Rcpp Masterclass / Workshop
Part I: Introduction

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So what are doing today?

Some high-level motivation

The three main questions for the course today are:

- Why? There are several reasons discussed next ...
- How? We will cover that in detail later today ...
- What? This will also be covered ...

Before the Why/How/What

Maybe some mutual introductions?

How about a quick round of intros with

- Your name and background (academic, industry, ...)
- R experience (beginner, intermediate, advanced, ...)
- Created / modified any R packages?
- C and/or C++ experience
- Main interest in **Rcpp**: speed, extension, ...,
- Following `rcpp-devel` ?

but any disclosure is of course strictly voluntary.

Examples

A tar file name `RcppWorkshopExamples.tar.gz` (as well as a corresponding zip file) containing all examples is at

- http://dirk.eddelbuettel.com/code/rcpp/
- http://dl.dropbox.com/u/15584721/

from where you should be able to download it.

We also have copies on two USB drives.

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1. Introduction
2. Why? The Main Motivation
   - Why R?
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   - Speed
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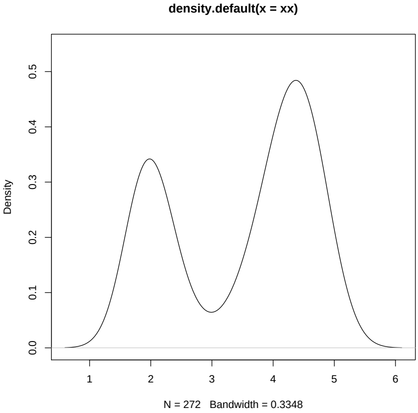
3. How? The Tools
   - Preliminaries
   - Compiling and Linking
   - R CMD SHLIB
   - Rcpp
   - inline

A Simple Example

Courtesy of Greg Snow via r-help last fall: `examples/part1/gregEx1.R`

```
xx <- faithful$eruptions
fit <- density(xx)
plot(fit)
```

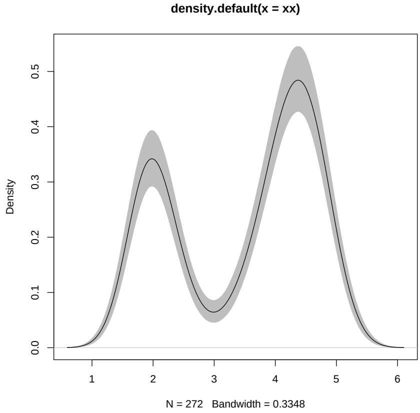


Standard R use: load some data, estimate a density, plot it.

A Simple Example

Now more complete: examples/part1/gregEx2.R

```
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)
```



What other language can do that in seven statements?

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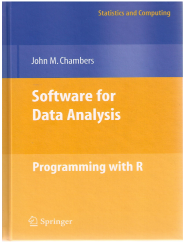
Motivation

Why would extending R via Rcpp be of interest?



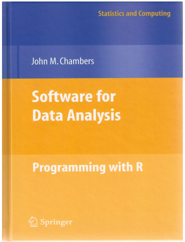
Chambers. *Software for Data Analysis: Programming with R*. Springer, 2008

Chambers (2008) opens chapter 11 (*Interfaces I: Using C and Fortran*) with these words:

> *Since the core of R is in fact a program written in the C language, it's not surprising that the most direct interface to non-R software is for code written in C, or directly callable from C. All the same, including additional C code is a serious step, with some added dangers and often a substantial amount of programming and debugging required. You should have a good reason.*

Motivation

Why would extending R via Rcpp be of interest?



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Chambers (2008) opens chapter 11 (*Interfaces I: Using C and Fortran*) with these words:

> *Since the core of R is in fact a program written in the C language, it's not surprising that the most direct interface to non-R software is for code written in C, or directly callable from C. All the same, including additional C code is a serious step, with* ***some added dangers*** *and often a* ***substantial amount of programming and debugging*** *required. You should have a good reason.*

Motivation

Why would extending R via Rcpp be of interest?

Chambers proceeds with this rough map of the road ahead:

Against:

- It's more work
- Bugs will bite
- Potential platform dependency
- Less readable software

In Favor:

- New and trusted computations
- Speed
- Object references

So the why...

