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UAL User Guide

Nikolay Malitsky and Richard Talman (BNL)

December 20, 2002

BROOKHAVEN
NATIONAL LABORATORY

Collider Accelerator Development Department
Spallation Neutron Project

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UAL User Guide

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The Unified Accelerator Libraries (UAL) provide a modularized environment for applying diverse accelerator simulation codes. Development of UAL is strongly prejudiced toward importing existing codes rather than developing new ones. This guide provides instructions for using this environment. This includes instructions for acquiring and building the codes, then for launching and interpreting some of the examples included with the distribution. In some cases the examples are general enough to be applied to different accelerators by mimicking input files and input parameters. The intention is to provide just enough computer language discussion (C++ and Perl) to support the use and understanding of the examples and to help the reader gain a general understanding of the overall architecture. Otherwise the manual is "documentation by example." Except for an appendix concerning maps, discussion of physics is limited to comments accompanying the numerous code examples. Importation of codes into UAL is an ongoing enterprise and when a code is said to have been imported it does not necessarily mean that all features are supported. Other than this, the original documentation remains applicable (and is not duplicated here.)

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Chapter 1. Introduction

This is supposed to be something of a "quick start" manual. The reader looking for a *quickest possible* start should skip to Chapter 3, Code Checkout and Environment Variables, and from there to Chapter 6, Annotated Examples.

If "pure physics" is the analysis of physical systems made possible by their idealization, then the pure physics of accelerators reduces to a rather small package. Circular accelerators *basically work*, with properties matching the expectations of Lawrence, Kerst-Serber, McMillen-Veksler, Courant-Snyder, and a few others. The rest of accelerator physics amounts to understanding why accelerators *don't work very well,* or rather, to efforts to make them work better. The problem is that the actual performance of an accelerator depends on features that violate the idealization mentioned previously. At the risk of exaggerating the point, one might therefore say that the bulk of accelerator physics is an antithesis of pure physics, in that it amounts to analyzing non-ideal systems. Hamiltonian requirements are easily met only in a linearized approximation that becomes progressively less valid as accelerators become larger. This has called for modest extensions of the theoretical foundations, but far more essential difficulty comes from the vastly increased number of influential degrees of freedom that enter as *deviation* from the ideal needs to be described. This is nowhere more true than in accelerator physics, where thousands of pieces of uncorrelated data are needed to describe a large accelerator. Since the handling of complicated data is more nearly the subject of computer science than of physics, it seems sensible to take advantage of advances that have been made in computer science. This requires a certain amount of reorientation for those physicists who think of themselves as having invented computer science.

Of the many contributors, some to TEAPOT, some to UAL, the following deserve special mention: Chris Iselin (for establishing a standard to be emulated), Maury Tigner (for suggesting the task), Lindsay Schachinger (for establishing the pattern and getting the project off the ground), Alexander Reshatov (for contribution to the UAL conceptual design), and George Bourianoff and Jie Wei (for enthusiastic support).

1.1. General description of UAL

The Unified Accelerator Libraries (UAL)[1–2] attempt to “manage the complexity” of accelerators by providing an environment[3] for simulating a variety of properties of a variety of accelerators using a variety of simulation codes and methods. The intended value of the environment is to provide homogeneous access to these resources while masking their diversity yet assuring their consistency. This allows different methods to be consistently applied to the same accelerator and the same methods to be applied to different accelerators. Another potential benefit is the feasability and economy of “infrastructure” (shared resources) such as postprocessors, plotting/histogramming/fitting, input and output translation, and parallel processing.

At this time, the object-oriented programs included in UAL are: PAC (Platform for Accelerator Codes), ZLIB (Numerical Library for Differential Algebra), TEAPOT (Thin Element Program for Optics and Tracking), ACCSIM (Accumulator Simulation Code), ORBIT (Objective Ring Beam Injection and Tracking Code). Modules that are partially supported and are under active development are ICE (Incoherent and Coherent Effects), AIM (Accelerator Instumentation Module), SPINK (tracks polarized particles in circular accelerator), and TIBETAN (longitudinal phase space tracking). The Application Programming Interface (API), written in Perl, provides a universal shell for integrating and managing all project extensions.

Three UAL manuals are planned of which this is the first:

- User Guide. A manual containing the bare minimum of information needed to acquire and build the code and to run the examples. In many cases the example codes should be close enough to a problem of interest to enable the user to perform other simulations by mimicking external inputs and Perl scripts.
- Physics Manual. This manual will describe and explain the physical methods used in the various modules, in many cases giving annotated reference to external manuals and documentation. This manual will also provide sufficient reference to the Developer’s Manual and online documentation to support “looking under the hood” to enable the user to perform code modifications and additions.

- Developer's Manual. This manual supplies full technical documentation. It consists largely of online documentation, much of which is available at `http://www.ual.bnl.gov`.

The primary programming languages of UAL are C++, which provides fast, secure, basic calculations and Perl, which provides a flexible user interface. Both are object oriented.

In this manual `typewriter font` is used to exhibit text that would be visible on a computer monitor, either because the text is being viewed by a text editor or because a program has generated it as output. *Italic font* is used when a term or program having a narrow technical sense is first introduced (often without even the pretense of immediate definition) or *for emphasis.* "Quotation marks" indicate either that a term is actually being defined or that it is being used loosely.

1.2. Modularity and object orientation

As has been stated already, the prime purpose of UAL is to "unify" diverse codes and procedures. Diverse codes are to form "modules" in an evolving, unified, coherent environment. Modularity is a challenging and universally-applauded attribute that all computer codes strive for, and some achieve, at least in individually-developed, single-purpose codes. Two such codes being applied to the same system would certainly be modular, relative to each other, but they would be *too* modular if their representations of the system were too different and too complicated. In this situation it is hard to assure that the systems represented in the two codes are, in fact, the same. This consideration makes the task of unifying multipurpose, multideveloper codes all the more challenging.

To facilitate such unification UAL has introduced an *open* architecture in which diverse accelerator codes are connected together via common accelerator objects such as *Element, Bunch, Twiss,* etc. In this architecture each accelerator code is implemented as an object-oriented library of C++ classes. There is a very natural identification of physical elements, such as magnets, with their representation by computer objects. UAL supports considerable flexibility in the attributes of all objects—certainly enough that all attributes of objects contained in modules included so far have been describable without constraint. Such flexibility has made it practical to evaluate, compare, and integrate a variety of design models and to build heterogeneous, project-specific applications. This experience has motivated the development of the *Element-Algorithm-Probe framework*[4] that will be a core part of the UAL release currently being completed. This framework is intended to provide a uniform mechanism for combining diverse modules to simulate complex combinations of physical effects and dynamic processes.[†]

One of the purposes of this manual is to make clear the way *object orientation* helps in such unification, and thereby justify its adoption by UAL. Object-oriented methodology affects code developers far more than it affects code users. It is not necessary for a user of UAL to endorse object-orientation or even to understand exactly what constitutes an object-oriented program. The single consideration that most distinguishes object-oriented code from procedural code is the priority assigned to, on the one hand, *data*, and, on the other hand, the *procedures* used to process data. (Procedures are always mathematics, broadly defined.) The procedural program lavishes great care on the procedures and treats data casually if not contemptuously—like a feudal lord managing his vassals. In object-oriented code the data is pre-eminent and demands orderly management—like a democratic people demanding to be governed by laws.

Since data is usually descriptive of the structure of stationary objects, and procedures change data, it can be said that procedures represent behavior, a subject inherently more complicated than structure. In this sense object-orientation should be expected to be simpler than procedural-orientation. A system built around objects rather than around functionality more closely corresponds to the humanly-comprehended world.

[†] The *Element-Algorithm-Probe framework* is not actually used in the Perl-based examples described in this manual. There is, however, a preliminary directory, `$UAL/examples/FastTeapot` (symbol `$UAL` is defined in Chapter 3) that contains code which applies the Element-Algorithm-Probe framework. The script `rhic.pl` in this directory applies standard, Perl-based, UAL analysis (as documented in this guide) to a RHIC lattice as it is defined by its SXF (Standard Exchange Format).This same lattice is used by the FastTeapot code contained in subdirectories of the same directory. The main incentive for speeding up the UAL simulation capability has been to improve its serviceability for online modeling. In order to be *fast* as well as *control-system-embeddable,* FastTeapot is written in C++. The C++ code is contained in the `$UAL/examples/FastTeapot/src` directory and the examples of its use for map generation and map-tracking are in `$UAL/examples/FastTeapot/linux`. Instructions for compiling the code and running the examples are given in a `README` file. Except for brief comments in section 6.7, FastTeapot is not otherwise documented in this guide, but understanding the material in this guide is something of a prerequisite to using FastTeapot.

Here is an example of *encapsulation*, which is one of the cornerstones of object-orientation. Consider the distinction between file names in Unix and in Windows. The filename of a Unix text file merely identifies the file, with no necessary implication whatsoever as to the intended use or treatment of the data it contains. In the "8+3" file name plus extension convention[†] of Windows the data is organized in such a way as to be accessible only by the collection of calculational procedures that is identified by the 3-character *extension* of the file name.

The term *encapsulation* is perhaps not as descriptive of this feature of object-orientation as the closely related term *data hiding*. The organization of data into *structure*'s in procedural languages like C or Fortran might deserve to be called "encapsulation" in the colloquial use of that term. But in those languages this does not imply any reduction in accessability. Data hiding intentionally restricts access to data.

There would be no point in hiding data if there were no mechanism for accessing the hidden data. So the term *encapsulation* also conveys the meaning that the calculational procedures needed to access the hidden data (they are always called *methods* in this context) are linked to the data as part of the same encapsulation. These methods will have been authenticated by the same developer whose job has been to organize the data. This helps to make the access to, and processing of, data contained in complicated data structures more reliable. Any spreadsheet user will agree that is is more reliable to use the spreadsheet's methods than it would be to search for and find, and then process, the data "hidden" in the spreadsheet file.

The distinction between object-orientation and procedural-orientation can be continued by comparing *structures* and *functions,* the procedural mechanisms supporting modularization, with *objects, classes,* and *methods,* the object-oriented mechanisms. As far as the data it contains and its having a name, an object is the same thing as a structure. But, by virtue of its belonging to a class, the *attributes* of an object are subject to manipulation (including creation and destruction) exclusively by the *methods* of its class. "Method" and "function" would be synonyms except that a method must "belong to" a class and a function need not. Both *attributes* and *methods* are referred to as *class members.*

[†] The "8+3" file name plus extension file naming of Windows, though an abomination for most purposes, has undoubtedly helped Microsoft's profits by billions of dollars.

Two other features that characterize object-oriention, *overloading* (also known as "polymorphism") and *inheritance*, will be mentioned below when their application within UAL is being explained.

Within UAL the object-orientation is "enforced" by C++ and, *a priori,* one might expect no other computer language to be required. But, by now, it is universally agreed that this approach is too inconvenient for users, and that it is necessary to produce a consistent interface using a "control" language. For UAL (at this time) this language is Perl. The interface is textual† (not graphical) and, line-by-line, its instructions may look to the user very much like the directives in a procedural code like MAD.[5] This makes it possible to "pay no attention to the man behind the curtain" and treat the input as an old-fashioned, procedural control file. The most important step in going beyond this level is to acquire an understanding of the *modularization* mechanism of the code, which is based on the *naming* of directories, classes, modules, and so on. This puts the greatest demands on Perl, as the interface, and on the user, trying to use and understand the code. This discussion continues below in Section 4.

Even apart from the diversity of codes supported, there is inherent difficulty in documenting a modularized *open* environment. Many or most of the users for whom the UAL environment is potentially of greatest value are probably most familiar with a *closed* code having strict input language, such as MAD. Such input languages capture relevant "use cases" (computer science jargon) of accelerator applications and organize them as a sequence of commands, starting from the lattice description, proceeding through "actions" (magnet field error distribution, tuning, etc.) and finally to results (lattice function determination, etc.) This use-case-organized interface matches the expectations of most

† Because the UAL command language is Perl, a graphical interface to Perl would serve as a graphical interface to UAL. Something approaching this is provided by a free utility called DDD which provides a graphical debugging interface to various languages, including Perl. DDD permits the user to proceed step-by-step through a Perl script, or to continue to the next user-inserted breakpoint. While the script is stopped variable values can be inspected, or even altered. Other typical debugging capabilities are also supported. This is an excellent facility for the user to gain familiarity with UAL's example scripts. At this time DDD is restricted to the Perl level as it is not mature enough to "step" down into the C++ extensions UAL employs, or even to exhibit values in the C++ domain. Failure to respect this causes DDD to crash, so one has to learn to avoid making such requests. Fortunately the cost of crashing is not high as the same state can be recovered quickly with a few button clicks. Crashes can sometimes be avoided by setting multiple breakpoints and *continuing* from breakpoint to breakpoint rather than *stepping* from instruction to instruction. Perhaps a more powerful displaying debugger will come available in the future.

users. Such “sequentially-organized” codes proceed from start to finish with minimal branching and it is natural for the documentation to be organized along the same lines. An *open* environment, on the other hand, is “module-organized”, allowing the user to pick and choose among various modules for building project-specific applications. If the modules are well-designed, with clean interfaces, they tend to be “self-documenting”, as the existence of modern “documentation engines” proves. UAL uses the utility *doxygen* for automatic generation of on-line documentation. The existence of this documentation helps to amortize the initial expenditure in code development for the code developer and in conceptual effort required of the code user. The clean interfaces make it practical for a user to make controlled *ad hoc* changes to localized blocks of code without the need to understand the rest of the code.

UAL strives to preserve the advantages of both use-case and module-oriented approaches, by encouraging a division of labor between code developer and code user. Working in an object-oriented “research environment” the goal of the developer is to supply a “use case” view of the code which, ideally, allows the code user to be most productive. The mechanism for accomplishing is known as a *Shell* (or *Façade*) layer. This layer hides the complexity of the numerous interfaces of the underlying UAL components and implements a list of MAD-like Perl commands that delegate user requests to appropriate modules.

Since this manual is intended primarily for the code user rather than for the code developer, technical code features are discussed only to a depth judged appropriate to provide the user with general orientation and critical appreciation of the fundamental issues.

This manual therefore consists mainly of “documentation by example”. It is supposed to supply a minimal set of intructions adequate to guide the user through meaningful calculations while treating UAL as a traditional accelerator code. The variety of examples is intended to carry the user part way along a path of acquiring confidence in the results without requiring detailed understanding of the mechanisms by which they have been obtained. To obtain fuller confidence the user is expected either to develop test examples or to delve more deeply into the code, guided by other manuals and documentation.

It would be a formidable task to study thoroughly the various programming tools, languages and systems on which UAL depends. References are given to literature that seem to us to be appropriately elementary and useful. The instructions in this manual are supposed to be mechanical enough that these references are inessential for first running of the examples, but they may be useful in advancing past the beginning stage.

Chapter 2.
The Architecture of UAL

The architecture of UAL has evolved gradually over more than a decade, starting as a special purpose, Fortran, symplectic tracking code and evolving into a home for diverse codes. The early evolution, and its motivation, is described briefly in Appendix A. The main goal was, and still is, to simulate the performance of accelerators. What has changed is the methodology used to achieve this end.

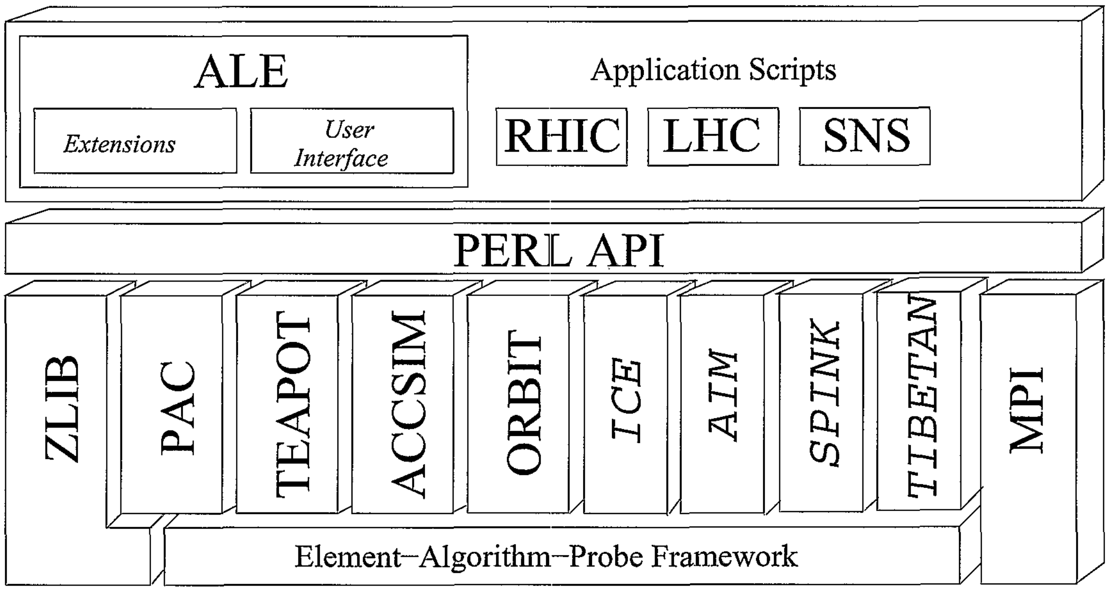


Figure 2.1: UAL architecture. The modules labeled with fainter type are only partially implemented at this time. The figure is a bit futuristic in that the interfaces are not yet quite as simple as the Element-Algorithm-Probe layer suggests.

The components of UAL and their relationships are illustrated pictorially in Fig. 2.1. The figure represents dependency metaphorically, by gravity; codes appearing higher up are supported by (that is use) objects and methods belonging to codes appearing lower down. The lowest tier consists of the Element-Algorithm-Probe framework, which uses *algorithms* to evolve *probes* (i.e. bunches, maps, Twiss functions, etc.) through accelerator *elements.* Along with ZLIB (Numerical Library for Differential Algebra) this supports PAC (Platform for Accelerator Codes) which defines *Accelerator Objects*, such as magnets, lattice, particles, bunch, etc. These components form the "model" part of a three part simulation environment containing elements that are common to all modules, and therefore support connections between different modules. They are the glue that holds UAL together.

The second major part of the simulation environment consists of the boxes, TEAPOT, ACCSIM, ..., TIBETAN, which stand for accelerator simulation modules, coded in C++. In most cases these modules derive from earlier, procedural, Fortran codes, which have been ported to C++. They constitute the "physics" supported at this time; things like tracking, analysis, optimization, correction algorithms, etc. They form the "actions" part of the organization. Each of these modules is a separate, self-contained library of C++ classes having its own internal organization and methods. For completeness the module MPI (Message-Passing Interface)[6] which supports parallel processing is also shown.

The separation mentioned so far, into accelerator objects, on the one hand, and actions, on the other, is very comparable to the similar separation in any procedural program deriving its input from a file such as MAD.†

The upper levels of Fig. 2.1 contain the "controller" part of the environment. The API (Application Program Interface), written in Perl, makes available to the user the capabilities of the various modules while "hiding" as much as possible of their complexity. Scripts appropriate to particular accelerators, RHIC, LHC, SNS, etc. are based on the user-friendly facade or interface ALE (Accelerator Library Extension). However, most of the examples documented in this guide use directly the more generic ALE shell that is not specific to any particular accelerator.

Much of the heterogeneity that UAL is intended to address concerns the diversity of lattice descriptions. The UAL mechanism for the accommodation of input sources is illustrated in Fig. 2.2.

Internal to UAL the lattice description is known as SMF (Standard Machine Format). SMF, the *sine qua non* of UAL, is a parameterization of a general accelerator and its components. It was designed to be very general, and furthermore it is extensible,

† Because "closed" codes have their own specializations, it is natural for them to have their own proprietary "embedded" parsers. There is then a tendency toward "Tower of Babel" divergence, especially concerning the actions part of the input language.

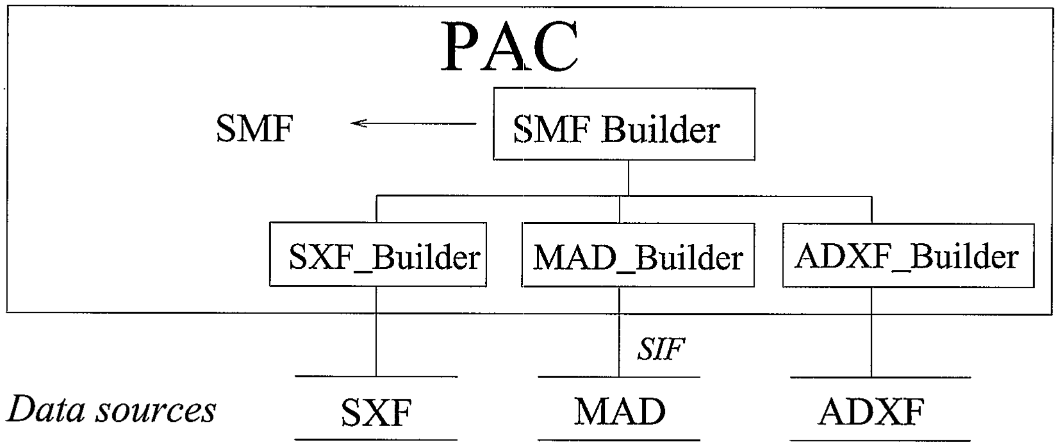


Figure 2.2: Treatment of input data by UAL. This figure can be regarded as an extension of Fig. 2.1, with the box labeled PAC being repeated here, and with the part of its internals used for input processing exhibited.

and completely *neutral* as regards physical methods of analysis. So it is possible to add attributes that happen to be needed for any particular module being added. But it is only feasible to simulate things that are recognizably "accelerators". At this time only "circular" accelerators have been modeled, but a way to incorporate linear accelerators has been worked out. More detail will be given below concerning many of the boxes in Fig. 2.1 and Fig. 2.2. Further details concerning SMF are given in appendix D.

Chapter 3. Code Checkout and Environment Variables

As part of the object orientation of the code the various modules are referenced by symbolic names. A helpful convention is that these names are consistently related to the names of the code-containing directories, but these directory names may themselves be expressed relative to symbolic environment variables. To use the UAL environment it is therefore *absolutely essential* for all environment variables to be set correctly. One way of helping to establish and preserve this state is to set up a dedicated account for a UAL user (called *ualusr* in this manual) who performs nothing but UAL calculations and who has established appropriate environment variables, most easily by using an appropriately-updated, code-managed, login script that is part of the distribution. This avoids the unwitting alteration of the environment by other programs or shells or initialization routines. In this manual we assume that *ualusr* is performing all the set-up, checking out of codes, and calculations. The UAL user chooses a base directory, for example ∼`ualusr`, into which the UAL simulation(s) is to be installed.

There is more than one way to obtain the UAL code, which is *code managed* by CVS[7](Concurrent Version System). It is most convenient, if required access is not denied by a firewall, to *checkout* the code from the central CVS repository. This check out method allows the user to keep track of code changes. This manual assumes that the code is being acquired this way. An alternate approach uses the web, following instructions given at `http://www.ual.bnl.gov.` The user acquiring the code from the web will have to replicate the next few instructions as appropriate, before rejoining the subsequent discussion. The following instructions perform an initial code checkout, assuming the Unix C-shell;[†]

```
      $ cd ~ualusr
      $ setenv CVSROOT :pserver:anonymous@sun1.sns.bnl.gov:/home/ual/cvsroot
      $ cvs login
   CVS password: <CR>
      $ cvs co ual1 >& checkout.log
```

[†] In this manual commands to be entered are always shown preceeded by the $ shell prompt; this prompt depends on the shell being used and is, of course, not to be typed in. The (required) line-ending carriage returns are not shown.

Here `anonymous@sun1.sns.bnl.gov:/home/ual/cvsroot` represents an anonymous remote login (followed by user-supplied carriage return as response to the request for CVS password) to the central CVS code repository applicable at this date—it may change—and `ual1` is the name of the particular version of the code being checked out. The steps performed in the CVS checkout are logged into `checkout.log`. The code is extracted to the subdirectory `ual1` and to its subdirectories, along with supporting files and documentation. This may take a few minutes.

Before continuing to compile and link the codes it is necessary to confirm that all required environment variables have been set correctly. Appropriate setup scripts and instructions are included in the code just checked out. An environment variable specifying the local architecture (preferably Linux) will be set by the appropriate set-up script.† On the local computer all directories contained in the UAL simulation being worked on (version *ual1* in this manual) will be referred to a single, absolute address, named UAL or, to be recognized by the shell, as $UAL. For Linux architecture, the commands

```
$ setenv UAL ~/ual1
$ source $UAL/setup-linux-ual
```

establishes the entire environment. At this time the environment variables (standing for directory names) are:

UAL_ZLIB	$UAL/codes/ZLIB
UAL_PAC	$UAL/codes/PAC
UAL_TEAPOT	$UAL/codes/TEAPOT
UAL_ORBIT	$UAL/codes/ORBIT
UAL_ACCSIM	$UAL/codes/ACCSIM
UAL_ICE	$UAL/codes/ICE
UAL_DA	$UAL/codes/DA
UAL_SPINK	$UAL/codes/SPINK
UAL_MPI_PERL	$UAL/tools/shortmpi
UAL_EXTRA	$UAL/ext
SXF	$UAL/tools/sxf
SXF_ARCH	$UAL_ARCH

The setup script (and scripts it invokes) may also contain, as comments, requirements as to codes that UAL assumes will be findable on the search path, and the least senior

† On SUN computers it is possible to have a pure *g++* installation of UAL using GNU software included under Solaris-9 (and, presumably, later releases) provided `/opt/sfw/bin` is on the search path. It is also necessary for *doxygen* to have been installed. For *doxygen*, which is a utility that produces documentation automatically, installation should use `$ ./configure --platform solaris-g++`. Under Solaris the setup script (included in the release) is *setup-solaris9-ual.* It defines the starting LD_LIBRARY_PATH to be `/opt/sfw/lib`.

version number that has been tested to be satisfactory. (An up-to-date Linux release, such as Red Hat 7.3 or later, has essentially all required code.) Detailed specification of required codes are given at `http://www.ual.bnl.gov/v1/download.htm`, along with brief installation instructions. In a few cases public domain code may be included with the UAL code checkout and build.

