StatML CDT Computational Training Part 2: Extending R with Rcpp

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Aims

1. Cursory overview of Rcpp
2. Motivate extending R, and why Rcpp
3. Learn through examples
4. Provide references to resources for more in depth understanding

Materials available at github.com/jscott6/StatML-Comp-Training-2020

Why Interface R with C++?

C++ is a *compiled* language.

- Safety (type checking as C++ is *statically typed*)
- Performance (compile time optimizations)

Some tasks require advanced algorithms and data structures

- Not available directly in R
- C++ STL and Boost libraries

Advantages of both compiled and interpreted languages.

Rcpp makes it easy...

Rcpp

Rcpp is an extension tool for R

Provides C++ classes which help to interface R and C++ using `.Call()` interface.

An approachable API (unlike the R API).

R Objects C Representation

Everything in R is an object, and has a **base type**

`typeof()` returns the base type of an arbitrary R object

- Examples: “closure”, “integer”, “double”, “list”, “S4”

R is (largely) written in C.

R objects are stored, at the C-level as a `SEXP` (S-expression). 27 sub-types including

- `NILSXP` (null)
- `REALSXP` (double Vector)
- `INTSXP` (integer Vector)
- `LGLSXP` (logical Vector)
- `CLOSXP` (function)
- `ENVSXP` (environment)
- `XPTRSXP` (external pointers)

R API

```
.Call("myfunc", arg1, arg2, ...)
```

On the C++ side:

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

SEXP myfunc(SEXP arg1, SEXP arg2,...);
```

(For details, see “Writing R extensions”)

Example: convert `dot <- function(a,b) sum(a * b)` into a C++ function

1. using R API
2. using Rcpp API

Using R API

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

SEXP dot(SEXP a, SEXP b) {
  int n;
  SEXP sum;
  a = PROTECT(coerceVector(a, REALSXP));
  b = PROTECT(coerceVector(b, REALSXP));
  n = length(a);
  sum = PROTECT(allocVector(REALSXP, 1));
  REAL(sum)[0] = 0;
  for (int i = 0; i < n; i++) {
    REAL(sum)[0] += REAL(a)[i] * REAL(b)[i]
  }
  UNPROTECT(3);
  return sum;
}
```

Rcpp Equivalent

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

// [[Rcpp::export]]
double dot(const NumericVector& a,const NumericVector& b) {
  return sum(a * b);
}
```

Rcpp

Provides helper classes through `Rcpp.h`, and converters.

Simpler to read and maintain.

- automatic type conversions (most of the time)
- Automatic wrapping for use with `.Call`
- Rcpp sugar

Safer : automatic memory management.

- No manual calls to `PROTECT` and `UNPROTECT`

Rcpp Matching Classes

Rcpp provides matching C++ classes for R data types.

Can easily pass from R to C++, or from C++ to R.

Atomic Vector Type	C Representation	Rcpp Vector	Rcpp Matrix
"double"	REALSXP	NumericVector	NumericMatrix
"integer"	INTSXP	IntegerVector	IntegerMatrix
"logical"	LGLSXP	LogicalVector	LogicalMatrix

Rcpp provides converter functions

- From SEXP to Rcpp type: `Rcpp::as<>()`
  -**Example**: `NumericVector b = as<NumericVector>(a);`

- From Rcpp type to SEXP: `Rcpp::wrap()`
  -**Example**: `SEXP c = wrap(b);`

Rcpp: A first example

Install using `install.packages("Rcpp")`

C++ source file `timesTwo.cpp` has

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

// [[Rcpp::export]]
NumericVector timesTwo(NumericVector x) {
  return x * 2;
}
```

R script `timesTwo.R` with

```r
library(Rcpp)
sourceCpp("examples/timesTwo/timesTwo.cpp")
a <- 1:3
timesTwo(a)
```

```
## [1] 2 4 6
```

Rcpp Attributes

Rcpp attributes are annotations to C++ files that provide additional information to the compiler.

