



CXXR and Add-on Packages

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- 1 CXXR
- 2 Compatibility with CRAN Packages
- 3 Exploiting CXXR in Packages
- 4 Looking Forward

The CXXR Project

The aim of the CXXR project¹ is progressively **to reengineer the fundamental parts of the R interpreter from C into C++**.

By converting the interpreter internals to a well-documented object-oriented design, we hope that it will become easier for researchers to produce experimental versions of the interpreter, and explore new avenues for possible R development.

Work on CXXR started in May 2007, shadowing R-2.5.1; current work shadows R-2.10.1, with an upgrade to R-2.11.1 imminent.

We'll refer to the standard R interpreter as **CR**.

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CXXR Constraints

At every stage of refactorization, CXXR aims to preserve the full functionality of the standard R distribution. In particular it is intended that as far as possible:

- The behaviour of R code is unaffected (unless it probes into the interpreter internals);
- The `.C`, `.Fortran`, `.Call` and `.External` call-out interfaces are unaffected;
- The `R.h` and `S.h` APIs are unaffected. (However, code compiled against `Rinternals.h` may need minor alterations.)

Progress So Far

Important aspects of CXXR development to date include:

- The `SEXP` union has been replaced by an extensible hierarchy of C++ classes rooted at class `CXXR::RObject`. (All of CXXR's C++ code is placed within the C++ namespace `CXXR`, and we'll usually omit the prefix from now on.)
- Memory allocation and garbage collection have been completely refactored, and decoupled from R-specific functionality. Garbage collection is now based primarily on reference counting, with (non-generational) mark-sweep as a backstop.
- R's evaluation logic has been refactored into C++, with the exception so far of method dispatch.
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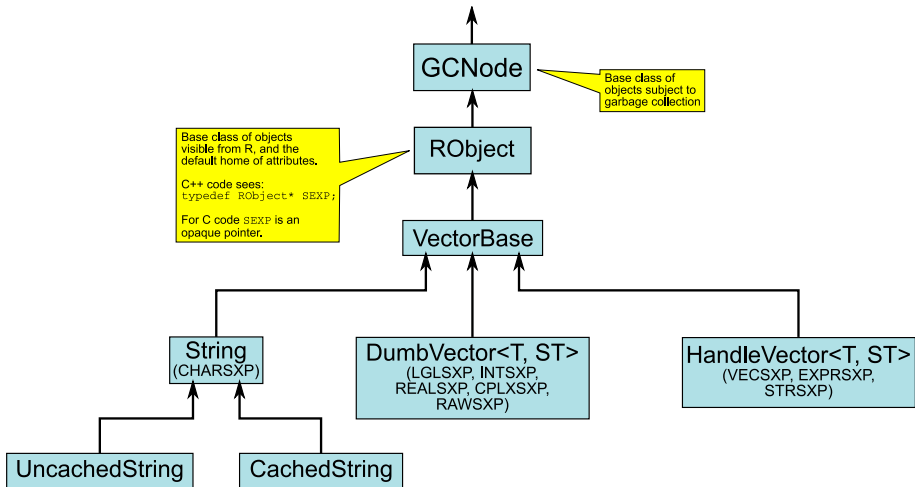
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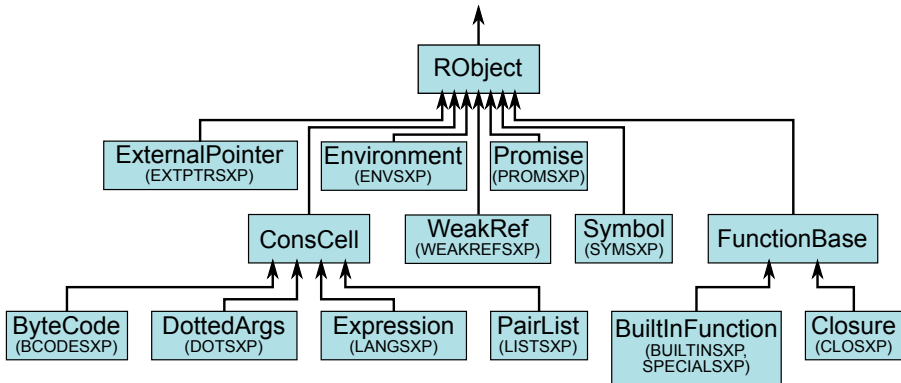
The R Object Class Hierarchy

Vector classes



The RObject Class Hierarchy

Other classes



The RObject Class Hierarchy

Objectives

- As far as possible, move all program code relating to a particular datatype into one place.
- Use C++'s public/protected/private mechanism to conceal implementational details and to defend class invariants, e.g.:
 - Every attribute of an RObject shall have a distinct Symbol object as its tag.
 - No two Symbol objects shall have the same name.
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Performance

The following tests were carried out on a 2.8 GHz Pentium 4 with 1 GB RAM and 1 MB L2 cache, comparing R-2.10.1 with CXXR release 0.29-2.10.1, using comparable optimization options. Times are CPU time (user + system).