Finally the code is compiled with output from `make` stored in `make.log`:

```
    $ cd $UAL
    $ make clean
    $ make >& make.log
```

The `make` will take several minutes. To confirm its validity you can perform a case-insensitive search for the (absence of) string " error " in `make.log`. If the `make` succeeds, you may wish to gain some insight into the directory structure and build process by browsing this log file or, if the `make` fails, you can use the file to make a stab at diagnosis. A practical diagnostic procedure, for example to view temporary files that are removed in the full `make`, is to mimic the actual `make` by first changing directory by cutting and pasting to the directory shown in any line beginning `make[n]: Entering directory '...'` (where `n` is a small integer) and then cutting and pasting the subsequent compiler instructions one-by-one.

Though long, the `make` output is less complicated than might first appear. The subdirectories of the top directory ($UAL) are `env`,"environment", `ext`, "extensions", `codes`, "codes", `examples`, "examples", and `doc`, "documentation". The `Makefile` in $UAL steps down sequentially into each of these subdirectories and, if there is a `Makefile`, performs a `make`. Every `Makefile` encountered recursively steps down through every subdirectory encountered at its own level. In this way all the code in the entire directory tree is processed recursively. Since all `Makefiles` assume default rules, they are all quite similar. Each `Makefile` has a companion file (or rather one for each computer architecture) called `Makefile.config` that contains data specific to its system's compiler. For example, the `codes` subdirectory contains among its subdirectories `ACCSIM`, `PAC`, `SPINK`, `TEAPOT`, `UAL`, and `ZLIB`, one for each of the simulation-capable modules currently installed in UAL.[†] The Makefile.config file specific to ACCSIM (running under Linux architecture) is $UAL_ACCSIM/config/linux/Makefile.config. Other configuration file names are constructed by making obvious transcriptions in this pathname. The Makefile.config file accesses its own pathname using its matching environment variable.

The general purposes for the codes in the various directories can largely by guessed from the directory names (which match the corresponding environmental variables given above.) Details will emerge in the sequel. The user wishing to browse a file referred to in a script can locate the file by using these environment variables. For example, note how the full pathname of the configuration file mentioned in the previous paragraph follows from $UAL_ACCSIM. Paths to C++ and Perl code specific to ACCSIM are derived similarly.

UAL also supports multiprocessor applications. Logically the instructions for installation of the environment supporting these applications would be contained in a continuation of this section. But, because most users will use this environment only later, if at all, these instructions are deferred until Chapter 7.

[†] The relationships among modules ACCSIM, PAC, SPINK, TEAPOT, UAL, and ZLIB is actually a bit more complicated than is suggested by this sentence.

Chapter 4.
Perl as Interface Language

A user starting to use a specific accelerator simulation code probably expects to begin by studying its proprietary input language, in order to learn how to use the language to define the lattice and to specify the desired calculations. UAL handles lattice description similarly, in the form of conventional ASCII files, either MAD (the lattice description part only)† or SXF or ADXF. But there is no proprietary UAL command language. Instead, the simulation to be performed is specified by the statements of a Perl script. Standard references are Schwartz[8] and Wall et al.,[9] the latter of which is the definitive Perl reference which, however, makes it fairly dense reading. For exploiting the "object oriented" aspects Conway,[10] is appropriate. The best reference dedicated to interfacing Perl with compiled languages, especially C and C++ is by Jenness and Cozens.[11] The `man` pages `perlxs`, `perlxstut`, and `xsubpp` are useful for the same purpose, as is Srinivasan.[12]

Detailed documentation can be obtained by using `$ man perl` which mainly provides a list of all the Perl `man` files. After identifying `perlvar` as the most promising source of information concerning Perl variables, one uses `$ man perlvar`.

Fortunately, it is unnecessary for the beginning user (or the advanced user either) to understand how Perl performs its control function. But the apparent effect of this control is that everything "appears to be Perl" even if the code being executed is some other language. For this reason the UAL user *has to* become at least somewhat conversant with Perl. Though this may cause some initial difficulty, it should soon have become comforting to be working with a highly-supported modern computer language rather than with a homemade, perhaps ambiguous, special-purpose input language. This power is perhaps most impressive when it comes to controlling multiprocessor applications using MPI.

† Because the MAD input languages includes both lattice description and calculation directives it is useful to have a term that describes just the lattice description part. For this purpose we will use the term SIF (Standard Input Format) in spite of the fact that the MAD format has evolved substantially from its correspondance with the original SIF specification.[31] So, in this manual the term SIF is to be interpreted as the lattice description part of MAD, version 8.

4.1. Elementary Perl

This section contains a short description of the Perl language. It is too brief even to be called a "tutorial" but is intended to at least mention every language ingredient appearing in the examples appearing in subsequent sections. In the interest of making the UAL/Perl interface as "clean" as possible, only a restricted set of valid Perl syntax is actually used by UAL. In some cases usage that is deprecated (or at least not used) by UAL even though used in other Perl sources. When this situation arises this guide shows the (UAL)-preferred usage in the body of the text and includes alternative usage or clarification in a footnote.

Perl is a "scripting language" that can be used either as a standalone procedural programming language (such as C or Fortran) or as an object oriented languages (such as C++). Its syntax is much like C, but with features drawn from other languages, especially AWK. By practicing with Perl to perform simple Fortran-like calculations, the reader can acquire a useful introduction to the language (and then the courage to later insert minor postprocessing manipulations into the example scripts).

4.1.1. Variables and statements

Perl statements terminate with semi-colons ; and a single line is allowed to have more than one statement. Comments begin with # and continue to the end of the line.

The most visually striking notational aspect of Perl is that (single value) variable names begin with $ signs, as in `$variablename`. (So a C program with $ signs inserted in front of every variable name has a chance of being a valid Perl program.) Such a variable, called a *scalar* in Perl jargon, can stand for a real number or for a string or for a reference to something else, without the need for declaration as to which is intended. Some examples:

```
$aScalar=42; # an integer
$aScalar=3.14; # a real number
$aScalar="perl"; # a string
```

Perl implicitly interprets and converts $aScalar as it considers appropriate. Two multiple data types are also supported: *arrays* and *hashes*, both one-dimensional.

Array. An *array* variable is a list of scalars that have been grouped together so they can be manipulated as a single Perl variable. Array names are prefixed with the @ symbol, and an array is *defined*, that is, entered literally, by a comma-separated list[†] [‡] as in

```
@languages=("perl", "fortran", "c++");
```

These scalars will commonly be homogeneous (as in this example) but they need not be. For example some entries may point to other things—that is the way more complicated structures, such as two dimensional arrays, can be established. Array elements are *indexed* by their sequential order (starting with 0, as in C). A particular value from the array is denoted by using its index enclosed in square brackets; so[¶]

```
my $first_language=$languages[0];  # assigns "perl" to $first_language
$languages[0]="perl 6";           # replaces "perl" by "perl 6"
```

For understanding the UAL architecture it is useful to compare the support for one dimensional, sequential data types in Perl, C++, and Fortran. This is done in Table 4.1.1. In C++ there are three one dimensional types: (fixed length) array, (variable length) standard vector template and list. With sequential elements, random access can be a very fast operation. Some types are "dynamic" (meaning the number of elements can change) as examples in the table show. In Perl there is only one *array* type but, even so, all of the C++ manipulations (and then some) are supported. But this comes at the cost of slower access, because the structure is implemented by doubly-linked list. This (along with the compiler/interpreter issue) is the sort of speed/convenience compromise that drives the use of C++ for compute bound computation and Perl for interface implementation.

Hashes (also known as associative arrays, or dictionaries, or two-column tables) have names beginning with % as in %hashname. Like lists, hashes contain multiple scalars, but these scalars are referenced not by sequential integers but by symbolic *keys* (which are

[†] Perl documentation distinguishes between the term *array* and the term *list* even though both consist of sequences of scalars. This distinction should probably be ignored. The literal representation of a list may include an array or hash but, if so, the elements of the array are simply "flattened" (broken out and strung together, comma-separated) into the enclosing list—the original grouping is forgotten.

[‡] In Perl documentation the phrase *list context*, is distinguished from the other possibility, namely *scalar context*. Here "context" means the type of the variable a function is expected to return. This is a kind of overloading in which a function &func can return either a scalar or list depending on context. For example $x = &func expects a scalar and @x = &func expects a list. This distinction should probably be ignored during casual browsing of code examples, but it may have to be understood when writing new code.

[¶] The scope-defining word my will be explained shortly.

	Perl	Fortran	C++

Declaration	my @anArray;	Integer,dimension(4)::anArray	int anArray[4];
			vector⟨int⟩ aVector(4);
			list⟨int⟩ aList(4);

Initialization	my @anArray=(2,3,4);	DATA anArray/2,3,4/	int @anArray[]=2,3,4;

Direct access	$i1=$anArray[2];	i1 = anArray(3)	i1 = anArray[2];
			i1 = aVector[2];

Array as stack	push @anArray,(5,6);		aList.push_back(5);
			aList.push_back(6);

Deletion from list	splice @anArray,2,3;
	# offset is 2
	# 3 elements removed
			aList.erase(aList.begin()
			+2, aList.begin()+5);

Insertion into list	splice @anArray,2,0,(9);
	# offset is 2
	# inserted list is (9)
			aList.insert(aList.begin()
			+2,9);

Table 4.1.1: Array methods supported by Perl and C++ used in UAL, plus the three matching Fortran entries.

strings serving as names for the entries.) Hashes are therefore lists of *key/value* pairs. Because of this lookup mechanism the elements of a hash are unordered (and correspondingly slow to access.) The hash definition syntax customarily used by UAL is†

```
%perl_language = ("version" => 5.6,
                  "applications" => 1003,
                  "web site" => "http://www.perl.com")
```

Here "version", "applications", and "web site", are keys to the heterogeneous values 5.6, 1003, and "http://www.perl.com".

Selection of the particular entry of hash `%hashname` whose key is `¨keyname¨` is expressed using curly brackets, as in `$hashname{¨keyname¨}`. For example:

```
my $apps = $perl_language{"applications"}; # returns the application entry
$perl_language{"applications"} = $apps + 1; # increments the applications entry
```

When describing an accelerator element quantitatively (or anything else for that matter) a numerical value is assigned to each of the parameters characterizing the element. It is very natural to store this information in a hash, from which the numerical value of the parameter is retrieved using the parameter name as key. Because of this self-describing feature, *hash* has been selected as the main variable type used in the UAL shell commands. Practically

† An alternative Perl syntax (not used by UAL) for definition of the same hash is

```
%hash = ("version", 5.6, "applications", 1003, "web site", "http://www.perl.com")
```

any data structure can be described by hash variables. Like Perl, UAL uses them as the structures on which objects are based. Hashes are *too* flexible to be built-in data types in compiled languages such as Fortran, C, and C++ but they can be implemented by special classes in these languages.

The reader wishing to learn the power of hashes in as elementary context as possible can read the documentation for AWK,[13] the language from which Perl copied this feature.

Support of multidimensional arrays requires the use of references, a topic to be discussed in section 4.1.4. What with the possibility of multiple nesting, the syntax used to select a single element from such a structure can be a bit obscure, but one generality is worth remembering: a scalar variable name *always* begin with $, even if the scalar is identified by its index in array, or by its key in a hash.

Perl has many "built-in" variables. For UAL the important ones are `%ENV`, `@ARGV` and `@ARG` (which UAL refers to by its equivalent name `@_`).[†] These variables are evaluated automatically and are available globally, unqualified by package names (a term to be explained shortly). Documentation defining the names of Perl's implicitly-defined variables is obtained by typing `man perlvar`.

4.1.2. Subroutines

The primary mechanism for passing arguments to subroutines is based on the built-in array variable `@_` (which contains the arguments). UAL uses one or the other of two equivalent calls[‡]

```
subr($a,1);             # arguments are $a and 1
subr("B"=>1,"A"=>$a); # subroutine deciphers arguments from hash
```

[†] Perl has duplicate, abbreviated names for its built-in variables. For example `@_` is a valid abbreviation for `@ARG`. Use of Perl built-in variables other than `%ENV`, `@ARGV`, and `@_`, (and especially their abbreviated versions) is deprecated by UAL because they complicate the interface unnecessarily, perhaps impeding eventual migration to a more disciplined interface language. For postprocessing applications the user is, of course, invited to use whatever features of Perl seem useful.

[‡] Perl subroutine names (optionally) begin with &; the option is related to the way arguments are passed to or from the subroutine. So there are two other calls, also equivalent to the two listed above. Assuming `@_`=($a,1), they are `&subr`; and `&subr($a,1)`;. That is, the presence of the prefix & implies that the arguments are to be taken from `@_` if they are not given explicitly. The & prefix *must* be suppressed when the subroutine is defined. The versions given above are favored by UAL so that neither `@_` nor & (as function name prefix) is visible at the interface level.

The second version (used prominently in UAL) relies on code built into the subroutine to save the argument as a hash from which the actual arguments can be sorted out. This syntax has two major advantages; the argument order does not matter and it is not necessary to provide all arguments; arguments that are not provided are either not used or are assigned default values.

For object orientation, if a subroutine is to be a method of a particular class of objects, it is necessary to provide this association. This is done by passing a reference to the class as the first argument of `@_`. For example, consider the subroutine call

```
$shell->hsteer("adjusters" => "^kickh", "detectors" => "^bpmh");
```

which calls an orbit-smoothing method `hsteer` from the `ALE::UI::Shell` class.

The class reference is automatically included as the first entry of `@_` and the other arguments specify families of adjusters and detectors. A few lines of the `hsteer` definition are

```
sub hsteer
{
   my $this = shift;
   $this->code->hsteer(@_, ...);
   ...
}
```

In Perl, when the "object" of a "verb" such as `shift` is not written, the implied object is `@_`. So the first statement here "shifts off" the class reference, saving it as `$this`. The next statement passes the remaining arguments to another subroutine. In this case the arguments are the names of adjusters and detectors (encoded using "regular expressions" as will be explained in section 6.2) to be used in the algorithm. A fully-detailed example of argument passing is contained in code fragment ③ in section 6.4.

4.1.3. Modules, packages/name-spaces, scopes

Like any Perl program, every UAL program has a Perl `main` routine, which is contained in a file with a name such as `simulation.pl`—extension `.pl` stands for "Perl". This "program" provides all input directions to the simulation. There are also *modules*[†] such as `modulename.pm` with extension `.pm`, for "Perl module". Perl code in such modules is either "made available" by the Perl command `use`, or immediately "sourced" (i.e. read in, or imported) by the `require` command. A statement such as

```
use lib ("$ENV{UAL_EXTRA}/ALE/api");
```

near the beginning of a UAL script directs Perl to use the environment variable `$UAL_EXTRA` as part of the name of a directory, in this case `$UAL/ext/ALE/api`, to be added to the Perl search path for the module. For this line and several examples of `use` see code fragment ① in section 6.2. In those lines of code line #5 makes accessible `File::Path` from the standard Perl release, and line #12 makes accessible the code `Ale::UI::Shell` (Accelerator Library Extensions, User Interface) which is provided by UAL.

Another term, similar to, but not really equivalent to module, is *package*; while getting started a certain fuzziness concerning the distinction between *module* and *package* is to be expected.[‡] It is probably satisfactory to treat the terms "package" and "name space" as synonyms. Within any one package each variable name has to be unique, but each package has its own independent name space. The purpose of allowing more than one name space is to make it easier to avoid unwitting name clashes, thereby allowing the casual introduction of brief variable names.

To be used globally a variable name such as `$vname` needs to be qualified with a package name. So a variable `$vname` introduced in `mainprog.pl` would be accessed globally by its "fully-qualified name" `$main::vname`[¶] and the global name for a variable `$vname` introduced in package `modulename.pm` would be `$modulename::vname`. This accounts for the double colon `::` notation appearing in the examples shown previously. All variables

[†] Beware: the term *module* has more than one meaning in this manual, as will be clarified gradually.

[‡] It is considered to be good form for modules and packages to coincide, but Perl does not enforce this—the absence of this discipline may have been required for backward compatibility as Perl imposed the package mechanism on the pre-existing module mechanism?

[¶] Just one exception: the name `$main::vname` can be abbreviated to `$::vname`, only in the case of variable introduced in the `main` package.

introduced discussed so far are available globally using their fully qualified package-related names. They are therefore *not* "hidden". The `use package` directive (to be discussed below) allows the use of the briefer, unqualified name.

A term related to "name space", but not at all equivalent, is "scope". As a variable is defined, its scope, which restricts its access and specifies its access mechanism, is part of its definition. Variables introduced so far have *global* scope. In Perl there are (primarily) two restricted scopes: `my`-scope, which is also referred to as "lexical-scope" or as "personal"; and `local`-scope, which is also referred to as "temporary". UAL does not use `locally`-scoped variables.†

A *my* variable is declared by a statement `my $varname;`. The space of these names is completely disjoint from the package-related names. A *my* variable is said to be *lexical,* meaning "if you can read it you can use it" where you can only read from the code *block* (enclosed in curly brackets { }) in which it is introduced, or in the whole file, if the variable is not declared within a block.‡ The scope of a *my* variable is often as small as a few lines but it can be as great as the enclosing file, but no greater. A `my` variable name declared in a routine can only be interpreted in its called subroutine if the subroutine has been declared within the calling block. So, if the variable is required in a subroutine, it has to be passed explicitly and the values of `my` variables declared in subroutines also have to be returned explicitly. In spite of these limitations, for a large program (like UAL), because they are *private,* inaccessable by any package-related naming mechanism, the use of `my` variables is recommended wherever possible.

By default the code starts in package `main` but one can "switch" to package `Whatever;` by issuing the directive `package Whatever;` . Variables introduced from then on belong to the name-space `Whatever` until there is another switch. A variable `$foo` previously introduced in some other name-space `Other` must be referred to as `$Other::foo`. To avoid

† Warning: contrary to what one might expect, the Perl operator `local` (not used by UAL) does *not* declare a local variable. Rather, when applied to a pre-existing (global) variable, `local` simply squirrels away the current value of that variable, in order to later restore the saved value automatically at the end of the block. `local` *does not* create a *local* variable; in fact it does not create any variable at all. Rather it makes a pre-existing global variable available, and writable, but the original value will be restored upon exit from the block. As it happens, unlike *my* variables, *local* variables are implicitly available in subroutines called from within the block even if they have not been passed explicitly.

‡ On a programmable hand calculator, a lexical variable would be recoverable from its remembered position on the visible stack, rather than from having been assigned a named memory location.

the need for qualification one can switch back and forth between packages while remaining in the same file. For example, after directive `package Other;` the same variable could be referenced just as `$foo`. It is probably best to avoid using this freedom however, as it can be confusing, and hence prone to error. Because of possible ambiguity, Perl provides the option of issuing the `use strict;` directive. After this directive all package variables have to be fully qualified. For safety `use strict;` appears at the beginning of most UAL modules. When making *ad hoc* changes to the code one may be tempted to introduce a global variable, such as `$myvariable`, without declaring it to be a *my*. In the `use strict` regime this would trigger the error message "`Global symbol ''$myvariable'' requires explicit package name`". Naming the variable `$::myvariable` avoids this error by explicitly assigning the global variable to the main package. Better yet is to avoid introducing global variables for fear they will be forgotten and later cause trouble.

4.1.4. References

This sub-section is very much a continuation of subsection 4.1.1 as it expands the discussion of variables. For elementary use of Perl as a procedural language, the new method of specifying a variable might seem to be little more than an optional syntax, which the user could simply decline to employ. But for object-oriented application of Perl the notion of *reference* is essential. UAL exploits the reference mechanism to allow user scripts to ignore scope issues when addressing object variables and methods. When addressing object variables and methods the UAL-provided shell uses references to allow the user to ignore scope-of-variable considerations.

Within a Perl program a single scalar datum has at least three sorts of identity. It has its actual value, say `3.14`, it has its variable name, say `$pi`, and it has its location in memory. For elementary purposes the user is shielded from the need to be aware of the third of these identities. But to support object-orientation it turns out to be necessary to name this location (thereby increasing the number of identities by one.) The storage location is symbolized by `\$pi`, which is known as a *reference,* or sometimes as a *hard* reference (in which case `$pi` is itself referred to as a *soft* reference.) The possible references are

```
$rs = \$s;  # reference to scalar $s
```

```
$ra = \@a;  # reference to array @a
$rh = \%h;  # reference to hash %h
$rf = \&f;  # reference to subroutine &f
```

One can start to understand the role of references by considering an alternate Perl notation for defining an array (frequently used in UAL but not previously mentioned in this manual). An example of this syntax taken from code fragment (11) in section 6.2 is

```
my $qSigB  = [0.0, 0.0, -2.46, -0.76, -0.63, 0.00, 0.02, -0.63];
```

This defines an array (of multipole coefficients in this case) having the values shown. But the name of the array is *not* $qSigB; rather $qSigB is a *reference* or pointer to the location of the array which, in this case, is said to be "anonymous" or "reference-identified".† This shows that "references" can identify multi-element structures. (In fact, they enable dynamic memory allocation which is their main virtue.) When an array is to be populated one element at a time it is convenient to start with an empty array using `my $rarray = [];` .

To retrieve the data pointed to by reference `$rp` it is necessary to "dereference" the reference, by `$$rp` or by `@$rp` or by `%$rp` depending on whether it is a scalar, an array, or a hash being retrieved. Without this distinguishing notation Perl would not be able to determine the extent of the data to be retrieved.

There is a short-cut notation for selecting individual elements of reference-identified arrays without the need for explicit dereferencing. An element can be selected from the array defined two paragraphs back by `$qSigB->[2]` which, in this case, would return the value `-2.46`.

The notation for creating an anonymous hash uses braces instead of square brackets. For example, an anonymous two-element hash is created and referenced by

```
$rhash  = {"k1", "v1", "k2", "v2"};
```

The short-cut notation for selecting an element from such a reference-identified hash is `$rhash->`"{k2}" which, in this case, would produce "v2". When a hash is to be populated

† One has to tolerate the inelegant syntax of Perl which (like C) fails to distinguish between a scalar variable name and a reference. Hence, for example, the statement $p=\$q makes sense; it assigns reference \$q to reference $p, both of which are therefore both *scalars* and *references*. Perhaps this absence of explicit syntax for references is the reason that they are not referred to as *pointers* in Perl documentation?

one element at a time it is convenient to start with an empty hash using `my $rhash = {};`.

To support object orientation there needs to be a mechanism for representing structures more complicated than arrays or hashes. References can be used for this purpose. Without going into detail, the Perl keyword `bless` associates a reference with the particular *package* that is capable of digesting the contents of the structure that is referenced. An example is given in the block of code below (1) in section 6.2.

4.1.5. Regular expressions

It is often necessary to perform some action on only a subset of the elements in an accelerator. Some examples of actions a simulation program performs on all elements of such "families" are:

- element subdivision
- retrieval of parameter values
- update of parameter values
- establishment of detector families (such as BPM's)
- establishment of adjuster families (such as kickers)
- print out of lattice parameters

In some simulation codes, provision for specifying such a family of elements is built into the lattice description file by a flag assigned to elements in the particular family and to no other elements. For example in SIF (Standard Input Format) the `type=A` flag is assigned to all members of family `A`. In some cases such a family corresponds to actual hardware in the accelerator (magnets on a single bus for example) but usually assignment to families is best left to the tuning algorithms of the control system. In UAL philosophy it is therefore inappropriate to burden the lattice description with "hard-wired" family assignment.

In UAL a family is specified by the "explicit" listing of the names of all the elements that, for some immediate purpose, are usefully regarded as belonging to the same set. The word "explicit" is placed in quotation marks because the so-called "regular expression" mechanism is used to specify families and the element selection by regular expression may not look all that explicit to a reader unfamiliar with regular expressions. A *regular expression* is a highly-abbreviated shorthand ascii string that has been tailored (consistent with well-defined rules) to match the names of all elements in a family and to fail to match any other element name (of elements present in the ring.) By this time regular expressions have come to be a powerful and indispensable part of most computer languages. In this manual the mechanism will be clarified mainly by examples.

