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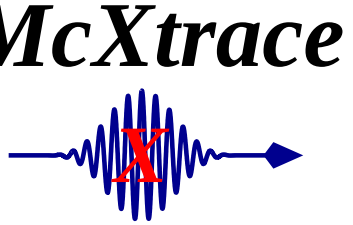

User and Programmers' Guide to the X Ray-Tracing Package McXtrace, version 3.5

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The software package McXtrace is a tool for carrying out highly complex Monte Carlo ray-tracing simulations of X-ray beamlines to high precision. The simulations can compute all aspects of the performance of instruments and can thus be used to optimize the use of existing equipment, design new instrumentation, and carry out virtual experiments for e.g. training, experimental planning or data analysis. McXtrace is based is based on a unique design, inhereted from its sister McStas, where an automatic compilation process translates high-level textual instrument descriptions into efficient ANSI-C code. This design makes it simple to set up typical simulations and also gives essentially unlimited freedom to handle more unusual cases.

This report constitutes the reference manual for McXtrace, and, together with the manual for the McXtrace components, it contains full documentation of all aspects of the program. It covers the various ways to compile and run simulations, a description of the meta-language used to define simulations, and some example simulations performed with the program.

This report documents McXtrace version 3.5, released November, 2026

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Preface and acknowledgements

This document contains information on the Monte Carlo x-ray tracing program McXtrace version 3.5, building on the initial release in October 1998 of the neutron ray tracing program McStas version 1.0 as presented in Ref. [LN99]. The reader of this document is expected to have some knowledge of x-ray and/or neutron scattering, whereas only little knowledge about simulation techniques is required. In a few places, we also assume familiarity with the use of the C programming language and UNIX/Linux.

Support has been kindly given by SAXLAB Aps. through its CEO Karsten Joensen as well the ESRF and MAX IV Laboratory. We acknowledge all contributing parties.

In case of errors, questions, or suggestions, please do not hesitate to contact the team and the community by either writing to the user mailing list `mcxtrace-users@mcxtrace.org`, consulting the McXtrace home page [Mcx], or leaving a note on the McXtrace facebook page `https://www.facebook.com/McXtrace`. A special bug/request reporting service is available [Mcz].

If you **appreciate** this software, please subscribe to the `mcxtrace-users@mcxtrace.org` email list, send us a smiley message, and contribute to the package.

We encourage you to refer to this software when publishing result with the following citation: E. B. Knudsen, et. al., *Journal of Applied Crystallography*, vol. 46, 2013.

Third party software included in the distribution McXtrace is:

- perl Math::Amoeba from John A.R. Williams `J.A.R.Williams@aston.ac.uk`.
- perl Tk::Codetext from Hans Jeuken `haje@toneel.demon.nl`.
- and optionally PGPLOT from Tim Pearson `tjp@astro.caltech.edu`.

The McXtrace project was initially supported by Det Strategiske Forskningsråd through the NaBiIT programme. Partners in this joint venture were:

- Materials Research Division, Risø DTU, Roskilde, Denmark.
- Niels Bohr Institute, University of Copenhagen, Denmark.
- Faculty of Life Sciences, University of Copenhagen, Denmark.
- SAXLAB ApS. Lundtofte, Denmark.
- ESRF, Grenoble, France.

1. Introduction to McXtrace

Efficient design and optimization of x-ray beamlines are formidable challenges. In many cases Monte Carlo techniques are well matched to meet these challenges. McXtrace is an effort to port the framework provided to the neutron scattering community by the McStas package, to x-ray scattering. McStas has, since its inception in October '98, been used successfully at all major neutron scattering facilities in the world. A particular power of McStas is its geometry engine, which has been adopted by McXtrace, with little modification. The device library of McXtrace is not yet as complete as its sibling McStas but is growing rapidly. At the time of writing it is complete enough to be able to perform simulations approximating any standard beamline.

McXtrace is a fast and versatile software tool. It is based on a meta-language specially designed for x-ray (and neutron) simulation. Specifications are written in this language by users and automatically translated into efficient simulation codes in ANSI-C. The present version supports both continuous and pulsed source beamlines, and includes a library of standard components with total around 100 components.

The McXtrace package is written in ANSI-C and is freely available for download from the McXtrace website [Mcx]. The package is actively developed and supported by Physics Department, Technical University of Denmark, Kgs. Lyngby, Denmark., Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark., European Synchrotron Radiation Facility, Grenoble, France.and SAXSLAB Aps. The system is tested and is supplied with examples and documentation. Besides this manual, a separate component manual exists which details each individual component separately.

1.1. Development of Monte Carlo x-ray simulation

Monte Carlo simulation of x-ray instrumentation has been used for many years — in particular the SHADOW package [WCC94; Rio+11] has found widespread use, and is still actively developed, yet has some limitations. *Ray*[Sch08] and *Xtrace*[Bau+07] are other packages using the same basic techniques.

What sets McXtrace apart is, among other things, its open source development strategy and its inherent modularity. This combination lets independent scientists work indepently on separate modules that they have use for, and contribute to the whole with only a small effort.

1.2. Scientific background

What makes scientists happy? Probably to collect good quality data, pushing beamlines to their limits, and fit that data to physical models. Among available measurement techniques, x-ray scattering provides a large variety of beamlines to probe structure and dynamics of all kinds of samples.

Achieving a satisfactory experiment on the best beamline is not all. Once collected, the data analysis process raises some questions concerning the signal: what is the background signal? What proportion of coherent and incoherent scattering has been measured? What are the contributions from the sample geometry, the container, the sample environment, and generally the beamline itself? And last but not least, how does multiple scattering affect the signal? Most of the time, the physicist will elude these questions using rough approximations, or applying analytical corrections [Cop+86]. Monte-Carlo techniques provide a mean to evaluate some of these quantities. The technicalities of Monte-Carlo simulation techniques are explained in detail in chapter 4.

1.2.1. The goals of McXtrace

Initially, the McStas project and hence also the present subject the McXtrace project had four main objectives that determined its design.

Correctness. It is essential to minimize the potential for bugs in computer simulations. If a word processing program contains bugs, it will produce bad-looking output or may even crash. This is a nuisance, but at least you know that something is wrong. However, if a simulation contains bugs it produces wrong results, and unless the results are far off, you may not know about it! Complex simulations involve hundreds or even thousands of lines of formulae, making debugging a major issue. Thus the system should be designed from the start to help minimize the potential for bugs to be introduced in the first place, and provide good tools for testing to maximize the chances of finding existing bugs.

Flexibility. When you commit yourself to using a tool for an important project, you need to know if the tool will satisfy not only your present, but also your future requirements. The tool must not have fundamental limitations that restrict its potential usage. Thus the McXtrace systems needs to be flexible enough to simulate different kinds of instruments as well as many different kind of optical components, and it must also be extensible so that future, as yet unforeseen, needs can be satisfied.

Power. "*Simple things should be simple; complex things should be possible*". New ideas should be easy to try out, and the time from thought to action should be as short as possible. If you are faced with the prospect of programming for two weeks before getting any results on a new idea, you will most likely drop it. Ideally, if you have a good idea at lunch time, the simulation should be running in the afternoon.

Efficiency. Monte Carlo simulations are computationally intensive, hardware capacities are finite (albeit impressive), and humans are impatient. Thus the system must assist in producing simulations that run as fast as possible, without placing unreasonable burdens on the user in order to achieve this.

1.3. The design of McXtrace

In order to meet these ambitious goals, it was decided that McXtrace should be based on its own meta-language, specially designed for simulating scattering beamlines. Simulations are written in this meta-language by the user, and the McXtrace compiler automatically translates them into efficient simulation programs written in ANSI-C.

In realizing the design of McXtrace, the task was separated into four conceptual layers:

1. Modeling the physical processes of scattering, *i.e.* the calculation of the fate of a photon that passes through the individual components of the beamline (absorption, scattering at a particular angle, etc.)

2. Modeling of the overall beamline geometry, mainly consisting of the type and position of the individual components.

3. Accurate calculation, using Monte Carlo techniques, of beamline properties such as resolution function from the result of ray-tracing of a large number of photons. This includes estimating the accuracy of the calculation.

4. Presentation of the calculations, graphical or otherwise.

Though obviously interrelated, these four layers can be treated independently, and this is reflected in the overall system architecture of McXtrace. The user will in many situations be interested in knowing the details only in some of the layers. For example, one user may merely look at some results prepared by others, without worrying about the details of the calculation. Another user may simulate a new instrument without having to reinvent the code for simulating the individual components in the instrument. A third user may write an intricate simulation of a complex component, e.g. a detailed description of a high resolution fast chopper, and expect other users to easily benefit from his/her work, and so on. McXtrace attempts to make it possible to work at any combination of layers in isolation by separating the layers as much as possible in the design of the system and in the meta-language in which simulations are written.

The usage of a special meta-language and an automatic compiler has several advantages over writing a big monolithic program or a set of library functions in C, Fortran, or another general-purpose programming language. The meta-language is more *powerful*; specifications are much simpler to write and easier to read when the syntax of the specification language reflects the problem domain. For example, the geometry of beamlines would be much more complex if it were specified in C code with static arrays and pointers. The compiler can also take care of the low-level details of interfacing the various parts of the specification with the underlying C implementation language and

each other. This way, users do not need to know about McXtrace internals to write new component or beamline definitions, and even if those internals change in later versions of McXtrace, existing definitions can be used without modification.

The McXtrace system also utilizes the meta-language to let the McXtrace compiler generate as much code as possible automatically, letting the compiler handle some of the things that would otherwise be the task of the user/programmer. *Correctness* is improved by having a well-tested compiler generate code that would otherwise need to be specially written and debugged by the user for every beamline or component. *Efficiency* is also improved by letting the compiler optimize the generated code in ways that would be time-consuming or difficult for humans to do. Furthermore, the compiler can generate several different simulations from the same specification, for example to optimize the simulations in different ways, to generate a simulation that graphically displays x-ray trajectories, and possibly other things in the future that were not even considered when the original instrument specification was written.

The design of McXtrace makes it well suited for doing "what if..." types of simulations. Once an instrument has been defined, questions such as "what if a slit was inserted", "what if a focusing monochromator was used instead of a flat one", "what if the sample was offset 0.2 mm from the center of the axis" and so on are easy to answer. Within minutes the beamline definition can be modified and a new simulation program generated. It also makes it simple to debug new components. A test beamline definition may be written containing a source, the component to be tested, and whatever monitors are useful, and the component can be thoroughly tested before being used in a complex simulation with many different components.

The McXtrace system is based on ANSI-C, making it both efficient and portable. The meta-language allows the user to embed arbitrary C code in the specifications. *Flexibility* is thus ensured since the full power of the C language is available if needed.

1.4. Overview

The McXtrace system documentation consists of the following major parts:

- A short list of new features introduced in this McXtrace release appears in chapter 2
- Chapter 3 explains how to obtain, compile and install the McXtrace compiler, associated files and supportive software
- Chapter 4 concerns Monte Carlo techniques and simulation strategies in general
- Chapter 5 includes a brief introduction to the McXtrace system (section 5.2) on running the compiler to produce simulations. section 5.3 explains how to run the generated simulations. Running McXtrace on parallel computers requires special attention and is discussed in section 5.6. A number of front-end programs are used to run the simulations and to aid in the data collection and analysis of the results. These user interfaces are described in section 5.4.

- The McXtrace meta-language is described in chapter 6. This chapter also describes a set of library functions and definitions that aid in the writing of simulations. See appendix B for more details.
- The McXtrace component library contains a collection of well-tested, as well as user contributed, beam components that can be used in simulations. The McXtrace component library is documented in a separate manual and on the McXtrace web-page [Mcx], but a short overview of these components is given in chapter 8 of the Manual.

A list of library calls that may be used in component definitions appears in appendix B, and an explanation of the McXtrace terminology can be found in appendix C of the Manual. Plans for future extensions are as a rule presented on the McXtrace web-page [Mcx].

2. New features in McXtrace 3.5

McXtrace is an ongoing evolving project with features being added frequently. While we strive to test it's features thoroughly, bugs are inevitable. Bugs are generally reported using the user-mailing list: mcxtrace-users@mcxtrace.org and subsequently (after initial triage) tracked using the McXtrace Trac system [Mcc] (shared with its sister project McStas). We will not present here an extensive list of improvements and corrections, and we let the reader refer to this bug reporting service for details. Only important changes are indicated here. Of course, we can not guarantee that the software is bullet proof, but we do our best to correct bugs, when they are reported.

The main focus of the 1.2 release has been to improved stability and fixing bug, rather than new developments.

2.1. Kernel

An important update has been made to the approach of negative propagation lengths. Instead of inplicitly absorbing photons these are now generally restored. In many cases the previous behaviour casued confusion and counter-inutitive operation, in particular regarding mutually exclusive monitors with the flag `restore_xray` set.

2.2. Run-time

New intersection routines include `ellipsoid_intersect` and `sphere_intersect`.

2.3. Components and Library

We here list the new and updated components (found in the McXtrace `lib` directory) which are detailed in the *Component manual*. For an overview see the *Component Overview* of the *User Manual*(This Document).

2.3.1. New components

Sources

We have revised the following source models to make them work as conherently as possible while retaining the backwards compatibility.

Source_pt Point source.

Source_flat Flat surface uniform source

Source_div Flat surface uniform source with divergence distribution

Source_gaussian Gaussian crossection source approximating a Bending Magnet

Furthermore we now also supply an experimental model of a bending magnet `Bending_magnet`. The following experimental components have been set up to facilitate interfacing with SPECTRA, Simplex, and GENESIS 1.3. In general they take the output of the relevant external program to get a phase space distribution of photons from which McXtrace samples rays to trace.

Source_genesis Reads the output of a GENESIS 1.3 simulation. Useful for FEL-simulations.

Source_spectra Reads the output of a SPECTRA simulation. Useful for Synchrotron simulations.

Source_simplex Reads the output of a Simplex simulation. Useful for FEL simulations.

Samples

Single_crystal Now has support for wavelength dependent absorption.

Molecule_2state Also includes absorption support.

Molecule_2state Option for supplying a q-parametrized scattering amplitude curve. This is for instance useful to add the effect of a well known solvent (e.g. Water) to a simulation.

SAXS A whole set of SAXS-related samples is now available for various cases.

Optics

Filter Now has the option of taking any shape (through an .off or .ply-file.

Filter Added a refraction-option.

Multilayer_elliptic Elliptical multilayer mirror. This component now has the option of using a analytical kinematical approximation to compute refleticity as opposed to supplying a datafile. This is faster, but often less accurate.

Lens_parab_* The lenses now behave in a similar manner wrt. parameter naming etc., also fixes to an error in the absorption computation. Note that the lens version will be merged in the next release (see the component manual).

Mirror_elliptic Elliptical shape mirror. Major geometry bug-fixes. Is scheduled to be merged with `Mirror_curved`.

Mirror_parabolic Parabolic shape mirror. Major geometry bug-fixes. Is scheduled to be merged with `Mirror_curved`.

Mirror_curved Cylindrical mirror. Fixed a bug which prevented its use as an azimuthal focusing mirror, with sideways incidence.

Chopper_simple Optional random jitter was added.

Mask A component that takes an image file as input, which is used to mask the beam. For instance to exmine linited resolution effects.

Monitors

TOF_monitor New Intensity vs. time of flight monitor. Useful for sime-resolved studies with pulsed sources.

2.3.2. Example instruments

The following beamline models have been added (in addition to unit test models that test specific components):

XFEL_SPB A rough model of the SPB beamline at the Euorpean XFEL.

MAXII_711 A model of the 711 powder diffraction beamline at Maxlab in Lund, Sweden.

MAXII_811 Model of the 811 surface diffraction and EXAFS beamline at Maxlab in Lund, Sweden.

2.4. Tools, installation

2.4.1. Selected Tool features

- standard FreeBSD port
- Possibility to run MPI or grid simulations by default from mxgui.
- We provide syntax-highlighting setup files for eamcs, vim and gedit editors.

2.4.2. Warnings

WARNING: The 'dash' shell which is used as /bin/sh on some Linux system makes the 'Cancel' and 'Update' buttons fail in mxgui. Solutions are:

a) If your system is a Debian or Ubuntu, please dpkg-reconfigure dash and say 'no' to install dash as /bin/sh

b) If you run another Linux with /bin/sh beeing dash, please install bash and manually change the /bin/sh link to point at bash.

3. Installing McXtrace

Up to date information on installation procedures on the various supported platforms are available under the installation heading on the McXtrace project webpage: http://www.mcxtrace.org

3.0.1. Platform support

McXtrace is a multiplatform effort. The team policy is to supply native style installation packages for:

Mac OS X The aim is to supply installation packages for the 3 latest releases.

Windows We make packages for system supported by Microsoft.

Linux .deb based distributions.

Linux .rpm based distributions.

FreeBSD Through the ports system.

Plus probably any UNIX/POSIX type environment with a bit of effort, using the source distribution of McXtrace.

The team will be happy to make package builds for other types of systems on request. Please write to the user mailing list `mcxtrace-users@mcxtrace.org` to request a special build.

4. Monte Carlo Techniques and simulation strategy

This chapter explains the simulation strategy and the Monte Carlo techniques used in McXtrace. We first explain the concept of the x-ray weight factor, and discuss the statistical errors in dealing with sums of x-ray weights. Secondly, we give an expression for how the weight factor transforms under a Monte Carlo choice and specialize this to the concept of direction focusing. Finally, we present a way of generating random numbers with arbitrary distributions. More details are available in the Appendix concerning random numbers in the User manual.

4.1. X-ray simulations

X-ray scattering beamlines are built as a series of optical elements. Each of these elements modifies the beam characteristics (e.g. divergence, wavelength spread, spatial and temporal distributions) in a way which, for simple x-ray beam configurations, may be modelled with analytical methods.

However, real x-ray beamlines consist of a large number of optical elements, and this brings additional complexity by introducing strong correlations between x-ray beam parameters like divergence and position - which is the basis of the acceptance diagram method - but also wavelength and time. The usual analytical methods, such as phase-space theory, then reach their limit of validity in the description of the resulting effects.

In order to cope with this difficulty, Monte Carlo (MC) methods (for a general review, see Ref. [Jam80]) may be applied to the simulation of x-ray beamlines. The use of probability is commonplace in the description of microscopic physical processes. Integrating these events (absorption, scattering, reflection, ...) over the x-ray trajectories results in an estimation of measurable quantities characterizing the beamline. Moreover, using variance reduction (importance sampling) where possible, reduces the computation time and gives better accuracy.

Implementations of the MC method for X-ray beamlines already exist, most notable is probably *SHADOW*[WCC94], originally developed by the late Franco Cerrina and coworkers, now developed further by M. Sanchez Del Rio at the ESRF[Rio+11][Sha]. Other implementations of the same concept are *RAY*[Sch08] from BESSY and *Xtrace*[Bau+07]. hosted at ANKA

4.1.1. Monte Carlo ray tracing simulations

Mathematically, the Monte-Carlo method is an application of the law of large numbers [Jam80; GRR92]. Let $f(u)$ be a finite continuous integrable function of parameter u for which an integral estimate is desirable. The discrete statistical mean value of f (computed as a series) in the uniformly sampled interval $a < u < b$ converges to the mathematical mean value of f over the same interval.

$$\lim_{n\to\infty} \frac{1}{n} \sum_{i=1, a\leq u_i\leq b}^{n} f(u_i) = \frac{1}{b-a} \int_a^b f(u)du \tag{4.1}$$

In the case were the u_i values are regularly sampled, we come to the well known midpoint integration rule. In the case were the u_i values are randomly (but uniformly) sampled, this is the Monte-Carlo integration technique. As random generators are not perfect, we rather talk about *quasi*-Monte-Carlo technique. We encourage the reader to refer to James [Jam80] for a detailed review on the Monte-Carlo method.

4.2. The x-ray weight

A totally realistic semi-classical simulation will require that each x-ray is at any time either present or lost. On many beamlines the sheer abundance of x-ray photons makes it impractical to trace each and every photon from the source. This is particularly the case at XFELs. Additionally, only a very small fraction of the initial x-rays will ever be detected, and simulations of this kind will therefore waste much time in dealing with x-rays that never hit the detector.

A way of dealing with these issues and speed up calculations is to introduce a x-ray "weight factor" for each simulated ray and to adjust this weight according to the path of the ray. If *e.g.* the reflectivity of a certain optical component is 10%, and only reflected x-rays ray are considered later in the simulations, the x-ray weight will be multiplied by 0.10 when passing this component, but every x-ray is allowed to reflect in the component. In contrast, the totally realistic simulation of the component would require on average ten incoming x-rays for each reflected one.

Let the initial x-ray weight be p_0 and let us denote the weight multiplication factor in the j'th component by π_j. The resulting weight factor for the x-ray ray after passage of the whole beamline becomes the product of all contributions

$$p = p_n = p_0 \prod_{j=1}^{n} \pi_j. \tag{4.2}$$

Each adjustement factor should be $0 < \pi_j < 1$, except in special circumstances, so that total flux can only decrease through the simulation. For convenience, the value of p is updated (within each component) during the simulation.

Simulation by weight adjustment is performed whenever possible. This includes

- Transmission through filters and windows.

- Reflection from monochromator (and analyser) crystals with finite reflectivity and mosaicity.
- Reflections from mirrors.
- Passage of a continuous beam through a chopper.
- Scattering from all types of samples.

4.2.1. Statistical errors of non-integer counts

In a typical simulation, the result will consist of a count of x-ray histories ("rays") with different weights. The sum of these weights is an estimate of the mean number of x-rays hitting the monitor (or detector) per second in a "real" experiment. One may write the counting result as

$$I = \sum_i p_i = N\overline{p}, \tag{4.3}$$

where N is the number of rays hitting the detector and the horizontal bar denotes averaging. By performing the weight transformations, the (statistical) mean value of I is unchanged. However, N will in general be enhanced, and this will improve the accuracy of the simulation.

To give an estimate of the statistical error, we proceed as follows: Let us first for simplicity assume that all the counted x-ray weights are almost equal, $p_i \approx \overline{p}$, and that we observe a large number of x-rays, $N \geq 10$. Then N almost follows a normal distribution with the uncertainty $\sigma(N) = \sqrt{N}$ [1]. Hence, the statistical uncertainty of the observed intensity becomes

$$\sigma(I) = \sqrt{N}\overline{p} = I/\sqrt{N}, \tag{4.4}$$

as is used in real x-ray experiments (where $\overline{p} \equiv 1$). For a better approximation we return to Eq. (4.3). Allowing variations in both N and $\overline{p}$, we calculate the variance of the resulting intensity, assuming that the two variables are independent:

$$\sigma^2(I) = \sigma^2(N)\overline{p}^2 + N^2\sigma^2(\overline{p}). \tag{4.5}$$

Assuming as before that N follows a normal distribution, we reach $\sigma^2(N)\overline{p}^2 = N\overline{p}^2$. Further, assuming that the individual weights, p_i, follow a Gaussian distribution (which in some cases is far from the truth) we have $N^2\sigma^2(\overline{p}) = \sigma^2(\sum_i p_i) = N\sigma^2(p_i)$ and reach

$$\sigma^2(I) = N\left(\overline{p}^2 + \sigma^2(p_i)\right). \tag{4.6}$$

The statistical variance of the p_i's is estimated by $\sigma^2(p_i) \approx (\sum_i p_i^2 - N\overline{p}^2)/(N-1)$. The resulting variance then reads

$$\sigma^2(I) = \frac{N}{N-1}\left(\sum_i p_i^2 - \overline{p}^2\right). \tag{4.7}$$

[1] This is not correct in a situation where the detector counts a large fraction of the x-rays in the simulation, but we will neglect that for now.

For almost any positive value of N, this is very well approximated by the simple expression

$$\sigma^2(I) \approx \sum_i p_i^2. \tag{4.8}$$

As a consistency check, we note that for all p_i equal, this reduces to eq. (4.4)

In order to compute the intensities and uncertainties, the detector components in McXtrace will keep track of $N = \sum_i p_i^0, I = \sum_i p_i^1$, and $M_2 = \sum_i p_i^2$.

4.3. Weight factor transformations during a Monte Carlo choice

When a Monte Carlo choice must be performed, *e.g.* when the initial energy and direction of the x-ray ray is decided at the source, it is important to adjust the x-ray weight so that the combined effect of x-ray weight change and Monte Carlo probability of making this particular choice equals the actual physical properties we like to model.

Let us follow up on the simple example of transmission. The probability of transmitting the real x-ray is P, but we make the Monte Carlo choice of transmitting the x-ray every time: $f_{\mathrm{MC}} = 1$. This must be reflected on the choice of weight multiplier π_j given by the master equation In the "real" semi-classical world, there is a distribution (probability density) for the x-rays in the six dimensional (energy, direction, position) space of $\Pi(E, \mathbf{\Omega}, \mathbf{r}) = dP/(dEd\mathbf{\Omega}d^3\mathbf{r})$ depending upon the source type and its parameters (such as gap, period, field strength etc. for an undulator). In the Monte Carlo simulations, the six coordinates are for efficiency reasons in general picked from another distribution: $f_{\mathrm{MC}}(E, \mathbf{\Omega}, \mathbf{r}) \neq \Pi(E, \mathbf{\Omega}, \mathbf{r})$, since one would *e.g.* often generate only x-rays within a certain parameter interval. However, we must then require that the weights are adjusted by a factor π_j (in this case: $j = 1$) so that

$$f_{\mathrm{MC}}\pi_j = P. \tag{4.9}$$

This probability rule is general, and holds also if, e.g., it is decided to transmit only half of the rays ($f_{\mathrm{MC}} = 0.5$). An important different example is elastic scattering from a powder sample, where the Monte-Carlo choices are the particular powder line to scatter from, the scattering position within the sample and the final x-ray direction within the Debye-Scherrer cone.

4.3.1. Direction focusing

An important application of weight transformation is direction focusing. Assume that the sample scatters the x-rays in many directions. In general, only x-rays in some of these directions will stand any chance of being detected. These directions we call the *interesting directions*. The idea in focusing is to avoid wasting computation time on x-rays scattered in the other directions. This trick is an instance of what in Monte Carlo terminology is known as *importance sampling*.

