Visualisation of Quantum Chromodynamics

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EPCC–SS94–09

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September 1994

Abstract

Quantum Chromodynamics (QCD) involves modelling particles and forces at a quantum level. Until now the data created from these simulations has been viewed on two-dimensional graphs, generally of the evolution of a property in time or space. The aim of this project is to visualise the data in two, three or four dimensions and to make the visualisation techniques available to the researcher by way of a manual and various programming and visualisation facilities.

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1 Introduction

The aim of this project was to provide facilities and documentation to aid in the visualisation of data created by the Quantum Chromodynamics (QCD) group on machines at the University of Edinburgh. Documentation has been provided both in the form of a manual, and on-line help via the World Wide Web. This project was carried out as part of the Summer Scholarship Programme at the Edinburgh Parallel Computer Centre (EPCC) and in collaboration with the United Kingdom Quantum Chromodynamics (UKQCD) group at Edinburgh University.

Content of report:

- benefits of the project
- the approach taken
- use of raw data in visualisation
- visualisation packages
- results

- conclusion
- glossary

This report will begin by explaining why this project was necessary, followed by an explanation of the general approach taken. The rest of the report will follow the data through from it's raw state, after it is taken from the UKQCD simulations, to the visualisations stage. QCD terms will be explained in the relevant sections as they occur.

Four dimensional spacetime datasets are created by the UKQCD group using the Monte Carlo method (see section 3.1) These sets of data describe how gluons (see section 3.2) interact with each other. From these datasets various physical properties can be calculated, some of which will be mentioned later. The fact that these data sets are four dimensional complicates the visualisation. Because of this most existing visualisation occurs in the form of two dimensional graphs representing the evolution of a physical property with time or space. However this does not take full advantage of the four dimensional nature of the simulations and important properties may be overlooked by the user. Visualisation gives the UKQCD group a new aspect on their data simply because it provides a new way of viewing it.

Visualisation of QCD data is a relatively new field. This means that the work carried out was a trial and error procedure. It was not known if visualisation of the properties was possible, nor if it would make any sense physically. The work done does provide a basic structure and background to the visualisation techniques available at EPCC. Hopefully this will lead to more properties being visualised, and give the physicist insight into previously hidden properties.

The first part of this project involves combining the data to produce particles called *mesons* (see section 2.3) The data which result describe the motion of a particle that originated at a point in space (the centre of the data set). It is almost impossible to see what is happening to a three dimensional object by looking at two dimensional graph, so visualisation of the volume is important. Included in the manual written to accompany this project are the details of how to go about creating and visualising *mesons*, starting with the original data taken from the QCD simulations.

The second part of the project looks at visualising the function used in the gauge fixing stage (see section 2.4). This is a process that is carried out to make calculations easier Without visualisation of this property it is very hard to tell if this stage has been implemented correctly.

It is therefore an important part of both validating the simulations, and for further research, to be able to visualise the various physical properties in a variety of ways.

2 Approach to project

The following section describes the approach taken whilst tackling this project.

This project could be broken down into the following stages:

- learning how to use the visualisation packages (see section 5)
- understanding the basics of the physics behind QCD
- extracting the physical properties from the raw data

The best course of action seemed to be to get to grips with the physics over the first few weeks whilst learning how to navigate about the visualisation packages. The first week was spent on familiarisation with two of the visualisation packages available at EPCC, BOB (see section 5.1) and Explorer (see section 5.2). BOB was chosen because of it's speed, the idea being to use BOB as an initial viewing tool. The other visualisation packages available at EPCC are AVS and Explorer. Explorer and AVS are very similar, however the choice of Explorer over AVS was mainly taken because one of my supervisors (Gordon Cameron) had experience with this package. During this time basic visualisations were created in both packages to become familiar with the type of visualisation it was possible to create.

During this period time was also spent becoming familiar with the area of physics it was necessary to work with for this project. Several books and scientific articles were looked at including *The Cosmic Onion* [Close, 1983], which proved to be very useful throughout the project, initially for getting a good basic understanding of particle physics, and later for reference. *The Cosmic Onion* also revealed a new way of explaining QCD to others — this proved very useful where talks were concerned.

Once familiar with these packages the next step was to extract various properties and try and visualise them in the most suitable way. This involved writing various programmes which provided a quick and easy route for the user to extract those properties required. The two types of properties looked at were creating *mesons* (see section 2.3) and *gauge fixing* (see section 2.4). From this stage onwards time was spent between both writing code and visualising data.

As progress was made into this project it became increasingly obvious that an important outcome of this project was a manual specifically aimed at the UKQCD group to aid them in visualising the data they were producing. There seemed no point in creating facilities for visualising the data if there was no explanation of how to use the facilities, and what to do when things went wrong!

The nature of this project meant that long term planning was hard to do, as it was necessary to complete one stage of the project before moving on. This proved an annoyance at times when things really needed to be left and returned to later.

2.1 Quarks

The current view in Physics as to the construction of all matter is that it is all *built* from two fundamental particles, *quarks* and *leptons*. *Leptons* are a family of particles that contains the electron, and neutrinos and other particles that are not affected by the strong force. The quark family consists of six *flavours* of quarks (see figure 1) and their respective anti-particles.