The consistent naming of lattice elements has always been an important consideration in writing lattice description files. It is important for conveying the intended purposes for the various elements in the original design and eventually every element needs a unique "site-wide" name by which elements in external models are associated with elements in the tunnel. The UAL mechanism for selecting families of elements makes naming-scheme discipline all the more important. It would be convenient for all elements of a family to have the same name; for example, all quad correctors on a harmonic corrector bus could have the name QDH. But this is too much to ask in general as it fails to allow for "overlap" of the different sorts of family that need to be defined. The regular expression mechanism permits the efficient selection of elements even in the face of such type overlap, but the mechanism is succinct only if a consistent naming scheme is carefully respected. As a last resort a family can, in fact, be defined within UAL as a *really* explicit list of all of its elements. An example of this will be given below. When first encountered the regular expression approach may seem awkward to the user but it is a "feature", not a "bug", as it solves a really hard simulation problem—how to specify families without the need for ad hoc tampering with the lattice description language? Such tampering frequently leads to errors and always erodes portability.

An example of the use of regular expressions for selecting a set of lattice elements is code fragment ⑤ in section 6.2. Because this example uses an actual SNS lattice file ④ , further explanation of regular expressions will continue in connection with explaining that code. The reader is encouraged to jump to that explanation and then return.

4.1.6. Printing out results

There are various mechanisms for outputting results. They can be printed to standard output or to a file, either from Perl or from C++. It is conventional for the Perl scripts of UAL to issue progress reports announcing the commencement of major steps in the simulation. These progress reports are generated by lines like

```
print "Create the ALE::UI::Shell instance (", __LINE__, ")\n"; #15
```

which is line #15 in listing (1) in section 6.2 (the example script to be documented first in this manual.) Incidentally this line shows how Perl-specific information (in this case `__LINE__`, the line number in the script) can be output. Usually it will be a string or a Perl variable, such as `$aScalar`, or a Perl built-in, such as `$_` that is output in this way. (The symbol `__LINE__` is peculiar-looking because it relates to the script as a file rather than to its execution as a Perl program.) One convenience is the ability to interpolate special variables into strings, as is illustrated by the following fragment of Perl code:

```
my $name = "test";
print "My name is $name","\n";
print 'My name is $name',"\n";
```

which produces output

```
My name is test
My name is $name
```

—with double quotes the value of the variable `$name` is interpolated, with single quotes it is not. To get printout under controlled-format the command `printf` (which is equivalent to `print sprintf`) has to be used. These are identical to C-commands of the same names.

The opening and closing of files proceeds as in any other computer language. To write from Perl to a file the file must first be *opened* with a statement such as[†]

```
open(OUTPUT, '>output/dat') || die 'Cannot create file "output/dat".';
```

which fails with an error message if the file cannot be created (for example because the directory `output` does not exist or is not writeable.) Note that the access mode (read, write, or append) begins the string containing the filename. Perl refers to the name "`OUTPUT`" as a *file handle*. Variables `$x` and `$y` can then be written to the file with defined format using a command such as

```
printf OUTPUT ("%6.3f %6.3f  ", $x, $y);
```

An example of a file handle being represented by a string with an interpolated variable is line #191 in code fragment (12) of section 6.2. Note also the use of "." (dot) as the string

[†] The symbol || stands for *or* in Perl. As it happens or can be used instead of || in this context and is even preferred style, according to Perl documentation, because it has lower precedence (i.e. reduces the need for placing adjacent elements in brackets). The symbol for *and* is & or and.

concatenating operator when filename `./out/test/fort.8` is formed from `''./out/'' . $job_name . ''/fort.8''`. (The string `''test''` had been assigned to variable `$job_name` earlier in line `#4`.) An example of formatted output appears a few lines later (line `#198`) in the same code fragment.

A more fully spelled out example of saving results, which exhibits the output of lattice parameters at specified lattice locations is given in section 6.3. Other than these brief comments, the formatting of output is too complicated for useful discussion in this manual. There are many samples to mimic in the examples.

Finally it can be mentioned that print statements can also be introduced into C++ code, for example for debugging purposes, or to obtain ad hoc access to an otherwise inaccessable variable value. An example line of code is

```
cout << "desired chromaticicities are " << mux << " " << muy << ''\n'';
```

which sends output to *standard out.* Many other examples are available in the UAL source code. Of course the C++ code has to be recompiled for any added lines like this to effective.

4.1.7. Issuing system commands

There is another benefit coming from the use of a scripting language to control the simulation—it is possible to issue system commands from within the script. An example of this is code fragment (1) in section 6.2. The relevant lines of code are

```
my $job_name = "test";
use File::Path;
mkpath(["./out/" . $job_name], 1, 0755);
```

Here the variable `$job_name` contains a string `''test''` that is concatenated (the dot (.) operator) with the string `''./out/''` to form the pathname `''./out/test''` of a directory which will be written to in a later command. The `mkpath` command (from within the `File::Path` module) establishes the directory, with permissions specified by the final argument.[†] Detailed documentation for `File::Path` and `mkpath` (and all other Perl routines) can be obtained from Perl documentation; for example with `$ man perlmod` and `$ man perlmodlib`.

[†] If the `mkpath` command had not been included Perl would have issued the error message "can't create ./out/test/log at /export/home/ualusr/development/ual1/ext/ALE/api/ALE/UI/Shell.pm line 32", which is the first occurence of writing to that directory.

4.2. UAL file directory structure and packages

Because there is a near one-to-one correspondance between packages and files there can be (within UAL) a standard relation between filenames and package names. Examples of this convention can be observed by the following instructions, which are followed by the resulting output:

```
    $ cd $UAL_ACCSIM
    $ find . -name '*.pm' -print | xargs grep "package Accsim"
./api/Accsim/Bunch.pm:package Accsim::Bunch;
./api/Accsim/Facade.pm:package Accsim::Facade;
./api/Accsim/Plot.pm:package Accsim::Plot;
./api/Accsim.pm:package Accsim;
./config/linux/Accsim/MakeMaker.pm:package Accsim::MakeMaker;
./config/sun_gcc/Accsim/MakeMaker.pm:package Accsim::MakeMaker;
```

Note that package `Accsim` resides in file `$UAL_ACCSIM` and "sub-packages"[†] `Accsim::Bunch`, `Accsim::Facade`, and `Accsim::Plot` are in correspondingly-named directories. (Note also that the Unix command used above can be modified to

```
    $ find . -name '*.someextension' -print | xargs grep "some text"
```

to search for "some text" in all files having extension "someextension". Most of the filename extensions appearing within the UAL environment are spelled out in Appendix B.2.)

4.3. Perl extensions

Even though all compute-bound UAL processing takes place using C++ code (archived into libraries) overall control of any simulation is managed by Perl code. The codes required to support calling C++ routines from Perl are known as *Perl extensions.* (The converse operation, *embedding* Perl within C++, does not occur in UAL.) All data structures used within the C++ code are declared in `.h` or `.hh` *header* files. Only some of the variables declared in these files are used for input to or output from the C++ routines. But the structures that *are* used as input or output need to be unambiguously related to the corresponding structures within the Perl program. Apart from enabling the calling of

[†] The reason "sub-packages" is in quotation marks is that, in Perl, this package naming convention is a bit artificial. It suggests that there is some kind of inheritance established automatically from, say, package `Accsim` to, say, package `Accsim::Bunch`. In fact, if such inheritance is required, the programmer would have to set it up using the `@ISA` array. The packaging just restricts variable names.

C++ routines, the main task for the extension code is therefore to translate Perl outputs into C++ inputs and then to translate C++ return variables into variables acceptable by Perl. The data describing these required translations is contained in files with extension `.xs` for eXternal Subroutine. There are tools available to establish such data mechanically for simple enough structures, but for more complicated structures it has to be done "by hand" and can be a formidable task.

Within the $UAL directory tree, all such `.xs`, files are contained in subdirectories called `api`, which stands for Application Program Interface. These `.xs` files are converted to C programs having `.c` extensions by a Perl utility called `xsubpp`.

This is the mechanism that gives an entire simulation the *appearance* of occuring within a Perl script. Since the file interrelationships supporting this are complicated, it is not an area in which casual recoding, or even browsing, is recommended. On the other hand, modification of the Perl code should be routine and (perhaps temporary) modification of the C++ code should not be unduly feared.

Chapter 5.
Online Documentation of Simulation Methods

Online documentation is available at `http://www.ual.bnl.gov`. Especially useful for the reader of this guide is to follow the links, under UAL 1.x: Documentation, ALE : UI, then Shell. This provides technical details for the basic user shell (or façade) which accesses the following UAL libraries and extensions:

- setMapAttributes (set dimensionality)
- readMAD (read in lattice)
- addSplit (segment element)
- addAperture (shape and size of vacuum chamber)
- addMap (for elements described by maps)
- use (select lattice from input file)
- writeFTPOT (produce file processable by Fortran version)
- addFieldError (field imperfection)
- addMisalignment (position imperfection)
- setBeamAttributes (adjust beam properties)
- analysis (perform complete linear lattice analysis)
- map (produce truncated map)
- survey (calculates and prints global geometry)
- twiss (calculates and prints all standard lattice functions)
- run (tracking)

Most of these methods will be exercised in the examples in Chapter 6.

Another link, Bunch, defines the attributes of the particles in a bunch $(x, p_x, y, p_y, ct, dp, m, E)$ and shows how they are set and retrieved.

Also appearing in the examples will be correction methods, that are not yet described in the online documentation:

- hsteer (horizontal steering)
- vsteer (vertical steering)
- ftsteer (first turn steering)
- tunethin (tune adjustment)
- chromfit (chromaticity adjustment)
- decouple (decoupling)

These are defined in `$UAL/codes/TEAPOT/api/Teapot/Main.pm` along with their supporting routines.

Chapter 6.
Annotated Examples

6.1. Introduction

The simulation scripts for this manual are mainly contained in sub-directories of the directory `$UAL/examples`. [†] Of these, the first, to be referred to as the "basic example", is the most important as it includes most of the commands that would be present in any simulation. Routine steps that have been explained in this example will not be repeated in subsequent examples. The first few examples are closely related, and represent an evolution from using the code as delivered, through making minor changes, to establishing a personalized, independent environment that can be used to reliably perform more extreme surgery on the delivered code, and finally to incorporating maps for special elements. These examples are all based on the same SNS lattice. The other examples illustrate some of the special features of UAL, and introduce other accelerators. Since only code fragments are exhibited in this manual there will inevitably be "loose ends" (apparently undefined quantities for example) that the reader can only sort out up by bringing up the complete code in a text editor.

Starting lattice files and other input information are in directories named `data`. For SNS the starting file is `$UAL/examples/UI/data/ff_sext_latnat.mad`. There are also RHIC and LHC examples based on SXF input; these are discussed in section 6.6.[‡]

In using a computer code having any flexibility whatsoever a certain amount of detective work is required of the user. Apart from getting help from an expert or trial-and-error running of the code—which one will always resort to eventually for confirmation—there are two sources of information: the (often ambiguous or obscure, like the present guide)

[†] There are example scripts in directories other than `$UAL/examples`. They are available for browsing and testing, and they function correctly when run, but they may rely on specialized shell features that are considered to be obsolete.

[‡] Some scripts involving RHIC have complicated input descriptions that cannot be traced because they are derived using RHIC databases and dedicated and complicated "filters" not included in the UAL distribution. These descriptions, which are also Perl scripts, have to be regarded as yet another (though archaic) input format. They are discussed further in section D.2 to illustrate the UAL lattice object model (SMF).

documentation or the source code (assuming it is available). Even though the source code is, by definition, accurate, most users are unwilling to follow the latter route.

Because UAL supports the flexibility of each of a multiplicity of codes the problem of documentation is all the more acute. But UAL is structured in such a way that there is a source of information intermediate between text documentation (such as this manual) and C++ source code; it is the Perl code of the numerous examples included in the distribution. Like source code, this source of information is, by definition, accurate. The serious user of UAL has no real alternative to looking at this Perl code to figure out how the environment is to be used. The annotation supplied with the following examples is intended to provide help in this endeavor.

In an ideal world the UAL code would be architecturally and stylistically homogeneous, to improve its intelligibility. In fact, having evolved over quite a few years, the organization of recently developed code may seem to be, and is, stylistically inconsistent with modules developed earlier. For example most of the examples in this guide do not need to rely on the Element-Algorithm-Probe framework mentioned in a lengthy footnote to section 1.2 and in section 6.7. The prime purpose of this framework is to support *extensions,* which are typically quite specialized. It is expected that mastery of the material in the present guide will help to make using these more advanced applications straightforward. The recently completed `FastTeapot` code, explained in section 6.7, is an example of such an extension. Installation and checkout of another extension, MPI (Message Passing Interface,) is described in Chapter 7. Working accelerator simulation examples that use multiple processors will be included in the distribution shortly, and a simulation of injection "painting" will also be included.

The online C++ documentation is currently being mechanically upgraded using *doxygen* and *swig*, software tools that are continually being improved.

6.2. Basic example

To run the first example, a simulation of SNS with realistic errors, enter

```
$ cd $UAL/examples/UI; perl shell_sns.pl
```

expecting to see the following output[†‡]:

```
mkdir ./out/test
Create the ALE::UI::Shell instance (15)
Define the space of Taylor maps (23)
Read MAD input file (33)
Define aperture parameters (46)
Select and initialize a lattice (78)
Define beam parameters (92)
Linear analysis (100)
Add systematic errors (119)
Add random errors (141)
Track bunch of particles (175)
End (202)
```

These lines are issued by the code to indicate its progress, as can be seen by correlating with line numbers in the script `shell_sns.pl`, fragments of which will be displayed in this section (with blank lines and comments suppressed), starting with the first several lines which are listed next: ①

```
#!/usr/bin/perl #1
my $job_name   = "test"; #3
use File::Path; #5
mkpath(["./out/" . $job_name], 1, 0755); #6
use lib ("$ENV{UAL_EXTRA}/ALE/api"); #12
use ALE::UI::Shell; #13
print "Create the ALE::UI::Shell instance (", __LINE__, ")\n"; #15
my $shell = new ALE::UI::Shell("print" => "./out/" . $job_name . "/log"); #17
```

Here line numbers in the script have been appended to each line as `#1`, `#3`, etc. These numbers are included for reference purposes in this manual; they would not normally be present but, as it happens, since they are expressed as comments (everything following # on the same line) their presence would have no affect on the script. The substantial accomplishment of ① is contained in line `#17` which has defined the "user shell" to be an `ALE::UI::Shell`. To find this, line `#12` instructs Perl to look in `$UAL_EXTRA/ALE/api`, which is to say, of `$UAL/ext/ALE/api`, relative to which the script

[†] The numbers in parenthesis are line numbers in the Perl script. These numbers were arranged to be present for this particular script just for purposes of reference in this manual. (See `__LINE__ in code fragment` ① .) Normal scripts would not issue these numbers. For reference elsewhere in the manual code fragments are identified by circled numbers like ① , along with the number of the section the fragment appears in.

[‡] To follow the code more closely and examine values of relevant variables it is possible to step through the Perl script line-by-line using a Perl debugger, which is invoked by `$ perl -d shell_sns.pl` or `$ ddd --perl shell_sns.pl`.

pathname is `ALE/UI/Shell.pm`.[†] This script initializes many UAL objects: *shell, code, lattice, beam, orbit, bunch, space, map, twiss,log,* and *constants,* all objects that the shell needs to access as Perl commands are interpreted and executed. Most of this will be spelled out more fully below.

The next statement in `shell_sns.pl` declares the maximum order of truncated power series to be 5, (also known as "dodecupole order"); ②

```
$shell->setMapAttributes("order" => 5); #25
```

and statement ③ specifies the lattice input file;

```
$shell->readMAD("file" => "./data/ff_sext_latnat.mad"); #35
```

In this case the lattice is described by the mad file `ff_sext_latnat.mad`, a few lines of which are excerpted next, to give a general idea of its content: ④

```
!  ff_sext_latnat.mad
   ...
   Brho := 5.6573735 ! 1.0 GeV (for 1.3 GeV: factor 1.1981566)
   ...
   lbnd := 1.5
   lq := 0.5
   LSEX:=0.15
   LREF:=1.7
   ...
   O3 : DRIFT, L = 6.25
   O31 : DRIFT, L = O3[L]/5
   ...
   ANG:= 2*PI/32
   EE := ANG/2
   BL: Sbend, L=lbnd/2, Angle=EE, E1=0., E2=0.
   BR:  Sbend, L=lbnd/2, Angle=EE, E1=0., E2=0.
   BND: Sbend, L=lbnd, Angle=ANG, E1=0.0, E2=0.0
   ...
   KD:=-4.94176/1.1981566
   QDH : QUADRUPOLE, L = lq/2, K1 = KD/Brho ! focusing arc quad (21Q40)
   QFH : QUADRUPOLE, L = lq/2, K1 = KF/Brho ! defocusing arc quad (21Q40)
   QFBH : QUADRUPOLE, L = lq/2, K1 = KF/Brho ! large focusing arc quad
   QDMH : QUADRUPOLE, L = lq/2, K1 = KMAT/Brho ! "matching" quad (21Q40)
   ...
```

[†] The `ALE::UI::Shell.pm` script itself depends on other libraries that it accesses with the command use lib (..., "ENV{$UAL_ZLIB}/api", "ENV{$UAL_TEAPOT}/api", "ENV{$UAL_EXTRA}/PAC/api");. These libraries, for example, make UAL tools such as power series capability available. These capabilities will not be discussed at this point. It is more appropriate to defer this discussion to section 6.5.1 where the map generation features of UAL are exercised.

```
...
QDH1 : MARKER
QD : LINE = (QDH1,QDH,QDH,QDH2)
QF : LINE = (QFH1,QFH,QFH,QFH2)
...
VS1D:=-2.891275
S1D:   SEXTUPOLE, L=LSEX, K2=VS1D
...
RF1 : RFCAVITY, L = LREF, HARMON = 1, VOLT =  0.0
...
ARC    : line = (ACF,ACFM,ACS1,ACS2,ACS3,ACS4,ACF,ACFL)
INSERT : line = (SC,DZ,SCM)
SP : line = (INSERT,ARC)
RING : line = (SP,SP,SP,SP)
```

Because this UAL example reflects the realistic complexity of an actual (SNS) lattice, the script is fairly long so, for brevity in this manual, lines that are pedagogically repetitive will not be shown. The line numbers shown refer to the actual file. The reader is expected to read along in the actual file using a text editor, tolerant of minor line numbering disagreements that may have occurred due to reformatting or line-wrapping.

Since particle tracking is to be done by numerical integration, it is necessary to specify integration intervals. The intervals can be full elements, or quarter elements (¨`ir`¨ => 1) or eighth elements (¨`ir`¨ => 2), and so on.[†] It is often adequate to treat entire quadrupoles as single kicks, especially when the quads are, in fact, represented as paired half-quads in the lattice description, as is the case in the lattice being studied. For some purposes overly fine splitting is "apple polishing", unjustified by the accuracy of the element descriptions. But for the exact comparison of results from different codes a fine subdivision is appropriate when computation time is not an issue. Deciding the extent to which any particular element is to be subdivided belongs to the domain of the tracking engine to be used rather than to the domain of the lattice description. This is why the subdivision has to be taken care of in the present Perl script. To specify which elements are to be subdivided the regular expression mechanism introduced in section 4.1.5 is used: ⑤

[†] The name "ir" is archaic; it derives from the common circumstance that intersection region quadrupoles are most sensitive and most in need of fine subdivision. In future this usage will be specific to TEAPOT and a corresponding parameter will be known as a "complexity index" or as a "divisibility index". Different simulation modules may interpret this parameter differently. The fourfold subdivision is used by TEAPOT because it permits a near-optimal, unequal-interval kick algorithm, somewhat more accurate than uniform interval splitting. The same unequal interval splitting is available in MAD. Unlike any thick element truncated map, these algorithms preserve exact symplecticity.

```
$shell->addSplit("elements" => "^(q[df]h|q[fd][lmc]h|qfbh)$", "ir" => 2);  #40
$shell->addSplit("elements" => "^(bnd)$", "ir" => 2);  #42
...
```

The cryptic expression `"^(q[fd][lc]h|qfbh)$"` is the regular expression specifying the quadrupoles that are to be subdivided into eighths (because `"ir" => 2`).

Only enough comments will be made about this process to give the general idea of how regular expressions work. (i) For compatability with most simulation codes, UAL element names are case-insensitive. Uppercase names are converted to lowercase before regular expression matching. Hence, for example, "QFBF" becomes "qfbh". (ii) The symbol `"^"` forces name matching to start at the beginning of the name. So the `"^(q..."` part of the regular expression allows names beginning with "q" to be candidates for inclusion (though they must also pass later tests). (iii) The symbol `"...$"` forces name matching to end at the end of the name. So the `"^( ... )$"` part of the regular expression limits both the beginning and ending match. (iv) The part of the regular expression `( ... |qfbh)` gives qfbh as one of the strings whose presence makes the name a candidate for inclusion. This (along with the requirements already mentioned) shows that the element "QFBH" from the lattice file ④ will be one of the magnets to be subdivided; its name (after conversion to lower case) includes the string "qfbh" and matches both at beginning and end. This is an example of a "last resort" explicit name inclusion in that element name "QFBH" is *really* specified explicitly (not counting upper/lower case.) (v) The regular expression also allows other matches, though all must start with `q` and end with `h`. The portion `[fd]` allows the second character of a three character name to be either `f` or `d`, so quadrupole names QDH and QFH also match. (vi) The portion `[fd][lmc]` admits certain 4 character names, such as QDMH. Putting it all together, it turns out that all quads exhibited in ④ will be subdivided. If there were a non-quadrupole (say an RF cavity, for which subdivision makes no sense) with name QFCH, the name would match the regular expression but the processing algorithm would just ignore the selection. Nevertheless, to reduce the likelihood of error, it makes sense to maintain naming conventions such as "all quadrupoles, and only quadrupoles, have names beginning with Q".

If vacuum chamber dimensions are important, they should, because they are installed hardware, be included in the lattice description file. But, since the SIF description language does not support this, it is necessary to introduce aperture information (for bends, quads, and sextupoles) via the present script: (6)

```
$shell->addAperture("elements" => "^(bnd)$",
                    "aperture" => [1, 0.116, 0.079]); #51
$shell->addAperture("elements" => "^(q[fd]h|qdmh)$",
                    "aperture" => [1, 0.105, 0.105]); #56
$shell->addAperture("elements" => "^(s[24][fd])$",
                    "aperture" => [1, 0.13, 0.13]);
  ...
```

The aperture attributes are 1 (ellipse) with half-widths and half-heights as shown. Such apertures have no effect on analytical lattice calculations, but in particle tracking they correctly model the loss of particles that would strike a vacuum chamber wall.

At this point all lattice description is complete, though not yet fully specific in the sense that options remain as to what constitutes the actual beamline to be investigated. The next command fixes this: (7)

```
$shell->use("lattice" => "ring"); #82
$shell->writeFTPOT("file" => "./out/" . $job_name . "/tpot"); #86
```

Here line #86 has also output a file `$UAL/examples/UI/out/test/tpot` that can serve as input to the Fortran version of TEAPOT. To run this file with FTPOT it is only necessary to append the lines

```
use, ring
makethin
twiss
analysis, energy=1.93827231, xtyp=1.e-6, pxtyp=1.e-6, ytyp=1.e-6, &
          pytyp=1.e-6, dptyp=1.e-6, particle=proton, print
```

This facilitates code comparison and result checking and makes available certain TEAPOT algorithms that are not supported in UAL as well as certain post-processing tools.[†] performed by the ZLIB module (an approach first taken by Forest.) This is probably the most significant analytical improvement of the present version of TEAPOT compared to earlier versions. The earlier approach, though exact in principle, was in fact limited to low order (roughly through sextupole order) by considerations of machine precision. Differential algebra gives results exact to all orders, limited only when computation resources are exhausted. These thin element results also converge exactly to continuum results in the limit of vanishing interval lengths. (This was confirmed by Forest.) A fragment of a

[†] Incidentally, the original version of TEAPOT uses the arguments xtyp, pxtyp, ..., to the `analysis` command as "infinitesimals" in the evaluation of lattice functions by numerical differentiation. This is *really* crude! As TEAPOT is implemented within UAL all differentiation is performed by differential algebra

file written in this format is given in section D.2 ⑤ The next step in the simulation is to define beam parameters: ⑧

```
        $shell->setBeamAttributes("energy" => 1.93827231, "mass" => 0.93827231); #94
```

Here only particle mass and total energy have been specified, but other properties such as charge, or revolution frequency could be entered. At this point the *ideal* physical system to be simulated has been fully described. Before incorporating "blemishes" it is appropriate to investigate its linearized behavior and its momentum dependence: ⑨

```
        my $dp; #104
        for($dp = -0.02; $dp <= 0.02; $dp += 0.005){
           $shell->analysis("print" => "./out/" . $job_name . "/analysis" . "." . $dp,
           "dp/p" => $dp);
        } #108
        $shell->map("order" => 1, "print" => "./out/" . $job_name . "/map1");  #112
```

The `for` loop ending at line #108 performs Twiss analyses for each of nine fractional momenta, from -0.02 to +0.02. The construct `"./out/".$job_name."/analysis"."."".$dp` opens a sequence of files, `./out/test/analysis.-0.02`, ..., one for each of the momenta in the `for` loop. Line #112 outputs the 6×6 once-around transfer matrix of the ring for the most recent analysis. More precisely the output consists of a ZLIB-formatted listing of all orders up to 1 (i.e. 0 and 1) of the "VTps" (vector of truncated power series) that make up the nonlinear once-around transfer map. The (reduced-precision) output is: ⑩

```
    ZLIB::VTps : size = 6 (dimension = 6  order = 1 )
     0 -3.512e-17 -1.387e-17  0.000e+00  0.000e+00 -1.022e-15  0.000e+00   0 0 0 0 0 0
     1  2.338e-01 -4.801e-01  0.000e+00  0.000e+00 -2.090e-05  0.000e+00   1 0 0 0 0 0
     2  2.497e+00 -8.513e-01  0.000e+00  0.000e+00  2.000e-05  0.000e+00   0 1 0 0 0 0
     3  0.000e+00  0.000e+00  2.458e+00  4.715e-01  0.000e+00  0.000e+00   0 0 1 0 0 0
     4  0.000e+00  0.000e+00 -1.171e+01 -1.840e+00  0.000e+00  0.000e+00   0 0 0 1 0 0
     5  0.000e+00  0.000e+00  0.000e+00  0.000e+00  1.000e+00  0.000e+00   0 0 0 0 1 0
     6  5.689e-05 -2.744e-05  0.000e+00  0.000e+00  6.414e+01  1.000e+00   0 0 0 0 0 1
```

As well as the closed orbit in the first line (which vanishes on-momentum), the 2×2 horizontal and vertical transfer matrices are included in lines 1 through 4, and longitudinal matrix elements are also included. The vanishing of "off-diagonal" transverse elements shows that the lattice is uncoupled at this stage. The meaning of the indexing columns on the far right should be obvious. A cubic map is exhibited in section 6.5.1 ⑨ .

