
  for (int i = 0; i < nstrip; ++i) {
    // strip value and noise from channelset
    sl[i].value = ss.strip(i,1);
  }
}
```cpp
sl[i].noise = ss.strip(i,2);} // strips initialised

delete clusters; // remove former clusters
clusters = new list<cluster>; // create empty cluster list
for (i = 0; i< nstrip; ++i) {
    // determine clusters
    if (sl[i].value/sl[i].noise > hitquot) { // hit found in strip i
        float total =sl[i].value-sl[i].noise;
        float posit = sl[i].dist*total;
        int k = i+1;
        bool b = (k < nstrip);
        if (b) {b = b & sl[k].value/sl[k].noise > hitquot;}
        while (b) {
            total =total+(sl[k].value -sl[k].noise);
            posit = posit+sl[k].dist *float(sl[k].value-sl[k].noise);
            k++;
            b = (k < nstrip);
        }
        if (b) {b = b & sl[k].value/sl[k].noise > hitquot;}
    } // end if ( sl[i]........
}
}
```

---

**horizontal cluster and plane**  Both cluster and plane need the inherited classes `v_plane`, `h_plane`, `h_cluster` and `v_cluster` to make the code independent of the orientation. Below is shown how. A cluster is defined by three coordinates of which in a particular plane only two are interesting: the transverse and the longitudinal coordinate. Therefore, a horizontal (or vertical) cluster can be defined with these two coordinates and the other coordinate \( y \) (or the vertical cluster) is filled with 0. The code of `assign` is orientation independent as long as clusters of the right orientation are created and added to the attribute `clusters`. This is possible when the `addcluster` method of plane creates clusters with the correct orientation (vertical or horizontal). This is assured by defining `addcluster` virtual in plane and specifying it for `h_plane` and `v_plane` separately.

```cpp
class h_cluster: public cluster{
public:
    h_cluster(float cx,float cs,float sz)
        :cluster(cx, 0., cs, sz) { // y-coordinate =0
          t_c = cx; s_c = cs; }
};
```

For a plane three methods are orientation dependent: the constructor, `addcluster` and `storealignment`. For the calculation of the strip coordinates different sizes for horizontal and vertical planes are possible, defined by constants `xwidth` and `ywidth`. In the constructor `h_plane` (`v_plane`) the correct values along the x-axis (y-axis) are defined.

In `addcluster` a horizontal (vertical) cluster is created with new. The right cluster coordinate along the x-axis (y-axis) is calculated by adding the x- (y-) coordinate of the plane.

The method `storealignment` is self explaining.

```cpp
class h_plane: public plane{
public:
    h_plane(coord cc): plane(cc) {
        for (int i = 0; i<nstrip; ++i) {
            sl[i].dist = xwidth*float(i); // x-position of strips from x=0
        }
    }
```
line, projection  A line is defined in a flat plane and is given by the formula

$$t = ts_{tg} * s + s_{off}$$  \hspace{1cm} (1)$$

where $s_{off}$ and $ts_{tg}$ represent the offset and slope respectively. The constructor creates a line with the specified offset and slope. The fit method takes as parameter a list of clusters. Fit is independent of the orientation of the clusters. It is assumed that they are all horizontal or vertical. The following items are calculated for all clusters $c$: $S_s = \sum s_c$, $S_{ss} = \sum s_c * s_c$, $S_t = \sum t_c$, $S_{tt} = \sum t_c * t_c$. In the usual way the offset and and slope are calculated from these values. The method fit returns false if the number of clusters is smaller than three, determinant is smaller than 0 or $\chi^2$ is greater than some constant linchi. Otherwise, fit returns true.

class s_line{
public:
  float s_off;
  float ts_tg;
  float chi;
  s_line(float xt,float yt,float of){
    s_off = of; ts_tg = yt; chi = 0;}
bool fit(list<cluster>* proj) {
  cluster* clpt = proj->first();
  int ncl =0; // number of clusters
  float S_s = 0.; float S_ss = 0.;
  float S_t = 0.; float S_tt = 0.;
  while ( clpt != null){
    if (clpt->weight > 0){
      ncl = ncl + 1; // number of entries
      S_s = S_s+clpt->s_c; //sum over s
      S_t = S_t+clpt->t_c; //sum over t
      S_ss = S_ss+clpt->s_c*clpt->s_c; //sum over s*s
      S_st = S_st+clpt->s_c*clpt->t_c; //sum over t*s
      S_tt = S_tt+clpt->t_c*clpt->t_c; //sum over t*t
    }
    clpt = proj->next();
  }
  if (ncl < 3){ return false;} // at least three coordinates required
  float det = float(ncl)*S_SS - S_s*S_s ;
  if (det <= 0) { return false;)
    s_off = (S_SS*S_t - S_s*S_ST)/det;
    ts_tg = (ncl*S_ST - S_s*S_T)/det;
    chi = S_tt-s_off*S_t - ts_tg*S_st;
    return abs(chi) < linchi;
};

The projection contains a list of clusters that define the projection and a line as defined above. The constructor defines an empty list of clusters and a line with offset = 0, slope = 0 and $\chi^2$ = 0. The method add adds a cluster to the list of clusters. The assumption is that only clusters of a given orientation are entered. This is not checked. The valid method invokes the line fit of the cluster list and returns the result of the fit to the valid invoking code. The method tline calculates the t-coordinate of the line for a given s-coordinate defined as the parameter $sc$.  

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The method `AddDev` needs more explanation. The assumption is that clusters are added in the plane number order, i.e. first a cluster of plane 0 then of plane 1 and finally clusters from planes 2 and 3 are entered. The first cluster to be returned is the cluster from plane 3 or failing that one from plane 2. At the start of `AddDev`, the variable `cp` contains the first cluster of the projection and the index `i` is initialised to 3. In the while loop it is checked that the cluster s-coordinate is equal to the plane s-coordinate. When this is not the case, plane `i` did not contribute to this projection and `i` is decreased until both s-coordinates match. For matching coordinates the t-coordinate value of the cluster is subtracted from the line coordinate and added to the deviation statistics of the plane. The loop is executed over all clusters in the projection and ends when `clp->next()` returns null, meaning that all clusters from `clp` have been used.

```cpp
const int nplane = 8; // number of planes in SiBT
class projection{
    list<cluster>* clp; // pointer associated cluster
    s_line line; // fitted line
public:
    projection(): line(0,0,0) { clp = new list<cluster>; }
    ~projection(){ delete clp;}
    bool valid(){ return line.fit(clp);}
    float tline( float sc){ return line.ts_tg*sc + line.s_off;}
    void add(cluster* clref) { if (clref != null) {clp->enter(clref);}}
    void AddDev( plane* planes[]){
        cluster* cp = clp->first();
        int i = (nplane/2)-1;
        while (cp != null) { // assume that clusters come from 3,2,1,0
            while (cp->s_c != planes[i]->scoord() & i >0) { i--;}
            planes[i]->adddeviation(cp->t_c - tline(cp->s_c));
            cp = clp->next();} // end while over clusters
    }
};
```

**projlist, track** The class projlist is added to construct all projections possible from a set of four horizontal or four vertical planes. The class is mainly introduced to avoid duplication of code for projection finding in the horizontal and vertical plane. A destructor and constructor are needed to initialise attribute `lp` and remove the list of projections pointed to by `lp`.

`FindProj` is the main method that takes an array of planes as parameter. `FindProj` can be invoked for horizontal and vertical planes. It is based on the following principle. Suppose that each plane contains two clusters, notated as `pxcy` denotes cluster `y` of plane `x`. For example: `p0c1` is cluster 1 of plane 0. The following projections are then constructed in this order:

\[
\begin{align*}
p0c1 & \quad p1c1 \quad p2c1 \quad p3c1 \\
p0c2 & \quad p1c1 \quad p2c1 \quad p3c1 \\
p0c1 & \quad p1c2 \quad p2c1 \quad p3c1 \\
p0c2 & \quad p1c2 \quad p2c1 \quad p3c1 \\
p0c1 & \quad p1c1 \quad p2c2 \quad p3c1 \\
p0c2 & \quad p1c2 \quad p2c2 \quad p3c2 \\
\end{align*}
\]

such that all combinations have been done. In the last case it can be seen that for all planes the last cluster has been used. In all other cases there is at least one plane where cluster 1 has been used. This leads to the introduction of the boolean `b` for which the value `false` represents: there is a plane that has not returned the last cluster. Boolean `b = true` means: all planes have returned their last cluster. Testing whether the last cluster is returned is done with the method `sequel` that returns true if there is a cluster left in the list of clusters in the plane.

The first projection, `pp`, is found by returning the first cluster from each plane. The valid projection, `pp`, is entered in the projection list `lp`. The initialisation of `lp` is discussed later. The boolean `b` is true when other projections are possible. The second part of `FindProj` is started at the sign `==>` . Another boolean `sw` is introduced. When `sw` is true, the next cluster of a plane is solicited or the first cluster in case no more clusters are left in the plane. Variable
**Variable** `sw` is true for plane `i+1` when the first cluster had to be reread from cluster `i`. In all other cases `sw` is set to false. When `sw` is false the current cluster is taken from the plane. When `sw` is true, the next cluster (if available or the first cluster) is inserted in the projection.

At the end of the loop over the planes, a valid projection is added to the list. The loop over all projections is ended when `b` reaches false. At the end of **FindProj** the attribute `lp` contains a list of 0 or more valid projections.

It is, of course, possible that a plane contains no clusters. Then **first** returns null. In **enter** a test on null is done. Nothing is entered in the list when the argument of **enter** is null. This caters for projections with less than four clusters.

```cpp
class projlst {
protected:
    list<projection>* lp;
    projlst() { lp = null;}
    ~projlst() { if (lp != null) { delete lp; } }
public:
    projection* first() { return lp->first();}
    virtual projection* newproj() { return new projection();}
    int number() { return lp->number;}
    virtual void FindProj(plane* planes[]){
        // find the list of projections in array of planes
        bool b = false;
        projection* pp = newproj();
        for (int i = 0; i<4; ++i){
            pp->add(planes[i]->first());
            b = b | planes[i]->sequel();} // more than one cluster in plane?

            // b implies there is a plane with more than 1 cluster
            // not b implies all planes have less than 2 clusters
            if (pp->valid()){lp->enter(pp);} // if good projection add to lvp
            else {delete pp;} // else remove contents and memory
        }
        // try all possible cluster combinations from vertical planes that have clusters
        cluster* cp;
        while (b){
            pp = newproj();
            b = false;
            bool sw = true;

                // sw implies get next cluster from plane or first one
                // not sw implies get current cluster from plane
                for (i = 0; i<4; ++i){
                    if (sw) {cp = planes[i]->next();}
                    else { cp = planes[i]->get();}
                    if (cp == null) { cp = planes[i]->first();}
                    else { sw = false;}
                }

                // sw remains true when first cluster was taken from former plane
                pp->add(cp);
                b = b | planes[i]->sequel();} // end for (i=0; i<4)

                // not b implies last cluster is found in all planes
                if (pp->valid()){lp->enter(pp);}
                else {delete pp;}
            } // end of while(b)
    }
};
```
A track is composed of one valid horizontal and one valid vertical projection. Two methods, _hproj_ and _vproj_, return the horizontal and vertical projection respectively. A destructor is needed to remove the horizontal and vertical projection when the track is deleted.

```cpp
class track{
    projection* hpr;
    projection* vpr;
public:
    track(projection* h, projection* v) {hpr = h; vpr = v;}
    ~track() { delete hpr; delete vpr;}
    projection* hproj() {return hpr;}
    projection* vproj() {return vpr;}
};
```

**horizontal projection list** A horizontal (vertical) projection and projection list have been defined as well. Their reason of existence is explained in the paragraph on visualisation of data structure. The method _newproj_ is used to have _pp_ point to horizontal (vertical) projections. Consecutively, a horizontal projection list is filled with horizontal projections.

The method _FindProj_ is the application interface to projlst. It initialises _lp_ with an empty list of horizontal projections after which _FindProj_ is invoked and all manipulations in _FindProj_ only take place on horizontal projections.

```cpp
class h_projlst: public projlst {
protected:
    projection* newproj(){ return new h_projection();}
public:
    void FindProj(plane* planes[]){
        // find the list of projections in array of vertical planes
        delete lp; // remove old list
        lp = (list<projection>*)(new list<h_projection>);
        projlst::FindProj(planes);
    }
};
```

**SiBTOO** The class _SiBTOO_ represents the silicon beam telescope _SiBT_. It consist of four horizontal and four vertical planes. Additionally it maintains a list of horizontal and vertical projections in the attributes _lhp_ and _lvp_ respectively. A constructor is provided. Remark that _lhp_ and _lvp_ are initialised with _h_projlst_ and _v_projlst_ respectively. No destructor is provided because _SiBTOO_ is never removed. If _SiBTOO_ is removed in an application, a destructor is needed to remove the planes and the projection lists.

Two methods are provided _FindTracks_ and _Calibrate_. _FindTracks_ initialiseds the strip values of all 8 planes, finds the vertical and horizontal projections and if one projection is found in each direction a track is returned. The method _Calibrate_ takes as input a list of tracks and loops over all tracks. For each track and for each projection in the track, deviation statistics are added to all planes. After treating all tracks, the mean deviations stored in the planes are added to the plane coordinates.

```cpp
class SiBTOO{
    plane* hplanes[nplane/2]; // 4 horizontal planes
    plane* vplanes[nplane/2]; // 4 vertical planes
    h_projlst* lhp; // list of horizontal projections
    v_projlst* lvp; // list of vertical projections
public:
    SiBTOO() {
```
// initialise with 0 projections
lhp = new h_projlst();
lvp = new v_projlst();

// initialise plane coordinates
for (int i = 0; i<nplane/2; ++i){
    coord cc;
    cc.z = 2*i*(sbt_ds-0.05)/nplane; // s-coordinate
    cc.x = .1; // x-coordinate
    cc.y = cc.x; // y coordinate
    vplanes[i] = new v_plane(cc); // vertical plane
    cc.z = cc.z+.05; // s-coordinate
    // (slightly different from
    // vertical plane s-coordinate)
    hplanes[i] = new h_plane(cc); // horizontal plane
}

track* FindTracks(event ev){
    for (int i = 0; i<nplane/2; ++i){
        vplanes[i]->assign(ev.plane(i*2)); // vertical plane strips
        hplanes[i]->assign(ev.plane(i*2+1)); // horizontal plane strips
    }
    // clusters of event are found and stored in planes
    lvp->FindProj( vplanes); // lvp contains vertical projections
    lhp->FindProj( hplanes); // lhp contains horizontal projections

    // only one projection from each orientation is allowed
    if(lhp->number() == 1 & lvp->number() == 1)
    {return new track(lhp->first(), lvp->first());}
    else { return null;}
}

void Calibrate(list<track>* lst){
    for (int i = 0; i<nplane/2; ++i){
        vplanes[i]->clearstatistics();
        hplanes[i]->clearstatistics();
    }
    track* trp = lst->first(); // get first track from list
    while (trp != null) { // loop over all tracks
        // horizontal projections
        trp->hproj()->AddDev( hplanes);
        // vertical projections
        trp->vproj()->AddDev( vplanes);
        trp = lst->next();} // end while over all tracks
    // realign planes
    for (i = 0; i<nplane/2; ++i){
        hplanes[i]->storealignment(-hplanes[i]->meandev());
        vplanes[i]->storealignment(-vplanes[i]->meandev());
    }
}

Show contents of SiBTOO  For every class a print function is added. Below, the print function of SiBTOO is shown. It prints the contents of the horizontal and vertical projections and of the individual planes. Here the inheritance of vertical planes and horizontal planes is motivated as the print function of the horizontal plane prints that it is a horizontal plane without any test on orientation parameters. Instead of printing, more sophisticated graphics visualisation routines can be foreseen that actually exploit the orientation of the object to visualise.

void SiBTOO::print(){

}
void h_plane::print()
{
    cout << " HORIZONTAL ";
    plane::print();
    cout << " clusters are: \n"; clusters->print();
    cout << " --------------------- H_PLANE \n \n";
}

Finally, the print of the list is shown. For every item in the list, it invokes val->print(). This means that every class for which a list is defined, should provide its own print() method. More elaborate code is shown in the appendix A.

```cpp
void list::print()
{
    cout << " list with " << number << " entries \n" << flush;
    int k =0; Link* temp = head;
    while (temp != null){
        cout << " item " << ++k << " : "; temp->val->print();
        temp = temp->next;} // get next element from list
}
```

### 2.5 Evaluation

In a design it is always difficult to decide whether efficiency should be the most important aspect or generality. This is the case in the design of the s_line class. The tline code of the projection class uses the ts_tg and s_off attributes of line directly to calculate the intersection point. When other lines instead of straight lines are used, this is unacceptable. Then a method t_coordinate of line should return the transverse coordinate given the longitudinal coordinate. Substituting the line class for circle or helix class leaves the tline method of the projection class unmodified.