The pictures that represent the quarks here may be childish, but since we cannot actually see quarks, they are as realistic as any. The image of the Top quark is a question mark because the evidence for its existence it not yet conclusive — The FermiLab recently announced results that hint at the existence of the *top* quark with an approximate mass of 174GeV, however as yet there is still not quite enough evidence to constitute a discovery [Yam, 1994].

Each pair of quarks is known as a generation. The first generation quarks, *up* and *down*, are the constituents of the protons and neutrons which form all the atoms which exist in the world about us. The second and third generations of quarks, *strange, charmed, top* and *bottom*, only exist in high energy laboratories where the more exotic particles that these pairs produce are studied.

Each quark has certain properties. First there is its *flavour*, that is if it is an up, down, strange, charmed, top or bottom quark or anti-quark. Each flavour also has an electric charge of $+\frac{2}{3}$ or $-\frac{1}{3}$ as shown on the previous diagram. Quarks also have a *spin*, of $\pm\frac{1}{2}$, and a *colour* (see section 2.2).

2.2 Colour

Each quark is given one of three colours (see figure 2). When talking about quarks colour is not the same thing as we perceive it in our everyday life. Here colour is only named such because there are three types: *red, yellow* and *blue* (six if the anti-colours are included).

Differing colours attract, like colours repel (just as with electric charges). However the strongest attraction is between a colour and its anti-colour. This force of attraction and repulsion is called the *colour force* and is the *glue* which holds these quarks together. Hence the carriers of this force are called *gluons* (see section 3.2).