Having completed the analysis of the ideal machine, to make the simulation more realistic, one adds imperfections using commands like: ⑪

```
$shell->addFieldError("elements" => "^(bnd)$",    "R" => 0.13,
        "b" => [0.0, 0.1, 51.0, 0.5, -26.0, 0.2, 0.0, 0.0, 0.0, 0.0]); #124
...
my $iseed = 973431; #143
my $rgenerator = new ALE::UI::RandomGenerator($iseed); #144
my $qSigB  = [0.0, 0.0, -2.46, -0.76, -0.63, 0.00, 0.02, -0.63,  0.17, 0.00]; #148
my $qSiqA = [0.0, 0.0, -2.50, -2.00,  1.29, 1.45, 0.25,  0.31, -0.11, 1.04]; #149
$shell->addFieldError("elements" => "^qdh",   "R" => 0.1,
                      "b" => $qSigB, "a" => $qSiqA, "engine" => $rgenerator); #157
...
```

As before, the element selection is performed by regular expression matching. Field errors can be systematic, and added to BND elements, as in line #124, or they can be random, and added to elements whose names begin with QDH, as in lines #157. For the random assignments a starting seed is assigned in line #143 and the random number generator is specified in #144. "Erect" field multipoles are introduced via the "b" list and "skew" multipoles are introduced via the "a" list. Not shown are the many error assignment commands for the other elements in the ring.

This example ends with multiturn particle tracking; ⑫

```
my ($i, $size) = (0, 10); #177
my $bunch = new ALE::UI::Bunch($size); #179
$bunch->setBeamAttributes(1.93827231, 0.93827231); #181
for($i =0; $i < $size; $i++){
    $bunch->setPosition($i, 1.e-2*$i, 0.0, 1.e-2*$i, 0.0, 0.0, 1.e-3*$i);
} #185
$shell->run("turns" => 100, "step" => 10,
   "print" => "./out/" . $job_name . "/fort.8", "bunch" => $bunch); #188
open(BUNCH_OUT, ">./out/" . $job_name . "/bunch_out_new")
               || die "can't create file(bunch_out_new)"; #191
my @p; #193
for($i =0; $i < $size; $i++){ #194
    @p = $bunch->getPosition($i); #195
    $output= sprintf
    ("i=%5d x=%14.8e px=%14.8e y=%14.8e py=%14.8e ct=%14.8e dp/p=%14.8e \n",
     $i,$p[0],     $p[1],     $p[2],     $p[3],     $p[4],     $p[5]);  #198
     print BUNCH_OUT $output; #199
} #200
print "End (", __LINE__, ")\n"; #202
1; #204
```

In line #177 the number of particles is set to 10. In line #181 the energy and particle mass (both in GeV, as always) are set.[†] The first argument of `$bunch->setPosition` is a particle index; the remaining arguments are starting coordinates for the particles to be tracked, expressed as functions of `$i`. In this case they all lie on a x, y, dp diagonal. Line #188 starts

[†] By using the DDD debugger to trace through the code it is possible to step down into the code where inputs like these are actually used in order to confirm what physical quantities the inputs stand for. This is easier and more reliable than hunting for the information in external documentation (such as this manual).

the tracking process, requesting tracking of all particles for 100 turns. (The "step" argument is ignored and should be deleted from example.) The remaining lines give the output of the tracking. The file handle BUNCH_OUT is set to `./out/test/bunch_out_new` in line #191, the output is generated by line #198, and the printing is performed by line #199. The output file `out` therefore contains the six phase space coordinates of all ten particles after they have been tracked for one hundred turns.

(The purpose of the lonely final statement (`1;` #204) is to produce a non-zero return value (indicating successful completion) when control "falls out" the bottom of the routine. In general the most recently calculated value is what is returned from a subroutine. Exiting from the middle of a subroutine, with return value `$value`, can be accomplished by the statement `return $value`; .)

6.3. Selective lattice function output

One frequently wishes to output lattice functions evaluated at particular locations in the lattice. Locations in the lattice can be specified by their longitudinal coordinates or by the names of the elements at those locations. The latter approach is easier because it can use the regular expression mechanism described earlier.

Consider the same SNS lattice as was studied in the basic example (section 6.2) and suppose that we want global position (i.e. survey) data at every element and Twiss output at every bend element named BND. The script `$UAL/examples/UI_Analysis/shell_sns.pl` has been tailored to this task. When this script is run the immediate output is much the same as in section 6.2, except for the lines ①

```
Linear analysis:
 ...
 survey
 twiss
```

The new lines in the script that generate this output are ②

```
$shell->survey("elements" => "", "print" => "./out/" . $job_name . "/survey");
$shell->twiss("elements" => "bnd", "print" => "./out/" . $job_name . "/twiss");
```

The `survey` output appears in `$UAL/examples/UI_Analysis/out/test/survey`. Output occurs at every element since the empty string `‘‘’’` matches all element names. The first several lines of output (slightly reformatted for this guide) are: ③

```
-------------------------------------------------------------------------------------------
# name   suml(thick)  suml(thin)    x        y        z           theta    phi      psi
-------------------------------------------------------------------------------------------
0 qdmh1  0.0000e+00   0.0000e+00   0.0e+00  0.0e+00  0.0e+00     0.0e+00  0.0e+00  0.0e+00
1 qdmh   0.0000e+00   0.0000e+00   0.0e+00  0.0e+00  0.0e+00     0.0e+00  0.0e+00  0.0e+00
2 qdmh   2.5000e-01   2.5000e-01   0.0e+00  0.0e+00  2.5e-01     0.0e+00  0.0e+00  0.0e+00
3 qdmh2  5.0000e-01   5.0000e-01   0.0e+00  0.0e+00  5.0e-01     0.0e+00  0.0e+00  0.0e+00
4 o11    5.0000e-01   5.0000e-01   0.0e+00  0.0e+00  5.0e-01     0.0e+00  0.0e+00  0.0e+00
5 o11    2.2125e+00   2.2125e+00   0.0e+00  0.0e+00  2.2125e+00  0.0e+00  0.0e+00  0.0e+00
6 o11    3.9250e+00   3.9250e+00   0.0e+00  0.0e+00  3.9250e+00  0.0e+00  0.0e+00  0.0e+00
7 o11    5.6375e+00   5.6375e+00   0.0e+00  0.0e+00  5.6375e+00  0.0e+00  0.0e+00  0.0e+00
8 qflh1  7.3500e+00   7.3500e+00   0.0e+00  0.0e+00  7.3500e+00  0.0e+00  0.0e+00  0.0e+00
9 qflh   7.3500e+00   7.3500e+00   0.0e+00  0.0e+00  7.3500e+00  0.0e+00  0.0e+00  0.0e+00
 ...
```

The next request is for `twiss` output at all BND elements. The output appears in `$UAL/examples/UI_Analysis/out/test/twiss`, the first several lines of which (also reformatted) are: ④

```
------------------------------------------------------------------------------------------------------------
#  name  suml      betax      alfax       qx         dx         betay      alfay       qy         dy
------------------------------------------------------------------------------------------------------------
0       0.00e+00  2.626e+00  5.705e-01  0.000e+00  1.406e-05  1.232e+01 -2.260e+00  0.000e+00  0.000e+00
46 bnd  3.15e+01  4.271e+00 -1.075e+00  6.547e-01  3.253e-05  8.293e+00  1.764e+00  4.720e-01  0.000e+00
53 bnd  3.55e+01  8.281e+00  1.652e+00  7.330e-01  5.396e-01  4.190e+00 -1.055e+00  6.442e-01  0.000e+00
62 bnd  3.95e+01  4.137e+00 -1.075e+00  9.074e-01  2.050e+00  8.490e+00  1.812e+00  7.216e-01  0.000e+00
71 bnd  4.35e+01  8.374e+00  1.624e+00  9.867e-01  3.617e+00  4.116e+00 -1.020e+00  8.929e-01  0.000e+00
80 bnd  4.75e+01  4.271e+00 -1.075e+00  1.155e+00  2.857e+00  8.293e+00  1.764e+00  9.720e-01  0.000e+00
89 bnd  5.15e+01  8.281e+00  1.652e+00  1.233e+00  3.246e+00  4.190e+00 -1.055e+00  1.144e+00  0.000e+00
98 bnd  5.55e+01  4.137e+00 -1.075e+00  1.407e+00  8.067e-01  8.490e+00  1.812e+00  1.222e+00  0.000e+00
 ...
```

The `survey` and `twiss` subroutines called in code fragment ② are contained in scripts `Shell.pm`, `SimpleSurvey.pm`, and `SimpleTwiss.pm` in directory `$UAL/ext/ALE/api/ALE/UI`. From these files one sees that the separate calls each trigger multiple calculations. Most of the function calls are self-explanatory; in any case fuller explanations will not be given here. But from this code it should be obvious how one can tailor the output, as regards quantities to be printed out, lattice locations where the quantities are to be exhibited, and general formatting. Perhaps one prefers $\sqrt{\beta}$ rather than β? One need only replace `$columns[3]` by `sqrt($columns[3])` (and similarly for β_y) in the output statement near the end of the SimpleTwiss script and similarly for β_y. It is also straightforward to format the output file appropriately for graphing the lattice functions by a graphing program such as `gnuplot`.

Most theoretical formulas in lattice physics involve integration (usually approximated by summation) over all elements in the ring, of element parameters such as quadrupole gradients, length-strength products, inverse focal lengths, sextupole strengths etc., weighted by fractional powers or other functions of lattice functions (β_x, β_y, ϕ_x,, dispersion, etc.) All of the required lattice functions are available from `$UAL/ext/ALE/api/ALE/UI/Shell.pm`. An example in section 6.4 will show how to gain access to the magnet strengths required. Once this information is in hand one can use Perl to evaluate the accelerator physics formulas involving such summations (or even integrations if necessary). Though Perl may not be as fast as a compiled language, it is plenty fast for typical postprocessing tasks.

6.4. A personalized shell for code development

The examples presented so far showed how to run canned UAL scripts. If these are classified as "elementary UAL" we now advance to "intermediate level UAL". A key purpose of UAL is to be an environment in which an accelerator physicist's attention can be concentrated on a specialized problem without being overwhelmed by the complication of "the rest of the system". The reason this is important is that the detailed and correct understanding of any subsystem requires that the rest of the accelerator perform more-or-less as it is supposed to. A perfect simulation code would correctly model all systems and be prepared to answer any question concerning the functioning of the accelerator, but it is unrealistic even to strive for such a utopian situation. Rather, individual physicists strive to define and then answer sufficiently narrow, well-posed questions concerning the performance of accelerator subsystems. The purpose of UAL is to support such activity.

The physicist zeroing in on some area of interest, and wishing to use the tools of UAL, will often have to alter the existing code in the area of concentration as well as generating new code. In this sense "hacking into the code" is strongly encouraged. This is fairly straightforward, especially when only Perl code is involved. What may be less straightforward is keeping track of the changes in case it is necessary to "back them out" or to cause the improved code to be integrated eventually into the distributed version of

UAL. Failure to do this leads, at best, to multiple versions or, at worst, to dis-use and eventual loss of the improvement.

The present example suggests a discipline to be followed, when revising the code; it is intended to facilitate the coordination of revised UAL code with the CVS-installed version of the code, with the goal of eventually facilitating the merging of the codes. The idea is to use the object-oriented feature called *inheritance* to establish a specialized user shell `UALUSR::Shell` that inherits all methods from the generic user shell `ALE::UI::Shell`, overriding some and generating others as required.

The physics of this example concerns itself with a family of quadrupoles, each equipped with a steering elements (kicker), and a BPM. The task is to center the beam horizontally at each of the (imperfectly aligned) quadrupoles. This example is based on an actual study of beam-based alignment of quadrupoles in the SNS and is discussed in detail in a technical note by Talman and Malitsky.[14]

This example is located in directory `$UAL/examples/BmBasedBPMAlign`. The Perl script is `BmBasedBPMAlign.pl`; it reads the lattice from `data/BmBasedBPMAlign.mad`. These files differ only slightly from the corresponding files in the basic example, section 6.2. The reader looking for a comprehension-testing exercise could generate these files by hand rather than accepting the distributed versions. The main purpose is to establish an environment from which subsequent code development can proceed.

In the SIF (i.e. MAD) lattice description, the quadrupoles, eight in all, are treated as paired half-quads called QFH and, for simplicity the kickers and BPM's are treated as if centered on the quadrupoles. In the lattice file these packages are described by ①

```
QF_a : LINE = (QFH, kickha, bpmha, QFH)
QF_b : LINE = (QFH, kickhb, bpmhb, QFH)
...
QF_h : LINE = (QFH, kickhh, bpmhh, QFH)
```

As mentioned already, this example continues to use the same SNS lattice as the previous example. The present changes are that the line `QF : LINE = (QFH1,QFH,QFH,QFH2)` in lattice file ④ of section 6.2 has been replaced by the eight lines just shown, in order to be able to adjust their elements individually. Where QFH pairs appears at eight places further down in the lattice file they are replaced respectively by `QF_a, QF_b,...,QF_h`.

Proceeding as in the first example, we start by applying random misalignments to the QFH elements, using the instruction (2)

```
my ($rMisalignIndices,$rdelx,$rdely,$rdeltheta) = $shell->addMisalignment
        ("elements" => "^qfh$", "dx" => 0.01, "dy" => 0.01);
```

This `$shell->addMisalignment` simulation method did not appear in the previous examples, but it was listed above in Chapter 5 and it differs from `$shell->addFieldError` only in that it perturbs magnets in position rather than in magnetic field. For present purposes we wish not only to misalign the magnets but also to know what misalignments have been applied. In real life these displacements would be unknown but, since we are testing a method, we need to "cheat" by peeking at the assigned values. The return arguments `($rMisalignIndices,$rdelx,$rdely,$rdeltheta)` in (2) point to this information. The first argument is a reference to the array of element indices of the displaced elements and the others arguments are references to the arrays of misalignments (of which we will discuss only the first in this example.) Unfortunately, by viewing the file `$UAL_EXTRA/ALE/api/ALE/UI/Shell.pm`, one sees that subroutine `$shell->addMisalignment` does not, in fact, return any values. We therefore have to modify that code by inserting the lines marked `# USR extension` in the following: (3)

```
sub addMisalignment
{
  my $this = shift;
  my %params = @_;
  my $pattern = " ";
  if(defined $params{"elements"}) {$pattern = $params{"elements"}; }
  my $arg_counter = 0;
  my $sigx = 0;
  if(defined $params{"dx"}) {$sigx = $params{"dx"}; $arg_counter++;}
  ...
  my @elemIndices =  $lattice->indexes($pattern);
  ...
  # - USR extension --------------------------------
  my @delx;
  my @dely;
  my @deltheta;
  # ----------------------------------------------------
  ...
  for($i=0; $i < $#elemIndices + 1; $i++){
    $element = $lattice->element($elemIndices[$i]);
    ...
    if($sigx){
        $element->add(($sigx*$rvalue)*$dxKey);
        ${\@delx}[$i] = $sigx*$rvalue; # USR extension
    }
    ...
  }
  return (\@elemIndices,\@delx,\@dely,\@deltheta); # USR extension
}
```

Too little detail has been given here to understand this code in every detail, but the following things have been accomplished. The first seven lines decipher the input arguments as was explained in section 4.1.2 and provide the example that was promised there. The next line shown saves the indices of displaced elements in the array `@elemIndices`. So far there has been no change but the following lines squirrel away information that is now known will be needed later. Then (because `dx` was included in the argument list) `$sigx` is *true*, so the misalignment values `$sigx*$rvalue` are saved in the array `@delx`. The last line returns the array reference.† The other return values will be ignored.) We have therefore modified code block ③ to be consistent with the call in code block ② .

A major virtue of CVS is that changes like these can be hacked into the code without worrying about polluting the original version, since the original can always be retrieved. But, once your revisions have been frozen, you will want to save them; so you may as well plan for this from the start.

A new personalized "application interface" `UALUSR::Shell` is needed. This is something that you would have to generate and save as the file `api/Shell.pm`. Here, since this is an example, the script is supplied for you:‡ ④

```
package UALUSR::Shell;
use Carp;
use strict;
use vars qw(@ISA);
use lib ("$ENV{UAL_EXTRA}/ALE/api");
use ALE::UI::Shell;
@ISA = qw(ALE::UI::Shell);
sub new
{
  my $type = shift;
  my %params = @_;
  my $this = new ALE::UI::Shell(%params);
  ...
  return bless $this, $type;
```

† A quicker and dirtier approach to accessing the parameter changes would have been to make the saved arrays global variables so they would not have to be returned by reference. But this is the sort of slipshod practice that evolves inexorably into *spaghetti* code.

‡ The line `use Carp` modifies error reporting and is therefore inconsequential. The curious Perl construct `qw(x y z)` is equivalent to placing quotation marks around the individual arguments; i.e. equivalent to "x" "y" "z". The statement `use strict` prevents access to global variables and the statement `use vars qw(@ISA)` restores access to just the `@ISA` array. The `@ISA` array array is used three lines further down to declare that the newly-defined shell will start with all methods defined in `ALE::UI::Shell`.

```
}
sub addMisalignment
{
   ...
   return (\@elemIndices,\@klvalue);
}
sub getErectMagnetStrengths
{
   ...
   return (\@elemIndices,\@delx,\@dely,\@deltheta);
}
```

The subroutine `addMisalignment` listed here was spelled out above in ③ . In this new shell the inherited method `addMisalignment` has been over-ridden; also a new method `getErectMagnetStrengths` has been defined (of which only one line is shown in ④ .)

To make use of the new shell the UAL command script (call it `BmBasedBPMAlign.pl`) now begins with ⑤

```
  ...
use lib ("./api");
use UALUSR::Shell;
my $shell = new UALUSR::Shell("print" => "./out/" . $job_name . "/log");
  ...
```

which creates the new UALUSR shell instance. This replaces code fragment ① of section 6.2. Following this will be the lattice definition commands, for example fragments from section 6.2: ② , ③ , ⑥ , ⑦ , ⑧ , and ⑪ . Finally lines specific to the simulation being developed are included, such as: ⑥

```
 ...
my ($rMisalignIndices,$rdelx,$rdely,$rdeltheta) = $shell->addMisalignment
    ("elements" => "^qfh$", "dx" => 0.01); #190
my $numMisaligns = $#{$rMisalignIndices}; #192
my $numkicks = ($numMisaligns + 1)/2; #193
 ...
$shell->hsteer("adjusters" => "^kickh", "detectors" => "^bpmh"); #204
 ...
my ($rErectIndices,$rkickhs) = $shell->getErectMagnetStrengths
    ("elements" => "^kickh", "multindex" => 0); #208
 ...
```

Line `#190` is the revised command discussed above as code fragment ② . Line `#192` illustrates the Perl syntax for obtaining the number of elements in an array and line `#193` accounts for the pairing of the quadrupoles (artificially present in the SIF lattice description.) Line `#204` uses the `hsteer` algorithm to resteer the beam through quad centers and line `#208` uses the newly-defined method `getErectMagnetStrengths` to obtain the strengths that have been determined by `hsteer`. From these strengths the quad misalignments can be inferred and then compared to the (known by cheating) actual quad misalignments. The calculations (not shown) required for this comparison are the sort of postprocessing activity for which Perl is ideal.

6.5. Fringe field map

Trajectory evolution through lattice sectors can be represented by maps. In this example the end fields of quadrupoles in the SNS will be modeled. Just as the end fields of dipole magnets are (predominantly) of quadrupole order, the end fields of quadrupoles are predominantly of octupole order—deflections are cubic functions of the transverse coordinates. A theoretical discussion of maps is given in appendix E.

Especially for hadron accelerators, it is essential to preserve symplecticity to high accuracy. No special treatment is required for dipole magnets with end fields modeled by quadrupoles, since the end fields are linear and symplectic. Often the end fields of quadrupoles can simply be ignored but, for a large aperture accelerator like the SNS, the octupole end fields have significant effect—their leading effect is dependence of tune on amplitude. To a good approximation an end field can be treated as if it acts impulsively at a single plane. The relation between input-to and output-from coordinates for this plane can be represented by a vector of truncated power series.

For extremely large amplitudes the convergence of such power series may simply be too poor for the series to be applicable. But when the fields are weak, as here, this is not expected to be an issue. The quad end deflections are approximated well by the cubic terms in the power series of the map. Yet one cannot simply include cubic terms without further investigation. Truncation causes nonsymplecticity[†] that can invalidate long term tracking. A cubic map, even if symplectic "to cubic order", is necessarily nonsymplectic "to quartic order" or, in general, a truncated map can be symplectic to its own order, but not to higher order.

To be able to investigate these issues it is valuable to have the capability of introducing maps that are truncated to arbitrary order and that are symplectic at least to their order

[†] There are techniques involving (nonlinear) transformation to new variables such that the exact map elements are actually polynomials rather than infinite series. No such procedure is being considered here.

of truncation. The so-called "Lie transform" formalism makes this possible. In this approach the map element corresponding to each phase space coordinate is obtained by appropriate differentiation of a polynomial "Hamiltonian" (sometimes known as a pseudo-Hamiltonian). The actual differentation process is in fact a Poisson bracket evaluation, an operation that is provided by ZLIB. What results, for each coordinate, is a power series representing its output value as a power series of all input coordinates. In first approximation the polynomial order of each of these series is one less than the order of the Hamiltonian. But it is possible, by iterating, by keeping more terms in the exponential series entering the Lie transform, and by truncating to higher order, for the resulting map to be symplectic to higher order than the initially-truncated Hamiltonian. This does not make the map "correct" to higher order, but it does make it symplectic to higher order. Starting from an approximate map this process can therefore produce a map that is symplectic to whatever order one is willing to evaluate the power series.

These mapping capabilities of UAL are the subjects of this section. First the map or maps have to be generated and then they have to be introduced into the simulation script. These are the tasks of the next two sections.

6.5.1. Map generation

The code illustrating map generation is located in directory `$UAL/examples/HardEdge`. The script `ff.pl` begins ①

```
use lib ("$ENV{UAL_ZLIB}/api", "$ENV{UAL_DA}/api");
use Zlib::Tps;
use HardEdge;
my $dimension = 6;
my $maxOrder  = 5;
my $space = new Zlib::Space($dimension, $maxOrder);
```

This example uses the truncated power series tools made available by the command `use Zlib::Tps;`. This capability was already exhibited, with minimal explanation, in section 6.2; a linear order, once-around, transfer map for the whole SNS ring was displayed as ⑩ . Here, as there, the full 6×6 phase space dimensionality is specified and the maximum truncation order is set to 5.[†] Continuing with script `ff.pl` ②

```
my $I = new Zlib::VTps($dimension);
$I += 1.0;
# N - number of terms in the Lie transformation
# K - MAD quad coefficient multiplied by +1 (entrance) or -1 (exit)
my $ff_integrator = new HardEdge("N" => 1, "K" => -4.353051/5.6575, );
```

an identity map `$I` is defined, number of terms parameter `N` and strength parameter `K` assigned and the routine `HardEdge.pm` for propagation through fringe field (from the `HardEdge` package) declared. The header material of script `HardEdge.pm` is[‡]: ③

```
package HardEdge;
use vars qw(@ISA);
use Da::Const qw($X_ $PX_ $Y_ $PY_ $CT_ $DE_);
use Da::Lie::Integrator;
@ISA = qw(Da::Lie::Integrator);
```

As well as associating map variables with physical coordinates this causes the script to inherit all the methods of the parent class `Da::Lie::Integrator`. The `Da::Const` package relies on the Perl *typeglob* data type which is too technical and idiosynchratic to be explained here. The package defines and exports global references to read-only constants such as particle rest energies or (in this case) the indices 0,1,2,3,4,5, as they correspond to the variables x, p_x, y, p_y, ct, de. This has the seemingly cosmetic, self-documenting purpose of permitting a variable value such as `$p0->value(0)` to be expressed as `$p0->value($X_)`— the actual purposes are: to support the overloading of coordinate representations by both scalar value and power series; and to allow the truncated power series code to be mathematically general, absent of any particular identification of its variables with physical quantities.