The *why* boils down to:

- **speed!** Often a good enough reason for us ... and a major focus for us today.
- **new things!** We can bind to libraries and tools that would otherwise be unavailable
- **references!** Chambers quote from 2008 somehow foreshadowed the work on the new *Reference Classes* released with R 2.12 and which work very well with Rcpp modules. More on that this afternoon.

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Speed example

examples/part1/straightCurly.R

A blog post from last summer discussed how R's internal parser could be improved.

It repeatedly evaluates $\frac{1}{1+x}$ using

```
## Xian's code, using <- for assignments and passing x down
f <- function(n, x=1) for (i in 1:n) x=1/(1+x)
g <- function(n, x=1) for (i in 1:n) x=(1/(1+x))
h <- function(n, x=1) for (i in 1:n) x=(1+x)^(-1)
j <- function(n, x=1) for (i in 1:n) x={1/{1+x}}
k <- function(n, x=1) for (i in 1:n) x=1/{1+x}
```

Speed example (cont.)

examples/part1/straightCurly.R

We can use this to introduce tools such as **rbenchmark**:

```
# now load some tools
library(rbenchmark)

# now run the benchmark
N <- 1e5
benchmark(f(N,1), g(N,1), h(N,1), j(N,1), k(N,1),
          columns=c("test", "replications",
          "elapsed", "relative"),
          order="relative", replications=10)
```

Speed example (cont.)

examples/part1/straightCurly.R

```
R> N <- 1e5
R> benchmark(f(N,1),g(N,1),h(N,1),j(N,1),k(N,1),
+            columns=c("test", "replications",
+            "elapsed", "relative"),
+            order="relative", replications=10)
     test replications elapsed relative
5 k(N, 1)           10   0.961  1.00000
1 f(N, 1)           10   0.970  1.00937
4 j(N, 1)           10   1.052  1.09469
2 g(N, 1)           10   1.144  1.19043
3 h(N, 1)           10   1.397  1.45369
R>
```

Speed example: Now with C++

examples/part1/straightCurly.R

So let us add **Rcpp** to the mix and show **inline** too:

```
## now with Rcpp and C++
library(inline)

# and define our version in C++
src <- 'int n = as<int>(ns);
        double x = as<double>(xs);
        for (int i=0; i<n; i++) x=1/(1+x);
        return wrap(x); '
l <- cxxfunction(signature(ns="integer",
                           xs="numeric"),
                 body=src, plugin="Rcpp")
```

Speed example: Now with C++

examples/part1/straightCurly.R

The key line is almost identical to what we would do in R

```
## now with Rcpp and C++
library(inline)

# and define our version in C++
src <- 'int n = as<int>(ns);
        double x = as<double>(xs);
        for (int i=0; i<n; i++) x=1/(1+x);
        return wrap(x); '
l <- cxxfunction(signature(ns="integer",
                           xs="numeric"),
                 body=src, plugin="Rcpp")
```

Speed example: Now with C++

examples/part1/straightCurly.R

Data input and output is not too hard:

```
## now with Rcpp and C++
library(inline)

# and define our version in C++
src <- 'int n = as<int>(ns);
        double x = as<double>(xs);
        for (int i=0; i<n; i++) x=1/(1+x);
        return wrap(x); '
l <- cxxfunction(signature(ns="integer",
                           xs="numeric"),
                 body=src, plugin="Rcpp")
```

Speed example: Now with C++

examples/part1/straightCurly.R

And compiling, linking and loading is a single function call:

```
## now with Rcpp and C++
library(inline)

# and define our version in C++
src <- 'int n = as<int>(ns);
        double x = as<double>(xs);
        for (int i=0; i<n; i++) x=1/(1+x);
        return wrap(x); '
l <- cxxfunction(signature(ns="integer",
                           xs="numeric"),
                 body=src, plugin="Rcpp")
```

