Seamless R and C++ Integration with Rcpp: Part 1 – Rcpp Introduction

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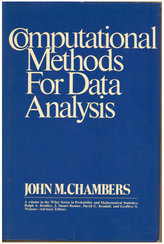
Outline

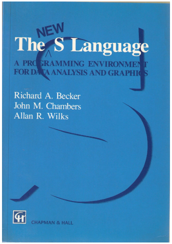
1. Why?
   - R
   - C++
   - Vision
   - Features

Why R?

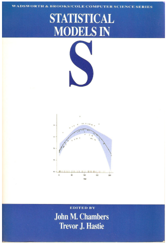
Programming with Data



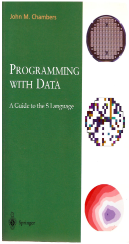
Chambers, *Computational Methods for Data Analysis*. Wiley, 1977.



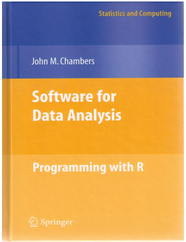
Becker, Chambers, and Wilks. *The New S Language*. Chapman & Hall, 1988.



Chambers and Hastie. *Statistical Models in S*. Chapman & Hall, 1992.



Chambers. *Programming with Data*. Springer, 1998.



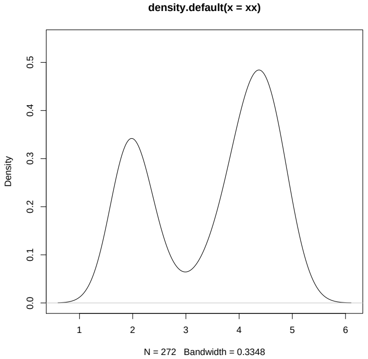
Chambers. *Software for Data Analysis: Programming with R*. Springer, 2008

Thanks to John Chambers for sending me high-resolution scans of the covers of his books.

Why R?

Succinct and expressive

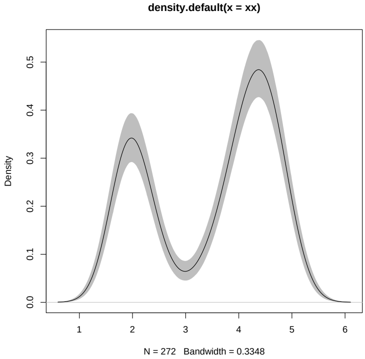
```
xx <- faithful[,"eruptions"]
fit <- density(xx)
plot(fit)
```



Why R?

Succinct and expressive

```
xx <- faithful[,"eruptions"]
fit1 <- density(xx)
fit2 <- replicate(10000, {
  x <- sample(xx,replace=TRUE);
  density(x, from=min(fit1$x),
          to=max(fit1$x))$y
})
fit3 <- apply(fit2, 1,
  quantile,c(0.025,0.975))
plot(fit1, ylim=range(fit3))
polygon(c(fit1$x,rev(fit1$x)),
  c(fit3[1,], rev(fit3[2,])),
  col='grey', border=F)
lines(fit1)
```



The example was posted by Greg Snow on r-help a few years ago.

Why R?

Extensible

R has always been extensible via

C	via a bare-bones interface described in *Writing R Extensions*
Fortran	which is also used internally by R
Java	via **rJava** by S Urbanek
C++	but essentially at the bare-bones level of C

So 'in theory' this worked – yet tedious 'in practice'.

Why C++?

- Asking Google leads to 37,400,000 hits.
- Wikipedia: *C++ is a statically typed, free-form, multi-paradigm, compiled, general-purpose, powerful programming language.*
- C++ is industrial-strength, vendor-independent, widely-used, and *still evolving*.
- In science & research, one of the most frequently-used languages: If there is something you want to use / connect to, it probably has a C/C++ API.
- As a widely used language it also has good tool support (debuggers, profilers, code analysis).

Why C++?

Scott Meyers: *"View C++ as a federation of languages"*

C provides a rich inheritance and interoperability as Unix, Windows, ... are all build on C.

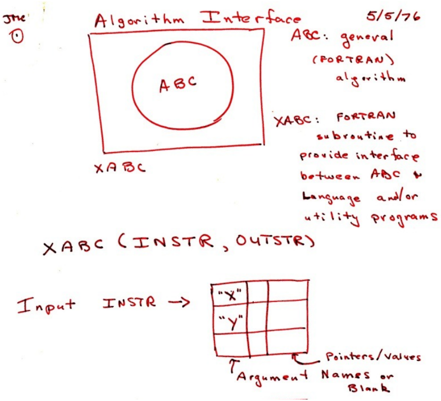
Object-Oriented C++ just to provide endless discussions about exactly what OO is or should be.