The instantiation code in the new integrator is ④

```
sub new
{
  my $type = shift;
```

[†] The order of a polynomial in UAL is dynamically determined as the power series is being evaluated. The order of any particular power series can therefore be less than the maximum order, but it cannot be greater.

[‡] Header material like this was explained in a footnote to section 6.4.

```
    my %params = @_;
    my $self = new Da::Lie::Integrator(@_);
    $self->{K} = 0.0 unless defined ( $self->{K} = $params{K} );
    return bless $self, $type;
}
```

which receives K and N (not visible in the code fragment shown because it is received by `Da::Lie::Integrator`) as input arguments. The Lie integrator assumes propagation through drift as default; this behavior has to be overridden (in `HardEdge.pm`) by introducing a Hamiltonian appropriate for propagation through the hard edge of a quadrupole;[15]
(5)

```
sub hamiltonian
{
  my ($this, $p) = @_;
  my $h = 1.;
  if($p->size < $PX_) { return $h;}
  # Beam
  my $v0byc  = $this->{v0byc};
  my $charge = $this->{charge};
  my $p0 = new Zlib::VTps($p->size);
  $p0 += 1;
  # Hamiltonian
  my $x2 = $p0->value($X_)*$p0->value($X_);
  my $y2 = $p0->value($Y_)*$p0->value($Y_);
  $h  = 3.*$x2*$p0->value($Y_)*$p0->value($PY_);
  $h -= 3.*$y2*$p0->value($X_)*$p0->value($PX_);
  $h +=    $y2*$p0->value($Y_)*$p0->value($PY_);
  $h -=    $x2*$p0->value($X_)*$p0->value($PX_);
  $h *= $this->{K}/12.;
  return $h;
}
```

Note the line `my $p0 = new Zlib::VTps($p->size);` which has defined a new vector of (initially vanishing) power series. The subsequent operations in the subroutine are *overloaded* in the sense that all operations (such as $=$, $- =$, and $*$) are performed on complete (truncated) power series.

Continuing with script `ff.pl`; (6)

```
my $ff_map = $I + 0.0;
$ff_integrator->propagate($ff_map, $beam_att);
```

the map is instantiated and then propagated through the fringe region using a method inherited from `$UAL_DA/api/Da/Lie/Integrator.pm`. This subroutine (with four inconsequential lines deleted) reads: (7)

```
sub propagate
{
  my ($this, $object, $beam_att) = @_;
  my $morder =  $this->{N};
  ...
  my $h = $this->hamiltonian($object) + 0.0;
  my $i;
  my $tmp = $object + 0.0;
  my $sum = $object + 0.0;
  for($i = 1; $i <= $morder; $i++){
     $tmp = $h->vpoisson($tmp)/$i;
     $sum  += $tmp;
  }
  for($i =0; $i < $object->size; $i++) { $object->value($i, $sum->value($i)); }
  $object->order($object->order);
}
```

The final lines of `ff.pl` (with their accompanying explanatory comments describing their purpose) are (8)

```
# truncate the order of power series
$ff_map->order($maxOrder - 2);
# write power series coefficients into the specified file
$ff_map->write("./out/ff_map.new");
```

The hard edge map has now been calculated and saved to `./out/ff_map.new`. The non-zero cubic rows are: (9)

```
ZLIB::VTps : size = 6 (dimension = 6  order = 3 )
28 -6.411917e-02  0.000000e+00  0.000000e+00  0.000000e+00  0. 0.  3 0 0 0 0 0
29  0.000000e+00  1.923575e-01  0.000000e+00  0.000000e+00  0. 0.  2 1 0 0 0 0
30  0.000000e+00  0.000000e+00  1.923575e-01  0.000000e+00  0. 0.  2 0 1 0 0 0
31  0.000000e+00  0.000000e+00  0.000000e+00 -1.923575e-01  0. 0.  2 0 0 1 0 0
35  0.000000e+00  0.000000e+00  0.000000e+00  3.847150e-01  0. 0.  1 1 1 0 0 0
39 -1.923575e-01  0.000000e+00  0.000000e+00  0.000000e+00  0. 0.  1 0 2 0 0 0
40  0.000000e+00 -3.847150e-01  0.000000e+00  0.000000e+00  0. 0.  1 0 1 1 0 0
54  0.000000e+00  1.923575e-01  0.000000e+00  0.000000e+00  0. 0.  0 1 2 0 0 0
64  0.000000e+00  0.000000e+00  6.411917e-02  0.000000e+00  0. 0.  0 0 3 0 0 0
65  0.000000e+00  0.000000e+00  0.000000e+00 -1.923575e-01  0. 0.  0 0 2 1 0 0
```

The format of this file was explained along with output (10) in section 6.2. This time (not shown) there are identity matrix elements in the linear part and zero elements in the constant and quadratic part. After calculating maps like these for all quadrupoles in the lattice one proceeds to incorporate the maps into the lattice description.

6.5.2. Map application

The code illustrating the inclusion of maps in lattice descriptions is located in directory `$UAL/examples/UI_FF`. The starting lattice file is

`$UAL/examples/UI_FF/data/ff_sext_latnat.mad`

It is an SNS lattice much like the lattices in previous examples. The end field maps for its quads have been pre-calculated and reside in directory `quadff`. The first seventy or so lines of the `shell_sns_ff.pl` script are much like the corresponding lines of the script in section 6.2. Deviation begins with the lines ①

```
print "Define 3D fringe fields", "\n";
# We include ff only for quads because it was shown
# that contribution from bends was negligible
$shell->addMap("elements" => "^(qdh1)$",
                "map" => "./quadff/fr1qd.zmap");
$shell->addMap("elements" => "^(qdh2)$",
                "map" => "./quadff/fr2qd.zmap");
 ...
$shell->addMap("elements" => "^(qfbh2)$",
                "map" => "./quadff/fr2qf.zmap");
```

Because the deflections (and even displacements that make the orbit discontinuous) caused by fringe fields occur at fixed longitudinal positions, their treatment by TEAPOT is just like the treatment of deflections by thin multipole elements. Therefore, nothing more needs to be done. The remaining lines of script `shell_sns_ff.pl` are identical to the corresponding lines of `shell_sns_.pl`.

6.6. SXF input to UAL

6.6.1. SXF rationale

There has always been a need for a portable, fully-instantiated lattice description. When parameter deviations are entered by a particular code from a measurement database or, even more so, when errors are generated by Monte Carlo programs, it becomes difficult to perform accurate result comparisons. Commonly one is forced to repeat calculations already performed, using possibly-suspect code, just for the purpose of regenerating identical data. This limitation was felt strongly when the US-LHC collaboration was starting to perform LHC simulations. The result was SXF (Standard eXchange Format).[22]

By now an even more important use for SXF has been realized at RHIC. It is for capturing "snapshots" of actual lattice conditions, encountered during operations, to be used for offline simulations and "post mortem" analysis. Though it is straightforward, starting from an SIF input, to collect and apply all the field imperfections, misalignments, apertures, operational procedures, etc. needed to instantiate all lattice elements, this is very time consuming and hard to maintain. Furthermore (for better of for worse from the point of view of database management) it is easier to output the current, fully-instantiated lattice parameters, than to update the original data sources.

To understand some of the issues involved in reconstructing a lattice from an SXF file some understanding of SMF (the UAL accelerator model) is useful; a brief description is contained in Appendix D. For now the only point to be made is that each element in the lattice has two names, a design/generic *GenName* and a fully-instantiated *LatName*; sometimes known as a site-wide name. Within SXF the lattice is represented by a sequence of *LatName*'s, along with their attributes. Since one of these attributes (the *tag* attribute) is the *GenName*, it is easy to cross-reference one name to the other, even when only SXF information is available. But, within the original SIF lattice design, there are hierarchical features like sub-lines, symmetric sections, repetitions, and so on. None of this information finds its way into the SXF file. Hence a simulation that depends on hierarchical information (other than *GenName* association) must either start from a SIF lattice description or re-insert the required relationships *post facto*. So far this has turned out to be either unnecessary or straightforward, so the absence of hierarchical information from SXF files has proved not to be a serious impediment.

6.6.2. RHIC example

RHIC simulation documented in this guide will be based purely on the SXF lattice description.[†]

[†] Historically the RHIC lattice description, like the SNS description in the basic example of section 6.2, started from a MAD file. Both the lattice descriptions and the UAL scripts from that era are obsolete but, primarily for the benefit of RHIC workers, there are functioning scripts from that era residing in directory `$UAL_SXF/examples/codes/ual`. They have self-expanatory names, `rhic2sxf.pl`, `sxf2lhc.pl`, and `sxf2rhic.pl`, The `README` file in the same directory contains some information about the scripts. These examples assume that the appropriate SIF lattice description is available.

The example to be described is $UAL/examples/UI_SXF/rhic. The SXF lattice description is up-to-date, as of Fall, 2002. Suppressing only print statements, the script reads; (1)

```
#!/usr/bin/perl
my $job_name   = "rhic"; #3
use File::Path; #5
mkpath(["./out/" . $job_name], 1, 0755); #6
use lib ("$ENV{UAL_EXTRA}/ALE/api"); #12
use ALE::UI::Shell; #13
my $shell = new ALE::UI::Shell("print" => "./out/" . $job_name . "/log"); #17
$shell->setMapAttributes("order" => 5); #25
use lib ("$ENV{UAL_SXF}/api"); #35
use UAL::SXF::Parser; #36
my $sxf_parser = new UAL::SXF::Parser(); #37
$sxf_parser->read("./data/blue-dAu-top-swn-no_sexts.sxf","./out/".$job_name."/echo.sxf"); #39
$shell->use("lattice" => "RHIC"); $49
$sxf_parser->write("./out/" . $job_name . "/rhic.sxf"); #51
$shell->setBeamAttributes("energy" => 250, "mass" => 0.93827231); #59
$shell->analysis("print" => "./out/" . $job_name . "/analysis"); #67
$shell->map("order" => 2, "print" => "./out/" . $job_name . "/map2"); #71
print "End", "\n";
```

Other than obtaining its input directly from an SXF file, this script is not essentially different from the basic script in section 6.2. The syntax and content of an SXF lattice description file can be inferred from the fragment of SXF file blue_dAu_top_swn-no_sexts.sxf displayed next (2)

```
RHIC sequence {
  g6-markx marker { tag = clock6
  };
  g6-solx drift { tag = hstar l = 3.1
  };
  ...
  g6-dhx sbend { tag = dxmp l = 3.70021937559
    body = { kl = [ -0.0188607907827]}
    body.dev = { kl = [ 0 ] kls = [ 0 ]
    }
  };
  noswn.14 multipole { tag = erdxmp
    body.dev = { kl = [ 0 -9.61487901076e-05 ] kls = [ 0 0 ]
    }
  };
  ...
  ...
  bo6-qd1 quadrupole { tag = q1o6 l = 1.44 n = 2
    body.dev = { kl = [ 0 -0.0830140433294 ] kls = [ 0 0 ]
    }
  };
 ...
  noswn.5834 drift { tag = oflstar l = 5.03589178
  };
endsequence at = 3833.84518146
}
```

A few of the lattice elements supported by SXF—`marker`, `sbend`, `multipole`, `quadrupole`—are visible in this listing. A complete listing of supported elements is given in section D.3. Also visible in ② are *LatName's* such as `g6-markx`, `g6-solx`, `g6-dhx`, `noswn.14`, and `noswn.5834`, the final two of which show the mechanism for making *LatName's* unique when the same the same *GenName* appears more than once in the design lattice. As mentioned above, the *GenName's*, i.e. design names, such as `clock6` and `hstar` are retained using the `tag=` syntax. The `n=2` entry records a "complexity" index, which TEAPOT interprets as `ir=2`. Element lengths are given by `l=` entries and their strengths by multipole lists such as `kl = [ 0 -0.0830140433294 ]`.

Browsing the simulation script ① , the first few lines are routine. From line `#17` one sees that this simulation is performed using the shell `ALE::UI::Shell`, the code of which is `$UAL_EXTRA/ALE/api/ALE/UI/Shell.pm`. (This pathname is constructed using statement `#12` and the conventional file naming prescription.) By lines `#35` through `#37` the SXF parser code is `$UAL_SXF/api/UAL/SXF/Parser.pm`. Note that these scripts are generic; i.e. they are not RHIC-specific. Line `#39` reads in the SXF file, a fragment of which was shown above under ② . After establishing beam attributes in line `#59`, this script, in line `#67`, evaluates and prints out beginning and ending Twiss parameters to file `./out/rhic/analysis` and prints out the second order, once-around transfer map in line `./out/rhic/map2`.

For completeness the elements and element attributes supported by SXF would be documented here. But this guide (in section D.3) documents ADXF instead, correlating its properties with the SMF lattice object model. Of course the elements described by SXF and ADXF are essentially similar, differing, in the case of, say, RHIC, by RHIC-specific features. The *extensibility* feature of SMF is what makes the support of alternative descriptions straightforward.

6.7. FastTeapot

As mentioned in the introduction, `FastTeapot` consists of recently developed C++ code whose purpose is implied by its name. Since the present user guide primarily documents the Perl interface, as contrasted with the C++ code, it cannot properly document `FastTeapot`. However, a few words can be said about the motivation behind examples

```
$UAL/examples/FastTeapot/linux/evolver,
$UAL/examples/FastTeapot/linux/tracker,
```

both of which are C++ executables. (Compilation instructions are given in the README file.) Their purpose is to exercise the Element-Algorithm-Probe framework and to compare computation times and results obtained using traditional element-by-element TEAPOT results with (matrix multiplication through sectors) `FastTeapot` results. Matrix multiplication is the most obvious speed-up mechanism for mapping through sectors. An application that came up recently requires tracking that needs to be fast while retaining a faithful representation of chromatic effects; in particular the second order coefficients T_{116}, T_{226}, T_{336}, and T_{446} need to be accurate.

With canonical (x, p_x) variables, even transport through drifts brings in chromatic effects which, being second order, are not accurately modeled by pure linear matrix multiplication. On the other hand drifts sections *are* linear when $(x, x' \equiv dx/ds)$, (position, slope) variables, are used instead of x, p_x (and likewise for y, p_y). In these coordinates, even with no quadratic terms included, the desired chromatic effects are retained. So matrix evolution through drifts retains the correct contribution of drifts to chromaticity. Of course quadrupoles, sextupoles, and octupoles continue to need symplectic, TEAPOT kick treatment. It is not claimed that this particular procedure is universally applicable, but it does exercise the Element-Algorithm-Probe framework.

Program `evolver` calculates second order, once-around maps two ways: one uses only traditional element-by-element TEAPOT kick-tracking; the other uses kick-tracking through quadrupoles and nonlinear elements, but uses the non-canonical (x, x') coordinates of the previous paragraph through other elements. Of the second order coefficients determined, it is only T_{116}, T_{226}, T_{336}, and T_{446}, that are expected to agree in this comparison. Program `tracker` is similarly motivated. It uses the same two evolution mechanisms to perform multiparticle tracking of a bunch of particles. The idea is that tunes obtained by FFT processing of the outputs of program `tracker` can be used to extract, and hence compare, off-momentum tune dependence.

Chapter 7. MPI Multiprocessor Support

Since tracking many particles for many turns through a long and complicated accelerator lattice takes a long time, it is extremely useful to have access to a cluster of workstations working simultaneously. Sometimes one wishes to run the same simulation for a variety of parameter values. This leads to the "lowest tech" use of multiple processors—one simply uses one computer for each of the parameter combinations. This requires no multiprocessing software. The next simplest case is that of Monte Carlo calculations, for example to determine dynamic aperture, in which randomly selected particles are tracked through multiple lattices having randomly assigned error fields and misalignments. In the past calculations like this have often used multiple computers in the trivial way just mentioned. But already in this case, which is known as "embarassingly parallelizable" because so little interprocess communication is required, it is extremely useful to have special purpose multiprocessor software. Without such software lengthy output files tend to exceed the available storage space and the book-keeping becomes onerous. Multiprocessor software permits one node—the term node is normally used instead of processor in this context—both to do this bookkeeping and to take responsibility for assigning particles and/or lattices to the remaining nodes. The MPI module of UAL is ideal for this purpose.

The MPI module of UAL is also ideal for the next more complex type of calculation in which there are multiple particles (probably with a single lattice) and a large (but "not overwhelming") amount of interprocess communication is required. Here we have in mind multiparticle simulations involving space charge or beam-beam interactions, for which considerations of computation time make it all but obligatory to employ multiple processors. Again it is natural to distribute equal numbers of particles to all but one of the nodes. Then, since every particle is influenced by every other particle, the information about a particle in one node has to be made available to all the other nodes. However this information need not be "overwhelming". The calculation can be performed in two steps such that all-on-all intercommunication is avoided. Gathering data from each of the tracking nodes, a managing node can work out a space charge field, which it redistributes to all the tracking nodes. As long as this computation time is short compared to the tracking times the overall computation rate can be almost proportional to the number of nodes in the cluster.

The so-called "message-passing" model of parallel computing is just one of the ways of harnessing the power of multiple computers. It is the one adopted by MPI (Message Passing Interface). It seemed to be the best approach for the level of complexity of parallel processing most frequently encountered in accelerator simulation (though not necessarily for all multiprocessing tasks.) An excellent reference is by Gropp, Lusk, and Skjellum.[16] MPI is a *specification* for libraries of subroutines written in Fortran, C, and C++. As such MPI is not a "language" and there is no MPI compiler. Rather the subroutines are compiled and linked by the appropriate Fortran, C, or C++ compiler. There can be more than one implementation of the MPI standard. The one employed by UAL is known as MPICH[17] where the "CH" derives from "Chameleon" which apparently was the name of an early version. When the letter combination "ch" appears, for example in device type "chp4" they refer back to this early code. MPICH and its various utilities are public domain software.

7.1. MPI installation

Instructions will be given here for downloading, configuring, and testing the MPI software on a single node. This is not to suggest that there is a great advantage to running multiple processes on the same computer. Rather, the purpose is to get the software running in the simplest possible environment. Configuration of multiple nodes is straightforward, but specific to the number and types of nodes available; instructions are included as part of the download in the file `doc/mpichman-chp4.pdf`.

To start, one downloads file `mpich.tar.gz` from `http://www.mcs.anl.gov/mpi/mpich`, saving it, for example, in dirctory `~ualusr/tools/tmp`. For documentation see

`http://www-unix.mcs.anl.gov/mpi/mpich/docs/mpichman-chp4.pdf`

The code is unpacked (into a directory mpich-1.2.4, possibly with a later version number), compiled, and installed using the instructions

```
$ cd ~ualusr/tools/tmp
$ gzip -d mpich.tar.gz
$ tar xvf mpich.tar
```

```
    $ cd mpich-1.2.4
    $ ./configure --with-device=ch_p4 --prefix=/export/home/ualusr/tools/mpich
 --enable-sharedlib > & configure.log
    $ make > & make.log
    $ make install > & install.log
```

Since this example assumes a private version of MPI is being installed in the directory ~ualusr/tools/mpich, root privilege is unnecessary to complete these steps.[†]

In the configuration step the device was specified to be --with-device=ch_p4 which is the correct type for MPMD (multiple-processor, multiple-data) (possibly heterogeneous) Unix clusters. The shared library flag --enable-sharedlib is supported in systems (like UAL) compiled using gcc. Other configuration flags are specified in section 4.1 of the mpichman-chp4 documentation listed above. As the make finishes, near the bottom of make.log, the following paragraph appears:

```
Completed build of MPI.  Check the output for errors. Also try
executing 'make testing' in examples/test (This relies on mpirun,
which currently works for many but not all systems.  For workstation
networks, mpirun requires that you first setup a "machines" file
listing the machines available; this is covered in the installation
manual.)
```

Other than checking the output for errors this test should be deferred as it tries to access more than one node.

After MPICH has been built, appropriate environment variable and path have to be set;

```
    $ setenv MPIHOME ~ualusr/tools/mpich
    $ set path = ($MPIHOME/bin $path)
    $ setenv LD_LIBRARY_PATH $MPIHOME/lib/shared/$LD_LIBRARY_PATH
```

Then one can test the set-up by

```
    $ cd $MPIHOME/examples
    $ make
    $ mpirun -np 1 cpi
```

[†] For later convenience in starting up multiple nodes on heterogeneous clusters the configuration looks for, and tests rsh and ssh. Depending on the local set-up, either of these can appear to hang the configuration process with the most recent line in configure.log saying, for example, checking whether /usr/kerberos/bin/rsh works..., but, after a seemingly interminable delay, the time-out(s) will end and the configuration will continue. If this problem occurs it need not fixed right away since it will not disable the examples given here as they function in a single computer.

This runs a toy program `cpi` that calculates π by the thoroughly impractical method of evaluating numerically an integral whose value is known analytically to be π. The program subdivides the range of integration and distributes the ranges to the available processors. In this case the command line arguments `-np 1` state that one processor is available. The utility script `./mpirun` detects what is needed from the environment—its defaults correspond to the present installation—and then runs the program.

The program `cpi` is the compiled version of the C program `cpi.c`. This program is thoroughly documented in reference[16]. The same calculation is performed by the Fortran program `pi3.f` which is run identically, replacing `cpi` by `pi3` in the listing above.

Using MPICH on multiple nodes requires that the available nodes are correctly configured and described. The main requirement is that `rsh`, or an equivalent remote shell access, function correctly. This is too specialized for further discussion in this manual. What needs to be done is clearly explained in the the `mpichman-chp4.pdf` documentation mentioned above. Some access may require the intervention of the system administrator.

7.2. Overview of MPI

Just to skim the general ideas, this section extracts key points from Gropp et al.[16]. For any kind of detail this reference, and the others listed previously, should be referred to.

For the calculations being performed in multiple processors to be coordinated by message passing there are certain minimal requirements that have to be met. Basically data from the address space of one processor has to be written into the address space of another. This process requires cooperation between the two participants. One process *sends* the data, but the transaction is only complete when the other has *received* it. The minimal message interface for these two actions is

```
send(address, length, destination, tag)
receive(address, length, source, tag, actlen)
```

The `send` line specifies the location and length (in sequential bytes) of the data to be transferred, and identifies the recipient. In MPI functioning on n processors, each process has an identifier, known as its *rank*, an integer in the range from 0 to $n-1$; destination and source are so identified. The `tag` argument is the beginnings of a mechanism for differentiating among a possible multiplicity of messages. Assuming a match of the `tags`, the `receive` line identifies the sender, and specifies the address where the data is to be placed and its expected length. The argument `actlen`, specifying the actual length of the received data, provides the beginnings of an error flagging mechanism.

The MPI protocol goes well beyond this minimal specification of message transfer. For one thing the data being transferred can be organized into far more complicated, non-contiguous *structures.* Also a *communicator* object, identified by a `comm` argument, supports communication. So the actual MPI send/receive interface is

```
MPI_Send(address, count, datatype, destination, tag, comm)
MPI_Recv(address, maxcount, datatype, source, tag, comm, status)
```

The more-complicated data structure location information is encoded into the `address`, `count`, and `datatype` arguments.

Before these operations can be used a certain amount of initialization is required, and graceful termination of the multiprocessor program is also essential. Along with `MPI_Send` and `MPI_Recv`, a minimal MPI version would therefore contain[16]

```
MPI_Init        Initialize MPI
MPI_Comm_size   Find out how many processes there are
MPI_Comm_rank   Find out which process I am
MPI_Finalize    Terminate MPI
```

As mentioned previously, these and all other MPI routines need to be compiled into the simulation programs running on the various machines, using the native compiler for the computer language of the simulation being run.

7.3. MPI applied to UAL

One thing to be appreciated is that the UAL user accesses MPI indirectly via Perl, and the Perl interface does not necessarily make all MPI routines described in MPI documentation *directly* accessable to the user—not even all the routines mentioned in the previous section. Routines needed to establish and terminate multiprocessor computations are supported, but arbitrary internode communication is not. The reason for this is that, because of its interpreted rather than compiled nature, message passing via Perl is slow. To circumvent this, message passing among nodes within UAL occurs at the C++ level. The primary purpose of the UAL interface is to support this indirection. So the UAL/MPI is not to be regarded as a general purpose interface to MPI. Rather it is an interface specialized to the limited set of capabilities needed to control UAL simulation tasks, such as modeling space charge effects.

Another thing to be admitted is that, though a functioning UAL multiple processor space charge application exists, it is not included in the CVS distribution at this time (December, 2002). The present documentation covers only the downloading and testing of the MPI environment. To proceed beyond this point to actual simulation, technical help and special instructions are required for downloading working code examples.