For performance reasons also the strips are arranged in an array and attributes of strips are addressed directly and not via a method.

As can be seen in the code it is assumed that the minimum number of activated strips in a cluster is 2. This shows in the design of the assign method where two variables i and k are used with the assumption that k > i for a valid cluster. Another point is the assumption that the number of horizontal planes and vertical planes is the same as reflected by the choice of a constant nplanes that represents all available planes.

It is also debatable whether the inheritance for creating horizontal and vertical clusters, projections and planes is really necessary. These points are addressed in the exercises below. However, the introduction of more specialization in the planes favours the actual design choice of using inheritance.

A few clear advantages and general design rules need to be pointed out:

- **Information hiding** The clearest example is the list, where all pointer handling or list structure is hidden from the other classes. The structure of the list (e.g. doubly linked) can be changed without any changes to the remaining code. Other examples are:
  - **ProjLst** The algorithm to attribute clusters to a projection is completely confined to the ProjLst class.
  - **Projection** The testing of the validity of a projection and the determination of the measurement mismatch of projection clusters is confined to the projection.
  - **Plane** The calculation of clusters is confined to the plane class. Differences between horizontal planes and vertical planes can be added without modifications to the code.
  - **Line** The line fitting algorithm is confined to the s_line class.

- **Divide and Conquer** The above cited classes show that to each class a limited functionality is attributed. The development of small pieces of code with a limited functionality is easier than making large monolithic pieces of code.
• **Performance** Most classes have interfaces defined by functions. A few classes allow direct access to attributes. This is done for classes where little change is expected or/and that are used by a very limited (≤ 4) number of classes.

• **Case dependency** Methods that contain many IF statements usually contain too much functionality. The use of inheritance to separate these functions to simplify the code is then recommended. Here, this is done for planes with horizontal and vertical orientation. Inheritance leads to more complexity due to the multiple definitions. The advisability of inheritance must be judged on the basis of the properties of the individual cases. Here, we are confronted with an unclear case.

• **Generality** When inheritance is used, the danger exists that almost identical code that differs at only a few locations is reproduced as many times as there are derived classes. It is advisable to construct methods in the base class that can be used as much as possible for all inherited classes. This is established for `FindProj`, `AddDev` and `assign`.

• **Layering** The code is built up of classes with more and more capability by exploiting the functionality of the classes from lower layers (for example: a projection that uses a cluster that is based on strips).

Not following these guidelines leads to monolithic programs with many dependent execution paths that are difficult to test and maintain. In such programs, modifications have the nasty habit not to stay localized but needing unexpected additional modifications. For example in this example responsibility for cluster allocation, projection finding, line fitting etc are assigned to different classes. Another possibility is to group all this functionality inside the SiBTOO class. The other classes are then reduced to simple data containers. It is left as an exercise to the reader to see the consequences for the final code.

### 2.6 Exercises

1. Remove all horizontal and vertical inheritance and add a boolean to the base class to assign an orientation to the class. Modify all orientation dependent methods to obtain the same results as before.

2. Change the vertical plane such that there is an empty space between any two strips.

3. Change the line fitting and add the possibility to do a circle fitting. Both fit possibilities exist simultaneously. Straight line fits are done for four cluster projections and circle fits are done for three cluster projections.

4. Change the number of planes from 8 to 10.

5. Calculate the cluster width in an orientation dependent way.

6. Treat the planes as pairs and calculate clusters on a pair basis. This should lead to quite a lot of changes. Try to identify the code that needs no change.

7. Determine the quality of the realignment by calculating the standard deviation of the plane alignment statistics during calibration.

8. Make the list of clusters an ordered list and order clusters according to s coordinate value.

9. Change the code such that the type checking of C++ verifies that vertical (horizontal) clusters are added to vertical (horizontal) projections.
3 Layers example

This example is based on the layers that can be identified in the CMS detector. The layer structure is used to do a fast track searching algorithm starting from the outside of the detector and ending at the centre. Within a detector installation different types of detectors can be found. It is shown how the SiBT can be considered as a detector type from the set of detector types that constitute the detector installation (this is actually not true but is assumed as a hypothetical example).

3.1 Layers description

In Fig. 8, a detector installation composed of several detectors with a circle symmetric layout is shown. Particles originate at the centre and the passage of the particles is recorded by the detector through which they pass. Detectors in the detector installation can have different characteristics. Several types of detectors can be discerned and usually detectors of the same type are organised in one layer around the centre. The detectors have one thing in common: the detection of the particle within the detector volume. Per particle that passes, several points are measured where the particle interacts with the detector. This is similar to SiBT where the passage of a particle is detected at eight different places. The number of places that a particle can be detected, can change from detector to detector. Also the sensitivity for a particular type of particle changes from detector to detector. Although SiBT was capable of detecting the passage of at most one particle, other detectors are capable of detecting the passage of several particles simultaneously.

A series of points that are associated with the passage of one particle through one detector is called a track segment. The determination of a track segment inside a detector may change from detector to detector. In some detectors track segments are identified by fitting a straight line through the measurement points, in other detectors a helix or circle is fitted through the points.

In this section a series of segments from a set of detectors associated with one particle is called a track. An algorithm tries to combine all track segments to a candidate track. An example algorithm looks at the largest outer circle and determines all the points at which a particle leaves the detector installation. It associates each track segment with one particle. For all these track segments it determines the location where the particle enters the outer layer. It then inspects the next lower layer and combines the track segments that leave the lower layer at some position, with track segments of the outer layer that enter the outer layer at the same location. This goes on
until the lowest layer (the centre) is reached. It is possible that a track segment can be combined with more than one lower level track segment. When n valid combinations are found, n candidate tracks are created. When all layers have been tried, a helix is fitted through all measurement points of a candidate track. Candidate tracks for which the helix fit is not good enough are rejected. The remaining candidate tracks are called valid tracks.

3.2 Analysis

![Class diagram based on layers analysis](image)

The classes associated with the analysis are shown in Fig. 9. A detector installation (e.g. CMS) consists of a set of detectors that are organised in layers. Each detector occupies a volume in space where particles can be detected. The passage of a particle generates measurement points within the detector volume. These measurement points are represented in the coordinate system of the detector installation that can be different from the coordinate system of the individual detectors. For the detector installation a cylindrical coordinate system looks appropriate, while a Cartesian coordinate system seems reasonable for an individual detector (see SiBT). Measurement points are measured with a precision that is detector dependent. The measurement points inside a detector define track segments. Fitting these track segments with a line allows to extend the track segments and determine the exit and entry points of the segment from/to the detector volume. Track segments leave and enter the volumes with a certain orientation in space. Track segments are combined to candidate tracks. A track contains a given track segment only once but a segment may belong to several candidate tracks. Again, a line can be fitted through the measurement points of a track. The intersection points of this line with the different detector volumes determine the exit and entry points of the track.

This analysis is based on the description of section 3.1 and the use case described below. It is assumed that for a given event all detectors have combined the measurement points into track segments.

1. **Combine segments** It is assumed that detectors return zero or more track segments expressed in the coordinate system of the detector installation. The detector installation is constructed in concentric layers of detectors. Track segments of adjoining layers are related when their entry- and exit-point at the layer interface coincide and the orientation of the segments is identical. A set of related segments is combined to a track. Tracks can start at the centre or within the detector installation volume. Tracks can terminate in the detector installation volume or at the outside of the detector.

3.3 Design

Scenario diagrams are used to show the responsibilities for the different proposed classes. **Main** is the actor for the use case mentioned above. The same design aims as those for SiBT are applied here as well. The class **Installation** hides all implementation details from **Main**.
Figure 10: Scenario for determining a list of tracks

Combine segments The central idea is to visit each track segment only once during the construction of all possible tracks. Therefore, it is assumed that in each layer the detectors are ordered according to the angle in the cylindrical coordinate system and the track segments inside the detector are ordered accordingly. The tracks in construction should be ordered also according to the angle of the track at the lower layer interface. On the basis of the angle the next track segment from a layer can be searched or the next track in construction.

The scenario of Fig. 10 supports this construction. Similar to SiBT, a tracklist is constructed. The tracks in the list are created from a segment or tracks are extended with segments. The track creation and extension is started for a given layer by creating the tracklist class. The tracklist gets the first layer from the layerlist and asks the layer to return the first segment from this layer. The layer invokes the detector that returns the segment with the smallest \( \phi \) angle. The segment is added to the list of tracks as the start of a track. This is repeated for all detectors in the layer. Invoking all layers—from the outside to the inside consecutively—leads to the construction of all possible track candidates. In the scenario, after invocation of GetTracks, the track list is created. At the start, track list retrieves the first (outer) layer from the layer list, continuing for all possible segments in the installation. When all layers have been invoked, track list asks every track to determine its validity. Invalid tracks are removed. The final implemented scenario is different from the one proposed here. This is explained in section 3.4.

3.3.1 Tentative class definitions

In this section a first effort is done to determine the required classes with their attributes and methods. The class set is a guideline for the final implementation presented in section 3.4. The following classes are needed:

Installation The Installation class is the computer model of the whole detector installation. Hidden attributes are LayerList that represents the list of layers and TrackList that represents the tracks found in the detector installation. Two public methods are needed: (1) Create to create the whole detector installation (2) GetTracks that returns the tracks found in the installation associated with an event. This is in analogy with the SiBT example.

Layer The class Layer models the set of detectors that form a layer around the inner detectors. The ordered list of detectors is a private attribute of Layer. The public methods FirstSegment returns the segment with the smallest \( \phi \) coordinate detected within a detector in the layer. The public method NextSegment returns the segments with a \( \phi \) coordinate that is larger than the former returned segment but with the smallest \( \phi \) coordinate of all not yet returned segments in this layer. The public method Assign assigns a set of measurement values to the detectors in the layer.
Figure 11: Class diagram based on scenario

**Detector**  This class models a piece of equipment called a detector. The private attribute \emph{Coordinates} represents the position of the detector in the installation’s coordinate system. Within the detector, measurements are stored that can be combined to segments. These are represented with the ordered private attributes: "list of segments" and "list of measurements". The public method \emph{Assign} assigns a set of measurement values to the detector. The public methods \emph{FirstSegment} and \emph{NextSegment} have the same functionality as the corresponding methods of the layer.

**TrackList**  The class TrackList represents the tracks that are being recognised on the basis of the measurements contained in the detector objects. The ordered private attribute "list of tracks" represents the list of already identified tracks. The public method \emph{Extend} adds new tracks to TrackList or extends tracks within the tracklist. The public \emph{Create} method creates an object of this class.

**Track**  An object of the Track class represents one candidate track. The private attribute "list of segments" represents all segments that constitute this track. The private attributes \emph{Entry} and \emph{Exit} represent the entry and exit points of the track respectively. The public attribute \emph{Add} extends the track with a segment. The public attribute \emph{Valid} tests whether the track is a valid one.

**Segment**  This class represents the measurements in one detector associated with one particle. The private attribute "list of coordinates" represents the track measurements expressed in the coordinate system of the installation. The public attributes \emph{Exit} and \emph{Entry} represent the points where the particle respectively leaves and enters the layer associated with this detector. The public methods \emph{Enter} and \emph{Valid} add measurements to the segment and test whether the segment is a valid one, respectively. Validity is tested by fitting a straight line.

**Event, LayerSet**  These classes (not shown in the Fig. 11) represent the measurements associated with the whole installation, a layer and a detector respectively.

### 3.3.2 Discussion

The same design strategy has been used as for the SiBT example. There is a clear analogy between installation and SiBT, planes and layers, strips and detectors, clusters and segments and projections and tracks. Analogous to the ProjList class a TrackList has been defined. A TrackList object combines the measurements of different layers to create complete tracks. The particulars of a specific track recognition algorithm are confined to the TrackList class. The fitting of a line with a particular geometry is confined to the Segment class. As in the SiBT example, lists of segments, tracks, measurements and detectors are needed.
3.3.3 Ordered lists

Similar to the lists of SiBT, the lists of the layered installation needs to be ordered according to the $\phi$ coordinate of the segment, track or detector. The ordering can be added to the list defined for SiBT, but this is deemed to much work considering that ordered lists are supported by the STL library [MS96]. Sorted lists are wanted from which elements can be retrieved ordered according to a key. The key here is the $\phi$ angle of the installation’s coordinate system. No random access is wanted. The order in the list of tracks is changed infrequently. This leads us to the choice of the simplest STL container: the vector. The list is another good candidate but the syntax allowed by the STL library made it a poor choice.

![Concrete vectors based on STL](image1)

Fig. 12: Concrete vectors based on STL

3.4 Implementation

In the above we have done a top-down approach. Using the class diagrams and scenarios a more detailed design and implementation is done in this section. The lowest level classes are started first and other classes are built on top, finally ending with a program in which tracks are recognised. The final code is shown in appendix B.

cylpoint, measur  In contrast to the SiBT example, a cylindrical coordinate system is needed. A coordinate is defined by the radius, angle and cylinder axis. The class cylpoint has been defined for that purpose. A measurement is not associated with a point only but occupies a volume in space. The size of this volume is given by the individual sizes in the three coordinates. The measur class is derived from the cylpoint class. Another possibility for defining measur is the definition of an attribute of class cylpoint. This not used as a too complex naming scheme is the consequence.

class cylpoint{
  // point in cylindrical coordinate system
  public:
    float r; // r coordinate
    float phi; // phi angle coordinate
    float s; // cylinder axis coordinate
};

class measur: public cylpoint{
  // measurement point in cylindrical coordinate system
  public:
    float dr,ds,dphi; // measurement uncertainties in above
};

The vector of measur is used to show some vector syntax.