Speed example: Now with C++

examples/part1/straightCurly.R

```
R> # now run the benchmark again
R> benchmark(f(N,1), g(N,1), h(N,1), j(N,1),
+            k(N,1), l(N,1),
+            columns=c("test", "replications",
+            "elapsed", "relative"),
+            order="relative", replications=10)
     test replications elapsed relative
6 l(N, 1)           10   0.013   1.0000
1 f(N, 1)           10   0.944  72.6154
5 k(N, 1)           10   0.944  72.6154
4 j(N, 1)           10   1.052  80.9231
2 g(N, 1)           10   1.145  88.0769
3 h(N, 1)           10   1.425 109.6154
R>
```

Speed example: Now with C++

examples/part1/straightCurly.R

```
R> # now run the benchmark again
R> benchmark(f(N,1), g(N,1), h(N,1), j(N,1),
+            k(N,1), l(N,1),
+            columns=c("test", "replications",
+            "elapsed", "relative"),
+            order="relative", replications=10)
     test replications elapsed relative
6 l(N, 1)           10   0.013   1.0000
1 f(N, 1)           10   0.944  72.6154
5 k(N, 1)           10   0.944  72.6154
4 j(N, 1)           10   1.052  80.9231
2 g(N, 1)           10   1.145  88.0769
3 h(N, 1)           10   1.425 109.6154
R>
```

More on speed

Other examples:

- The **RcppArmadillo** and **RcppGSL** packages each contain a `fastLM()` function
- This is a faster reimplmentation of `lm()`, suitable for repeated use in Monte Carlo
- **Armadillo** makes this a breeze. More on that later too.
- Other examples are being added.

Another angle on speed

Run-time performance is just one example.

Time to code is another metric.

We feel quite strongly that **Rcpp** helps you code more succinctly, leading to fewer bugs and faster development.

The **RcppDE** package aims to provide a concrete example of making an existing C implemention *shorter*, *easier* and at the same time *faster*.

NB: But of the speedup may have been due to a code review. Easier and shorter still apply.

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Doing new things more easily

Consider the two dozen CRAN packages using **Rcpp**—among these we find

RQuantlib	QuantLib	C++
RcppArmadillo	Armadillo	C++
RBrownie	Brownie	C++
RcppGSL	GSL	C
RProtoBuf	Protocol Buffers	C
RSNNS	SNNS	C

Easier access to new functionality by easier wrapping. We will look at **RcppGSL** and **RcppArmadillo** in more detail later.

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S3, S4, and now Reference Classes

The new Reference Classes which appeared with R 2.12.0 are particularly well suited for multi-lingual work, and C++ (via Rcpp) is the first example.

More in the afternoon...

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Some Preliminaries on Tools

- Use a recent version of R (>= 2.12.0 for Reference Classes; >= 2.13.0 for the R compiler package).
- Examples shown should work 'as is' on Unix-alike OSs; most will also work on Windows *provided a complete R development environment*
- *R Installation and Administration* is an excellent start to address the preceding point (if need be)
- We will compile, so Rtools, or X Code, or standard Linux dev tools, are required.
- `using namespace Rcpp;` may be implied in some examples.

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A Tradition to follow: `Hello, world!`

`examples/part1/ex1.cpp`

Let us start with some basic tool use.

Consider this simple C++ example:

```
#include <cstdio>

int main(void) {
    printf("Hello, World!\n");
}
```

A Tradition to follow: `Hello, world!`

Building and running: `examples/part1/ex1.cpp`

We can now build the program by invoking `g++`.

```
$ g++ -o ex1 ex1.cpp
$ ./ex1
Hello, World!
$
```

This use requires only one option to `g++` to select the name of the resulting *output* file.

Accessing external libraries and headers

An example using the R Math library: `examples/part1/ex2.cpp`

This example uses a function from the standalone R library :

```
#include <cstdio>
#define MATHLIB_STANDALONE
#include <Rmath.h>

int main(void) {
  printf("N(0,1) 95th percentile %9.8f\n",
  qnorm(0.95, 0.0, 1.0, 1, 0));
}
```

We *declare the function via the header file* (as well as defining a variable before loading, see 'Writing R Extensions') and provide a suitable *library to link to*.

Accessing external libraries and headers

An example using the R Math library: `examples/part1/ex2.cpp`

We use `-I/some/dir` to point to a header directory, and `-L/other/dir -lfoo -lbar` to link with the external libraries.

```
$ g++ -I/usr/include -c ex2.cpp
$ g++ -o ex2 ex2.o -L/usr/lib -lRmath
$ ./ex2
N(0,1) 95th percentile 1.64485363
$
```

This can be tedious as header and library locations may vary across machines or installations. *Automated detection* is key.