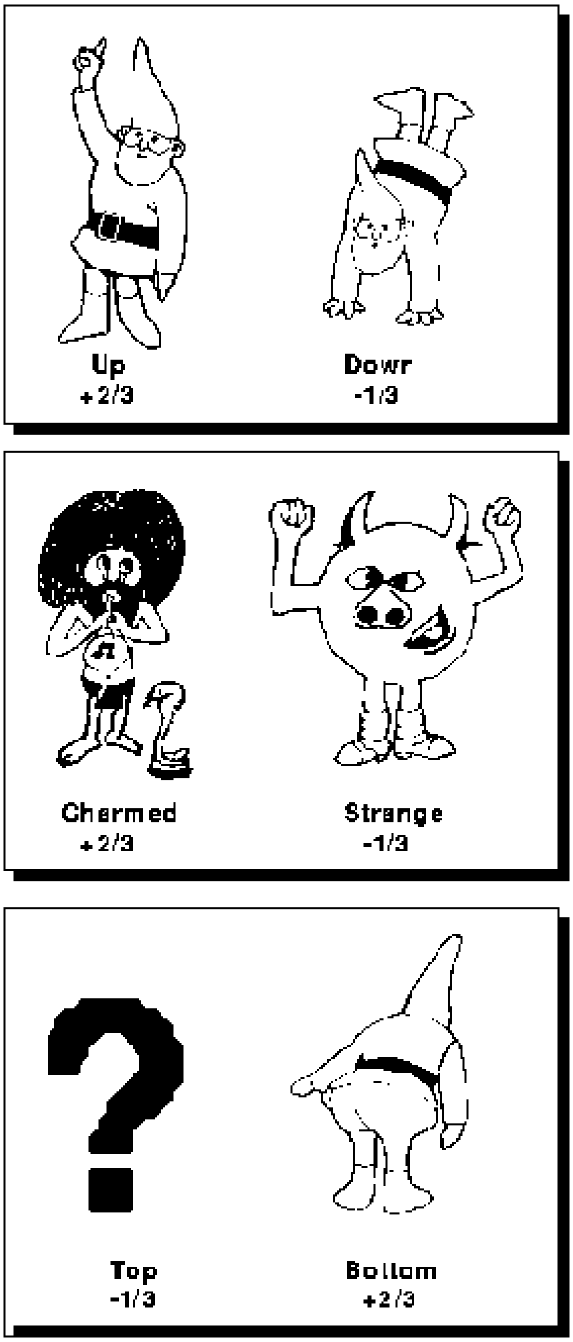

Figure 1: Quark Flavours

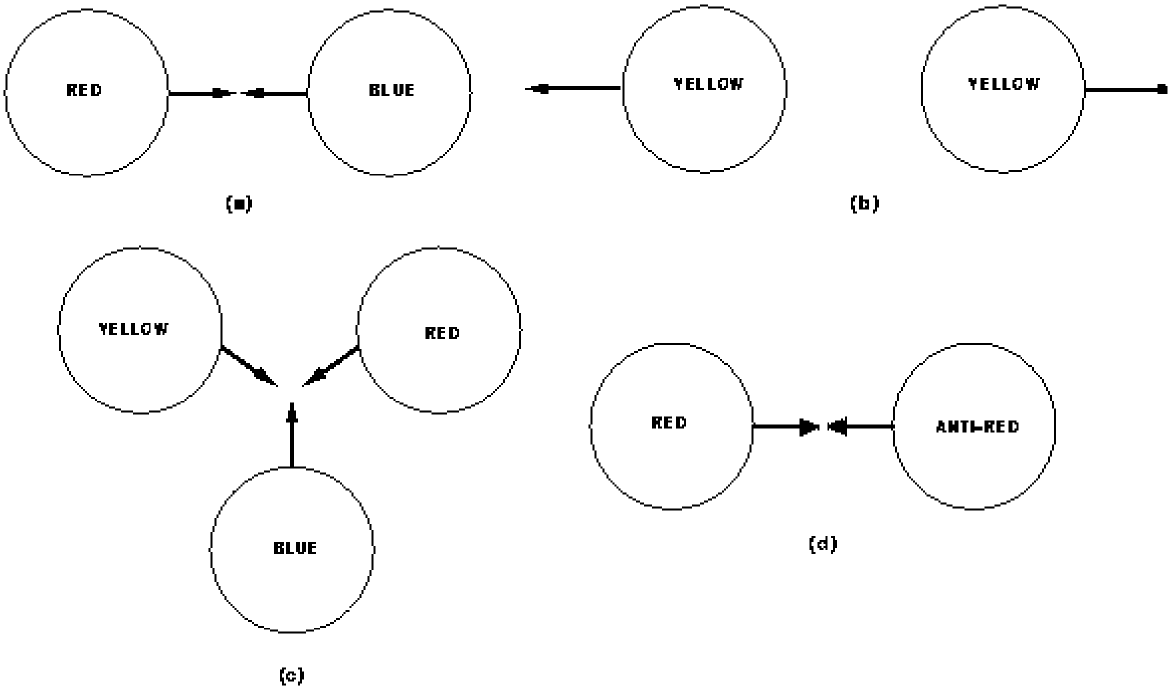

Figure 2: (a) attraction of opposite colours, (b) repulsion of like colours, (c) 3-way attraction and (d) strongest attraction between colour and anti-colour

2.3 Mesons

Quarks form together to create groups of two or three. A quark/anti-quark pair is called a meson. Amongst this group of mesons are the pion, which can be formed from one of four combinations:

- up + anti-down: π^+
- up + anti-up: π^0
- down + anti-down: π^0
- down + anti-up: π^-

This group also includes the rho particle amongst others. The pion and the rho particle were both visualised in this project.

2.4 Gauge Fixing

This section explains the basics of gauge fixing.

In electromagnetism the magnetic field is described by the following equation:

$B = \nabla \times A$

where A is the Vector potential. This vector potential can be given any value such that

$A = A^{'} + \nabla\lambda$

This describes a gauge configuration. The gauge can be *fixed* by applying a condition to `A` such as that used in electromagnetism:

$\nabla \cdot A = 0$

This condition does not change the physical meaning of the quantities calculated. This is because there is a symmetry in the mathematics. In a sense the gauge fixing is equivalent to the choice of the co-ordinate system used in the mathematics of the simulations. For example when simulating particles travelling in space the mechanics involved are unaffected by what direction is labelled as up. In the case of gauge fixing the space is not normal physical space, but a mathematical space. Generally the condition chosen is that which is easiest to apply. Gauge fixing reduces the degrees of freedom that the lattice contains. In the QCD simulations the function used to *fix* the gauge also smooths the data locally. This generally means that randomness contained in physical properties will have been reduced.

3 Data

This section explains the form of the data taken from the UKQCD group, what it describes and how physical properties are selected from this data. The end of the section contains brief explanations of some QCD terms used.

The UKQCD group at Edinburgh University use the Monte Carlo method (see section 3.1) and lattice gauge theory (see section 2.4) to create simulations at a quantum level.

The various facilities included in this report are intended to take data from the UKQCD group in its initial form (IEEE floating point, 32-bit, single precision, binary representation. X should be the fastest varying axis, followed by Y, then Z). If the data is not in this form then it will be necessary to convert it for use of the programmes that have been provided. If only the visualisation packages are to be used there are various data import modules available which will be mentioned later (see section 5.4.1).

The data that is produced from these simulations describes the interactions between gluons (see section 3.2) and quarks (see section 2.1).

In the case of mesons simple matrix multiplication, along with some knowledge of the gamma matrix (this is the *fingerprint* of the particle — see section 6) for that meson, will extract the properties of that particle. The resulting data describes the probabilities of the location of the meson having been certain it was at the centre of the box at timeslice 00.

3.1 Monte Carlo

Named after the famous Monte Carlo casino, a Monte Carlo method is a random statistical method. There are many versions of Monte Carlo methods.

A Monte Carlo simulation is carried out by applying a random perturbation to the system and updating according to a selection rule. This selection rule defines whether a perturbation to the system is accepted or not, and in QCD this acceptance depends on the energy of the system. Generally if a perturbation brings the system closer to it's preferred state it will be accepted, if not it will be rejected. However the selection rule allows some perturbations that would normally be rejected to slip through to account for the physical nature of the system. Certain physical quantities are measured after every update, regardless of acceptance, and these are used to calculate the average properties such as energy, temperature etc.

The Monte Carlo method is a very powerful statistical method used for a variety of simulations from modelling the magnetisation of ferromagnets, to simulating QCD, to modelling the electrostatics in water (the subject of another EPCC project, summer 1994).

3.2 Gluons - the carriers of the colour force

The concept of gluons can be imagined as follows:

When two electric charges are separated, there is a force between them. The carriers of this force are photons. In a similar way the carriers of the colour force are the gluons. The colour force is very strong, and it's strength is the reason that free quarks are not observed. An analogy would be holding the ends of an elastic band and pulling it apart. The further it is stretched, the more it pulls back, until finally it snaps. This is analogous to quarks and the colour force. The further the quarks 'pull' apart from each other the more the colour force pulls them back. This differs from most forces which weaken as the distance increases. As the distance between quarks increases so does the energy. When this energy reaches a certain level the *elastic band* breaks, and the energy released goes to form quarks on the new ends of the *elastic band*. For this reason free quarks are not observed.