Vector  The list of measur is introduced to show how vectors are used in this example. An ordered list is required which means that the ordering needs to be defined. For the purpose of this example measurements are ordered according to their $\phi$ value. The equal and lessthan operators are defined for the measur class. Once they are defined, ordered vectors can be defined.
// Define == on measur objects
bool operator==(const measur& m1, const measur& m2)
{ return m1.phi == m2.phi; }

// Define < on measur objects
bool operator<(const measur& m1, const measur& m2)
{ return m1.phi < m2.phi; }

Below, the object points is defined as a vector of measur. The iterator m is used to access elements in the vector. In the example, m is started by initialising it with the begin of points. For the next element in the vector it is sufficient to state (m++) or m++. This is done at the end of the for loop. The for loop is ended when m is equal to value returned by points.end(). Remark that points.end() is a pointer to the last element plus 1. The operation m++ can be executed on m when it has passed the value points.end() but leads to invalid iterators that point to nowhere.

vector<measur> points;
vector<measur>::iterator m;
for (m = points.begin(); m != points.end(); ++m){
        cout << "point with radius: " << m->r;
        cout <<" and angle: " " << m->phi << "\n";}

In the for loop, the phi- and r- attributes of all elements in points are printed in the order they are stored. To be sure that elements in points are ordered according to phi, the order function needs to be invoked, as shown later.

layerset, event The class event consists of an array of nlayer layersets where the values returned from the equipment are stored. For the example some possible values are stored (see Appendix B). The large difference with SiBT, where the number of strips is known, is that the number of measurements per detector are not known beforehand. This has some consequences for the design of the detector class, as shown later.

const int nlayer = 8; // number of layers in installation
class event{
layerset set[nlayer]; // 1 event: nlayer layersets
public:
        event(){ initialise }
layerset layer(int pl){ return set[pl];}
};

The rest of the event and layerset class is self explanatory (see Appendix B). However, the structure of the event data has a large consequence for the whole design, as shown later as well.

segment The segment class uses the same line fitting method as used for SiBT. A segment has the attribute points that represents the measurement points associated with this segment. Measurement points are added piecemeal with the method enter. For the example of adding them one by one is suggested by the assumption made on the detector and the event layout (i.e. variable number of measurements per detector and event structure not known to detector). In enter the new measurement is added to points with the push_back method delivered by the STL library.

The most complex method is valid. It returns True when a straight line can be fitted through the points projected to the plane perpendicular to the s-axis. In contrast to SiBT, the line is not entered as a special class because the line fit is only needed for the segment determination and not for other purposes. If other fit algorithms are needed, the whole valid method needs to be replaced. It can be envisaged to inherit different segments from the base class segment differentiated according to the type of fit that is applied. Examples are helix-segment or circle-segment (not done here).

A segment enters the layer at the inside and exits at the outside. An addition to the SiBT method valid is added here. The fitted line is intersected with the layer border. The intersection points entry and exit are calculated and stored in the segment. These two points are used to determine if two segments can belong to one track.

const float linchi = 10.;
class segment{
    public:
        vector<measur> points;
        cylpoint entry;
        cylpoint exit;

    void enter(measur *m){ points.push_back(*m);}
    bool valid(float r,float phi) {
        float ts_tg ,s_off, chi; // line fitting variables
        float of, tg; // variables for detector surface
        float s,t; // coordinates after transformations
        int nms =0; // number of measurements
        float S_s = 0., S_ss = 0., S_t = 0., S_tt = 0., S_st = 0.;

        if (points.begin() != points.end()){
            vector<measur>::iterator m;
            for (m= points.begin(); m != points.end(); ++m){
                nms = nms + 1; // number of entries
                s = m->r*cos(m->phi);
                t = m->r*sin(m->phi);
                S_s = S_s + s; //sum over s
                S_t = S_t + t; //sum over t
                S_ss = S_ss+s*s; //sum over s*s
                S_st = S_st+t*s; //sum over t*s
                S_tt = S_tt+t*t; //sum over t*t
            }
            if (nms < 3){ return false;} // at least three coordinates required
            float det = float(nms)*S_ss - S_s*S_s ;
            if (det <= 0) { return false;}
            s_off = (S_ss*S_t - S_s*S_st)/det; ts_tg = (nms*S_st - S_s*S_t)/det;
            chi = S_tt-s_off*S_t - ts_tg*S_st;
            // calculate entry and exit points of line
            entry.s = 0; exit.s = 0; // default values
            tg = (sin(phi)-sin(phi+2.*dphi))/(cos(phi)-cos(phi+2.*dphi));
            // inner layer, entry point
            of = r*sin(phi)-tg*r*cos(phi);
            t = tg*s+of; s = (s_off-of)/(tg-ts_tg);
            entry.r = sqrt(s*s + t*t); entry.phi = atan2(t,s);
            // outer layer exit point
            r = r+detcdr+rspace; of = r*sin(phi)-tg*r*cos(phi);
            s = (s_off-of)/(tg-ts_tg); t = tg*s+of;
            exit.r = sqrt(s*s + t*t); exit.phi = atan2(t,s);
            return abs(chi) < linchi;
        }
    }
};

One can test whether a vector is empty by comparing the begin and end iterator. When they are unequal, the vector is filled. This test at the start of enter is not really necessary because the for loop over m terminates directly when the vector is empty. In that case nms is not increased and remains smaller than 3.

The ordering of the segments is important for the track recognition algorithm. By looking at Appendix B it can be seen that for the segment also the equal (==) and the lessthan (<) operators are defined with as key the phi value of the exit attribute.

track A track consists of a vector of segments. A point to make is that the ordering for segments is already defined according to the value of the exit point. Segments in a track are preferably ordered according to their distance, r, from the installation center. This ordering of segments within a track is realized by entering the
segments in a given order and not applying the STL order method defined on the angle.

The track has an entry and exit point. A track enters from the inner layer and exits at the outer layer. The first entered segment is found in the outer layer and defines the exit point of the track. The last entered segment is from the innermost layer and determines the entry point of the track. This is reflected in the code of `enter`.

It is assumed that segments from the outer layer are entered to the track first, followed by segments from inner layers according to the decreasing segment entry radius value (defined by `entry.r`). This assumption is a logic consequence of the chosen track finding algorithm.

class track{
  vector<segment> trk; // segments that constitute track
public:
  cylpoint entry;
  cylpoint exit;
  void enter(segment* s){
    entry = s->entry;
    if (trk.begin() == trk.end()) { exit = s->exit;}
    trk.push_back(*s);
  }
}

Ordering of tracks is defined on the phi value of their entry point. Remark that the segments are ordered according to the phi value of the exit point.

detector  Detectors are assumed to be flat boxes that are defined by eight corner points: pt[8]. Two lists are defined in the detector: the list of measurement points and the list of segments composed of these measurement points. For simplicity it is assumed that a detector can produce only one segment composed of all measurements in the detector. Detector is the first class that needs a constructor. The detector class, like all former classes, does not need a destructor as no pointers to objects need to be initialised with new thus avoiding the destruction of these objects. All the objects inside vectors are deleted automatically by the destructor of the vector class.

The constructor defines a detector volume with the eight pt[8] coordinates calculated from the r and phi parameters of the constructor. One measurement at the time is added to the detector with the add method. The reason for this is explained when the tracklist is discussed. Before any measurements are added the clean method must be invoked to remove all former measurement points and associated segments.

Once all measurement points are added to the detector the FindSegment method determines whether the measurements belong to a segment. As already mentioned the segment finding algorithm is a very simple one. All measurements are taken from the vector of measurements and stored in a newly created vector called `seglst`. Remark that the same local object `sg` is used to construct the segment. This is allowed because `push_back` makes a copy of the item before it is stored into the vector. The `valid` method of the segment `sg` is invoked. Its parameters `pt[0].r` and `pt[0].phi` serve to calculate the entry and exit points of the segment. A valid segment is added to the segment list `seglst`. Only one segment is added in this case but the introduction of `seglst` leaves the possibility to add more segments in a later stage.

class detector{
public:
  cylpoint pt[8]; // detector defined by 8 points in space
  vector<segment> seglst; // list of segments
  vector<measur> measlst; // list of measurements
  detector() { }
  detector(float r, float phi){
    for (int i = 0 ; i< 4; i++) {pt[i].s = 0; pt[i+4].s=detcds;}
    pt[0].r = r; pt[1].r = r;
    pt[4].r = r; pt[5].r = r;
    pt[2].r = r+detcdr; pt[3].r = r+detcdr;
    pt[6].r = r+detcdr; pt[7].r = r+detcdr;
    pt[0].phi = phi - dphi; pt[4].phi = phi - dphi;
  }
}
pt[3].phi = phi - dphi; pt[7].phi = phi - dphi;
pt[1].phi = phi + dphi; pt[5].phi = phi + dphi;
pt[2].phi = phi + dphi; pt[6].phi = phi + dphi;
} // end of detector constructor
void add(measur m){measlst.push_back( m);}  

void clean(){
  // remove all segments and measurements
  seglst.erase(seglst.begin(),seglst.end());
  measlst.erase(measlst.begin(),measlst.end());
} // end of clean

void FindSegment(){
  if (measlst.begin() != measlst.end()){ // measurements present
    segment sg;
    vector<measur>::iterator m;
    for (m = measlst.begin(); m != measlst.end(); ++m){
      sg.enter(m);} // all measurements in one segment
      if (sg.valid(pt[0].r,pt[0].phi)){seglst.push_back(sg);}  
       // add sg to segment list
  } // end of if (measlst....
} // end of FindSegment

Ordering of detectors is defined on the phi value of their pt[0] coordinate (see appendix B.)

**layer**  The layer contains a set of detectors. The constructor of the layer creates the detectors and stores them into the detector vector dts. The detectors in dts are ordered according to the phi value of one of their corner points (see Appendix B).

The design of the layer class assign method deviates from the ones suggested earlier. These deviations have an impact on the design of the detector and tracklist classes. The assumption is that for each layer, the event data may have a different structure. This means that each individual layer is made responsible for the assignment of data to the detector. The amount of data per detector varies. In the layerset structure it is assumed that the phi angle of the measurement point can be used to attribute a data-item to a detector. Hiding the layerset structure to the detector means that the layerset method detect is asked to return a pointer to the next measurement corresponding with a given phi range. The result of these design decisions is that detectors cannot decide whether the last measurement point is added to the detector. It is the layer that knows when the last measurement point is furnished to the detector. This means that the layer first must clean the data in the detector by invoking the clean method of the detector before invoking the add method of the detector for each individual measurement point. After the insertion of all measurement points into a given detector, the FindSegment method of the detector can be invoked.

class layer{
public:
  vector<detector> dts;
  layer(float ri) {
    // create a layer with inner circle defined by ri
    for (int i=0; i < ndetect; i++)
      dts.push_back( * new detector(ri, dphi*i*2));
      sort(dts.begin(), dts.end(),less<detector>() );
  } //end of layer constructor
  void assign(layerset ls){
    float* pm;
    measur m;
    m.dr =0.; m.dphi = 0.; m.ds =0.;
    vector<detector>::iterator d;
    for (d = dts.begin(); d != dts.end(); ++d) {
      d->clean();  // remove segments and measurements
      pm = ls.detect(d->pt[0].phi);
      while (pm != null){
        m.phi = pm[0]; m.r = pm[1]; m.s = pm[2];
        d->add(m);
pm = ls.detect(d->pt[0].phi);} // end of while
d->FindSegment(); // construct segments
} // end of for
} // end of assign

In the discussion section 3.5 alternatives for the detector and event design are mentioned.

tracklist Like in the SiBT example, tracklist is the heart of the layers example. In this class the relation between the individual detectors and layers is made. The algorithm constructs tracks layer by layer starting at the outside and ending at the inside of the installation. The loop over all layers can be made inside tracklist or inside the invoking installation. To reduce the complexity of tracklist code, it is chosen to do one layer at the time inside tracklist. This is in contradiction with our original idea mentioned in section 3.3.1. A vector of tracks is maintained in the attribute tklst. This vector contains the zero tracks, the tracks under construction or the finished tracks after the treatment of the last layer. No destructor is needed. It is assumed that every time a new set of tracks is calculated a new tracklist object is created. Therefore, no clean method is needed to remove all former tracks from tklst.

Only one method extend with parameter the current layer is defined. The local object cr_ent maintains the entry point of the track under consideration. When no tracks are available, its value is set to a value larger than 2π. The method extend first copies the segments of all detectors in the layer into the local object sglst and orders the list.

In the next stage, segments are added to tracks when the entry point of the track is sufficiently near the exit point of the segment. When no appropriate track can be found for the segment a new track, composed of this one segment, is inserted into tklst.

A loop is done over all segments. As long as the exit φ value of the segment is less than cr_ent, the segment is entered as a new track. A local object tk is created, the segment s is entered and tk is pushed on tklst. The scope of tk is left at the end of the while loop and tk is automatically destroyed. This does not affect the track recently added to tklst as a copy of tk is inserted.

When the exit φ value is close enough to cr_ent, the segment is added to the current track. When the cr_ent value is less than the exit φ value of the current segment, the next track is considered until cr_ent is larger than s->exit.phi-phi_dev. Under the assumption that only one segment is found per detector and the detectors are sufficiently widely spaced, this code works well. However, if segments are close, a track may end up with two or more segments of one layer. This is in conflict with the track definition.

```cpp
class tracklist{
    vector<track> tklst; // list of tracks

public:
    void extend (layer* ly){
        float cr_ent; // entry point of current track
        vector<track>::iterator t = tklst.begin();
        if (t == tklst.end()) { cr_ent = 2*M_PI+dphi;} // empty track list
        else { cr_ent = t->entry.phi;}

        // store all segments of all detectors in layer ly into sglst
        vector<detector>::iterator d;
        for (d= ly->dts.begin(); d != ly->dts.end(); ++d){
            copy(d->seglst.begin(), d->seglst.end(), back_inserter(sglst));
            sort(sglst.begin(),sglst.end()); // sorted segments of layer ly

        // start extension of creation of tracks
        vector<segment>::iterator s= sglst.begin();
        while (s != sglst.end()){
            while ((s->exit.phi < cr_ent - phi_dev) & (s != sglst.end())){
                track tk; // new track
                tk.enter( s); s++; // track with one segment
                tklst.push_back( tk); // add new track to list
            }
        }
    }
```


```
t ++; // next track
if (t == tklist.end()) { cr_ent = 2*M_PI+dphi; }
else { cr_ent = t->entry.phi; }
} // end while ...
if (abs(s->exit.phi - cr_ent) < phi_dev) {
t->enter(s); s++;
} // extend track
} // end of if (s != ....
} // end while (s!=sglst ...

the STL convention to copy items and then store them into the vector has a profound influence on the creation and
deletion of objects. Suppose no copies were made by STL. Every time an object of class tracklist is removed, all
segments and the measurements in the segments are removed as well. Consequences are many fold: (1) possibly
all segments in the detectors are removed and a subset of all measurements are removed in the detectors, (2) to
prevent a double removal of some segments and or measurement points, measurements must be removed from the
measurement list in the detector before being put in a segment (3) same thing is true for a segment and (4) each
time a segment is moved to a track, it must be removed from the segment list in the corresponding detector.

When large elements are manipulated in the vector, it is advisable to store pointers to the elements into the vector.
This will increase the performance as much unwanted copying is suppressed. However, a lot of thought must be
put in the removal and creation of elements, as shown above.

installation The installation contains an array of layers and the tracks associated with an event. The constructor
defines the layers by invoking the layer constructors nlayer times with an appropriate radius value.

The method GetTracks determines the tracks associated with a given event passed as parameter. The former tracks
are removed by deleting the object pointed at by tklist. For all layers the measurements are assigned to the detectors
after which the tracks in tklist are extended with the segments of this layer.