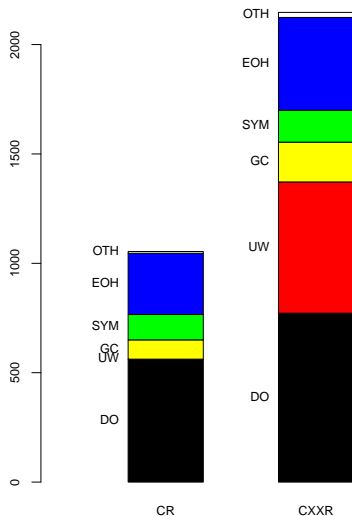
Benchmark	CR (secs)	CXXR (secs)	CR/CXXR
<code>bench.R</code> ²	129.1	114.5	1.13
<code>base5-Ex.R</code> ³	30.4	44.8	0.68
<code>stats-Ex.R</code>	48.7	92.7	0.53
<code>jens.R</code> ⁴	116.2	78.1	1.49

²By Jan de Leeuw, at <http://r.research.att.com/benchmarks>.

³Fivefold concatenation of `base-Ex.R`, omitting internal `quit()`s.

⁴Based on example R code from Jens Oehlschlägel *Managing Large Datasets in R—ff Examples and Concepts* [2010].

Timing Analysis with `stats-Ex.R`



- DO** Time servicing `do_` functions, excluding nested R expression evaluation and the next three categories below.
- UW** Stack unwinding, e.g. C++ exception propagation, or `findcontext()` in CR.
- GC** Garbage collection.
- SYM** Symbol look-up.
- EOH** Evaluation overhead, i.e. time spent evaluating R expressions not included in the categories above.
- OTH** Anything else, e.g. time spent outside the evaluation loop.

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How Compatible is CXXR with Packages from CRAN?

Until this year, CXXR had only been tested with packages forming part of the standard distribution, including the 'Recommended' packages.

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How well does it work with other packages from CRAN?

We have now tried CXXR with 50 other packages from CRAN.

In choosing packages to test, we asked 'How many other packages in CRAN depend on or suggest this package, directly or indirectly?' The packages tested were those for which this was a maximum.

Many thanks to Uwe Ligges for a script to identify these packages.

CRAN Packages Tested

akima	486	DBI	372	fBasics	318
rgl	472	RSQLite	360	e1071	318
RUnit	463	maps	359	ape	318
SparseM	461	mapproj	359	mix	317
RColorBrewer	446	robustbase	354	mclust	316
scatterplot3d	438	RODBC	342	leaps	316
mvtnorm	416	xtable	337	logspline	315
bitops	397	randomForest	335	quantreg	313
rsprng	395	gtools	335	numDeriv	311
rlecuyer	393	abind	333	multicore	309
Rmpi	392	tripack	326	mlmRev	308
nws	391	gee	322	lme4	308
sp	390	timeDate	321	MEMSS	308
rpvm	388	biglm	321	slam	304
coda	388	timeSeries	320	kernlab	303
snow	386	mlbench	318	car	302
tkrplot	384	gdata	318		

Package versions were those current on 2010-05-05.

Test Procedure

Working through the packages in order of decreasing number of reverse dependencies, each package was installed into CXXR with a (Unix shell) command such as:

```
> CXXR CMD INSTALL --install-tests foo_1.2-3.tar.gz
```

(For some packages a `--configure-args` flag was also necessary, and/or setting of environment variables.)