If *e.g.* a sample scatters isotropically over the whole 4π solid angle, and all interesting directions are known to be contained within a certain solid angle interval $\Delta\mathbf{\Omega}$, only these solid angles are used for the Monte Carlo choice of scattering direction. According to Eq. (4.9), the weight factor will then have to be changed by the amount $\pi_j = |\Delta\mathbf{\Omega}|/(4\pi)$. One thus ensures that the mean simulated intensity is unchanged during a "correct" direction focusing, while a too narrow focusing will result in a lower (*i.e.* wrong) intensity, since we cut x-rays rays that should have reached the final detector.

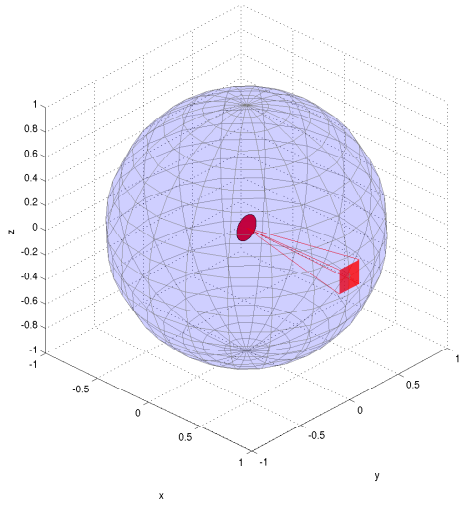

Figure 4.1.: Illustration of the effect of direction focusing in McXtrace. Weights of x-rays emitted into a certain solid angle are scaled down by the full unit sphere area.

4.4. Stratified sampling

One particular efficiency improvement technique is the so-called *stratified sampling*. It consists in partitioning the event distributions in representative sub-spaces, which are then all sampled individualy. The advantage is that we are then sure that each sub-space is well represented in the final integrals. This means that instead of shooting N events, we define D partitions and shoot $r = N/D$ events in each partition. We may define partitions so that they represent 'interesting' distributions, e.g. from events scattered on a monochromator or a sample. The sum of partitions should equal the total space integrated by the Monte Carlo method, and each partition must be sampled randomly.

In the case of McXtrace, the stratified sampling is used when repeating events, i.e. when using the SPLIT keyword in the TRACE section on beamline descriptions. We emphasize here that the number of repetitions r should not exceed the dimensionality of the Monte Carlo integration space (which is $d = 10$ for x-ray events) and the dimen-

Records	Accurarcy
10^3	10 %
10^4	2.5 %
10^5	1 %
10^6	0.25 %
10^7	0.05 %

Table 4.1.: Accuracy estimate as a function of the number of statistical events used to estimate an integral with McXtrace.

sionality of the partition spaces, i.e. the number of random generators following the stratified sampling location in the beamline.

4.5. Accuracy of Monte Carlo simulations

When running a Monte Carlo, the meaningful quantities are obtained by integrating random events into a single value (e.g. flux), or onto an histogram grid. The theory [Jam80] shows that the accuracy of these estimates is a function of the space dimension d and the number of events N. For large numbers N, the central limit theorem provides an estimate of the relative error as $1/\sqrt{N}$. However, the exact expression depends on the random distributions.

McXtrace uses a space with $d = 12$ parameters to describe x-rays (position, wavevector, weight, polarisation, phase, time). We show in Table 4.1 a rough estimate of the accuracy on integrals as a function of the number of records reaching the integration point. This stands both for integrated flux, as well as for histogram bins - for which the number of events per bin should be used for N.

5. Running McXtrace

This chapter describes usage of the McXtrace simulation package. In case of problems regarding installation or usage, the McXtrace mailing list [Mcx] or the authors should be contacted.

Performing a simulation using McXtrace can be divided into the following steps/elements

- To use McXtrace, an instrument definition file describing the instrument to be simulated must be written. Alternatively, an example instrument file can be obtained from the `examples/` directory in the distribution or from another source.
- The input files (instrument and component files) are written in the McXtrace meta-language and are edited either by using your favorite editor or by using the built-in editor of the graphical user interface (`mxgui`).
- Next, the McXtrace compiler `mcxtrace` is invoked to translate the instrument and component files into a C program. The program `mcxtrace` itself is written in C, using the parser *flex* and the compiler compiler *bison*.
- The resulting C program can then be compiled with a C compiler and run in combination with various front-end programs for example to present the intensity at the detector as a motor position is varied.
- The output data may be analyzed and visualized in the same way as regular experiments by using the data handling and visualization tools in McXtrace. As of McXtrace 3.x, these front-ends (`mxplot`, `mxdisplay`, ...) are all implemented in Python, using `matplotlib`, `pyqtgraph` and browser/HTML (D3.js) back-ends, see section 5.4. Further data output formats including NeXus are available, see section 5.5.

5.0.1. Important note for Windows users

It is a known problem that some of the McXtrace tools do not support filenames / directories with spaces. We recommend avoiding spaces in the paths used for McXtrace work directories and instrument files. As of McXtrace 3.x, all tools (`mxgui`, `mxrun`, `mxplot`, `mxdisplay`, ...) are pure Python and are bundled with the `conda-forge` package, so no separate Perl installation is required on any platform, including Windows.

5.1. Brief introduction to the graphical user interface

This section gives an ultra-brief overview of how to use McXtrace once it has been properly installed. It is intended for those who do not read manuals if they can avoid

it. For details on the different steps, see the following sections. This section uses the `Template_1Slit_Diff.instr` file supplied in the `examples/Templates` directory of the McXtrace distribution.

To start the graphical user interface of McXtrace, run the `mxgui` command which will open a window with a number of menus, see figure 5.1. To load an instrument,

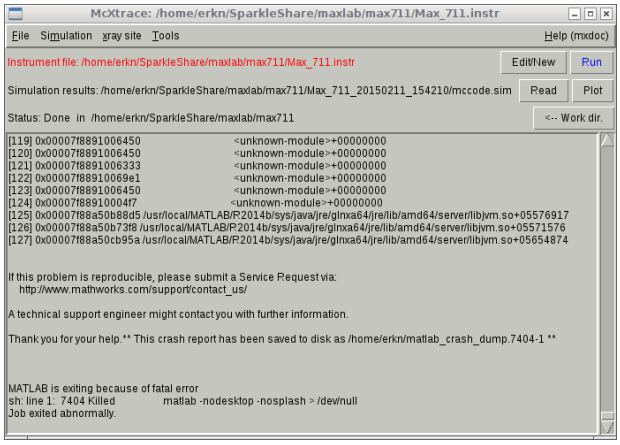

Figure 5.1.: The graphical user interface `mxgui`.

select "New from Template" (formerly known as the "X-ray Site" menu) and open the template/example `Template_1Slit_Diff`. Next, check that the current plotting back-end setting ("Preferences" in the **File** menu, or the `--autoplotter` option of `mxrun`) corresponds to your system setup:

- by editing the user configuration file, see `mxrun --edit-user-config`,
- or by setting the `MCXTRACE_FORMAT` environment variable.

Next, select "Run simulation" from the "Simulation" menu. The McXtrace compiler `mcxtrace` will translate the definition into an executable program. Then `mxgui` will pop up a dialog window. Type a value for the "ROT" parameter (*e.g.* 90), check the "Plot results" option, and select "Start". The simulation will run, and when it finishes after a while the results will be plotted in a window, using one of the Python plotting back-ends (`matplotlib`, `pyqtgraph` or an HTML/browser view), see section 5.4.6. For other options, execute `mxplot --help` to get help.

To visualize or debug the simulation graphically, repeat the steps but check the "Trace" option instead of the "Simulate" option. A window will pop up showing a sketch of the instrument, drawn by the `mxdisplay` front-end (section 5.4.5), again using one of the `matplotlib`, `pyqtgraph` or webGL back-ends.

For a slightly longer gentle introduction to McXtrace, see the McXtrace tutorial (available from [Mcx]), and as of version 3.5 built into the `mxgui` help menu. For more technical details, read on from section 5.2

5.2. Running the instrument compiler

This section describes how to run the McXtrace compiler `mcxtrace` manually. Often, it will be more convenient to use the front-end program `mxgui` (section 5.4.1) or `mxrun` (section 5.4.2), which run the compilation and the simulations automatically.

Upon a command of the form

```
1    mcxtrace name.instr
```

the compiler `mcxtrace` will read the instrument definition `name.instr`, written in the McXtrace meta-language, and translate it into a Monte Carlo simulation program in the programming language C. The output is by default written to a file in the current directory with the same name as the instrument file, but with extension `.c` rather than `.instr`. This can be overridden using the `-o` option as follows:

```
1    mcxtrace -o code.c name.instr
```

which gives the output in the file `code.c`. A single dash '`-`' may be used for both input and output filename to represent standard input and standard output, respectively.

5.2.1. Code generation options

By default, the code generated by `mcxtrace` is ISO-C with some extensions (currently the only extension is the creation of new directories, which is not possible in pure ISO-C). The use of extensions may be disabled with the `-p` or `--portable` option. With this option, the output is strictly ISO-C compliant, at the cost of some slight reduction in capabilities.

By default (`-t` or `--trace`) the generated code also contains special "trace" code, which makes it possible to get a complete trace of the path of every x-ray through the instrument, as well as the position and orientation of every component. This is mainly used by the `mxdisplay` front-end as described in section 5.4.5; the `--no-trace` option leaves it out.

The code generation options can also be controlled by using preprocessor macros in the C compiler, without the need to re-run `mcxtrace`. If the preprocessor macro `MC_PORTABLE` is defined, the same result is obtained as with the `--portable` option. The effect of the `--trace` option may be obtained by defining the `MC_TRACE_ENABLED` macro. Most Unix-like C compilers allow preprocessor macros to be defined using the `-D` option, e.g.

```
1    cc -DMC_TRACE_ENABLED -DMC_PORTABLE ...
```

Finally, the `--verbose` option will list the components and libraries being included in the instrument. The `--source` option embeds a copy of the instrument source code in the generated executable, and `-v`/`--version` (or `--version-num`) prints the full version header (or just the version number).

Alternative code generator: `mccode-antlr`

From McXtrace 3.5 onwards an alternative code generator, `mcxtrace-antlr`, is available alongside the classic generator. It is built on the ANTLR parser framework rather than the traditional `lex/yacc` toolchain, is implemented primarily in Python, and is a candidate replacement for the default generator in future releases.

Select it on a per-run basis with the `--cogen` flag:

```
mxrun --cogen=mcxtrace-antlr MyInstrument.instr -n 1e8
```

The active code generator can also be set permanently by editing the `MCCOGEN` field in `mccode_config.json`. This file is accessible from the command line with:

```
mxrun --edit-user-config
```

or via the *Save/Edit configuration* dialogue inside `mxgui`.

At the time of the McXtrace 3.6 release, `mcxtrace-antlr` is close to feature-complete for CPU simulations with a few more issues for GPU/OpenACC simulations.

Alternative code generator: `mcxtrace-pygen`

A third code generator, `mcxtrace-pygen`, targets McStasScript [Mcs] (a Python package for building and running instruments, including McXtrace ones) rather than C: given an `.instr` file, it generates an equivalent McStasScript Python module instead of a C program. Besides `-o FILE` (output file) it accepts `--instrument-name=NAME` (name of the generated McStasScript instrument; by default the instrument name followed by `_generated`), `--no-tests` (do not translate `%Test` (or `%Example`) lines into McStasScript tests), `--lint` (generate a script for McStasScript-style diagnostic linting), `--verbose` and the version options described above. The C-generator-only options (`-I`, `-t`, `-p`, `--no-main`, `--no-runtime`) are rejected. The generated module exposes a `make()` function returning a McStasScript instrument object:

```
import mcstasscript as ms
from INSTRUMENT_generated import make
instr = make()
instr.show_diagram()
instr.show_instrument()
data = instr.backengine()
ms.make_sub_plot(data)
```

The generator is normally invoked indirectly, via `mcxtrace-jupylab` (section 5.4.3), rather than run directly by the user.

5.2.2. Specifying the location of files

The McXtrace compiler `mcxtrace` needs to be able to find various files during compilation, some explicitly requested by the user (such as component definitions and files referenced by `%include`), and some used internally to generate the simulation executable.

McXtrace looks for these files in three places: first in the current directory, then in a list of directories given by the user, and finally in a special McXtrace directory. Usually, the user will not need to worry about this as `mcxtrace` will automatically find the required files. But if users build their own component library in a separate directory or if `mcxtrace` is installed in an unusual way, it will be necessary to tell the compiler where to look for the files.

The location of the special McXtrace directory is set when `mcxtrace` is compiled. It defaults to `/usr/share/mcxtrace/version` on Debian and derivatives, to `/usr/local/mcxtrace/version` on RedHat and derivatives and on other Unix-like systems, including Mac OS X, where it is a link to the actual location `/Applications/McXtrace-version.app/Contents/Resources/mcxtrace/version`, and `C:\mcxtrace-version\lib` on Windows systems, but it can be changed to something else, see the installation instructions for details.

The location can be overridden by setting the environment variable `MCXTRACE`:

```
1    setenv MCXTRACE /home/joe/mcxtrace
```

for csh/tcsh users, or

```
1    export MCXTRACE=/home/joe/mcxtrace
```

for bash/Bourne shell users. Windows users should define `MCXTRACE` from the menu 'Start/Settings/Control Panel/System/Advanced/Environment Variables' by creating `MCXTRACE` with the value `C:\mcxtrace\lib`

To make `mcxtrace` search additional directories for component definitions and include files, use the `-I` switch:

```
1    mcxtrace -I/home/joe/components -I/home/joe/mcxtrace/include name.instr
```

Multiple `-I` options can be given, as shown.

5.2.3. Embedding the generated simulations in other programs

By default, `mcxtrace` will generate a stand-alone C program, which is what is needed in most cases. However, for advanced usage, such as embedding the generated simulation in another program or even including two or more simulations in the same program, a stand-alone program is not appropriate. For such usage, `mcxtrace` provides the following options:

- `--no-main` This option makes `mcxtrace` omit the `main()` function in the generated simulation program. The user must then arrange for the function `mcxtrace_main()` to be called in some way.
- `--no-runtime` Normally, the generated simulation program contains all the run-time C code necessary for declaring functions, variables, etc. used during the simulation. This option makes `mcxtrace` omit the run-time code from the generated simulation program, and the user must then explicitly link with the file `mcxtrace-r.c` as well as other shared libraries from the McXtrace distribution.

Users that need these options are encouraged to contact the authors for further help.

5.2.4. Running the C compiler

After the source code for the simulation program has been generated with `mcxtrace`, it must be compiled with the C compiler to produce an executable. Since the generated C code obeys the ISO-C standard, it should be easy to compile it using any ISO-C (or C++) compiler. *E.g.* a typical Unix-style command would be

```
1    cc -O -o name.out name.c -lm
```

The McXtrace team recommends these compiler alternatives for the Intel (and AMD) hardware architectures:

A `gcc` which is a very portable, open source, ISO-C compatible c compiler, available for most platforms. For Linux it is usually part of your distribution, for Windows the McXtrace distribution package includes a version of `gcc` (in the Dev-CPP sub-package), and for Mac OS X `gcc` is part of the Xcode tools package available on the installation medium.

B `icc` or the Intel c compiler is available for Linux, Mac OS and Windows systems and is a commercial software product. Generally, simulations run with the Intel compiler are **a factor of 2 faster** than the identical simulation run using `gcc`. To use `icc` with McXtrace on Linux or Mac OS X, set the environment variables

- `MCXTRACE_CC=icc`
- `MCXTRACE_CFLAGS="-g -O2 -wd177,266,1011,181"`

To use `icc` with MPI on Unix system (see Section 5.6) installations, it seems that *editing* the mpicc shell script and setting the CC variable to "`icc`" is the only requirement! On Windows, the Intel c compiler is 'icl', not 'icc' and has a dependency for Microsoft Visual C++. If you have both these softwares available, running McXtrace with the Intel compiler should be possible (currently untested by the McXtrace developer team).

The `-O` option typically enables the optimization phase of the compiler, which can make quite a difference in speed of `mcxtrace`-generated simulations. The `-o name.out` sets the name of the generated executable. The `-lm` options is needed on many systems to link in the math runtime library (like the cos() and sin() functions).

Monte Carlo simulations are computationally intensive, and it is often desirable to have them run as fast as possible. Some success can be obtained by adjusting the compiler optimization options. Here are some example platform and compiler combinations that have been found to perform well (up-to-date information will be available on the McXtrace WWW home page [Mcx]):

- Intel x86 ("PC") with Linux and GCC, using options `gcc -O3`.
- Intel x86 with Linux and EGCS (GCC derivate) using options `egcc -O6`.

- Intel x86 with Linux and PGCC (pentium-optimized GCC derivate), using options `gcc -O6 -mstack-align-double`.
- HPPA machines running HPUX with the optional ISO-C compiler, using the options `-Aa +Oall -Wl,-a,archive` (the `-Aa` option is necessary to enable the ISO-C standard).
- SGI machines running Irix with the options `-Ofast -o32 -w`

Optimization flags will typically result in a speed improvement by a factor about 3, but the compilation of the instrument may be 5 times slower.

A warning is in place here: it is tempting to spend far more time fiddling with compiler options and benchmarking than is actually saved in computation times. Even worse, compiler optimizations are notoriously buggy; the options given above for PGCC on Linux and the ISO-C compiler for HPUX have been known to generate *incorrect code* in some compiler versions. `mcxtrace` actually puts an effort into making the task of the C compiler easier, by in-lining code and using variables in an efficient way. As a result, McXtrace simulations generally run quite fast, often fast enough that further optimizations are not worthwhile. Also, optimizations are highly time and memory consuming during compilation, and thus may fail when dealing with large instrument descriptions (e.g. more that 100 elements). The compilation process is simplified when using components of the library making use of shared libraries (see `SHARE` keyword in chapter 6). Refer to section 5.3.4 for other optimization methods.

5.3. Running the simulations

Once the simulation program has been generated by the McXtrace compiler `mcxtrace` and an executable has been obtained with the C compiler, the simulation can be run in various ways.

Simple McXtrace options

In this section, the most common simulation parameters are discussed. For a full list, please consult Tables 5.1 and 5.2.

The simplest way is to run it directly from the command line or shell:

```
1 ./name.out
```

Note the leading ".", which is needed if the current directory is not in the path searched by the shell. When used in this way, the simulation will prompt for the values of any instrument parameters such as angular settings, and then run the simulation. Default instrument parameter values (see section 6.3), if any, will be indicated and entered when hitting the `Return` key. This way of running McXtrace will only give data for one instrument setting which is normally sufficient for *e.g.*, time-of-flight, SANS or powder instruments, but not for *e.g.* continuous-beam reflectometers or triple-axis spectrometers where a scan over various instrument settings is required. Often the simulation will be

run using one of several available front-ends, as described in the next section. These front-ends help manage output from the potentially many detectors in the instruments, as well as running the simulation for each data point in a scan.

The generated simulations accept a number of options and arguments. The full list can be obtained using the `--help` option:

```
./name.out --help
```

The values of instrument parameters may be specified as arguments using the syntax *name*=*val*. For example

```
./Template_1Slit_Diff.out SLITW=5e-6
```

The number of x-ray histories to simulate may be set using the `--ncount` or `-n` option, for example `--ncount=2e5`. The initial seed for the random number generator is by default chosen based on the current time so that it is different for each run. However, for debugging purposes it is sometimes convenient to use the same seed for several runs, so that the same sequence of random numbers is used each time. To achieve this, the random seed may be set using the `--seed` or `-s` option.

By default, McXtrace simulations write their results into several data files in the current directory, overwriting any previous files stored there. The `--dir=`*dir* or `-d`*dir* option causes the files to be placed instead in a newly created directory *dir* (to prevent overwriting previous results an error message is given if the directory already exists).

The complete list of options and arguments accepted by McXtrace simulations appears in Tables 5.1 and 5.2.

5.3.1. Choosing an output data file format

Data files contain header lines with information about the simulation from which they originate. Use `--format` to select among the available formats (see below).

The format of the output files from McXtrace simulations is described in more detail in section 5.5. It may be chosen either with `--format=FORMAT` for each simulation or globally by setting the MCXTRACE_FORMAT environment variable. The available format list is obtained using the `name.out --help` option. McXtrace can presently generate data in the McXtrace/McCode text format or the NeXus format (see section 5.5.2).

It is also possible to read and write x-ray event lists using the `MCPL_input`/`MCPL_output` components (see the Component Manual), which use the portable, compressed, multi-code MCPL event format rather than any particular code's native event format. This is the recommended way to exchange x-ray events between McXtrace/McXtrace and other Monte Carlo codes. The older, code-specific event-file components (`Virtual_input`/`Virtual_output`, `Virtual_mcnp_input`/`Virtual_mcnp_output`, `Virtual_tripoli4_input`/`Virtual_tripoli4_output`, `Vitess_input`/`Vitess_output`) still exist for backward compatibility, but have moved to the `obsolete` component category (see the Component Manual) and are no longer recommended for new instrument work in favour of MCPL.

Additionally, adding the `raw` keyword to the FORMAT will produce raw $[N, p, p^2]$ data sets instead of $[N, p, \sigma]$ (see Section 4.2.1). The former representation is fully additive,

and thus enables to add results from separate simulations. Other acceptable format modifiers are `transpose` to transpose data matrices and `append` to concatenate data to existing files.

5.3.2. Basic import and plot of results

The previous example will result in a `mccode.sim` index file plus one data file per monitor in the output directory. These are plain-text McXtrace/McCode format files (see section 5.5) that can be read directly with NumPy (`numpy.loadtxt`) or any other language capable of reading text tables, or, more conveniently, with the `mxplot` front-end and its underlying data loader (`mccodelib.mxplotloader`), see section 5.4.6.

When using the HTML plotting back-end (`mxplot-html`), simulation results are rendered as an interactive, self-contained web page (using D3.js) rather than being saved as static images.

The full, up-to-date list of options accepted by `mxrun` and by the generated `<instr>.out` executable is given in Tables 5.1 and 5.2 below. These tables are generated automatically from the `mxrun` Python source (`tools/Python/mxrun/mxrun.py`) by the script `gen_mxrun_options_table.py` in this directory, so that they cannot silently go out of date; run `mxrun --help` for the same information at the command line.

Table 5.1.: `mxrun`-specific options (compilation, scanning, optimisation, MPI/OpenACC).

Option	**Description**
`-c` `--force-compile`	force rebuilding of instrument
`--cogen` *cogen*	Choice of code-generator (implies -c)
`-C` `--c-lint`	Use c-linter (e.g. cppcheck) to lint the generated code. Configure linter via mccode_config.json. Implies -c and -v, but also NO simulation will be run.
`-I`	Append to McCode search path (implies -c)
`--D1` *D1*	Set extra -D args (implies -c)
`--D2` *D2*	Set extra -D args (implies -c)
`--D3` *D3*	Set extra -D args (implies -c)
`-p` `--param` *FILE*	Read parameters from file FILE
`-N` `--numpoints` *NP*	Set number of scan points
`--seeds` *SEEDS*	Set range of seeds to scan (each must be: SEED != 0)
`-L` `--list`	Use a fixed list of points for linear scanning
`-M` `--multi`	Run a multi-dimensional scan

Option	Description
`--scan_split` *scan_split*	Scan by parallelising steps as individual cpu threads. Initialise by number of wanted threads (e.g. your number of cores).
`--autoplot`	Open plotter on generated dataset
`--invcanvas`	Forward request for inverted canvas to plotter
`--autoplotter`	Specify the plotter used with –autoplot
`--embed`	Store copy of instrument file in output directory *(default: True)*
`--mpi` *NB_CPU*	Spread simulation over NB_CPU machines using MPI
`--openacc`	parallelize using openacc
`--funnel`	funneling simulation flow, e.g. for mixed CPU/GPU
`--machines` *machines*	Defines path of MPI machinefile to use in parallel mode
`--optimise-file` *FILE*	Store scan results in FILE (defaults to: "mccode.dat")
`--no-cflags`	Disable optimising compiler flags for faster compilation
`--no-main`	Do not generate a main(), e.g. for use with mcstas2vitess.pl. Implies -c
`--verbose`	Enable verbose output
`--write-user-config`	Generate a user config file
`--edit-user-config`	Generate and edit user config file in EDITOR
`--override-config` *PATH*	Load config file from specific dir
`--optimize`	Optimize instrument variable parameters to maximize monitors
`--optimize-maxiter` *optimize_maxiter*	Maximum number of optimization iterations to perform. Default=1000 *(default: 1000)*
`--optimize-tol` *optimize_tol*	Tolerance for optimization termination. When optimize-tol is specified, the selected optimization algorithm sets some relevant solver-specific tolerance(s) equal to optimize-tol
`--optimize-method` *optimize_method*	Optimization solver in [...] (default: [...]) You can use your custom method method(fun, x0, args, **kwargs, **options). Please refer to scipy documentation for proper use of it: https://docs.scipy.org/doc/scipy/reference/generated/scipy.optimi

Option	Description
`--optimize-eval` *optimize_eval*	Optimization expression to evaluate for each detector "d" structure. You may combine: "d.intensity" The detector intensity; "d.error" The detector intensity uncertainty; "d.values" An array with [intensity, error, counts]; "d.X0 d.Y0" Center of signal (1st moment); "d.dX d.dY" Width of signal (2nd moment). Default is "d.intensity". Examples are: "d.intensity/d.dX" and "d.intensity/d.dX/d.dY"
`--optimize-minimize`	Choose to minimize the monitors instead of maximize
`--optimize-monitor` *optimize_monitor*	Name of a single monitor to optimize (default is to use all)
`--showcfg` *ITEM*	Print selected cfg item and exit (paths are resolved and absolute). Allowed values are particle.

Table 5.2.: Instrument/simulation options (also accepted directly by the generated `<instr>.out` executable).

Option	Description
`-s` `--seed` *SEED*	Set random seed (must be: SEED != 0)
`-n` `--ncount` *COUNT*	Set number of particles to simulate *(default: 1000000)*
`-t` `--trace` *trace*	Enable trace of particles through instrument *(default: 0)*
`--no-trace` *notrace*	Disable trace of particles in instrument (combine with -c)
`-y` `--yes`	Assume any default parameter value in instrument
`-d` `--dir` *DIR*	Put all data files in directory DIR. If unspecified INSTRUMENT_TIMESTAMP is used
`--dirprefix` *dirprefix*	Put all data files in directory PREFIX_TIMESTAMP
`--dirsuffix` *dirsuffix*	Put all data files in directory INSTRUMENT_DIRSUFFIX
`-a` `--append`	Append data files to those already in directory DIR
`--format` *FORMAT*	Output data files using format FORMAT, usually McCode or NeXus (format list obtained from ¡instr¿.out -h) *(default: McCode)*
`--bufsiz` *BUFSIZ*	Monitor_nD list/buffer-size (defaults to [...])