If this was the whole picture then it would be a simple task to use the techniques developed for Quantum Electrodynamics (QED) in QCD. There is, however, an added complication. Gluons not only carry the colour force, but they also posses colour themselves, and can exchange this colour with other gluons. If were were talking about photons it would be like having light bouncing off light. This means there are more interactions, and therefore making the simulations more complicated.

4 Programmes

Programmes have been written to carry out the operations mentioned in this section.

The following options are available:

creating mesons — This programme carries out matrix operations on the data obtained from the Monte Carlo simulations. The user requires knowledge of the gamma matrix for the required meson — this matrix describes the internal organisation of the particle. The resulting output data file contains data, in the form of floating point numbers, X varying fastest then Y, then Z, which can now be visualised. The data relates to the probability of the meson being at a certain point in space having been placed at the centre of the data set at timeslice 00.

averaging over configurations — This programme will average data over a number of files. The purpose of this is to create data sets that have greater physical meaning.

changing into probabilities — To aid the user in locating their data at the visualisation stage, and to give the data values physical meaning, it is necessary to convert the data into probabilities. In otherwords scaling the data so that the total sum of all the data values is one, one being 100% probable, ie. certainty.

The programmes to create mesons, average data and create probabilities are to be found within `menu` (see section 4.4).

There are a couple of things the user should note before using the programmes provided. It is very likely that the user will use a different machine to create the data for visualisation than that used to visualise the data. This can cause problems. Two specific problems have been discovered. The first is concerning the size the machine assigns to reals. On UKQCD this size is one, but on the Suns and SGI's this is four. A parameter called *fsize* has been encorporated into the programmes to compensate for this. The programme, `menu`, (see section 4.4) has been set up with a size of one for use on UKQCD, however if the programme is to be used elsewhere then this size will need to be checked and altered as appropriate. The second thing to note is the way the machine stores floating point numbers. For further information on this see section 4.2. Finally the user should read section 4.1 for an explanation of how to enter in filenames when using these programmes.

4.1 Filenames

To aid the user and to minimise the amount of time spent entering information, part of the design of the programme includes *styles* of filenames. This section will contain a description of what is meant by a filename style and how to make best use of this facility.

This facility was designed around the way the filenames are structured in the raw data files from the UKQCD simulations. These files tend to be of the form

```
C60L4320L00    C62L4320L00    C64L4320L00
C60L4320L01    C62L4320L01    C64L4320L01
C60L4320L02    C62L4320L02    C64L4320L02     etc...
```

where `L4320L` relates to the pion mass.

There is an obvious underlying structure to this of

C <*configuration*> L4320L <*timeslice*>

When using the programmes in `menu` to extract the physical properties, the base and extension tend to stay constant throughout a number of executions, with either the first or second number altering. It would therefore make sense to combine this into the programme to free the user from entering filenames manually and being tied up during the execution of the programme.

For example, if the files are named as those mentioned above, the dialogue would be as follows:

```
 You will be asked to enter in the input
    filenames in the following form:
     base   number1   ext   number2

 If you do not wish anything in base or
  ext then simply press return and ignore it
 If it is a number category you do not
  require then type -1

 the base
C
 the first number of number1 (integer please)
60
 the last number of number1
64
 the step between the numbers (integer)
2
 the extension
L4320L
 the first number of number2
0
 the last number of number2
2
 the step between the numbers
1
```

This will produce the required filenames. For verification the filenames will be displayed as they are opened.

As mentioned in the above dialogue it is possible to vary the style of filenames by pressing `return` when prompted for a string and `-1` when prompted for an integer.

The best way to use this facility is always to have filenames in the form of

<*Base*> configuration number <*extension*> timeslice number

to speed up the use of programmes and to avoid renaming files. For an easy way of renaming files see section 4.3 on shell scripts.

4.2 Converting data

This programme provides two facilities. It swaps the bytes of the floating point numbers and translates the data into *brick of bytes* form for use with BOB.

Swapping bytes is only relevant when using the same data on different machines. When using all the facilities described in this manual, the user will most likely be using the UKQCD machine and an SGI machine. This is when problems occur and data transferred from one machine to the other may have made perfect sense on one machine, but will be incompatible on the next. In other words one machine is big endian and the other little endian.

Therefore it is necessary is take account of this when changing from one machine to another. A programme has been provided called `convert` (written by Stephen Booth) which enables these bytes to be swapped (output file extension .swap) and to convert the file into character form (output file extension .char) for use in BOB. The swap stage can be done on either machine, but the character stage must be done on the machine where the data makes sense, ie. the meaningful floating point numbers must be changed into the character file.

4.3 Shell scripts

Shell scripts are a very useful way of carrying out tasks which involve entering a very similar command at the prompt numerous times, for example renaming a large number of files. For further information and examples please refer to the manual that accompanies this project. For more information on the manual this see section 6.

4.4 Further Information

A manual has been written to aid the user in visualisting QCD data. More information about the programmes and how to use them can be found here. For more informations see section 6.

