

MFE Programming Workshop

Interfacing R to Other Languages

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Why would you want to use another language?

- ▶ R is great, but it has some weaknesses.
 - ▶ For example, loops can be slow.
- ▶ It is sometimes desirable to call code written in other languages from R.
- ▶ Also, you may want to call R from another language.
- ▶ R interfaces have been developed for a number of other languages
 - ▶ We will focus on C/C++.
- ▶ The main motivation is performance enhancement.
 - ▶ C/C++ code may run much faster than R.

Writing C/C++ Functions to be called from R

- ▶ Key points to remember:
 - ▶ All the arguments passed from R to C/C++ are received by C/C++ as pointers
 - ▶ The C/C++ function itself must return `void`.
 - ▶ Hence, we need to pass a pointer for the result
 - ▶ For R to work with C++ code (or even C code compiled with `g++`), you need to wrap your functions inside an `extern` statement.
 - ▶ `extern "C" { your C++ code }`
 - ▶ Don't use `extern` for C code (it may be less efficient).
- ▶ We will learn to compile code using R (via `gcc` and `g++`) and Visual C++.
- ▶ The end product is a dynamic shared library file (`.so`) on Linux/OS X or a dynamic-link library (`.dll`) on Windows.

Required software

- ▶ On windows, you need to install Rtools, available [here](#)
 - ▶ Just choose the version that matches your computer architecture (i.e. 64 bit or 32 bit)
 - ▶ You have to make sure Rtools is in your path (may need to restart)
- ▶ Please verify:
 - ▶ On Linux you need to have GNU gcc and g++ (probably already installed)
 - ▶ Do you need r-base-dev?
 - ▶ On OS X, you may need Xcode.

Our program: timesTwo.cpp

```
extern "C" void
    timesTwo(double *in, double *out)
{
    double value = in[0] * 2.0;
    out[0] = value;
}
```

What does `extern "C"` do?

- ▶ Remember R is written in C.
- ▶ `extern "C"` makes our C++ function available to a program written in C (i.e. R).
 - ▶ It declares the functions with C linkage.
 - ▶ If we write a C program (and use a C compiler), we don't need it.
- ▶ Note that the parameter and return types are constrained.
 - ▶ For example, cannot write a function that passes a (nontrivial) C++ class to a C program.
 - ▶ The C program would not know what to do about the constructors, destructors, and other class-specific operations.

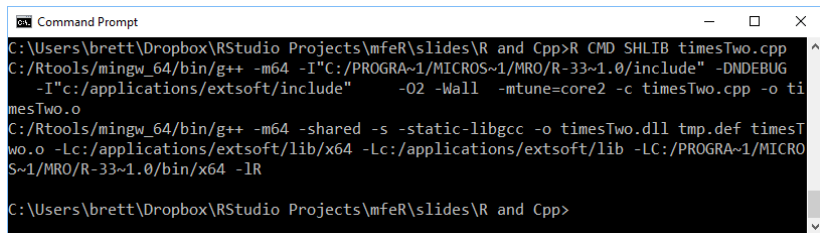
```
extern "C" void
timesTwo(double *in, double *out)
{
    double value = in[0] * 2.0;
    out[0] = value;
}
```

Compile using R's command line tools

- In R, you can type:

```
system("R CMD SHLIB ./examples/timesTwo.cpp")
```

- Or, on the command line:



```
Command Prompt
C:\Users\brett\Dropbox\RStudio Projects\mfeR\slides\R and Cpp>R CMD SHLIB timesTwo.cpp
C:/Rtools/mingw_64/bin/g++ -m64 -I"C:/PROGRA~1/MICROS~1/MRO/R-33~1.0/include" -DNDEBUG
-I"c:/applications/extsoft/include" -O2 -Wall -mtune=core2 -c timesTwo.cpp -o ti
mesTwo.o
C:/Rtools/mingw_64/bin/g++ -m64 -shared -s -static-libgcc -o timesTwo.dll tmp.def timesT
wo.o -Lc:/applications/extsoft/lib/x64 -Lc:/applications/extsoft/lib -LC:/PROGRA~1/MICRO
S~1/MRO/R-33~1.0/bin/x64 -lR
C:\Users\brett\Dropbox\RStudio Projects\mfeR\slides\R and Cpp>
```