```
class installation{
layer* ly[nlayer]; // nlayer layers in installation
tracklist* tklist; // list of tracks
public:
installation(){
    tklist = new tracklist();
    for (int i = 0; i < nlayer; i++) {
        ly[i]= new layer(i*(router-rinner)/nlayer + rinner);
    }
}
tracklist* GetTracks(event ev){
delete tklist; // remove old tracks
    tklist = new tracklist(); // new empty track list
    // find tracks by going from outer layer to inner layer
    for (int i = nlayer-1; i>-1; i--) {
        ly[i]->assign(ev.layer(i)); // measurements into layer i
        tklist->extend(ly[i]); // tracks include layer i segments
    }
    // measurements are assigned to layers
    return tklist;
}
};
```

### 3.5 Evaluation

Having done the detector installation, it is clear that the track returned by the SiBTOO example is not correct.
Too much information is still included in the track that is composed of two projections. SiBTOO should return
a segment. each measurement in a segment should conform with a cluster in SiBTOO converted to cylindrical
coordinates. The y-value of the horizontal clusters and the x-value of the vertical clusters need to be determined.

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An adequate point plus deviations need to be determined. Knowing that several type of detectors are possible, a base class detector with virtual methods needs to be defined. Other detector types can then be derived from detector with inheritance. A good example is the derivation of SiBTOO (see Fig. 13).

![Detector](image)

**Figure 13: Specialisation of detectors**

The use of the STL library has introduced the possibility to return the complete vector of segments from the detector. The TrackList class exploits this by copying all segment lists of all detectors in a layer in one go to another ordered segment list. Therefore, the NextSegment and FirstSegment methods defined in section 3.3 have not been used.

The structure of the event has a large influence on the design. When it can be assumed that for every event the number of data per detector is constant, the event data can be stored in a large array with pointers to the array portion that is relevant for a given detector. Every detector knows where its data area starts and how much data it is supposed to treat. Determining tracks can then be done in one go. The detector removes old results, reads in the data and constructs accompanying tracks. This is similar to what is done for SiBT but was not done in the layer example. Another assumption may be that the amount of data for a given detector can change from event to event. Then a structure needs to be added to the event. The question is whether this structure is known to the individual detectors. If the structure is unknown to the detectors (because it changes all the time) a design must be done like was done here with clean, assign and FindSegment methods. If the structure is stable but changes from layer to layer, then it is best to have each layer assign the values to the detectors.

The "Combine Segments" scenario suggested in section 3.3 is different from the one that is implemented. The scenario for the implementation discussed in section 3.4 is shown in Fig. 14.

![Main track list GetTracks Installa- tion layer detector track](image)

**Figure 14: Implemented scenario for determining a list of tracks**

The design of the layers has followed the same guidelines as for the SiBT example. However, a few things can be said about the layer design not covered by the SiBT design

- **Performance** should especially be considered in relation with the STL library. Another design step is needed to improve the performance. As suggested in the text, vectors of pointers to items instead of vectors of items can be used. Additionally, the copying of the segments of the detectors into a one vector can be avoided to diminish the copying overhead. This will render the code less comprehensible.

- **Information hiding** The layer structure is hidden from Main. The detector structure in a layer is hidden to the installation. The calculation of a track is hidden within the TrackList class. The fitting of a line through a segment is hidden inside the segment class. The measurement determination is hidden inside the vector. A
point of debate is what part of the structure of the event should be hidden.

- **Layering** The abstractions needed are much clearer after this example. An installation returns tracks. An installation is composed of layers that are composed of detectors. A detector returns segments. A track is composed of segments such that per layer at most one segment occurs. Inside a detector measurements are done and measurement points are calculated. A segment is composed of measurement points.

### 3.6 Exercises

1. Change the event structure such that the *assign* of a detector is invoked with a pointer to the event data that concern the detector. The detector should be able to recognize the end of event or know the total amount of event data that concern it. The methods *clean* and *FindSegment* are suppressed.

2. Use inheritance to define points with Cylindrical coordinates, Cartesian coordinates and Polar coordinates. Define the constructors such that for a coordinate of a given type, the values in the two other coordinate systems are defined as well. Inherit Cylindrical, Cartesian and Polar measurements from the appropriate point classes.

3. The same as above, but first inherit measurement from point and then inherit the three types of measurements. Which of the two inheritance hierarchies is the more appropriate one?

4. Change SiBTOO such that it returns segments.

5. Instead of a vector of *meas*, use a vector of pointer to *meas*. Carefully consider all creation and removals of *meas* objects. Do the same with vectors of segments.

6. Change the *insert* method in the *tracklist* class such that the copying of segments is not needed any more at the beginning.

7. Change the *insert* code such that a segment can be attributed to two tracks. This means that the track has to be copied every time another segment of the same layer is a candidate for addition to this same track.
4 Tracing example

This example builds on the layers example of section 3. It assumes the same simplified layer structure. Particles are traced through the detectors to determine their trajectory.

4.1 Tracing description

In this section the tracing of a particle trajectory is based on local decisions inside the detector. In the former example of section 3.1, tracks were determined on a layer basis. This is not done for the trajectory. A particle enters a detector at a given coordinate of a wall. It traces a trajectory until it hits the opposite or neighbouring wall of the entered detector. The intersection of the detector wall with the particle trajectory leaving the detector is called the exit point. At that point the particle enters the neighbouring detector. The exit and entry points of the particle passing through neighbouring detectors are assumed to be identical for simplicity reasons.

In Fig. 15 the additional structure required of the detectors is shown. For simplicity reasons only the plane perpendicular on the s-axis of the installation is considered. Each detector has a pointer to its upper, lower, former and forward detector. The outer and inner layer detectors have no upward or forward detector respectively.

In Fig. 15 the phi_bak pointer points to the neighbour in the same layer with a smaller \( \phi \) angle, the phi_for pointer points to the neighbour in the same layer with a larger \( \phi \) angle, r_for and r_bak point to neighbours with a larger respectively smaller layer radius.

4.2 Analysis

The classes associated with tracing, excluding the ones defined already in Fig. 9, are shown in Fig. 16. A neutral particle traces one straight trajectory through a detector from entry point to exit point. A charged particle traces one curved trajectory through a detector. A particle does not interact with the detectors. A detector has 3-4 neighbours. A particle traces as many trajectories as it passes detectors. There is a relation between the exit point of one trajectory with the entry point of the consecutive trajectory.

The following use case is considered:

1. **Particle tracing** A particle with a certain mass passes through a magnetic field that pervades the whole installation. Charged particles trace curved trajectories and neutral particles trace straight lines. A particle
enters the installation at a detector in the innermost layer. It traces a trajectory until it passes the detector wall. At the exit point it leaves the detector and enters the neighbouring detector at its entry point. The entry point of the neighbour is equal to the exit point. The particle continues its way from the entry point of the neighbouring detector until the exit point of the neighbouring detector. This continues until the particle leaves a detector at the outer layer without entering a neighbour.

4.3 Design

The scenario diagrams are used to show where the responsibilities are put for the different classes identified above. A first design decision is to hide the structure of the installation from Main that provides the entry point of a particle.

![Scenario diagram for particle tracing](image)

**Particle tracing** The central idea is to decide inside each detector which neighbouring detector is entered when the particle leaves the detector under consideration. Main provides a particle with some initial values that enters the first detector. Dependent on the mass, charge, momentum and orientation of the particle, the particle traces a curve. This curve is particle dependent and therefore the detector asks the particle to determine the intersection of the particle trace with one of the four walls. The detector determines whether the calculated intersection point lies within the detector boundaries. If not, the intersection with the next wall is calculated. When the exit point is calculated, the particle is propagated to the exit point. At the exit point, the neighbour can be found. The neighbour is asked to continue the tracing of the particle. When the particle exits the installation, the coordinates and kinetic parameters of the particle at the exit point of the installation are returned to Main.

4.3.1 Tentative class definitions

Additions to the layers example are mentioned.

**detector** The Detector class is extended with local attributes that are references to the detector’s neighbour. The B-field is a local attribute that represents the magnetic field in this detector. The method Trace starts the tracing of a particle in the detector.

**Particle** A Particle class is introduced. It has coordinates and a direction. The private attributes charge, mass and momentum determine the curvature of the particle. When the exit point of the particle’s trajectory is known, the particle’s coordinates are updated with the method Propagate to continue the tracing in the next detector. Because charged particles have a different trajectory as neutral particles, inheritance is used to differentiate the Intersect methods. The charged particle’s Intersect intersects the specified line with a curved trajectory, while the neutral particle intersects it with a straight trajectory.

**Installation** The method Trace is added to trace a particle through the installation. The particle starts at a detector in the inner layer and terminates at the outer layer. After invocation the particle’s coordinate is the exit.
point coordinate.

Detector
- list of segments
- list of measurements
- coordinates
- B-field
- neighbors
- assign(set)
- Trace(Particle)

Particle
- coordinates
- direction
- charge
- mass
- momentum
- Propagate(coordinate)

installation
- layerList
- TrackList
- Create
- GetTrack(event)
- Trace(particle)

4.4 Implementation

In the above, we have discussed an extension to the layers example. In this section the same approach is followed. First the particle tracing is considered followed by the geometry and initialisation of the detectors. The final total code is shown in appendix C and is an extension to the code in appendix B.

**vect, particle** The particle has a direction and a coordinate. In addition to *cylpoint*, the class *vect* is introduced that is an extension of *cylpoint*. The angle of direction in the plane perpendicular to the s-axis is added to the coordinate. The class *vect* inherits from the class *cylpoint*.

```cpp
class vect: public cylpoint{
    // point with direction in plane perpendicular to s
    public:
        float angle; // orientation in plane perpendicular to s
};
```

The *particle* class inherits from the *vect* class. This follows from the observation that the location and direction of the particle are intrinsic properties of the particle. Another more practical argument to use inheritance is the simplified code that is obtained to access the *vect* values of the particle. The method *Propagate* advances the particle to the coordinates and direction specified in the parameter *vc*. The method *Intersect* is virtual as the propagation of a particle trough a medium and magnetic field depends on the properties of the particle. In the particle class it is assumed that a particle needs to be described by its mass and momentum. The methods *Intersect* and *Propagate* are two separate methods as a particle can intersect with the four walls of a detector. First, it needs to be determined where the particle trajectory intersects with the detector wall. Intersection with the wall does not necessarily take place inside the detector volume. A correct intersection takes place within the detector volume. Consequently the intersection of the particle with one given wall can be chosen by invoking *Propagate* with the chosen intersection point as parameter.