Templated C++ which is mighty powerful; template meta programming unequalled in other languages.

The STL which is a specific template library which is powerful but has its own conventions.

C++11 adds enough to be called a fifth language.

Interface Vision



JMC
⊙
ABC
XABC
"X"
"Y"

Algorithm Interface

5/5/76

ABC: general (FORTRAN) algorithm

XABC: FORTRAN subroutine to provide interface between ABC & Language and/or utility programs

XABC (INSTR, OUTSTR)

Input INSTR →

Pointers/Values

Argument Names or Blank

Source: John Chambers, personal communication.

Why Rcpp?

Easy to use it really does not have to be that complicated – we will look at a few examples

Expressive it allows for *vectorised* C++ using *Rcpp Sugar*

Seamless access to all R objects: vector, matrix, list, S3/S4/RefClass, Environment, Function, ...

Speed gains for a variety of tasks **Rcpp** excels precisely where R struggles: loops, function calls, ...

Extensions greatly facilitates access to external libraries using eg *Rcpp modules* (but we will not have time for a walkthrough)

Outline

2 What?
- R API
- C++

What can Rcpp do?

Everything evolves around .Call

At the C++ level:

```
SEXP foo(SEXP a, SEXP b, SEXP C, ...)
```

and at the R level:

```
res <- .Call("foo", a, b, c, ...,
             package="mypkg")
```

What can Rcpp do?

Seamless interchange of R objects: C API of R

```
#include <R.h>
#include <Rdefines.h>
SEXP convolve2(SEXP a, SEXP b) {
    int i, j, na, nb, nab;
    double *xa, *xb, *xab;
    SEXP ab;

    PROTECT(a = AS_NUMERIC(a));
    PROTECT(b = AS_NUMERIC(b));
    na = LENGTH(a); nb = LENGTH(b); nab = na + nb - 1;
    PROTECT(ab = NEW_NUMERIC(nab));
    xa = NUMERIC_POINTER(a); xb = NUMERIC_POINTER(b);
    xab = NUMERIC_POINTER(ab);
    for(i = 0; i < nab; i++) xab[i] = 0.0;
    for(i = 0; i < na; i++)
        for(j = 0; j < nb; j++) xab[i + j] += xa[i] * xb[j];
    UNPROTECT(3);
    return(ab);

}
```

What can Rcpp do?

Seamless interchange of R objects: Rcpp version

```
#include <Rcpp.h>

using namespace Rcpp;

// [[Rcpp::export]]
NumericVector convolveCpp(NumericVector a, NumericVector b) {
    int na = a.size(), nb = b.size();
    int nab = na + nb - 1;
    NumericVector xab(nab);

    for (int i = 0; i < na; i++)
        for (int j = 0; j < nb; j++)
            xab[i + j] += a[i] * b[j];

    return xab;
}
```

What can Rcpp do?

Seamless interchange of R objects

- Any R object can be passed down to C++ code: vectors, matrices, list, ...
- But also functions, environments and more.
- This includes S3 and S4 objects as well as Reference Classes.
- Object attributes can be accessed directly.
- Objects can be created at the C++ level, and the R garbage collector *does the right thing* as if it were an R-created object.

What can Rcpp do?

Seamless use of RNGs

```
set.seed(42); runif(5)

## [1] 0.9148 0.9371 0.2861 0.8304 0.6417

cppFunction('
NumericVector r1(int n) {
   NumericVector x(n);
   for (int i=0; i<n; i++) x[i] = R::runif(0,1);
   return(x);
}')
set.seed(42); r1(5)

## [1] 0.9148 0.9371 0.2861 0.8304 0.6417

cppFunction('NumericVector r2(int n) { return runif(n,0,1); }')
set.seed(42); r2(5)

## [1] 0.9148 0.9371 0.2861 0.8304 0.6417
```

What can Rcpp do?

Sugar: R version

```r
piR <- function(N) {
    x <- runif(N)
    y <- runif(N)
    d <- sqrt(x^2 + y^2)
    return(4 * sum(d <= 1.0) / N)
}
```

What can Rcpp do?

Sugar: C++ version

```
#include <Rcpp.h>
using namespace Rcpp;

// [[Rcpp::export]]
double piSugar(const int N) {
    NumericVector x = runif(N);
    NumericVector y = runif(N);
    NumericVector d = sqrt(x*x + y*y);
    return 4.0 * sum(d <= 1.0) / N;
}
```

NB: Use of `RNGScope` ensured via Rcpp Attributes.

Outline

3 When?
- Example 1
- Example 2

When do we use Rcpp?

