Higher-Performance R Programming with C++ Extensions

Part 2: First Steps with Rcpp

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The R API

The R API

- R is a C program, and C programs can be extended
- R exposes an API with C functions and MACROS
- R also supports C++ out of the box with `.cpp` extension
- R provides several calling conventions:
  - `.C()` provides the first interface, is fairly limited, and discouraged
  - `.Call()` provides access to R objects at the C level
  - `.External()` and `.Fortran()` exist but can be ignored
- We will use `.Call()` exclusively

The .Call Interface

At the C level, everything is a SEXP, and all .Call() access use this interface:

```
SEXP foo(SEXP x1, SEXP x2){
...
}
```

which can be called from R via

```
.Call("foo", var1, var2)
```

Example: Convolution

```c
#include <R.h>
#include <Rinternals.h>

SEXP convolve2(SEXP a, SEXP b) {
    int na, nb, nab;
    double *xa, *xb, *xab;
    SEXP ab;

    a = PROTECT(coerceVector(a, REALSXP));
    b = PROTECT(coerceVector(b, REALSXP));
    na = length(a);
    nb = length(b);
    nab = na + nb - 1;
    ab = PROTECT(allocVector(REALSXP, nab));
    xa = REAL(a);
    xb = REAL(b);
    xab = REAL(ab);
    for (int i = 0; i < nab; i++)
        xab[i] = 0.0;
    for (int i = 0; i < na; i++)
        for (int j = 0; j < nb; j++)
            xab[i + j] += xa[i] * xb[j];
    UNPROTECT(3);
    return ab;
}
```

Example: Convolution

```
#include <Rcpp.h>

// [[Rcpp::export]]
Rcpp::NumericVector
convolve2cpp(Rcpp::NumericVector a,
             Rcpp::NumericVector b) {
    int na = a.length(), nb = b.length();
    Rcpp::NumericVector ab(na + nb - 1);
    for (int i = 0; i < na; i++)
        for (int j = 0; j < nb; j++)
            ab[i + j] += a[i] * b[j];
    return(ab);
}
```

Rcpp Usage

Basic Usage: evalCpp()

`evalCpp()` evaluates a single C++ expression. Includes and dependencies can be declared.

This allows us to quickly check C++ constructs.

```
library(Rcpp)
evalCpp("2 + 2")      # simple test
```

```
## [1] 4
```

```
evalCpp("std::numeric_limits<double>::max()")
```

```
## [1] 1.79769e+308
```

Basic Usage: cppFunction()

`cppFunction()` creates, compiles and links a C++ file, and creates an R function to access it.

```
cppFunction("
    int exampleCpp11() {
        auto x = 10;
        return x;
}", plugins=c("cpp11"))
exampleCpp11()  # same identifier as C++ function
```

Basic Usage: sourceCpp()

`sourceCpp()` is the actual workhorse behind `evalCpp()` `and`cppFunction()‘. It is described in more detail in the package vignette Rcpp-attributes.

`sourceCpp()` builds on and extends `cxxfunction()` from package inline, but provides even more ease-of-use, control and helpers – freeing us from boilerplate scaffolding.

A key feature are the plugins and dependency options: other packages can provide a plugin to supply require compile-time parameters (cf RcppArmadillo, RcppEigen, RcppGSL).

Types Overview

RObject

- The `RObject` can be thought of as a basic class behind many of the key classes in the `Rcpp` API.
- `RObject` (and our core classes) provide a thin wrapper around `SEXP` objects
- This is sometimes called a *proxy object* as we do not copy the R object.
- `RObject` manages the life cycle, the object is protected from garbage collection while in scope—so we do not have to do memory management.
- Core classes define several member common functions common to all objects (e.g. `isS4()`, `attributeNames`, ...); classes then add their specific member functions.

Overview of Classes: Comparison

Rcpp class	R `typeof`
`Integer(Vector|Matrix)`	`integer` vectors and matrices
`Numeric(Vector|Matrix)`	`numeric` ...
`Logical(Vector|Matrix)`	`logical` ...
`Character(Vector|Matrix)`	`character` ...
`Raw(Vector|Matrix)`	`raw` ...
`Complex(Vector|Matrix)`	`complex` ...
`List`	`list` (aka generic vectors) ...
`Expression(Vector|Matrix)`	`expression` ...
`Environment`	`environment`
`Function`	`function`
`XPtr`	`externalptr`
`Language`	`language`
`S4`	`S4`
...	...