```cpp
class particle: public vect{
    // physical characteristics of particle
    public:
        float mass; // particle’s mass
        float p; // particle’s momentum
    void Propagate(vect vc) {
        phi = vc.phi; r = vc.r; s = vc.s; angle = vc.angle;
    }
    virtual vect Intersect(cylpoint cc1, cylpoint cc2, float B) {
        vect vc;
        vc.phi = 4*M_PI; vc.angle =0;
        vc.r = 2*router; vc.s =0;
        return vc;
    }
};
```

Figure 18: Association realizations
neutral particle  The neutral particle is clearly a refinement of a particle. The class neutral\_particle inherits from particle. A concrete Intersect method is defined for this class. The particle is assumed to move along a straight trajectory. The particle does not interact with the surrounding material. The wall line is defined by the two parameters cc1 and cc2 that represent two corners of a detector. Some assumptions are made in this method: (1) the particle trajectory intersects the wall line within a reasonable distance (no parallel lines) and (2) the local variables tg1 and tg2 never evaluate to $\infty$. For production code these assumption cannot be made and necessitate additional coding.

class neutral\_particle: public particle{
    // neutral particle trajectory is straight line
    vect Intersect(cylpoint cc1, cylpoint cc2, float B) {
        double tgl1 = tan( angle);
        double of1 = r*sin(phi)-r*cos(phi)*tgl1;
        double tgl2 = (cc1.r*sin(cc1.phi) - cc2.r*sin(cc2.phi)) / 
            (cc1.r*cos(cc1.phi) - cc2.r*cos(cc2.phi));
        double of2 = cc1.r*sin(cc1.phi)-cc1.r*cos(cc1.phi)*tgl2;
        double x = (of2-of1)/(tgl1-tgl2);
        double y = tgl1*x + of1;
        vect vc;
        vc.s = 0;
        vc.phi = atan2(y,x);
        vc.r = sqrt(x*x + y*y);
        vc.angle = angle;
        return vc;
    }
};

charged particle  The class charged\_particle inherits from particle. The attribute charge represents the charge of the particle. It can have two values: -1 or +1. A concrete Intersect method is defined for this class. The particle is assumed to move along a circle trajectory. The particle does not interact with the surrounding material. Like for the neutral particle case, the wall line is defined by the two parameters cc1 and cc2. A simple quadratic equation determines 0, 1 or 2 intersection points. When no intersection point exists a intersection point value is returned outside the detector volume. When one of the two possible intersection points intersects the wall outside the detector volume the second intersection point is returned. Of course, this is not necessarily a point within the detector volume. A check on the correctness of the returned intersection point is done within the detector. Again, an assumption is made on the trajectory and wall line parameters: the variable $tg$ should never evaluate to $\infty$.

class charged\_particle: public particle{
    // charged particle trajectory is circle
    public:
        int charge;  // particle’s charge (+1 or -1)
    vect Intersect(cylpoint cc1, cylpoint cc2, float B) {
        double x1 = cc1.r*cos(cc1.phi);
        double x2 = cc2.r*cos(cc2.phi);
        // calculate centre coordinates of circle
        double Radius = curv*p/B;
        float xm = Radius*cos(angle+charge*M_PI/2.) + r*cos(phi);
        float ym = Radius*sin(angle+charge*M_PI/2.) + r*sin(phi);
        // calculate intersection point of line with circle
        double tg = (cc1.r*sin(cc1.phi) - cc2.r*sin(cc2.phi)) / 
            (cc1.r*cos(cc1.phi) - cc2.r*cos(cc2.phi));
        double of = cc1.r*sin(cc1.phi)-cc1.r*cos(cc1.phi)*tg;
        double a = 1+tg*tg;
        double b = 2.*tg*(of -ym)-2*xm;
        double c = xm*xm+(of-ym)*(of-ym)-Radius*Radius;
        double det = b*b - 4*a*c;
        //...
detector::trace Within a detector, a particle is traced from entry wall to exit wall. The method trace traces a particle defined by the ptk parameter. Origin and direction of trace are defined by ptk. It is assumed that a particle intersects with the lines defined by corner pairs (pt[2],pt[3]), (pt[1],pt[2]) and (pt[0],pt[3]). The intersection point with the line defined by (pt[2],pt[3]) is done first under the assumption that the outer wall is the most likely wall to be intersected. Notice that the parameter ptk can be of class charged_particle or of class neutral_particle. Once an intersection point has been found (the algorithm assumes the existence of such a point), the particle is propagated to this intersection point. By setting the detector pointer dtp equal to one of the pointers r_fw, ph_bk or ph_fw, dtp points to the appropriate neighbour detector that shares the found intersected wall. Accordingly, the detector invokes the trace method of the neighbour detector.

dummy detector To terminate the tracing, the class dummy_detector is introduced. The trace method of this class returns without doing anything and consequently terminates the tracing through all neighbouring detectors.

layer connections The wanted connection of neighbouring detectors is done in the layer. Two options are created with as many connect methods (overloading of connect).

For the method connect(layer* ly) it is assumed that the ly parameter points to the neighbouring outer layer. Two vectors of detectors are used: dts the vector of the executing layer and ly->dts the vector of the outer neighbouring layer. It is assumed (by construction) that the same number of detectors are found in both layers and that the nth detector of the one layer is the upper neighbour of the nth detector in the other layer. Connecting detectors within a layer and between two neighbouring layers is then rather straightforward.

For the method connect(detector* dup) it is assumed that the dup parameter points to the neighbouring outer detector. For the outer layer this is a pointer to a dummy_detector. The result is that when the trace is invoked of the outer neighbour of a detector in an outer layer, the tracing stops.
void connect(layer* ly){
  vector<detector>::iterator dup = ly->dts.begin();
  vector<detector>::iterator d,dbk = dts.begin();
  for (d= dts.begin(); d != dts.end(); ++d){
    dbk->ph_fw = d; d->ph_bk = dbk;
    d->r_fw = dup; dup->r_bk = d; ++dup;
    dbk = d;}
  // dbk points to last detector
  d = dts.begin(); dbk->ph_fw = d; d->ph_bk =dbk;
} // end of connect(layer)

void connect(detector* dup){
  vector<detector>::iterator d,dbk = dts.begin();
  for (d= dts.begin(); d != dts.end(); ++d){
    dbk->ph_fw = d; d->ph_bk = dbk;
    d->r_fw = dup;
    dbk = d;}
  // dbk points to last detector
  d = dts.begin(); dbk->ph_fw = d; d->ph_bk =dbk;
} // end of connect(detector)

installation::Trace
The tracing of a particle is started by invoking the Trace method of the installation for a suitably chosen particle. It is assumed that such a particle is chosen to be on the inner wall of a detector in the inner layer. The detector with the right angle is found by invoking the STL find function that acts on the vector of detectors till it finds a detector that is equal to key. The equal operator on detectors is defined to operate on the phi attribute of the pt[0] corner of the detector. The detector key is defined to be the detector with the wanted pt[0].phi value. The consequence is that after invocation of find, the where variable points to the specified detector. When no such detector is found, where points to dts.end().

Invoking the trace method of the found detector starts the tracing. Tracing ends when the particle enters a dummy_detector on leaving the outer layer.

void Trace(particle& ptk){
  float phip = ptk.phi+dphi;
  phip = int(phip/(2*dphi))*2*dphi;
  detector key = detector(rinner,phip);
  vector<detector>::iterator where = find(ly[0]->dts.begin(),
  ly[0]->dts.end(), key);
  if (where != ly[0]->dts.end()) {where->trace(ptk);}
  else { cout << " COULD NOT FIND DETECTOR for Tracing \n" << flush;}
}

Invocation from Main
The invocation from Main is shown here. In trlst->tklst a set of tracks is returned by GetTracks. The inner intersection point of each track is used as starting point for the particle tracing. Particles with different momenta and masses can be traced to determine whether their exit points are in accordance with the particle trajectory exit point contained in cptk after termination of Trace.

tracklist* trlst = instal.GetTracks(ev);
vector<track>* vt = &(trlst->tklst);
vector<track>::iterator t;
charged_particle cptk;
cptk.charge = -1;
cptk.mass = 1;
cptk.p = 1;
for (t = vt->begin(); t != vt->end(); t++)
{ cptk.phi = t->entry.phi;
  cptk.r = t->entry.r;
  cptk.s = t->entry.s;
  dx = t->exit.r*cos(t->exit.phi)-cptk.r*cos(cptk.phi);
\begin{align*}
dy &= t->exit.r*\sin(t->exit.phi)-cptk.r*\sin(cptk.phi); \\
cptk.angle &= \text{atan2}(dy,dx); \\
\text{instal.Trace}(cptk); \\
\end{align*}

4.5 Evaluation

The layer design was such that the extension for particle tracing could be added without problems. No modifications to the general structure were needed. A problematic area is the design of the particles class in relation with the detector class. The trajectory of the particle is determined by the physical properties of the particle and the material of the detector. Assuming that there are more particle variants than detector materials, the detector characteristics are taken as parameter for the particle trace trajectory. This way particles can be added for the known set of detector textures.

![Figure 19: Volume and detector class](image)

In the above, the empty space between detectors was neglected. In Fig. 15 it is assumed that detectors touch each other. This is not the case. Between a layer of detectors, there is a layer of air of a given thickness represented by the constant \( rspace \) in the code. In Fig. 19, a more appropriate design is presented. A volume is defined by its corner points. A particle is traced through a volume with a certain magnetic field and of a given texture. A detector inherits from the volume and contains a number of measurements and segments. The installation consists of layers of detectors separated by a layer of air volumes.

Some points need special attention:

- **Coordinate system** Maintaining a cylindrical coordinate system proves to be rather calculation intensive. Using cylindrical coordinates only to define the layers and detectors is sufficient. A Cartesian coordinate system looks better in all other cases.

- **Information hiding** The installation class and the layer class do not know about the propagation of a particle. A particle can pass from a detector in one layer to a detector of another or same layer without awkward case sensitive statements.

- **Performance** Performance can be improved by looking at the chosen coordinate system and chosen tracing algorithm. This can be done without any modification to the total structure.

4.6 Exercises

1. Store the detector coordinates in a Cartesian coordinate system. What other classes need to be modified.

2. Modify the Intersect methods such that they work under any circumstance without overflow problems.

3. Change the finding of the wanted detector in the Trace method in the installation class:

   - by doing a loop over all detectors and testing their corner pt[0] angle,
   - by using find and specifying another equal operator.

4. Add the volume class as suggested above and change the installation to include layers of air.
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References


A SiBTOO code

#include <stdlib.h>
#include <iostream.h>
#include <math.h>

// standard definition of NULL and bool
const int null = 0;
#define bool int
#define true 1
#define false 0

//definition of contants for SiBT geometry
const int nplane = 8; // number of planes in SiBT
const float sbt_ds = 200.; // length of SiBT over s-axis
const float sbt_dx = 40.; // width of SiBT over x-axis
const float sbt_dy = 38.; // height of SiBT over y-axis
const float length = .003; // length of strip over s-axis
const int nstrip = 1024; // number of strips
const float xwidth = .9*sbt_dx/nstrip; // width of strip in x direction
const float ywidth = .9*sbt_dy/nstrip; // width of strip in y direction
const int hitquot = 3; // hit is represented by val/noise > hitquot
const float linchi = 10.; // chi of accepted line fit

// definition of classes

template<class T> class list{
// parametrized class List
// singly linked list of items
// initialized with zero items, with head and cur initialized to null
protected:
    class Link{
    public:
        Link* next;
        T* val;
        Link(Link* n, T* v) {next = n; val = v; }
    };
    Link* head; // head of singly linked list
    Link* cur; // last selected item

public:
    int number; // number of items in list
    list() {head = null; cur=null; number=0; }
    ~list(){
        while ( head != null){
            cur = head;
            delete head->val;
            head = head->next;
            delete cur;
        }
    }
    void enter(T* item) {
        Link* temp = head;
        if (item != null){
            head = new Link( temp, item);
            number ++;
        }
    }
    T* first() {cur=head;
if (cur != null) {return (cur->val);}
else { return null;}

T* next() {
if (cur != null){
    cur = cur->next;
    if (cur != null){return (cur->val);}
    else {return null;}}
else {return null;}
};
T* current() {
    if (cur != null){ return (cur->val);}
    else {return null;}
};
bool sequel(){
    if (cur == null){ return false;}
else {return cur->next != null;}};
void remove(T* item) {
    Link** temp = &head; // temp contains the location of the pointer to the item
    // temp is initialized with the location of head
    for (Link** temp = &head; *temp == null; temp = &(*temp)->next){
        if ((*temp)->val == item){
            Link* rm = *temp;
            delete item;
            delete rm;
            temp = &((*temp)->next);
            if (cur == *temp) cur = null; // cur points to removed item,
            // so cur is set to null
        }
    }
};
#endif DEBUG
void print(){
    cout << " list with " << number " entries \n" << flush;
    int k =0;
    Link* temp = head;
    while (temp != null){
        if ( cur == temp) { cout << "current ";}
        else { cout << " ";}
        cout << " item "<< ++k << ": " << flush;
        temp->val->print();
        temp = temp->next;
    }
};

class coord{
public:
    float x,y,z;
};
class channelset{
    int items[50];
    int as;
    public:
        channelset(){
            as = 0;
            for( int i =0; i<50; ++i) {items[i] = 0;}
    }
    int strip(int pl, int st) {
        for (int i = 0; i<as ; i = i+3){

    }}
if (items[i] == pl)
    return items[i+st]; // hit of channel pl found
}
return 1; // no hit found
// (minimum noise of 1 to prevent div by zero

void assign( int strip, int value, int noise){
    items[as] = strip; as++;
    items[as] = value; as++;
    items[as] = noise; as++;
}
#endif

class event{
    channelset set[8]; // 1 event: 8 channel sets for 8 planes
public:
    event(){
        for (int pl = 0; pl <8 ; ++pl){
            if (pl != 2) {
                set[pl].assign(40+abs(pl-4),20,4);
                set[pl].assign(41+abs(pl-4),21,5);
                set[pl].assign(42+abs(pl-4),35,6);
                // set[pl].assign(254+abs(pl-4),59,8);
                set[pl].assign(255+abs(pl-4),63,9);
            }
        }
        /*
        if (pl != 2){
            set[pl].assign(40,20,4);
            set[pl].assign(41,21,5);
            set[pl].assign(42,35,6);
            // set[pl].assign(254,59,8);
            set[pl].assign(255,63,9);
        }
        */
}
    channelset plane(int pl){ return set[pl];}
#endif DEBUG

void print(){
    cout << " EVENT print \n";
    for (int i =0; i<8; ++i){
        cout << " Plane " << i+1 << " \n" << flush;
        set[i].print();
    }
    cout<< " -------- End Event \n \n" << flush;
}
#endif
class strip {
public:
    int noise;
    int value;
    float dist; //distance from origin
float width; // width of strip
float length; // length of strip over s-axis

class cluster{
  protected:
    coord cc; // coordinates of cluster
  public:
    float size; // number of hits (>1)
    float weight; // weight =0 for dummy cluster
    float s_c; // coordinate along s_axis (z_axis)
    float t_c; // coordinate along transverse axis (x_ or y_ axis)
    cluster(float cx, float cy, float cs, float sz)
      { cc.x = cx; cc.y = cy; cc.z = cs; weight =1.; size = sz; }
    #ifdef DEBUG
    virtual void print(){
        cout << "Cluster " << "t: " << t_c << " s: "
        << s_c << " size: " << size << " \n" << flush;
    }
    #endif
};

class h_cluster: public cluster{
  public:
    h_cluster(float cx, float cs, float sz)
      :cluster(cx,0.,cs,sz) { // y-coordinate =0
        t_c = cx; s_c = cs; }
    #ifdef DEBUG
    void print(){
        cout << "Horizontal " << flush; cluster::print();
    }
    #endif
};

class v_cluster: public cluster{
  public:
    v_cluster(float cy, float cs, float sz)
      :cluster(0.,cy,cs,sz) { // x-coordinate = 0
        t_c = cy; s_c = cs; }
    #ifdef DEBUG
    void print(){
        cout << " Vertical " << flush; cluster::print();
    }
    #endif
};

class plane {
  protected:
    list<cluster>* clusters; // cluster set
    strip sl[nstrip]; // array of strips
    float x,y,s; // coordinates of lower left corner of plane
    float mean; // statistics
    int nr; // number of entries
  public:
    plane(coord c){
      clusters = new list<cluster>; // empty cluster list to allow access to clusters
      x = c.x; y=c.y; s = c.z; // coordinates of plane
      mean = 0.; nr = 0.; //statistics for calibration
      for (int i = 0; i<nstrip; ++i) {
        sl[i].value = 0;
        sl[i].noise = 1; // to prevent division by zero
    
    #ifdef DEBUG
      virtual void print(){
        cout 
    
    #endif
  }
cluster* first() {return clusters->first();};
cluster* get() {return clusters->current();};
cluster* next() {return clusters->next();};
bool sequel() { return clusters->sequel(); }
void assign(channelset s);
void clearstatistics() { mean = 0.; nr = 0.; }
float meandev() { return mean; }
float scoord() { return s; }
virtual void storealignment(float cc)();
void adddeviation(float dt){
    if (nr == 0) {mean = dt; nr = 1;}
    else { mean = mean*(nr/(nr+1)); nr ++; mean = mean+(dt/nr); };
}
virtual void addcluster(float t_c, float s_c, float sz) {};

#ifdef DEBUG
virtual void print(){
    cout << "PLANE coordinates:: " << "x: " << x << " y: " << y << " s: " << s << " \n";
    for (int i = 0; i<nstrip; ++i) {
        if (sl[i].strip > 0) {
            cout << " stripe: " << i << " value: " << sl[i].value << " noise: " << sl[i].noise << " distance: " << sl[i].dist << " \n" << flush;}
    }
}
#endif

void plane::assign(channelset ss) {
    for (int i = 0; i<nstrip; ++i) { // strip value and noise from channelset
        sl[i].value = ss.strip(i,1);
        sl[i].noise = ss.strip(i,2); // strips initialized
    }
delete clusters; // remove former clusters
    clusters = new list<cluster>; // empty cluster list
    for (i = 0; i<nstrip; ++i) { // determine clusters
        if (sl[i].value/sl[i].noise > hitquot){
            float total = sl[i].value - sl[i].noise;
            float posit = sl[i].dist*total;
            int k = i+1;
            bool b = (k < nstrip);
            if (b) { b = b & sl[k].value/sl[k].noise > hitquot; }
            while (b) {
                total += sl[k].value - sl[k].noise;
                posit += sl[k].dist *float( sl[k].value - sl[k].noise);
                k++;
                b = (k < nstrip);
            }
            if (b) { b = b & sl[k].value/sl[k].noise > hitquot; }
        }
        k--; // k always one too large
        if (k > i) {
            // more than two consecutive hits, add cluster
            addcluster(posit/total, s,
                sl[k].dist - sl[i].dist + sl[k].width);
            i = k+1; // skip already inspected strips
        }
    }
}

class h_plane: public plane{
public:
  h_plane(coord cc): plane(cc) {
    for (int i = 0; i<nstrip; ++i) {
      sl[i].dist = xwidth*float(i); // x-position of strips from x=0
      sl[i].width = xwidth; // dx width of strips
      sl[i].length = length; // thickness of strip over s-axis
    }
  }
  void addcluster(float t_c, float s_c, float sz) {
    // add x coordinate of plane to position within plane
    h_cluster* h_cl = new h_cluster(t_c+x, s_c, sz);
    clusters->enter( h_cl);
  }
  void storealignment(float cc){ x = x+cc;};
  #ifdef DEBUG
  void print(){
    cout << " HORIZONTAL ";
    plane::print();
    cout << " clusters are: \n";
    clusters->print();
    cout << " --------------------- H_PLANE \n \n" << flush;
  }
  #endif
};

class v_plane: public plane {
public:
  v_plane(coord cc): plane(cc) {
    for (int i = 0; i<nstrip; ++i) {
      sl[i].dist = ywidth*float(i); // y-position of strips from y=0
      sl[i].width = ywidth; // y-width of strips
      sl[i].length = length; // length of strip over s-axis
    }
  }
  void addcluster(float t_c, float s_c, float sz) {
    // add y coordinate of plane to position within plane
    v_cluster* v_cl = new v_cluster(t_c+y, s_c, sz);
    clusters->enter( v_cl);
  }
  void storealignment(float cc){ y = y+cc;};
  #ifdef DEBUG
  void print(){
    cout << " VERTICAL ";
    plane::print();
    cout << " clusters are: \n";
    clusters->print();
    cout << " --------------------- V_PLANE \n \n" << flush;
  }
  #endif
};

class s_line{
public:
  float s_off;
  float ts_tg;
  float chi;
  s_line(float xt,float yt,float of){
    s_off = of; ts_tg = yt; chi = 0;}
  bool fit(list<cluster>* proj) {
    cluster* clpt = proj->first();
    int ncl = 0;
    // number of clusters

  }
};
float S_s = 0.;
float S_ss = 0.;
float S_t = 0.;
float S_tt = 0.;
float S_st = 0.;

while (clpt != null) {
    if (clpt->weight > 0) {
        ncl = ncl + 1; // number of entries
        S_s = S_s + clpt->s_c; // sum over s
        S_t = S_t + clpt->t_c; // sum over t
        S_ss = S_ss + clpt->s_c * clpt->s_c; // sum over s*s
        S_st = S_st + clpt->s_c * clpt->t_c; // sum over t*s
        S_tt = S_tt + clpt->t_c * clpt->t_c; // sum over t*t
    }
    clpt = proj->next();
}

if (ncl < 3) { return false; } // at least three coordinates required

float det = float(ncl)*S_ss - S_s*S_s;
if (det <= 0) { return false; }
s_off = (S_ss*S_t - S_s*S_st)/det;
ts_tg = (ncl*S_st - S_s*S_t)/det;
chi = S_tt - s_off*S_t - ts_tg*S_st;
return abs(chi) < linchi;

#endif DEBUG
void print(){
    cout << "LINE ts_tg: " << ts_tg << " s_off: "
    << s_off << " chi: " << chi << " \n" << flush;
}
#endif

class projection{
protected:
    list<cluster>* clp; // pointer associated cluster
    s_line line; // fitted line
public:
    projection(): line(0,0,0) { clp = new list<cluster>; }
    ~projection(){ delete clp; }
    bool valid(){ return line.fit(clp); }
    float tline( float sc){ return line.ts_tg*sc + line.s_off; }
    void AddDev( plane* planes[]){
        cluster* cp = clp->first();
        int i = (nplane/2)-1;
        while (cp != null) { // assume that clusters come from 4,3,2,1
            while (cp->s_c != planes[i]->scoord() & i >0) { i--; }
            planes[i]->adddeviation(cp->t_c - tline(cp->s_c));
            cp = clp->next(); } // end while over clusters
    }
}
#ifdef DEBUG
virtual void print(){
    cout << " projection \n" << flush;
    clp->print();
    line.print();
}
#endif

class v_projection: public projection{
public:
    #ifdef DEBUG
    void print () {
cout <<" VERTICAL ";
    projection::print();
}
#endif
};

class b_projection: public projection{
public:

#ifdef DEBUG
    void print () {
        cout <<" HORIZONTAL ";
        projection::print();
    }
#endif
};

class projlst {
protected:
    list<projection>* lp;
    projlst () { lp = null;}
    ~projlst () { if (lp != null) { delete lp;} }
public:
    projection* first() { return lp->first();}
    virtual projection* newproj() { return new projection();}
    int number() { return lp->number();}
    virtual void FindProj(plane* planes[]){
// find the list of projections in array of planes
    bool b = false;
    projection* pp = newproj();
    for (int i = 0; i<4; ++i){
        pp->add(planes[i]->first());
        b = b | planes[i]->sequel();} // more than one cluster in plane?
        // b implies there is a plane with more than 1 cluster
        // not b implies all planes have less than 2 clusters
    if (pp->valid()){lp->enter(pp);} // if good projection add to lvp
    else {delete pp;} // else remove contents and memory
    // try all possible cluster combinations from vertical planes that have clusters
    cluster* cp;
    while (b){
        pp = newproj();
        b = false;
        bool sw = true;
        // sw implies get next cluster from plane or first one
        // not sw implies get current cluster from plane
        for (i = 0; i<4; ++i){
            if (sw) {cp = planes[i]->next();}
            else { cp = planes[i]->get();}
            if (cp == null) { cp = planes[i]->first();}
            else { sw = false;}
        }
        // sw remains true when when first cluster was taken from former plane
        pp->add(cp);
        b = b | planes[i]->sequel();} // end for (i=0; i<4)
        // not b implies last cluster is found in all planes
    if (pp->valid()){lp->enter(pp);}
else {delete pp;}
} // end of while(b)
} // end of FindProj

#ifdef DEBUG
virtual void print() {
    cout << "projection list \n";
    if (lp==null) {cout << " no list present \n";}
    else {lp->print();}
}
#endif
};

class v_projlst: public projlst {
protected:
    projection* newproj(){ return new v_projection();}
public:
    void FindProj(plane* planes[]){
        // find the list of projections in array of vertical planes
        delete lp; // remove old list
        lp = (list<projection>*) new list<h_projection>;<br>
        projlst::FindProj( planes);
    }
#ifdef DEBUG
    void print() {
        cout << " Vertical ";
        projlst::print();
    }
#endif
};

class h_projlst: public projlst {
protected:
    projection* newproj(){ return new h_projection();}
public:
    void FindProj(plane* planes[]){
        // find the list of projections in array of vertical planes
        delete lp; // remove old list
        lp = (list<projection>*) new list<h_projection>;<br>
        projlst::FindProj( planes);
    }
#ifdef DEBUG
    void print() {
        cout << " Horizontal ";
        projlst::print();
    }
#endif
};

class track{
    projection* hpr;
    projection* vpr;
public:
    track(projection* h, projection* v) {hpr = h; vpr = v;}
    ~track() { delete hpr; delete vpr;}
    projection* hproj() {return hpr;}
    projection* vproj() {return vpr;}
}
#ifdef DEBUG
void print()
{
    cout << " TRACK \n" << flush;
    if (hpr != null) (hpr->print());
    else { cout << " no horizontal projection \n" << flush;}
    if (vpr != null) {vpr->print();}
    else { cout << " no vertical projection \n" << flush;}
}
#endif

};

class SiBTOO{
plane* hplanes[nplane/2]; // 4 horizontal planes
plane* vplanes[nplane/2]; // 4 vertical planes
h_projlst* lhp; // list of horizontal projections
v_projlst* lvp; // list of vertical projections
public:
SiBTOO() {
    // initialize with 0 projections
    lhp = new h_projlst();
    lvp = new v_projlst();
    //initialize plane coordinates
    for (int i = 0; i<nplane/2; ++i)
    {
        coord cc;
        cc.z = 2*i*(sbt_ds-0.05)/nplane;// s-coordinate
        cc.x = .1; // x-coordinate
        cc.y = cc.x; // y coordinate
        vplanes[i] = new v_plane(cc); // vertical plane
        cc.z = cc.z+.05; // s-coordinate
        // (slightly different from
        // vertical plane s-coordinate)
        hplanes[i] = new h_plane(cc);} // horizontal plane
}
track* FindTracks(event ev){
for (int i = 0; i<nplane/2; ++i)
    {vplanes[i]->assign(ev.plane(i*2)); // vertical plane strips assigned
     hplanes[i]->assign(ev.plane(i*2+1));} // horizontal plane strips assigned
    // clusters of event are found and stored in planes
    // VERTICAL projections
    lvp->FindProj( vplanes); // lvp contains vertical projections
    // HORIZONTAL projections
    lhp->FindProj( hplanes); // lhp contains horizontal projections
    // only one projection from each orientation is allowed
    if(lhp->number() == 1 & lvp->number() == 1)
    {return new track(lhp->first(), lvp->first());}
    else { return null;}
}
void Calibrate(list<track>* lst){
for (int i = 0; i<nplane/2; ++i)
    {vplanes[i]->clearstatistics();
     hplanes[i]->clearstatistics();}
track* trp = lst->first(); // get first track from list
while (trp != null) { // loop over all tracks

// horizontal projections
    trp->hproj()->AddDev( hplanes);
// vertical projections
    trp->vproj()->AddDev( vplanes);

    trp = lst->next(); // end while over all tracks
}

// realign planes
for (i = 0; i<nplane/2; ++i){
    hplanes[i]->storealignment(-hplanes[i]->meandev());
    vplanes[i]->storealignment(-vplanes[i]->meandev());
}

#ifdef DEBUG
    void print(){
        lhp->print();
        lvp->print();
        for (int i = 0; i<nplane/2; i++){
            vplanes[i]->print();
            hplanes[i]->print();
        }
    }
#endif

int main()
{
    SiBTOO sbt; // some well chosen values
    event ev; // some well chosen values
    list<track>* lst = new list<track>; //initialize SiBTOO
    #ifdef DEBUG
        ev.print(); // print event contents
        sbt.print(); // print all plane contents of SiBTOO
        cout << "\n Track list first time \n\n\n" << flush;
        lst->print(); // print all tracks
    #endif
    lst->enter( sbt.FindTracks(ev)); // find one track
    #ifdef DEBUG
        sbt.print();
        cout << "\n Track list 2nd time\n\n\n" << flush;
        lst->print();
    #endif
    sbt.Calibrate(lst); // calibrate with one track
    #ifdef DEBUG
        sbt.print();
    #endif
    lst->enter( sbt.FindTracks(ev)); // find same track in calibrated SiBTOO
    #ifdef DEBUG
        sbt.print();
        cout << "\n Track list 3rd time\n\n\n" << flush;
        lst->print();
    #endif

cout << " main stopped\n";
# B Layer code

