Wire-Cell Toolkit Point Cloud

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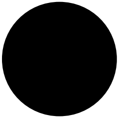
Topics

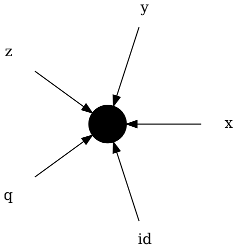
- Points and point data
- Point cloud, point data array and dataset
- k-d tree operations
- Data representation conversions
- WIP: extending point-cloud to point-graph

Point



An abstract entity, no intrinsic meaning.

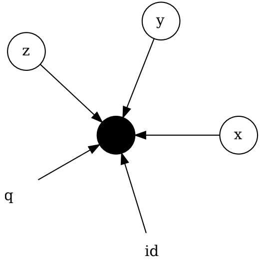
Point data



We may *associate* information with a point.

- shapes: scalar, vector, matrix, tensor
- numeric types: integer or floating point
  - homotypic if non-scalar

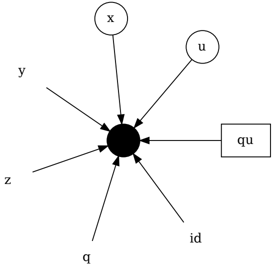
Data interpretation, *eg* coordinates



We may *interpret* specific *point data* in some way.

- An ordered set of n *coordinates* may provide a *position* in an n dimensional Cartesian space.
- Interpretation are *extrinsic* to the point and the associated data.

Shared interpretations



Different interpretations of subsets of point data.

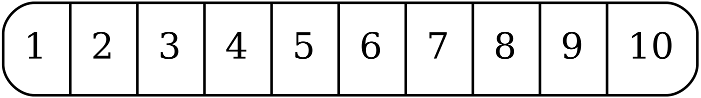
- The "x" point-data interpreted as part of a 3D position may also be used as part of a 2D position (projected x-u wire view).
- A charge, "qu" may be found with the projected 2D position and then later used along with 3D positions.

Point cloud

An abstract, **ordered** collection of N *points*.

- Well defined ordering of points (but may be arbitrary).
- An extrinsic **point index** reflects the ordering.

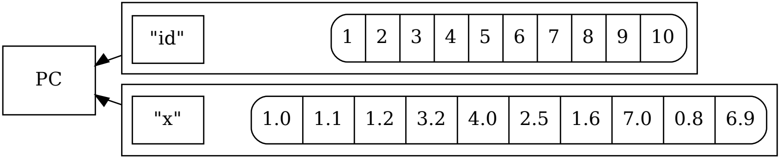
Point-data array



Collect all of one type of point data for the points in a point cloud into an array.

- The *point-cloud index* also identifies associated point data in the array.
- Array elements have common data type and shape.
  - (here, scalar integers one larger than point index)

Point-cloud dataset



Associate multiple *point-data arrays* to a point cloud.

- Each array is identified by a “name” in the context of the dataset.
- Heterogeneous type and shape across the arrays, but common length.

`WireCell::PointCloud`

`Array` model of a *point-data array*

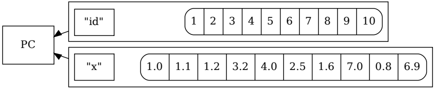
`Dataset` model of a *point-cloud dataset*

`PointCloud::Array`

1	2	3	4	5	6	7	8	9	10

- Provide *type-erased* array data wrapper.
  - Required to form a heterotypic collection.
- Read-only, zero-copy shared or read-write copy of user array.
- Supports **minimal** but efficient set of array operations.
  - Essentially only: `append(Array)` which assures type/shape constraints.
- Read-only, zero-copy and typed, full featured wrappers:
  - `span<T>` a flat `vector<T>` like view of underlying array
  - `boost::multi_array<T,NDim>` full featured multi-dimensional array operations

PointCloud::Dataset



- Access an `Array` by its associated name.
- Assure array length constraints.
- Implement `append(Dataset)`.
  - Assure completeness, shape, type constraints of appended tail dataset.
- Call user-provided *callback hooks* on successful `append()`.
  - Needed for dynamic k-d tree support (comming up).
- Retrieve collection of references to `Array`'s via list-of-names.

`WireCell::PointCloud` code snippet

```
#include "WireCellUtil/PointCloud.h"
using namespace WireCell::PointCloud;

Dataset d;
// Add an integer array named "one" of shape (5,)
d.add("one", Array({1,2,3,4,5}));
// Add a double array named "two" of shape (5,)
d.add("two", Array({1.1,2.2,3.3,4.4,5.5}));

auto sel = d.selection({"two","one"});
const Array& one = sel[1];
assert(sel[0].get().num_elements() == 5);

const auto& one = d.get("one");
```

Many other ways to make `Array` and add them to `Dataset`.

`Array::` and `Dataset::metadata()`

```
using metadata_t = Configuration;

metadata_t& metadata();
const metadata_t& metadata() const;
```

- Type is `WireCell::Configuration`,
  - aka JsonCPP's `Json::Value`.
- Merely carried and not directly utilized by `Array/Dataset`.
  - Utilized in I/O related conversions (coming up).
- Users are free to stash their own structured data.

Point-cloud position queries

We may interpret certain arrays in a dataset as holding coordinate point data.

- Each array represents a location in a given Cartesian dimension.
  - eg `"x"` array of X-coordinates.
- Any set of scalar and common numeric type arrays may provide coordinates.