Option	Description
`--vecsize` *VECSIZE*	vector length in OpenACC parallel scenarios
`--numgangs` *NUMGANGS*	number of 'gangs' in OpenACC parallel scenarios
`--gpu_innerloop` *INNERLOOP*	Maximum particles in an OpenACC kernel run. (If INNERLOOP is smaller than ncount we repeat)
`--no-output-files`	Do not write any data files
`-i` `--info`	Detailed instrument information
`--list-parameters`	Print the instrument parameters to standard out
`--meta-list`	Print all metadata defining component names
`--meta-defined`	Print metadata names for component, or indicate if component:name exists
`--meta-type`	Print metadata type for component:name
`--meta-data`	Print metadata for component:name

`-g`
`--gravitation`
`--gravity`
	Enable gravitation for all trajectories

`--IDF`	Flag to attempt inclusion of XML-based IDF when –format=NeXus (format list obtained from ¡instr¿.out -h)

5.3.3. Interacting with a running simulation

Once the simulation has started, it is possible, under Unix, Linux and Mac OS X systems, to interact with the on-going simulation. This feature is not available when using MPI parallelization.

McXtrace attaches a signal handler to the simulation process. In order to send a signal to the process, the process-id *pid* must be known. Users may look at their running processes with the Unix 'ps' command, or alternatively process managers like 'top' and 'gtop'. If a *file.out* simulation obtained from McXtrace is running, the process status command should output a line resembling

```
1 <user> 13277 7140 99 23:52 pts/2    00:00:13    file.out
```

where `user` is your Unix login. The *pid* is there '13277'.

Once known, it is possible to send one of the signals listed in Table 5.3 using the 'kill' unix command (or the functionalities of your process manager), e.g.

```
1     kill -USR2 13277
```

This will result in a message showing status (here 33 % achieved), as well as the position in the instrument of the current x-ray.

```
1 # McXtrace: [pid 13277] Signal 12 detected SIGUSR2 (Save simulation)
2 # Simulation: file (file.instr)
3 # Breakpoint: MyDetector (Trace) 33.37 % (  333654.0/ 1000000.0)
```

`USR1`	Request information (status)
`USR2, HUP`	Request information and performs an intermediate saving of all monitors (status and save). This triggers the execution of all `SAVE` sections (see chapter 6).
`INT, TERM`	Save and exit before end (status)

Table 5.3.: Signals supported by McXtrace simulations.

```
4 # Date       : Wed May  7 00:00:52 2003
5 # McXtrace: Saving data and resume simulation (continue)
```

followed by the list of detector outputs (integrated counts and files). Finally, sending a `kill 13277` (which is equivalent to `kill -TERM 13277`) will end the simulation before the initial 'ncount' preset.

A typical usage example would be, for instance, to save data during a simulation, plot or analyze it, and decide to interrupt the simulation earlier if the desired statistics has been achieved. This may be done automatically using the `Progress_bar` component.

Whenever simulation data is generated before end (or the simulation is interrupted), the 'ratio' field of the monitored data will provide the level of achievement of the computation (for instance '3.33e+05/1e+06'). Intensities are then usually to be scaled accordingly by the user.

Additionally, any system error will result in similar messages, giving indication about the occurrence of the error (component and section). Whenever possible, the simulation will *try* to save the data before ending. Most errors appear when using a newly written component, in the `INITIALIZE`, `TRACE` or `FINALLY` sections. Memory errors usually show up when C pointers have not been allocated/unallocated before usage, whereas mathematical errors are found when, for instance, dividing by zero.

5.3.4. Optimizing simulation speed

There are various ways to speed up simulations

- Optimize the compilation of the instrument, as explained in section 5.2.4.
- Execute the simulation in parallel on a computer cluster using MPI, or simply across the cores of a single machine, as explained in section 5.6.
- Divide simulation into parts using a file for saving or generating x-ray events. In this way, a guide may be simulated only once, saving the x-ray events at the guide exit as a file, which is being read quickly by the second simulation part. Use the `MCPL_output` and `MCPL_input` components for this technique (see the Component Manual).
- Use source optimizers like the components Source_adapt or Source_Optimizer. Such component may sometimes not be very efficient, when no x-ray importance

sampling can be achieved, or may even sometimes alter the simulation results. Be careful and always check results with a (shorter) non-optimized computation.

- Complex components usually take into account additional small effects in a simulation, but are much longer to execute. Thus, simple components should be preferred whenever possible, at least in the beginning of a simulation project.

- The SPLIT keyword may artificially repeat events reaching specified positions in the instrument. This is *very* efficient, but requires to cast random numbers in the course of the remaining propagation (e.g. at samples, crystals, ...). See section 6.4.7 for details.

A general comment about optimization is that it should be used cautiously, checking that the results are not significantly affected.

5.3.5. Optimizing instrument parameters

Often, the user may wish to optimize the parameters of a simulation, i.e. the best geometry of a given component, for example the optimal curvature of a monochromator.

The choice of the optimization routine, of the simulation quality value to optimize, the initial parameter guess and the simulation length all have a large influence on the results. The user is advised to be cautious when interpreting the optimization results.

Using iFit for optimization

One of the authors of McXtrace has developed a very flexible and general data analysis and fitting package called iFit [EF14; Ifi] based on Matlab. Matlab itself is not required, as a stand-alone distributable binary of iFit exists.

iFit contains wrapper functionality for compiling and running McXtrace simulations as object functions, and allows to select many different optimizers, including swarms and other non-gradient methods. Please see the iFit documentation for more information.

Our experience is that iFit together with McXtrace can be a more robust optimization solution than the McXtrace built-in `--optimize` mode described next, in particular for problems with many free parameters.

Using the built-in `--optimize` mode

The McXtrace package comes with a built-in optimization mode to find instrument parameters that maximize (or minimize) the value of all, or some specified, monitors. As of McXtrace 3.x this is implemented in `mxrun` using the `scipy.optimize.minimize` family of solvers [Sci], replacing the earlier built-in Simplex/Nelder–Mead implementation. Available methods include `powell` (the default), `nelder-mead`, `cg`, `bfgs`, `newton-cg`, `l-bfgs-b`, `tnc`, `cobyla`, `slsqp`, `trust-constr`, `dogleg`, `trust-ncg`, `trust-exact` and `trust-krylov`; consult the SciPy documentation for the properties of each. As with any non-linear optimizer, results depend on the initial guess and the chosen method, and

higher-dimensional problems (many free parameters) are not guaranteed to converge to a meaningful, global optimum.

When using `mxrun` (section 5.4.2), the optimization mode is set by using the `--optimize` flag, together with instrument parameter ranges specified exactly as for a scan, e.g. `param=min,max`. The solver is selected with `--optimize-method=METHOD`, the convergence tolerance with `--optimize-tol=TOL`, and the maximum number of iterations with `--optimize-maxiter=N`. By default all monitors are summed as the figure of merit; a single monitor may be targeted instead with `--optimize-monitor=NAME`, and `--optimize-minimize` inverts the sense of the search (minimize rather than maximize). For full control over the optimized quantity (e.g. optimizing on peak width rather than intensity), use `--optimize-eval=EXPR` with an expression combining the fields of a detector structure `d` (`d.intensity`, `d.error`, `d.values`, `d.X0`/`d.Y0`, `d.dX`/`d.dY`), e.g. `--optimize-eval="d.intensity/d.dX"`. See Table 5.1 for the complete, up-to-date option list.

Example:

```
mxrun MyBeamline.instr --optimize --optimize-monitor=detector Slit_width
    =0.1,2
```

From `mxgui` (section 5.4.1), one should choose the 'Optimization' execution mode (instead of the Simulation or Trace mode). Then specify the instrument parameters to optimize by indicating their variation range `param=min,max` (e.g. Lambda=1,4) just like parameter scans. Finally, run the simulation. The optimum set of parameters is then printed at the end of the simulation process. You may ask to maximize only a given monitor (instead of all) by selecting its component name in the Run Dialog.

If you would like to maximize the flux at a given monitor, with some divergence constrains, you should for instance simply add a divergence collimator before the monitor. Alternatively, write a new component that produce the required 'figure-of-merit'.

The optimization search interval constrains the evolution of parameters. It should be chosen carefully. In particular it is safer for it to indeed contain a high signal domain, and be preferably symmetric with respect to that maximum.

Using custom optimization routines

For cases the built-in `--optimize` mode (or iFit) does not cover, the user may still write a custom function/script or program that

- inputs the simulation parameters, which are usually numerical values such as a mirror curvature or a slit width, taken from an instrument in the `examples` directory of the package.
- builds a command line from these parameters.
- executes that command, and waits until the end of the computation.
- reads the relevant data from the monitors.

- outputs a simulation quality measurement from this data, usually the integrated counts or some peak width.

For instance, we could write a function for Python using `scipy.optimize` (or Matlab, if preferred) in order to study the effect of a beamline parameter `P` on a given monitor's intensity:

```
import subprocess
from scipy.optimize import minimize_scalar
import numpy as np

def instr_value(P):
    outdir = f"opt_{P:.3f}"
    subprocess.run(["mxrun", "MyBeamline.instr", "-d", outdir, "-n", "1e6",
                    f"P={P}"], check=True)
    # read back the relevant monitor's plain-text McCode data file directly
    data = np.loadtxt(f"{outdir}/detector.dat")
    return -data[:, 1].sum()   # negative intensity column sum: we minimize below

result = minimize_scalar(instr_value, bounds=(0.1, 2.0), method="bounded")
```

will determine the best value of `P` in order to maximize the mean detector counts. This is essentially what `mxrun --optimize` already automates for you (section 5.3.5); writing a custom driver like this remains useful mainly when the figure of merit cannot be expressed as a simple `--optimize-eval` expression, or when a non-scipy optimizer (e.g. a Matlab/iFit swarm optimizer) is preferred.

5.4. Using simulation front-ends

McXtrace includes a number of front-end programs that extend the functionality of the simulations. A front-end program is an interface between the user and the simulations, running the simulations and presenting the output in various ways to the user.

The list of available McXtrace front-end programs is (see `mxdoc --tools`, or run any tool with `-h` for its specific help):

```
    McXtrace Tools
       mcxtrace           Main instrument compiler
       mcxtrace-pygen     Alternative code generator: McStasScript Python model
       mxrun              Instrument build and execution utility
       mcxtrace-jupylab   Opens a generated instrument model in JupyterLab
       mxgui              Graphical User Interface instrument builder
       mxdoc              Component library documentation generator/viewer
       mxplot             Simulation result viewer (default: pyqtgraph backend)
       mxplot-html        Simulation result viewer, in a web browser (D3.js)
       mxplotdiff-html    Difference plot between two simulation results, in a browser
       mxcoplot-html      Overlay (co-plot) of two simulation results' 1D monitors
```

```
12        mxdisplay       Instrument geometry viewer (default: pyqtgraph
              backend)
13        mxtest          Self-test / benchmark of the current McXtrace
              installation
14        mxviewtest      Viewer for mxtest results, with mxplotdiff-html
              comparisons
15      Each tool also exists in dedicated *-matplotlib, *-pyqtgraph, *-html,
16      *-webgl or *-webgl-classic variants where applicable, see sections
            below.
17      DOC:        Please visit https://www.mcxtrace.org
```

5.4.1. The graphical user interface (mxgui)

The front-end `mxgui` provides a graphical user interface that interfaces the various parts of the McXtrace package. It may be started with the single command

```
1   mxgui
```

The mxgui program may optionally be given the name of the instrument file to use.

Dependencies: As of McXtrace 3.x, `mxgui` is a pure Python/Qt application (PyQt), bundled with the standard conda-forge McXtrace package; no separate Perl, Tk, or PGPLOT installation is required.

The menus

When the front-end is started the main window is opened (see figure 5.1). This window displays the output from compiling and running simulations, and contains a few menus and buttons for easy navigation. The main purpose of the front-end is to edit and compile instrument definitions, run the simulations, and visualize the results.

The **File** menu has the following features:

File/Open instrument selects the name of an instrument file to be used.

File/Edit current opens a simple editor window with McXtrace syntax highlighting for editing the current instrument definition. This function is also available from the **Edit** button to the right of the name of the instrument definition in the main window.

File/Spawn editor This starts the editor defined in the environment variable `VISUAL` or `EDITOR` on the current instrument file. It is also possible to start an external editor manually; in any case `mxgui` will recompile instrument definitions as necessary based on the modification dates of the files on the disk.

File/Compile instrument forces a recompile of the instrument definition, regardless of file dates. This is for example useful to pick up changes in component definitions, which the front-end will not notice automatically. This might also be required when choosing MPI and NeXus options.

File/Save log file saves the text in the window showing output of compilations and simulations into a file.

File/Clear output erases all text in the window showing output of compilations and simulations.

File/Preferences Opens the configuration dialog shown in figure 5.2. Several settings can be chosen here:

- Selection of the desired plotting/display backend (`pyqtgraph`, `matplotlib`, `html`, ...) for `mxplot` and `mxdisplay`.
- Choice of code generator (`mccode` or `mccode-antlr`, see section 5.2.1).
- Choice of editor to use when editing instrument files.
- Automatic quotation of strings when inserting in the built-in editor.
- Possibility to *not* optimize when compiling the generated c-code. This is very handy when setting up an instrument model, which requires regular compilations.

To save the chosen settings for your next McXtrace run, use Save Configuration in the File menu.

File/Save configuration saves user settings from Configuration options and Run dialogue to disk.

File/Quit exits the graphical user interface front-end.

The **Simulation** menu has the following features:

Simulation/Read old simulation prompts for the name of a file from a previous run of a McXtrace simulation (usually called `mccode.sim`). The file will be read and any detector data plotted using the `mxplot` front-end. The parameters used in the simulation will also be made the defaults for the next simulation run. This function is also available using the "Read" button to the right of the name of the current simulation data.

Simulation/Run simulation opens the run dialog window, explained further below.

Simulation/Plot results plots (using `mxplot`) the results of the last simulation run or spawns a load dialogue to load a set of results.

The **New from Template** menu (known as "X-ray Site" in older McXtrace releases) contains a list of template and example instruments as found in the McXtrace library, sorted by category/facility (e.g. `Templates`, `ILL`, `ISIS`, `ESS`, `Union_demos`, ...). When selecting one of these, a local copy of the instrument description is transferred to the active directory (so that users have modification rights) and loaded. One may then view its source (Edit) and use it directly for simulations/trace (3D View).

The **Tools** menu gathers minor tools.

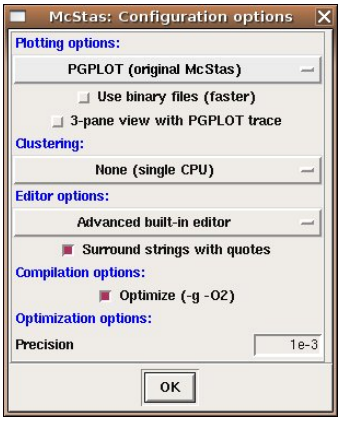

Figure 5.2.: The "configuration options" dialog in `mxgui`.

Tools/Plot current/other results Plot current simulation results and other results.

Tools/Dataset convert/merge Opens a GUI to merge scattered data sets (e.g. from successive runs or an MPI job) or assemble scan sets.

Tools/Shortcut keys displays the shortcut keys used for running and editing instruments.

The **Help** menu has the following features, through use of `mxdoc` and a web browser. To customize the used web browser, set the `BROWSER` environment variable. If `BROWSER` is not set, `mxgui` uses `netscape/mozilla/firefox` on Unix/Linux and the default browser on Windows.

Help/McXtrace User manual calls `mxdoc --manual`, brings up the local pdf version of this manual, using a web browser.

Help/McXtrace Component manual calls `mxdoc --comps`, brings up the local pdf version of the component manual, using a web browser.

Help/Component library index displays the component documentation using the component `index.html` index file.

Help/McXtrace web page calls `mxdoc --web`, brings up the McXtrace website in a web browser.

Help/Tutorial opens the McXtrace tutorial for a quick start.

Help/Current instrument info generates a description web-page of the current edited instrument.

Help/Test McXtrace installation launches `mxtest` to check that the McXtrace package is installed properly and generates accurate results (see section 5.4).

Help/Generate component index (re-)generates locally the component `index.html`.

The run dialog

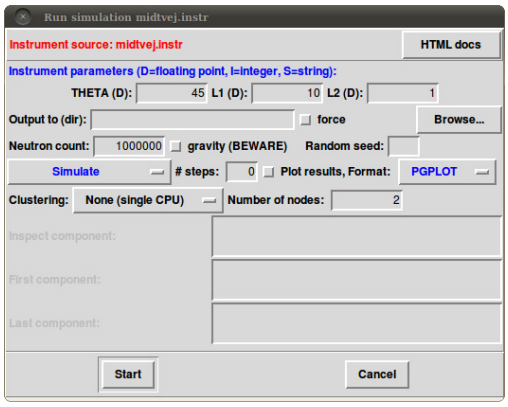

Figure 5.3.: The run dialog in `mxgui`.

The run dialog is used to run simulations. It allows the entry of instrument parameters as well as the specifications of options for running the simulation (see section 5.3 for details). It also allows to run the `mxdisplay` (section 5.4.5) and `mxplot` (section 5.4.6) front-ends together with the simulation.

The meaning of the different fields is as follows:

Run:Instrument parameters allows the setting of the values for the input parameters of the instrument. The type of each instrument parameter is given in parenthesis after each name. Floating point numbers are denoted by (D) (for the C type "`double`"), (I) denotes integer parameters, and (S) denotes strings. For parameter scans and optimizations, enter the minimum and maximum values to scan/optimize, separated by a comma, e.g. `1,10` and do not forget to set the **# Scanpoints** to more than 1.

Run:Output to allows the entry of a directory for storage of the resulting data files in (like the `--dir` option). If no name is given, the results are stored in the current directory, to be overwritten by the next simulation.

Run:Force Forces McXtrace to overwrite existing data files

Photon count sets the number of x-rays to simulate (the `--ncount` option).

Run:Gravity Activates gravitation handling. Not all components full support the use of gravitation, but all transport in "free space" using the PROP_DT, PROP_Z0 etc. macros will include propagation with gravity. Only local, internal component propagation without the PROP routines will be gravity-less. As a conclusion it

is considered safe and to high precision correct to apply the gravitation setting if one takes care to use the Guide_gravity component and other gravity-supporting guide types in combination with non-gravity components that are "small" in size, i.e. samples, lenses, etc.

Run:Random seed/Set seed to selects between using a random seed (different in each simulation) for the random number generator, or using a fixed seed (to reproduce results for debugging).

Run:Simulate/Trace (3D)/Optimize selects between several modes of running the simulation:

- Simulate: perform a normal simulation or a scan when #steps is set to non-zero value
- Trace (3D view): View the instrument in 3D tracing individual x-rays through the instrument
- Optimize: find the optimum value of the simulation parameters in the given ranges (see section 5.3.5).
- Backgrounding (bg): Simulate or Optimize in the background.

Run:# steps / # optim sets the number of simulation to run when performing a parameter scan or the number of iterations to perform in optimization mode.

Run:Plot results – if checked, the `mxplot` front-end will be run after the simulation has finished, and the plot dialog will appear (see below).

Run:Format quick selection of output format (`McCode` or `NeXus`).

Run:Clustering method selects between running locally or via MPI. See section 5.6 on parallel computing for more informations.

Run:Number of nodes sets the number of MPI nodes to use.

Run:Inspect component (Trace mode) will trace only x-ray trajectories that reach a given component (e.g. sample or detector).

Run:First component (Trace mode) seletcs the first component to plot (default is first) in order to define a region of interest.

Run:Last component (Trace mode) seletcs the last component to plot (default is first) in order to define a region of interest.

Run:Maximize monitor (Optimization mode) seletcs up to three monitors which integral value should be maximized, varying instrument parameters. If no monitor is selected, the sum of all monitors is optimized.

Run:Start runs the simulation.

Run:Cancel aborts the dialog.

Most of the settings on the run dialog can be saved for your next McXtrace run using 'Save configuration' in the File menu.

Before running the simulation, the instrument definition is automatically compiled if it is newer than the generated C file (or if the C file is newer than the executable). The executable is assumed to have a `.out` suffix in the filename. NB: If components are changed, automatic compilation is *not* performed. Instead, use the File/Compile menu item in mxgui.

The editor window

The editor window provides a simple editor for creating and modifying instrument definitions. Apart from the usual editor functions, the "Insert" menu provides some functions that aid in the construction of the instrument definitions:

Editor Insert/Instrument template inserts the text for a simple instrument skeleton in the editor window.

Editor Insert/Component... opens up a dialog window with a list of all the components available for use in McXtrace. Selecting a component will display a description. Double-clicking will open up a dialog window allowing the entry of the values of all the parameters for the component (figure 5.4). See section 6.3 for details of the meaning of the different fields.

The dialog will also pick up those of the users own components that are present in the current directory when `mxgui` is started. See section 6.7 for how to write components to integrate well with this facility.

Editor Insert/Type These menu entries give quick access to the entry dialog for the various component types available, i.e. Sources, Optics, Samples, Monitors, Misc, Contrib and Obsolete.

5.4.2. Running simulations on the commandline (mxrun)

The `mxrun` front-end provides a convenient command-line interface for running simulations with the same automatic compilation features available in the `mxgui` front-end. It also provides a facility for running a series of simulations while varying an input parameter.

The command

```
1 mxrun sim args ...
```

will compile the instrument definition *sim*`.instr` (if necessary) into an executable simulation *sim*`.out`. It will then run *sim*`.out`, passing the argument list *args*

The possible arguments are the same as those accepted by the simulations themselves as described in section 5.3, with the following extensions:

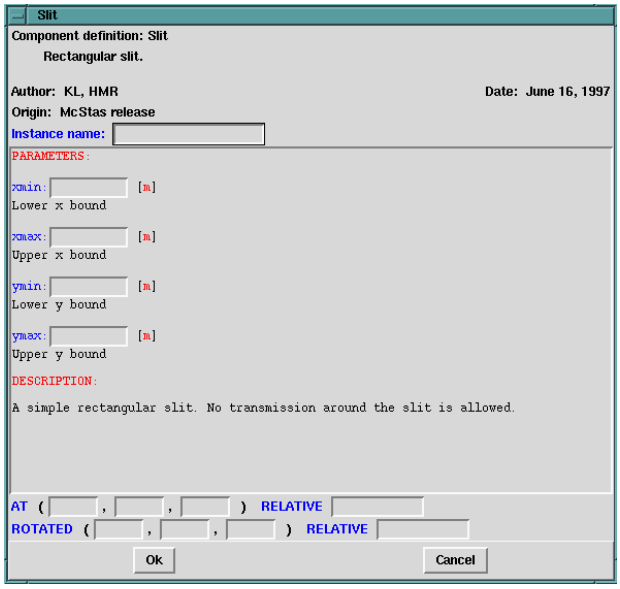

Figure 5.4.: Component parameter entry dialog.

- The `-c` or `--force-compile` option may be used to force the recompilation of the instrument definition, regardless of file dates. This may be needed in case any component definitions are changed (in which case `mxrun` does not automatically recompile), or if a new version of McXtrace has been installed.

- The `-p` *`file`* or `--param=`*`file`* option may be used to specify a file containing assignment of values to the input parameters of the instrument definition. The file should consist of specifications of the form *`name=value`* separated by spaces or line breaks. Multiple `-p` options may be given together with direct parameter specifications on the command line. If a parameter is assigned multiple times, later assignments override previous ones.

- The `-N` *`count`* or `--numpoints=`*`count`* option may be used to perform a series of *count* simulations while varying one or more parameters within specified intervals. Such a series of simulations is called a *scan*. To specify an interval for a parameter X, it should be assigned two values separated by a comma. For example, the command

```
1 mxrun sim.instr –N4 X=2,8 Y=1
```

  would run the simulation defined in `sim.instr` four times, with X having the values 2, 4, 6, and 8, respectively.

  After running the simulation, the results will be written to the file `mccode.dat` by default (see the `--optimise-file` option). This file contains one line for each

simulation run giving the values of the scanned input variables along with the integrated intensity and estimated error in all monitors. This file can be plotted with any of the `mxplot` backends, see section 5.4.6.

- When performing a scan, the `--optimise-file` *file* option makes `mxrun` write the scan summary to *file* instead of the default `mccode.dat`.
- Two further scan modes are available besides the default one, in which all scanned parameters step together from their minimum to their maximum value. With `-M` or `--multi`, the cartesian product of all scanned parameters' points is run (a multi-dimensional "grid" scan); the point count of each parameter is then given as a comma-separated list to `-N`, in the order the parameters appear on the command line. For example

```
mxrun sim.instr -M -N3,5 X=2,8 Y=0,1
```

runs $3 \times 5 = 15$ simulations. With `-L` or `--list`, each scanned parameter is instead given as an explicit comma-separated list of values (which also allows non-numerical values such as file names); lists of equal length are stepped through together, and combined with `-M` the cartesian product is run (the lists may then have different lengths). A parameter may also be given as *min*`:`*delta*`:`*max*, in which case the point count follows from the requested step size and the parameter may be freely mixed with explicit lists. The option `--seeds` scans over a range of random seeds (each non-zero). In a scan with `--seed`, point i uses the seed SEED $+ 1024\,i$ (without `--seed` the base seed is taken from the current time and logged).

- With `--autoplot`, `mxrun` opens a plotter on the generated data set when done (the back-end is chosen with `--autoplotter`, and `--invcanvas` requests an inverted canvas). With `-C` or `--c-lint`, the generated C code is only passed through a C linter (e.g. `cppcheck`, configured in `mccode_config.json`) and no simulation is run.
- When performing a scan, the `-d` *dir* and `--dir=`*dir* options make `mxrun` put all output in a newly created directory *dir*. Additionally, the directory will have subdirectories `1`, `2`, `3`,... containing all data files output from the different simulations. When the `-d` option is not used, no data files are written from the individual simulations (in order to save disk space).

