Classdesc and Graphcode: support for scientific programming in C++

Russell K. Standish
School of Mathematics
University of New South Wales
R.Standish@unsw.edu.au
http://parallel.hpc.unsw.edu.au/rks

Duraid Madina
Department of Systems Studies
University of Tokyo
durai@sacral.c.u-tokyo.ac.jp

October 23, 2008

Abstract

Object-oriented programming languages such as Java and Objective C have become popular for implementing agent-based and other object-based simulations since objects in those languages can reflect (i.e. make runtime queries of an object’s structure). This allows, for example, a fairly trivial serialisation routine (conversion of an object into a binary representation that can be stored or passed over a network) to be written. However C++ does not offer this ability, as type information is thrown away at compile time. Yet C++ is often a preferred development environment, whether for performance reasons or for its expressive features such as operator overloading.

In scientific coding, changes to a model’s code takes place constantly, as the model is refined, and different phenomena are studied. Yet traditionally, facilities such as checkpointing, routines for initialising model parameters and analysis of model output depend on the underlying model remaining static, otherwise each time a model is modified, a whole slew of supporting routines needs to be changed to reflect the new data structures. Reflection offers the advantage of the simulation framework adapting to the underlying model without programmer intervention, reducing the effort of modifying the model.

In this paper, we present the Classdesc system which brings many of the benefits of object reflection to C++, ClassdescMP which dramatically simplifies coding of MPI based parallel programs and Graphcode a general purpose data parallel programming environment.
1 Introduction

This paper describes Classdesc, ClassdescMP and Graphcode, techniques for building high performance scientific codes in C++.

Classdesc is a technique for providing automated reflection capabilities in C++, including serialisation support. ClassdescMP builds on Classdesc’s serialisation capability to provide a simple interface to using the MPI message passing library with objects. Graphcode implements distributed objects on a graph, where the objects represent computation, and the links between objects represent communication patterns. It is a higher level of abstraction than the message passing paradigm of ClassdescMP, yet more general and powerful than traditional data parallel programming paradigms such as High Performance Fortran[2] or POOMA[12].

This paper is organised into three sections, describing the three technologies in more detail. The final section concludes with a description of the current status of the code, and where it can be obtained from.

2 Classdesc

2.1 Reflection and Serialisation

Object reflection allows straightforward implementation of serialisation (i.e. the creation of binary data representing objects that can be stored and later reconstructed), binding of scripting languages or GUI objects to ‘worker’ objects and remote method invocation. Serialisation, for example, requires knowledge of the detailed structure of the object. The member objects may be able to be serialised (e.g. a dynamic array structure), but be implemented in terms of a pointer to a heap object. Also, one may be interested in serialising the object in a machine independent way, which requires knowledge of whether a particular bitfield is an integer or floating point variable.

Languages such as Objective C give objects reflection by creating class objects and implicitly including an isa pointer in objects of that class pointing to the class object. Java does much the same thing, providing all objects with the native (i.e. non-Java) method getClass() which returns the object’s class at runtime, as maintained by the virtual machine.

When using C++, on the other hand, at compile time most of the information about what exactly objects are is discarded. Standard C++ does provide a run-time type information mechanism (RTTI), however this is only required to return a unique signature for each type used in the program. Not only is this signature compiler dependent, it could be implemented by the compiler enumerating all types used in a particular compilation, and so the signature for a given type would differ from program to program! Importantly, standard RTTI does not provide any information on the internal structure of a type, nor methods implemented.

The solution to this problem lies (as it must) outside the C++ language per
se, in the form of a separate program which parses the interface header files. A number of C++ reflection systems do this: SWIG\[4\], being perhaps the oldest, parses a somewhat simplified C++ syntax with markup, provides exposure to scripting language of selected top level objects. Reflex\[13\], a more recent system than Classdesc\[9\], is interesting in that it use the GCC-XML parser (based on the C++ front end of GCC) to parse the input file to build a dictionary of type properties. Classdesc differs from these other attempts by traversing the data structures recursively at runtime, providing a genuine solution to serialisation, as well as allowing “drill down” of simulation objects in an interactive exploration of a running simulation.

These are generically termed *object descriptors*. The object descriptor generator only needs to handle class, struct and union definitions. Anonymous structs used in typedefs are parsed as well. What is emitted in the object descriptor is a sequence of function calls for each base class and member, similar in nature to compiler generated constructors and destructors. Function overloading ensures that the correct sequence of actions is generated at compile time.

For instance, assume that your program had the following class definition:

```cpp
class jellyfish: public animal
{
    double position[D], velocity[D], radius;
    int colour;
};
```

and you wished to generate a serialisation operator called `pack`. Then this program will emit the following function declaration for `jellyfish`:

```cpp
#include "pack_base.h"
void pack(pack_t *p, string nm, jellyfish& v)
{
    pack(p,nm,(animal&)v);
    pack(p,nm+.position",v.position,is_array()",1,D);
    pack(p,nm+.velocity",v.velocity,is_array()",1,D);
    pack(p,nm+.radius",v.radius);
    pack(p,nm+.colour",v.colour);
}
```

The use of auxiliary types like `is_array()` improves resolution of overloaded functions, without polluting global namespace further. This function is overloaded for arbitrary types, but is more than a template, so deserves a distinct name. We call these functions *class descriptors* (hence the name *Classdesc*), or simply an *action* for short.

Thus, calling `pack(p,"",var)` where `var` is of type `test1`, will recursively descend the compound structure of the class type, until it reaches primitive data types which can be handled by the following generic template defined for primitive data types:
given a utility routine `pack_t::append` that adds a chunk of data to a repository of type `pack_t`.

This can even be given an easier interface by defining the member template:

```cpp
template <class T>
pack_t& pack_t::operator<<(T& x)
{:::pack(this,"",x);}  
```

so constructions like `buf << foo << bla;` will pack the objects `foo` and `bla` into the object `buf`.

Classdesc is released as public domain software, and is available from the Classdesc website. The pack and unpack operations work more or less as described. The type `xdr_pack`, derived from `pack_t` uses the standard unix XDR library to pack the buffer in a machine independent way. This allows checkpoint files to be transported between machines of different architectures, or to run the simulation in a client-server mode, with the client downloading a copy of the simulation whilst the simulation is in progress.