Overview of key vector / matrix classes

- `IntegerVector` vectors of type `integer`
- `NumericVector` vectors of type ‘numeric
- `RawVector` vectors of type `raw`
- `LogicalVector` vectors of type `logical`
- `CharacterVector` vectors of type `character`
- `GenericVector` generic vectors implementing `list` types

Common core functions for Vectors and Matrices

Key operations for all vectors, styled after STL operations:

- `operator()` access elements via `()`
- `operator[]` access elements via `[]`
- `length()` also aliased to `size()`
- `fill(u)` fills vector with value of `u`
- `begin()` pointer to beginning of vector, for iterators
- `end()` pointer to one past end of vector
- `push_back(x)` insert `x` at end, grows vector
- `push_front(x)` insert `x` at beginning, grows vector
- `insert(i, x)` insert `x` at position *i*, grows vector
- `erase(i)` remove element at position *i*, shrinks vector

IntegerVector

IntegerVector: A first example

A simpler version of `prod()` for integer vectors:

```
#include <Rcpp.h>

// [[Rcpp::export]]
int intVec1a(Rcpp::IntegerVector vec) {
    int prod = 1;
    for (int i=0; i<vec.size(); i++) {
        prod *= vec[i];
    }
    return prod;
}
```

IntegerVector: A first example

We can also do this for STL vector types:

```
#include <Rcpp.h>

// [[Rcpp::export]]
int intVec1b(std::vector<int> vec) {
    int prod = 1;
    for (unsigned int i=0; i<vec.size(); i++) {
        prod *= vec[i];
    }
    return prod;
}
```

IntegerVector: Loopless

Loopless for `Rcpp::IntegerVector`:

```
#include <Rcpp.h>

// [[Rcpp::export]]
int intVec2a(Rcpp::IntegerVector vec) {
    int prod =
        std::accumulate(vec.begin(),
                        vec.end(), 1,
                        std::multiplies<int>());
    return prod;
}
```

IntegerVector: Loopless

Loopless for STL's `std::vector<int>`:

```
#include <Rcpp.h>

// [[Rcpp::export]]
int intVec2b(std::vector<int> vec) {
    int prod =
        std::accumulate(vec.begin(),
                        vec.end(), 1,
                        std::multiplies<int>());
    return prod;
}
```

NumericVector and NumericMatrix

NumericVector: A First Example

This example generalizes the sum of squares by supplying an exponentiation argument:

```
#include <Rcpp.h>
// [[Rcpp::export]]
double numVecEx1(Rcpp::NumericVector vec,
                 double p = 2.0) {
    double sum = 0.0;
    for (int i=0; i<vec.size(); i++) {
        sum += pow(vec[i], p);
    }
    return sum;
}
```

NumericVector: A Second Example

A second example alters a numeric vector:

```
#include <Rcpp.h>
// [[Rcpp::export]]
Rcpp::DataFrame numVecEx2(Rcpp::NumericVector xs) {
    Rcpp::NumericVector x1(xs);
    Rcpp::NumericVector x2(Rcpp::clone(xs));
    x1[0] = 22;
    x2[1] = 44;
    return(Rcpp::DataFrame::create(Named("orig", xs),
                                   Named("x1", x1),
                                   Named("x2", x2)));
}
```

NumericVector: A Second Example

Calling the last example with two different arguments:

```
Rcpp::sourceCpp("code/numVecEx2.cpp")
numVecEx2(c(1.0, 2.0))
```

```
##   orig x1 x2
## 1   22 22  1
## 2    2  2 44
```

```
numVecEx2(c(1L, 2L))
```

```
##   orig x1 x2
## 1   22 22  1
## 2    2  2 44
```

NumericVector: A Third Example

A third example overwrites one element:

```
#include <Rcpp.h>

// [[Rcpp::export]]
Rcpp::NumericVector f(Rcpp::NumericVector m) {
    m(0) = 0;
    return m;
}
```

NumericVector: A Third Example

Calling the last example with two different arguments:

```
Rcpp::sourceCpp("code/numVecEx3.cpp")
v <- c(1,2); data.frame(old=v, new=f(v))
```

```
##   old new
## 1   0   0
## 2   2   2
```

```
v <- c(1L,2L); data.frame(old=v, new=f(v))
```

```
##   old new
## 1   1   0
## 2   2   2
```

Constructors

```
SEXP x;
NumericVector y(x);     // from a SEXP

// cloning (deep copy)
NumericVector z = clone<NumericVector>( y );

// of a given size (all elements set to 0.0)
NumericVector y(10);

// ... specifying the value
NumericVector y(10, 2.0);

// with given elements
NumericVector y = NumericVector::create(1.0, 2.0);
```

NumericMatrix

`NumericMatrix` is a specialisation of `NumericVector` with a dimension attribute:

```
#include <Rcpp.h>

// [[Rcpp::export]]
Rcpp::NumericMatrix takeRoot(Rcpp::NumericMatrix mm) {
    Rcpp::NumericMatrix m =
                Rcpp::clone<Rcpp::NumericMatrix>(mm);
    std::transform(m.begin(), m.end(),
                   m.begin(), ::sqrt);
    return m;
}
```