The `-h` option will list valid options; see also Table 5.1 for the complete, current option list.

5.4.3. Interactive notebooks (mcxtrace-jupylab)

The `mcxtrace-jupylab` front-end offers an interactive, notebook-based alternative to editing an `.instr` file directly and running it via `mxgui`/`mxrun`. Given an instrument file:

```
mcxtrace-jupylab name.instr
```

it first runs `mcxtrace-pygen` (see above) to translate the instrument into an equivalent McStasScript Python model, writes that model into a notebook (*name*`_generated.ipynb`) built from a ready-made template (imports, and cells calling `show_diagram()`, `show_instrument()`, `backengine()` and the plotting helpers are already filled in), and opens it in JupyterLab[1]. From there the instrument can be inspected, modified and run cell by cell using McStasScript's own Python API, which is useful for exploratory work and for combining a simulation with other Python-based analysis in the same notebook.

Note that this generates a McStasScript model *once*, as a starting point; it is not kept in sync with later edits to the original `.instr` file, nor vice versa. See the McStasScript documentation [Mcs] for the Python API itself.

5.4.4. GPU acceleration via OpenACC

McXtrace 3.x supports GPU-accelerated simulations through the OpenACC framework, enabling substantial speed-ups over CPU-only execution on compatible NVIDIA hardware.

Requirements

- **Compiler:** NVIDIA HPC SDK version 20.x or newer. The free Community Edition is sufficient.
- **Hardware:** A CUDA-capable NVIDIA GPU with an up-to-date driver.
- **Platform:** GPU support is currently available on Linux only. Windows is not yet supported for OpenACC by NVIDIA; Windows users wishing to use GPU acceleration should do so via WSL 2 running a Linux distribution.

Running a GPU-accelerated simulation

Pass the `--openacc` flag to `mxrun`:

```
mxrun --openacc MyInstrument.instr -n 1e9
```

The OpenACC execution can be tuned with `--vecsize` (vector length), `--numgangs` (number of "gangs"), `--gpu_innerloop` (maximum number of particles per GPU kernel run; if smaller than the requested x-ray count, the kernel is repeated) and `--funnel` (funnelled simulation flow, e.g. for mixed CPU/GPU execution), see Table 5.2 and Table 5.1.

[1] A working `jupyter lab` installation is required; it is not currently bundled with the standard conda-forge McXtrace package.

Combined multi-core + GPU execution. It is also possible to use both CPU cores and the GPU simultaneously. Enable this by adding the following to the `OACCFLAGS` field of your `mccode_config.json`:

```
"OACCFLAGS": "-fast -Minfo=accel -acc=gpu,multicore
              -gpu=managed -DOPENACC -DMULTICORE"
```

Further information

GPU terminology specific to McStas/McXtrace 3 and detailed debugging tips are documented on the McCode wiki:

- GPU terminology table:
  `https://github.com/mccode-dev/McCode/wiki/McStas-McXtrace-3-and-GPU-terminolog`
- GPU debugging tips:
  `https://github.com/mccode-dev/McCode/wiki/GPU-Debugging-tips`

5.4.5. Graphical display of simulations (mxdisplay)

The front-end `mxdisplay` is a graphical visualization tool, very useful for debugging. It presents a schematic drawing of the instrument definition, showing the position of the components and the paths of the simulated x-rays through the instrument. It is thus very useful for debugging a simulation, for example to spot components in the wrong position or to find out where x-rays are getting lost.

To use the `mxdisplay` front-end with a simulation, run it as follows:

```
1 mxdisplay sim args ...
```

where `sim` is the name of either the instrument source *sim*`.instr` or the simulation program *sim*`.out` generated by `mcxtrace`, and *args ...* are the normal command line arguments for the simulation, as explained above. The `-h` option will list valid options.

The drawing back-end may be selected by invoking one of the dedicated front-ends directly:

- `mxdisplay-pyqtgraph` (the default when running plain `mxdisplay`): interactive PyQtGraph 3D view.
- `mxdisplay-matplotlib`: static/interactive matplotlib 3D view. This is a thin wrapper script, so its options differ slightly from the default front-end: `--trace={1,2}` selects the classic (1) or new (2, default) drawing mode, `--backend=NAME` selects the matplotlib back-end (the hard-copy back-ends `pdf`, `pgf`, `ps` and `svg` save a file instead of opening a window), and the number of traced rays is capped at 100.
- `mxdisplay-webgl` and `mxdisplay-webgl-classic`: browser-based WebGL views. The former ships as a prebuilt web application served by a small local web server (only if its `dist/` folder is missing does the first run perform a one-time `npm`

`install && npm run build`, which needs internet access). Both accept `-t/--trace N` (visualisation mode, default 2: boxes, cylinders, OFF geometry etc. are drawn as 3D shapes; 1 selects the legacy line approximations), `-d/--dirname DIR`, `--inspect COMP` (show only rays reaching component `COMP`) and `--nobrowse` (do not open a browser). `mxdisplay-webgl` also has `--timeout SEC` (the shutdown time of its local viewer web server, default 300 s), while `mxdisplay-webgl-classic` additionally accepts `--first COMP`, `--last COMP` (the first and last component of the zoomed range) and `--invcanvas`.

- `mxdisplay-plopp`: draws the instrument and the traced rays with the `plopp`/`scipp` Python packages (install e.g. with `conda install -c conda-forge plopp ipympl jupyterlab`). By default it opens an interactive 3D view in JupyterLab; with `-o FILE` it instead writes a static `png`, `pdf` or `svg` with 2D projections. Accepts `-n N` (number of rays, default 100), `-y` (forwarded to `mxrun`: use defaults for unset parameters) and the instrument parameters as `name=value`.

- `mxdisplay-cad`: exports the instrument geometry to a CAD file and requires the `cadquery` Python package. The format is selected with `-f/--format`: `step` (default), `stl`, `xml`, `vrml`, `gltf` or `vtkjs`. As no rays are needed for a geometry export, `--ncount` defaults to 0 here.

- `mxdisplay-mantid_xml`: exports an approximate Mantid Instrument Definition File (IDF) describing the detector geometry.

For instance, calling

```
1 mxdisplay-webgl ./Template_1Slit_Diff.out SLITW=5e-6
```

will open a WebGL view of the instrument in a browser tab. The `mxdisplay` front-end can also be run from the `mxgui` front-end.

The (default, PyQtGraph) front-end accepts the following options, amongst others – run `mxdisplay --help` for the complete, current list:

- `--default`: automatically use the instrument's default parameter values, without prompting.

- `--dirname=DIR`: override the output directory name used while tracing.

- `--inspect=`*comp*: only display x-ray trajectories that reach the component named *comp*. This is useful when debugging, e.g. to hide x-rays absorbed upstream of the component of interest.

- `--invcanvas`: invert the canvas background from black to white (useful for printing or screenshots).

- `-n/--ncount=N`: number of x-rays to trace (default 300).

- `--no-mpi`: simulate without MPI (forwards `--no-mpi` to `mxrun`).

All variants run `mxrun --trace` underneath, so an instrument parameter may be given as *name=value* just as for `mxrun`. In the PyQtGraph viewer, `q` quits, `p` saves a PNG image, `s` saves an SVG image (not on Windows), `space` or `F5` shows the next ray, a click on a sub-plot zooms in on it (right-click to leave the zoomed view), and `h` or `F1` lists the components. A legacy Matlab/Octave variant, `mxdisplay-matlab`, also exists under `tools/matlab` (it falls back to the Python `mxdisplay` when neither Matlab nor Octave is found).

When debugging trajectories through a long or complex instrument, combining `--inspect` with a modest `--ncount` typically gives the clearest, fastest picture of what is happening around a particular component.

5.4.6. Plotting the results of a simulation (mxplot)

The front-end `mxplot` is a program that produces plots of all the monitors in a simulation, and it is thus useful to get a quick overview of the simulation results.

In the simplest case, the front-end is run simply by typing

```
1  mxplot
```

This will plot any simulation data stored in the current directory, which is where simulations store their results by default. If the `--dir` option has been used (see section 5.3), the name of the file or directory should be passed to mxplot, *e.g.* "`mxplot dir`" or "`mxplot file`". It is also possible to plot one single text (not binary) data file from a given monitor, passing its name to mxplot.

As with `mxdisplay` (section 5.4.5), the drawing back-end may be selected by invoking the dedicated front-end directly: `mxplot-pyqtgraph` (the default), `mxplot-matplotlib`, `mxplot-plopp` (plopp/scipp based, see below), or `mxplot-html` (renders an interactive, self-contained web page using D3.js, see section 5.3.2), or by setting the `MCXTRACE_FORMAT` environment variable.

The back-ends share the simulation file or directory argument, and have a few options of their own. `mxplot-html` accepts `-n`/`--nobrowse` (do not open a browser), `-l`/`--log` (log scale), `--autosize` (expand the plots to the window size), `-o`/`--output FILE` (output `.html` file) and `-W`/`-H` (width and height of the plot frames). `mxplot-matplotlib` accepts `--log`, `--backend NAME`, `--format FMT` together with `--output FILE` (save as `pdf`, `png`, `eps`, `svg`, ... without opening a window) and `--html` (save as HTML via mpld3; Linux only), and `mxplot-pyqtgraph` accepts `--invcanvas` (white instead of black canvas). Both the matplotlib and PyQtGraph variants also take `-t`/`--test`, which only runs the data loader and prints the structure of the plot. A legacy Matlab/Octave/iFit variant, `mxplot-matlab`, exists under `tools/matlab`; it picks whichever of Matlab, iFit and Octave is available (falling back to the Python `mxplot`), and can export each monitor with `-png`, `-jpg`, `-fig`, `-eps` or `-pdf`.

`mxplot-plopp` opens the monitors of a simulation directory, `mccode.sim`, a single monitor file or a NeXus `mccode.h5` file in an interactive JupyterLab view built on `plopp`/`scipp` (install with e.g. `conda install -c conda-forge plopp ipympl jupyterlab`).

With `-o FILE` it writes a static `png`, `pdf` or `svg` instead, `--log` selects a logarithmic intensity scale, and `--source`/`--sample` name the source and sample components when plotting Monitor_nD event data from NeXus files through McStasToX.

All plotters read the plain-text McXtrace/McCode data format (section 5.5); NeXus files are not currently read back by the plotters.

The `mxplot` front-end can also be run from the `mxgui` front-end.

The initial display shows plots for each detector in the simulation.

Comparing simulation results: mxplotdiff and mxcoplot. Two companion tools share the loading and monitor-matching code of `mxplot` to compare simulation results (output directories, or single monitor files), matching monitors by output filename. Each exists in the same three rendering variants as `mxplot` (`-html`, `-matplotlib` and `-pyqtgraph`); the browser-based HTML variants are described here:

- `mxplotdiff-html a b` plots, for every monitor present with matching binning in both `a` and `b`, the difference `a - b` (with error-propagated error bars for 1D monitors, and a diverging blue/white/red colour scale for 2D monitors). This is useful to quickly spot the effect of a component or parameter change, an McXtrace version upgrade, or MPI vs. non-MPI results. By default, each difference is also written back out as a normal McXtrace/McCode-format data set (with an `mccode.sim` index), so the result directory can be reopened by any other McCode-format-aware plotter; pass `-D`/`--no-dat` to skip this. It always compares exactly two datasets.

- `mxcoplot-html a b [c ...]` instead overlays the 1D monitors of *two or more* datasets on the same axes, for a direct visual comparison of curve shape and position (only 1D monitors are supported; a monitor that is not a matching 1D monitor in every dataset is skipped with a warning). The compact legend letters `A`, `B`, `C`, ... are explained in an identity line under the title. Use `-L`/`--labels A,B,C` to set a short label per dataset, `-C`/`--colours c1,c2,...` to set the overlay colours, and `--no-legends` / `--no-titles` to leave out the on-plot legend respectively the in-plot title and identity line.

`mxplotdiff-html` accepts `-A LABEL_A`/`-B LABEL_B` to control the labels used for each input, and both tools accept `-o OUTPUT` to control the output directory name, `-n`/`--nobrowse`, `-l`/`--log` and `--autosize`; run either with `--help` for the complete option list. The matplotlib and PyQtGraph variants take the same dataset arguments and labelling options, plus the output options of the corresponding `mxplot` back-end. `mxplotdiff-html` and `mxcoplot-html` are also used internally by `mxviewtest` (section 5.4) to compare test runs against a reference.

5.4.7. Creating and viewing the library, component/instrument help and Manuals (mxdoc)

McXtrace provides an easy way to generate automatically an HTML help page about a given component or instrument, or the whole McXtrace library.

```
mxdoc
mxdoc searchterm
mxdoc file.comp
```

The first example generates an *index.html* catalog file using the available components and instruments (both locally, and in the McXtrace library), and browses it using the `BROWSER` environment variable (e.g. firefox, chromium, ...). Alternatively, if a search term or a *file.comp*/*file.instr* path is given, `mxdoc` will search within the library and open documentation for all matching entries. The search results are written to a separate page, `mxdoc_search.html`, next to the main library page (or in the temporary directory if that is read-only), so the main page is left untouched. Mathematics in component documentation is rendered locally with the MathJax copy installed with the documentation.

Additional options include `--install`/`-i` (regenerate the local installation-wide index), `--dir=DIR`/`-d` (add search results from a given directory), and `--verbose`/`-v` (print a parsing log). HTML is always written; `--md`/`-M` and `--tex`/`-T` also emit Markdown respectively LaTeX documentation files (`--all-formats`/`-A` for all three) — the LaTeX snippets of the component library that make up the Component Manual are produced this way. With `--in-repo` the output is placed next to the source files instead of in the installed documentation directory (and no master page is made), and `--outdir=DIR`/`-o` selects the output directory (in-repo use only). The options `--manual`/`-m`, `--comps`/`-c` and `--web`/`-w` will open the User Manual (this document), the Component Manual, and the McXtrace web site, respectively, all requiring `BROWSER` to be defined. Finally, the `--help` option will display the command help, as usual.

See section 6.7 for more details about the McDoc usage and header format. `mxdoc` is a pure Python tool, part of the standard McXtrace conda-forge package.

Online wiki. In addition to this manual, extensive and frequently updated documentation is maintained on the McCode GitHub wiki [Wik]:

`https://github.com/mccode-dev/McCode/wiki`

The wiki includes end-user guides, component development howtos, GPU acceleration information, and migration guides from McXtrace 2.x to 3.x.

5.4.8. Self-testing the installation (mxtest, mxviewtest)

McXtrace ships with a Python self-test/benchmark harness, replacing the earlier `mxrun --test` command. `mxtest` compiles and runs a selection (or all) of the example instruments found under the current installation(s), and stores each run's results (including any test-defined `%Test` reference values) in a timestamped output folder. Each test compiles the instrument, displays it with a single particle, runs it, and compares the result with the target value recorded in the instrument header. Useful options include `--ncount` (default 10^6), `--seed` (default 1000; 0 randomizes), `--mpi`, `--no-mpi`, `--openacc` and

`--nexus` (forwarded to `mxrun` for every tested instrument), `--lint` (only run the C linter, no simulations), `--config=LABEL` (test only a specific McCode installation/config), `--instr=REGEX` (test only matching instrument names), `--comp=COMP[,COMP...]` (test only instruments using any of the given components), `--local=DIR` (test instruments from `DIR` instead of the installation), `--limit=N` (test only the first N instruments per version), `--skipnontest` (skip instruments without an `%Test`/`%TestScan` line), `--strict` (fail instruments without `%Test`/`%TestScan` line(s) immediately) and `--permissive` (exit with status 0 even if tests fail), `--testdir=DIR` and `--suffix=SUFFIX` (where the results are written), `--compilemax`, `--runmax` and `--displaymax` (time limits in seconds) and `--noplots` (do not generate the overview plots); run `mxtest --help` for the full list. generate the overview plots); run `mctest --help` for the full list.

A test is defined in the instrument header by a `%Test:` line (older name `%Example:`), giving instrument parameters and the expected monitor value, *e.g.* `%Test: lambda=2.36 Detector: He3H_I=9.84026e-10`. A `%TestScan:` line (older name `%Scan:`) defines a parameter scan using the `mxrun` scan syntax, followed by a {}-enclosed list with one target value per scan point (it may span several header lines), *e.g.* `%TestScan: dBz=-0.0001,0.0001 -N41 -n1e5 Detector: detector_I={...}`. A `%Test:` always runs at the global `--ncount` (scaled by `--statfactor`); a scan uses its own `-n` if given, otherwise at most 10^5 per point, and runs its points in parallel (`--scan_split=auto`) unless MPI is used. By default a value (every point of a scan) passes when it is within 20 % of its target. With `--nsigma N` or `--pvalue P` it is instead accepted within the statistical tolerance of the combined error bars, using the error bar of the target when the test line gives it (*e.g.* `NAME_I=2.00752e+08 NAME_ERR=2.28872e+06`). `--statfactor F` scales the particle count of every test (*e.g.* 0.01 for quick runs, 100 for reference-quality ones) and `--noscans` skips the `%TestScan` tests. The statistics are described in more detail in `tools/Python/mctest-statistics.md`.

`mxviewtest` then generates an HTML report of one or more `mxtest` runs found in a given folder (the current directory by default). When more than one run is present (e.g. a reference run and a run on a different platform, GPU vs. CPU, or a different McXtrace branch), it takes the oldest subfolder as the reference column (override with `--reflabel=LABEL`), and additionally runs `mxplotdiff-html` and `mxcoplot-html` (section 5.4.6) between each other column's monitor output and the reference's, adding a `DIFF [vs ref]` link next to each such row in the report. These comparisons are cached on disk and generated in parallel (`--diffworkers`, each limited to `--diffmax` seconds), so re-running `mxviewtest` is fast (each test, and each scan, is one row of the report, coloured pass/fail by the rule `mxtest` used for that result set; hovering a scan cell lists every point's value, target and percentage); use `--nodiff` to skip generating them entirely, or `--diff-errors-only` to only diff rows that already show a discrepancy (by default every valid row is diffed). `--nobrowse` keeps the finished report from being opened in a browser.

5.5. Data formats - Analyzing and visualizing the simulation results

To analyze simulation results, one uses the same tools as for analyzing experimental data, *i.e.* programs such as Python/NumPy, Matlab, IDL. The output files from simulations are usually simple text files containing headers and data blocks. If data blocks are empty they may be accessed referring to an external file indicated in the header.

Each data file contains information about the simulation, the instrument, the parameters used, and of course the signal, the estimated error on the signal, and the number of events used in each bin. Additionally, all data files indicate their first moment (mean value) and second moment (half width) in the 'statistics' field.

The available data formats are the legacy McXtrace (McCode) format, and the HDF/NeXus binary when the needed libraries are installed.

In order for the user to choose the data format, we recommend to set it using the `--format=FORMAT` or alternatively *via* the MCXTRACE_FORMAT environment variable, which will also make the front-end programs able to import and plot data and instrument consistently (see Section 5.3).

Note that the x-ray event counts in detectors are typically not very meaningful except as a way to measure the performance of the simulation. Use the simulated intensity instead whenever analyzing simulation data.

5.5.1. The McXtrace/McCode text format

The McXtrace original format, sometimes still referred to by its historical name "PGPLOT format" (the plotting package used in McXtrace 1.x/2.x), is simply columns of ASCII text that most programs should be able to read.

One-dimensional histogram monitors (time-of-flight, energy) write one line for each histogram bin. Each line contains a number identifying the bin (*i.e.* the time-of-flight) followed by three numbers: the simulated intensity, an estimate of the statistical error as explained in section 4.2.1, and the number of x-ray events for this bin.

Two-dimensional histogram monitors (position sensitive detectors) output M lines of N numbers representing x-ray intensities, where M and N are the number of bins in the two dimensions. The two-dimensional monitors also store the error estimates and event counts as additional matrices.

Single-point monitors output the x-ray intensity, the estimated error, and the x-ray event count as numbers on the terminal. (The results from a series of simulations may be combined in a data file using the `mxrun` front-end as explained in section 5.4.2).

When using one- and two-dimensional monitors, the integrated intensities are written to terminal as for the single-point monitor type, supplementing file output of the full one- or two-dimensional intensity distribution. Both one- and two-dimensional monitor output by default start with a header of comment lines, all beginning with the '`#`' character. This header gives such information as the name of the instrument used in the simulation, the values of any instrument parameters, the name of the monitor component for this data file, *etc.*

In addition to the files written for each one- and two-dimensional monitor component, another file (by default named `mccode.sim`) is also created. This file is in a special McXtrace ASCII format. It contains all available information about the instrument definition used for the simulation, the parameters and options used to run the simulation, and the monitor components present in the instrument. It is read by the `mxplot` front-end (see section 5.4.6). This file stores the results from single monitors, but by default contains only pointers (in the form of file names) to data for one- and two-dimensional monitors. By storing data in separate files, reading the data with programs that do not know the special McXtrace file format is simplified.

5.5.2. NeXus format

The NeXus format [Nex] is a platform independent HDF binary data file. To have McXtrace use it

1. the HDF5 library must have been installed (libhdf5 and headers)

2. the compilation of instruments must be done with the `-DUSE_NEXUS -lhdf5` flag (see Section 6.3.4). This is automated with the `mxrun` tool (Section 5.4.2).

All results are saved in a single file, containing 'groups' of data. To view such files, install and use HDFView (or alternatively HDFExplorer). This Java viewer can show content of all detectors, including metadata (attributes). Basic detector images may also be generated.

5.6. Using MPI for parallel computing

Parallelizing a computation is in general possible when dependencies between each computation are not too strong. The situation of McXtrace is ideal since each x-ray can be simulated without interfering with other simulated x-rays. Therefore each x-ray can be simulated independently on a set of computers.

When computing N x-rays with p computers, each computer will simulate $\frac{N}{p}$ x-rays. As a result there will be $p \cdot \frac{N}{p} = N$ x-rays simulated. As a result, McXtrace generates two kinds of data sets:

- intensity measurements, internally represented by three values (p_0, p_1, p_2) where p_0, p_1, p_2 are additive. Therefore the final value of p_0 is the sum of all local value of p_0 computed on each node. The same rule applies for p_1 and p_2. The evaluation of the intensity errors σ is performed using the final p_0, p_1, and p_2 arrays (see Section 4.2.1).

- event lists: the merge of events is done by concatenation

McXtrace provides two methods in order to distribute computations on many computers.

- when using an homogeneous computer cluster, each simulation (including scan steps) may be computed in parallel using MPI. We recommend this method on clusters (see section 5.6.1).

- `mxrun`'s built-in scan-splitting (`--scan_split=N`, see Table 5.1) distributes the individual steps of a parameter scan across `N` local CPU cores/threads (`auto`, or 0, uses the number of cores minus one), without requiring MPI. It is ignored, with a warning, when an explicit multi-process `--mpi` is given. This is a lightweight alternative on a single multi-core machine.

All of these methods can be used, when available, from `mxgui`.

5.6.1. Parallel computing (MPI)

The MPI support requires that an MPI implementation (MPICH or OpenMPI are both known to work) is installed on a set of nodes, together with a properly configured passwordless `ssh` between nodes if running across more than one machine.

There are 2 methods for using MPI

- Basic usage requires to compile and run the simulation by hand (mpicc, mpirun).

- A much simpler way is to use `mxrun -c --mpi=NB_CPU ...` which will recompile and run with MPI support.

- The McGUI interface also supports MPI from within the Run Dialog.

The MPI support is especially suited on clusters.

Requirements and limitation (MPI)

To use MPI you will need

1. A working MPI installation (MPICH or OpenMPI) on all nodes, and a McXtrace installation accessible from all nodes (e.g. on a shared filesystem, or installed identically on each node).

2. If running across more than one machine, `ssh` access between nodes without a password (e.g. using `ssh-keygen` and `ssh-copy-id`), and a machine list file (see `--machines` in Table 5.1).

3. Signals are *not* supported while simulating with MPI (since asynchronous events cannot be easily transmitted to all nodes). This means it is not possible to cancel an on-going computation. However, simulation scans can be interrupted as soon as the on-going computation step ends.

MPI Basic usage

To enable parallel computation, compile `mcxtrace`-generated C code with `mpicc` with the flag `-DUSE_MPI` and run it using the wrapper of your MPI implementation (`mpirun` for mpich or lammpi) :

```
# generate a C-source file [sim.c]
mcxtrace sim.instr

# generate an executable with MPI support [sim.mpi]
mpicc -DUSE_MPI -o sim.mpi sim.c

# execute with parallel processing over <N> computers
# here you have to list the computers you want to use
# in a file [machines.list] (using mpich implementation)
# (refer to MPI documentation for a complete description)
mpirun -machinefile machines.list -n <N> \
       ./sim.mpi <instrument parameters>
...
```

If you don't want to spread the simulation, run it as usual:

```
./sim.mpi <instrument parameters>
```

5.6.2. McRun options for MPI

The two relevant `mxrun` options are (see Table 5.1):

- `--mpi=<number>`: tells `mxrun` to use MPI, and to spread the simulation over `<number>` nodes
- `--machines=<file>`: defines a text file where the nodes which are to be used for parallel computation are listed, one node per line.

When available, the MPI option will show up in the `mxgui` Run dialog. Specify the number of nodes required.

Suppose you have four machines named `node1` to `node4`. A typical machine list file, `machines.list` looks like :

```
node1
node2
node3
node4
```

You can then spread a simulation `sim.instr` using `mxrun` :

```
mxrun -c --mpi=4 --machines=machines.list \
      sim.instr <instrument parameters>
```

Warning: when using `mxrun` with MPI, be sure to recompile your simulation with MPI support (see `-c` flag of `mxrun`): a simulation compiled without MPI support cannot be used with MPI, whereas a simulation compiled with MPI support can be used without MPI.

5.6.3. McXtrace/MPI Performance

Theoretically, a computation which lasts T seconds on a single computer, should lasts at least $\frac{T}{p}$ seconds when it is distributed over p computers. In practice, there will be overhead time due to the split and merge operations.