The code, maps, modules and other files needed to use the facilities mentioned in this report have been compressed using

`tar cvf QCDvis_?????  tar` *`directories`*

then

`gzip QCDvis_?????.tar`

These will need to be uncompressed before use as follows:

`gunzip QCDvis_?????.tar.gz`

followed by

`tar xvf QCDvis_?????.tar`

The following `tar` files exist:

QCDvis_code.tar.gz contains all code written. Following decompression contains `.../Fortran` directory which contains all the code.

QCDvis_doc.tar.gz contains all documentation. Following decompression contains `.../REPORT` directory, which contains the files to create the report and manual for this project, and a `.../POSTER` directory which contains the files to create the poster for this project.

QCDvis_images.tar.gz contains some of the images created during this project. After decompression this will contain directories `.../IMAGES` and `.../GIF` which contain the various images.

QCDvis_packages contains facilities for Explorer and BOB. Following decompression consists of `.../Maps` and `.../Modules` directories which contain the Maps and Modules for Explorer, and `.../colour` and `.../opaque` directories which contain colour and opacity maps used in BOB. This file also contains `...DOTexplorerrc` file needed for Explorer.

All directories contain `README` files describing their contents.

5 Visualisation

Visualisation packages were created to convert data into meaningful images. In many cases this is the only way data will make any sense. For example, the numbers in a dataset that describes the image of a lamp will not help in working out what the image is. The best way to find out what is contained in the data set is to look at the two or three dimensional image. There are various types of visualisation packages. Some packages are designed for a specific type of visualisation and/or data. Others provide a base on which to build tools to create the required image. Both have advantages and disadvantages.

The three packages available for visualisation at EPCC are BOB, Explorer and AVS. BOB was chosen because of it's speed, the idea being to use BOB as an initial viewing tool. The other visualisation packages available at EPCC are AVS and Explorer. Explorer and AVS are very similar, however the choice of Explorer over AVS was mainly taken because one of my supervisors (Gordon Cameron) had experience with this package.

5.1 BOB

BOB stands for Brick Of Bytes which is the data format (see section 5.3.1) for this visualisation package. BOB was created for use in the American Army high performance Computing research center. The key feature was to allow images of three dimensional volumes to be viewed quickly and interactively. Although there is little that can be done apart from viewing all of, or sections of, a 3D volume and rotation, BOB is a very useful tool. It has stability and speed firmly on its side. It enables the user to browse through data files very quickly, and therefore choose those which require more detailed viewing. This is where Explorer comes in (see section 5.2).

5.2 Explorer

Explorer is another visualisation tool. However it is quite different from BOB. Explorer uses *modules* (see section 5.4.1) to create *maps* (see section 5.4.2) to view the data in the required way. This enables the user to view the data in many different ways. As for disadvantages Explorer is much slower than BOB, especially for large data sets. The stability of this package is not one of its strong points. It is possible to create maps which go round infinite loops, or *hang* Explorer by reading in data files of the wrong type, or which are too large. Often the only way to rectify errors like this is to *kill* the package and restart. It is therefore important to view any data in BOB initially to help avoid these problems.

5.3 About BOB

As mentioned earlier (see section 5.1) BOB is a visualisation package that creates fast, interactive images of three dimensional volumes of data (see section 5.3.1). Bob has many benefits...

- BOB is extremely fast
- There are no problems with locating the data range of the image
- BOB is extremely stable