Two important attributes:

- `Rcpp::export`: export a C++ function to R
- `Rcpp::depends`: specify build dependencies for `sourceCpp`

For a C++ function to be handled using `Rcpp::export` it must

- Return type either `void` or compatible with `Rcpp::wrap`
- Arguments compatible with `Rcpp::as<>()`
- Global namespace
- Fully qualified type names for arguments and return value (apart from Rcpp types).

Making Available in R

Use `sourceCpp("path/to/foo.cpp")`:

- parses c++ file “foo.cpp”
- looks for `Rcpp::export` attributes to determine exported C++ functions
- creates wrappers for exported functions (check using `verbose = TRUE`)
- compiles, links and loads wrapper into R under the C++ name

Related functions include

```r
library(Rcpp)
evalCpp("2+2")
```

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

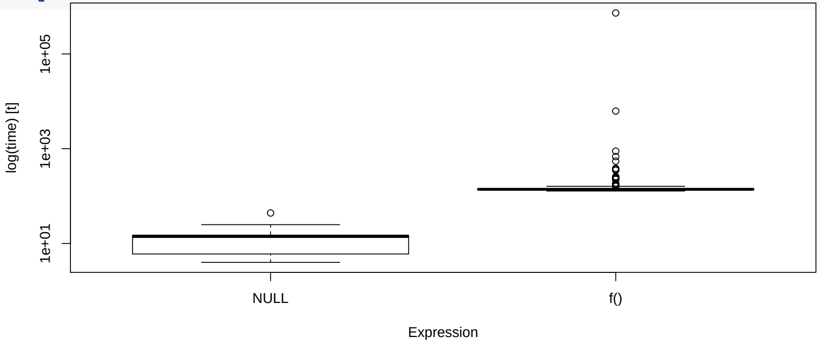
```r
cppFunction("double add(double a, double b) { return a + b; } ")
add(3,2)
```

```
## [1] 5
```

Slow R

Function calls have a **high overhead** in R.

```r
f <- function() NULL
res <- microbenchmark::microbenchmark(NULL, f(), times=1000L)
boxplot(res)
```



Why? code translated by interpreter, variables scoped, type checked dynamically, methods dispatched etc...

Avoid large numbers of function calls

Loops which cannot be vectorised, i.e. each iteration not independent of others. Think MCMC

Recursive functions, i.e. naive implementation of Fibonacci sequence

Second Example: Fibonacci Sequence

$$F_n = F_{n-1} + F_{n-2}$$

with initial conditions $F_1 = 1$, $F_2 = 2$.

A recursive R implementation

```
fibR <- function(n) {
  if (n < 3) n
  else fibR(n-1) + fibR(n-2)
}
```

How many calls are made to `fib` for a given `n`?

- `fib(n)` has $2F_n - 1$ function calls (check). Grows exponentially.

Intermission: how to improve without C++? *Hint: avoid repeated work*

Fibonacci Sequence: C++

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

// [[Rcpp::export]]
int fibCpp(int n) {
  if (n < 3) return n;
  return fibCpp(n-1) + fibCpp(n-2);
}
```

Benchmark

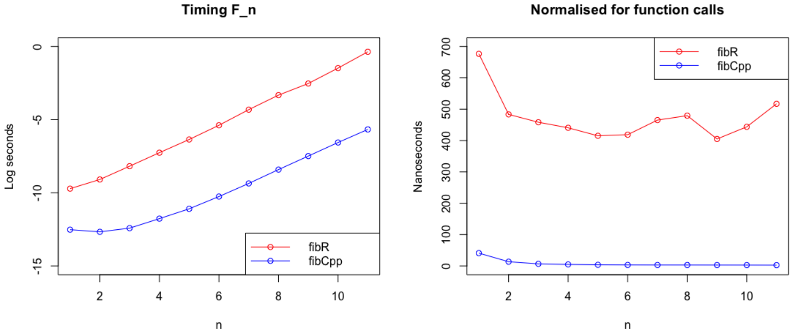


Figure 1: Benchmarking recursive Fibonacci programs in R and C++

Exercise 1

Create a dataframe in R