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Building an R module

examples/part1/modEx1.cpp

Building a module to be used by R is similar to the direct compilation.

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

extern "C" SEXP helloWorld(void) {
  Rprintf("Hello, World!\n");
  return R_NilValue;
}
```

Building an R module

examples/part1/modEx1.cpp

We use R to compile and build this:

```
$ R CMD SHLIB modEx1.cpp
g++ -I/usr/share/R/include -fpic -O3 \
       -g -c modEx1.cpp -o modEx1.o
g++ -shared -o modEx1.so \
       modEx1.o -L/usr/lib64/R/lib -lR
$
```

R selects the `-I` and `-L` flags appropriately.

Running the R module

examples/part1/modEx1.cpp

We load the shared library and call the function via `.Call`:

```
R> dyn.load("modEx1.so")
R> .Call("helloWorld")
Hello, World!
NULL
R>
```

Other operating systems may need a different file extension.

`R CMD SHLIB` options

`R CMD SHLIB` can take linker options.

Using the variables `PKG_CXXFLAGS` and `PKG_LIBS`, we can also select headers and libraries — which we'll look at with **Rcpp** below.

But this gets tedious fast (and example is in the next section).

Better options will be shown later.

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Rcpp and R CMD SHLIB

examples/part1/modEx2.cpp

Let us (re-)consider the simple **Rcpp** example from above. In a standalone file it looks like this:

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

RcppExport SEXP modEx2(SEXP ns, SEXP xs) {
  int n = as<int>(ns);
  double x = as<double>(xs);

  for (int i=0; i<n; i++)
    x=1/(1+x);

  return wrap(x);
}
```

Rcpp and R CMD SHLIB

examples/part1/modEx2.cpp

We use PKG_CPPFLAGS and PKG_LIBS to tell R which headers and libraries. Here we let **Rcpp** tell us:

```
$ export PKG_CPPFLAGS=`Rscript -e 'Rcpp:::CxxFlags()'`
$ export PKG_LIBS=`Rscript -e 'Rcpp:::LdFlags()'`
$ R CMD SHLIB modEx2.cpp
g++ -I/usr/share/R/include \
    -I/usr/local/lib/R/site-library/Rcpp/include \
    -fpic  -O3 -pipe  -g -c modEx2.cpp -o modEx2.o
g++ -shared -o modEx2.so modEx2.o \
    -L/usr/local/lib/R/site-library/Rcpp/lib -lRcpp \
    -Wl,-rpath,/usr/local/lib/R/site-library/Rcpp/lib \
    -L/usr/lib64/R/lib -lR
```

Note the result arguments—it is helpful to understand what each part is about. Here we add the **Rcpp** library as well as information for the dynamic linker about where to find the library at run-time.

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inline

inline makes compiling, linking and loading a lot easier. As seen above, all it takes is a single call:

```
src <- 'int n = as<int>(ns);
        double x = as<double>(xs);
        for (int i=0; i<n; i++) x=1/(1+x);
        return wrap(x); '
l <- cxxfunction(signature(ns="integer",
                           xs="numeric"),
                 body=src, plugin="Rcpp")
```

No more manual `-I` and `-L` — **inline** takes over.

It also allows us to pass extra `-I` and `-L` arguments for other libraries. An (old) example using GNU GSL (which predates the **RcppGSL** package) follows:

inline – with external libraries too

examples/part1/gslRng.R

```
## a really simple C++ program calling functions from the GSL
src <- 'int seed = Rcpp::as<int>(par) ;
       gsl_rng_env_setup();
       gsl_rng *r = gsl_rng_alloc (gsl_rng_default);
       gsl_rng_set (r, (unsigned long) seed);
       double v = gsl_rng_get (r);
       gsl_rng_free(r);
       return Rcpp::wrap(v); '

## turn into a function that R can call
fun <- cfunction(signature(par="numeric"), body=src,
                 includes="#include <gsl/gsl_rng.h>",
                 Rcpp=TRUE,
                 cppargs="-I/usr/include",
                 libargs="-lgsl -lgslcblas")
```