- Now we have timesTwo.dll (or timesTwo.so) ready to use in R

Now run the DLL in R

```
dyn.load("./examples/timesTwo.dll")  
value_in <- 32; value_out <- 0  
.C("timesTwo", as.double(value_in),  
    res=as.double(value_out))$res
```

```
## [1] 64
```

```
dyn.unload("./examples/timesTwo.dll")
```

- ▶ `dyn.load` loads the .dll into R
- ▶ `.C` calls `timesTwo`, and passes `value_in` and `value_out` to the function.
 - ▶ `.C` returns a list, so we define 'result' and extract 'result' from the list.
- ▶ `dyn.unload` unloads the .dll from R (you need to unload the dll if you want to rebuild it).

Wrapper Functions

- For convenience, consider writing a wrapper function.

```
dyn.load("./examples/timesTwo.dll")
timesTwoC <- function(val) {
  out <- 0
  .C("timesTwo", as.double(val),
    res=as.double(out))$res
}
timesTwoC(32)
```

```
## [1] 64
```

```
dyn.unload("./examples/timesTwo.dll")
```

Using R's Library

- ▶ You can access C versions of many basic R functions, including `dnorm()`, `rnorm()`, etc.
- ▶ A nice reference is [here](#).

```
/*randNorm.c*/  
#include <R.h>  
#include <Rmath.h>  
void randNorm(double *out)  
{  
    GetRNGstate();  
    out[0] = norm_rand();  
    PutRNGstate();  
}
```

Running randNorm in R

```
system("R CMD SHLIB ./examples/randNorm.c")
dyn.load("./examples/randNorm.dll")
n <- function() {out <- 0; .C("randNorm", out)[[1]]}
set.seed(2016)
c(n(), n(), n())
```

```
## [1] -0.91474184  1.00124785 -0.05642291
```

```
c(n(), n(), n())
```

```
## [1]  0.2966452 -2.7914709 -0.2827404
```

```
set.seed(2016)
c(n(), n(), n())
```

```
## [1] -0.91474184  1.00124785 -0.05642291
```

```
dyn.unload("./examples/randNorm.dll")
```

Using Vectors

```
/*vec.c*/  
void cumsum(double *x, int *n, double *res) {  
    res[0] = x[0];  
    for (int i = 1; i < *n; ++i) {  
        res[i] = x[i] + res[i-1];  
    }  
}
```

Running cumsum in R

```
system("R CMD SHLIB ./examples/vec.c")  
dyn.load("./examples/vec.dll")  
n <- 3  
out <- rep(0,n)  
x <- 1:n  
.C("cumsum", as.double(x), as.integer(n),  
    cumsum = as.double(out))$cumsum
```

```
## [1] 1 3 5
```

```
dyn.unload("./examples/vec.dll")
```

Using C++11

```
//file: randC11.cpp
#include <random>

extern "C" {
    void randNorm(int *seed, double *out)
    {
        std::mt19937 e(*seed);
        std::normal_distribution<double> N(0.0, 1.0);
        out[0] = N(e);
    }
}
```

Using C++11: Set USE_CXX1X to some value

- ▶ The USE_CXX1X allows us to use the C++11 standard.

```
Sys.setenv(USE_CXX1X = "NA")
system("R CMD SHLIB ./examples/randC11.cpp")
dyn.load("./examples/randC11.dll")
out <- 0
.C("randNorm", 9L, out)
```

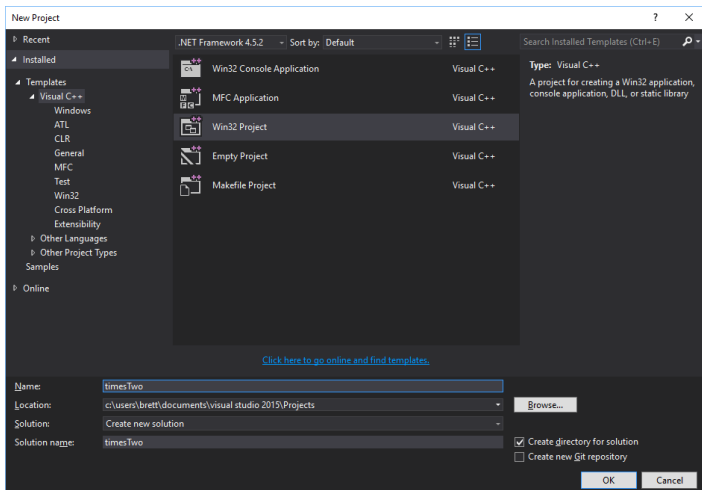
```
## [[1]]
## [1] 9
##
## [[2]]
## [1] -0.01466065
```

```
dyn.unload("./examples/randC11.dll")
```