Easy speedup: An Introductory Example

Consider a function defined as

$$f(n) \quad \text{such that} \quad \begin{cases} n & \text{when} \quad n < 2 \\ f(n-1) + f(n-2) & \text{when} \quad n \geq 2 \end{cases}$$

When do we use Rcpp?

Easy speedup: Simple R Implementation

```r
fibR <- function(n) {
    if (n < 2) return(n)
    return(fibR(n-1) + fibR(n-2))
}
## Using it on first 11 arguments
sapply(0:10, fibR)

##  [1]  0  1  1  2  3  5  8 13 21 34 55
```

When do we use Rcpp?

Easy speedup: Timing R Implementation

```
benchmark(fibR(10),fibR(15),fibR(20))[,1:4]

##       test replications elapsed relative
## 1 fibR(10)          100   0.037     1.00
## 2 fibR(15)          100   0.509    13.76
## 3 fibR(20)          100   4.305   116.35
```

When do we use Rcpp?

Easy speedup: C++ Implementation

```
cppFunction("
  int fibCpp(int n) {
    if (n < 2) return(n);
    return(fibCpp(n-1) + fibCpp(n-2));
}")
## Using it on first 11 arguments
sapply(0:10, fibCpp)

##  [1]  0  1  1  2  3  5  8 13 21 34 55
```

When do we use Rcpp?

Easy speedup: Putting it all together

```
fibR <- function(n) {
    if (n<2) return(n)
    return(fibR(n-1) + fibR(n-2))
}
cppFunction('int fibCpp(int n) {
    if (n<2) return n;
    return fibCpp(n-2) + fibCpp(n-1);
}')
benchmark(fibR(25),fibCpp(25),order="relative")[,1:4]


##         test replications elapsed relative
## 2 fibCpp(25)          100   0.084      1.0
## 1   fibR(25)          100  49.286    586.7
```

When do we use Rcpp?

Easy speedup:: VAR(1) Simulation

Let's consider a simple possible VAR(1) system of k variables.

For $k = 2$:

$$X_t = X_{t-1} B + E_t$$

where X_t is a row vector of length 2, B is a 2 by 2 matrix and E_t is a row of the error matrix of 2 columns.

When do we use Rcpp?

Easy speedup:: VAR(1) Simulation

In R code, given both the coefficient and error matrices (revealing *k* and *n*):

```r
rSim <- function(B,E) {
    X <- matrix(0,nrow(E), ncol(E))
    for (r in 2:nrow(E)) {
        X[r,] = X[(r-1),] %*% B + E[r,]
    }
    return(X)
}
```

When do we use Rcpp?

Easy speedup: VAR(1) Simulation

```
cppFunction('arma::mat cppSim(arma::mat B, arma::mat E) {
    int m = E.n_rows; int n = E.n_cols;
    arma::mat X(m,n);
    X.row(0) = arma::zeros<arma::mat>(1,n);
    for (int r=1; r<m; r++) {
        X.row(r) = X.row(r-1) * B + E.row(r);
    }
    return X;
}', depends="RcppArmadillo")
a <- matrix(c(0.5,0.1,0.1,0.5),nrow=2)
e <- matrix(rnorm(10000),ncol=2)
benchmark(cppSim(a,e),rSim(a,e),order="relative")[,1:4]

##           test replications elapsed relative
## 1 cppSim(a, e)          100   0.027      1.0
## 2   rSim(a, e)          100   4.561    168.9
```

When do we use Rcpp?

New things: Easy access to C/C++ libraries

- Sometimes speed is not the only reason
- C and C++ provide a enormous amount of libraries and APIs we may want to use
- Easy to provide access to as **Rcpp** eases data transfer to/from R
- *Rcpp modules* can make it even easier

Outline

4 Where?

Where is Rcpp being used?

Numbers as of late September 2013

Rcpp is

- used by 150 packages on CRAN
- used by another 16 package on BioConductor
- cited 77 times (Google Scholar count for 2011 paper in JSS)

Where is Rcpp being use?

Several well-known packages

Amelia Gary King et al: Multiple Imputation; uses **Rcpp** and **RcppArmadillo**

forecast Rob Hyndman et al: (Automated) Time-series forecasting; uses **Rcpp** and **RcppArmadillo**

RStan Andrew Gelman et al: Bayesian models / MCMC

rugarch Alexios Ghalanos: Sophisticated financial models; using **Rcpp** and **RcppArmadillo**

lme4 Doug Bates et al: Hierarchical/Mixed Linear Models; uses **Rcpp** and **RcppEigen**.

bigviz Hadley Wickham: High-dimensional visualization of data with 10-100 million obs.

Outline

5 How?
- Setup
- evalCpp
- cppFunction
- sourceCpp
- skeleton

How do we use Rcpp?