(**RcppGSL** offers a plugin to `cxxfunction()` which alleviates four of the arguments to `cfunction` here.)

inline also good for heavily templated code

Whit's rcpp-devel post last fall: `examples/part1/whit.R`

```
library(inline)
library(Rcpp)

inc <- '
#include <iostream>
#include <armadillo>
#include <cppbugs/cppbugs.hpp>

using namespace arma;
using namespace cppbugs;

class TestModel: public MCModel {
public:
  const mat &y, &x; // given

  Normal<vec> b;
  Uniform<double> tau_y;
  Deterministic<mat> y_hat;
  Normal<mat> likelihood;
  Deterministic<double> rsq;

  TestModel(const mat& y_,const mat& X_):
    y(y_), X(X_), b(randn<vec>(X_.n_cols)),
    tau_y(1), y_hat(X*b.value),
    likelihood(y_,true), rsq(0)
  {
    add(b); add(tau_y); add(y_hat);
    add(likelihood); add(rsq);
  }
  // [....and more ...]'
```

The `inc=inc` argument to `cxxfunction` can includes headers before the `body=src` part.

And the templated `CppBUGS` package by Whit now easily outperforms PyMC / Bugs.

And is still easily accessible from R.

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4 What? Applications
- Rcpp*
- Others
- RInside

Rcpp* packages

A number of CRAN packages are directly in the **Rcpp** realm and repo:

RcppArmadillo an easy-to-use R interface to **Armadillo**

RcppBDT using Rcpp Modules to access **Boost Date_Time**

RcppClassic maintenance of the deprecated earlier API

RcppDE a 'port' of **DEoptim** from C to C++

RcppExamples (incomplete) collection of examples

RcppGSL an interface (for vectors + matrices) to GNU GSL

and there is even a bit more inside the **Rcpp** repo...

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Other packages

A short selection of other CRAN packages using **Rcpp** to interface

RProtoBuf	Google's Protocol Buffers
RQuantLib	Quantlib, large quantitative finance library
RSNNS	SNNS, the Stuttgart Neural Network Simulator

and several other packages interface the GNU GSL and / or specialised domain-specific libraries.

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RInside

examples/part1/rinsideEx1.cpp

Another key user of **Rcpp** is **RInside** which makes it easy to embed R inside your C++ applications. Numerous examples are included in the package; this is the simplest one:

```
#include <RInside.h>                    // embedded R via RInside

int main(int argc, char *argv[]) {

    RInside R(argc, argv);              // create embedded R inst.

    R["txt"] = "Hello, world!\n";       // assign   to 'txt' in R

    R.parseEvalQ("cat(txt)");           // eval string, ignore result

    exit(0);
}
```

More examples will follow.

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5 The R API
- Overview
- First Example: Operations on Vectors
- Second Example: Operations on Characters
- Third Example: Calling an R function
- Fourth Example: Creating a list

R support for C/C++

- 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: use `.cpp` extension
- R provides several calling conventions:
  - `.C()` provided the first interface, it is fairly limited
  - `.Call()` provides access to R objects at the C level
  - `.External()` and `.Fortran` exist but can be ignored

but we will use `.Call()` exclusively.

R API via `.Call()`

At the C level, *everything* is a `SEXP`, and all functions correspond to this interface:

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

which can be called from R via

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

and more examples will follow.

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A simple function on vectors

examples/part1/R_API_ex1.cpp

Can you guess what this does?

```
#include <R.h>
#include <Rdefines.h>
extern "C" SEXP vectorfoo(SEXP a, SEXP b){
  int i, n;
  double *xa, *xb, *xab; SEXP ab;
  PROTECT(a = AS_NUMERIC(a));
  PROTECT(b = AS_NUMERIC(b));
  n = LENGTH(a);
  PROTECT(ab = NEW_NUMERIC(n));
  xa=NUMERIC_POINTER(a); xb=NUMERIC_POINTER(b);
  xab = NUMERIC_POINTER(ab);
  double x = 0.0, y = 0.0 ;
  for (i=0; i<n; i++) xab[i] = 0.0;
  for (i=0; i<n; i++) {
    x = xa[i]; y = xb[i];
    res[i] = (x < y) ? x*x : -(y*y);
  }
  UNPROTECT(3);
  return(ab);
}
```