### 2.2 Object Exposure

Another application of reflection is exposing object internals to an external environment, such as a scripting language, or another object oriented programming language. For computational science models, adding a scripting language has many advantages. Initialisation of the model is simply achieved by setting a few variables within a script. Data collected can be customised without code recompilation by simple script changes. GUI widgets can allow the real time monitoring of the model’s variables in a graphical form during debugging and model development. A drill down facility can be readily provided in the scripting language that allows the model to be stopped, and values of the model’s variables queried. Being a scripted environment, the same executable can be used for exploration in a GUI mode, or for production in a batch mode, simply by using a different script.

Automated techniques for exposing objects to a scripting environment, or to a different OO environment already exist. Examples include VTK, CORBA/IDL and SWIG. However these either straight-jacket the programmer into using a particular programming style, or require the class definitions to be coded in a different language, (often termed an `IDL`). SWIG at least has the advantage of being able to parse any ISO standard C/C++ code. Its strong advantage is that it already has bindings for many popular languages, including TCL, Python, Perl and Java. Where Classdesc and SWIG might work well together is scripting Fortran applications. An experimental Fortran version of Classdesc (called

[1]http://ecolab.sourceforge.net/classdesc.html
FClassdesc) was developed under a grant from the Australian Partnership for Advance Computing, with serialisation of Fortran modules and a descriptor to produce C-syntax code for use as input to SWIG.

The EcoLab agent based modelling system[^2] uses Classdesc to expose C++ objects to the TCL scripting language[^10]. If the authors had been aware of SWIG at the time of EcoLab's development, SWIG would probably have been used instead, however, Classdesc's recursive approach to analysing data structures is more useful for interactive exploration of scientific models in a simulation framework than SWIG's approach of requiring explicit exposure of top level objects only.

Virtually any model that is implemented as a C++ object can be dropped into EcoLab, and one instantly has a scriptable simulation system, with GUI plotting and drill down tools and checkpointing functionality. The main programming constraint is the DCAS requirement (§2.4), although departures from DCAS tend to result in degraded capability rather than catastrophic failure (such as un compilable code).

The exposure of objects into TCL is handled by a descriptor TCL_obj. Simple data members generate a TCL command which returns the value of that member, and set the member if an argument is supplied (if corresponding ostream::operator<< and istream::operator>> are defined).

Member functions whose arguments match a limited range of signatures are also callable from TCL.

2.3 Resource Acquisition Is Initialisation (RAII)

The RAII principle[^21] §14.4.1] uses stack resident objects to control the lifetime or states of objects elsewhere in the system, such as heap resident objects. One of the simplest and most obvious application of RAII is prevention of memory leaks that occur through forgetting to destroy objects once they are no longer needed. By making the raw pointer a private member of a class, placing the calls to new and delete within member functions of the class and arranging for the destructor to call a final delete to dispose of the object, we can then use this class to declare a stack variable that controls the lifetime of a heap object. Figure 1 shows a simple implementation of the ISO C99 variable length automatic arrays that is not part of the C++ standard. Like the C version, data is allocated when control passes through the statement declaring the array variable, and is deallocated automatically when control leaves the scope containing the array variable, relieving the programmer of having to remember to delete the object. Unlike the C version, however, the data is actually allocated on the heap (via the new statement called in the constructor, rather than the stack. This is often advantageous as many modern operating systems restrict the stack size to a few megabytes which cannot support large arrays.

RAII is useful for many other tasks, such as ensuring files are closed and flushed, network connections are terminated properly, software licenses released

[^2]: http://parallel.hpc.unsw.edu.au/rks/ecolab
template <class T> class Array
{
    T* data;
public:
    Array(size_t n): data(new T[n]) {}
    T& operator[](size_t i) {return data[i];}
    const T& operator[](size_t i) const {return data[i];}
    ~Array() {delete [] data;}
};

Figure 1: Implementation of C99 variable length automatic array feature in C++.

and very importantly, ensuring partly constructed objects are correctly cleaned up in the event of an exception occurring[21].

By way of contrast, languages such as Java and C# do not allow the RAII technique to be deployed, as complex objects cannot reside on the stack. Instead, garbage collection is relied upon to release objects on the heap that are no longer needed. Since this occurs at rather indeterminate times (if ever), it cannot be relied upon for anything other than controlling memory leaks.

One mistake seasoned Java or C# programmers make when writing C++ is to assume that the C++ new operator should be used in the same way as it is used in the other languages. This leads to code that is hard to debug and maintain, and has given C++ a reputation for being difficult to avoid memory problems.

2.4 The DCAS principle

The C++ compiler automatically provides a default constructor, a copy constructor and an assignment operator, if none are explicitly provided by the programmer, which recursively call the default constructor, copy constructor or assignment operator respectively of the base classes and members. The use of Classdesc is analogous — Classdesc recursively applies its descriptor on base classes and member functions. Since serialisation is the most important Classdesc application, I call this the DCAS principle (Default constructor, Copy constructor, Assignment and Serialisation). Classes whose members and base classes are DCAS are also DCAS automatically, alleviating a lot of programmer effort.

To create a DCAS object from a non-DCAS object requires wrapping. Primitive types (ints, floats, etc) are DCAS, although their default constructors do not initialise them to any particular value, so some care must be taken with default constructors of classes taking such types. Pointers, on the other hand are not DCAS at all. The default constructor for a pointer does not initialise the pointer to a valid value. The copy constructor and assignment operator merely copies the pointer, which ends up with two references to the same object.
To get around this problem, various solutions have been developed. The C++ standard defines `auto_ptr<T>` [14.4.2], which is DCAS (to a degree). The default constructor set the reference to NULL, and copy and assignment operators pass control of the target object to the target of the copy or assignment operation, leaving the original object set to NULL, which breaks some notions of “copy”. It supports the notion of “resource acquisition is initialisation” or RAII, so that the pointer is released when the `auto_ptr` object is destroyed. Its main use is to provide a means for returning an object by reference from a function, avoiding any performance penalties of a copy constructor or the possibility of an exception being thrown during the copy constructor.

The Boost library [5] defined the `shared_ptr<T>` and `intrusive_ptr<T>` concepts, which allow for multiple references to a single object, whilst still supporting RAII, which are DCA. The `shared_ptr<T>` concept is so useful that it has been included into TR1 [1], which is scheduled to be standardized as part of the next C++ standard.

However, none of these concepts can be serialised, as these objects are initialised to the address of an object created by an earlier `new` statement. The actual type of the object is unknown at serialisation time, only the base class `T` declared in the template argument is known. This arrangement allows the handling of polymorphic objects, which we will return to in §2.6.