A first test of MPI under UAL consists of

```
$ cd $UAL/examples/ShortMPI
$ mpirun -np 1 test_MPI.pl
```

This runs the script `test_MPI.pl`, which is listed next: (1)

```
#!/usr/bin/perl
use lib ("$ENV{UAL_MPI_PERL}/api");
use Short_MPI;
# ------------------------------------------------------------------
#Create the MPI environment
#Define the total number of MPI processes available - $numprocs
#Define the rank of the calling process in group    - $myid
# ------------------------------------------------------------------
my $status_mpi;
Short_MPI::MPI_Initialized($status_mpi);
print "Status MPI (before MPI_Init) = ",$status_mpi,"\n";
my @mpi_argv = ($0, @ARGV);
my $mpi_argc = $#mpi_argv + 1;
Short_MPI::MPI_Init($mpi_argc, @mpi_argv);
my $numprocs;
Short_MPI::MPI_Comm_size($Short_MPI::MPI_COMM_WORLD, $numprocs);
my $myid;
Short_MPI::MPI_Comm_rank($Short_MPI::MPI_COMM_WORLD, $myid);
printf(STDERR "Process starts on the node %d, (host = %s)\n", $myid, $ENV{HOST});
Short_MPI::MPI_Initialized($status_mpi);
if($myid == 0) {
  print "Status MPI (after MPI_Init) = ", $status_mpi,
        ", number of nodes = ", $numprocs, " \n";
}
#######################################################################
print "\nReplace these print statements by any Perl instructions\n";
print "For example cut and paste the entire contents of \n";
print "   $ENV{UAL}/examples/UI/shell_sns.pl \n";
print "(see $ENV{UAL}/examples/UI_MPI/shell_sns_mpi.pl)\n\n";
#######################################################################
Short_MPI::MPI_Barrier($Short_MPI::MPI_COMM_WORLD);
my $timeStop = Short_MPI::MPI_Wtime();
my $time_proc = $timeStop - $timeStart;
printf(STDERR "Node %d : time = %e \n", $myid, $time_proc );
```

```
# -----------------------------------------------------------------
# Finalize MPI
# -----------------------------------------------------------------
Short_MPI::MPI_Finalize();
1;
```

When this script is run the output suggests a certain modification the user should perform before re-running the script. The suggested change is to replace the three printout lines (between the lines marked ####...) by arbitrary Perl instructions. For example, inserting the script `shell_sns.pl`, the basic script annotated in section 6.2 of this manual, (roughly speaking) converts the MPI script into `shell_sns.pl`. Then running the MPI script produces the same calculation as running the basic script itself. Of course, since only one processor is in use, this has no useful purpose other than demonstration.

Of the six basic MPI commands described in the previous section, only the commands `MPI_Init`, `MPI_Comm_size`, `MPI_Comm_rank`, and `MPI_Finalize`, inherited by class `Short_MPI`, are present in `test_MPI.pl`. Because these are one-time, initialization and finalization commands, they have to be, and can be, issued directly from the Perl script. As mentioned before, `MPI_Send` and `MPI_Recv` are not supported at the Perl level.

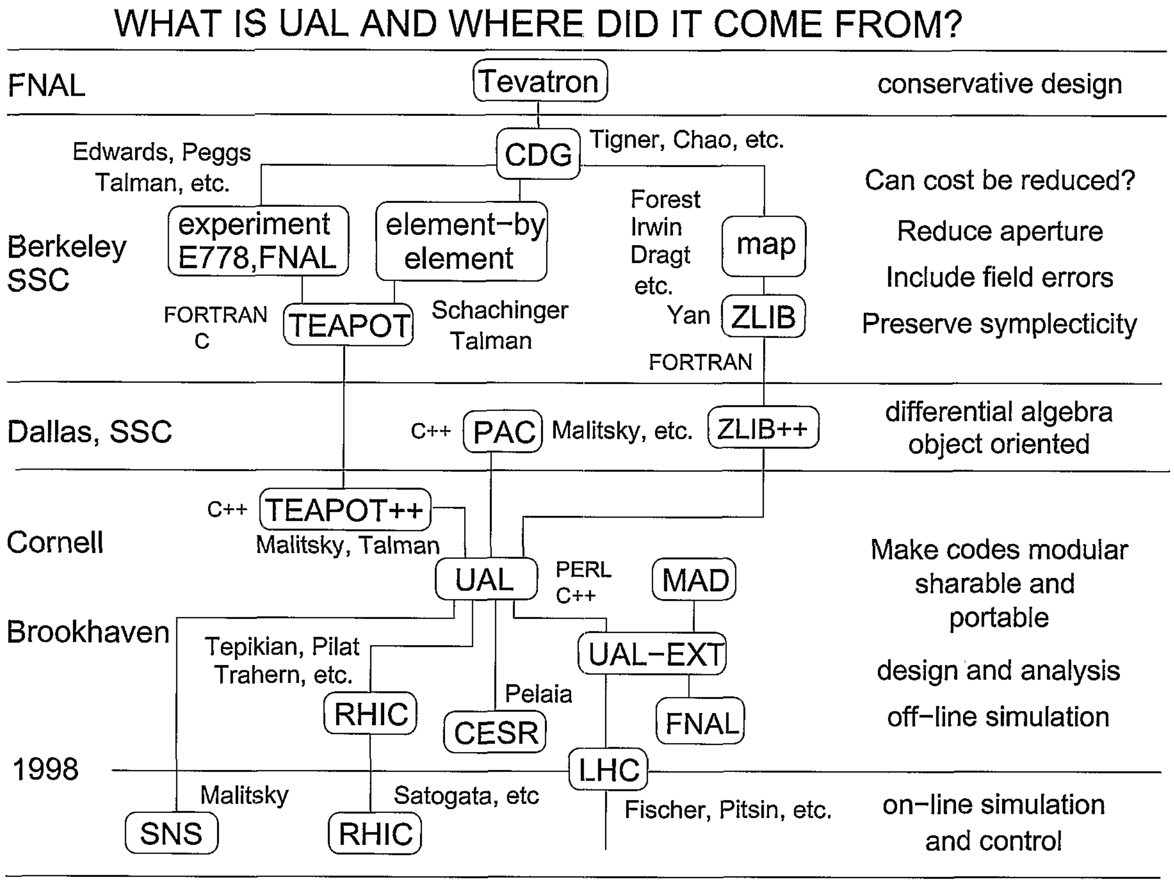
Two other MPI commands appearing in the script, `MPI_Wtime()` and `MPI_Barrier`, are concerned with timing the calculation. When the same program, such as this one, is running on multiple processors, there needs to be a mechanism for determining when all processes are complete. A "barrier" is a special collective operation that does not let the process continue until all processes have called `MPI_Barrier`. In this script this capability is applied only to the mundane task of establishing `$timeStop`.

Appendix A. Ancestry of UAL

The ancestry of UAL can be traced back as far as the early days of the SSC (Superconducting SuperCollider) even before it had that name, when it was being designed at the CDG (Central Design Group) in Berkeley.

As the SSC was being planned, it was realized that a design as conservative as the Fermilab Tevatron might be unacceptably expensive. At the CDG plans were set in motion to study this issue experimentally (Fermilab Experiment E778) and by computer simulation and other theoretical studies.

The program TEAPOT[18], was developed both to design and analyse experiment E778 and to anticipate performance of the SSC using computer simulation. At the same time, and the same place, mapping techniques and differential algebra were being developed to put the numerical work on a firmer and more powerful theoretical foundation. After the SSC project moved to Dallas a computational structure called PAC (Platform for Accelerator Computations)[19–20] was developed, with the purpose of permitting the integration of diverse computer codes. PAC adopted the "object oriented" approach (whose value was just becoming universally appreciated at the time) to computer software. At Cornell, in the period following the termination of the SSC, this architecture was exploited to integrate TEAPOT++ (upgraded from procedural Fortran and C to object oriented C++) along with PAC and DA into UAL (Unified Accelerator Libraries.)[1] For the first time in UAL, this permitted element-by-element tracking to be integrated with analyses using maps of arbitrary order. This satisfied the goal: "Special-purpose codes should be modular in ways that permit them to be combined as parts of more general calculations." (Aside: the recently developed Element-Algorithm-Probe framework greatly expands this capability.) The next code to be integrated (though only through adoption of input format) into this environment was MAD (Methodical Accelerator Design) which is the pre-eminent lattice code for designing transfer lines and sectors of high energy lattices. Shortly thereafter, responsive to "Call for a New Accelerator Standard"[21] and driven by the need, within the US-LHC collaboration, for a mechanism to share design information of the LHC, a Standard Exchange Format (SXF)[22] was developed and integrated into UAL, (as well, of course, as into CERN database programs.) (ADXF) Accelerator Description Exchange Format, a closely related, XML-based, self-describing lattice description standard was developed (but not implemented) at the same time.[23] Much of this history is indicated by the flowchart Fig. A.1, shown here:



Subsequent work concentrated on applying this computational environment to practical accelerators. Much of the effort has been of a fairly mundane nature, performing input conversions and interfacing between UAL and heterogeneous "proprietary" codes by placing "wrappers" around the programs and data files that have developed over the years of operation of accelerators like FNAL and CESR. It was more straightforward to apply UAL to RHIC (Relativistic Heavy Ion Source), because of its more recent vintage, and UAL contributed to the design of RHIC[24], and even, to some extent, to its model-based control. This begins to achieve the design goal: "The same code used for the design and analysis of the accelerator should be built into the control system of the accelerator." Work on UAL continued after Malitsky went to the SNS in 1999.[25–26] This has included the capability of importing special purpose codes ACCSIM and ORBIT into the UAL environment. This adds capabilities such as space charge analysis, radiation damage, and injection "painting" into the simulation environment.[27–28] Also progress was made toward integrating UAL into the SNS control system. Currently FastTeapot is being incorporated into the RHIC control system.

Appendix B. Glossary

B.1. Acronyms

ACCSIM	F. Jones Material/Bunch/Collimation code,[29]
ADXF	Accelerator Description Exchange Format[23]
AIM	Accelerator Instrumentation Module
ALE	Accelerator Libraries Extensions
APD	Accelerator Propagator Description
API	Application Program Interface
CVS	Concurrent Version System[7]
DA	Differential Algebra
DDD	Data Display Debugger
DOXYGEN	Documentation Generator
FTPOT	Fortran Teapot
MAD	Methodical Accelerator Design[5]
ICE	Incoherent and Coherent Effects (M. Blaskiewicz)
MPI	Message-Passing Interface[16] or if one prefers, MultiProcessor Interface
ORBIT	Objective Ring Beam Injection and Tracking[30]
PAC	Platform for Accelerator Codes[20]
PERL	Practical Extraction and Report Language
PERLXS	Perl eXternal Subroutine
SIF	Standard Input Format[31], MAD etc. input language
SMF	Standard Machine Format[1]
SPINK	tracks polarized particles in circular accelerator
SXF	Standard eXchange Format[22]
TEAPOT	Thin Element Program for Optics and Tracking[18]
TIBETAN	Jie Wei's acceleration code
UAL	Unified Accelerator Libraries[1]
UAL2	Java accelerator-commissioning version of UAL[26]
UI	User Interface
XML	eXtensible Markup Language
ZLIB	Y. Yan DA library,[32–33]

While browsing the UAL directory tree to "get the big picture" it can be useful to see all files with a given file name extension. For example, one might wish to see all available examples. All such examples are Perl main programs, and all such programs have the file name extension `.pl`. The rough area of applicability of a script can be inferred from the name of the directory in which it is contained. Here is an instruction to list all examples, followed by two lines of response:

```
    % cd $UAL; find . -name "*.pl" -print
 ...
 ./examples/ShortMPI/test_MPI.pl
 ./examples/UI/shell_sns.pl
 ...
```

As mentioned before, the scripts in directories other than `./examples`, though out-dated, can be browsed and, in most cases, run. Some may be useful for code test purposes.

B.2. File name extensions

.bs, .xs, .xsc, .PL	Perl/C++ interface
.c	C source code
.cc, .cpp	C++ source code
.css	Cascading Style Sheet
.hh, .h	C++/C header
.ll, .yy	lex, yacc parser support
.pl	Perl main program
.pm	Perl Module
.map, .zmap	DaVTps map
.cfg	configuration data
.so	shared library
.sxf	SXF lattice description

Appendix C. Accelerator Parameters

The contents of this appendix will probably move to the "UAL Physics Manual" when that document comes into existence.

C.1. Global geometry and survey

The global (X, Y, Z) and local (x, y, s) coordinate systems used by UAL are identical to those used by MAD[5]. The global survey code was ported from that source, as was much of the discussion in this section. There is a strong prejudice towards having the reference orbit lie close to a plane perpendicular to the Z-axis.[†]

The `survey` command reconstructs the global coordinates of all elements in the lattice. For this purpose all elements except RBEND's and SBEND's are treated as drifts. Elements like KICKER's, which could, in practice, influence the closed orbit, are assumed to have been set to zero. Similarly, QUAD's etc., which would steer the beam centroid if they were misaligned, are assumed not to be misaligned for purposes of first calculating the ideal closed orbit. For the lattice to make sense as a storage ring the lattice should "close", but exact closure (or any degree of closure whatsoever) is not required. In multiturn tracking every particle is displaced to take up any closure defect as its orbit passes the origin. Though unphysical, this discontinuous translation is at least symplectic and is unlikely to cause any harm to a simulation, provided it is not very large.

Unlike the `survey` command, the `analysis` command calculates the closed orbit in the presence of all steering perturbations just mentioned, and also includes any vertical steering due to RBEND and SBEND roll errors.

The global coordinates, both displacements and angles relative to the global (X, Y, Z) frame, are exhibited in Fig. C.1.1, which is a revised (but not intentionally changed) version

[†] Within the TEAPOT module the prejudice toward the reference orbit lying in a single plane goes so far as to exclude non-horizontal RBEND and SBEND components. Out of plane reference orbits have to be modeled by KICK elements. This restriction could be, but has not been, lifted using the Element-Algorithm-Probe framework. In any case this restriction is orthogonal to the definition of both local and global coordinates.

of a figure in the MAD manual.[5] Fig. C.1.2 shows the beginning of the reference trajectory. It starts, by definition, at $(X, Y, Z) = (0, 0, 0)$ and is directed along the global Z-axis.

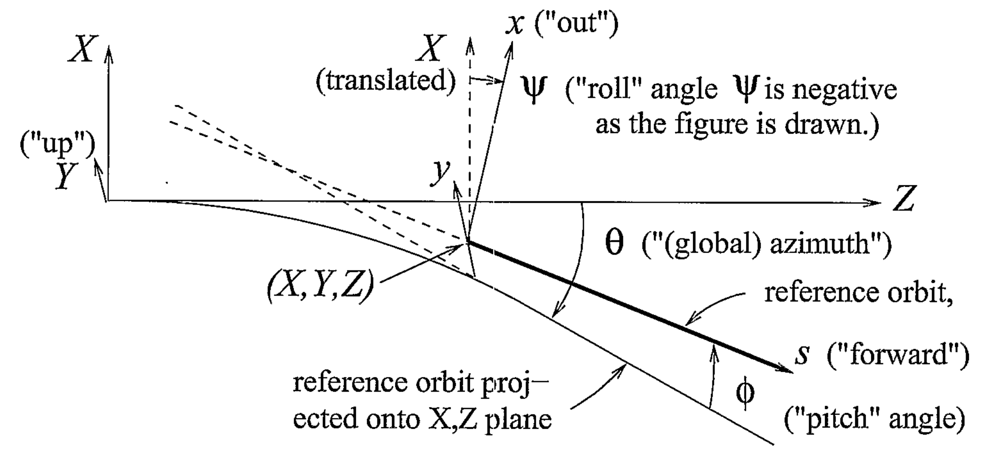


Figure C.1.1: Global coordinate definitions showing angles that define the direction of the reference orbit relative to the global (X, Y, Z) frame. Copied (with revision, but no intentional change) from MAD[5].

A local coordinate triad for the reference orbit passing through global position (X, Y, Z) can be obtained by successively applying, to the global triad, the rotation matrix $\mathbf{W} = \Theta\Phi\Psi$, where Θ, Φ, and Ψ are 3×3-matrices, expressed in terms of the respective angles θ, ϕ, and ψ shown in Fig. C.1.1:†

$$\Theta = \begin{pmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{pmatrix}, \; \Phi = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{pmatrix}, \; \Psi = \begin{pmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{pmatrix}. \tag{C.1.1}$$

The local s-axis points along the reference orbit, the local y-axis is (ordinarily) parallel to the magnetic field axis, and x is chosen to be positive "outwards"; y-axis orientation is fixed by the requirement that the (x, y, s) triad be right-handed. The signs depend on the sign of the particle charge and the magnetic field. Fig. C.1.2 is drawn assuming positively charged particles in an accelerator with bending magnetic field directed along the positive Y axis. (For these choices the entire accelerator lies in the negative X half-space.) Because the x and y axes would vary erratically (i.e. angle ψ would be erratic) if referred to the local magnetic field direction, the best policy is probably to require the y axis to be always

† The orientation of matrix Θ in Eq. (C.1.1) has been reversed relative to the formula given in the MAD manual in order to conform to Fig. C.1.1 while leaving global azimuth angle positive.

parallel to the Y axis, which defines a kind of globally-averaged magnetic field direction. In any case it is required that there be no net "twist" of coordinate ψ while advancing completely around the ring.

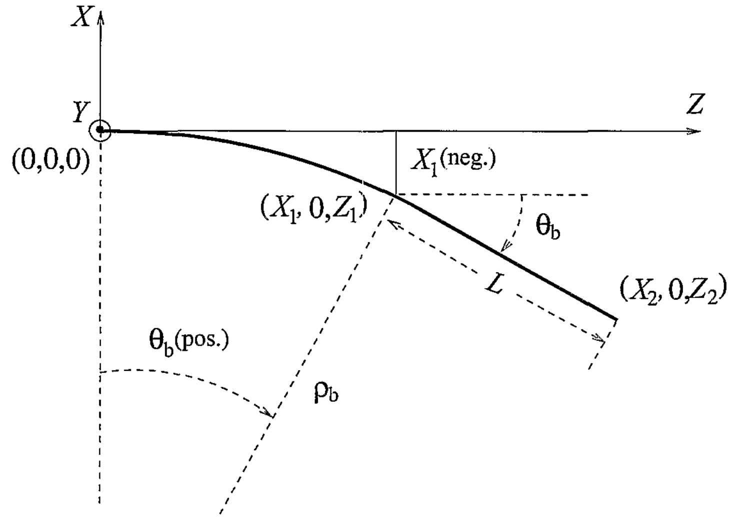


Figure C.1.2: The reference particle starts at the lattice origin and passes through a bend followed by a drift. The orientation of the orbit and the signs of the coordinates assume the particle charge is positive and that the magnetic field points (up) along the positive Y axis.

With the global position of the reference orbit specified by vector $\mathbf{V} = (X, Y, Z)^T$ and its local orientation by matrix $\mathbf{W}$, these quantities are updated element-by-element using the equations

$$\mathbf{V}_i = \mathbf{W}_{i-1}\mathbf{R}_i + \mathbf{V}_{i-1}, \quad \mathbf{W}_i = \mathbf{W}_{i-1}\mathbf{S}_i, \tag{C.1.2}$$

where, at the origin, $\mathbf{V}_0 = \mathbf{0}$, and $\mathbf{W}_0 = \mathbf{1}$ (the identity matrix) and where $\mathbf{R}_i$ and $\mathbf{S}_i$ are, respectively, the translation vector and the rotation matrix appropriate for the i-th element.

To illustrate this evolution, and especially the signs, consider the bend element at the beginning of the lattice in Fig. C.1.2. Its displacement vector $\mathbf{R}_1$ and rotation matrix $\mathbf{S}_1$ are

$$\mathbf{R}_1 = \begin{pmatrix} \rho_b(\cos\theta_b - 1) \\ 0 \\ \rho_b \sin\theta_b \end{pmatrix}, \quad \mathbf{S}_1 = \begin{pmatrix} \cos\theta_b & 0 & -\sin\theta_b \\ 0 & 1 & 0 \\ \sin\theta_b & 0 & \cos\theta_b \end{pmatrix}, \tag{C.1.3}$$

where radius of curvature ρ_b and bend angle θ_b are both positive (for the assumed charge and field direction). Then, by Eqs. (C.1.2), $\mathbf{V}_1 = \mathbf{R}_1$ and $\mathbf{W}_1 = \mathbf{S}_1$. For the drift that follows

$$\mathbf{R}_2 = \begin{pmatrix} 0 \\ 0 \\ L \end{pmatrix}, \quad \mathbf{S}_2 = \mathbf{1}, \qquad (C.1.4)$$

which yield

$$\mathbf{V}_2 = \mathbf{W}_1\mathbf{R}_2 + \mathbf{V}_1 = \begin{pmatrix} \cos\theta_b & 0 & -\sin\theta_b \\ 0 & 1 & 0 \\ \sin\theta_b & 0 & \cos\theta_b \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ L \end{pmatrix} + \begin{pmatrix} \rho_b(\cos\theta_b - 1) \\ 0 \\ \rho_b \sin\theta_b \end{pmatrix} \qquad (C.1.5)$$

and

$$\mathbf{W}_2 = \mathbf{W}_1\mathbf{S}_2 = \begin{pmatrix} \cos\theta_b & 0 & -\sin\theta_b \\ 0 & 1 & 0 \\ \sin\theta_b & 0 & \cos\theta_b \end{pmatrix} \mathbf{1} \qquad (C.1.6)$$

C.2. Local particle coordinates

There has been an unfortunate lack of consistency in the definition of particle phase space coordinates in accelerator programs. In no case are the coordinates precisely equal to canonical coordinates (x, y, z, p_x, p_y, p_z). For the sake of generality and neutrality a generic set of coordinates will be referred to here as $(x_1, x_2, x_3, x_4, x_5, x_6)$ and some of the choices are indicated in Table C.2.1. In all of the cases in the table (though not necessarily for other codes) longitudinal momenta offsets are "normalized" by a reference momentum p_0 or energy offsets are normalized by reference energy E_0.

The transverse (x, y) coordinates are common to all systems and, in all cases, the transverse "momentum" coordinates (x_2, x_4) are identical in the "paraxial" or "linearized" order of approximation. As a result it is relatively straightforward, because they are "first order" to compare transfer matrices produced by different programs. Quantities that can be extracted from the transfer matrices, such as tunes, are easily compared for the same reason. But to the next, and higher, orders there is no consistency. This makes it especially difficult to compare high order maps generated by different programs, or even elementary accelerator parameters such as chromaticity. Within UAL there needs to be provision for translating between pairs of these conventions; the most important combination being MAD/TEAPOT. UAL performs these translations transparently to the user.

Fortunately the coordinate choice option has no impact on the external description of the standard hardware elements that enter accelerator lattice descriptions.

Table C.2.1: Comparison of various (input file) notations for particle phase-space variables.

Source	Related quantities					
general	x_1	x_2	x_3	x_4	x_5	x_6
canonical	x	p_x	y	p_y	z	p_z
Courant-Snyder	x	$x' = dx/ds$	y	$y' = dy/ds$	Δt	$(p - p_0)/p_0$
TRANSPORT	X(1) x	X(2)= $\sin^{-1} \frac{p_x}{p}$	X(3)= y	X(4)= $\sin^{-1} \frac{p_y}{p}$	X(5)= Δl	X(6)= $(p - p_0)/p_0$
MAD	X= x	PX= p_x/p_0	Y= y	PY= p_y/p_0	DT= $-c\Delta t$	DELTAP= $(E - E_0)/(p_0 c)$
TEAPOT	X= x	PX= p_x/p_0	Y= y	PY= p_y/p_0	DT= $-\Delta l$	DP= $(p - p_0)/p_0$

Appendix D.
The Evolution of Standard Machine Format (SMF)

D.1. The SMF object model

The heart of UAL is SMF (Standard Machine Format). It is an abstract accelerator object model capable of including all parameters of a lattice or lattices under study. It is, in principle, capable of being realized in various forms, internal or external, human or machine-readable. But, in this manual, the term SMF will mainly apply to the internal (to UAL) classes containing all lattice parameters.

The organization of SMF is exhibited graphically in Fig. D.1.1; actually two separate object models are shown in the same figure. The more detailed version, (a), exhibits the original implementation. Version (b) exhibits a more succinct, pattern-based, model, which represents the same data in an up-to-date implementation.

The historical evolution of lattice descriptions is briefly reviewed in Appendix A. The first attempt at standardization was SIF (Standard Input Format)[31] which has evolved into MAD.[5] These formats have been sufficiently general to support much accelerator design and simulation. They are however "closed", meaning they are non-extensible, or rather, extensions can be made only unilaterally or by mutual agreement. Though the former has been common, the latter, more satisfactory, approach has typically required a degree of organization greater than the community has been able to muster. One attempt, SXF[22], a portable lattice description supporting fully-instantiated parameter values (i.e. including deviations), has had some acceptance.

SMF is an abstraction or generalization of formats such as these; the primary motivation is to support *extensibility.* The default accelerator types and their attributes are pretty much the same as in these formats, but the introduction in a disciplined way of new types, and new attributes for existing types, is supported. Without this flexibility it would not be possible to incorporate diverse modules.