Visual Studio

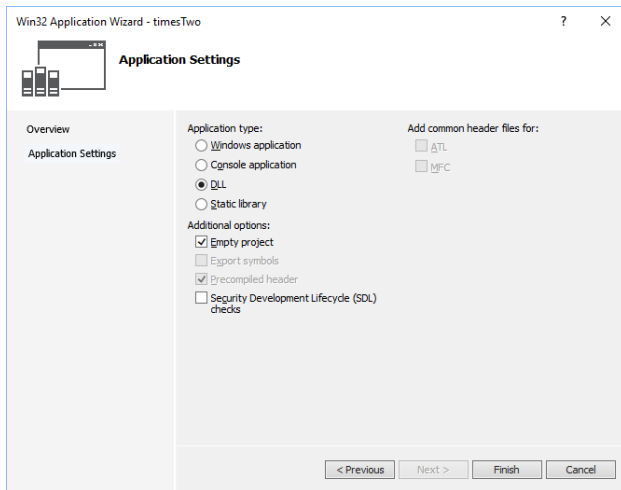
Creating a DLL project in Visual Studio 2015

- Choose File/New/Project../Win32 Project

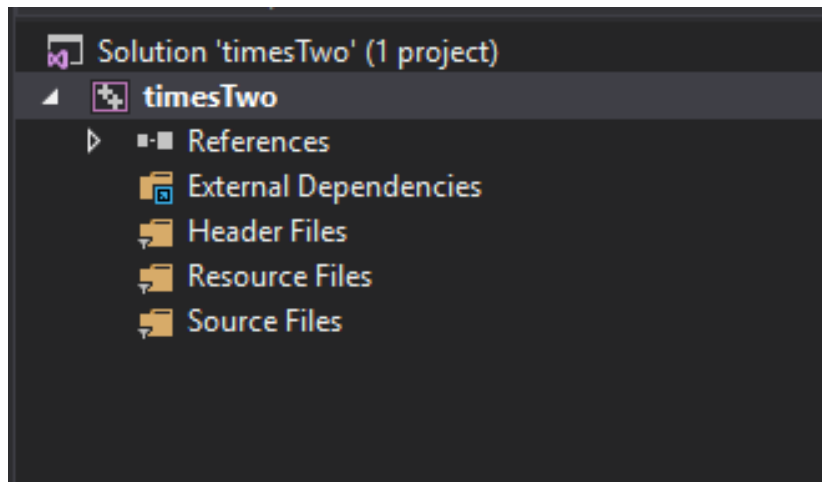


Creating a DLL project in Visual Studio 2015

- Specify a DLL and an Empty project

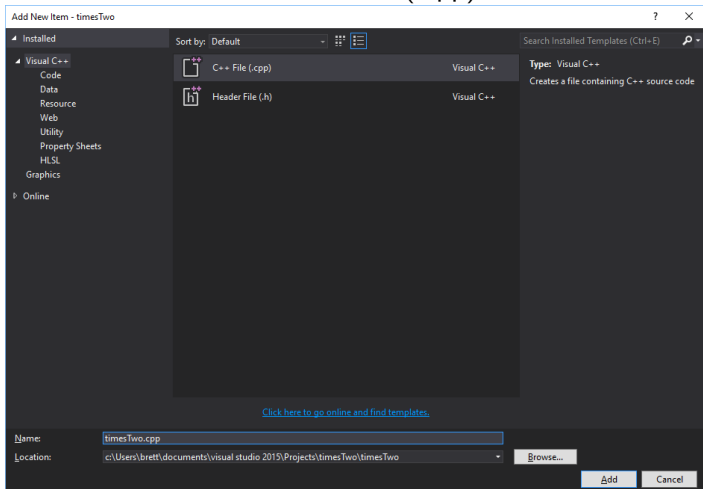


Project at This Point



Add a C++ Source File

-Right-click Source Files in the Solution Explorer, then select Add New Item, and then select C++ File (.cpp)



Add C++ Code to the Source File

- ▶ (this is actually C code)

```
extern "C" void __cdecl  
    timesTwo(double *in, double *out)  
{  
    double value = in[0] * 2.0;  
    out[0] = value;  
}
```

What is `__cdecl` about?