The Classdesc package includes the `ref<T>` concept, which implements a reference counted dynamic reference class similar to Boost’s `intrusive_ptr<T>` concept, which is serialisable (hence DCAS). Instead of creating the target object outside the `ref` class with a `new` statement, as done in Boost’s smart pointer concepts, the target object is created on first dereference. This has the advantage that the reference counter can be stored alongside the object of type `T` on the heap like `intrusive_ptr<T>` does, without the need for `T` to support any reference counting API, however `T` is required to be DCAS. Polymorphism (§2.6), which requires special treatment, is not supported by `ref` at all, however.

The use of reference counting (whether the Classdesc `ref` or the Boost versions) allows heap allocated objects to be used as simply as they would with classic garbage collection. However copying reference counted references is about twice as expensive as simple pointer assignment, so under some circumstances, the use of such classes may be a performance issue. By judicious use of standard C++ references, and function inlining, this performance impact can be ameliorated, and if necessary, bare pointers can be used within the innermost scope of pointer chasing algorithms as a performance optimisation.

Reference counted references prove effective in implementing acyclic graph structures — deleting the reference to the head node is sufficient to ensure that all nodes are deleted. However, cycles of references will cause objects to remain in existence, even when no references remain to the graph structure. One possible means of dealing with this is to perform a graph walk at graph destruction time, deleting links to objects that have already been traversed in the walk, thus deleting any cycles. Then deleting the head node reference is sufficient to delete the entire structure. This operation is most conveniently handled in the destructor of some `Graph` class.
2.5 Pointers

Pointers create difficulties for Classdesc, since pointers may point to a single object, an array of objects, functions, members or even nothing at all. When array sizes are known at compile time, Classdesc issues an object descriptor that loops over the elements, however arrays allocated dynamically on the heap through the use of `new` cannot be handled, even in principle.

Because pointers cause problems with the DCAS and RAII paradigms, it is worth discussing the uses that pointers are put to in C++, and alternatives that are available. Many of the uses have been inherited from C, where pointer usage is almost unavoidable in practical codes. Pointers are used in C++ for the following purposes:

**Passing by reference.** This use is inherited from C, but superseded by C++’s reference types.

**Dynamic arrays.** C++’s `std::vector<T>` container can be used for most dynamic array purposes without any extra overhead. It is DCAS, provided the element type T is also DCAS, and satisfies the RAII technique. If a standard container is not suitable, then a purpose-built container such as shown that in figure 1 can be provided.

**Strings.** `std::string` provides a safe and DCAS-ready alternative to `char*` variables.

**Graph structures.** Classdesc provides the DCAS-ready `ref<T>` which is suitable for graphs and trees.

**Polymorphic objects.** Classdesc provides the `poly<T>` for handling polymorphic object hierarchies in a DCAS fashion (§2.6).

**Opaque handles.** Opaque handles are used to improve compile times by hiding the actual implementation details, including instance variables, in a separate compilation unit. This is not a major problem, but specific methods must be provided by the programmer for construction, destruction, copying and serialisation of the object referenced by the opaque handle. These may call automatically generated versions of the methods in the separate compilation unit to reduce programmer burden.

**Libraries.** C language API libraries will often use pointers to data structures. Where the details of these data structures are provided as part of the interface file, it is possible to use the automatically generated (whether compiler or Classdesc generated) methods to implement a DCAS wrapper around these objects. Where opaque handles are used, however, one’s choices are limited depending on whether the appropriate methods for implementing copying and serialisation have been provided (some means of construction and disposing of objects will always be provided), or whether source code is available.
It turns out that one can distinguish between member pointers and normal pointers quite easily through overloading of object descriptors. Member pointers are relevant for exposing an object’s methods to a scripting interface, for example, and are also serialised and passed between processes in ClassdescMP to implement a form of remote procedure calling. Classdesc does not distinguish between pointers to functions and pointers to objects as simple function overloading is not sufficient to distinguish them. However, the Boost library provides a template metaprogramming technique for distinguishing between function pointers and objects pointers in its types_trait package, so providing overloading for function pointers is planned for the future.

By default, an attempt to serialise a pointer will issue a runtime warning. However, if pointer members are genuinely necessary, it is possible for the programmer to specify that pointers either point to a single object of the specified DCAS type or are NULL if invalid. We call this the graphnode protocol. This situation is most likely to occur when using a “legacy” library that deals with pointers, and wrapping the data with something like ref is prohibitive. The gSOAP package is an example.

Within the Classdesc system it is possible to specify that all pointers of a given pointer type satisfies the graphnode protocol, or that all pointers within a given graph structure satisfy the graphnode protocol. The pack descriptor than walks the graph structure keeping a track of nodes visited so that cycles are handled, and recursion cut off to avoid stack limits being breached.

2.6 Polymorphism

C++ has two notions of polymorphism, compile-time and runtime. Compile-time polymorphism (aka generic programming) is implemented in terms of templates, and allows the provision of code that can work on many different types of objects. On the other hand, runtime polymorphism involves the use of virtual member functions. Whereever generic programming can solve a task, it is to be preferred over runtime polymorphism, as virtual member functions introduce procedure call overhead, and inhibit optimisation. Furthermore, the use of a DCAS class like poly introduces additional overheads.

Nevertheless, there are situations that cannot be solve with compile-time polymorphism, for example a container containing objects of varying types. For this purpose, Classdesc’s poly type is useful. To use poly, your object heirarchy must implement the following interface (provided as an abstract base class object).

```c++
struct object
{
    typedef int TypeID;
    virtual TypeID type() const=0;
    virtual object* clone() const=0;
    virtual void pack(pack_t *b) const=0;
    virtual void unpack(pack_t *b)=0;
};
```
virtual ~object() {}
};

The type() method implements a simple runtime type identifier system. In the case of object, it uses simple integer tags, which are assumed to be allocated more or less consecutively to types in the type hierarchy. However, any type may be used provided it is exported as the typedef TypeID, and an appropriate customised type table class is defined (see below). One possibility, although by no means the most efficient, is to use the object’s type_info object returned by C++’s inbuilt run time type identification system [21 §15.4.4].

It is not actually necessary to use this abstract base class to use poly. The base class (which must be default constructible, hence not abstract) is passed to the poly template. Classdesc provides an empty concrete class Eobject which can be used for this purpose.