Position queries

knn the k'th nearest neighbors to query position.

radius all point positions within some *metric distance* to a query position.

Results in two arrays:

index an array of point indices into the original dataset.

distance the *metric distance* between point and query positions.

Metric distance

A *distance* between two positions in a space requires a *metric*.

L2 the usual, **but squared** Cartesian distance

L1 sum of steps, each strictly taken in one dimension

SO2 2D angular distance

SO3 3D angular distance

The query *radius* and returned *distances* are expressed in this metric.

- *eg*, units are $[length]^2$ for choice of the L2 metric.

`WireCell::KDTree` for position queries

- Uses a `Dataset`
- Provides a thin wrapper around `nanoflann`
  - Simplifies and regularizes `nanoflann` API.
  - Converts complex `nanoflann` templated types to option variables.
- Common result set type for both `knn` and `radius` searches.

WireCell::KDTree code snippet

```
#include "WireCellUtil/KDTree.h"
using namespace WireCell::KDTree;
using namespace WireCell::PointCloud;
void func() {
    Dataset d = ...;
    std::vector<double> query_pos = {1,2,3};

    auto qptr = query<double>(d, {"x","y","z"});

    size_t k = 3;
    auto knn = qptr->knn(k, query_pos);
    const size_t nfound = knn.index.size();
    for (size_t ifound=0; ifound<nfound; ++ifound) {
        cerr << ifound << ":" << " index=" << knn.index[ifound]
             << " distance=" << knn.distance[ifound] << "\n";
    }
    double rad = 5*units::cm;
    auto radn = qptr->radius(rad*rad, query_pos);
    // use radn just like knn....
```

WireCell::KDTree::query<TYPE>()

For TYPE $\in$ {int, float, double}

```
template<typename Type>
std::unique_ptr<Query<TYPE>>
query(PointCloud::Dataset& dataset,
      const PointCloud::name_list_t& selection,
      bool dynamic = false,
      Metric mtype = Metric::l2simple);
```

- The TYPE is coordinate numeric type.
- The `selection` names the arrays in `dataset` to use as coordinates.
- The `dynamic` enables `Dataset::append()` callback to update k-d tree.
- A `unique_ptr` needed, wrapped `nanoflann` objects are not copyable.

KDTree::MultiQuery

Bundle multiple k-d tree queries on a common `Dataset`.

```
void func(MultiQuery& mq) {
  auto qptr = mq.get<double>({"x","y","z"});
  std::vector<double> p = {1,2,3};
  auto knn = qptr->knn(3,p);
  // ... use knn result in some way

  auto& d = mq.dataset();
  Dataset tail = ...;
  d.append(d);
}

Dataset dorig = ...;
MultiQuery mq(dorig);
func(mq);
```

- The orginal `Dataset` is only borrowed by the `MultiQuery`.
- That `Dataset` can be retrieved back from `MultiQuery` later.
- A `MultiQuery::get<T>(name_list)` will return existing or a new

Dataset I/O with TensorTools.h API

$$\texttt{PointCloud::Array} \longleftrightarrow \texttt{ITensor}$$
$$\texttt{PointCloud::Dataset} \longleftrightarrow \texttt{ITensorSet}$$

```
#include "WireCellAux/TensorTools.h"

ITensor::pointer as_itensor(const PointCloud::Array&);
PointCloud::Array as_array(const ITensor::pointer&, bool);
ITensorSet::pointer as_itensorset(const PointCloud::Dataset&);
PointCloud::Dataset as_dataset(const ITensorSet::pointer&, bool);
```

- If `bool` is `true`, utilize zero-copy data sharing, requires programmer care. Default is `false`
- The `ITensor::ident()` mapped to `Dataset::metadata()["ident"]`.
- `ITensorSet::metadata()["_dataset_arrays"]` holds list of `Array` names known in the `Dataset`.

Related ongoing I/O work

Get round trip I/O working for:

- Frame $\longleftrightarrow$ "Frame file"
- Cluster $\longleftrightarrow$ "Cluster file"

Wish to deprecate these "direct I/O" patterns and instead standardized on intermediate Tensor representation.

- Dataset $\longleftrightarrow$ Tensor Set $\longleftrightarrow$ "Tensor file"
- Frame $\longleftrightarrow$ Tensor Set $\longleftrightarrow$ "Tensor file"
- Cluster $\longleftrightarrow$ Tensor Set $\longleftrightarrow$ "Tensor file"

A WCT "tensor file" is JSON+Numpy files in Zip/Tar streams. Essentially follows HDF5 schema. So, expect it easy to add:

- Tensor Set $\longleftrightarrow$ HDF5

WIP: pipelines of heuristic functions

Essential idea: support a pipeline of functions operating on a point-cloud.

- The point cloud must be mutable.
- Avoid re-creating identical k-d trees.
- Variety of possible pipelines as defined by configuration.
- Each implement a “point cloud visitor” interface.
- Defines a method accepting a non-const `KDTree::MultiQuery`.

WIP: extending point-cloud to point-graph

Essential idea: use a "node" and an "edge" `Dataset`.

node
: Exactly a point-cloud `Dataset`.

edge
: A second `Dataset` with `"tail"` and `"head"` arrays holding point indices in to the **node** dataset. May have additional arrays to hold *edge features*.

Benefits:

- Leverage existing converters to Tensor Set representations and file I/O.
- Easy to use alongside `boost::graph` representations.