Fig. D.1.1(a) shows the original SMF implementation. One sees both a *DESIGN* lattice and a *FLAT* lattice. The *DESIGN* lattice is based on generic elements `GenElement's` and

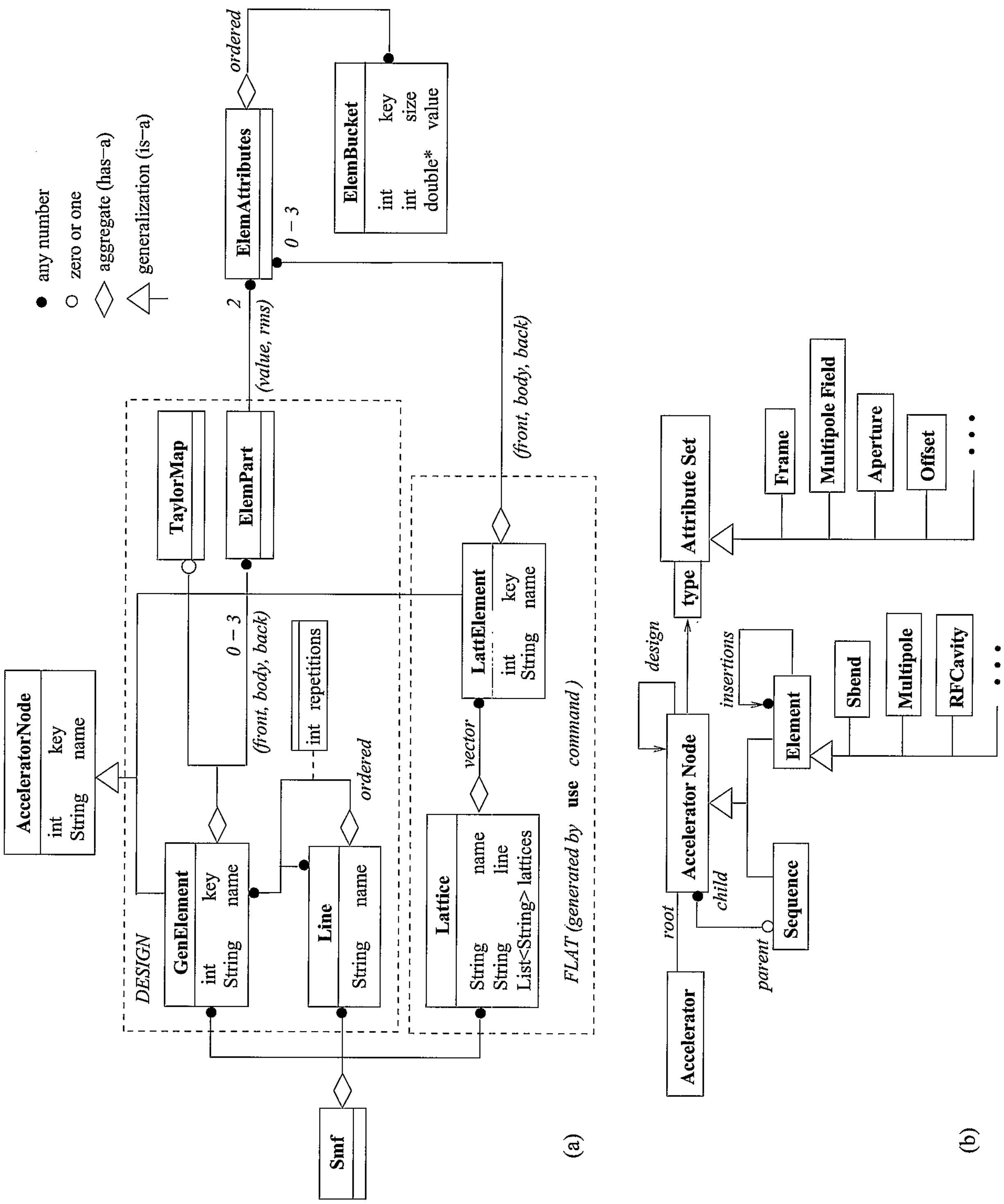


Figure D.1.1: Standard Machine Format (SMF) accelerator lattice object models: (a) Initial implementation. Object classes are indicated by rectangles, associations by connecting lines. (b) Up-to-date, design pattern representation of the same data; less detail is exhibited.

(sub-)`Line`'s recursively aggregated into `Line`'s. Line repetition, for example to represent multiperiodicity, is supported as part of the *DESIGN*. Element parts *front, body,* and *back* are explicitly recognized. `LatElement`'s are the fully-instantiated (deviations-included) physical elements existing in the tunnel. (At least initially) the *FLAT* lattice is logically equivalent to the *DESIGN* lattice, but it represents the lattice as a single line, with no sub-lines and no element repetitions. At this level the element attributes are simply repeated even though this involves a lot of duplication if (as is usual) the same generic elements are used repeatedly. Alternatively, for describing the ideal machine, it would be sufficient to retain pointers to the design parameters. Ultimately though, every element in the tunnel has its own identity, so each of its attributes does also. A typical purpose for simulation is to study the effect of the deviations of these parameters from their design values. Unless storage capacity is an issue it is therefore most useful to have both elements and attributes flattened in the *FLAT* lattice. Also, because comparisons with the design lattice will always be of interest, it is appropriate to maintain copies of both *DESIGN* and *FLAT* lattices.

Fig. D.1.1(b) shows a more succinct but more-or-less equivalent object model of SMF. It represents the evolution, based on experience, to a more efficient organization. In this figure the distinction between design and flat lattice is not exhibited explicitly (even though it is still present.) More essential differences are the presence of a single `Element` class, the introduction of *design* and *insertion* associations, and the treatment of "front", "body", and "back" as explicit elements.

Rather than giving a full verbal explanation of SMF only a few comments will be made, starting with distinctions between Fig. D.1.1(a) and (b):

- `GenElement`'s and `LatElement`'s are distinguished primarily by their parameter values, a somewhat artificial distinction. This is why only `Element` appears in (b). Nevertheless, as noted above, it is appropriate to retain the design parameters even when an element's parameters are changed. The *design* association of Fig. D.1.1(b) models this.
- When SIF was introduced, since every physical element has an entrance and an exit, and the fields in these regions influence orbits, it seemed natural to include

frontend and backend descriptions along with the body descriptions of accelerator elements. This feature has been retained in (external) descriptions such as MAD and SXF. But, in practice, the effects of these ends are usually modeled as if they were individual elements, typically multipole elements. There is a substantial cost, in coding effort and complexity, of maintaining the "front", "body", and "back" categories of element attributes, since all evolution-modeling algorithms have to support the distinction. In the up-to-date (internal) implementation of SMF the distinction is suppressed as shown in Fig. (b). The functionality is restored by the *insertion* operation, and the `Accelerator Node` abstraction. For external lattice representations that package end effects with elements it is necessary for the input parser to separate the end data appropriately.

- The grouping of element attributes into classes `Frame` (for gross geometry), `Multipole Field` (for deflections), `Aperture` (for particle loss) and `Offset` (for misalignment), etc. packages the data contained in the `ElemBucket` part of Fig (a).

Further comments about Fig. D.1.1:

- The actual implementation of lattice description can have a significant impact on performance (computation speed) of simulations. Depending on the complexity of the lattice and the computation power available, this may or may not be significant. When SMF was first implemented, to speed the traversal of the flat lattice, lines were represented by (fixed length) vectors, as shown in Fig. D.1.1. But a vector does not support insertion, an essential feature according to the above argument. It has therefore been necessary to represent the lattice by a list rather than by a vector.†
- Objects are identified by their names, as indicated by the "String" attributes shown in the figure. The "key" attributes shown provide an alternative object identification provided for fast access.

† Changes such as the replacement of vector by list are straightforward in principle, but they have not yet been made uniformly across all modules of UAL. To the extent possible such heterogeneity is hidden at the level of user scripts, but this causes the scripts to be more specialized and restrictive than they would ideally be.

- One novel aspect of SMF is the inclusion of both *value* and *rms* uncertainty for parameters of the design lattice. In Monte Carlo simulations the random assignment of parameter deviations to actual elements can be based on the *rms* entries.
- Another novel feature is the (optional) inclusion of a Taylor map to describe the effect of the element on a particle or bunch of particles.
- It has sometimes been considered essential to preserve the hierarchical organization of the *DESIGN* lattice even after the flattening process. Consider, for example, structure resonances; they depend critically on lattice symmetries which are only apparent in a hierarchical description. Another example is families of elements distributed around the ring, perhaps sharing the same bus because they form a systematic correction circuit. We have found it easy to model features such as these even in the fully flattened description in which hierarchy has not been explicity retained. This is is accomplished using families specified by regular expressions, as has been explained previously. Several examples are given in this manual.

D.2. SMF/RHIC example

This example is not useful as a template from which to generate a practical simulation. Its input format will soon be made obsolete in an upgraded UAL and the files may be available only on the RHIC system. Te purpose of the example is make concrete the sort of information stored in SMF, to show its features, and to explain the motivation that has driven its evolution. This section should be skipped by anyone concentrating on building a new simulation.

To run this example, using the environment variable `$UAL_RHIC` (available only on RHIC systems) enter

```
$ cd $UAL_RHIC/examples/SMF
$ cat SMF.pl
$ perl SMF.pl
```

to view and run the following UAL script: ①

```
use lib ("$ENV{UAL_RHIC}/api/"); #1
use RHIC::SMF::SMF; #2
my $dir = "$ENV{UAL_RHIC}/data/injection"; #4
local $smf = new RHIC::SMF::SMF(); #5
require "$dir/rhicSMF_level_1.pl"; #10
require "$dir/rhicSMF_level_2.pl"; #11
require "$dir/rhicSMF_level_3.pl"; #12
$smf->restore(line   => "blue",
              fields => ["$dir/rhicSMF_QR4_deviations.pl",
                         "$dir/rhicSMF_D96_deviations.pl",],); #18
$smf->store(file  => "./out/smf/optics",
            field => "./out/smf/errors"); #26
```

In line #5 the lattice description is declared to be of type `RHIC::SMF::SMF`, which is to say, specialized to RHIC. Lines #10 through #12 amount to being a simple continuation of the present script. (Recall that the `require` inlines the listed script, as if it were simply part of the enclosing script.) A few lines at both the beginning and end of script `rhicSMF_level_1.pl`, which defines parameter values, are shown next: ②

```
$Nothing = 0;
$lxspace = 8.749000000000001;
$lbx = 0.225;
$ldxb = 0.826;
$k1lexdx = 0;
 ...
$k04c2b = 0;
$k3a4 = 0.0548196561;
1;
```

This block lists the values of all previously defined parameters. (As it happens these parameters are not actually used in the present script.) Next shown are lines from `rhicSMF_level_2.pl` which names elements and defines their attributes: ③

```
$smf->elements->declare($Marker, "clock6");
$smf->elements->declare($Drift, "oxspace");
$oxspace->set(8.749000000000001*$L);
$smf->elements->declare($Drift, "obx");
$obx->set(0.225*$L);
$smf->elements->declare($Vmonitor, "bpmv");
$bpmv->set(0*$L);
$smf->elements->declare($Monitor, "cplmon");
$cplmon->set(0*$L);
 ...
$smf->elements->declare($Quadrupole, "q1i6");
$q1i6->set(1.44*$L, 0.080074761264*$KL1, 0*$TILT, 2*$N);
$smf->elements->declare($Sbend, "d0mm05");
$d0mm05->set(3.588966230691121*$L, -0.01518625207276691*$ANGLE, 0*$TILT);
1;
```

Some of the entries in this file can be recognized to be reserved words. Some are element types, such as `$Marker`, `$Drift`, `$Vmonitor`, `$Quadrupole`, and `$Sbend`, and some are attributes, such as `$L`, `$KL1`, `$TILT`, and `$ANGLE`. File ③ names all the `GenElement`'s and assigns values to all of their attributes.

The remaining `require`'d script is `rhicSMF_level_3.pl`: ④

```
$smf->lines->declare("str06bx");
$str06bx->set($oxspace);
$smf->lines->declare("dx06b");
$dx06b->set($obx, $bpmv, $cplmon, $bpmh, $odxb, $dxmp, $odxcltrp);
$smf->lines->declare("str06b0");
$str06b0->set($o0space, $mvalve, $obelski);
 ...
# beamline level 8
$smf->lines->declare("bper8");
$bper8->set($b06, $b07, $b08, $b09);
$smf->lines->declare("bper12");
$bper12->set($b10, $b11, $b12, $b01);
$smf->lines->declare("bper4");
$bper4->set($b02, $b03, $b04, $b05);
# beamline level 9
$smf->lines->declare("blue");
$blue->set($clock6, $bper8, $bper12, $bper4);
```

This script defines all beamlines and, in particular, the complete lattice `blue`. This has completed the definition of the *DESIGN* lattice shown in Fig. D.1.1.

There are two subsidiary scripts that are useful in performing the simulation. One of them is `$UAL_RHIC/examples/SMF/out/smf/optics` which contains lines like ⑤

```
 ...
clock6   : marker
 ...
oxspace  : drift       , l = 8.749
 ...
dxmp     : sbend       , l = 3.70021937558562, angle = -0.0188607907827331
 ...
xki4     : sbend       , l = 0.8 , tilt = 1.5707963267949
xlamb    : drift       , l = 4.00072211
blue : line = ( &
  clock6   , oxspace , obx      , bpmv     , cplmon   , bpmh     &
, odxb     , dxmp    , odxcltrp, o0space , mvalve   , obelski  &
, od0flx   , d0pp06  , od0fla   , obeld0q1, oflq1x   , bpmv     &
, cplmon   , bpmh    , obq1     , q1o6     , oflq1a   , obelq1q2 &
, ocfl2    , olmp1   , kickh    , b3m06c1b, b4m06c1b, b5m06c1b &
 ...
, odxb     , bpmh    , cplmon   , bpmv     , obx      , oxspace  &
)
```

As well as defining all elements, they are here listed sequentially in the fully-flattened line `blue`. This file has been generated by the code that was described in section 6.2 ⑦ . After appending the commands listed there this file can be processed by FTPOT.

Another useful subsidiary file is `$UAL_RHIC/data/injection/rhicSMF_index.pl` which contains: ⑥

```
%smfI = (
0 => "clock6",
1 => "oxspace",
2 => "obx",
3 => "bpmv",
4 => "cplmon",
5 => "bpmh",
6 => "odxb",
7 => "dxmp",
 ...
4648 => "obx",
4649 => "oxspace",
);
1;
```

One sees that this has defined a Perl hash which permits the rapid, sequential lookup of element names (hash *value*) in the flattened lattice from their position in the lattice (hash *key*). Lookup times for hashes like this are minimized by using the *gperf* utility.

Finally, field deviations are encorporated by the script `rhicSMF_QR4_deviations.pl` which, as the comment states, contains a hash of arrays for Q4 deviations, to be applied to elements matching the given regular expression. It begins ⑦

```
# create hash of arrays for Q4 deviations
$field_set_pattern = "^(q4i(?!t)|q4o(?!t))";
$field_set = [
 [ "QR4120",  [3.061873504273504e-10, 0, -0.0006297661423589744,
               0.0008720215740170938, -0.7227001269606835, -126.8879572151795,
              -73.9944598536752, -37022.31279458461, -41135.90310509401,
              -169279257.8510112, 0, 0, 3.294690580168208e-296,
               4.458448388071409e-316, 0.6893869432341878, -118.6576412356923,
               120.397765185641, 2307.623832724786, -171566.8153895384,
               27651353.40430221,],
 ],
 [ "D96524",  [4.564153846153912e-05, 7.410902400000001e-07,
               -0.01897419042166154, -0.008756266220307693, ...],
 ], ...
];
1;
```

The script `rhicSMF_D96_deviations.pl` is similar.

The data files that have been introduced, ② , ③ , ④ , and ⑦ , are human readable and are, in principle, editable. Some have been produced by hand, some by machine. They represent yet another method of populating SMF, but this method is now obsolete and will cease to be supported in the future. The files have been exhibited here only to lend concreteness to SMF.

One supported method of populating SMF uses `Mad Parser` which inputs a design lattice and, optionally, outputs the corresponding SXF or TEAPOT file. Another supported method is `SXF Parser`, which inputs a flat, fully-instantiated lattice. The ancestry of any particular SXF file cannot be inferred explicitly from the SXF file itself, but it would be possible to reconstruct the design lattice (from which the SXF derives) by associating a generic parent element with each flattened element.

D.3. ADXF: Accelerator Description Exchange Format

ADXF is an XML-based lattice description language.[23] The schema for a matching "Optics database", patterned to some extent after the LAMBDA design of Peggs et al.,[34] has been designed by Malitsky.[35] The variety of element attributes are shown in Table D.3.1, grouped into "attribute sets".[†] The supported accelerator elements are listed in Table D.3.2 along with their applicable attribute sets. All elements have a length attribute apart separate from any attribute set. As well as this length, magnetic elements also have a magnetic length. As has been emphasized, both element types and attribute list types are extensible.

[†] Internal to UAL "attribute sets" are referred to as "buckets". The replacement has been made in external documentation since the term "bucket" has been said to be confusing.

Table D.3.1: ADXF attribute sets and their attributes

Attribute Set Type	Attributes	Comments
bend	hangle	horizontal bend angle
	vangle	vertical bend angle
mfield	lmag	magnetic length
	knl	array of normal multipole coefficients
	ktl	array of skew multipole coefficients
rffield	volt	array of RF voltages
	lag	array of phase lags
	harmon	array of harmonic numbers
alignment	x	x-direction offset
	y	y-direction offset
	z	z-direction offset
	phi	(small) rotation around x-axis
	theta	(small) rotation around y-axis
	psi	rotation around s-axis
aperture	shape	aperture shape
	x	horizontal half-aperture
	y	vertical half-aperture
efield	ex,ey	E_x, E_y
sfield	ksl	integrated solenoid strength
beambeam ("weak-strong" representation as lattice element)	xma,yma	$\langle x \rangle$,$\langle y \rangle$
	sigx,sigy	$\sqrt{\langle (x - \langle x \rangle)^2 \rangle}, \sqrt{\langle (y - \langle y \rangle)^2 \rangle}$
	npart	number of particles
	charge	charge

Table D.3.2: Basic elements recognized by ADXF, and their attributes. All elements have a *length* attribute, and may have an aperture attribute set.

Element type MAD	attribute sets
marker	
drift	
rbend sbend	bend mfield alignment
quadrupole sextupole octupole multipole hkicker vkicker kicker	mfield alignment
solenoid	sfield
rfcavity	rffield
elseparator	efield
monitor vmonitor monitor	
instrument	
ecollimator rcollimator	aperture
beambeam	beambeam

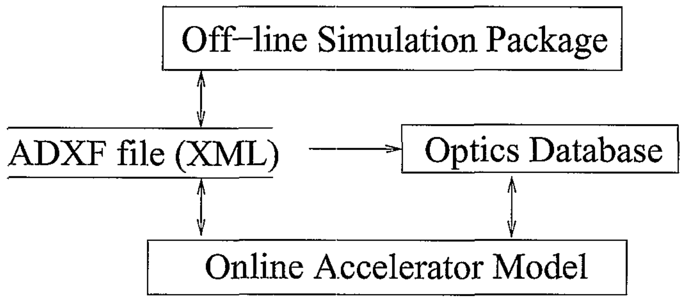


Figure D.3.1: Interconnections of Optics database, online model, and off-line simulation package via the ADXF file.

The interconnections of Optics database, online model, and off-line simulation package via the ADXF file is exhibited in Fig. D.3.1. The database structure is readily describable in XML (Extensible Markup Language). The self-describing feature of XML makes the extensibility of SMF straightforward. Another virtue of ADXF file (and the essentially similar SXF file) is to provide a "snapshot" of the instantaneous operational optics configuration of the accelerator. This can be used for off-line or, for that matter, online analysis.

The RHIC/SXF elements and attributes are essentially, though not exactly, the same as in the tables of this section.

Appendix E.
Truncated Power Series and Lie Maps

This section more properly belongs in the "UAL Physics Manual". It is parked here until that manual comes into existence.

E.1. Function evolution

Truncated power series play an important role in UAL. Their role is to approximate the "maps" that express "output" particle coordinates (at some place in the ring) in terms of "input" particle coordinates (at a different place in the ring). When truncated to linear order these power series reduce to the elements of the traditional, Courant-Snyder, transfer matrix description of the accelerator lattice. Historically, most of accelerator physics has been (very successfully) based on analysis performed in this limit. But effects appearing already at a "next order of approximation" such as chromaticity and amplitude-dependent detuning, have ways of intruding, even in elementary contexts, and nonlinearity becomes increasingly important as amplitudes are increased to achieve higher beam current. As soon as any nonlinearity whatsoever is allowed to enter the description the issue of symplecticity, or rather lack thereof, rears its head. Especially for hadron accelerators, for which there is essentially no true damping, any anti-damping artificially and erroneously introduced through non-symplecticity can ruin an accelerator simulation program's ability to predict the long term future.

Symplectic maps (typically nonlinear) are also known as Lie maps. One therefore seeks to describe particle trajectories in an accelerator by a Lie map. As with all physics, such a description can only be approximate. For one thing the idealized model of the accelerator, on which the "idealized map" is based, is undoubtedly inaccurate and incomplete. Accepting this as inevitable, possible further inaccuracy results from the computer program representation of the map. It is the latter source of inaccuracy that is the subject of this appendix. Maps based on truncated power series can only approximate idealized maps. For reasons explained in the previous paragraph, failure of symplecticity is expected to be more serious than other inaccuracy. An important goal of UAL is to preserve symplecticity, or rather to keep the inevitable failure of symplecticity controllably small.

There is no shortage of excellent reference material concerning Lie maps; for example Dragt[36] and Forest[15]. Because the subject is abstract, and is sometimes considered impenetrable, this appendix tries to give a self-contained, elementary discussion of the general ideas. To reduce complexity the discussion will be restricted to two dimensional, (x, p), phase space; (for simplicity p is used instead of p_x). All results generalize easily to higher dimensions.

If (x_0, p_0) represents input particle coordinates, the sort of map $\mathcal{M}'_{10}$ under discussion expresses output coordinates (x_1, p_1) as functions of input coordinates (x_0, p_0). For linear maps this map reduces to a 2×2 matrix, the traditional transfer matrix of standard accelerator theory. If nonlinearity is present it is natural to introduce a "generalized transfer matrix" $\mathcal{M}'_{10}$ in which the four matrix elements are nonlinear functions of x_0 and p_0). Like it or not, this is the representation one is forced to use in a computer representation of the map.

Consider an arbitrary function $f(x, p)$—one may think of f as expressing the dependence on position in phase space of some physical quantity. A particle trajectory defines an evolution of the particle coordinates and it is natural to inquire about the corresponding evolution of f. One has to be aware of the ambiguity accompanying the distinction between function *form* and function *value*. For example, suppose transformation $\mathcal{M}'_{10}$ yields forward formula $x_1 = x_1(x_0, p_0) = ap_0 + bp_0$ and backward formula $x_0 = x_0(x_1, p_1) = cx_1 + dp_1$, and that the value of function f is defined to be "the first component squared"; at input this is x_0^2, at output it is x_1^2. An assignment one might have received in calculus class was to figure out the value of x_0^2 from knowledge only of x_1 and p_1. Expressed in terms of output coordinates the input value of f is $(x_0(x_1, p_1))^2 = (cx_1 + dp_1)^2$. From a physicist's point of view, this is tortured usage. By the "evolved value of f" one presumably means x_1^2, the square of the first component, evaluated at the evolved location. This is the way functions of coordinates are to be interpreted; for example

$$x_1^2 = f(x_1, p_1) = f\left(\mathcal{M}'_{10}(x_0), \mathcal{M}'_{10}(p_0)\right) = (ax_0 + bp_0)^2 . \qquad (E.1.1)$$

Since the *form* of the function does not change, to evaluate this evolution, as Eq. $(E.1.1)$ shows, it is adequate to have formulas for the evolution of individual components. This is the functionality provided by the vectors of truncated power series provided, for example, by UAL. But, for theoretical purposes, a slightly more abstract generalization of transfer matrices is preferable. Let us define transfer map $\mathcal{M}_{10}$ as operating on *functions* (of location phase space) rather than acting individually on the components. That is

$$f_1 = \mathcal{M}_{10} f_0, \tag{E.1.2}$$

which is defined to mean the same thing as Eq. (E.1.1). Forest calls $\mathcal{M}$ a "compositional map". It is a one-component map acting in an infinite dimensional space (of functions defined on phase space.) Note that it is the *value* of the function that evolves; the *form* of the function does not change. Since x_0 and p_0 can, individually, be thought of as functions of the (x_0, p_0) pair, the specialization back to the representation by a vector-organized set of nonlinear functions is immediate. So there is no "physics" in Eq. (E.1.2) to distinguish it from Eq. (E.1.1).

Assuming, as we are, that the physical elements in the lattice are known perfectly, the equations of motion can, in principle, be used to determine $x(s), p(s)$, the dependence on longitudinal coordinate s of a particle trajectory. Commonly the equations of motion are written in Hamiltonian form and knowing the equation of motion is sometimes expressed as "knowing the Hamiltonian". Because of the complexity of accelerator lattices it is almost never practical to solve the equations of motion analytically and it is rarely practical to solve them numerically. Rather the map through a sector of the lattice is formed by concatenating the maps of the individual elements in the sector. This usually involves truncation of power series.

E.2. Taylor series in more than one dimension and Lie maps

The Taylor series representation of one dimensional functions is second nature to most scientists (perhaps because learned about in high school as the binomial theorem?) The function of Lie maps is to generalize this description to more than one dimension.