- the split is immediate: constant time cost $\mathcal{O}(1)$
- the merge is at worst linear against the number of computers:
  - linear time cost : $\mathcal{O}(p)$ when saving an event list
  - logarithmic time cost: $\mathcal{O}(\log p)$ when not saving an event list

The efficiency of McXtrace using MPI has been tested on large clusters, up to 500 nodes. The computation time decreases in the same proportion as the number of nodes, showing an ideal efficiency. However, a small overhead may appear depending on the cluster internal network load, which may be estimated at most of about 10-20 s. This overhead comes from the spread and the fusion of the computations. For instance, spreading a computation implies often an `rsh` or and `ssh` session to be opened on every node. To reach the best efficiency, the computation time should not be lower than 30 seconds, or the overhead time may become significant compared to total time.

5.6.4. MPI Bugs and limitations

- Some header of output files might contain minor errors.
- The computation split does not take into account the speed or the load of nodes: the overall time of a distributed computation is forced by the slowest node; for optimal performance, the "cluster" should be homogeneous.
- Interacting with a running simulation (USR1 and USR2 signals) is disabled with MPI.

6. The McXtrace kernel and meta-language

Beamline definitions are written in a special McXtrace meta-language which is translated automatically by the McXtrace compiler into a C program which is in turn compiled to an executable that performs the simulation. The meta-language is custom-designed for x-ray scattering and serves two main purposes: (i) to specify the interaction of a single x-ray with a single optical component, and (ii) to build a simulation by constructing a complete beamline from individual components.

For maximum flexibility, efficiency and portability, the meta-language is based on C. Instrument geometry, propagation of x-rays between the different components, parameters, data input/output etc. is handled in the meta-language and by the McXtrace compiler. Complex calculations are written in C embedded in the meta-language description of the components. However, it is possible to set up an instrument from existing components and run a simulation without writing a single line of C code, working entirely in the meta-language.

Apart from the meta-language, McXtrace also includes a number of C library functions and definitions that are useful for x-ray tracing simulations. The definitions available for component developers are listed in appendix B. The list includes functions for

- Computing the intersection between a photon flight-path and various objects (such as planes, cylinders, boxes and spheres).
- Functions for generating random numbers with various distributions.
- Functions for reading or writing informations from/to data files.
- Convenient conversion factors between relevant units, etc.

The McXtrace meta-language was designed to be readable, with a verbose syntax and explicit mentioning of otherwise implicit information. The recommended way to get started with the meta-language is to start by looking at the examples supplied with McXtrace, modifying them as necessary for the application at hand.

6.1. Notational conventions

Simulations generated by McXtrace use a semi-classical description of the x-rays to compute the x-ray trajectory through the instrument and its interaction with the different components.

An instrument consists of a list of components through which the x-ray ray passes one after the other. The order of components is thus significant since McXtrace does not

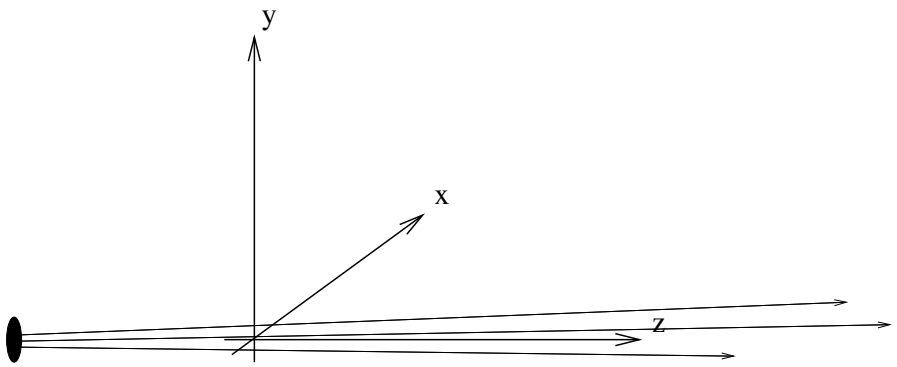

Figure 6.1.: conventions for the orientations of the axis in simulations.

automatically check which component is the next to interact with the x-ray at a given point in the simulation. Note that in case of a negative propagation length from one component to the next, the x-ray is by default *absorbed* as this is often an indication of unphysical conditions. If a large part of the simulated rays are *absorbed* on account of this a warning is issued, as this is often caused by a misplaced component.

The instrument is given a global, absolute coordinate system. In addition, every component in the instrument has its own local coordinate system that can be given any desired position and orientation (though the position and orientation must remain fixed for the duration of a single simulation). By convention, the z axis points in the direction of the beam, the x axis is perpendicular to the beam in the horizontal plane pointing left as seen from the source, and the y axis points upwards (see fig. 6.1). Nothing in the McXtrace metalanguage enforces this convention, but if every component used different conventions the user would be faced with a severe headache! It is therefore necessary that this convention is followed by users implementing new components.

In the instrument definitions, units of length (*e.g.* component positions) are given in meters and units of angles (*e.g.* rotations) are given in degrees. The state of the x-ray is given by its position (x, y, z) in m, its wavevector (k_x, k_y, k_z) in Å^{-1}, the time in s,, the phase ϕ in rad, and a polarisation vector (E_x, E_y, E_z), and finally the x-ray weight p in photons s^{-1} as described in chapter 4.

6.2. Syntactical conventions

Comments follow the normal C syntax "`/* ... */`". C++ style comments "`// ...`" may also be used.

Keywords are not case-sensitive, for example "`DEFINE`", "`define`", and "`dEfInE`" are all equivalent. However, by convention we always write keywords in uppercase to distinguish them from identifiers and C language keywords. In contrast, McXtrace identifiers (names), like C identifiers and keywords, *are* case sensitive, another good reason to use a consistent case convention for keywords. All McXtrace keywords are reserved, and thus

should not be used as C variable names. The list of these reserved keywords is shown in table 6.1.

It is possible, and usual, to split the input instrument definition across several different files. For example, if a component is not explicitly defined in the instrument, McXtrace will search for a file containing the component definition in the standard component library (as well as in the current directory and any user-specified search directories, see section 5.2.2). It is also possible to explicitly include another file using a line of the form

```
%include "file"
```

Beware of possible confusion with the C language "`#include`" statement, especially when it is used in C code embedded within the McXtrace meta-language. Files referenced with "`%include`" are read when the instrument is translated into C by the McXtrace compiler, and must contain valid McXtrace meta-language input (and possibly C code). Files referenced with "`#include`" are read when the C compiler generates an executable from the generated C code, and must contain valid C.

Embedded C code is used in several instances in the McXtrace meta-language. Such code is copied by the McXtrace compiler into the generated simulation C program. Embedded C code is written by putting it between the special symbols `%{` and `%}`, as follows:

```
%{
        ... Embedded C code ...
%}
```

The "`%{`" and "`%}`" must appear on a line by themselves (do not add comments after). Additionally, if a "`%include`" statement is found *within* an embedded C code block, the specified file will be included from the 'share' directory of the standard component library (or from the current directory and any user-specified search directories) as a C library, just like the usual "`#include`" *but only once*. For instance, if many components require to read data from a file, they may all ask for "`%include "read_table-lib"`" without duplicating the code of this library. If the file has no extension, both `.h` and `.c` files will be searched and included, otherwise, only the specified file will be imported. The McXtrace'run-time' shared library is included by default (equivalent to "`%include "mcxtrace-r"`" in the `DECLARE` section). For an example of `%include`, see the optics/Lens_simple.comp component. See also section 6.4.2 for insertion of full instruments in instruments (instrument catenation).

If the instrument description compilation fails, check that the keywords syntax is correct, that no semi-colon `;` sign is missing (e.g. in C blocks and after an ABSORB macro), and there are no name conflicts between instrument and component instances variables.

Keyword	Scope	Meaning
ABSOLUTE	I	Indicates that the AT and ROTATED keywords are in the absolute coordinate system.
AT	I	Indicates the position of a component in an instrument definition.
COPY	I,C	copy/duplicate an instance or a component definition.
DECLARE	I,C	Declares C internal variables.
DEFINE	I,C	Starts an INSTRUMENT or COMPONENT definition.
DEFINITION	C	Defines component parameters that are constants (#define).
END	I,C	Ends the instrument or component definition.
SPLIT	I	Enhance incoming statistics by event repetition.
EXTEND	I	Extends a component TRACE section (plug-in).
FINALLY	I,C	Embeds C code to execute when simulation ends.
GROUP	I	Defines an exclusive group of components.
%include	I,C	Imports an instrument part, a component or a piece of C code (when within embedded C).
JUMP	I	Iterative (loops) and conditional jumps.
INITIALIZE	I,C	Embeds C code to be executed when starting.
ITERATE	I	Defines iteration counter for JUMP.
MCDISPLAY	C	Embeds C code to display component geometry.
NEXUS	I	Defines NeXus output type (4,5,XML,compression).
OUTPUT	C	Defines internal variables to be public and protected symbols (usually all global variables and functions of DECLARE).
PARAMETERS	C	Defines a class of component parameter (DEFINITION, SETTING,STATE).
PREVIOUS	C	Refers to a previous component position/orientation.
RELATIVE	I	Indicates that the AT and ROTATED keywords are relative to an other component.
ROTATED	I	Indicates the orientation of a component in an instrument definition.
SAVE	I,C	Embedded C code to execute when saving data.
SETTING	C	Defines component parameters that are variables.
SHARE	C	Declares global functions and variables to be shared.
STATE	C	Defines x-ray state coordinates.
TRACE	I,C	Defines the instrument as a the component sequence.
WHEN	I	Condition for component activation and JUMP.

Table 6.1.: Reserved McXtrace keywords. Scope is 'I' for instrument and 'C' for component definitions.

6.3. Writing instrument definitions

The purpose of the instrument definition file is to specify a sequence of components, along with their position and parameters, which together make up a beamline. Each component is given its own local coordinate system, the position and orientation of which may be specified by its translation and rotation relative to another component. Examples of instrument definitions can be found in the `example` directory of your McXtrace installation. Further examples may be found as they are built on the McXtrace web-page [Mcx].

As a summary, the usual grammar for instrument descriptions is

```
DEFINE INSTRUMENT name(parameters)
DECLARE C_code
INITIALIZE C_code {NEXUS}
TRACE components
{FINALLY C_code}
END
```

6.3.1. The instrument definition head

`DEFINE INSTRUMENT` *name* $(a_1, a_2, \ldots)$

This marks the beginning of the definition. It also gives the name of the instrument and the list of instrument parameters. Instrument parameters describe the configuration of the instrument, and usually correspond to setting parameters of the components, see section 6.5. A motor position is a typical example of an instrument parameter. The input parameters of the instrument constitute the input that the user (or possibly a front-end program) must supply when the generated simulation is started.

By default, the parameters will be floating point numbers, and will have the C type `double` (double precision floating point). The type of each parameter may optionally be declared to be `int` for the C integer type or `char *` for the C string type. The name `string` may be used as a synonym for `char *`, and floating point parameters may be explicitly declared using the name `double`. The following example illustrates all possibilities:

```
DEFINE INSTRUMENT test(d1, double d2, int i, char *s1, string s2)
```

Here `d1` and `d2` will be floating point parameters of C type `double`, `i` will be an integer parameter of C type `int`, and `s1` and `s2` will be string parameters of C type `char *`. The parameters of an instrument may be given default values. Parameters with default values are called *optional parameters*, and need not be given an explicit value when the instrument simulation is executed. When executed without any parameter value in the command line (see section 5.3), the instrument asks for all parameter values, but pressing the `Return` key selects the default value (if any). When used with at least one parameter value in the command line, all non specified parameters will have their value

set to the default one (if any). A parameter is given a default value using the syntax "*param*`=` *value*". For example

```
DEFINE INSTRUMENT test(d1= 1, string s2="hello")
```

Here `d1` and `d2` are optional parameters and if no value are given explicitly, "1" and "hello" will be used.

Optional parameters can greatly increase the convenience for users of instruments for which some parameters are seldom changed or of unclear significance to the user. Also, if all instrument parameters have default values, then the simple command `mxdisplay test.instr` will show the instrument view without requesting any other input, which is usually a good starting point to study the instrument design.

6.3.2. The `DECLARE` section

```
DECLARE
%{
      ... C declarations of global variables etc. ...
%}
```

This gives C declarations that may be referred to in the rest of the instrument definition. A typical use is to declare global variables or small functions that are used elsewhere in the instrument. The `%include ''file''` keyword may be used to import a specific component definition or a part of an instrument. Variables defined here are global, and may conflict with internal McXtrace variables, particularly symbols like `x,y,z,Ex,Ey,Ez,kx,ky,kz,t,phi` and generally all names starting with `mc` nad `mx` should be avoided. If you can not compile the instrument, this may be the reason. The `DECLARE` section is optional.

6.3.3. The `INITIALIZE` section

```
INITIALIZE
%{
      ... C initializations. ...
%}
```

This section contains code that is executed once when the simulation starts. This section is optional. Instrument setting parameters may be modified in this section (e.g. doing tests or automatic settings).

6.3.4. The `NEXUS` extension

To use the NeXus format [Nex] the simulation must be linked with the HDF5 library, which must have been pre-installed. Preferrably, McXtrace should have been installed with the `./configure --with-nexus` on Unix/Linux systems. To activate the NeXus output, the instrument must be compiled with the flags `-DUSE_NEXUS -lhdf5`.

The default NeXus format is NeXus 5 with compression. However, that format may be changed with the optional keyword `NEXUS` to follow the INITIALIZE section, namely:

```
INITIALIZE
%{
        ... C initializations. ...
%} NEXUS {"4"|"5"|"XML"|"compress"|"zip"}
```

It is possible to set the type of NeXus file with a string argument, containing words "4", "5" or "XML". Optionally, if the string also contains the `compress` or `zip` word, the NeXus file will use compression for Data Sets. We recommend the syntax `NEXUS "5 compress"` which is the default.

You may choose the name of the output file with the `-f filename` option from the instrument executable or `mxrun` (see Sections 5.3, 5.4.2 and Table 5.2).

Then, the output format is chosen as usual with the `--format=NeXus` option when launching the simulation. All output files are stored in the output *filename*, as well as the instrument description itself. Other formats are still available. When run on a distributed system (e.g. MPI), detectors are gathered, but list of events (see e.g. component Virtual_output) are stored as one data set per node.

6.3.5. The `TRACE` section

As a summary, the usual grammar for component instances within the instrument TRACE section is

```
COMPONENT name = comp(parameters)
  AT (...) [RELATIVE [reference|PREVIOUS] | ABSOLUTE]
 {ROTATED  {RELATIVE [reference|PREVIOUS] | ABSOLUTE} }
```

The `TRACE` keyword starts a section giving the list of components that constitute the instrument. Components are declared like this:

`COMPONENT` $name = comp(p_1 = e_1, p_2 = e_2, \ldots)$

This declares a component named *name* that is an instance of the component definition named *comp*. The parameter list gives the setting and definition parameters for the component. The expressions $e_1, e_2, \ldots$ define the values of the parameters. For setting parameters arbitrary ANSI-C expressions may be used, while for definition parameters only *constant* numbers, strings, names of instrument parameters, or names of C identifiers are allowed (see section 6.5.1 for details of the difference between definition and setting parameters). To assign the value of a general expression to a definition parameter, it is necessary to declare a variable in the `DECLARE` section, assign the value to the variable in the `INITIALIZE` section, and use the variable as the value for the parameter.

The McXtrace program takes care to rename parameters appropriately in the output so that no conflicts occur between different component definitions or between component and instrument definitions. It is thus possible (and common) to use a component definition multiple times in an instrument description.

Be aware of the C variable type conversions when setting numerical parameter values, as in `p1=12/1000`. In this example, the parameter `p1` will be set to 0 as the division of the two integers is indeed 0. To avoid that, use explicitely floating type numbers as in `p1=12.0/1000`.

The McXtrace compiler will automatically search for a file containing a definition of the component if it has not been declared previously. The definition is searched for in a file called "*name*`.comp`". See section 5.2.2 for details on which directories are searched. This facility is often used to refer to existing component definitions in standard component libraries. It is also possible to write component definitions in the main file before the instrument definitions, or to explicitly read definitions from other files using `%include` (not within embedded C blocks).

The physical position of a component is specified using an `AT` modifier following the component declaration:

`AT` (x, y, z) `RELATIVE` *name*

This places the component at position (x, y, z) in the coordinate system of the previously declared component *name*. Placement may also be absolute (not relative to any component) by writing

`AT` (x, y, z) `ABSOLUTE`

Any C expression may be used for x, y, and z. The `AT` modifier is required. Rotation is achieved similarly by writing

`ROTATED` (ϕ_x, ϕ_y, ϕ_z) `RELATIVE` *name*

This will result in a coordinate system that is rotated first the angle ϕ_x (in degrees) around the x axis, then ϕ_y around the y axis, and finally ϕ_z around the z axis. Rotation may also be specified using `ABSOLUTE` rather than `RELATIVE`. If no rotation is specified, the default is $(0, 0, 0)$ using the same relative or absolute specification used in the `AT` modifier. We recommend to apply all rotations of an instrument description on Arm class components only, acting as goniometers, and position the optics on top of these. This usually makes it much easier to orient pieces of the beamline, and avoid positioning errors.

The *position* of a component is actually the origin of its local coordinate system. Usually, this is used as the input window position (e.g. for guide-like components), or the center position for cylindrical/spherical components.

The `PREVIOUS` keyword is a generic name to refer to the previous component in the simulation. Moreover, the `PREVIOUS(n)` keyword will refer to the n-th previous component, starting from the current component, so that `PREVIOUS` is equivalent to `PREVIOUS(1)`. This keyword should be used after the `RELATIVE` keyword, but not for the first component instance of the instrument description.

`AT` (x, y, z) `RELATIVE PREVIOUS ROTATED` (ϕ_x, ϕ_y, ϕ_z) `RELATIVE PREVIOUS(2)`

Invalid `PREVIOUS` references will be assumed to be absolute placement.

The order and position of components in the `TRACE` section does not allow components to overlap, except for particular cases (see the `GROUP` keyword below). Indeed, many components of the McXtrace library start by propagating the x-ray event to the begining of the component itself. If the corresponding propagation length is found to be negative (*i.e.* the x-ray is already *after* or *aside* the component, and has thus passed the 'active' position), the x-ray event is ABSORBed, resulting in a zero intensity and event counts after a given position. The number of such removed x-rays is indicated at the end of the simulation. Getting such warning messages may be an indication that either some components overlap, or some x-rays are getting outside of the simulation, for instance this usually happens after a monochromator, as the non-reflected beam is indeed lost. A special warning appears when no x-ray has reached some part of the simulation. This is usually the sign of either overlapping components or a very low intensity.

For experienced users, we recommend as well the usage of the `WHEN` and `EXTEND` keywords, as well as other syntax extensions presented in section 6.4.2 below.

6.3.6. The `SAVE` section

```
SAVE
%{
      ... C code to execute each time a temporary save is required ...
%}
```

This gives code that will be executed when the simulation is requested to save data, for instance when receiving a USR2 signal (on Unix systems), or using the `Progress_bar` component with intermediate savings. It is also executed when the simulation ends. This section is optional.

6.3.7. The `FINALLY` section

```
FINALLY
%{
      ... C code to execute at end of simulation ...
%}
```

This gives code that will be executed when the simulation has ended. When existing, the `SAVE` section is first executed. The `FINALLY` section is optional. A simulation may be requested to end before all x-rays have been traced when recieving a TERM or INT signal (on Unix systems), or with Control-C, causing code in `FINALLY` to be evaluated.

6.3.8. The end of the instrument definition

The end of the instrument definition must be explicitly marked using the keyword

```
END
```

6.4. Writing instrument definitions - complex arrangements and syntax

In this section, we describe some additional ways to build instruments using groups, code extension, conditions, loops and duplication of components.

As a summary, the nearly complete grammar definition for component instances within the instrument TRACE section is:

```
{SPLIT} COMPONENT name = comp(parameters) {WHEN condition}
  AT (...) [RELATIVE [reference|PREVIOUS] | ABSOLUTE]
  {ROTATED {RELATIVE [reference|PREVIOUS] | ABSOLUTE} }
  {GROUP group_name}
  {EXTEND C_code}
  {JUMP [reference|PREVIOUS|MYSELF|NEXT] [ITERATE number_of_times | WHEN condition]
```

6.4.1. Embedding instruments in instruments TRACE

The `%include` insertion mechanism may be used within the TRACE section, in order to concatenate instruments. This way, each DECLARE, INITIALIZE, SAVE, and FINALLY C blocks, as well as instrument parameters from each part are catenated. The TRACE section is made of inserted COMPONENTS from each part. In principle, it then possible to write an instrument as:

```
DEFINE catenated()
TRACE

%include "part1.instr"
%include "part2.instr"

END
```

where each inserted instrument is a valid full instrument. In order to avoid some components to be duplicated - e.g. Sources from each part - a special syntax in the TRACE section

```
INSTRUMENT COMPONENT a=...
```

marks the component a as removable when inserted. In principle, inserted instruments may themselves use `%include`.

6.4.2. Component extensions - EXTEND

It is sometimes desirable to slightly modify an existing component of the McXtrace library. One would usually make a copy of the component, and extend the code of its `TRACE` section. McXtrace provides an easy way to change the behaviour of existing components in an instrument definition without duplicating files, using the `EXTEND` modifier

```
EXTEND
%{
      ... C code executed after the component TRACE section ...
%}
```

The embedded C code is appended to the component `TRACE` section, and all its internal variables (as well as all the `DECLARE` instrument variables, *except* instrument parameters) may be used. To use instrument parameters, you should copy them into global variables in the DECLARE instrument section, and refer to these latter. This component declaration modifier is of course optional. You will find usage examples in the Component manual[BK+12].

6.4.3. Mutually exclusive components in parallell - GROUP

In some configurations it is necessary to position one or more groups of components, nested, in parallel, or overlapping. One example is a multiple crystal monochromator. One would then like the x-ray to interact with *one of* the components of the group and then continue.

In order to handle such arrangements without removing x-rays, groups are defined by the `GROUP` modifier (after the AT-ROTATED positioning):

`GROUP` *name*

to all involved component declarations. All components of the same named group are tested one after the other, until one of them interacts (uses the SCATTER macro). The selected component acts on the x-ray, and the rest of the group is skipped. Such groups are thus exclusive (only one of the elements is active).

Within a `GROUP`, *all* `EXTEND` sections of the group are executed. In order to discriminate components that are active from those that are skipped, one may use the SCATTERED flag, which is set to zero when entering each component or group, and incremented when the x-ray is SCATTERed, as in the following example

```
COMPONENT name0 = comp(p1 = e1, p2 = e2, ...)
  AT (0, 0, 0) ABSOLUTE
COMPONENT name1 = comp(...) AT (...) ROTATED (...)
  GROUP GroupName EXTEND
  %{
      if (SCATTERED) printf("I scatter");
      else printf("I do not scatter");
  %}
COMPONENT name2 = comp(...) AT (...) ROTATED (...)
  GROUP GroupName
```

Components *name1* and *name2* are at the same position. If the first one intercepts the x-ray (and has a SCATTER within its `TRACE` section), the SCATTERED variable becomes true, the code extension will result in printing "I scatter", and the second component

will be skipped. Thus, we recommend to make use of the SCATTER keyword each time a component 'uses' the x-ray (scatters, detects, ...) within component definitions (see section 6.5). Also, the components to be grouped should be consecutive in the TRACE section of the instrument, and the GROUPed section should not contain components which are not part of the group.

Note that a `GROUP` construct is *not* applicable to a situation where an x-ray which has interacted (`SCATTER`ed) with one component in the group, may interact with another. In this case a more complex arrangement is needed. See [Wil+11] for a description of how to do this in McStas. This is approach is *directly* applicable in McXtrace without modification.

Combining EXTEND, GROUP and WHEN can result in unexpected behaviour. Please read the related warning at the end of section 6.4.5.

6.4.4. Duplication of component instances - COPY

Often, one has a set of similar component instances in an instrument. These could be e.g. a set of identical monochromator blades, or a set of detectors. Together with JUMPs (see below), there is a way to copy a component instance, duplicating a parameter set, as well as any EXTEND, GROUP, JUMP and WHEN keyword. Position (AT) and rotation (ROTATED) specification must be explicitely entered in order to avoid component overlap.

The syntax for instance copy is

`COMPONENT` name = `COPY`(instance_name)

where *instance_name* is the name of a preceeding component instance in the instrument. It may be 'PREVIOUS' as well.

If you would like to change only some of the parameters in the instance copy, you may write, e.g.:

`COMPONENT` name = `COPY`(instance_name)(par1=0, par2=1)

which will override the original instance parameter values. In case EXTEND, GROUP, JUMP and WHEN keywords are defined for the copied instance, these will override the settings from the copied instance.

In the case where there are many duplicated components all originating from the same instance, there is a mechanism for automating copied instance names:

`COMPONENT COPY`(root_name) = `COPY`(instance_name)

will append a unique number to *root_name*, to avoid name conflicts. As a side effect, referring to this component instance (for e.g. further positioning) is not straight forward as the name is determined by McXtrace and does not depend completely on the user's choice, even though the PREVIOUS keyword may still be used. We thus recommend to use this naming mechanism only for components which should not be refered to in the instrument.

This automatic naming may be used anywhere in the TRACE section of the instrument, so that all components which do not need further referral may be labeled as COPY(Origin).

As an example, we show how to have a set of three equivalent pinholes (Slits). Only the first instance of the Slit component is defined explicitly, whereas following instances are copies of that definition. The instance names of `Slit` components are set automatically.

```
COMPONENT S_in = Arm() AT (...)

COMPONENT S_1  = Slit(radius=0.1)
  AT (0,0,0) RELATIVE PREVIOUS

COMPONENT COPY(S_1)  = COPY(S_1)
  AT (0,0,d) RELATIVE PREVIOUS

COMPONENT COPY(S_1)  = COPY(S_1)
  AT (0,0,d) RELATIVE PREVIOUS
...
COMPONENT S_Out = Arm() AT (0,0,d) RELATIVE PREVIOUS
```

6.4.5. Conditional components - WHEN

One of the most useful features of the extended McXtrace syntax is the conditional `WHEN` modifier. This optional keyword comes before the AT-ROTATED positioning. It basically enables the component only when a given condition is true (non null).

`COMPONENT` $name = comp(p_1 = e_1, p_2 = e_2, \ldots)$ `WHEN` $(condition)$

The condition has the same scope as the EXTEND modifier, i.e. may use component internal variables as well as all the `DECLARE` instrument variables.