The package was then tested within a CXXR session with the R command:

```
> print(tools::testInstalledPackage('foo'))
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This will carry out any package-specific tests as well as testing the package's code examples and vignettes.

How good a test this is varies enormously from package to package.

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Of the 50 packages:

- 36 installed and tested OK 'out of the box'.
- A further two packages installed OK, and `testInstalledPackage` returned 0 (signifying OK) but under CXXR there were additional R warnings.
- In a further five packages, the test suite exhibited problems under both CXXR and our CR installation.⁵ With appropriate tweaks and workarounds, three of these five packages then passed the tests under CXXR (and all of them under CR).

This makes a total of 41 packages that passed `testInstalledPackage` without altering either the package or CXXR.

⁵For example, there were three packages for which `testInstalledPackage` would only work if the working directory had the same name as the package.

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Results

The not-so-good

- Five packages revealed bugs in CXXR (seven bugs in all). When these were fixed, all of them passed `testInstalledPackage`.
- Four packages proved to contain bugs (five bugs in all) that had remained latent under CR. In three cases, these were gaps in protection against garbage collection (i.e. missing `PROTECT()`/`UNPROTECT()`).
After fixing these problems, three of the four packages then passed `testInstalledPackage`; the remaining package also fell foul of the next problem.
- Two packages included C code that was inconsistent with CXXR. Fixing these problems required changing three lines of code in all, and did not affect the packages' compatibility with CR.

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Exploiting CXXR in Packages

Extending the RObject hierarchy: The internal RObject class hierarchy can be extended by packages, rather than their having to use external pointers and finalizers. This brings further benefits. . .

'Virtual attributes': C++ classes within the RObject hierarchy can apply their own checks on attribute settings, and determine how attribute values are stored within the class object.

Delegated serialization/deserialization: C++ classes within the RObject hierarchy can control how objects of that class are serialized. So custom objects can be saved as part of the CXXR session. (Work in progress.)

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Next Stages

- Upgrade CXXR to shadow R 2.11.1
- Port CXXR to Windows. Any volunteers?
- Improve performance.
- At present data provenance is tracked only within a single R session. This is being extended to cross-session tracking.
- Refactor method-dispatch code into C++.
- Consider how better to handle R's array subscripting/subsetting operations within a C++ framework. The present `VectorBase` class is underpowered, and does not provide a mature base for CXXR package-writers to build on.

Performance

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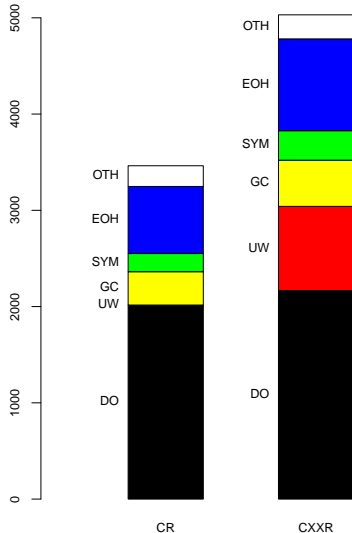
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Timing Analysis with `base5-Ex.R`



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UW Stack unwinding, e.g. C++ exception propagation, or `findcontext()` in CR.

GC Garbage collection.

SYM Symbol look-up.

EOH Evaluation overhead, i.e. time spent evaluating R expressions not included in the categories above.

OTH Anything else, e.g. time spent outside the evaluation loop.

Nested LCONS

In CXXR, objects of type `LANGSXP` (implemented by C++ class `Expression`), `DOTSXP` (class `DottedArgs`) and `BCODESXP` (class `ByteCode`) are permitted only to appear at the head of a pairlist; all remaining elements of the list must be of type `LISTSXP` (class `PairList`).

So for example the C code:

```
SEXP hcall = LCONS(h, LCONS(cond, R_NilValue));
```

needs to be changed to

```
SEXP hcall = LCONS(h, CONS(cond, R_NilValue));
```

for use under CXXR.

Code Migration from R to C++

In CXXR, underlying every R object (whether of an R class type or not) is a C++ object of a class inheriting from `RObject`.

Very often in R packages, much code is specifically associated with a particular type of R object. This is most obvious in R class definitions. The code in question may be written in R itself, in C or C++, or maybe in some other language.

CXXR aims to allow you easily to migrate the functionality of that code into the C++ class underlying those objects. This can be done in small steps, and to the extent that you see fit.

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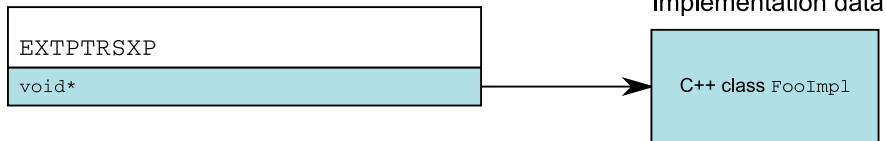
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Evolution of an R Class under CXXR

R Class "foo"

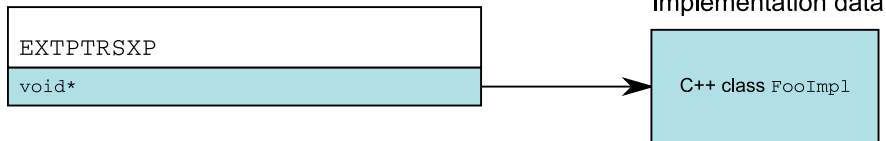


An 'external pointer' R object contains an untyped pointer, which can be configured to point to an arbitrary C/C++ data structure.

A common issue is how to recover the memory space used by this data structure when the external pointer object is garbage-collected. The standard approach is to use a **finalizer**...

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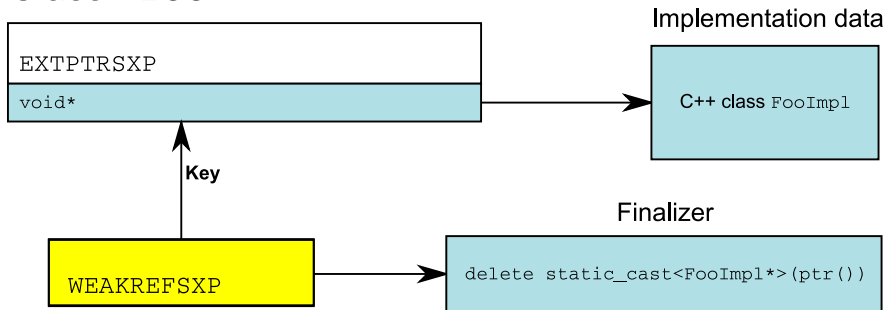


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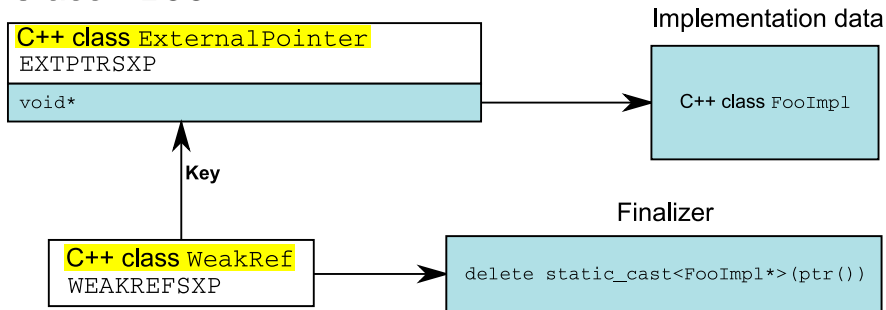


Finalization is implemented using an auxiliary 'weak reference' object, which designates the object to be finalized as its **key**.

During a mark-sweep garbage collection, if it is determined that the key of a weak reference is unreachable, the finalizer is executed. Then the key and the weak reference are garbage-collected.

Evolution of an R Class under CXXR

R Class "foo"



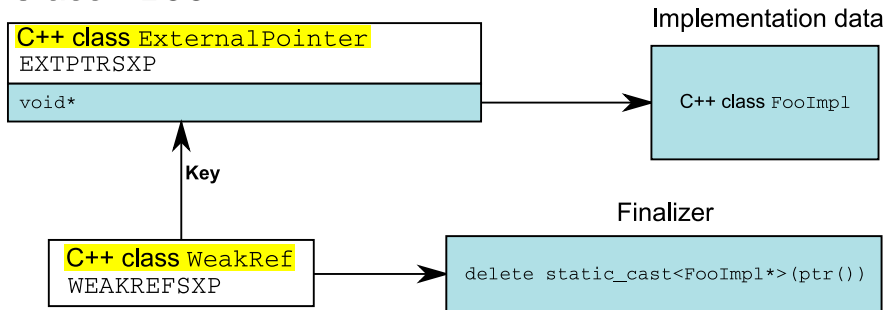
The same mechanism remains available under CXXR, implemented via the class `WeakRef`.

A drawback is that neither weak reference objects nor their keys can be garbage-collected by the reference counting scheme.

Consequently objects of class "foo" will remain in existence until the next full garbage collection.

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R Class "foo"