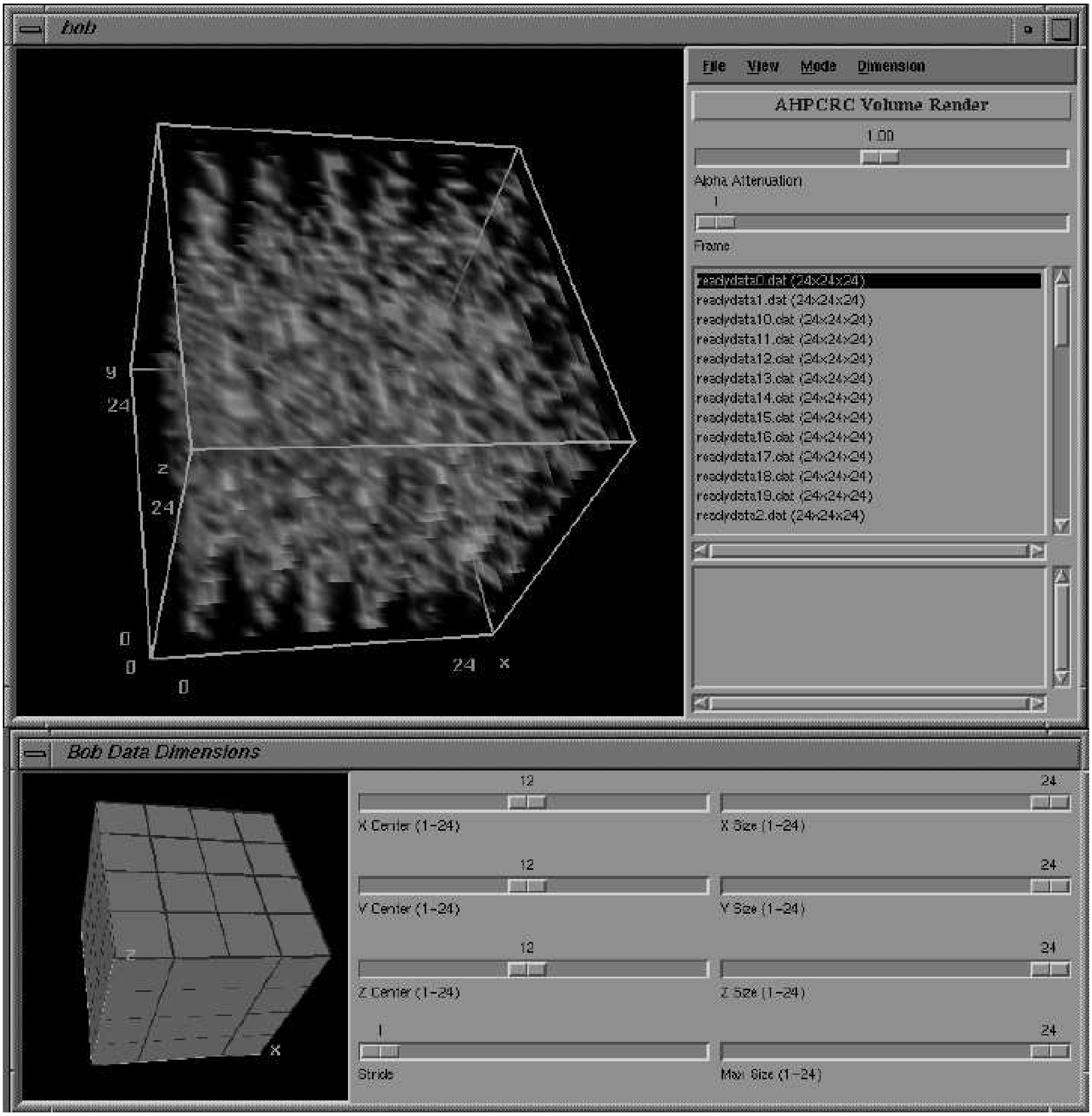

Figure 3: A screenshot of BOB

- Many files can be loaded in at once and browsed through rapidly

... and drawbacks...

- BOB runs only on an SGI terminal — no remote logins!
- BOB offers only one viewing style — volume rendering
- BOB data must be in a particular form (see section 5.3.1)

Due to the limited facilities available in BOB this proved to be the easier of the two packages to become familiar with. To use BOB it is necessary for the user to learn how to load in files, use the colour and alpha maps and the dimensions window.

These are described in more detail in the manual provided (see section 6).

5.3.1 Data types

As mentioned earlier BOB's data type is bricks of bytes. In other words data must be in the form of one value per site, with this value being between 0 and 255. A program called `Convert` (see section 4.2) has been written, by Stephen Booth, to translate data into this format.

5.4 About Explorer

Explorer is the more complicated of the two packages used, however this does mean it is possible to visualise data in a larger variety of forms. Explorer has

- a variety of data types and the facilities to create import modules using `dscribe`
- numerous modules that combine together to create a large variety of images
- the facility to create time animations

however

- it is not very stable
- it can be slow
- it is hard to quit when things go wrong

To use Explorer it was necessary to learn how to use the modules (see section 5.4.1), and how to create maps (see section 5.4.2) from these modules. This was done mainly by creating small sets of testdata, out of Explorer or by using the `GenLat` module which creates different types of data within Explorer, and starting by creating simple maps and building these up to something more complicated, and more useful.

5.4.1 What are modules?

In Explorer a module is like a programme that can be run within the Explorer environment. Numerous modules have been provided, each performing a different operation: reading in files, slicing data, viewing images, etc. The user can also write their own modules, or add modules which have been provided by others.

All Modules contain the following features:

- the name of the module - this is placed at the top of the module
- a circle in the top right corner - clicking on this with the left mouse button enlarges the module box to allow the user to see the widgets provided