To assist in deriving classes from object, the Object template is provided.

template <class This, int Type, class Base=object> struct Object;

The first template argument This is the class you’re currently defining, the second (Type) is the integer value of its type tag and Base is the base class you are deriving from. Eobject is defined as

class Eobject: public Object<Eobject,0> {}
;

and a new class (eg foo) with type ID 1 can be defined

class foo: public Object<foo,1,Eobject> {...

This saves having to explicitly provide versions of the virtual functions type(), clone(), pack() and unpack(), as these are provided by Object. It also provides a utility method cloneT() which executes clone(), but instead of returning a bare object pointer, returns a pointer to an object of the same type as the calling object (if legally convertible via dynamic_cast).

The synopsis of poly is:

template <class T=Eobject, class TT=SimpleTypeTable<T> >
class poly
{
public:
  TT TypeTable;
  poly();
  poly(const polyref& x);
  poly(const T& x);
  poly& operator=(const poly& x);
  poly& operator=(const T& x);

  template <class U> void addObject();
  template <class U, class A> void addObject(A);
  template <class U, class A1, class A2> void addObject(A1, A2);
}
T* operator->();
T& operator*();
const T* operator->() const;
const T& operator*() const;

template <class U> U& cast();
template <class U> const U& cast();
void swap(poly& x);
};

Most of this is fairly straightforward. However the addObject() and cast() methods need a little more explanation. To make the poly object an object of type (say foobar), use the following calls:

poly.addObject<foobar>(); //calls foobar()
poly.addObject(1);        //calls foobar(1)
poly.addObject(1,"hello"); //calls foobar(1,"hello");
poly.addObject(foobar(x,y,z)); //more than 2 arguments

The cast method provides a convenient method casting the poly object to a specific type. It is equivalent to calling dynamic_cast, but a little easier to use, ie

poly.cast<foobar>().grunge() <=> dynamic_cast<foobar&>(*poly).grunge();

The return type was chosen to be a reference, not a pointer, as this is the more convenient form. It can easily be converted to a pointer with the & operator.

The TypeTable member of poly must implement the following interface

class typetable
{
    Base& operator[](TypeID);
    void register_type(const Base&);
};

where Base is the base type of the poly class, and is basically a database of reference objects, from which new objects can be constructed using clone(), given a type identifier. This is used for implementing serialisation. Classdesc provides simple implementation of this as SimpleTypeTable<Base>, where the TypeIDs are integers that are reasonably close to each other.

2.7 Member Privacy

Serialisation descriptors need access to all members of an object, including private and protected ones. Since in C++ class namespaces are closed by design (no new members can be added, except by inheritance), descriptors need to be placed in a global or an open namespace. This means that friend declarations need to be added to all class definitions with private or protected areas. The
convention adopted by Classdesc is to define two macros that expand to a list of friend declarations for the descriptors, similar to the following:

```c
#define CLASSDESC_ACCESS(type)\
friend void pack(pack_t *,eco_string,type&);
friend void unpack(unpack_t *,eco_string,type&);

#define CLASSDESC_ACCESS_TEMPLATE(type)\
friend void pack<>(pack_t *,eco_string,type&);
friend void unpack<>(unpack_t *,eco_string,type&);
```

Then placing a `CLASSDESC_ACCESS` statement in the class definition allows the descriptor access to the private members of the class:

```c
class foo
{
    int bar;
    CLASSDESC_ACCESS(foo);
public:
    float bar2;
};
```

An auxiliary program `insert-friend` is provided as part of the Classdesc package to automatically insert these macros into class definitions.

For object exposure, only public members need to be processed by the descriptor. Classdesc provides a `-respect_private` flag to indicate that private and protected members should be ignored by the descriptor.

3 ClassdescMP: easy MPI programming in C++

3.1 MPIbuf

MPI\[17\] is an industry standard API for constructing distributed memory parallel applications using the message passing metaphor. Originally designed for use with Fortran77 and C, it primarily deals with passing arrays of simple types such as characters, integers or floating point numbers. In a later incarnation, C++ bindings to the library were provided as part of the MPI-2 standard. It primarily added support for the MPI namespace, communicators as objects and support for C++ exception handling. However, messages are fundamentally composed of arrays of simple types.

Classdesc's general serialisation operation solves the problem of passing messages of complex objects as the pack descriptor turns a sequence of complex objects into an array of bytes. In ClassdescMP, the `MPIbuf` type is derived from `pack_t`, so messages can be constructed in a streaming fashion, eg:

```c
buf << a << b << send(1);
```
which sends $a$ and $b$ to process 1.

Streaming MPI messages is not new — it is used in PARA++ [6], and in OOMPI [3], for example. However, in these packages, programmers are required to provide explicit serialisation routines for complex types.

To receive a message, use the `MPIbuf::get()`:

```cpp
buf.get() >> a >> b;
```

Optional arguments to `get` allow selective reception of messages by source and tag.

By setting the preprocessor macro `HETERO`, `MPIbuf` is derived from `xdr_pack` instead of `pack_t`. This allows ClassdescMP programs to be run on heterogeneous clusters, where numerical representation may differ from processor to processor.

In MPI-2 C++ bindings, the basic object handling messages is a `communicator`. In ClassdescMP, an `MPIbuf` has a communicator. It also has a buffer, and assorted other housekeeping members. Some of these are used for managing asynchronous communication patterns:

```cpp
{  
  MPIbuf buf;
  buf << a << isend(1);
  while (something_to_do && !buf.sent()) do_something;
  buf.wait();
  buf << b << isend(2);
  ...
}
```

When `buf` goes out of scope, an implicit `MPI_Wait` is called to ensure that the message has been correctly sent.

Often, one needs to perform all-to-all exchange of data. To do this, we use an `MPIbuf_array`:

```cpp
{  
  ...
  tag++;
  MPIbuf_array sendbuf(nprocs());
  for (unsigned proc=0; proc<nprocs(); proc++)
    {  
      if (proc==myid()) continue;
      sendbuf[proc] << requests[proc] << isend(proc,tag);
    }
  for (int i=0; i<nprocs()-1; i++)
    {  
      MPIbuf b;
      b.get(MPI_ANY_SOURCE,tag);
      b >> rec_req[b.proc];
    }
}
```
This piece of code is copied verbatim from the *Graphcode* library ([4]). Note the use of a tag variable to ensure that unrelated groups of communication do not get mixed up. Also, when `sendbuf` goes out of scope, an implicit `MPI_Waitall` called, which ensures that all messages in the group have been sent.