- ▶ Applies only to Windows.
- ▶ The Visual C++ compilers allow you to specify conventions for passing arguments and return values between functions and callers.
- ▶ Two options we care about:
 - ▶ `__cdecl` is used by C/C++ programs, R, Matlab, SAS, others.
 - ▶ `__stdcall` is used by Excel, Win32 API functions, Pascal, others.
- ▶ This all essentially amounts to conventions for who (function caller or function) pops arguments off the stack.
- ▶ For more information, see [this webpage](#).

```
extern "C" void __cdecl
timesTwo(double *in, double *out)
{
    double value = in[0] * 2.0;
    out[0] = value;
}
```

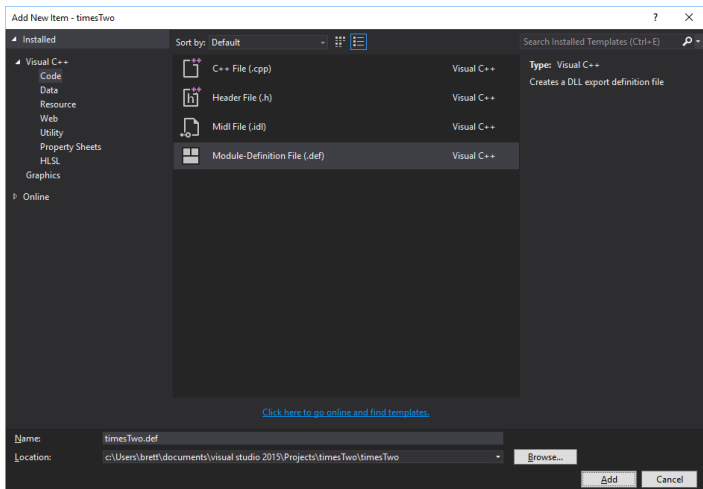
Pointers

- ▶ For C++, `timesTwo(double& in, double& out)` works as well.
- ▶ We need to pass a pointer to store the result of the function.

```
extern "C" void __cdecl  
    timesTwo(double *in, double *out)  
{  
    double value = in[0] * 2.0;  
    out[0] = value;  
}
```

Add a Module Definition File (.def)

- Add New Item... Under Visual C++ / Code you will find the .def file.



Module Definition File

- ▶ A .def file is a module definition file. This is a convenient way to tell the linker which parts of our C++ code we want to export.

```
// timesTwo.def  
LIBRARY timesTwoDLL  
EXPORTS  
    timesTwo
```

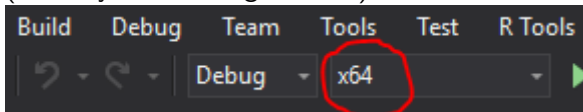
- ▶ LIBRARY is the name of the DLL
- ▶ EXPORTS lists the functions to be exported (each one on a separate line)
 - ▶ If you want to use a different function name use `newName = oldName`

Another option: `__declspec(dllexport)`

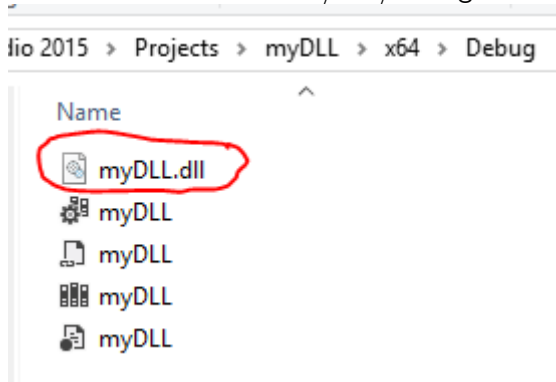
- ▶ Windows-specific.
- ▶ On Windows, we need to tell which functions are exported from the DLL.
 - ▶ That is, which functions will be available in R.
- ▶ we
- ▶ When building your DLL, you typically create a header file that contains the functions you are exporting and add `__declspec(dllexport)` to the declarations in the header file.
- ▶ For more information, see [this](#).
- ▶ Instead of `__declspec(dllexport)`, you can use a [DEF file](#).