A simple function on vectors

examples/part1/R_API_ex1.cpp

The core computation is but a part:

```
#include <R.h>
#include <Rdefines.h>
extern "C" SEXP vectorfoo(SEXP a, SEXP b){
  int i, n;
  double *xa, *xb, *xab; SEXP ab;
  PROTECT(a = AS_NUMERIC(a));
  PROTECT(b = AS_NUMERIC(b));
  n = LENGTH(a);
  PROTECT(ab = NEW_NUMERIC(n));
  xa=NUMERIC_POINTER(a); xb=NUMERIC_POINTER(b);
  xab = NUMERIC_POINTER(ab);
  double x = 0.0, y = 0.0 ;
  for (i=0; i<n; i++) xab[i] = 0.0;
  for (i=0; i<n; i++) {
    x = xa[i]; y = xb[i];
    res[i] = (x < y) ? x*x : -(y*y);
  }
  UNPROTECT(3);
  return(ab);
}
```

A simple function on vectors

examples/part1/R_API_ex1.cpp

Memory management is both explicit, tedious and error-prone:

```
#include <R.h>
#include <Rdefines.h>
extern "C" SEXP vectorfoo(SEXP a, SEXP b){
  int i, n;
  double *xa, *xb, *xab; SEXP ab;
  PROTECT(a = AS_NUMERIC(a));
  PROTECT(b = AS_NUMERIC(b));
  n = LENGTH(a);
  PROTECT(ab = NEW_NUMERIC(n));
  xa=NUMERIC_POINTER(a); xb=NUMERIC_POINTER(b);
  xab = NUMERIC_POINTER(ab);
  double x = 0.0, y = 0.0 ;
  for (i=0; i<n; i++) xab[i] = 0.0;
  for (i=0; i<n; i++) {
    x = xa[i]; y = xb[i];
    res[i] = (x < y) ? x*x : -(y*y);
  }
  UNPROTECT(3);
  return(ab);
}
```

Outline

5 The R API
- Overview
- First Example: Operations on Vectors
- Second Example: Operations on Characters
- Third Example: Calling an R function
- Fourth Example: Creating a list

A simple function on character vectors

examples/part1/R_API_ex2.cpp

In R , we simply use

```
c( "foo", "bar" )
```

whereas the C API requires

```
#include <R.h>
#include <Rdefines.h>
extern "C" SEXP foobar(){
  SEXP res = PROTECT(allocVector(STRSXP, 2));
  SET_STRING_ELT( res, 0, mkChar( "foo" ) ) ;
  SET_STRING_ELT( res, 1, mkChar( "bar" ) ) ;
  UNPROTECT(1) ;
  return res ;
}
```

Outline

5 The R API
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Calling an R function

examples/part1/R_API_ex2.cpp

In R , we call

```
rnorm(3L, 10.0, 20.0)
```

but in C this becomes

```
#include <R.h>
#include <Rdefines.h>
extern "C" SEXP callback(){
  SEXP call = PROTECT( LCONS( install("rnorm"),
    CONS( ScalarInteger( 3 ),
      CONS( ScalarReal( 10.0 ),
            CONS( ScalarReal( 20.0 ), R_NilValue )
          )
        )
  ) );
  SEXP res = PROTECT(eval(call, R_GlobalEnv)) ;
  UNPROTECT(2) ;
  return res ;
}
```

Outline

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Fourth Example: Lists

examples/part1/R_API_ex4.cpp

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

extern "C" SEXP listex(){
    SEXP res = PROTECT( allocVector( VECSXP, 2 )  ) ;
    SEXP x1  = PROTECT( allocVector( REALSXP, 2 ) ) ;
    SEXP x2  = PROTECT( allocVector( INTSXP, 2 ) ) ;
    SEXP names = PROTECT( mkString( "foobar" ) ) ;

    double* px1 = REAL(x1) ; px1[0] = 0.5 ; px1[1] = 1.5 ;
    int* px2 = INTEGER(x2); px2[0] = 2 ; px2[1] = 3 ;