### 3.2 MPISPMD

Whilst `MPIbuf` and `MPIbuf_array` are the heart of ClassdescMP, there is also some application framework support. Two programming models are supported: an SPMD mode, which simply wraps up the MPI setup and teardown into an object, and a *master-slave* mode in which the master thread controls slave thread objects via remote method invocation.

The SPMD mode is rather similar to that of PARA++ ([6]). By instantiating an object of type `MPISPMD`, the MPI environment is initialised. One key feature of Classdesc’s implementation is that `MPI_Finalize()` is called from the `MPISPMD` object’s destructor — not only does this save the programmer from having to remember to do this, but it is also called during stack unwinding if an exception is thrown. This alleviates the problem with some MPI implementations (eg MPICH) which leave active threads running and consuming CPU time if `MPI_Finalize()` is not called.

### 3.3 MPIslave

The master-slave mode is a more powerful feature of ClassdescMP. Setting up the structure of a master-slave program is very tedious and error prone. The `MPIslave` class is designed to make master-slave algorithms simple to program.

When a `MPIslave` object is instantiated, a slave “interpreter” object is instantiated on each process to receive messages from the master. As `MPIslave` needs to know the type of object to be instantiated on the slave processes, it is implemented as a template, with the type of slave object passed as the template parameter.

A message sent to the slave process starts with a method pointer of type:

```
void (S::*)(MPIbuf&) where S is the slave object type, followed by the arguments to be passed. That method of the slave object is then called, with the arguments passed through `MPIbuf` argument, and any return values also passed through `MPIbuf` argument:
```

```c
struct S
{
  void foo(MPIbuf& args)
  {
    int x,y,r;
    args >> x >> y;
    ...
    args.reset() << r;
  }
}
```
main(int argc, char** argv)
{
    MPIslave<S> C;
    MPIbuf buf;
    int x=1, y=2;
    buf << &S::foo << x << y << send(1);
}

When the MPIslave object is destroyed on the master process, it arranges for all the slave objects to be MPI_Finalized() and destroyed also.

MPIslave also has features for managing a pool of idle slaves:

MPIslave<S> C(argc, argv);
vector<job> joblist;
for (int p=1; p<C.nprocs && p<joblist.size(); p++)
    C.exec(C << &S::do_job << joblist[p]);
while (p<joblist.size())
{
    process_return(C.get_returnv());
    C.exec(C << &S::do_job << joblist[p++]);
}
while (!C.all_idle())
    process_return(C.get_returnv());

3.4 Access to underlying MPI functions

The philosophy of ClassdescMP is not to hide the underlying MPI transport layer. It is possible to mix MPI calls with ClassdescMP calls, which may be done to provide a more efficient implementation of a particular operation, or to provide functionality not provided in ClassdescMP (reductions for example). This allows ClassdescMP to concentrate on providing new functionality, rather than simply wrapping existing MPI functionality in a new syntax.

In terms of performance, the only overhead ClassdescMP adds is copying data into the MPIbuf variable. In the case of sending a large array of a simple type, it may well be more efficient to call the appropriate MPI call directly. On the other hand, if one is sending a lot of different small variables, it is more efficient to marshal the data into a single array, before sending it as a single message, for which task ClassdescMP is extremely effective.

This philosophy of coexisting with the underlying MPI library is in sharp contrast with PARA++, which was designed to allow the transport layer to be swapped completely for another one (eg PVM). However, MPI is now so ubiquitous that swapping the transport layer no longer seems to have much of an advantage.

Currently, ClassdescMP is implemented completely in terms of MPI-1 functionality. As MPI-2 implementations become available, increased performance,
and or functionality dependent on MPI-2 functionality may be added. The most obvious MPI-2 feature to impact ClassdescMP is one-sided messaging, which would allow the implementation of the global pointer concept\cite{7}. Unfortunately, one-sided messaging appears to be the one area of MPI-2 left out of existing implementations, or implemented badly. One could implement one-sided messaging using a standard threads API, such as Posix threads, however in real applications encountered to date, separating the communication and computation steps (see \cite{4.6}) has proved effective, so we haven’t needed to explore one-sided communication.

4 Graphcode

Whilst MPISPMD and MPIslave provide rather simple application frameworks for message passing codes, Graphcode provides a far richer framework within which programming is closer to data parallel programming than the lower level message passing environment on which it is based. The underlying paradigm of Graphcode is objects distributed on a graph. Computation takes place within the objects (vertices of the graph), and communication takes place along the edges of the graph.

Graphcode calls the \texttt{PARM Ellis} parallel graph partitioner\cite{15, 14} to partition the graph across the available processors, given a suitable weighting of computational and communication costs (which defaults to a uniform weighting). Since the solution found by \texttt{PARM Ellis} is a Pareto non-dominated solution (no other partitioning exists that has better load balancing and less communication), the costs do not need to be provided in any normalised fashion — only the leading order of computational or communication complexity need be provided.

Since traditional data parallel programs can be expressed as a graph (put aligned data elements on the same node, express communication patterns as graph links, eg shifts as nearest neighbour connections), it could be argued that Graphcode embraces and extends the data parallel programming model. However the data layout within a compute node differs. For instance, if one considers a 5-point stencil of some hypothetical 2 component field:

\begin{align*}
    u'_{i,j} &= v_{i,j} - \frac{1}{4}(v_{i-1,j} + v_{i+1,j} + v_{i,j-1} + v_{i,j+1}) \\
    v'_{i,j} &= u_{i,j} - \frac{1}{4}(u_{i-1,j} + u_{i+1,j} + u_{i,j-1} + u_{i,j+1})
\end{align*}

then Graphcode will store $u_{i,j}$ next to $v_{i,j}$, whereas an HPF implementation will store $u_{i,j}$ next to $u_{i+1,j}$. It remains to be seen what impact this has on performance in typical situations.
4.1 Graphcode objects

A Graphcode graph is represented by the Graph class. Nodes of the graph are polymorphic objects, derived from the object abstract base class. Being polymorphic allows more complex topologies, such as hypergraphs, where nodes may belong to more than groupings. For example consider an object class representing a human being, and also another object representing the families that human being might belong to, for instance the family e was born into, and the family e married into:

```cpp
class human: public object
{
  ...
};

class family: public object
{
  ...
};
```

The relationship belongs to is represented by a link connecting a human object with a family object. The reverse link represents the relationship contains.