Uses only standard R tools to build packages

Depending on the platform, one needs

Windows	the Rtools kit for Windows, properly installed – see CRAN, the Installation manual and many tutorials; the **installr** package may help
OS X	the Xcode *command-line tools* (plus possibly the Fortran compiler) – see Simon's pages
Linux	generally just work out of the box

Several environments can be used to work with **Rcpp** – RStudio is very popular.

No additional requirements for Rcpp beyond *being able to compile R packages*.

How do we use Rcpp?

Easy to test

```
## evaluate a C++ expression, retrieve result
evalCpp("2 + 2")

## [1] 4

## a little fancier
evalCpp("std::numeric_limits<double>::max()")

## [1] 1.798e+308

## create ad-hoc R function 'square'
cppFunction('int square(int x) { return x*x;}')
square(7L)

## [1] 49
```

How do we use Rcpp?

Basic Usage: `evalCpp`

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

This allows us to quickly check C++ constructs.

```
evalCpp( "2 * M_PI" )

## [1] 6.283
```

How do we use Rcpp?

Basic Usage: cppFunction()

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

```
cppFunction("
    int useCpp11() {
        auto x = 10;
        return x;
}", plugins=c("cpp11"))
useCpp11()  # same identifier as C++ function

## [1] 10
```

How do we use Rcpp?

Basic Usage: `sourceCpp()`

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

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**).

We are also starting to provide plugins for other compiler features. A first plugin to enable C++11 support was added recently, as was a second one for OpenMP.

How do we use Rcpp?

Basic Usage: `Rcpp.package.skeleton()`

- To create a complete and working package, the `Rcpp.package.skeleton()` function can be used.
- It extends the base R function `package.skeleton()` and supports the same set of options.
- For **Rcpp** use is also supports (via additional options) *Rcpp Modules* and *Rcpp Attributes* both of which can be included with working examples
- The vignette Rcpp-package has complete details.

Outline

6 What Else?
- Basics
- Gallery
- Book

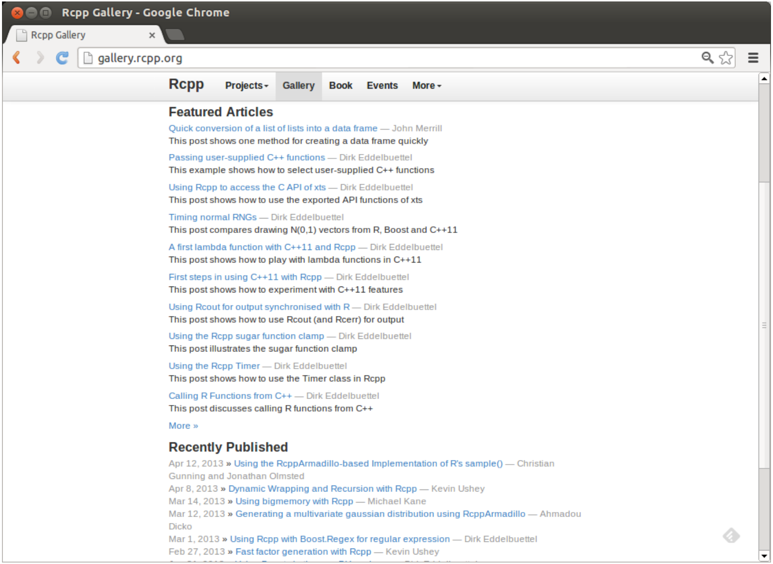
What Else?

Basic Documentation

- The package comes with **eight pdf vignettes**, and numerous help pages.
- The introductory vignettes are now **published** (Rcpp and RcppEigen in *J Stat Software*, RcppArmadillo in *Comp. Stat.& Data Anal.*).
- The **rcpp-devel** list is *the* recommended resource, generally very helpful, and fairly low volume.
- **StackOverflow** has a fair number of posts too.
- Several blog posts introduce/discuss features.

What Else?

Rcpp Gallery: 70+ working and detailed examples



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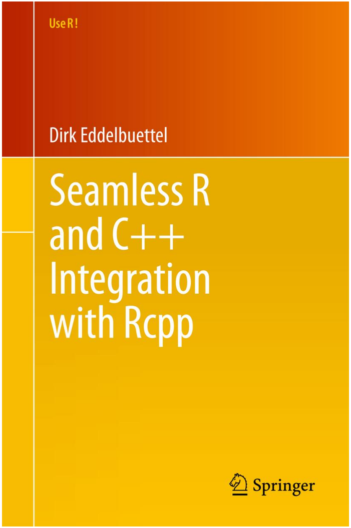
What Else?

The Rcpp book



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