```cpp
#include <stdlib.h>
#include <iostream.h>
#include <math.h>
#include <vector.h>
#include <algo.h>

// standard definition of NULL and bool
const int null = 0;

// constants for detector installation
const int nlayer = 8; // number of layers in installation
const int ndetct = 16; // number of detectors in layer
const float rinner = 20.; // inner radius of installation
const float router = 40.; // outer radius of installation
const float rspace = .2; // space between two layers
const float detcdr = (router - rinner)/nlayer - rspace; // thickness of detector
const float detcds = 6.2; // length of detector over s-axis
const float dphi = M_PI /ndetct; // angle over which detector extends

// constants for event layout
const int nr_det = 3; // 3 entries per detector in event

// acceptance limits and allowed deviations
const float linchi = 10.; // chi of accepted line fit
const float phi_dev = dphi/100.; // tolerated segment deviations

class cylpoint{
    // point in cylindrical coordinate system
    public:
    float r; // r coordinate
    float phi; // phi angle coordinate
    float s; // cylinder axis coordinate
};

class measur: public cylpoint{
    // measurement point in cylindrical coordinate system
    public:
    float dr, ds, dphi; // measurement uncertainties in above
};

// Define == on measur objects
bool operator==(const measur& m1, const measur& m2)
{
    return m1.phi == m2.phi;
}

// Define < on measur objects
bool operator<(const measur& m1, const measur& m2)
{
    return m1.phi < m2.phi;
}

class layerset{
    float items[50];
    int as, k;
    public:
    layerset()
    {
        k = 0;
    
