**Lesson Plan**

**Learn Physics with IceCube: distance, speed and direction of movement**

**Basic Learning goals**

Learn what distance and speed are, and how they relate to displacement and velocity.

Measure the distance traveled by an object moving in a 3D environment and calculate its speed.

Measure the direction of an object moving in a straight line in a 3D environment.

Gain knowledge about uncertainties in a measurement.

**What’s needed**

One computer per every one or two students, connected to the internet.

A white board and paper.

**Resources provided**

Online IceCube displays, accessible [here](http://icecube.wisc.edu/viewer/speed_of_light).

A description of the IceCube detector and how IceCube displays work can be found on the IceCube MasterClass website ([link](https://masterclass.icecube.wisc.edu/))

Other resources available upon request include large format printed events to perform some initial measurements as a group.

**Activity overview**

The final goal of this activity is to calculate the speed and direction of a relativistic particle travelling through the IceCube Neutrino Observatory.

IceCube is a cubic-kilometer telescope buried in Antarctica’s ice shed, spanning from 1.5 to 2.5 kilometers below the South Pole ice.

The energy of the particles detected in IceCube is so high that their speed is very close to the speed of light in vacuum. This is as fast as any particle in the universe can move.

While guiding students to calculate the speed and direction of a particle in IceCube, we will work on the concepts of displacement/distance, velocity/speed and direction of movement.

The activity is designed in three parts.

1.- Use the geometry of the IceCube detector to calculate the distance travelled by a particle moving in a straight line in the detector. We can also calculate a first estimate of the speed of the particle using the time information.

2.- Use information from individual IceCube sensors to improve the measurement of the distance and the speed of the particle. We can also calculate a first estimate of the direction of movement of the particle.

3.- Use information from all IceCube sensors that lit to get the best estimates of the distance, speed and direction of movement of the particle.

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1. Distance travelled by a high-energy particle in IceCube

* Teachers will guide students in a discussion about what are the important properties of the IceCube geometry to be able to perform measurements of the speed of a particle moving through IceCube and its direction.

Students should note that the distance between strings (125 meters) is different than the distance between sensors in a string (17 meters). They should also be aware that while the particle (a muon) is crossing the detector, in fact what IceCube detects is a blue light induced by it’s movement through the detector.

* Now students can choose one the events in any of the provided displays, expect for displays 12 and 13. Display 0 shows a particle in a one-dimensional trajectory and can be used to introduce the main concepts before moving to a 3D (vector) trajectory.

On the right of the display there are a few extra features that can be added to the displays. At this time, students should be using the basic display, ie. all features disabled.

We also provide a large format printed event, where students can discuss and show the type of measurements they will perform on the displays. They can also try to perform a rough estimate using the geometry of the detector.

* Working by pairs or in small groups students will calculate the distance travelled by the particle in their display. Without activating any of the extra features, they will also discuss if they have enough information to also calculate the speed of the particle.
* One of the groups will explain to the class how they did the calculations. The other groups will confirm if they followed the same technique or if they used some modifications.

At this point we want the students to realize that to do the best measurement they need to measure the distance by counting strings and sensors in a string. We are not measuring the distance directly, but we are first measuring the displacement in each direction. Distance is a scalar quantity, while displacement is a vector quantity. distance =|displacement|

* The final discussion in this first section will focus on how precise is our measurement. Which are the main uncertainties of our measurement? Can we assess the (relative) size of these uncertainties?

The precision of the time stamps from IceCube sensors is of a few nanoseconds and the precision of the position for each sensor is of about a meter horizontally and less than a meter vertically. The total depth of each string varies within 3-4 meters. The light produced by the muon at a given position will trigger a signal in the closest sensor later than what could be expected by using the speed of light in ice (~0.76c). Impurities in the ice produce scattering of light. Even if the speed of the particle is basically constant during its journey through IceCube, by using 2 distant points we minimize the effect of the delayed time from interaction to the sensor due to scattering.

1. Distance travelled by and speed of a high-energy particle in IceCube

* Teachers will guide now students to improve previous measurements by using information of individual IceCube sensors. To do that, we will enable the feature called “full last dom info”.

When doing that, a purple sphere shows the position of the last IceCube sensor, or DOM, that has lit. Students can play the event back and forward using the time slide in the color map scale at the bottom of the display. On the right of the display, the exact x,y and z coordinates of the purple sphere is given.

* We will again measure the displacement between two points to obtain the distance travelled. Using the time interval, we can again measure the speed of the particle.

In some cases, this speed will be closer to the speed of light than with the measurements in section 1. In other cases, the result might seem to get worse. Teachers will again raise discussion about uncertainties and assess if both measurements are compatible within known uncertainties.

Students can also try to measure the uncertainty of this measurement technique by measuring the speed of the particle using different pairs of sensors in the same event display. Events 7, 9 and 10 have a nice pattern for this type of measurements.

* Finally, we will parameterize the line along which the particle is traveling. To do that, we will use the two points used to measure the speed.

If P0 = (x0, y0, z0, t0) and P1 = (x1, y1, z1, t1), then the line that passes through both points is:

Students should realize that the quantities that provide the time factor, i.e. the slope, are in fact the coordinates of the velocity vector. They should observe that they can work with IceCube units, i.e. time measured in nanoseconds. The direction of the movement of an object along a straight line is defined by the direction of its velocity vector.

Students could also built a parameterization of this line in a different coordinate system, e.g. the one we used in the measurements of section one.

1. Direction of a high-energy particle in IceCube

* Teachers will guide now students to improve previous measurements by using information of all the IceCube sensors that have lit during the event. To do that, we will download the information about each sensor by clikcking on “Download CSV of Pulses”.

The file contains the time and position of each DOM that lights up.

* Students will try to improve the parameterization they obtained in section 2, with two approximations. First, they will fit the best fit line (least squares) for each of the coordinates independently. Then they will fit two coordinates at a time, x=f(y), x=f(z) and y=f(z).

For each x, y and z, the least squares fit follows:

x = x0 + vx t

Then, we will do similar calculations for x-y, x-z, and y-z, and we will use the following parameterization to transform the two coordinate best line fit, into the x, y, z coordinates for the 3D best fit line.

and similar equations for x-z and y-z.

* Finally we will compare these results to the best fit by IceCube, which can be seen by enabling the “Enable linefit” on the right of the display.

To compare our results with those of the linefit, we will need to normalize the velocity vector to a vector of magnitude 1.