The theory of function evolution, as invented by Lie, has been applied a century later, in the context of celestial mechanics, by Hori[37] and, in the context of accelerator mechanics, by Dragt.[38] The discussion here more nearly follows Hori than Dragt.

Let (x, p) be coordinates in 2D phase space, and $f(x, p)$ be a function that is arbitrary (except for possible requirements such as smoothness and absence of vanishing derivatives.)

We wish to express the value of f at some phase space point in terms of the values of its derivatives at some other point.

We know how to do this in 1D—use a Taylor series. We therefore try to reduce the 2D problem to 1D. Toward this end we draw a family of smooth curves in phase space (to be referred to as a "congruence" of curves) that have properties: (a) there is a curve through every point, (b) no curve crosses any other in the region under discussion, and (c) there is a function $S(x,p)$, not necessarily unique, such that $x(\tau), p(\tau)$ (the coordinates of the curve as functions of a running parameter τ) are solutions of the equations

$$\frac{dx}{d\tau} = \frac{\partial S}{\partial p}, \quad \frac{dp}{d\tau} = -\frac{\partial S}{\partial x}. \tag{E.2.1}$$

The function $S(x,p)$ is such that its derivatives on the right hand side of this equation define, at every point (x,p), the direction of the tangent to the curve passing through that point. Note that S is an arbitrary function.

Along any one of the curves of the congruence, the value of arbitrary function f can be expressed, as a function of τ, by $f(x(\tau), p(\tau))$. One can define an along-the-curve derivative operator

$$\{\cdot, S\} \equiv \left.\frac{d}{d\tau}\right|_S = \frac{dx}{d\tau}\frac{\partial}{\partial x} + \frac{dp}{d\tau}\frac{\partial}{\partial p} = \frac{\partial S}{\partial p}\frac{\partial}{\partial x} - \frac{\partial S}{\partial x}\frac{\partial}{\partial p}. \tag{E.2.2}$$

In this notation the $\cdot$ is a "place holder" indicating the operator $\{\cdot, S\}$ is "waiting for" a function, such as f, for its argument. (Except for change in sign/order-of-arguments, $\{\cdot, S\}$ is the same as the function for which Dragt introduced the notation $: S :$.) When acting on function f, the result is $\{f, S\}$, which can be recognized as the "Poisson bracket" of f and S.

Now we can exploit our congruence of curves for its advertised purpose of relating values of f at separated points, at least if the points lie on the same curve because, on that curve, the function depends only on the single variable τ. Let the parameters of the points that are to be related be τ and $\tau + \epsilon$. It may be helpful conceptually to regard ϵ as being "small", and this may be appropriate when discussing the convergence of the series, but no such formal requirement is assumed. Expressing the Taylor series in somewhat unconventional form, we have

$$f(\tau+\epsilon) = \left(1 + \epsilon\{\cdot, S\} + \frac{1}{2!}\epsilon^2\{\{\cdot, S\}, S\} + \frac{1}{3!}\epsilon^3\{\{\{\cdot, S\}, S\}, S\} + \cdots\right) f(\tau+\epsilon)\Big|_{\epsilon=0}, \tag{E.2.3}$$

As usual the derivatives on the right hand side must be evaluated for general ϵ but then ϵ is set to zero. This is known as the Lie map corresponding to function S. Recognizing the terms in this series as corresponding to an exponential function, this series is traditionally abbreviated to

$$f(\tau+\epsilon) = e^{\epsilon\{\cdot,S\}}\, f(\tau)\,; \qquad (E.2.4)$$

but, to evaluate the series, expansion Eq. $(E.2.3)$ is what is required. Furthermore the evaluation has to be truncated at some point. Any differential algebra package, such as COSY[39] or the ZLIB module of UAL, can calculate derivatives of functions, and can therefore evaluate the Poisson bracket expressions appearing in Eq. $(E.2.3)$.

This section has been about calculus, no more, no less. There has been no mechanics, Hamiltonian or otherwise. If the signs in Eq. $(E.2.1)$ had been chosen differently, say both positive, the analysis would go through unchanged except for the switching the sign in the bracket expression, which would therefore no longer deserve be called a "Poisson bracket".

E.3. Symplecticity of Lie map

Hori[37] gave a different interpretation to Eq. $(E.2.4)$, regarding it as a change of variable rather than as an evolution equation. To encourage this interpretation let us replace (x_0, p_0) by (ξ, η) and (x_1, p_1) by (x, p) and interpret the equation as a change of variables from (ξ, η) coordinates to (x, p) coordinates. The coordinates (ξ, η) are assumed to be "canonical"—this means that their Poisson brackets reckoned using some known-to-be canonical starting coordinates, call them (x', p'), have the appropriate, 0 or 1 values. Copying from Eq. $(E.2.3)$ and restoring the 2D arguments of f;

$$f(x,p) = \left(1 + \epsilon\{\cdot,S\} + \frac{1}{2!}\epsilon^2\{\{\cdot,S\},S\} + \frac{1}{3!}\epsilon^2\{\{\{\cdot,S\},S\},S\} + \cdots\right) f(\xi,\eta)\Big|_0 . \qquad (E.3.1)$$

Here S is, as before, an arbitrary function, and evaluation of the derivatives on the right hand side depends upon the congruence of curves determined by Eqs. $(E.2.1)$. (The cryptic subscript 0 is supposed to convey this.)

It was mentioned above that either one of the coordinates, say ξ, is a satisfactory version of the function f. Plugging this into Eq. $(E.3.1)$ yields

$$x = \left(1 + \epsilon\{\cdot,S\} + \frac{1}{2!}\epsilon^2\{\{\cdot,S\},S\} + \frac{1}{3!}\epsilon^2\{\{\{\cdot,S\},S\},S\} + \cdots\right) \xi\Big|_0 , \qquad (E.3.2)$$

and a similar formula relates p to η. By restoring the single variable, along-curve parameterization (and for compactness introducing a vector display) these equations can be written in a more useful form;

$$\begin{pmatrix} \xi\,(\tau+\epsilon) \\ \eta\,(\tau+\epsilon) \end{pmatrix} = \begin{pmatrix} x \\ p \end{pmatrix} = \left(1 + \epsilon\,\{\cdot,\mathrm{S}\} + \frac{1}{2!}\epsilon^2\,\{\{\cdot,\mathrm{S}\},\mathrm{S}\} + \frac{1}{3!}\epsilon^2\,\{\{\{\cdot,\mathrm{S}\},\mathrm{S}\},\mathrm{S}\} + \cdots\right) \begin{pmatrix} \xi\,(\tau+\epsilon) \\ \eta\,(\tau+\epsilon) \end{pmatrix}\Bigg|_{\epsilon=0} \tag{E.3.3}$$

This shows that the pair (x,p) are, except for "translation" along a curve of the congruence, the same as the pair (ξ,η).

This has still been "just calculus", but let us now use the assumption that (ξ,η) are canonical variables of a Hamiltonian system. Then Eq. $(E.3.3)$ provides a change of variables to new variables (x,p). Now the amazing part; since the (ξ,η) variables are, by hypothesis canonical through the region under discussion and (x,p) are just "translations" of (ξ,η), transformation $(E.3.3)$ is necessarily canonical.

Hori[37] goes on to develop a perturbation theory based on this formulism. He regards the function S as a *kind of* "generating function" (though it must not be confused with a "Goldstein" generating function) and goes on to develop an iterative procedure to determine S and new coordinates in ascending powers of a "small parameter" of the perturbation. None of this is relevant for UAL. What *is* relevant is that transformations generated by Lie maps are symplectic. By controlling the number of terms retained in the power series evaluation one can control (or even make negligible) the degree of nonsymplecticity.

E.4. Hamiltonian maps

Returning to the trajectory evolution interpretation of our equations, the Taylor series derived so far might seem to be useless for the following reason: it relates only phase space points lying on the same curve and no prescription has been given for choosing the function $S(x,p)$ such that two arbitrarily chosen points lie on the same curve. But, as it happens, we do not have to insist that the points be arbitrarily chosen. We are interested in points lying on a single particle trajectory. One visualizes this trajectory as a three dimensional curve in the (x,p,t) space, where t is time, or if one prefers, a longitudinal coordinate. Projected onto the (x,p) plane the curve passing through input point (x_0, p_0) necessarily passes through output point (x_1, p_1). The orbit is determined by solving Hamilton's equations;

$$\frac{dx}{dt} = \frac{\partial H}{\partial p}, \quad \frac{dp}{dt} = -\frac{\partial H}{\partial x}. \tag{E.4.1}$$

where $H(x,p)$ is the Hamiltonian function. Notice that these equations are identical to Eqs. $(E.2.1)$ if the function S in those equations is replaced by H (and τ by t.) This magically eliminates both limitations of the formalism of the previous section. The map has become

$$f(t_0 + t) = e^{t\{\cdot,H\}} f(t_0). \tag{E.4.2}$$

(As explained above, when written in this form, this notation is too compressed for the required operations to be exhibited explicitly, as they are in Eq. $(E.2.3)$.) Replacing f by the individual coordinates, as before, yields

$$\begin{pmatrix} x(t_0+t) \\ p(t_0+t) \end{pmatrix} = e^{t\{\cdot,H\}} \begin{pmatrix} x(t_0) \\ p(t_0) \end{pmatrix}. \tag{E.4.3}$$

Generalized to six dimensions and truncated to arbitrary order, Eq. $(E.4.3)$ is a form in which the evolution of a particle trajectory can be simulated in a computer. If Hamiltonian H is only approximate the evolution it produces can be only approximate, but any failure of symplecticity can be reduced by keeping more terms in the expansion.

E.5. Discrete maps

Eq. $(E.4.3)$ represents a continuous mapping—the explicit appearance of t invites taking the limit $t \to 0$. Similarly the occurence of factor ϵ in Eqs. $(E.3.3)$ invites the limit $\epsilon \to 0$ and a continuous interpretation. But, if the ϵ factor is subsumed into the S function, Eqs. $(E.2.4)$ represents a discrete map, potentially propagating the particle coordinates through a sector of arbitrary length.

For example consider the function

$$S = S_0^3 x^3 + S_1^3 x^2 p + S_2^3 x p^2 + S_3^3 p^3. \tag{E.5.1}$$

Substitution into Eq. $(E.3.3)$ yields propagation $(x,p) \to (x', p')$

$$\begin{aligned} x' &= x + \{x, S\} + \ldots = x + S_1^3 x^2 + 2S_2^3 xp + 3S_3^3 p^2 + \ldots, \\ p' &= p + \{p, S\} + \ldots = p - 3S_0^3 x^2 - 2S_1^3 xp - S_2^3 p^2 + \ldots. \end{aligned} \tag{E.5.2}$$

This map is special in that it is an identity map to linear order. It could therefore not represent arbitrary propagation through a general sector. But, after "factoring out" the linear part of a general map the remaining part could be reduced to Eq. (E.5.1) by truncation to quadratic order.

Perhaps the procedure just mentioned can be reversed? Suppose that propagation formulas (E.5.2) have been determined by applying some integrator to an arbitrary lattice sector. If the sector has more than a few nonlinear elements such a determination would have required truncation, for example to quadratic order, as in Eq. (E.5.2). The integrator will therefore have determined the coefficients in expansions

$$\begin{aligned} x' &= x + X_0^2 x^2 + X_1^2 xp + X_2^2 p^2 + \dots, \\ p' &= p + P_0^2 x^2 + P_1^2 xp + P_2^2 p^2 + \dots. \end{aligned} \qquad (E.5.3)$$

For these equations to be consistent with Eqs. (E.5.2) the six equations obtained by equating coefficients must be satisfied. Regarding the four S_i^3 coordinates as the unknowns, they can be determined from just four of the equations. The remaining two equations will not, in general, be satisfied. But, if the integrator determining series (E.5.3) were symplectic (to the order of terms retained), then these equations would be redundant and the redundant equations would necessarily be satisfied. These equations can therefore be applied as a check on the symplecticity of the integrator.

Assuming the integrator is symplectic so that the redundant equations (to quadratic order) are satisfied, the function S will have been determined to cubic order. A function S determined in this way can be called a "pseudo-Hamiltonian". By using this function in Eq. (E.3.3), and retaining more terms in the series, propagation formulas for the coordinates can be obtained to higher than quadratic order. Such formulas would be useless for studying large amplitude features such as resonant islands, onset of chaos, or dynamic aperture. But for "intermediate" amplitude trajectories the formulas can represent propagation that is both "correct to quadratic order" (for example modeling chromaticity) while being symplectic to higher than quadratic order.

This procedure can be illustrated by explicit example. Consider a map

$$\mathbf{x}_2 = \mathbf{M}\,\mathbf{x}_1 \approx \mathbf{M}^{(1)}\,\mathbf{x}_1, \qquad (E.5.4)$$

where $\mathbf{M}^{(1)}$ is the necessarily symplectic, linearized matrix approximation of the map. (Since $\mathbf{x}$ represents the components as a vector, we may as well take it to represent the coordinates in 6D phase space.) Define $\widetilde{\mathbf{M}}$ such that

$$\mathbf{x}_2 = \widetilde{\mathbf{M}}\mathbf{M}^{(1)}\mathbf{x}_1, \quad \text{or} \quad \widetilde{\mathbf{M}} = \mathbf{M}\,{\mathbf{M}^{(1)}}^{-1}. \tag{E.5.5}$$

Suppose that $\mathbf{M}$ has been obtained to some order of accuracy, say $\mathbf{M}^{(2)}$. Then $\widetilde{\mathbf{M}}$ is known to corresponding order. Let S be determined such that

$$\widetilde{\mathbf{M}}^{(2)} = \mathbf{M}^{(2)}\,{\mathbf{M}^{(1)}}^{-1} = 1 + \{\cdot, S\}. \tag{E.5.6}$$

Defining

$$\widetilde{\mathbf{M}}^{(3)} = 1 + \{\cdot, S\} + \frac{1}{2}\{\{\cdot, S\}, S,\}, \tag{E.5.7}$$

then

$$\mathbf{M} \approx \widetilde{\mathbf{M}}^{(3)}\mathbf{M}^{(1)}, \tag{E.5.8}$$

is symplectic to higher order than was $\widetilde{\mathbf{M}}^{(2)}$. The quadrupole end field correction described in section 6.5.2 is an example of this procedure. Since the longitudinal interval for this correction was taken to have zero length, terms beyond the first vanish because they are proportional to higher powers of ϵ.

E.6. Computation time estimates

This section will need to be modified after detailed benchmark time measurements have been performed.

If a lattice is represented entirely by "kicks" (as in TEAPOT) the computation time is proportional to N_k which is at least equal to the number of magnetic elements in the ring, but is typically greater because elements have been subdivided in order to better include thick element effects. A typical value might be $N_k \sim 10^3$. If the computation time per kick is T_k (say $T_k \sim 10^{-6}$ in arbitrary units)[†] then the computation time for kick-tracking N_p particles (e.g. $N_p \sim 10^3$) for N_t turns (e.g. $N_t \sim 10^3$) around the lattice using a kick code is $N_pN_tN_kT_k \sim 10^3$. Since kick evolution is "exact" (in the context of the thin-element-approximated model) it is symplectic to all orders (until computer round-off precision becomes an issue). Also kick-tracking automatically makes output available at every location in the ring.

[†] In a test with $N_k = 701$, $N_p = 10$, $N_t = 10^4$, the total time on a Pentium III laptop was 93 s, which yields $T_k \approx 1.3 \times 10^{-6}$ s.

Instead of element-by-element tracking one can consider the use of nonlinear maps to model particle orbits. Usually one is interested in particle positions at a limited set of positions in the ring. For investigation of long term stability or determination of beam distributions this set may reduce to a single point but, in general, one is interested in particle positions at an appreciable number of selected points that is still far less than the number of localized kicks in the ring. One therefore contemplates breaking the lattice into sectors and using nonlinear maps to compute trajectory evolution sector by sector. The hope would be that the map-tracking would be much faster than the kick-tracking.

For concentrating attention on a short segment of a lattice, perhaps representable only by Runge Kutta numerical tracking or some other specialized method, one could model "the rest of the lattice" by a nonlinear map. Since only a single nonlinear mapping is required this application is sure to be "fast" even for a relatively high order map. But one is also interested in intermediate cases where the lattice is subdivided into some appreciably large number N_s (e.g $N_s \sim 100$) of sectors. For example sector boundaries could be taken at every sextupole, in which case N_s would be the number of sextupoles.

Apart from the faithfulness of the simulation one wants to be sure that the time spent in first determining the needed maps is smaller than the time spent in applying the maps to the simulation task for which they are intended. This ratio depends on arbitrary factors such as N_t and N_p and the number of times each map can be usefully re-used. We will see that, for typically large values of these numbers, the map-determination time is acceptably small, at least for modest order of nonlinearity.

The sort of nonlinear effect one may wish to model correctly is tune dependence on amplitude. The dominant nonlinear elements in lattices are typically sextupoles, but a single sextupole causes no tune shift in lowest order. A mapping procedure limited to "sextupole order", cannot, therefore, be expected to usefully model tune dependence on amplitudes. Any octupoles present in the ring cause first order tune shift but, whether present intentionally or not, such octupoles are normally "weak" compared to the intentionally-present sextupoles. It is not uncommon for the tune shifts caused by octupoles in lowest order to be comparable with the tune shifts caused by sextupoles in second order. A sensible "lowest useful order of nonlinearity" might therefore be to perform calculations to octupole order—this would correctly include tune dependence due to sextupoles, would be symplectic to one higher than sextupole order, and would include octupole effects symplectic to their own order. This corresponds to determining to quartic order the polynomial S introduced in the previous section. Let us adopt the proposition that, for any computation going beyond simple matrix multiplication, it is appropriate to carry the computation to this, one higher than sextupole, order. A table below shows that the generating function for this mapping already has 210 terms, and the computer cost increases steeply as the order is increased beyond this level.

To estimate the cost (in computer time) of performing map calculations it is useful to know the number N_c of coefficients appearing in each of the truncated power series that have to be calculated. The needed formula, given by Yan[40], is

$$N_c = \frac{(n+\Omega)!}{n!\Omega!}, \qquad (E.6.1)$$

where n is the phase space dimensionality and Ω is the polynomial order. Some numerical examples are contained in Table E.6.1.

Since the map calculation time per sector is proportional to the number of elements per sector, the time to obtain the needed maps should be more of less independent of the number of sectors N_s. The second last column of Table E.6.1 gives the once-around map calculation time for the same 0.7×10^3-kick lattice as mentioned in an earlier footnote. Even for a fairly high order map the map calculation time for this lattice is much less than the kick-tracking number (10^3) calculated above. For multiparticle, multiturn tracking, it seems therefore that the time for initial generation of the maps is likely to be acceptably short. Certainly this will be true for the $\Omega = 3$ option recommended here for general purpose nonlinear tracking. One can note also that distributing the various lattice sectors to multiple processors makes the task of map generation readily parallelizable.

It remains to compare computation times for map-tracking and kick-tracking. A crude estimate of the time for each order=Ω map application, relative to the time per kick application, is $\Omega N_c(\Omega)/N_c(1)$. This accounts roughly for the number of multiplications per power series evaluation. It underestimates the kick evaluation time, which is greater than a linear matrix multiplication time. Accepting this estimate, the ratio of map-tracking

Table E.6.1: Number of terms N_c in truncated power series. The second last column contains the time taken in "arbitrary units" (which are something like "seconds on Pentium III laptop") to calculate a once-around SNS map with truncated power series of order Ω. Time (per particle, per turn) is 0.93×10^{-3} for kick-tracking around the same lattice, in the same units. The final column is explained in the text.

n	Ω	N_c	sample terms	calculation time arbitrary units	suggested minimum (average) kicks/sector
2	0	1	1		
	1	3	$1, x, p$		
	2	6	$1, x, p, x^2, xp, p^2$		
	3	10	$1, x, p, x^2, xp, p^2, x^3, x^2p$		
6	0	1	1		
	1	7	$1, x, p_x, y, p_y, l, \delta$		
	2	28	$1, x, p_x, ..., x^2, ...$	$<< 1$	8
	3	84	$1, x, p_x, ..., x^2, ...x^3...$	< 1	36
	4	210		3	120
	5	462		9	330
	6	924		33	780
	7	1716		129	1680

time $T_{\text{map}}(\Omega)$ to kick-tracking time T_{kick} can be approximated as

$$\frac{T_{\text{map}}(\Omega)}{T_{\text{kick}}} \lesssim \frac{N_s}{N_k} \frac{\Omega N_c(\Omega)}{N_c(1)}. \tag{E.6.2}$$

For the Ω=3, "intermediate order" nonlinear map that has been recommended in this appendix, this suggests that map-tracking will be quicker than kick-tracking as long as $N_s/N_k < 1/36$—i.e. the average sector subsumes more than 36 kicks. This estimate is incorporated into the last column of Table E.6.1, where it is expressed as a minimum (useful) average number of kicks per sector. For sectors containing fewer elements, kick-tracking is estimated to be quicker than map-tracking.

E.7. Future directions

Pure kick tracking has the advantage of being "exact" and hence certainly symplectic, but also the disadvantage of being too slow for some purposes, especially online modeling of very large rings. Also kick-tracking needs to be augmented by some sort of mapping representation in order to provide humanly-accessible parameterizations such as tune-dependence on amplitude.

The Element-Algorithm-Probe Framework provides a promising approach to combining the virtues of both kick and map approaches. The capability of using different evolution algorithms in different sectors is what is new. An important step that will need to be taken to start along this route is to establish a sectorization description format APD (Accelerator Propagator Description), which will specify the assignment of algorithms to sectors. The next few sections indicate possible approaches.

E.7.1. Flexible FastTeapot implementations

Some of the special accelerator properties to which FastTeapot-like code can be applied in the near future, and their ingredients are indicated in Table E.7.1.

Table E.7.1: Applications for FastTeapot within the Element-Algorithm-Probe framework.

Task	Method
coupling	6D sector matrices
chromatic effects	matrices plus sextupole kicks
transition crossing	matrices plus TIBETAN RF cavities
IR nonlinearity	matrices plus multipole kicks
beam beam	matrices plus beam-beam kicks

E.7.2. Sector maps plus sextupole kicks

It would be highly desirable to have a lattice model robust enough and fast enough to be applicable to all operational problems without any need for task-specific specialization.

The option of combining kick-tracking and map-tracking may meet this need, especially if there is a relatively small number of "strong" nonlinear elements (for example chromaticity sextupoles) and a relatively large number of "weak" nonlinear elements (for example magnetic field errors or quadrupole end fields). By treating the strong elements as kicks their individual deflections as well as the dependence of their kicks on other strong kicks are accurately represented. Their resonant effects and tune dependences would therefore be accurately modeled. The modifications of these effects by weak elements would then be handled accurately only to the order of the sector maps. We conjecture that the choice Ω=3 for map-tracking through the sectors between chromaticity sextupoles, along with explicit kicks at each of these sextupoles, will give tracking that is sufficiently accurate for all short term effects and most long term effects, such as dynamic aperture. This conjecture has not been tested however.

For RHIC, with 5300 elements and 144 sextupoles, accepting the entry 36 from the last column of Table E.6.1, the ratio of computation time for map/kick mixed tracking to pure kick tracking would be less than $5300/144/36 \approx 1$—optimistically the kick-map tracking would be two or three times faster than the pure kick tracking. But that is not the real point, since other potential benefits accrue. For example, there would be no penalty for finer subdivision, and hence more faithful, thick element and end field representations of elements within the mapped sectors.

A more important benefit would be the adoption of the mapping approach. For current day accelerator operation there are nominal beta functions at every lattice position, as well as nominal phase advances and transfer matrices between different positions. Even though it is no small achievement to have agreement at this level, the suggestion here is for these matrices to be generalized to $\Omega = 3$ maps, *which would be the basis for all machine studies investigations.* For large amplitude, large momentum offset, investigations these maps would be used as described so far. For operational investigations concerning only a small number of lattice positions, for example kicker and pickup in a transfer function determination, it would be natural to concatenate the maps to obtain a speed up factor close to one hundred, while retaining nearly exact contact with the nominal lattice model.

Another promising approach, not begun as yet, would be to reduce all the sector maps to "normal form". As well as making available the "physics" that this implies, it would open the possiblility of "lightning fast" tracking using some form of normal form representation of the sector maps combined with treating strong nonlinear elements as kicks.

E.7.3. Irwin factorization

From the numerical estimates of the previous section it appears that the use of maps of order higher than $\Omega = 3$ will be impractical because of being too slow. Even so, the kick-factorization scheme of Irwin[41] could, in principle, make higher order maps practical for online modeling. Irwin gives a formula for the number of kicks needed to faithfully represent maps as a function of their order. For $\Omega = 2, 3, 4, 5, 6, 7, 8, ...$ his formula gives $8, 12, 18, 27, 36, 48, 64, ...$ as the number of kick factors required. The fact that this series increases far less rapidly with increasing Ω than does N_c (given in Table E.6.1) suggests that high order maps should be represented by kick factorization. But for the sextupole-to-sextupole sectorization example of the previous section, the number of kicks per sector seems to be insufficiently greater than the Irwin factor to justify his kick factorization for the $\Omega = 3$ case.

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