Usage examples could be to have specific monitors only sensitive to selected processes, or to have components which are only present under given circumstances (e.g. removable filter or radial collimator), or to select a sample among a set of choices.

In the following example, an EXTEND block sets a condition when a scattering event is encoutered, and the following monitor is then activated.

```
COMPONENT Sample = V_sample(...) AT ...
  EXTEND
  %{
    if (SCATTERED) flag=1; else flag=0;
  %}

COMPONENT MyMon = Monitor(...) WHEN (flag==1)
  AT ...
```

The WHEN keyword only applies to the TRACE section and related EXTEND blocks of instruments/components. Other sections (INITIALIZE, SAVE, MCDISPLAY, FINALLY) are executed independently of the condition. As a side effect, the 3D view of the instrument (`mxdisplay`) will show all components as if all conditions were true.

A usage example of the WHEN keyword can be found in the `X-ray site/ESRF/ESRF_ID11` instrument from the `mxgui`, where the source model may be chosen by an external parameter.

The `WHEN` keyword is compatible with `GROUP`, and thus may be used to activate/deactivate members in a `GROUP` just like non-grouped components. Combining `WHEN`, `EXTEND` and `GROUP` can result in unexpected behaviour, please use them with caution! As an example, let a `GROUP` of components all have the same `WHEN` condition. If the condition is false, none of the elements `SCATTER`, meaning that all x-rays will be `ABSORB`ed. As a solution to this problem, we propose to include an `EXTEND`ed Arm component in the `GROUP`, but with the opposite `WHEN` condition and a `SCATTER` keyword in the `EXTEND` section. This means that when none of the other `GROUP` elements are present, the Arm will be present and `SCATTER`.

6.4.6. Component loops and non sequential propagation - JUMP

There are situations in which one would like to repeat a given component many times, or under a given condition. The JUMP modifier is meant for that and should be mentioned after the positioning, GROUP and EXTEND. This breaks the sequential propagation along components in the instrument description. There may be more than one JUMP per component instance.

The jump may depend on a condition:

> `COMPONENT` *name* = *comp*($p_1 = e_1, p_2 = e_2, \ldots$) `AT` (...) `JUMP` *reference*
> WHEN *condition*

in which case the instrument TRACE will jump to the *reference* when *condition* is true.

The *reference* may be an instance name, as well as PREVIOUS, PREVIOUS(n), MYSELF, NEXT, and NEXT(n), where n is the index gap to the target either backward (PREVIOUS) or forward (NEXT), so that PREVIOUS(1) is PREVIOUS and NEXT(1) is NEXT. MYSELF means that the component will be iterated as long as the condition is true. This may be a way to handle multiple scattering, if the component has been designed for that.

The jump arrives directly inside the target component, in the local coordinate system (i.e. without applying the AT and ROTATED keywords). In order to better control the target positions, it is *required* that, except for looping MYSELF, the target component type should be an *Arm*. Similarly to the `WHEN` modifier (see section 6.4.5), `JUMP` only applies within the TRACE section of the instrument definition. Other sections (INITIALIZE, SAVE, MCDISPLAY, FINALLY) are exectuted independently of the jump. As a side effect, the 3D view of the instrument `mxdisplay` will show components as if there was no jump. This means that in the following example, the very long mirror 3D view only shows a single mirror element.

It is *not* recommended to use the `JUMP` inside `GROUP`s, as the JUMP condition/counter applies to the component instance within its group.

We would like to emphasize the potential errors originating from such jumps. Indeed, imbricating many jumps may lead to situations were it is difficult to understand the flow of the simulation. We thus recommend the usage of JUMPs only for experienced and cautious users.

6.4.7. Enhancing statistics reaching components - SPLIT

The following method applies when the incoming x-ray event distribution is considered to be representative of the real beam, but x-rays are lost in the course of propagation (with low efficiency processes, absorption, etc). Then, one may think that it's a pity to have so few events reaching the 'interesting' part of the beamline (usually close to the end of the instrument description). If some components make extensive use of random numbers (MC choices), they shuffle this way the distributions, so that identical incoming events will not produce the same outgoing event. In this case, you may want to use a technique known as *stratified sampling* (see chapter 4) which in McXtrace is implemented through the `SPLIT` keyword with the syntax

`SPLIT` r `COMPONENT` $name = comp(\ldots)$

where the optional number r specifies the number of repetitions for each event. Default is $r = 10$. Each x-ray event reaching component *name* will be repeated r times with a weight divided by r, so that in practice the number of events for the remaining part of the simulation (down to the END), will potentially have more statistics. This is only true if following components (and preferably component *name*) use random numbers. You may use this method as many times as you wish in the same instrument, e.g. at the monochromator and sample position. This keyword can also be used within a GROUP. The efficiency is roughly r raised to the number of occurences in the instrument, so that enhancing two components with the default $r = 10$ will produce an enhancement effect of 100 wrt. the number of events at the end. The execution time will increase but at a slower rate than the statistical quality, provided that the above criteria are met. If the instrument makes use of global variables - e.g. in conjunction with a WHEN or User Variable monitoring (see Monitor_nD) - you should take care that these variables are set properly for each SPLIT loop, which usually means that they must be reset inside the SPLITed section and assigned/used further on.

6.5. Writing component definitions

The purpose of a McXtrace component is to model the interaction of an x-ray with a physical component of a real beamline. Given the state of the incoming x-ray, the component definition calculates the state of the x-ray when it leaves the component. The calculation of the effect of the component on the x-ray is performed by a block of embedded C code. One example of a component definition is given in section 6.5.10. All

other component definitions can be found on the McXtrace web-page [Mcx] and are also described in the McXtrace component manual.

A large number of functions and constants are available in order to write efficient components. See chapter B for

- x-ray propagation functions
- geometric intersection time computations
- mathematical functions
- random number generation
- physical constants
- coordinate retrieval and operations
- file generation routines (for monitors),
- data file reading

6.5.1. The component definition header

`DEFINE COMPONENT` *name*

This marks the beginning of the definition, and defines the name of the component.

`DEFINITION PARAMETERS` $(d_1, d_2, \ldots)$
`SETTING PARAMETERS` $(s_1, s_2, \ldots)$

This declares the definition and setting parameters of the component. These parameters can be accessed from all sections of the component (see below), as well as in `EXTEND` sections of the instrument definition (see section 6.3).

Setting parameters are translated into C variables usually of type `double` in the generated simulation program, so they are usually numbers. Definition parameters are translated into `#define` macro definitions, and so can have any type, including strings, arrays, and function pointers.

However, because of the use of `#define`, definition parameters suffer from the usual problems with C macro definitions. Also, it is not possible to use a general C expression for the value of a definition parameter in the instrument definition, only constants and variable names may be used. For this reason, setting parameters should be used whenever possible.

Outside the `INITIALIZE` section of components, changing setting parameter values only affects the current section.

There are a few cases where the use of definition parameters instead of setting parameters makes sense. If the parameter is not numeric, nor a character string (*i.e.* an array, for example), a setting parameter cannot be used. Also, because of the use of

`#define`, the C compiler can treat definition parameters as constants when the simulation is compiled. For example, if the array sizes of a multidetector are definition parameters, the arrays can be statically allocated in the component `DECLARE` section. If setting parameters were used, it would be necessary to allocate the arrays dynamically using *e.g.* `malloc()`.

Setting parameters may optionally be declared to be of type `int`, `char *` and `string`, just as in the instrument definition (see section 6.3).

`OUTPUT PARAMETERS` $(s_1, s_2, \ldots)$

This declares a list of C identifiers (variables, functions) that are output parameters (*i.e.* global) for the component. Output parameters are used to hold values that are computed by the component itself, rather than being passed as input. This could for example be a count of x-rays in a detector or a constant that is precomputed to speed up computation.

Using `OUTPUT PARAMETERS` is *highly* recommended for `DECLARE` and internal/global component variables and functions in order to prevent that instances of the same component use the same variable names. Moreover (see section 6.5.2 below), these may be accessed from any other instrument part (e.g. using the `MC_GETPAR` C macro). On the other hand, the variables from the SHARE sections should *not* be defined as OUTPUT parameters.

The `OUTPUT PARAMETERS` section is optional.

Optional component parameters

Just as for instrument parameters, the definition and setting parameters of a component may be given a default value. Parameters with default values are called *optional parameters*, and need not be given an explicit value when the component is used in an instrument definition. A parameter is given a default value using the syntax "*param* `=` *value*". For example

```
SETTING PARAMETERS (radius, height, pack= 1)
```

Here `pack` is an optional parameter and if no value is given explicitly, "1" will be used. In contrast, if no value is given for `radius` or `height`, an error message will result.

Optional parameters can greatly increase the convenience for users of components with many parameters that have natural default values which are seldom changed. Optional parameters are also useful to preserve backwards compatibility with old instrument definitions when a component is updated. New parameters can be added with default values that correspond to the old behavior, and existing instrument definitions can be used with the new component without changes.

Optional parameters should not be used in cases where no natural default value exists. For example the size of a slit should not be given a default value. This would prevent the error messages that should be given in the common case of a user forgetting to set an important parameter.

6.5.2. The DECLARE section

```
DECLARE
%{
      ... C code declarations (variables, definitions, functions)...
      ... These are usually OUTPUT parameters to avoid name conflicts
...
%}
```

This gives C declarations of global variables, functions, etc. that are used by the component code. This may for instance be used to declare a x-ray counter for a detector component. This section is optional.

Note that any variables declared in a DECLARE section are *global*. Thus a name conflict may occur if two instances of a component are used in the same instrument. To avoid this, variables declared in the DECLARE section should be OUTPUT parameters of the component because McXtrace will then rename variables to avoid conflicts. For example, a simple detector might be defined as follows:

```
DEFINE COMPONENT Detector
OUTPUT PARAMETERS (counts)
DECLARE
%{
  int counts;
%}
...
```

The idea is that the counts variable counts the number of x-rays detected. In the instrument definition, the counts parameter may be referenced using the MC_GETPAR C macro, as in the following example instrument fragment:

```
COMPONENT d1 = Detector()
...
COMPONENT d2 = Detector()
...
FINALLY
%{
  printf("Detector counts: d1 = %d, d2 = %d\n",
         MC_GETPAR(d1,counts), MC_GETPAR(d2,counts));
%}
```

This way, McXtrace takes care to transparently rename the two 'counts' OUTPUT parameters so that they are distinct, and can be accessed from elsewhere in the instrument (EXTEND, FINALLY, SAVE, ...) or from other components. Note that this particular example is obsolete rather artificial since McXtrace monitors will themselves output their contents.

6.5.3. The SHARE section

```
SHARE
%{
        ... C code shared declarations (variables, definitions, functions)...
        ... These should not be OUTPUT parameters ...
%}
```

The SHARE section has the same role as DECLARE except that when using more than one instance of the component, it is inserted *only once* in the simulation code. No occurence of the items to be shared should be in the OUTPUT parameter list (not to have McXtrace rename the identifiers). This is particularly useful when using many instances of the same component (for instance CRLs) if the declarations were in the DECLARE section, McXtrace would duplicate it for each instance (making the simulation code longer). A typical example is to have shared variables, functions, type and structure definitions that may be used from the component TRACE section. For an example of SHARE, see the samples/Single_crystal component. The `%include "file"` keyword may be used to import a shared library. The SHARE section is optional.

6.5.4. The INITIALIZE section

```
INITIALIZE
%{
        ... C code initialization ...
%}
```

This gives C code that will be executed once at the start of the simulation, usually to initialize any variables declared in the DECLARE section. This section is optional. Component setting parameters may be modified in this section, affecting the rest of the component.

6.5.5. The TRACE section

```
TRACE
%{
        ... C code to compute x-ray interaction with component ...
%}
```

This performs the actual computation of the interaction between the x-ray and the component. The C code should perform the appropriate calculations and assign the resulting new x-ray state to the state parameters. Most components will require propagation routines to reach the component entrance/area. Special macros `PROP_Z0;` and `PROP_DL();` are provided to automate this process (see section B.1).

The C code may also execute the special macro ABSORB to indicate that the x-ray has been absorbed in the component and the simulation of that x-ray will be aborted.

On the other hand, if the x-ray event should be *allowed* be backpropagated, the special macro `ALLOW_BACKPROP;` should preceed a call to the `PROP_**` call inside the component. When the x-ray state is changed or detected, for instance if the component simulates a reflecting mirror, the special macro `SCATTER` should be called. This does not affect the results of the simulation in any way, but it allows the front-end programs to visualize the scattering events properly, and to handle component `GROUP`s in an instrument definition (see section 6.3.5). It basically increments the SCATTERED counter. The `SCATTER` macro should be called with the state parameters set to the proper values for the scattering event., so that x-ray events are displayed correctly. For an example of `SCATTER`, see the optics/Mirror_curved component. Lately a new keyword `RESTORE` has been added, which generally

6.5.6. The `SAVE` section

```
SAVE
%{
        ... C code to execute in order to save data ...
%}
```

This gives code that will be executed when the simulation ends, or is requested to save data, for instance when receiving a USR2 signal (on Unix systems, see section 5.3), or when triggered by the `Progress_bar(flag_save=1)` component. This might be used by monitors and detectors in order to write results. An extension depending on the selected output format (see table 5.2 and section 5.3) is automatically appended to file names, if these latter do not contain extension.

In order to work properly with the common output file format used in McXtrace, all monitor/detector components should use standard macros for writing data in the SAVE or FINALLY section, as explained below. In the following, we use $N = \sum_i p_i^0$ to denote the count of detected x-ray events, $p = \sum_i p_i$ to denote the sum of the weights of detected x-rays, and $p2 = \sum_i p_i^2$ to denote the sum of the squares of the weights, as explained in section 4.2.1.

As a default, all monitors using the standard macros will display the integral p of the monitor bins, as well as the 2nd moment σ and the number of statistical events N. This will result in a line such as:

`Detector:` *CompName*_I=p *CompName*_ERR=σ *CompName*_N=N "*filename*"

For 1D and 2D monitors/detectors, the data histogram store in the files is given *per bin* when the signal is the x-ray intensity (most of the cases). Most monitors define binning for an x_n axis value as the sum of events falling into the $[x_n x_{n+1}]$ range, *i.e* the bins are *n*ot centered, but left aligned. Using the Monitor_nD component, it is possible to monitor other signals using the '`signal=`*variable_name*' in the 'options' parameter (refer to that component documentation).

Single detectors/monitors The results of a single detector/monitor are written using the following macro:

```
DETECTOR_OUT_0D(t, N, p, p2)
```

Here, t is a string giving a short descriptive title for the results, *e.g.* "Single monitor".

One-dimensional detectors/monitors The results of a one-dimensional detector/monitor are written using the following macro:

```
DETECTOR_OUT_1D(t, xlabel, ylabel,xvar, xmin, xmax, m,
                &N[0], &p[0], &p2[0],filename)
```

Here,

- t is a string giving a descriptive title (*e.g.* "Energy monitor"),
- *xlabel* is a string giving a descriptive label for the X axis in a plot (*e.g.* "Energy [meV]"),
- *ylabel* is a string giving a descriptive label for the Y axis of a plot (*e.g.* "Intensity"),
- *xvar* is a string giving the name of the variable on the X axis (*e.g.* "E"),
- *xmin* is the lower limit for the X axis,
- *xmax* is the upper limit for the X axis,
- m is the number of elements in the detector arrays,
- $\&N[0]$ is a pointer to the first element in the array of N values for the detector component (or NULL, in which case no error bars will be computed),
- $\&p[0]$ is a pointer to the first element in the array of p values for the detector component,
- $\&p2[0]$ is a pointer to the first element in the array of *p2* values for the detector component (or NULL, in which case no error bars will be computed),
- *filename* is a string giving the name of the file in which to store the data.

Two-dimensional detectors/monitors The results of a two-dimensional detector/monitor are written to a file using the following macro:

```
DETECTOR_OUT_2D(t, xlabel, ylabel, xmin, xmax, ymin, ymax, m, n,
                &N[0][0], &p[0][0],&p2[0][0],filename)
```

Here,

- t is a string giving a descriptive title (*e.g.* "PSD monitor"),

- *xlabel* is a string giving a descriptive label for the X axis in a plot (*e.g.* "X position [cm]"),
- *ylabel* is a string giving a descriptive label for the Y axis of a plot (*e.g.* "Y position [cm]"),
- *xmin* is the lower limit for the X axis,
- *xmax* is the upper limit for the X axis,
- *ymin* is the lower limit for the Y axis,
- *ymax* is the upper limit for the Y axis,
- m is the number of elements in the detector arrays along the X axis,
- n is the number of elements in the detector arrays along the Y axis,
- *&N[0][0]* is a pointer to the first element in the array of N values for the detector component,
- *&p[0][0]* is a pointer to the first element in the array of p values for the detector component,
- *&p2[0][0]* is a pointer to the first element in the array of *p2* values for the detector component,
- *filename* is a string giving the name of the file in which to store the data.

Note that for a two-dimensional detector array, the first dimension is along the X axis and the second dimension is along the Y axis. This means that element (i_x, i_y) can be obtained as $p[i_x * n + i_y]$ if p is a pointer to the first element.

Customizing detectors/monitors Users may want to have additional information than the default one written by the DETECTOR_OUT macros. A mechanism has been implemented for monitor components to output customized meta data. The macro:

```
DETECTOR_CUSTOM_HEADER(t)
```

defines a string to be written during the next `DETECTOR\_OUT*` call, as a field *custom*. This string should use the symbol `%PRE` which is replaced by the comment character '#'. The argument t to the macro may be a static string, e.g. *"My own additional information"*, or the name of a *character array variable* containing the meta data. After the detector/monitor file being written, the custom meta data output is unactivated. This way, each monitor file may have its own meta data definition by repeating the DETECTOR_CUSTOM_HEADER call. You may either do that inside the component SAVE section, or within an instrument description in an EXTEND code preceeding the monitor (e.g. following an Arm component).

6.5.7. The `FINALLY` section

```
FINALLY
%{
      ... C code to execute at end of simulation ...
%}
```

This gives code that will be executed when the simulation has ended. This might be used to free memory and print out final results from components, *e.g.* the simulated intensity in a detector. This section also triggers the SAVE section to be executed.

6.5.8. The `MCDISPLAY` section

```
MCDISPLAY
%{
      ... C code to draw a sketch of the component ...
%}
```

This gives C code that draws a sketch of the component in the plots produced by the `mxdisplay` front-end (see section 5.4.5). The section can contain arbitrary C code and may refer to the parameters of the component, but usually it will consist of a short sequence of the special commands described below that are available only in the MCDISPLAY section. When drawing components, all distances and positions are in meters and specified in the local coordinate system of the component.

The MCDISPLAY section is optional. If it is omitted, `mxdisplay` will use a default symbol (a small circle) for drawing the component.

The `magnify` command This command, if present, must be the first in the section. It takes a single argument: a string containing zero or more of the letters "x", "y" and "z". It causes the drawing to be enlarged along the specified axis in case `mxdisplay` is called with the `--zoom` option. For example:

```
magnify("xy");
```

The `line` command The `line` command takes the following form:

`line`(x_1, y_1, z_1, x_2, y_2, z_2)

It draws a line between the points (x_1, y_1, z_1) and (x_2, y_2, z_2).

The `dashed_line` command The `dashed_line` command takes the following form:

`dashed_line`(x_1, y_1, z_1, x_2, y_2, z_2, n)

It draws a dashed line between the points (x_1, y_1, z_1) and (x_2, y_2, z_2) with n equidistant spaces.

The `multiline` command The `multiline` command takes the following form:

`multiline(`n`, `x_1`, `y_1`, `z_1`, ..., `x_n`, `y_n`, `z_n`)`

It draws a series of lines through the n points (x_1, y_1, z_1), (x_2, y_2, z_2), ..., (x_n, y_n, z_n). It thus accepts a variable number of arguments depending on the value of n. This exposes one of the nasty quirks of C since *no* type checking is performed by the C compiler. It is thus very important that all arguments to `multiline` (except n) are valid numbers of type `double`. A common mistake is to write

```
multiline(3, x, y, 0, ...)
```

which will silently produce garbage output. This must instead be written as

```
multiline(3, (double)x, (double)y, 0.0, ...)
```

The `rectangle` command The `rectangle` command takes the following form:

`rectangle(`*`plane`*`, `x`, `y`, `z`, `*`width`*`, `*`height`*`)`

Here *plane* should be either `"xy"`, `"xz"`, or `"yz"`. The command draws a rectangle in the specified plane with the center at (x, y, z) and the size *width* $\times$ *height*. Depending on *plane* the width and height are defined as:

plane	*width*	*height*
xy	x	y
xz	x	z
yz	y	z

The `box` command The `box` command takes the following form:

`box(`x`, `y`, `z`, `*`xwidth`*`, `*`yheight`*`, `*`zlength`*`)`

The command draws a box with the center at (x, y, z) and the size *xwidth* $\times$ *yheight* $\times$ *zlength*.

The `circle` command The `circle` command takes the following form:

`circle(`*`plane`*`, `x`, `y`, `z`, `r`)`

Here *plane* should be either `"xy"`, `"xz"`, or `"yz"`. The command draws a circle in the specified plane with the center at (x, y, z) and the radius r.

6.5.9. The end of the component definition

```
END
```

This marks the end of the component definition.

6.5.10. A component example: Semi-transparent mirror

Below is an example of a complete component. A simple example of the component `Semi_mirror` is given.

```
/*******************************************************************
*
* McStas, X-ray tracing package
*          Copyright (C) 2015, All rights reserved
*          DTU Physics,  Kgs. Lyngby, Denmark
*
* Component: Semi_miror
*
* %I
*
* Written by: Erik B Knudsen
* Date:
* Version: Revision: 1.0
* Release: McXtrace manual
* Origin: DTU Physics
*
* Simple flat semi-reflecting mirror with constant reflectivity
*
* %D
* A perfectly flat plane mirror example, intended as an example of a
* very simple component.
* It also illustrates the concept of MC-choice for governing statstics.
*
* %P
* Input parameters:
* xwidth: (m) Width of the mirror.
* yheight: (m) Height of the mirror.
* reflectivity: ( ) Constant scalar reflectivity of mirror.
* frac_reflect: ( ) Fraction of statistics for reflecting branch.
* %E
*******************************************************************/

DEFINE COMPONENT Semi_mirror
DEFINITION PARAMETERS ()
SETTING PARAMETERS (xwidth, yheight, reflectivity, frac_reflect)

SHARE
%{
%}

INITIALIZE
%{
%}

TRACE
%{
  PROP_Z0;
  if( x>-xwidth/2.0 && x<xwidth/2.0 && y>-yheight/2.0 && y<yheight/2.0){
    double r;
```

```
50      r=rand01();
51      SCATTER;
52      if(r<frac_reflect){
53        vz=-vz;
54        p*=reflectivity/frac_reflect;
55        internal_color=1;
56      }else{
57        internal_color=0;
58        p*=(1-reflectivity)/(1-frac_reflect);
59      }
60    }else{
61      RESTORE_XRAY(INDEX_CURRENT_COMP,x,y,z,kx,ky,kz,phi,t,Ex,Ey,Ez,p);
62    }
63  %}
64
65  MCDISPLAY
66  %{
67
68    multiline(5, -xwidth/2.0, -yheight/2.0, 0.0,
69                  xwidth/2.0, -yheight/2.0, 0.0,
70                  xwidth/2.0,  yheight/2.0, 0.0,
71                 -xwidth/2.0,  yheight/2.0, 0.0,
72                 -xwidth/2.0, -yheight/2.0, 0.0);
73  %}
74
75  END
```

Listing 6.1: Complete listing of a semi-transparent mirror component. The component implements a Monte Carlo choice which lets the user decide how much of the available statistics should be used for the reflected and tranmitted branches respectively.

6.6. Extending component definitions

Suppose you are interested in one component in the McXtrace library, but you would like to customize it a little. There are different ways to extend an existing component.

6.6.1. Extending from the instrument definition file

If you only want to *add* something on top of the component existing behaviour, the simplest is to work from the instrument definition `TRACE` section, using the `EXTEND` modifier (see section 6.4.2). You do not need to write a new component definition, but only add a piece of code to execute.

6.6.2. Explicitly modify an existing library component

Copy the interesting component definition from the McXtrace library location (e.g. `/usr/local/mcxtrace/1.2/...` or `c:\mcxtrace\1.2\...`) into your working directory

next to your instrument definition file. This will cause McXtrace to pick this component definition up before the one in the library. Next, modify the local component file until you ae satisfied with it. If you feel that the newly modified componennt may be of use to the McXtrace community, please do not hesitate to contact the development team concerning the options for contributing. Rest assured that copyright remains with you.

6.6.3. Component heritage and duplication

There is a heritage mechanism to create children of existing components. These are exact duplicates of the parent component, but one may override/extend original definitions of any section.

The syntax for a full component child is

```
DEFINE COMPONENT child_name COPY parent_name
```

This single line will copy all parts of the *parent* into the *child*, except for the documentation header.

As for normal component definitions, you may add other parameters, `DECLARE`, `TRACE`, ... sections. Each of them will replace or extend (be catenated to, with the COPY/EXTEND keywords, see example below) the corresponding *parent* definition. In practice, you could copy a component and only rewrite some of it, as in the following example:

```
DEFINE COMPONENT child_name COPY parent_name


SETTING PARAMETERS (newpar1, newpar2)
INITIALIZE COPY parent_name EXTEND
%{
      ... C code to be catenated to the parent_name INITIALIZE ...
%}
SAVE
%{
      ... C code to replace the parent_name SAVE ...
%}
```

where two additional parameters have been defined, and should be handled in the extension of the original INITIALIZE section.

On the other hand, if you do not derive a component as a whole from a parent, you may still use specific parts from any component:

```
DEFINE COMPONENT name ...
DECLARE COPY parent1
INITIALIZE COPY parent2 EXTEND
%{
      ... C code to be catenated to the parent2 INITIALIZE ...
%}
TRACE COPY parent3
```

This mechanism may lighten the component code, but a special care should be taken in mixing bits from different sources, specially concerning variables. This may result in difficulties to compile components.

6.7. MxDoc, the McXtrace library documentation tool

McXtrace includes a facility called MxDoc to help maintain documentation of components and instruments. In the source code, comments may be written that follow a particular format understood by MxDoc. The MxDoc facility will read these comments and automatically produce output documentation in various forms. By using the source code itself as the source of documentation, the documentation is much more likely to be a faithful and up-to-date description of how the component/instrument actually works.