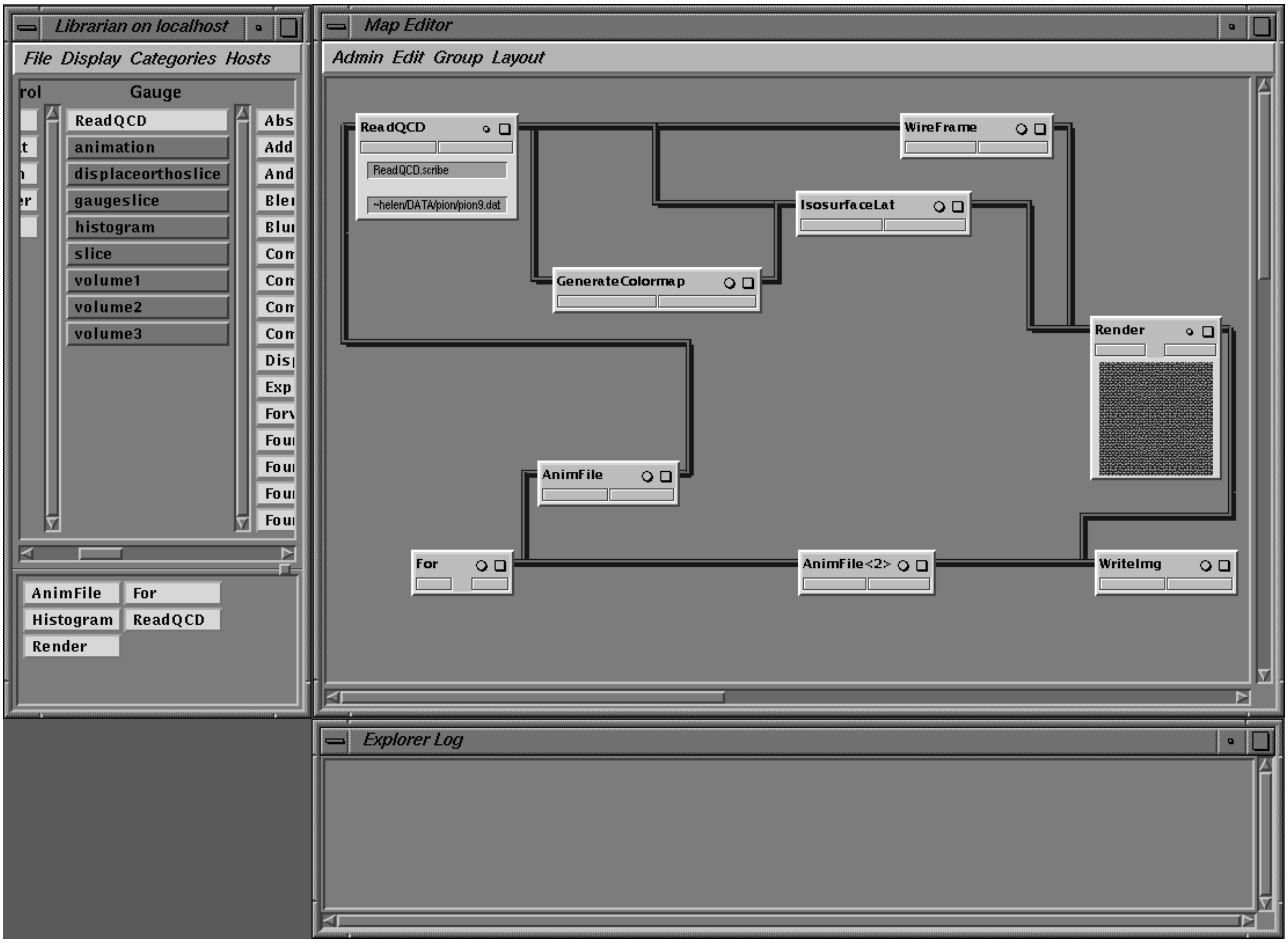

Figure 4: A screenshot of Explorer

Figure 5: Read module

- a square in the top right corner - clicking on this with the left mouse button will open a larger window of the controls (a help option is available in the `help` menu on the control bar of this window)
- a menu - this can be obtained by clicking the right mouse button on the top bar of the module (clicking on the module window produces a different menu). This menu contains things like *refire* which will restart the module, *duplicate*, *disable*, *interrupt* and the *help* menu mentioned above
- two horizontal bars which are positioned underneath the title - these are the input and output ports which are used to connect the modules together to create a *map*.

The `help` option contains a brief explanation of the function of the module as well as the input and output port requirements. A description of the widgets and any known problems and related modules is also included. This option proves useful, especially with new modules, in determining what form the input and output ports require.

Clicking the right button on either the input or output port will give the user a list of connections and what type they must be. Connecting modules together can often be a trial and error task, although experience and looking at maps that have already been created will help.

A data import module called `ReadQCD`, which was written using a package called `dscribe`, has been used in all the maps created to read in the data for QCD visualisation.

5.4.2 What are maps?

A map is a collection of modules that have been linked together. The links are represented by coloured pipes (either blue or purple), and these pipes connect the various input and output ports together. Maps are created so that particular parts of the data are visualised in the required way. In a sense it is like writing a programme (the map) to perform a certain task, and creating this programme from a set of routines (the modules). Various maps have been created to carry out specific tasks. Those relevant to visualising QCD data are to be found in the Librarian under Gauge and Meson, there are others under maps in the librarian that are useful for inspiration when creating maps. The following maps can be found in the *Meson* and *Gauge* lists in the *Librarian*.

animation has been set up to record snapshots of the image in the render window for use in a movie. This map should be used as a template for writing images of the form required. Once these images have been recorded there are facilities called `Movie` and `Movieplayer` available on SGI's which can be used to playback the images.

contour displays orthogonal contour slices.

displaceorthoslice takes orthogonal slices (i, j or k axis) or the image. It has also been set up to displace the image, place a wire frame around the data set and place a legend in the render window.

gaugeslice displaces orthogonal slices along with a histogram display showing the distribution of data. Again a legend is provided.

histogram displays the distribution of data along with maximum and minimum values of the data.

isosurface displays an isosurface (a 3-D contour).

orthoslice displays orthogonal slices.

slice can slice the data in any direction. Again this comes with a legend.

splatter renders a full volume display with an isosurface present (a 3-D contour).

volume1 renders a full volume display with legend.

volume2 renders an orthogonal slice of the data and an isosurface (a 3-D contour) in separate render windows — please note that isosurface can take time on large data sets.

volume3 renders an isosurface (a 3-D contour) and a histogram.

6 Manual

A manual has been written to provide those who wish to visualise QCD data with a concise introduction to the programmes written and packages used to visualise the physical properties contained in this report.

The manual is not intended to be a complete guide to the visualisation packages, but mearly enough to enable the user to use the facilities created and gain some confidence with the packages. It is hoped that the familiarity gained by using the manual will give the user the confidence and ability to modify what has been created and to create new facilities.