```
as = 0;
for (int i = 0; i < 50; ++i) {items[i] = 0.;}

float* detect(float phi) {
    for (int i = k; i < as; i = i + nr_det) {
        if (items[i] > phi & items[i] < phi + 2 * dphi) {
            k = i + nr_det;
            return &items[i];} // coordinate in detector with
            // angle phi
        }
    k = 0; // start from beginning
    return null; // no hit found
}

void assign(float phi, float r, float s) {
    items[as] = phi; as++;
    items[as] = r; as++;
    items[as] = s; as++;
}

#ifdef DEBUG
    void print() {
        int i = 0;
        while (i < as) {
            cout << " angle: " << items[i] << " r: " << items[i+1] << " s: " << items[i+2] << "\n" << flush;
            i = i + nr_det;
        }
    } // end define DEBUG
#endif

class event {
    layerset set[nlayer]; // 1 event: nlayer layersets
public:
    event() {
        for (int pl = 0; pl < nlayer; ++pl) {
            set[pl].assign(M_PI/4 + 0.5 * dphi,
                    pl*(router-rinner)/nlayer+rinner+detcdr*.25, 0);
            set[pl].assign(M_PI/4 + 0.5 * dphi,
                    pl*(router-rinner)/nlayer+rinner+detcdr*.3, 0);
            set[pl].assign(M_PI/4 + 0.5 * dphi,
                    pl*(router-rinner)/nlayer+rinner+detcdr*.5, 0);
            set[pl].assign(M_PI/4 + 0.5 * dphi,
                    pl*(router-rinner)/nlayer+rinner+detcdr*.66, 0);
            set[pl].assign(M_PI/4 + 0.5 * dphi,
                    pl*(router-rinner)/nlayer+rinner+detcdr*.75, 0);
    }
    layerset layer(int pl) { return set[pl];}
}
#ifdef DEBUG
void print(){
    cout << " EVENT print \n";
    for (int i =0; i<nlayer; ++i){
        cout << " Layer " << i << " \n" << flush;
        set[i].print();
    }
    cout<< " --------- End Event \n \n" << flush;
}
#endif

class segment{
public:
    vector<measur> points;
    cylpoint entry;
    cylpoint exit;

    void enter(measur* m){ points.push_back(*m);}
    bool valid(float r,float phi) {
        float s_off, of;
        float ts_tg, tg;
        float chi;
        float s,t; // coordinates after transformations
        int nms =0; // number of measurements
        float S_s = 0.;
        float S_ss = 0.;
        float S_t = 0.;
        float S_tt = 0.;
        float S_st = 0.;
        if (points.begin() != points.end()){ // at least three coordinates required
            vector<measur>::iterator m;
            for (m= points.begin(); m != points.end(); ++m){
                nms = nms + 1; // number of entries
                s = m->r*cos(m->phi);
                t = m->r*sin(m->phi);
                S_s = S_s + s; //sum over s
                S_t = S_t + t; //sum over t
                S_ss = S_ss+s*s; //sum over s*s
                S_st = S_st+t*s; //sum over t*s
                S_tt = S_tt+t*t;} //sum over t*t
            if (nms < 3){ return false;} // at least three coordinates required
            float det = float(nms)*S_ss - S_s*S_s ;
            if (det <= 0) { return false;}
            s_off = (S_ss*S_t - S_s*S_st)/det;
            ts_tg = (nms*S_st - S_s*S_t)/det;
            chi = S_tt-s_off*S_t - ts_tg*S_st;
            entry.s = 0; exit.s = 0; // default values
            tg = (sin(phi)-sin(phi+2.*dphi))/(cos(phi)-cos(phi+2.*dphi));
            // inner layer, entry point
            of = r*sin(phi)-tg*r*cos(phi);
            s = (s_off-of)/(tg-ts_tg);
            t = tg*s+of;
            entry.r = sqrt(s*s + t*t);
            entry.phi = atan2(t,s);
            // outer layer exit point
            r = r+detr+rspace;
            of = r*sin(phi)-tg*r*cos(phi);
            s = (s_off-of)/(tg-ts_tg);
            t = tg*s+of;

            // calculate entry and exit points of line
            entry.s = 0; exit.s = 0; // default values
            tg = (sin(phi)-sin(phi+2.*dphi))/(cos(phi)-cos(phi+2.*dphi));
            // inner layer, entry point
            of = r*sin(phi)-tg*r*cos(phi);
            s = (s_off-of)/(tg-ts_tg);
            t = tg*s+of;
            entry.r = sqrt(s*s + t*t);
            entry.phi = atan2(t,s);

            // outer layer exit point
            r = r+detr+rspace;
            of = r*sin(phi)-tg*r*cos(phi);
            s = (s_off-of)/(tg-ts_tg);
            t = tg*s+of;

        }
    }
}

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exit.r = sqrt(s*s + t*t);
exit.phi = atan2(t,s);

return abs(chi) < linchi;
}

// Define == on segment objects
bool operator==(const segment& s1, const segment& s2)
{
    return s1.exit.phi == s2.exit.phi;
}

// Define < on segment objects
bool operator<(const segment& s1, const segment& s2)
{
    return s1.exit.phi < s2.exit.phi;
}

class track{
    vector<segment> trk; // segments that constitute track
public:
    cylpoint entry;
    cylpoint exit;
    void enter(segment* s){
        entry = s->entry;
        if (trk.begin() == trk.end()){ exit = s->exit;}
        trk.push_back( *s);
    }
    #ifdef DEBUG
    void print(){
        cout << "TRACK with entry.phi: " << entry.phi << " exit.phi: " << exit.phi << "\n";
        cout << " entry.r: " << entry.r << " exit.r: " << exit.r << "\n";
        vector<segment>::iterator sg;
        for (sg= trk.begin(); sg != trk.end(); ++sg){
            cout << " segment exit phi: " << sg->exit.phi;
            cout << " exit r: " << sg->exit.r << "\n" << flush;
            cout << " segment entry phi: " << sg->entry.phi;
            cout << " entry r: " << sg->entry.r << "\n";
        }
    }
    #endif
}

// Define == on track objects
bool operator==(const track& t1, const track& t2)
{
    return t1.entry.phi == t2.entry.phi;
}

// Define < on track objects
bool operator<(const track& t1, const track& t2)
{
    return t1.entry.phi < t2.entry.phi;
}

class detector{
public:
    cylpoint pt[8]; // detector defined by 8 points in space
    vector<segment> seglst; // list of segments
    vector<measur> measlst; // list of measurements
    detector() { }
};
detector(float r, float phi){
    for (int i = 0 ; i< 4; i++) {pt[i].s = 0; pt[i+4].s=detcds;}
    pt[0].r = r; pt[1].r = r;
    pt[4].r = r; pt[5].r = r;
    pt[2].r = r+detcdr; pt[3].r = r+detcdr;
    pt[6].r = r+detcdr; pt[7].r = r+detcdr;
    pt[0].phi = phi - dphi; pt[4].phi = phi- dphi;
    pt[3].phi = phi - dphi; pt[7].phi = phi- dphi;
    pt[1].phi = phi + dphi; pt[5].phi = phi+ dphi;
    pt[2].phi = phi + dphi; pt[6].phi = phi+ dphi;
} // end of detector constructor
void add(measur m){measlst.push_back( m);} 
void clean(){
    // remove all segments and measurements
    seglst.erase(seglst.begin(),seglst.end());
    measlst.erase(measlst.begin(),measlst.end());
} // end of clean
void FindSegment(){
    if (measlst.begin() != measlst.end()){
        // measurements present
        segment sg;
        vector<measur>::iterator m;
        for (m= measlst.begin(); m != measlst.end(); ++m){
            sg.enter(m); // all measurements in one segment
            if (sg.valid(pt[0].r,pt[0].phi)){seglst.push_back(sg);}
        } // end of if (measlst...
    } // end of FindSegment

#define DEBUG
void print(){
    cout << " Detector ";
    cout << " pt[0].phi: " << pt[0].phi << " pt[0].r: " << pt[0].r;
    cout << " \n" << flush;
    if (seglst.size() !=0){
        vector<segment>::iterator sg;
        for (sg= seglst.begin(); sg != seglst.end(); ++sg){
            cout << " segment entry phi: " << sg->entry.phi;
            cout << " entry r: " << sg->entry.r << "\n";
            cout << " segment exit phi: " << sg->exit.phi;
            cout << " exit r: " << sg->exit.r << "\n" << flush;}
    } // end of if (seglst.size ...
    if (measlst.size() !=0){
        vector<measur>::iterator m;
        for (m= measlst.begin(); m != measlst.end(); ++m){
            cout << " measurement r: " << m->r << " phi: " << m->phi << " \n" << flush;}
    } // end of if
} // end of print
#endif

// Define == on detector objects
bool operator==(const detector& d1, const detector& d2) {
    return d1.pt[0].phi == d2.pt[0].phi;
} // Define < on detector objects
bool operator<(const detector& d1, const detector& d2) {
    return d1.pt[0].phi < d2.pt[0].phi;
class layer{
  public:
    vector<detector> dts;
  
    layer(float ri) {
      // create a layer with inner circle defined by ri
      for (int i=0; i < ndetct; i++) {
        dts.push_back(*new detector(ri, dphi*i*2));
      }
      sort(dts.begin(), dts.end(), less<detector>());
    }
  
    void assign(layerset ls) {
      float* pm;
      measur m;
      m.dr = 0; m.dphi = 0; m.ds = 0;
      vector<detector>::iterator d;
      for (d=dts.begin(); d != dts.end(); ++d) {
        d->clean();  // remove segments and measurements
        pm = ls.detect(d->pt[0].phi);
        while (pm != null) {
          m.phi = pm[0];
          m.r = pm[1];
          m.s = pm[2];
          d->add(m);
          pm = ls.detect(d->pt[0].phi);  // end of while
        }
        d->FindSegment();  // construct segments
      }
    }

    #ifdef DEBUG
    void print() {
      int i = 1;
      vector<detector>::iterator d;
      for (d=dts.begin(); d != dts.end(); ++d) {
        cout << i; i++;
        d->print();
      }
    }
    #endif
  
};

class tracklist{
  vector<track> tklst;  // list of tracks
  
  public:
    void extend (layer* ly) {
      float cr_ent; // entry point of current track
      vector<track>::iterator t = tklst.begin();
      if (t == tklst.end()) { cr_ent = 2*M_PI+dphi; }  // empty track list
      else { cr_ent = t->entry.phi; }

      // store all segments of all detectors in layer ly into sglst
      vector<segment> sglst;  // list of segments in layer ly
      vector<detector>::iterator d;
      for (d = ly->dts.begin(); d != ly->dts.end(); ++d) {
        copy(d->seglst.begin(), d->seglst.end(), back_inserter(sglst));
      }
      sort(sglst.begin(), sglst.end());  // sorted segments of layer ly

      // start extension of creation of tracks
      vector<segment>::iterator s = sglst.begin();
      while (s != sglst.end()) {
        track tk;  // new track
        tk.enter(s); s++;
        tklst.push_back(tk);  // add new track to list
      }
    }

};
while ( cr_ent < s->exit.phi-phi_dev)
    t ++; // next track
    if (t == tklist.end()) ( cr_ent = 2*PI+dphi;)
    else ( cr_ent = t->entry.phi;)
} // end while ...
if (abs(s->exit.phi - cr_ent) < phi_dev) {
    t->enter( s); s++;} // extend track
} // end of if (s != ....
} // end while (s!=sglst ...
sort(tklst.begin(),tklst.end());
} //end extend

#ifdef DEBUG
void print(){
    cout << "TRACK LIST \n";
    int cnt = 1;
    vector<track>::iterator t;
    for (t= tklist.begin(); t != tklist.end(); ++t){
        cout << cnt << " " ; cnt++;
        t->print();
    }
}
#endif

class installation{
    layer* ly[nlayer]; // nlayers in installation
    tracklist* tklist; // list of tracks
public:
    installation(){
        tklist = null;
        for (int i = 0; i <nlayer; i++) {
            ly[i]= new layer(i*(router-rinner)/nlayer + rinner; )
        }
    tracklist* GetTracks(event ev){
        delete tklist; // remove old tracks
        tklist = new tracklist(); // new empty track list
        // find tracks by going from outer layer to inner layer
        for (int i = nlayer-1; i>-1; i--) {
            ly[i]->assign(ev.layer(i)); // measurements into layer i
            tklist->extend(ly[i]); // tracks include layer i segments
        }
        // measurements are assigned to layers
        return tklist;
    }
#ifdef DEBUG
void print(){
    for (int i=0; i < nlayer; i++){
        cout << " Layer " << i << " \n";
        ly[i]->print();
        cout << " \n" << flush;
    tklist->print(); // print found tracks
    }
#endif
}

int main(){
    installation instal;
    event ev;
    tracklist* trlst;
#ifdef DEBUG
ev.print();
cout << "debug \n";
//
instal.print();
#endif
trlst = instal.GetTracks(ev);
#ifdef DEBUG
instal.print();
#endif
cout << " main stopped\n";
}
# C Layer code

```c
#include <stdlib.h>
#include <iostream.h>
#include <math.h>
#include <vector.h>
#include <algo.h>

// standard definition of NULL and bool
const int null = 0;

// constants for detector installation
const int nlayer = 8;     // number of layers in installation
const int ndetct = 16;    // number of detectors in layer
const float rinner = 20.; // inner radius of installation
const float router = 40.; // outer radius of installation
const float rspace = .2;  // space between two layers
const float detcdr = (router - rinner)/nlayer - rspace; // thickness of detector
const float detcds = 6.2; // length of detector over s-axis
const float dphi = M_PI /ndetct; // angle over which detector extends

// constants for event layout
const int nr_det = 3;     // 3 entries per detector in event

// acceptance limits and allowed deviations
const float linchi = 10.;  // chi of accepted line fit
const float phi_dev = dphi/100.; // tolerated segment deviations
const float curv = 100.;    // curvature of standard particle

class cylpoint{
    // point in cylindrical coordinate system
    public:
    float r;  // r coordinate
    float phi; // phi angle coordinate
    float s;  // cylinder axis coordinate
};

class measur: public cylpoint{
    // measurement point in cylindrical coordinate system
    public:
    float dr, ds, dphi; // measurement uncertainties in above
};

// Define == on measur objects
bool operator==(const measur& m1, const measur& m2)
{
    return m1.phi == m2.phi;
}

// Define < on measur objects
bool operator<(const measur& m1, const measur& m2)
{
    return m1.phi < m2.phi;
}

class vect: public cylpoint{
    // point with direction in plane perpendicular to s
    public:
    float angle;  // orientation in plane perpendicular to s
};
```

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class particle: public vect{
  // physical characteristics of particle
  public:
  float mass; // particle's mass
  float p; // particle's momentum
  void Propagate(vect cc) {
    phi = cc.phi; r = cc.r; s = cc.s; angle = cc.angle;
  }
  virtual vect Intersect(cylpoint cc1, cylpoint cc2, float B) {
    vect vc;
    vc.phi = 4*M_PI; vc.angle = 0;
    vc.r = 2*router; vc.s = 0;
    return vc;
  }
  #ifdef DEBUG
  virtual void print() {}
  #endif
};

class charged_particle: public particle{
  // charged particle trajectory is circle
  public:
  int charge; // particle's charge (+1 or -1)
  vect Intersect(cylpoint cc1, cylpoint cc2, float B) {
    double x1 = cc1.r*cos(cc1.phi);
    double x2 = cc2.r*cos(cc2.phi);

    // calculate centre coordinates of circle
    double Radius = curv*p/B;
    double xm = Radius*cos(angle+charge*M_PI/2.) + r*cos(phi);
    double ym = Radius*sin(angle+charge*M_PI/2.) + r*sin(phi);

    // calculate intersection point of line with circle
    double tg = (cc1.r*sin(cc1.phi) - cc2.r*sin(cc2.phi)) /
                (cc1.r*cos(cc1.phi) - cc2.r*cos(cc2.phi));
    double of = cc1.r*sin(cc1.phi)-cc1.r*cos(cc1.phi)*tg;
    double a = 1+tg*tg;
    double b = 2.*tg*(of-ym)-2*xm;
    double c = xm*xm+(of-ym)*(of-ym)-Radius*Radius;
    double det = b*b - 4*a*c;
    vect vc;
    vc.s = 0;
    if (det < 0) { // no intersection point
      vc.phi = 4*M_PI;
      vc.r = 2*router;
      return vc;
    }
    double x = (-b + sqrt(det))/(2*a);
    if (x < min(x1,x2) | x > max(x1,x2)) { // no intersection
      x = (-b - sqrt(det))/(2*a);
    }
    double y = tg*x + of;
    vc.s = 0;
    vc.phi = atan2(y,x);
    vc.r = sqrt(x*x + y*y);
    vc.angle = atan2(ym-y,xm-x)-charge*M_PI/2.;
    return vc;
  }
  #ifdef DEBUG
  void print() {
    cout << " Charged particle with phi: " << phi << " r: " << r << " angle " << angle << "\n" << flush;
  }
  #endif
};

class neutral_particle: public particle{
// neutral particle trajectory is straight line

vect Intersect(cylpoint c1, cylpoint c2, float B) {
    double tg1 = tan(angle);
    double of1 = r*sin(phi)-r*cos(phi)*tg1;
    
    double tg2 = (c1.r*sin(c1.phi) - c2.r*sin(cc2.phi)) / 
                (c1.r*cos(c1.phi) - cc2.r*cos(cc2.phi));
    double of2 = c1.r*sin(c1.phi)-cc1.r*cos(cc1.phi)*tg2;
    
    double x = (of2-of1)/(tg1-tg2);
    double y = tg1*x + of1;
    vect vc;
    vc.s = 0;
    vc.phi = atan2(y,x);
    vc.r = sqrt(x*x + y*y);
    vc.angle = angle;
    return vc;
}
#endif DEBUG
void print()
{
    cout << " Neutral particle with phi: " << phi << " r: " << r << " angle " << angle << "\n" << flush;
}
#endif

};

class layerset{
float items[50];
int as,k;
public:
    layerset(){
        k = 0;
        as = 0;
        for( int i =0; i<50; ++i) {items[i] = 0.;}
    }

float* detect(float phi ) {
    for (int i = k; i<as ; i = i+nr_det){
        if (items[i] > phi & items[i] < phi + 2*dphi){
            k = i+nr_det;
            return &items[i];} // coordinate in detector with
                                // angle phi
    }
    k = 0; // start from beginning
    return null;} // no hit found

void assign(float phi, float r, float s){
    items[as] = phi; as++;
    items[as] = r; as++;
    items[as] = s; as++;
#endif DEBUG
void print(){
    int i=0;
    while (i < as){
        cout << " angle: " << items[i] <<" r: " << items[i+1]
             << " s: " << items[i+2] << "\n" << flush;
        i = i+nr_det;
    }
}
#endif
class event{
    set[nlayer];  // 1 event: nlayer layersets
public:
    event(){
        for (int pl = 0; pl < nlayer; ++pl){
            set[pl].assign(M_PI/4+.5*dphi,
                pl*(router-rinner)/nlayer+rinner+detcdr*.25,0);
            set[pl].assign(M_PI/4+.5*dphi,
                pl*(router-rinner)/nlayer+rinner+detcdr*.3,0);
            set[pl].assign(M_PI/4+.5*dphi,
                pl*(router-rinner)/nlayer+rinner+detcdr*.5,0);
            set[pl].assign(M_PI/4+.5*dphi,
                pl*(router-rinner)/nlayer+rinner+detcdr*.66,0);
            set[pl].assign(M_PI/4+.5*dphi,
                pl*(router-rinner)/nlayer+rinner+detcdr*.75,0);
        }
    }
    layerset layer(int pl){ return set[pl];}
#endif DEBUG
    void print(){
        cout << " EVENT print 
";
        for (int i = 0; i < nlayer; ++i){
            cout << " Layer " << i << " \n" << flush;
            set[i].print();
        } 
        cout<< " --------- End Event \n \n" << flush;
    }
};

class segment{
public:
    vector<measur> points;
    cylpoint entry;
    cylpoint exit;

    void enter(measur* m){ points.push_back(*m);}
    bool valid(float r, float phi) {
        float s_off, of;
        float ts_tg, tg;
        float chi;
        float s,t;  // coordinates after transformations
        int nms = 0;  // number of measurements
        float S_s = 0.;
        float S_ss = 0.;
        float S_t = 0.;
        float S_tt = 0.;
        float S_st = 0.;
        if (points.begin() != points.end()){
            for (int i = 0; i < nlayer; ++i){
                set[pl].assign(M_PI/3+dphi*.01+pl*.023*dphi,
                    pl*(router-rinner)/nlayer+rinner+detcdr*.25,0);
                set[pl].assign(M_PI/3+dphi*.015+pl*.023*dphi,
                    pl*(router-rinner)/nlayer+rinner+detcdr*.3,0);
                set[pl].assign(M_PI/3+dphi*.017+pl*.023*dphi,
                    pl*(router-rinner)/nlayer+rinner+detcdr*.5,0);
                set[pl].assign(M_PI/3+dphi*.02+pl*.023*dphi,
                    pl*(router-rinner)/nlayer+rinner+detcdr*.66,0);
                set[pl].assign(M_PI/3+dphi*.022+pl*.023*dphi,
                    pl*(router-rinner)/nlayer+rinner+detcdr*.75,0);
            }
        }
    }

    #ifdef DEBUG
        void print(){
            cout << " EVENT print \n";
            for (int i = 0; i < nlayer; ++i){
                cout << " Layer " << i << " \n" << flush;
                set[i].print();
            }
            cout<< " --------- End Event \n \n" << flush;
        }
    #endif
};
```cpp
vector<measur>::iterator m;
for (m = points.begin(); m != points.end(); ++m) {
    nms = nms + 1; // number of entries
    s = m->r*cos(m->phi);
    t = m->r*sin(m->phi);
    S_s = S_s + s; // sum over s
    S_t = S_t + t; // sum over t
    S_ss = S_ss + s*s; // sum over s*s
    S_st = S_st + t*s; // sum over t*s
    S_tt = S_tt + t*t; // sum over t*t
}

if (nms < 3) { return false; } // at least three coordinates required
float det = float(nms)*S_ss - S_s*S_s;
if (det <= 0) { return false; }
s_off = (S_ss*S_t - S_s*S_st)/det;
ts_tg = (nms*S_st - S_s*S_t)/det;
chi = S_tt - s_off*S_t - ts_tg*S_st;