Graphcode objects may be located on any processor, and may need to be migrated to achieve dynamic load balancing. Objects are accessed through proxy variables, of type objref. An objref contains the object’s identifier, its location (processor ID), and may be dereferenced to obtain access to the object (if the object is located in the current process’s address space), or a copy of the object (if it exists in the current process’s address space):

```cpp
class objref
{
  public:
    GraphID_t ID;
    unsigned int proc;
    object& operator*( );
    object* operator->( );
    const object* operator->( ) const;
    bool nullref() const;
    inline void nullify();
    void addref(object* o, bool mflag=false);
};
```

The members nullref() allow one to test whether the objref points to a copy of the object in the current address space, and nullify() allows one to remove the copy of the object. addref(obj,mflag) points the objref at object obj, setting mflag (managed flag) to true allows the objref destructor to destroy the object.
Several virtual members need to be provided for any object, including virtual serialisation members pack and unpack as described in §2.6, a "virtual constructor", a "virtual copy constructor" and a virtual type identifier. "Virtual constructors" are described in [21, §15.6.2], and the exact procedure used in Graphcode is detailed below.

To migrate objects between processors, Graphcode will arrange the following sequence of operations:

```
--- Code on source processor ---

objref a;
MPIbuf b;
b << a.ID << a->type() << *a << send(dest);

--- Code on destination processor ---

MPIbuf b;
GraphID_t ID;
int type;
b.get() >> ID >> type;
objref& a=objects[ID];
if (a.nullref())
    a.addref(archetype[type]->lnew(),true);
b >> *a;
```

Note the use of the "virtual constructor" lnew(). We use the type information to index into a database of object archetypes, and call lnew() to obtain a new object of that type. A programmer defining an object class foo defines the virtual members as follows:

```cpp
class foo: public object
{
    public:
        virtual int type() {return vtype(*this);} 
        virtual object* lnew() {return vnew(this);} 
        virtual object* lcopy() {return vcopy(this);} 
        virtual void lpack(pack_t *b); 
        virtual void lunpack(pack_t *);
}
```

The template function vnew() returns a pointer to a new object of the same type as its argument, and vcopy() returns a copy of the object pointed to by its argument. Both of these functions use the C++ new operator, so can be disposed of using delete at a later stage.

Graphcode implements its own runtime type identification — the standard C++ RTTI typeid() call returns a complex object of type type_info. Not only is it inefficient to transfer the whole type_info object via MPI, and inefficient to use a complex object to index into the archetype database, we also have the potential scenario of the object codes on different processors being generated by
different compilers (a heterogeneous computer), and hence having incompatible type_info objects.

Graphcode’s RTTI system is very simple. An object’s virtual type member makes a call to the template function vtype, which places a version of itself into the archetype database:

```cpp
template <class T> int vtype(const T& x)
{
    static int t=-1;
    if (t==-1)
    {
        t=archetype.size();
        objref *o=new objref; o->addref(x.lnew());
        archetype.push_back(o);
    }
    return t;
}
```

Having discussed the virtual function interface of object, we are now ready to present to full definition of object:

```cpp
class object: public Ptrlist
{
public:
    /* serialisation methods */
    virtual void lpack(pack_t *buf)=0;
    virtual void lunpack(pack_t *buf)=0;
    /* virtual "constructors" */
    virtual object* lnew() const=0;
    virtual object* lcopy() const=0;
    virtual int type() const=0;
    virtual idxtype weight() const {return 1;}
    virtual idxtype edgeweight(const objref& x) const {return 1;}
};
```

As well as the virtual members we have described, there are two weight functions used by the ParMETIS partitioner, used to described the computational cost (weight()) represented by the object, and the communication cost (edgeweight(x)) in transferring a copy of a remote object x into local address space. As can be seen, these default to 1, but may be overridden by the programmer of the derived object. Finally, object is derived from Ptrlist, which is syntactically equivalent to a vector of objref’s, and represents the objects linked to this object.

As can be seen, there is a lot of similarity between the Graphcode object type and the object type used with the poly<T> class. Graphcode was the first real application of Classdesc to a polymorphic data structure, and so its design strongly influenced that of the poly<T>, which was developed later. At a later
stage, we hope to migrate the Graphcode API to use the \texttt{ref<T>} and \texttt{poly<T>} interfaces to more closely couple Graphcode with Classdesc.

\subsection{4.2 om\texttt{ap}}

Each object is identified by a unique identifier, so each process maintains a \texttt{map} object \texttt{Graph::objects} that can be used to locate the \texttt{objref} corresponding to a particular identifier. Graphcode supplies two possible map objects — a \texttt{vmap}, using a \texttt{std::vector} which is optimised for contiguous, or nearly contiguous ranges of object identifiers, and \texttt{hmap}, a hash map implementation suitable for non-contiguous identifiers. You select the version of om\texttt{ap} you wish to use by using the namespace \texttt{graphcode_vmap} or \texttt{graphcode_hmap} as appropriate.

It might seem puzzling why the \texttt{Graph} type is not a template, with the om\texttt{ap} type as a template argument. The problem is that internally, objects need to keep track of the map to which they belong in order to regenerate the neighbourhood linklist after migration. Therefore, the map type will need to be a template argument to the \texttt{objref}, but the map itself takes \texttt{objref} as a template argument, unfortunately leading to a circular template definition of \texttt{objref}:

\begin{verbatim}
template <class map> class objref;

template <class map>
class omap: public map
{
};

template <class map>
class objref
{
  omap<map> Map;
};

typedef std::map<int, objref<Map> > Map;
omap<Map> foo;
\end{verbatim}

In practice, compilers cannot cope with this code.

\subsection{4.3 Standard library syntax}

Wherever possible, the syntax of Graphcode’s containers follows that of the standard library, so should be familiar to C++ programmers. So \texttt{Ptrlist} and \texttt{omap} have iterators, and an \texttt{operator[]} . One slight departure from the standard library, is that \texttt{omap::iterator::operator*()} returns an \texttt{objref}, not \texttt{pair<GraphID_t, objref>}, as one might expect if one followed the \texttt{std::map} model. The reason for this is that \texttt{objref} objects already contain the object’s
identifier, and the pair construct is redundant and wasteful. It also leads to clearer code.