```
class Foo : public ExternalPointer
EXTPTRSXP

void*

Foo()
: ExternalPointer(new FooImpl)
{}

~Foo()
{
    delete static_cast<FooImpl*>(ptr());
}
```

Implementation data

C++ class FooImpl

An easy change: instead of using class `ExternalPointer` itself, we can introduce a new C++ class `Foo` inheriting from `ExternalPointer`, and **incorporate the finalization logic in the class destructor**. `Foo` objects can now be garbage-collected by reference counting.

Evolution of an R Class under CXXR

R Class "foo"

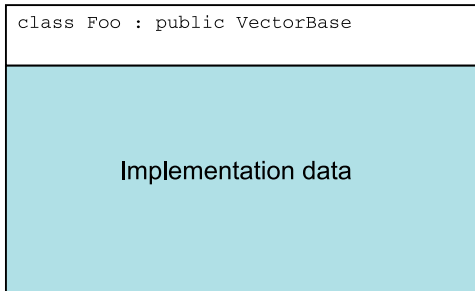
```
class Foo : public VectorBase  
  
FooImpl* m_impl;  
  
Foo(size_t size)  
: VectorBase(size),  
  m_impl(new FooImpl(size))  
{  
  
~Foo()  
{  
    delete m_impl;  
}
```

Implementation data

C++ class FooImpl

But why use `ExternalPointer` objects at all? If, for example, class "foo" has the characteristics of a data vector, we can make its C++ representation inherit instead from `VectorBase`.

R Class "f_{oo}"



Finally, we may be able to incorporate the C++ data structures implementing class "f_{oo}" directly into the F_{oo} object, eliminating an indirection and probably simplifying the code.

Attributes in CR

Each R object can have a list of named attributes associated with it. Under CR, the C function `setAttribute()` applies checks to the value supplied for any attribute named `"class"`, `"comment"`, `"dim"`, `"dimnames"`, `"names"`, `"row.names"` or `"tsp"`. Apart from that, anything goes.

CXXR: Virtual Attributes

In CXXR, the trend is to delegate attribute control to individual classes within the `RObject` hierarchy.

Class `RObject` contains a pairlist of attributes just as in CR. Attribute values are set using the method:

```
virtual void RObject::setAttribute(const Symbol* name,  
                                   RObject* value);
```

However, because this method (and other attribute-related methods) are declared `virtual`, their default implementations can be *overridden* by other C++ classes in the `RObject` hierarchy.

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CXXR: Virtual Attributes

Where CXXR packages provide new C++ classes within the `RObject` hierarchy, they can use this 'virtual attribute' facility in two ways:

- To apply class-specific checks that attribute values are consistent with the C++ class invariants. For example, arrays from package `ff` have a `"dimorder"` attribute which determines their layout (row-major, column-major etc.). The underlying C++ class could verify that any value supplied for this attribute is a permutation of $1 : n$.
- To use an internal representation of attribute values that augments or replaces the default representation. For example, the value of a `"rotation"` attribute may appear to the R user to be an angle but be stored internally as a sine/cosine matrix.

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Delegated Serialization/Deserialization

(Work in progress: early days!)

Being able to track data object provenance from one R session to another means that **information about the provenance of data objects must be saved alongside the data objects themselves**. This is leading to a revision to the way in which object serialization and deserialization are carried out in CXXR.

As part of this, serialization and deserialization will be carried out by virtual functions of the abstract class `CXXR::Serializable`, from which `CXXR::RObject` will inherit.

CXXR package-writers who augment the `RObject` class hierarchy will be able to exploit this to save and restore their custom objects between CXXR sessions.

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GC Protection Using Smart Pointers

The following example gives the flavour of C++ programming for CXXR:

```
// Return a reversed copy of a pairlist:

PairList* reverse(const PairList* inlist)
{
    GCStackRoot<PairList> revlist;
    while (inlist) {
        revlist
            = PairList::construct(inlist->car(), revlist,
                                  inlist->tag());
        inlist = inlist->tail();
    }
    return RObject::clone(revlist);
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        GCStackRoot is a (templated) 'smart pointer' type. It can be
        used like a pointer (PairList* in this case) but protects
        whatever it points to from garbage collection.
        GCStackRoot(inlist->car(), revlist,
                    inlist->tag());
    }
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No need for REPROTECT() here.

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The `revlist` smart pointer goes out of scope here, and its destructor automatically ends the GC protection it offers. No need for `UNPROTECT()`.

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    }  
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```

But if you prefer to do things the CR way, CXXR permits that too!