Two forms of documentation can be generated. One is the component entry dialog in the `mxgui` front-end, see section 5.4.1. The other is a collection of web pages documenting the components and instruments, handled via the `mxdoc` front-end (see section 5.4.7), and the complete documentation for all available McXtrace components and instruments may be found at the McXtrace webpage [Mcx], as well as in the McXtrace library (see 8.1). All available McXtrace documentation is accessible from the `mxgui` 'Help' menu.

Note that MxDoc-compliant comments in the source code are no substitute for a good reference manual entry. The mathematical equations describing the physics and algorithms of the component should still be written up carefully for inclusion in the component manual. The MxDoc comments are useful for describing the general behaviour of the component, the meaning and units of the input parameters, etc.

The format of the comments in the library source code

The format of the comments understood by MxDoc is mostly straight-forward, and is designed to be easily readable both by humans and by automatic tools. MxDoc has been written to be quite tolerant in terms of how the comments may be formatted and broken across lines. A good way to get a feeling for the format is to study some of the examples in the existing components and instruments. Below, a few notes are listed on the requirements for the comment headers:

The comment syntax uses `%IDENTIFICATION`, `%DESCRIPTION`, `%PARAMETERS`, `%EXAMPLE:`, `%LINKS`, and `%END` keywords to mark different sections of the documentation. Keywords may be abbreviated (except for `%EXAMPLE:`), *e.g.* as `%IDENT` or `%I`.

Additionally, optional keys `%VALIDATION` and `%BUGS` may be found to list validation status and possible bugs in the component.

- In the `%IDENTIFICATION` section, `author:` (or `written by:` for backwards compatibility with old comments) denote author; `date:`, `version:`, and `origin:` are also supported. Any number of `Modified by:` entries may be used to give the revision history. The `author:`, `date:`, etc. entries must all appear on a single line of their own. Everything else in the identification section is part of a "short description" of the component.

- In the %PARAMETERS section, descriptions have the form "*name*: [*unit*] *text*" or "*name*: *text* [*unit*]". These may span multiple lines, but subsequent lines must be indented by at least four spaces. Note that square brackets [] should be used for units. Normal parentheses are also supported for backwards compatibility, but nested parentheses do not work well.

- The %DESCRIPTION section contains text in free format. The text may contain HTML tags like <IMG> (to include pictures) and <A>...</A> (for links to other web pages, but see also the %LINK section). In the generated web documentation pages, the text is set in <PRE>...</PRE>, so that the line breaks in the source will be obeyed.

- The %EXAMPLE: (or %TEST:) lines in instrument headers indicate an example parameter set or command that may be run to test the instrument. A %TESTSCAN: (older name %SCAN:) line defines a parameter scan test with one expected value per scan point. A following Detector: <name>_I=<value> indicates what value should be obtained for a given monitor. More than one example line may be specified in instruments.

- Any number of %LINK sections may be given; each one contains HTML code that will be put in a list item in the link section of the description web page. This usually consists of an <A HREF="..."> ... </A> pointer to some other source of information.

- Optionally, an %INSTRUMENT_SITE section followed by a single word is used to sort *instruments* by origin/location in the 'X-ray Site' menu in mxgui.

- After %END, no more comment text is read by MxDoc.

7. The Union components

The **Union components** are a set of McXtrace components, originally developed for McStas by Mads Bertelsen [Ber17; BJL17] and subsequently ported to McXtrace, that take a fundamentally different approach to sample and sample-environment simulation than ordinary McXtrace components. This chapter explains the concepts behind the Union components and how to use them from an instrument file; the full parameter reference for every individual Union component is auto-generated from the component headers and found in the Component Manual's Union chapter.

The McXtrace port covers the core of the framework – processes, materials, geometries, masks, exit volumes and the master component – but not (yet) every feature of the McStas original: there is currently no logger, absorption-logger, conditional or surface (reflection/refraction) support, and no ray-history tagging system. Everything described in this chapter is available; where a feature exists in McStas but not McXtrace, this is noted explicitly.

7.1. Motivation

An ordinary McXtrace instrument is a linear sequence of self-contained components: an x-ray enters a component, something happens to it (or not), and it moves on to the next component in the sequence. This is a good match for the intended beam path through an instrument, but it means that

- a single sample component must contain *all* the physics relevant to that sample – absorption and every scattering process – as one monolithic block of code, and
- multiple scattering *between* physically separate parts of a sample environment (a sample inside a capillary, inside a sample changer, ...) is essentially impossible to capture, since each part would need to be a separate component and McXtrace components do not natively talk to each other.

The Union components solve this by splitting the sample simulation task into several cooperating component classes – *processes*, *materials*, *geometries* and a *master* – and performing the actual ray tracing for all of them together, inside the master component, with full native multiple scattering between every defined volume. Because physics (processes) and geometry are separated, adding a new scattering process is a comparatively small task, and existing processes can be freely combined and reused across different shapes.

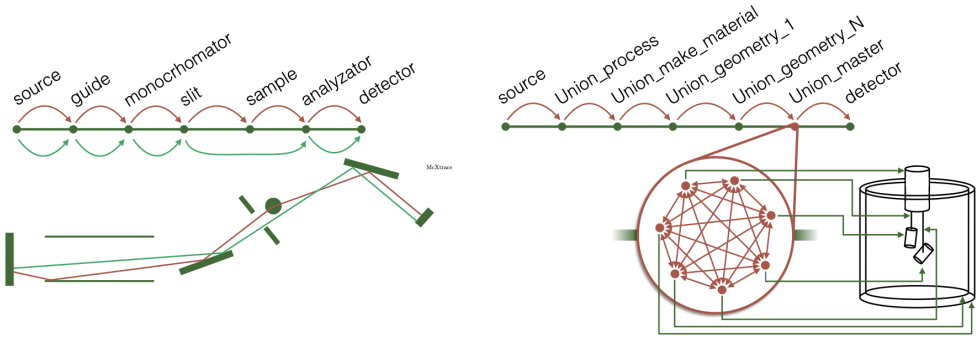

Figure 7.1.: Left: the linear succession of components in a traditional McXtrace instrument file. Right: the same instrument using Union components – all ray tracing for the sample environment happens inside a single master component, which works around the normal McXtrace component sequence to achieve native multiple scattering between an arbitrary number of volumes. (Originally illustrated for McStas; the same principle applies unchanged to McXtrace.)

It is entirely possible, and common, to mix ordinary McXtrace components with Union components in the same instrument file – the Union machinery only takes over at its `Union_master` components (section 7.2).

7.1.1. Volumes, priority and overlap

The central concept of the Union components is the *volume*: a geometrical shape (box, cylinder, sphere or cone) combined with a material definition (absorption plus zero or more scattering processes), placed in space using the ordinary `AT/ROTATED` mechanism. Volumes may be placed in any order in the instrument file, and, unlike ordinary McXtrace geometry, volumes are allowed to *overlap*.

Each volume is given a unique `priority` value. Wherever two or more volumes overlap in space, the material of the volume with the *highest* priority applies. This single rule makes it straightforward to build geometries that would otherwise require careful, error-prone manual splitting into non-overlapping pieces: a hollow capillary wall is simply a material cylinder with a vacuum cylinder of higher priority placed inside it, and a layered sample with several different materials is built from concentric or adjacent shapes, each its own volume and material.

7.2. Component classes

A Union simulation is assembled from components of several distinct classes, always used in the same overall order:

1. **Process components** – define a scattering process (section 7.2.2).

2. `Union_make_material` – collect processes and an absorption cross section into a named material (section 7.2.3).

3. **Geometry components** – place a volume with a given material in the simulation (section 7.2.4).

4. `Union_master` – performs the actual ray tracing for all volumes defined since the previous master (section 7.2.5).

7.2.1. Loading the Union library

Union components need no setup or cleanup components. Each one loads the Union library itself, and the library keeps the internal bookkeeping lists (of processes, materials, geometries, ...) that the components communicate through, freeing them once the last Union component has finished.

An instrument that uses Union components must contain at least one `Union_master`; without one it fails to compile, with an error naming `Union_components_need_a_Union_master_in_the`. Union components placed after the last `Union_master` have no effect, and the simulation warns about each of them when it finishes.

`Union_init` and `Union_stop`, which older instruments place first and last among their Union components, are no longer needed. They are kept without effect, apart from a deprecation warning, so that such instruments still compile. For the same reason every Union component still accepts the string parameter `init`, which older instruments set to the name of their `Union_init` component; its value is ignored.

7.2.2. Scattering processes

A process component has no physical shape of its own. It describes a single physical scattering mechanism: a function giving the inverse penetration depth (macroscopic cross section) as a function of incoming wavevector, and a function describing what happens to a ray in a scattering event. Table 7.1 lists the processes currently available. Note that x-ray-specific processes (`Compton_xrl_process`, `KN_xrl_process`, `Rayleigh_xrl_process`) take a `density` and an atomic number `atomno` rather than a cross section, and use the external `xraylib` library for the underlying physics.

Every process has an `interact_fraction` setting parameter, in the range $[0, 1]$ or -1 to disable, which can be used to artificially force a certain fraction of scattering events to that process (an importance sampling technique, entirely analogous to `p_interact` discussed below); the resulting ray weight is corrected automatically so the simulation remains unbiased. If left at -1 for every process in a material, the interact fractions default to the actual, physical scattering probabilities.

A minimal example defining a Compton scattering process for copper:

```
COMPONENT compton1 = Compton_xrl_process(density=8.92, atomno=29)
AT (0,0,0) ABSOLUTE
```

Component	Description
`Incoherent_process`	Isotropic, elastic incoherent scattering (cross-section based, ported from McStas).
`Compton_xrl_process`	Compton (incoherent) scattering via `xraylib`, using `density` and atomic number `atomno`.
`KN_xrl_process`	Klein-Nishina Compton scattering via `xraylib`.
`Rayleigh_xrl_process`	Rayleigh (coherent, elastic) scattering via `xraylib`.
`Powder_process`	Bragg scattering from a powder (based on `PowderN`, given a reflection list via `reflections`).
`Template_process`	Documented template for writing a new process.

Table 7.1.: Scattering processes currently available for the McXtrace Union components.

A process component's position in the instrument file is irrelevant to the physics (it has no shape); its *name* is what matters, since materials refer to processes by name.

7.2.3. Union_make_material

`Union_make_material` collects one or more previously defined processes into a named material, together with the absorption cross section (as the inverse penetration depth, `my_absorption`, in m^{-1}):

```
COMPONENT cmpton1 = Union_make_material(
    process_string="compton1", my_absorption=0)
AT (0,0,0) ABSOLUTE
```

As x-ray absorption and scattering are often already captured by the `xrl`-based processes' own physics, it is common to see `my_absorption=0` in practice, as in the example above and the complete worked example in section 7.4. If `process_string` is left unset, all processes defined since the previous `Union_make_material` are collected automatically; giving it explicitly is recommended, since it makes the resulting material self-documenting. Two material names are reserved and always available without being explicitly defined: `"Vacuum"` (no processes, no absorption) and `"Exit"` (behaves like vacuum, but see section 7.2.4 below). Setting `absorber=1` instead of giving a `process_string` creates a purely absorbing material with no scattering processes at all.

7.2.4. Geometry components

A geometry component places a volume of a given shape and material in the simulation, using the material name from `Union_make_material` and the ordinary `AT/ROTATED` keywords for position and orientation. The currently available shapes are `Union_box`,

Union_cylinder, Union_sphere and Union_cone (which can also represent a plain cylinder by setting radius_top=radius_bottom, or a full cone by leaving one of them at its default of 0). No ray tracing happens in a geometry component itself – it only registers the volume with the following Union_master.

Every geometry component shares a common set of setting parameters, summarized in table 7.2, in addition to its own shape-specific dimensions (e.g. radius/yheight for Union_cylinder; xwidth/yheight/zdepth for Union_box; radius_top/radius_bottom/yheight for Union_cone).

Parameter	Description
material_string	Name of a material from Union_make_material, or "Vacuum"/"Exit".
priority	Unique priority value; the volume with the highest priority wins where volumes overlap (section 7.1.1).
p_interact	Forces this probability [0-1] for a scattering event when a ray is inside the volume, regardless of path length (importance sampling; see note below).
visualize	Set to 0 to hide this volume in mcdisplay.
mask_string, mask_setting	Turn this volume into a *mask* restricting one or more other volumes (section 7.2.4).
number_of_activations	Number of subsequent Union_master components this volume should be simulated by (section 7.2.4).
target_index/ target_x,y,z, focus_aw/focus_ah, focus_xw/focus_xh, focus_r	Standard McXtrace focusing parameters, used by any process assigned to this volume's material that supports focusing.

Table 7.2.: Setting parameters common to all McXtrace Union geometry components.

Unlike the McStas Union components, the McXtrace geometry components do not yet have any surface/cut_surface-style parameters – there is no reflection/refraction (surface) support in the McXtrace port (section 7.1).

p_interact and multiple scattering

Unlike p_interact in an ordinary McXtrace sample component, p_interact on a Union volume applies at *every* step of the multiple scattering loop, not just once. Setting it to 50%, for instance, gives a 25% chance of *two* scattering events in that volume. It is therefore best kept well below 1; values close to 1 lead to very high probabilities of high-order multiple scattering and correspondingly large statistical weight corrections.

Masks

A mask volume restricts one or more other (*masked*) volumes: a ray only sees the masked volume's material where the masked volume and the mask volume(s) both cover the same space. This gives additional geometric freedom beyond what overlap-by-priority alone provides. A masked volume can have several masks; `mask_setting` (`"All"` or `"Any"`, default `"All"`) controls whether every mask or just any one of them must cover a point for the masked volume to apply there. A mask volume is set via `mask_string` (a comma-separated list of the geometry names it masks) rather than `material_string`.

Exit volumes and number_of_activations

Normally, once a ray enters the region of space covered by a `Union_master`, it stays inside the Union ray-tracing loop until it escapes all defined volumes. Sometimes it is useful to break out of this loop early – for example to place an ordinary McXtrace monitor or component somewhere inside an otherwise Union-simulated geometry. Assigning a volume the special material `"Exit"` achieves this: once a ray enters an exit volume, the current master stops and the *next* McXtrace component in the instrument sequence runs as normal.

`number_of_activations` (default 1) controls how many subsequent `Union_master` components will simulate a given volume, which is useful when a static piece of geometry should be present across more than one master section of the instrument without redefining it.

7.2.5. Union_master

`Union_master` is where the actual ray tracing happens – it is the component that is placed into the ordinary linear McXtrace component sequence, and by default it simulates every volume defined since the previous master (or, for the first master, since the start of the instrument). If a volume is defined after the last `Union_master` in the file, it will never be simulated – remember to place a master after your geometry.

```
1 COMPONENT master = Union_master()
2 AT (0,0,0) RELATIVE sample_position
```

`Union_master` also has an `allow_inside_start` setting (set to 1 if rays are expected to start already inside a volume at this master) and `verbal`/`list_verbal`/`finally_verbal` settings for diagnostic terminal output; see the Component Manual entry for the complete list. Unlike McStas's Union components, there is currently no separate GPU-enabled master variant for McXtrace.

7.3. The propagation algorithm

This section gives a conceptual outline of how `Union_master` actually propagates rays; see the original thesis [Ber17], written for the McStas Union components but describing the same underlying algorithm, for the full derivation and pseudocode.

Within a volume, the distance to the next scattering position is drawn from the usual exponential distribution set by the total inverse penetration depth (sum over the volume's absorption and all its processes' scattering contributions). If this distance is less than the distance to the volume's boundary, a scattering event occurs there; otherwise, the ray is propagated to the boundary and the simulation continues in whichever volume lies on the other side.

Naively, determining which volume lies on the other side of a boundary would require testing every other defined volume for intersection and containment, for every propagation step – prohibitively expensive once more than a handful of volumes are involved. Instead, in the `initialize` section of each `Union_master`, the whole ensemble of volumes is analysed once to build, for every volume, the (usually small) set of other volumes that actually need an intersection test from there, and the set of volumes the ray could possibly end up in immediately after leaving through its own boundary. This turns an $O(N)$-per-step cost into something close to $O(1)$ in typical geometries. Figure 7.2 sketches the resulting behaviour for a simple case (illustrated for a neutron ray, but the same principle applies unchanged to McXtrace's x-rays).

7.3.1. Known limitations

- **Coincident surfaces.** If two volume boundaries coincide exactly, the algorithm cannot reliably determine which volume a ray enters. It is safe, and normal, to *overlap* volumes – but two volumes should never be placed so that a face merely touches without any overlap or gap; leaving even a micron-scale gap or overlap avoids the problem entirely.
- **No gravity.** The underlying intersection algorithms are linear, so Union volumes propagate in straight lines regardless of any gravity setting elsewhere in the instrument (in practice rarely relevant for x-ray instruments).
- **Feature parity with McStas.** As noted in section 7.1, loggers, absorption loggers, conditionals, surfaces (reflection/refraction) and ray-history tagging are not currently available for McXtrace's Union components.

7.4. A complete example

The following excerpt, adapted from the `PowderCompton_union` example instrument (section 7.5), combines Compton scattering in a sphere with powder diffraction in a box:

```
1 COMPONENT compton1 = Compton_xrl_process(density=8.92, atomno=29)
2 AT (0,0,0) ABSOLUTE
3
4 COMPONENT pow2_proc = Powder_process(reflections=refs)
5 AT (0,0,0) ABSOLUTE
6
7 COMPONENT cmpton1 = Union_make_material(
8     process_string="compton1", my_absorption=0)
9 AT (0,0,0) ABSOLUTE
```

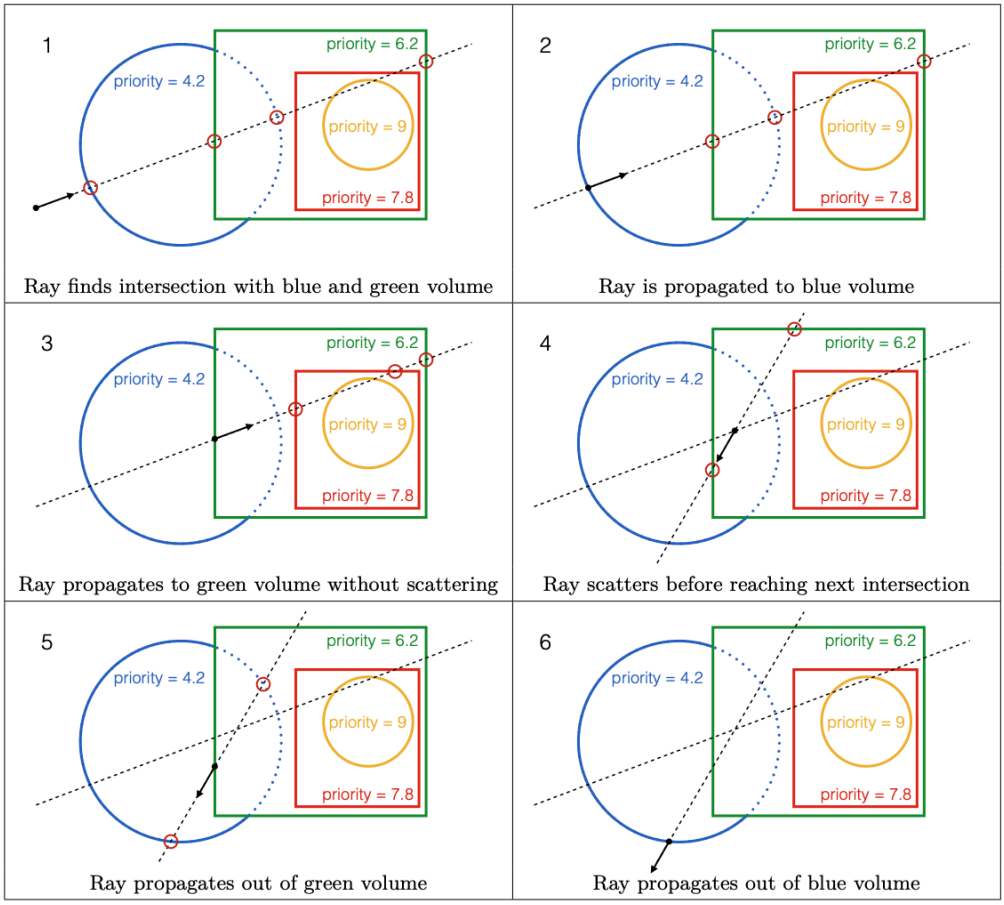

Figure 7.2.: Illustration of the Union propagation algorithm for a single scattering event between two overlapping volumes. Only intersections actually relevant given the ray's current volume are calculated at each step (the orange volume, never reachable from the ray's actual path here, is never tested).

```
10
11 COMPONENT pow2 = Union_make_material(
12       process_string="pow2_proc", my_absorption=0)
13 AT (0,0,0) ABSOLUTE
14
15 /* ... source, slits etc. as normal ... */
16
17 COMPONENT usphere = Union_sphere(radius=0.25e-3, material_string="cmpton1",
18       priority=2)
19 AT (0,-0.3e-3,0) RELATIVE sample_position
20
21 COMPONENT ubox = Union_box(xwidth=1e-3, yheight=0.75e-3, zdepth=0.5e-3,
22       material_string="pow2", priority=1)
23 AT (0,0.8e-3,0) RELATIVE sample_position
```

```
24
25 COMPONENT master = Union_master()
26 AT (0,0,0) RELATIVE sample_position
27
28 COMPONENT fpi = PSD_monitor_4PI(radius=1.25, nx=101, ny=101, filename="fpi"
       )
29 AT (0,0,0) RELATIVE sample_position
```

Note the two volumes overlap in neither space nor priority here (a sphere and a box placed side by side) – the priority mechanism only matters where volumes actually share space, as discussed in section 7.1.1.

7.5. Further examples

The example instrument library ships Union examples in the `Tests_union` category, including `PowderCompton_union` (the basis for the worked example above, combining Compton and powder scattering), `Test_KN_Comp_Rayl_union` (comparing the Klein-Nishina, Compton and Rayleigh processes) and `Geometry_test`. See the User Manual's chapter on instrument examples for how to browse these. A number of the individual component headers, documented in the Component Manual's Union chapter, contain further short usage examples.

8. The component library: Abstract

This chapter presents an abstract of the McXtrace component library's structure and categories. It intentionally does *not* attempt to enumerate every component with its parameter list – the library is large and changes between releases, so any hand-maintained table here would inevitably drift out of date (as earlier editions of this manual did). Instead, each component category chapter that follows (Sources, Optics, Samples, Monitors, ...) documents a curated selection of representative components in depth, with their full, current parameter lists pulled directly from the component source's McDoc header at build time (see section 6.7 for the McDoc comment format). For the complete, authoritative, always-current list of every component and its parameters, use the `mxdoc` front-end:

```
1 mxdoc
2 mxdoc searchterm
3 mxdoc file.comp
```

The first form generates and opens a browsable *index.html* catalog of the whole library (both the standard installation and any local/custom components); the second searches for and displays documentation for all components matching *searchterm*; the third displays the documentation of one specific component file. See section 5.4.7 in the User Manual for the full `mxdoc` reference.

8.1. Component categories

The library (located under the `mcxtrace-comps` directory of the McXtrace source/installation tree, see section 5.2.2 in the User Manual for how McXtrace locates it) is organised into the following top-level categories:

sources Components that define the initial photon ray state – including point, flat, divergent and full-featured laboratory-source models – see the Sources chapter of the Component Manual.

optics Mirrors, lenses, slits, crystal monochromators, and other beam-manipulating components.

samples Components modelling matter placed in the beam for scattering/absorption studies (SAXS models, powders, single crystals, ...) – see the Samples chapter of the Component Manual.

monitors Components that record/histogram the photon beam without otherwise affecting it.

misc Components that do not fit the other categories, e.g. the `Progress_bar` and beam-statistics utilities.

union The Union framework: a set of process/geometry components that can be freely combined to describe complex, possibly nested and overlapping sample environments with multiple scattering, decoupling the description of *where* matter is from *what* it does to the photon (Compton/Rayleigh scattering, photoelectric absorption, powder diffraction, ...).

sasmodels Small-angle scattering form factors generated from the SasView/sasmodels project, exposed via the `SasView_model` component.

astrox Components specific to the AstroX branch of McXtrace, modelling grazing-incidence X-ray optics for astronomical instrumentation (nested Wolter-type mirror shells, pore and micropore optics).

contrib Components contributed by McXtrace users. The McXtrace core team provides the same technical support as for other categories, but authored and maintained the code less directly; contributed components are generally reliable, but see each component's own validation/bugs notes. Components in `contrib` that mature and gain wide use are periodically promoted into one of the core categories above – always check with `mxdoc` rather than assuming a component's category from an older document.

obsolete Components that were renamed or superseded. They are kept, and continue to work, purely for backwards compatibility with existing instrument files; new instrument development should avoid them (`mxdoc` will point to the current replacement where one exists).

8.2. Data files

Some components require external data files, e.g. atomic form factors, element-specific absorption/refraction data from the NIST database, or multilayer/crystal reflectivity curves. Such files distributed with McXtrace are located in the `data` sub-directory of the library and are accessible to any component using the shared library read routines without needing local copies.

8.3. Component and instrument examples

An overview of the example instrument library, organised by facility and category, is given in the User Manual's chapter on instrument examples. Every `.instr` file there is discoverable via `mxgui`'s **New from Template** menu, or via `mxdoc`.

McXtrace/data	Description
Al.txt, He.txt, etc.	Data files from the NIST database (covering the elements with $Z \in [1..92]$) to be used for absorption and refraction.
FormFactors.txt	Atomic form factors for elements with $Z \in [1..92]$.
Ref_W_B4C.txt	Reflectivity of a W-B4C multilayer.
Ref_W_Si.txt	Reflectivity of a W-Si multilayer.

Table 8.1.: Data files of the McXtrace library.

A. Random numbers in McXtrace

A.1. Transformation of random numbers

In order to perform the Monte Carlo choices, one needs to be able to pick a random number from a given distribution. However, most random number generators only give uniform distributions over a certain interval. We thus need to be able to transform between probability distributions, and we here give a short explanation on how to do this.