4.4 Graph

Having introduced objects, objrefs and omaps, we are now in a position to present a skeleton of Graphcode’s Graph class.

class Graph: public Ptrlist
{
public:
    omap objects;
    void rebuild_local_list();
    void clear_non_local();
    template <class T> objref& AddObject(const T& type, GraphID_t id);
    void gather();
    void Prepare_Neighbours();
    void Partition_Objects();
    inline void Distribute_Objects();
};

Graph contains two main data members — the objects database mentioned previously, and a list of object references that refers those objects hosted in the current address space. This list is a base class of Graph, allowing a simple loop of the form:

    for (Ptrlist::iterator i=begin(); i!=end(); i++)

to be, in effect, a data parallel operation.

    The member rebuild_local_list() refreshes this list after a migration of objects, and the member clear_non_local() nullifies those objrefs that are not hosted locally, reclaiming memory.

Creating a graph involves calls to AddObject to add an object of type T (which must be derived from object), and adding the links to each object to form the graph. For example, the code for a 2D 5-point stencil might look like:

    for (i=0; i<nx; i++)
        for (j=0; j<ny; j++)
            AddObject(foo(),mapid(i,j));
    for (i=0; i<nx; i++)
        for (j=0; j<ny; j++)
        {
            objref& o=objects[mapid(i,j)];
            o->push_back(objects[mapid(i-1,j)]);
            o->push_back(objects[mapid(i+1,j)]);
            o->push_back(objects[mapid(i,j-1)]);
            o->push_back(objects[mapid(i,j+1)]);
        }
where the user supplied function `mapid(,)` converts a coordinate into a pin identifier. Boundary conditions can be handled by returning the special identifier `bad_ID` when no link is applicable. The `Graph::AddObject` and `Ptrlist::push_back()` members refuse to add an object having a `bad_ID` identifier.

### 4.5 Distribution of data over multiple processors

To distribute objects from the master thread to slave threads, according to some specified distribution, assign the desired destination of the objects to the `proc` member, then call `Graph::Distribute_Objects()`, which broadcasts the entire graph to all nodes. There is an inverse `Graph::gather()` function that gathers data from all the nodes into the master thread copy.

To partition the objects using PARMETIS, you must first distribute the graph according to some distribution (no matter how naïve and non-optimal), and then call `Graph::Partition_Objects()` to redistribute the Graph more optimally by calling the PARMETIS library. `Partition_Objects()` can be then called periodically to rebalance the load, if the graph contains mobile agents for instance.

Whilst it conceptually the easiest to construct the entire computation on the master process, and distribute the data using `Graph::Distribute_Objects()`, it is possible to for each process to construct just its part of the computation, and for `Graph::Partition_Objects()` to rebalance the load without all the data needing to pass through a single process’s address space.

### 4.6 Communication and computation steps

In typical Graphcode applications deployed to date, an update involves performing a computation on each object using the values of the neighbouring objects, storing the results into a backing buffer graph, and then swapping the backing buffer with the original graph, typical of a synchronous updating scheme. Asynchronous schemes could be employed as well with due care. The only communication required is to ensure a copy of all neighbours residing on remote processes is transferred to the processor hosting the object being updated. Whilst this could be done as needed via one-sided messages, it is more efficient to batch up all the objects that need to be transferred so that only one message is sent between each pair of processes. Since the communication pattern is already described by the graph’s links, all a programmer needs to do is make a call to `Graph::Prepare_Neighbours()` before starting the computation step.

Returning to our 5 point stencil example (Eq 1), the update code would be written as:

```cpp
graph->Prepare_Neighbours(); // communication step */
for (Ptrlist::iterator p=graph->begin(); p!=graph->end(); p++)
{
    foo* b=fooptr(back->objects[p->ID]);
    b->u = fooptr(p)->v;
```
b->v = fooptr(p)->u;
for (Ptrlist::iterator n=p->begin(); n!=p->end(); n++)
{
    b->u -= 0.25 * fooptr(n)->v;
    b->v -= 0.25 * fooptr(n)->u;
}
}
swap(graph, back);

Here graph and back are the graph and backing buffer for the calculation. We are also assuming a utility function fooptr() written by the programmer to return a foo* pointer to the object. A typical implementation of this might be:

foo *fooptr(objref & x) {return dynamic_cast<foo*>(&x);}  
foo *fooptr(Ptrlist::iterator x) {return dynamic_cast<foo*>(&**x);}

It is important to use the new `dynamic_cast` feature of C++ to catch errors such x not referring to a foo object, or an incorrect combination of dereferencing and address-of operators. `dynamic_cast` will return a NULL pointer in case of error, which typically causes an immediate NULL dereference error. Old fashioned C style casts (of the type (foo*)) will simply return an invalid pointer in case of error, which can be very hard to debug.

It should be noted that a Graph object appears as a list of those objects local to the executing processor. So this code will execute correctly in parallel. Each time Prepare_Neighbours is called, the message tag is incremented, preventing subsequent calls from interfering with the delivery of the previous batches of messages.

4.7 Deployed applications and performance

Within the EcoLab system[18], Graphcode is deployed with two of the example models provided with the EcoLab software. These models are working scientific models, not toy examples. The first model is the spatial Ecolab model[19], where the panmictic Ecolab model (Lotka-Volterra ecology equations, coupled with mutation) is replicated over a 2D Cartesian grid, and migration is allowed between neighbouring grid cells. The performance of this model has not been studied much yet.

The second model is one of jellyfish in assorted lakes on the islands of Palau. Each jellyfish is represented as a separate C++ object, commonly called agent based modelling. The jellyfish move around within a continuous space representing the lake, and from time to time bump into each other. In order to determine if a collision happens in the next timestep, each jellyfish must examine all the other jellyfish to see if its path intersects that of the other. This is clearly an $O(N^2)$ serial operation, which severely limits scalability of the model.