    SET_VECTOR_ELT( res, 0, x1 ) ;
    SET_VECTOR_ELT( res, 1, x2 ) ;
    setAttrib( res, install("class"), names ) ;

    UNPROTECT(4) ;
    return res ;
}
```

Outline

6 C++ for R Programmers

- Overview
- Compiled
- Static Typing
- Better C
- Object-Orientation
- Generic Programming and the STL
- Template Programming

C++ for R programmers

C++ is a large and sometimes complicated language.

We cannot introduce it in just a few minutes, but will will provide a number of key differences—relative to R which should be a common point of departure.

So on the next few slides, we will highlight just a few key differences.

One view we like comes from Meyers: C++ is a federation of four languages.

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Compiled rather than interpreted

We discussed this already in the context of the toolchain.

Programs need to be *compiled* first. This may require access to header files defining interfaces to other projects.

After compiling into object code, the object is *linked* into an executable, possibly together with other libraries.

There is a difference between *static* and *dynamic* linking.

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Static typing

R is dynamically typed: `x <- 3.14; x <- "foo"` is valid.

In C++, each variable must be declared before first use.

Common types are `int` and `long` (possibly with `unsigned`), `float` and `double`, `bool`, as well as `char`.

No standard string type, though `std::string` now comes close.

All variables are scalars which is fundamentally different from R where everything is a vector (possibly of length one).

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A Better C: Similarities to R

- control structures similar to what R offers: `for`, `while`, `if`, `switch`
- functions but note difference in positional-only matching, also same name but different arguments allowed
- pointers and memory management: very different, but lots of issues folks had with C can be avoided via STL (which is something **Rcpp** promotes too)
- that said, it is still useful to know what a pointer is ...

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Object-oriented programming

This is a second key feature of C++, and it does it differently from S3 and S4 (but closer to the new Reference Classes). Let's look at an example:

```
struct Date {
   unsigned int year
   unsigned int month;
   unsigned int date;
};

struct Person {
   char firstname[20];
   char lastname[20];
   struct Date birthday;
   unsigned long id;
};
```

These are just nested data structures.

Object-oriented programming

OO in the C++ sense marries data with code to operate on it:

```
class Date {
private:
   unsigned int year
   unsigned int month;
   unsigned int date;
public:
   void setDate(int y, int m, int d);
   int getDay();
   int getMonth();
   int getYear();
}
```

Here the data is hidden, access to get / set is provided via an interface.

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Standard Template Library: Containers

The STL promotes *generic* programming via an efficient implementation.

For example, the *sequence* container types `vector`, `deque`, and `list` all support

`push_back()` to insert at the end;

`pop_back()` to remove from the front;

`begin()` returning an iterator to the first element;

`end()` returning an iterator to just after the last element;

`size()` for the number of elements;

but only `list` has `push_front()` and `pop_front()`.

Other useful containers: `set`, `multisep`, `map` and `multimap`.

Standard Template Library: Iterators and Algorithms

Traversal of contains can be achieved via *iterators* which require suitable member functions `begin()` and `end()`:

```
std::vector<double>::const_iterator si;
for (si=s.begin(); si != s.end(); si++)
    std::cout << *si << std::endl;
```

Another key STL part are *algorithms*:

```
double sum = accumulate(s.begin(), s.end(), 0);
```

Other popular STL algorithms are

- `find` finds the first element equal to the supplied value
- `count` counts the number of matching elements
- `transform` applies a supplied function to each element
- `for_each` sweeps over all elements, does not alter
- `inner_product` inner product of two vectors

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Template Programming

Template programming provides the last 'language within C++'. One of the simplest template examples is

```
template <typename T>
const T& min(const T& x, const T& y) {
    return y < x ? y : x;
}
```

This can now be used to compute the minimum between two `int` variables, or `double`, or in fact *admissible type* providing an `operator<()` for less-than comparison.

Template Programming

Another template example is a class squaring its argument:

```
template <typename T>
class square : public std::unary_function<T,T>
{
public:
    T operator()( T t) const {
        return t*t;
    }
};
```

which can be used along with some of the STL algorithms. For example, given an object `x` that has iterators, then

```
transform(x.begin(), x.end(), square);
```

squares all its elements in-place.