```r
col1 <- runif (12^5, 0, 2)
col2 <- rnorm (12^5, 0, 2)
col3 <- rpois (12^5, 3)
col4 <- rchisq (12^5, 2)
df <- data.frame (col1, col2, col3, col4)
```

Consider a function intended to append a column to `df`, where entries take value `"greater_than_4"` if other four columns sum > 4, otherwise `"lesser_than_4"`.

1. Write an R function for this which is not vectorised.
2. Write a vectorised R version
3. Write a C++ implementation using Rcpp
4. Profile code using `system.time()`

Reference: https://www.r-bloggers.com/strategies-to-speedup-r-code/

Rcpp Modules

Rcpp modules are based on Boost.Python modules.

Particularly useful for exposing C++ classes to R.

Why Expose C++ Classes?

Manipulate C++ objects interactively in R.

Can be used to implement advanced data structures and efficient methods to operate on them

Leverage C++'s strong OOP system.

A Dummy Class

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

class Rectangle {
public:
  Rectangle(double width, double height):
    width_(width), height_(height) { }
  double area() { return width_ * height_; }
private:
  double width_, height_;
};
```

And the code required to expose it

```
RCPP_MODULE(Rectangle_Module) {
  class_<Rectangle>("Rectangle")

  .constructor<double, double>()
  .method("area", &Rectangle::area)
  ;
}
```

Declarations

An Rcpp module must declare methods and attributes to expose. Common things to expose include:

- `.constructor<>()`: templated by the constructor's signature.
- `.method()`: Exposes a method of the class.
- `.field()`: Expose field with read/write access
- `.field_readonly()`: ... read only
- `.property()`: used to specify getters and setters.

See the Rcpp modules vignette for more information.

Creating C++ objects in R.

```r
Rcpp::sourceCpp("examples/rectangle/rectangle.cpp")

r <- new(Rectangle, 2.5, 3)
r$area()
```

```
## [1] 7.5
```

R class called `Rectangle`. Objects creates using `methods::new()`.

Reference class, i.e. **C++ style encapsulated OOP**.

i.e. *methods belong to classes*. Access methods using `obj$method()`.

S4 Dispatch

It is more R-like to use **generic functions** for OOP.

Instead of methods belonging to a class, S4 classes use generic functions and *method dispatch*.

i.e. `mygeneric(obj)` results in `mymethod(obj)` where `mymethod()` is a specific implementation for `class(obj)`.

To create a generic function:

```r
setGeneric("mygeneric", function(object) {
  standardGeneric("mygeneric")
})
```

To set the method for class `"myclass"`:

```r
setMethod("mygeneric", signature("myclass"), function(obj) f(obj))
```

See more at adv-r.had.co.nz/S4.html.

S4 dispatch: Rectangle

```
# helper function to create objects
Rectangle <- function(width, height) {
  if(min(width,height) < 0) stop("width and height must be nonnegative.
  new("Rcpp_Rectangle", width, height)
}

# generic function and method for area
setGeneric("area", function(object) standardGeneric("area"))
```

```
## [1] "area"
```

```
setMethod("area", "Rcpp_Rectangle", function(object) object$area())
```

Example Usage

```r
Rectangle(-1,1)
```

```
## Error in Rectangle(-1, 1): width and height must be nonnegative.
```

```r
rec <- Rectangle(2.5, 3)
area(rec)
```

```
## [1] 7.5
```

Using Rcpp in Packages

As per instructions available at adv-r.had.co.nz, do the following.

1. Put all C++ files in an `src/` directory
2. In `DESCRIPTION` add `LinkingTo: Rcpp` and `Imports: Rcpp`
3. In `NAMESPACE` add `UseDynLib(mypackage)` and `importFrom(Rcpp, sourceCpp)`
4. Run `Rcpp::compileAttributes()`. This creates the glue code required to export to R.