Assume that we pick a random number, x, from a distribution $\phi(x)$. We are now interested in the shape of the distribution, $\Psi(y)$, of the transformed $y = f(x)$, assuming $f(x)$ is monotonous. All random numbers lying in the interval $[x; x+dx]$ are transformed to lie within the interval $[y; y + f'(x)dx]$, so the resulting distribution must be $\Psi(y) = \phi(x)/f'(x)$.

If the random number generator selects numbers uniformly in the interval $[0; 1]$, we have $\phi(x) = 1$ (inside the interval; zero outside), and we reach

$$\Psi(y) = \frac{1}{f'(x)} = \frac{d}{dy} f^{-1}(y). \tag{A.1}$$

By indefinite integration we reach

$$\int \Psi(y)dy = f^{-1}(y) = x, \tag{A.2}$$

which is the essential formula for random number transformation, since we in general know $\Psi(y)$ and like to determine the relation $y = f(x)$. Let us illustrate with a few examples of transformations relevant for the McXtrace components.

The circle For finding a random point within the circle of radius R, one would like to choose the polar angle, ϕ, from a uniform distribution in $[0; 2\pi]$, giving $\Psi_\phi = 1/(2\pi)$. and the radius from the (normalised) distribution $\Psi_r = 2r/R^2$.

For the radial part, eq. (A.2) becomes $y/(2\pi) = x$, whence ϕ is found simply by multiplying a random number (x) with 2π.

For the radial part, the left side of eq. (A.2), gives $\int \Psi(r)dr = \int 2r/R^2 dr = r^2/R^2$, which from (A.2) should equal x. Hence we reach the wanted transformation $r = R\sqrt{x}$.

The sphere For finding a random point on the surface of the unit sphere, we need to determine the two angles, (θ, ϕ).

Ψ_ϕ is chosen from a uniform distribution in $[0; 2\pi]$, giving $\phi = 2\pi x$ as for the circle.

The probability distribution of θ should be $\Psi_\theta = \sin(\theta)$ (for $\theta \in [0; \pi]$), whence by eq. (A.2) $\theta = \cos^{-1}(x)$.

Exponential decay In a simple 2-state model a molecule may be said to relax into its ground state at a time which is exponetially distributed after the initial excitation at $t = 0$. We thus want to pick a relaxation time from the normalised distribution $\Psi(t) = \exp(-t/\tau)/\tau$. Use of Eq. (A.2) gives $x = 1 - \exp(-t/\tau)$. For convenience we now use the random variable $x_1 = 1 - x$ (with the same distributions as x), giving the simple expression $t = -\tau \ln(x_1)$.

Normal distributions The important normal distribution can not be reached as a simple transformation of a uniform distribution. In stead, we rely on a specific algorithm for selecting random numbers with this distribution.

A.2. Random generators

As of McXtrace 3.x, the default random number generator is a 64-bit adaptation of Marsaglia's *KISS* ("Keep It Simple Stupid") generator, a composite of a linear congruential generator, a xorshift generator, and a multiply-with-carry generator, combined to give a very long period ($> 2^{127}$) while remaining fast and simple. Crucially, KISS runs identically on both CPU and GPU/OpenACC, which is why it replaced the previously used Mersenne Twister as the default: Mersenne Twister's large internal state does not parallelize well and is currently not functional for GPU-accelerated simulations.

The classic "Mersenne Twister" generator, by Makoto Matsumoto and Takuji Nishimura[MN98] (see `http://www.math.sci.hiroshima-u.ac.jp/~m-mat/MT/emt.html` for the original source), remains available as a build-time alternative for CPU-only simulations, selected by compiling the generated instrument with `-DRNG_ALG=1` (e.g. via the `MCXTRACE_CFLAGS` environment variable, or the C-compiler flag options). It has an extremely large period ($2^{19937} - 1$) and negligible cross-correlations up to 623 dimensions, but should not be selected for GPU/OpenACC runs.

B. Libraries and conversion constants

The McXtrace Library contains a number of built-in functions and conversion constants which are useful when constructing components. These are stored in the `share` directory of the `MCXTRACE` library.

Within these functions, the 'Run-time' part is available for all component/instrument descriptions. The other parts are dynamic, that is they are not pre-loaded, but only imported once when a component requests it using the `%include` McXtrace keyword. For instance, within a component C code block, (usually SHARE or DECLARE):

```
1  %include "read_table-lib"
```

will include the 'read_table-lib.h' file, and the 'read_table-lib.c' (unless the `--no-runtime` option is used with `mcxtrace`). Similarly,

```
1  %include "read_table-lib.h"
```

will *only* include the 'read_table-lib.h'. The library embedding is done only once for all components (like the SHARE section). For an example of implementation, see **Res_monitor**.

In this Appendix, we present a short list of both each of the library contents and the run-time features.

B.1. Run-time calls and functions (`mcxtrace-r`)

Here we list a number of preprogrammed macros and functions which may ease the task of writing component and instrument definitions. By convention macros are in upper case whereas functions are in lower case.

B.1.1. Photon propagation

Propagation routines perform all necessary operations to transport x-rays from one point to an other. Except when using the special `ALLOW_BACKPROP;` call prior to executing any `PROP_*` propagation, the x-rays which have negative propagation lengths are removed automatically.

- **ABSORB**. This macro issues an order to the overall McXtrace simulator to interrupt the simulation of the current x-ray history and to start a new one.
- **PROP_Z0**. Propagates the x-ray to the $z = 0$ plane, by adjusting (x, y, z), ϕ, and t accordingly from knowledge of the x-ray wavevector (kx, ky, kz). If the propagation length is negative, the x-ray is absorbed, except if a `ALLOW_BACKPROP;` preceeds it.

For components that are centered along the z-axis, use the `_intersect` functions to determine intersection time(s), and then a `PROP_DL` call.

- **PROP_X0, PROP_Y0**. These macros are analogous to `PROP_Z0` except they propagate to the $x = 0$ and $y = 0$ planes respectively.

- **PROP_DL**(dl). Propagates the x-ray by the length dl, adjusting (x, y, z), ϕ, t accordingly, from knowledge of the x-ray wavevector.

- **ALLOW_BACKPROP**. Indicates that the *next* propagation routine will not remove the x-ray, even if negative propagation lengths are found. Subsequent propagations are not affected.

- **SCATTER**. This macro is used to denote a scattering event inside a component. It should be used to indicate that a component has interacted with the x-ray (e.g. scattered or detected). This does not affect the x-ray state (see, however, **Beamstop**), and it is mainly used by the `MCDISPLAY` section and the `GROUP` modifier. See also the SCATTERED variable (below).

B.1.2. Coordinate and component variable retrieval

- **MC_GETPAR**(*comp*, *outpar*). This may be used in e.g. the FINALLY section of an instrument definition to reference the parameters of a component.

- **NAME_CURRENT_COMP** gives the name of the current component as a string.

- **POS_A_CURRENT_COMP** gives the absolute position of the current component. A component of the vector is referred to as POS_A_CURRENT_COMP.i where i is x, y or z.

- **ROT_A_CURRENT_COMP** and **ROT_R_CURRENT_COMP** give the orientation of the current component as rotation matrices (absolute orientation and the orientation relative to the previous component, respectively). A component of a rotation matrix is referred to as ROT_A_CURRENT_COMP[m][n], where m and n are 0, 1, or 2 standing for x, y and z coordinates respectively.

- **POS_A_COMP**(*comp*) gives the absolute position of the component with the name *comp*. Note that *comp* is not given as a string. A component of the vector is referred to as POS_A_COMP(*comp*).i where i is x, y or z.

- **ROT_A_COMP**(*comp*) and **ROT_R_COMP**(*comp*) give the orientation of the component *comp* as rotation matrices (absolute orientation and the orientation relative to its previous component, respectively). Note that *comp* is not given as a string. A component of a rotation matrice is referred to as ROT_A_COMP(*comp*)[m][n], where m and n are 0, 1, or 2.

- **INDEX_CURRENT_COMP** is the number (index) of the current component (starting from 1).
- **POS_A_COMP_INDEX**(*index*) is the absolute position of component *index*. POS_A_COMP_INDEX (INDEX_CURRENT_COMP) is the same as POS_A_CURRENT_COMP. You may use POS_A_COMP_INDEX (INDEX_CURRENT_COMP+1) to make, for instance, your component access the position of the next component (this is usefull for automatic targeting). A component of the vector is referred to as POS_A_COMP_INDEX(*index*).*i* where *i* is x, y or z.
- **POS_R_COMP_INDEX** works the same as above, but with relative coordinates.
- **STORE_XRAY**($index, x, y, z, kx, ky, kz, phi, t, Ex, Ey, Ez, p$) stores the current x-ray state in the trace-history table, in local coordinate system. *index* is usually INDEX_CURRENT_COMP. This is automatically done when entering each component of an instrument.
- **RESTORE_XRAY**($index, x, y, z, kx, ky, kz, phi, t, Ex, Ey, Ez, p$) restores the x-ray state to the one at the input of the component *index*. To ignore a component effect, use RESTORE_XRAY (INDEX_CURRENT_COMP, $x, y, z, kx, ky, kz, phi, Ex, Ey, Ez, p$) at the end of its TRACE section, or in its EXTEND section. These x-ray states are in the local component coordinate systems.
- **SCATTERED** is a variable set to 0 when entering a component, which is incremented each time a SCATTER event occurs. This may be used in the `EXTEND` sections to determine whether the component interacted with the current x-ray.
- **extend_list**(n, &*arr*, &*len*, *elemsize*). Given an array *arr* with *len* elements each of size *elemsize*, make sure that the array is big enough to hold at least n elements, by extending *arr* and *len* if necessary. Typically used when reading a list of numbers from a data file when the length of the file is not known in advance.
- **mcset_ncount**(n). Sets the number of x-ray histories to simulate to n.
- **mcget_ncount**(). Returns the number of x-ray histories to simulate (usually set by option `-n`).
- **mcget_run_num**(). Returns the number of x-ray histories that have been simulated until now.

B.1.3. Coordinate transformations

- **coords_set**(x, y, z) returns a Coord structure (like POS_A_CURRENT_COMP) with x, y and z members.
- **coords_get**(P, &x, &y, &z) copies the x, y and z members of the Coord structure P into x, y, z variables.

- **coords_add**(a, b), **coords_sub**(a, b), **coords_neg**(a) enable to operate on coordinates, and return the resulting Coord structure.
- **rot_set_rotation**(*Rotation t*, ϕ_x, ϕ_y, ϕ_z) Get transformation matrix for rotation first ϕ_x around x axis, then ϕ_y around y, and last ϕ_z around z. t should be a 'Rotation' ([3][3] 'double' matrix).
- **rot_mul***(Rotation t1, Rotation t2, Rotation t3)* performs $t3 = t1.t2$.
- **rot_copy***(Rotation dest, Rotation src)* performs $dest = src$ for Rotation arrays.
- **rot_transpose***(Rotation src, Rotation dest)* performs $dest = src^t$.
- **rot_apply***(Rotation t, Coords a)* returns a Coord structure which is $t.a$

B.1.4. Mathematical routines

- **NORM**(x, y, z). Normalizes the vector (x, y, z) to have length 1.
- **scalar_prod**$(a_x, a_y, a_z, b_x, b_y, b_z)$. Returns the scalar product of the two vectors (a_x, a_y, a_z) and (b_x, b_y, b_z).
- **vec_prod**(&a_x,&a_y,&a_z, b_x,b_y,b_z, c_x,c_y,c_z). Sets (a_x, a_y, a_z) equal to the vector product $(b_x, b_y, b_z) \times (c_x, c_y, c_z)$.
- **rotate**(&x,&y,&z,v_x,v_y,v_z,φ,a_x,a_y,a_z). Set (x, y, z) to the result of rotating the vector (v_x, v_y, v_z) the angle φ (in radians) around the vector (a_x, a_y, a_z).
- **normal_vec**(n_x, n_y, n_z, x, y, z). Computes a unit vector (n_x, n_y, n_z) normal to the vector (x, y, z).*
- **solve_2nd_order**(*t_0,*t_1, A, B, C). Solves the 2nd order equation $At^2+Bt+C = 0$ and puts the solutions in *t_0 and *t_1. The smallest positive solution into pointer *t_0. If t_1=`NULL` it is ignored and the second solution is discarded.

B.1.5. Output from detectors

Details about using these functions are given in the McXtrace User Manual.

- **DETECTOR_OUT_0D**(...). Used to output the results from a single detector. The name of the detector is output together with the simulated intensity and estimated statistical error. The output is produced in a format that can be read by McXtrace front-end programs.
- **DETECTOR_OUT_1D**(...). Used to output the results from a one-dimensional detector. Integrated intensities error etc. is also reported as for DETECTOR_OUT_0D.
- **DETECTOR_OUT_2D**(.....). Used to output the results from a two-dimentional detector. Integrated intensities error etc. is also reported as for DETECTOR_OUT_0D.

- **mcinfo_simulation***(FILE *f, mcformat, char *pre, char *name)* is used to append the simulation parameters into file f (see for instance **Res_monitor**). Internal variable $mcformat$ should be used as specified. Please contact the authors for further information.

B.1.6. Ray-geometry intersections

- **inside_rectangle**(x, y, xw, yh). Return 1 if $-xw/2 \leq x \leq xw/2$ AND $-yh/2 \leq y \leq yh/2$. Else return 0.

- **box_intersect**(&l_1, &l_2, x, y, z, k_x, k_y, k_z, d_x, d_y, d_z). Calculates the (0, 1, or 2) intersections between the x-ray path and a box of dimensions d_x, d_y, and d_z, centered at the origin for a x-ray with the parameters (x, y, z, k_x, k_y, k_z). The intersection lengths are returned in the variables l_1 and l_2, with $l_1 < l_2$. In the case of less than two intersections, t_1 (and possibly t_2) are set to zero. The function returns true if the x-ray intersects the box, false otherwise.

- **cylinder_intersect**(&l_1, &l_2, x, y, z, k_x, k_y, k_z, r, h). Similar to **box_intersect**, but using a cylinder of height h and radius r, centered at the origin.

- **sphere_intersect**(&l_1, &l_2, x, y, z, k_x, k_y, k_z, r). Similar to **box_intersect**, but using a sphere of radius r.

- **ellipsoid_intersect**(&l_1, &l_2, x, y, z, k_x, k_y, k_z, a,b,c,Q,). Similar to **box_intersect**, but using an ellipsoid with half-axis a,b,c oriented by the rotation matrix Q. If $Q = I$, a is along the x-axis, b along y and c along z

B.1.7. Random numbers

By default McXtrace uses a 64-bit KISS ("Keep It Simple Stupid") algorithm for generating pseudo random numbers, which runs on both CPU and GPU/OpenACC. The classic Mersenne Twister[MN98] algorithm remains available as a CPU-only, build-time alternative (see the User Manual's appendix on random numbers).

- **rand01**(). Returns a random number distributed uniformly between 0 and 1.

- **randnorm**(). Returns a random number from a normal distribution centered around 0 and with $\sigma = 1$. The algorithm used to sample the normal distribution is explained in Ref. [Pre+86, ch.7].

- **randpm1**(). Returns a random number distributed uniformly between -1 and 1.

- **randtriangle**(). Returns a random number from a triangular distribution between -1 and 1.

- **randvec_target_circle**(&v_x, &v_y, &v_z, &$d\Omega$, aim_x, aim_y, aim_z, r_f). Generates a random vector (v_x, v_y, v_z), of the same length as (aim_x, aim_y, aim_z), which is targeted at a *disk* centered at (aim_x, aim_y, aim_z) with radius r_f (in meters),

and perpendicular to the *aim* vector.. All directions that intersect the circle are chosen with equal probability. The solid angle of the circle as seen from the position of the x-ray is returned in $d\Omega$. This routine was previously called **randvec_target_sphere** (which still works).

- **randvec_target_rect_angular**(&v_x, &v_y, &v_z, &$d\Omega$, aim$_x$, aim$_y$, aim$_z$,h, w, Rot) does the same as randvec_target_circle but targetting at a rectangle with angular dimensions h and w (in **radians**, not in degrees as other angles). The rotation matrix *Rot* is the coordinate system orientation in the absolute frame, usually ROT_A_CURRENT_COMP.

- **randvec_target_rect**(&v_x, &v_y, &v_z, &$d\Omega$, aim$_x$, aim$_y$, aim$_z$,$height, width, Rot$) is the same as randvec_target_rect_angular but *height* and *width* dimensions are given in meters. This function is useful to e.g. target at a guide entry window or analyzer blade.

B.2. Reading a data file into a vector/matrix (Table input, `read_table-lib`)

The `read_table-lib` library provides functionalities for reading text (and binary) data files. To use this library, add a `%include "read_table-lib"` in your component definition DECLARE or SHARE section. Tables are structures of type `t_Table` (see `read_table-lib.h` file for details):

```
1    /* t_Table structure (most important members) */
2    double *data;      /* Use Table_Index(Table, i j) to extract [i,j]
         element */
3    long    rows;      /* number of rows */
4    long    columns;   /* number of columns */
5    char   *header;    /* the header with comments */
6    char   *filename;  /* file name or title */
7    double  min_x;     /* minimum value of 1st column/vector */
8    double  max_x;     /* maximum value of 1st column/vector */
```

Available functions to read *a single* vector/matrix are:

- **Table_Init**(&*Table*, *rows*, *columns*) returns an allocated Table structure. Use $rows = columns = 0$ not to allocate memory and return an empty table. Calls to Table_Init are *optional*, since initialization is being performed by other functions already.

- **Table_Read**(&*Table*, $filename$, *block*) reads numerical block number *block* (0 to catenate all) data from *text* file $filename$ into *Table*, which is as well initialized in the process. The block number changes when the numerical data changes its size, or a comment is encoutered (lines starting by '`# ; % /`'). If the data could not be read, then *Table.data* is NULL and $Table.rows = 0$. You may then try to read it using Table_Read_Offset_Binary. Return value is the number of elements read.

- **Table_Read_Offset**(&*Table*, *filename*, *block*, &*offset*, n_{rows}) does the same as Table_Read except that it starts at offset *offset* (0 means begining of file) and reads n_{rows} lines (0 for all). The *offset* is returned as the final offset reached after reading the n_{rows} lines.
- **Table_Read_Offset_Binary**(&*Table*, *filename*, *type*, *block*, &*offset*, n_{rows}, $n_{columns}$) does the same as Table_Read_Offset, but also specifies the *type* of the file (may be "float" or "double"), the number n_{rows} of rows to read, each of them having $n_{columns}$ elements. No text header should be present in the file.
- **Table_Rebin**(&*Table*) rebins all *Table* rows with increasing, evenly spaced first column (index 0), e.g. before using Table_Value. Linear interpolation is performed for all other columns. The number of bins for the rebinned table is determined from the smallest first column step.
- **Table_Info**(*Table*) print information about the table *Table*.
- **Table_Index**(*Table*, m, n) reads the *Table*[m][n] element.
- **Table_Value**(*Table*, x, n) looks for the closest x value in the first column (index 0), and extracts in this row the n-th element (starting from 0). The first column is thus the 'x' axis for the data.
- **Table_Free**(&*Table*) free allocated memory blocks.
- **Table_Value2d**(*Table*, X, Y) Uses 2D linear interpolation on a Table, from (X,Y) coordinates and returns the corresponding value.

Available functions to read *an array* of vectors/matrices in a *text* file are:

- **Table_Read_Array**(*File*, &n) read and split *file* into as many blocks as necessary and return a `t_Table` array. Each block contains a single vector/matrix. This only works for text files. The number of blocks is put into n.
- **Table_Free_Array**(&*Table*) free the *Table* array.
- **Table_Info_Array**(&*Table*) display information about all data blocks.

The format of text files is free. Lines starting by '`# ; % /`' characters are considered to be comments, and stored in *Table.header*. Data blocks are vectors and matrices. Block numbers are counted starting from 1, and changing when a comment is found, or the column number changes. For instance, the file 'MCXTRACE/data/Rh.txt' (Material data for Rhodium) looks like:

```
1 #Rh (Z  45)
2 #Atomic weight: A[r]  102.9055
3 #Nominal density: rho 1.2390E+01
4 #    14 edges. Edge energies (keV): K 23.22, L-I 3.41, ...
5 #-----------------------------------------------------------
6 #Form Factors, Attenuation and Scattering Cross-sections
```

```
#Z=45, E = 0.001 - 433 keV
#
#      E(keV)      f[1]        f[2]      [mu/rho]
 1.069000E-02   1.894E+00   4.805E+00   1.838E+05
 1.142761E-02   2.096E+00   5.102E+00   1.826E+05
 1.221612E-02   2.327E+00   5.401E+00   1.808E+05
 1.305903E-02   2.585E+00   5.699E+00   1.784E+05
 1.396010E-02   2.872E+00   5.993E+00   1.755E+05
   ...
```

Binary files should be of type "float" (i.e. REAL*32) and "double" (i.e. REAL*64), and should *not* contain text header lines. These files are platform dependent (little or big endian).

The *filename* is first searched into the current directory (and all user additional locations specified using the `-I` option, see the 'Running McXtrace ' chapter in the User Manual), and if not found, in the `data` sub-directory of the `MCXTRACE` library location. This way, you do not need to have local copies of the McXtrace Library Data files (see table 8.1).

A usage example for this library part may be:

```
t_Table Table;        // declare a t_Table structure
char file[]="Rh.txt"; // a file name
double x,y;

Table_Read(&Table, file, 1); // initialize and read the first numerical
    block
Table_Info(Table);           // display table informations
...
x = Table_Index(Table, 2,5); // read the 3rd row, 6th column element
                             // of the table. Indexes start at zero in C
                                .
y = Table_Value(Table, 1.45,1); // look for value 1.45 in 1st column (x
    axis)
                             // and extract 2nd column value of that row
Table_Free(&Table);          // free allocated memory for table
```

Additionally, if the block number (3rd) argument of **Table_Read** is 0, all blocks will be catenated. The **Table_Value** function assumes that the 'x' axis is the first column (index 0). Other functions are used the same way with a few additional parameters, e.g. specifying an offset for reading files, or reading binary data.

This other example for text files shows how to read many data blocks:

```
t_Table *Table;       // declare a t_Table structure array
long     n;
double y;

Table = Table_Read_Array("file.dat", &n); // initialize and read the all
    numerical block
n = Table_Info_Array(Table);      // display informations for all blocks (
    also returns n)

```

```
8  y = Table_Index(Table[0], 2,5);   // read in 1st block the 3rd row, 6th
       column element
9                                    // ONLY use Table[i] with i < n !
10 Table_Free_Array(Table);          // free allocated memory for Table
```

You may look into, for instance, the source files for **Lens_parab** or **Filter** for other implementation examples.

B.3. Constants for unit conversion etc.

The following predefined constants are useful for conversion between units

Name	Value	Conversion from	Conversion to
DEG2RAD	$2\pi/360$	Degrees	Radians
RAD2DEG	$360/(2\pi)$	Radians	Degrees
MIN2RAD	$2\pi/(360 \cdot 60)$	Minutes of arc	Radians
RAD2MIN	$(360 \cdot 60)/(2\pi)$	Radians	Minutes of arc
FWHM2RMS	$1/\sqrt{8\log(2)}$	Full width half maximum	Root mean square (standard deviation)
RMS2FWHM	$\sqrt{8\log(2)}$	Root mean square (standard deviation)	Full width half maximum
PI	3.14159265...	π	
CELE	1.602176487e-19	Elementary charge (C)	
M_C	299792458	Speed of light in vacuum (m/s)	
MELECTRON	9.10938291e-31	Electron mass (kg)	
ALPHA	7.2973525698e-3	Fine structure constant, α	
RE	2.8179402894e-5	Thomson scattering length (AA)	
E2K	0.506773091264796	Energy (keV)	Wavenumber (1/AA)
K2E	1.97326972808327	Wavenumber (1/AA)	Energy (keV)

C. The McXtrace terminology

This is a short explanation of phrases and terms which have a specific meaning within McXtrace. We have tried to keep the list as short as possible running the calculated risk that the reader may occasionally miss an explanation. In this case, you are more than welcome to contact the McXtrace core team.

- **Arm** A generic McXtrace component which defines a frame of reference for other components.
- **Component** One unit (*e.g.* optical element) in an x-ray beamline. These are considered as Types of elements to be instantiated in an Instrument description.
- **Component Instance** A named Component (of a given Type) inserted in an Instrument description.
- **Definition parameter** An input parameter for a component. For example the radius of a sample component or the divergence of a collimator. Technically, a definition parameter is translated into a literal constant, which prevents it from being edited at runtime.
- **Input parameter** For a component, either a definition parameter or a setting parameter. These parameters are supplied by the user to define the characteristics of the particular instance of the component definition. For an instrument, a parameter that can be changed at simulation run-time.
- **Instrument** An assembly of McXtrace components defining an x-ray beamline.
- **Kernel** The McXtrace language definition and the associated compiler
- **Output parameter** An output parameter for a component. For example the counts in a monitor. An output parameter may be accessed from the instrument in which the component is used using `MC_GETPAR`.
- **Run-time** C code, contained in the files `mcxtrace-r.c` and `mcxtrace-r.h` included in the McXtrace distribution, that declare functions and variables used by the generated simulations.
- **Setting parameter** Similar to a definition parameter, but with the restriction that the type of the parameter must be declared unless it is a number. In technical terms, a setting parameter is translated into an actual variable (as opposed to a definition parameter) which may be dynamically updated.

Bibliography

[Mcx] See http://www.mcxtrace.org (cit. on pp. 7, 8, 12, 23, 24, 28, 63, 74, 86).

[Mcz] See http://trac.mccode.org/report (cit. on p. 7).

[Mcc] See http://trac.mccode.org (cit. on p. 13).

[Sha] See http://www.esrf.eu/computing/scientific/raytracing/ (cit. on p. 17).

[Mcs] McStasScript documentation, see `https://panosc-vinyl.github.io/McStasScript/` (cit. on pp. 26, 47).

[Ifi] See `http://ifit.neutroncode.org` (cit. on p. 36).

[Sci] See `https://docs.scipy.org/doc/scipy/reference/generated/scipy.optimize.minimize.html` (cit. on p. 36).

[Wik] See `https://github.com/mccode-dev/McCode/wiki` (cit. on p. 52).

[Nex] See http://www.neutron.anl.gov/nexus/ (cit. on pp. 55, 64).

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