The location of both the manual [Ashton, 1994a] and report [Ashton, 1994b] that accompany this project can be found by viewing the World Wide Web,

URL:`http://www.epcc.ed.ac.uk/ epccssp/project09.html`.

7 Results

The images shown in this section were created using the `animation` map in Explorer with the `isosurface` module.

The images in figures 6, 7, 8 and 9 are the first four timeslices that show one value of the probability of the pion in time. As expected this is approaching spherical in shape. As time proceeds the pion hits the side of the box, and, because time and space wrap round on themselves, the pion picture becomes messy. This is due to the small size of the box containing the data - as soon as the pion hits the edge of the box the pion interacts with itself on the other side of the box. The image will contract into a sphere near the end of the timeslices due to the time dimension wrapping round on itself. This means that near the end of the set of timeslices the pion will appear to return to being spherical and shrink as time increases.

8 Conclusion

The aim of visualising QCD data has been achieved. However there are many more things that can be done. There are a variety of physical properties that can be extracted, and only two have been looked at: the probability of the pions existence in space and time, and the function used to fix the gauge.

As expected when looking at the pion it is approaching spherical in shape. As time proceeds the pion hits the side of the box, and, because time and space wrap round on themselves, the pion picture becomes messy for the reasons mentioned in section 7.

As one of the properties of gauge fixing is to smooth the data visualising this data enables the user to determine how well the data is smoothed and if it is smoothed locally or globally.

As part of this project a manual was produced to aid the user in visualising Quantum Chromodynamics data. This provides an introduction to both visualisation packages as well as specifics for the facilities required to visualise QCD data. This was a very important outcome of the project and a lot of time was spent making this as useful as possible. The manual is available on the World Wide Web.

However there are many more things that can be done. There are a variety of physical properties that can be extracted, and only two have been looked at in this project. Properties such as heavy/light particles as well as the light/light particles (Mesons) could be viewed. More visualisation maps can be created as new ways of visualising the data is required. Due to time constraints only two packages were used to visualise the data, and both of these have the drawback of only running on an SGI, which are in limited supply. Therefore it would make sense for a manual and facilities to be provided for AVS as this does not require an SGI.

This project really has endless extensions which will hopefully be applied as research requires them. However a base has now been provide to be built upon in the years to come.

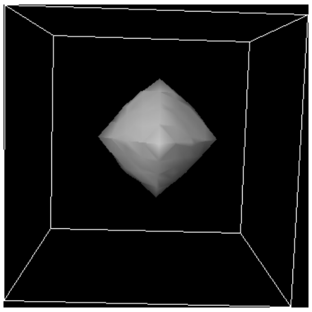

Figure 6: timeslice 00

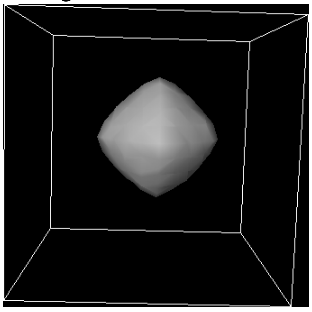

Figure 7: timeslice 01

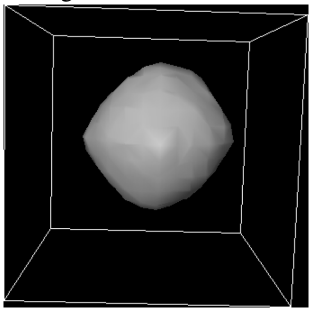

Figure 8: timeslice 02

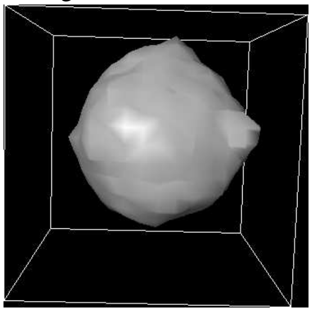

Figure 9: timeslice 03

9 Glossary

angular momentum a property relating to rotational motion

anti-particle a particle which is the same as its respective particle in almost every way except its charge is reversed.

colour a threefold property possessed by quarks, a bit like electric charge, which is believed to be the cause of the strong force.

colour force the force that binds quarks together

electron a negatively charged particle that is one of the constituents of atoms

flavour the property that distinguishes between types of quarks, there are six *flavours*: up, down, strange, charmed, top and bottom

gamma matrix a matrix used to describe the internal organisation of the constituent quarks inside the relevant particle

gauge theory a theory of particles and the forces which act on them

gluon the carriers of the strong force between quarks

lepton a particle that does not experience the strong force, ie. the electron

maps a collections of linked modules in Explorer

meson a particle constisting of a quark anti-quark pair

modules a *building block* within Explorer in which each module performs its own function

Monte Carlo a random statistical method used in many physical simulations

neutrino an electrically neutral, massless lepton of which there are three known varieties one of which partners the electron

pion the lightest known meson of which there are three forms: π^+, π^0 and π^- with charges +1, 0 and -1 respectively

QCD — Quantum Chromodynamics: the theory describing the interaction of colour and electric charges

quark regarded as one of the fundamental building blocks of matter

rho a meson

spin a particle property that is a measure of angular momentum

strong force the force that holds protons and neutrons together. It is believed to result from the force between quarks

UKQCD United Kingdom Quantum Chromodynamics Group

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