To improve scalability, the lake is subdivided into a Cartesian grid, and the jellyfish is allocated to the cell describing its position. If the cells are sufficiently large that the jellyfish will only ever pass from one cell to its neighbouring cell
in a given timestep, then only the jellyfish within the cell, plus those within the nearest neighbours need to be examined. This reduces the complexity of the algorithm to dramatically less than $O(N^2)$, and also allows the algorithm to be executed in parallel. In the field of molecular dynamics simulations, this method is often called a particle in cell method. \texttt{PARMETIS} allows nodes and edges to be weighted, so in this case we weight each cell by $w_i = n_i^2$, and each edge by $v_{ij} = n_j$. In figure 2, the speedup (relative performance of the code running on $n$ processors versus 1 processor) is plotted for different stages of the simulation. The simulation starts at 7am with the jellyfish uniformly distributed throughout the lake. As the sun rises in the east, the jellyfish track the sun, and become concentrated along the shadow lines. \texttt{PARMETIS} is called repeatedly to rebalance the calculation. As the sun sets at around 5pm, the jellyfish disperse randomly throughout the lake. In figure 3, the speedup is plotted as function of simulation time, so the effect of load unbalancing can be seen. It can be seen that Graphcode delivers scalable performance in this application.

Graphcode has also been deployed in a 3D artificial chemistry model\cite{8} exhibiting superlinear speedup over 64 processors due to the effectively enlarged
Figure 3: Speedup of the Jellyfish application as a function of simulation time. This is differential speedup, calculated from the wall time needed to simulate a 6 minute period, so does not include partitioning time.
memory cache.

5 Current Status

Classdesc and Graphcode are open source packages written in ISO standard C++. They have been tested on a range of platforms, and compilers, including Linux, Mac OS X, Cygwin (Windows), Irix, Tru64; gcc and Intel’s icc for Linux, as well as native C++ compilers for Irix and Tru64.

The source code is distributed through a SourceForge project, available from http://ecolab.sourceforge.net. The code is managed by the Aegis source code management system, which is browsable through a web interface. Version numbers of the form $x.Dy$ are considered “production ready” — they have been tested on a range of platforms, and are more likely to be reliable. These codes are also available through the SourceForge file release system. The versions $x.y.Dz$ are under active development, and have only undergone minimal testing (ie they should compile, but may still have significant bugs). Developers interested in contributing to the code base can register as a developer of the system by emailing one of the authors.

Classdesc and Graphcode are also included as part of the EcoLab simulation system, which is available from the same source code repository.

Acknowledgments

This work was funded by a grant from the Australian Partnership for Advanced Computing (APAC) under the auspices of its Computational Tools and Techniques programme. Computer time was obtained through the Australian Centre for Advanced Computation and Communication (ac3).

References

[1] Draft technical report on C++ library extensions. Technical Report DTR 19768, International Standards Organization, 2005.

[2] Charles H. Koelbel and David B. Loveman, Robert S. Schreiber, Guy L. Steele, Jr., and Mary E. Zosel. The High Performance Fortran Handbook. MIT Press, Cambridge, Mass., 1994.

[3] J. M. Squyres an B. C. McCandless and A. Lumsdaine. Object oriented MPI: A class library for the message passing interface. In Proceedings of the POOMA conference, 1996.

[4] David M. Beazley. SWIG : An easy to use tool for integrating scripting languages with C and C++. In Proceedings of 4th Annual USENIX Tcl/Tk Workshop. USENIX, 1996. http://www.usenix.org/publications/library/proceedings/tcl96/beazley.html.
[5] Greg Colvin, Beman Dawes, and Darin Adler. *Boost Smart Pointers*. http://www.boost.org/.

[6] O. Coulaud and E. Dillon. PARA++: C++ bindings for message passing libraries. users guide. Technical report, INRIA, 1995.

[7] Dennis Gannon, Shridar Diwan, and Elizabeth Johnson. HPC++ and the Europa call reification model. *ACM SIGAPP Applied Computing Review*, 4:11–14, 1996.

[8] Duraid Madina, Naoki Ono, and Takashi Ikegami. Cellular evolution in a 3d lattice artificial chemistry. In Banzhaf et al., editors, *Advances in Artificial Life*, volume 2801 of *Lecture Notes in Computer Science*, pages 59–68, Berlin, 2003. Springer.

[9] Duraid Madina and Russell K. Standish. A system for reflection in C++. In *Proceedings of AUUG2001: Always on and Everywhere*, page 207. Australian Unix Users Group, 2001.

[10] J. K. Ousterhout. *TCL and the Tk Toolkit*. Addison-Wesley, 1994.

[11] John K. Ousterhout. Scripting: Higher-level programming for the 21st century. *IEEE Computer*, 31(3):23–30, 1998.

[12] J.V.W. Reynders, P.J. Hinker, J.C. Cummings, S.R. Atlas, S. Banerjee, W.F. Humphrey, S.R. Karmesin, K. Keahey, M. Srikant, M.D. Tholburn, et al. POOMA: a framework for scientific simulations of parallel architectures. In *Parallel Programming in C++*, pages 547–588. MIT Press, Cambridge, MA, 1996.

[13] S. Roiser and P. Mato. The SEAL C++ reflection system. Interlaken, Switzerland, 2004. http://chep2004.web.cern.ch/chep2004/.

[14] Kirk Schloegel, George Karypis, and Vipin Kumar. Parallel multilevel algorithms for multi-constraint graph partitioning. In A. Bode et al., editors, *Euro-Par 2000*, volume 1900 of *Lecture Notes in Computer Science*, page 296, Berlin, 2000. Springer.

[15] Kirk Schloegel, George Karypis, and Vipin Kumar. A unified algorithm for load-balancing adaptive scientific simulations. In *Supercomputing 2000*, 2000. http://www.sc2000.org/proceedings/techpapr.

[16] Will Schroeder, Ken Martin, and Bill Lorensen. *The visualization toolkit: an object-oriented approach to 3-D graphics*. Prentice Hall, Upper Saddle River, N.J., 1996.

[17] Marc Snir et al. *MPI: the complete reference*. MIT Press, Cambridge, MA, 1996.

[18] Russell K. Standish. Ecolab documentation. Available at http://ecolab.sourceforge.net.
[19] Russell K. Standish. Cellular Ecolab. *Complexity International*, 6, 1999.

[20] Russell K. Standish and Richard Leow. EcoLab: Agent based modeling for C++ programmers. In *Proceedings SwarmFest 2003*, 2003. arXiv:cs.MA/0401026.

[21] Bjarne Stroustrup. *The C++ Programming Language*. Addison-Wesley, Reading, Mass., 3rd edition, 1997.

[22] Robert A. van Engelen and Kyle Gallivan. The gSOAP toolkit for web services and peer-to-peer computing networks. In *Proceedings of the 2nd IEEE International Symposium on Cluster Computing and the Grid (CC-Grid2002)*, pages 28–135, Berlin, Germany, May 2002.