// calculate entry and exit points of line
entry.s = 0; exit.s = 0; // default values
tg = (sin(phi)-sin(phi+2.*dphi))/(cos(phi)-cos(phi+2.*dphi));
// inner layer, entry point
of = r*sin(phi)-tg*r*cos(phi);
s = (s_off-of)/(tg-ts_tg);
t = tg*s+of;
entry.r = sqrt(s*s + t*t);
entry.phi = atan2(t,s);

// outer layer exit point
r = r+detcdr+rspace;
of = r*sin(phi)-tg*r*cos(phi);
s = (s_off-of)/(tg-ts_tg);
t = tg*s+of;
exit.r = sqrt(s*s + t*t);
exit.phi = atan2(t,s);

return abs(chi) < linchi;
}

// Define == on segment objects
bool operator==(const segment& s1, const segment& s2) {
    return s1.exit.phi == s2.exit.phi;
}

// Define < on segment objects
bool operator<(const segment& s1, const segment& s2) {
    return s1.exit.phi < s2.exit.phi;
}

class track {
    vector<segment> trk; // segments that constitute track
public:
    cylpoint entry;
    cylpoint exit;
    void enter(segment* s) {
        entry = s->entry;
        if (trk.begin() == trk.end()) { exit = s->exit; }
        trk.push_back(*s);
    }
} #ifdef DEBUG
```
void print(){
  cout << "TRACK with entry.phi: " << entry.phi << " exit.phi: " << exit.phi << "\n";
  cout << " entry.r: " << entry.r << " exit.r: " << exit.r << "\n";
  vector<segment>::iterator sg;
  for (sg= trk.begin(); sg != trk.end(); ++sg){
    cout << " segment exit phi: " << sg->exit.phi;
  }
}

// Define == on track objects
bool operator==(const track& t1, const track& t2)
{
  return t1.entry.phi == t2.entry.phi;
}

// Define < on track objects
bool operator<(const track& t1, const track& t2)
{
  return t1.entry.phi < t2.entry.phi;
}

class detector{
  float B;  // magnetic field in detector
  public:
    cylpoint pt[8];  // detector defined by 8 points in space
    vector<segment> seglst;  // list of segments
    vector<measur> measlst;  // list of measurements
    detector* r_bk;  // links to surrounding detectors
    detector* r_fw;
    detector* ph_bk;
    detector* ph_fw;

detector() {
}
detector(float r, float phi){
  r_bk = null; r_fw = null; ph_bk = null; ph_fw = null;
  for (int i = 0 ; i< 4; i++) {pt[i].s = 0; pt[i+4].s=detcds;
    B = 1.;
    pt[0].r = r; pt[1].r = r;
    pt[4].r = r; pt[5].r = r;
    pt[2].r = r+detcdr; pt[3].r = r+detcdr;
    pt[6].r = r+detcdr; pt[7].r = r+detcdr;
    pt[0].phi = phi - dphi; pt[4].phi = phi - dphi;
    pt[2].phi = phi - dphi; pt[6].phi = phi - dphi;
    pt[1].phi = phi + dphi; pt[5].phi = phi + dphi;
    pt[3].phi = phi + dphi; pt[7].phi = phi + dphi;
  }
}

void add(measur m){measlst.push_back( m);}

void clean(){
  // remove all segments and measurements
  seglst.erase(seglst.begin(),seglst.end());
  measlst.erase(measlst.begin(),measlst.end());
}

void FindSegment(){
  if (measlst.begin() != measlst.end()){
    for (m= measlst.begin(); m != measlst.end(); ++m){
      sg.enter(m);
    }
  }
}

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if (sg.valid(pt[0].r,pt[0].phi)) {seglst.push_back(sg);}
    // add sg to segment list
} // end of if (measl...
} // end of FindSegment

virtual void trace(particle &ptk) {
    detector* dtp;
    vect cc = ptk.Intersect(pt[2],pt[3], B);
    dtp = r_fw;
    if (cc.phi > pt[2].phi | cc.phi < pt[3].phi) {
        cc = ptk.Intersect(pt[0],pt[3], B);
        dtp = ph_bk;
        if (cc.r < pt[0].r | cc.r > pt[3].r) {
            cc = ptk.Intersect(pt[1],pt[2], B);
            dtp = ph_fw;
        }
    } // end if (cc.phi < pt[2].phi....
    ptk.Propagate(cc); // advance particle
#if defined DEBUG
    ptk.print();
#endif
    dtp->trace(ptk); // next detector
} // end of trace

#if defined DEBUG
void print() {
    cout << " Detector ";
    cout << " pt[0].phi: " << pt[0].phi << " pt[0].r: " << pt[0].r;
    cout << " \n" << flush;
    if (seglst.size() != 0) {
        vector<segment>::iterator sg;
        for (sg = seglst.begin(); sg != seglst.end(); ++sg) {
            cout << " segment entry phi: " << sg->entry.phi;
            cout << " entry r: " << sg->entry.r << "\n";
            cout << " segment exit phi: " << sg->exit.phi;
            cout << " exit r: " << sg->exit.r << "\n" << flush;
        }
    } // end of if (seglst.size ...

    if (measlst.size() != 0) {
        vector<measur>::iterator m;
        for (m = measlst.begin(); m != measlst.end(); ++m) {
            cout << " measurement r: " << m->r << " phi: " << m->phi << " \n" << flush;
        }
    } // end of if
} // end of print
#endif

};

class dummy_detector: public detector {
public:
    void trace(particle &ptk) {
#if defined DEBUG
    cout << "End of particle trace \n \n" << flush;
#endif
    }
};

// Define == on detector objects
bool operator==(const detector &d1, const detector &d2) {
    return d1.pt[0].phi == d2.pt[0].phi;
}
// Define < on detector objects
bool operator<(const detector& d1, const detector& d2)
{
    return d1.pt[0].phi < d2.pt[0].phi;
}

class layer{
public:
    vector<detector> dts;
    layer(float ri) {
        // create a layer with inner circle defined by ri
        for (int i=0; i < ndetct; i++){
            dts.push_back(*new detector(ri, dphi*i*2));
        }
        sort(dts.begin(), dts.end(), less<detector>());
    } //end of layer constructor
    void connect(layer* ly){
        vector<detector>::iterator dup = ly->dts.begin();
        vector<detector>::iterator d, dbk = dts.begin();
        for (d = dts.begin(); d != dts.end(); ++d){
            dbk->phi_fw = d; d->phi_bk = dbk;
            d->r_fw = dup; dup->r_bk = d; ++dup;
            dbk = d;}
        // dbk points to last detector
        d = dts.begin(); dbk->phi_fw = d; d->phi_bk = dbk;
    } // end of connect(layer)
    void connect(detector* dup){
        vector<detector>::iterator d, dbk = dts.begin();
        for (d = dts.begin(); d != dts.end(); ++d){
            dbk->phi_fw = d; d->phi_bk = dbk;
            d->r_fw = dup;
            dbk = d;}
        // dbk points to last detector
        d = dts.begin(); dbk->phi_fw = d; d->phi_bk = dbk;
    } // end of connect(detector)
    void assign(layerset ls){
        float* pm;
        measur m;
        m.dr = 0.; m.dphi = 0.; m.ds = 0.;
        vector<detector>::iterator d;
        for (d = dts.begin(); d != dts.end(); ++d){
            d->clean(); // remove segments and measurements
            pm = ls.detect(d->pt[0].phi);
            while (pm != null){
                m.phi = pm[0];
                m.r = pm[1];
                m.s = pm[2];
                d->add(m);
                pm = ls.detect(d->pt[0].phi); // end of while
            } // end of for
        } // end of for
        #ifdef DEBUG
    void print(){
        int i = 1;
        vector<detector>::iterator d;
        for (d = dts.begin(); d != dts.end(); ++d){
            cout << i; i++; d->print();
        }
    } // end of print
    #endif
};
class tracklist{
public:
vector<track> tklst; // list of tracks

void extend (layer* ly){
  float cr_ent; // entry point of current track
  vector<track>::iterator t = tklst.begin();
  if (t == tklst.end()){ cr_ent = 2*M_PI+dphi;} // empty track list
  else { cr_ent = t->entry.phi;}

  // store all segments of all detectors in layer ly into sglst
  vector<detector>::iterator d;
  vector<segment> sglst; // list of segments in layer ly
  for (d= ly->dts.begin(); d != ly->dts.end(); ++d){
    copy(d->seglst.begin(), d->seglst.end(), back_inserter(sglst));}
  sort(sglst.begin(),sglst.end()); // sorted segments of layer ly

  // start extension of creation of tracks
  vector<segment>::iterator s= sglst.begin();
  while (s != sglst.end()){
    while ((s->exit.phi < cr_ent - phi_dev) & (s != sglst.end())){
      track tk; // new track
      tk.enter( s); s++; // track with one segment
      tklst.push_back( tk);} // add new track to list
    if (s != sglst.end()){
      while ( cr_ent < s->exit.phi-phi_dev) {
        t ++; // next track
        if (t == tklst.end()){ cr_ent = 2*M_PI+dphi;}
        else { cr_ent = t->entry.phi;}
      } // end while ...
      if (abs(s->exit.phi - cr_ent) < phi_dev) {
        t->enter( s); s++;} // extend track
    } // end of if (s != ....
  } // end while (s!=sglst ...
  sort(tklst.begin(),tklst.end());
} //end extend

#endif DEBUG

void print(){
cout << "TRACK LIST \n";
if (tklst.end() == tklst.begin()) { cout << " EMPTY \n";}
int cnt = 1;
vector<track>::iterator t;
for (t= tklst.begin(); t != tklst.end(); ++t){
cout << cnt << "  " ; cnt++;
t->print();
}
}
#endif

class installation{
layer* ly[nlayer]; // nlayer layers in installation
tracklist* tklst; // list of tracks
detector* exitd; // end of tracing detector
public:
  installation(){
    exitd = new dummy_detector();
    tklst = new tracklist(); // for printing empty tracklist
    ly[nlayer-1]= new layer(router);
    ly[nlayer-1]->connect( exitd);
    for (int i = nlayer-2; i > -1; i--){
      ly[i]= new layer(i*(router-rinner)/nlayer + rinner);
      ly[i]->connect( ly[i+1]);
    }
  }
};
tracklist* GetTracks(event ev) {
    delete tklist; // remove old tracks
    tklist = new tracklist(); // new empty track list

    // find tracks by going from outer layer to inner layer
    for (int i = nlayer-1; i>-1; i--) {
        ly[i]->assign(ev.layer(i)); // measurements into layer i
        tklist->extend(ly[i]); // tracks include layer i segments
    }
    // measurements are assigned to layers
    return tklist;
}

void Trace(particle& ptk) {
    #ifdef DEBUG
    cout << " Start particle trace \n" << flush;
    ptk.print();
    #endif
    float phip = ptk.phi+dphi;
    phip = int(phip/(2*dphi))*2*dphi;
    detector key = detector(rinner,phip);
    vector<detector>::iterator where = find(ly[0]->dts.begin(),
        ly[0]->dts.end(), key);
    if (where != ly[0]->dts.end()) {where->trace(ptk);}
    else { cout << " COULD NOT FIND DETECTOR for Tracing \n" << flush;}
}

    #ifdef DEBUG
    void print(){
        for (int i=0; i < nlayer; i++){
            cout << " Layer " << i << " \n";
            ly[i]->print();
            cout << " \n" << flush;
        }
        tklist->print(); // print found tracks
    }
    #endif
}

int main(){
    installation instal;
    event ev;
    #ifdef DEBUG
    /* ev.print();
    cout << "debug \n";
    instal.print(); */
    #endif
    tracklist* trlst = instal.GetTracks(ev);
    vector<track>* vt = &(trlst->tklst);
    vector<track>::iterator t;
    neutral_particle ptk;
    ptk.mass = 1.;
    ptk.p = 1.;
    double dx, dy;
    for (t = vt->begin(); t != vt->end(); t++){
        ptk.phi = t->entry.phi;
        ptk.r = t->entry.r;
        ptk.s = t->entry.s;
        dx = t->exit.r*cos(t->exit.phi)-ptk.r*cos(ptk.phi);
        dy = t->exit.r*sin(t->exit.phi)-ptk.r*sin(ptk.phi);
        ptk.angle = atan2(dy,dx);
        instal.Trace(ptk);}
}
charged_particle cptk;
cptk.charge = -1;
cptk.mass = 1;
cptk.p = 1;
for (t = vt->begin(); t != vt->end(); t++){
cptk.phi = t->entry.phi;
cptk.r = t->entry.r;
cptk.s = t->entry.s;
dx = t->exit.r*cos(t->exit.phi)-cptk.r*cos(cptk.phi);
dy = t->exit.r*sin(t->exit.phi)-cptk.r*sin(cptk.phi);
cptk.angle = atan2(dy,dx);
instal.Trace(cptk);
}
cptk.charge = 1;
cptk.mass = 1;
cptk.p = 1;
for (t = vt->begin(); t != vt->end(); t++){
cptk.phi = t->entry.phi;
cptk.r = t->entry.r;
cptk.s = t->entry.s;
dx = t->exit.r*cos(t->exit.phi)-cptk.r*cos(cptk.phi);
dy = t->exit.r*sin(t->exit.phi)-cptk.r*sin(cptk.phi);
cptk.angle = atan2(dy,dx);
instal.Trace(cptk);
}

#ifdef DEBUG
instal.print();
#endif
cout << " main stopped
";