NumericMatrix

```
Rcpp::sourceCpp("code/numMatEx1.cpp")
takeRoot( matrix((1:9)*1.0, 3, 3) );
```

```
##          [,1]    [,2]    [,3]
## [1,] 1.00000 2.00000 2.64575
## [2,] 1.41421 2.23607 2.82843
## [3,] 1.73205 2.44949 3.00000
```

Other Types

Armadillo

We prefer Armadillo for math though – more later.

```
// [[Rcpp::depends(RcppArmadillo)]]

#include <RcppArmadillo.h>

// [[Rcpp::export]]
Rcpp::List armafun(arma::mat m1) {
    arma::mat m2 = m1 + m1;
    arma::mat m3 = m1 * 2;
    return Rcpp::List::create(m1, m2);
}
```

Other Vector Types

- `LogicalVector` very similar to `IntegerVector`: two possible values of a logical, or boolean, type – plus `NA`.
- `CharacterVector` can be used for vectors of character vectors ("strings").
- `RawVector` can be used for vectors of raw strings (used eg in serialization).
- `Named` can be used to assign named elements in a vector, similar to R construct `a <- c(foo=3.14, bar=42)`.
- `List` (aka `GenericVector`) is the catch-all, different-types-allowed container, more below.

GenericVector

`List` types can be used to receive (named) values to R. As lists can be nested, each element type is allowed.

```
double someFunction(Rcpp::List params) {
    std::string method =
        Rcpp::as<std::string>(params["method"]);
    double tolerance =
        Rcpp::as<double>(params["tolerance"]);
    Rcpp::NumericVector startvalues =
        params["startvalues"];

    // ... more code here ...
```

Similarly, `List` types are convenient for returning multiple values to R.

```
return
Rcpp::List::create(Rcpp::Named("method", method),
                   Rcpp::Named("tolerance", tolerance),
                   Rcpp::Named("iterations", iterations),
                   Rcpp::Named("parameters", parameters));
```

DataFrame

`DataFrame` can receive and return values.

```
Rcpp::IntegerVector v =
     Rcpp::IntegerVector::create(1,2,3);
std::vector<std::string> s =
     { "a", "b", "c" };                    // C++11
return Rcpp::DataFrame::create(Rcpp::Named("a") = v,
                               Rcpp::Named("b") = s);
```

But because a `data.frame` is a (internally) a list of vectors, not as easy to subset by rows as in R.

Functions

The `Function` class can access R functions we pass in:

```
#include <Rcpp.h>

// [[Rcpp::export]]

SEXP fun(Rcpp::Function f, SEXP x) {
    return f(x);
}
```

Functions

```
sourceCpp("code/functionEx1.cpp")
fun(sort, sample(1:5, 10, TRUE))
```

```
##  [1] 1 1 1 2 2 2 4 4 5 5
```

```
fun(sort, sample(LETTERS[1:5], 10, TRUE))
```

```
##  [1] "A" "A" "B" "B" "B" "B" "C" "C" "D" "E"
```

Functions

We can also instantiate functions directly:

```
#include <Rcpp.h>

// [[Rcpp::export]]
Rcpp::NumericVector fun() {
    Rcpp::Function rt("rt");
    return rt(3, 4);
}
```

Functions

```
sourceCpp("code/functionEx2.cpp")
set.seed(42)
fun()
```

```
## [1]  2.057339  0.100706 -0.075780
```

```
set.seed(42)
rt(3, 4)
```

```
## [1]  2.057339  0.100706 -0.075780
```

Environments

```
#include <Rcpp.h>

// [[Rcpp::export]]
Rcpp::NumericVector fun() {
    Rcpp::Environment stats("package:stats");
    Rcpp::Function rt = stats["rt"];
    return rt(3, Rcpp::Named("df", 4));
}
```

Environments

```
sourceCpp("code/environmentEx1.cpp")
set.seed(42)
fun()
```

```
## [1]  2.057339  0.100706 -0.075780
```

```
set.seed(42)
rt(3, 4)
```

```
## [1]  2.057339  0.100706 -0.075780
```

S4

S4 objects can be accessed as well as created.

```
#include <Rcpp.h>

// [[Rcpp::export]]
Rcpp::S4 fun(Rcpp::S4 x) {
    x.slot("x") = 42;
    return x;
}
```

S4

```
sourceCpp("code/s4ex1.cpp")
setClass("S4ex", contains="character",
         representation(x="numeric"))
x <- new("S4ex", "bla", x=10);  x
```

```
## An object of class "S4ex"
## [1] "bla"
## Slot "x":
## [1] 10
```

```
fun(x)
```

```
## An object of class "S4ex"
## [1] "bla"
## Slot "x":
## [1] 42
```