Build the Solution

- ▶ Make sure to change the architecture to x64 before building (unless you are using 32bit R)

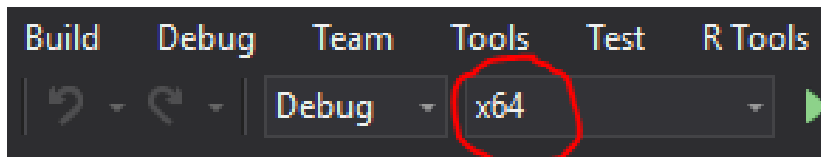


- ▶ Ctrl-Shift-B builds the solution.
- ▶ The DLL is found in the ./x64/Debug folder



Add an R project to Visual Studio

- ▶ Right click the solution...Add...New Project...Other Languages...R project



Now run the DLL in R

- ▶ `dyn.load` loads the .dll into R
- ▶ `.C` calls `timesTwo`, and passes `value_in` and `value_out` to the function
 - ▶ `.C` returns a list, so we define 'result' and extract 'result' from the list
- ▶ `dyn.unload` loads the .dll into R
 - ▶ you need to unload the dll if you want to rebuild it.

```
> dyn.load("../x64/Debug/timesTwo.dll")
> value_in <- 32
> value_out <- 0
> .C("timesTwo", as.double(value_in), result = as.double(value_out))$result
[1] 64
> dyn.unload("../x64/Debug/timesTwo.dll")
```

Let's change the code for Excel

- ▶ We don't need `extern "C"` anymore
- ▶ The function can return a `double`
- ▶ We need to use `__stdcall`
- ▶ Make sure the build matches the Excel version (x64 or x86)
- ▶ the `.def` file remains the same

```
double __stdcall timesTwo(double *in)
{
    double value = in[0] * 2.0;
    return value;
}
```

In Excel

- ▶ Alt-F11 opens the VBA editor window. Right click on workbook, Insert/Module
- ▶ We'll add a declaration for the function in the DLL.

```
Declare Function timesTwo _  
    Lib "C:\PATH_TO_PROJECT\timesTwo\Debug\timesTwo.dll" _  
    (ByRef valIn As Double) _  
    As Double
```

- ▶ Now we can use the function in Excel

fx		=timesTwo(D1)			
C	D	E	F		
	32				
	64				

Using R's Library

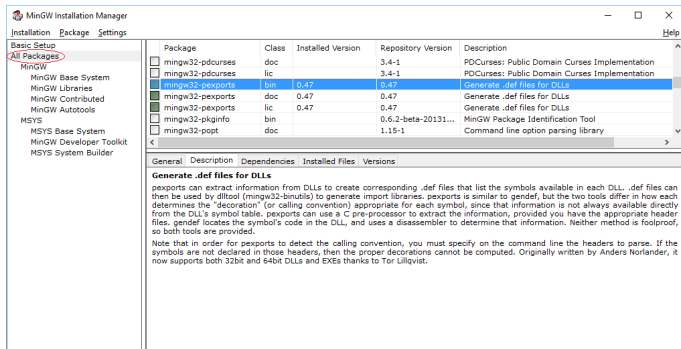
- ▶ Check out R-3.3.0\include
 - ▶ In that folder there are several header files with functions we can use in C/C++
 - ▶

Using R Inside C/C++ with Visual Studio

- ▶ On linux this is easy and well-documented
- ▶ On Windows, it's another story...
- ▶ I will show you how to do it on Windows,
- ▶ Once you know what to do, it is really easy

Setting up the R API

- ▶ First you need pexports from MinGW.
 - ▶ We will use pexports to extract information from R.dll to create a list of symbols in the DLL
 - ▶ Then, we will use this file to generate an import library
- ▶ Go to MinGW.org to download the installer. Then, install pexports.



Setting up the R API

1. Create the exports definition file from R.dll

- ▶ From the command prompt type

```
$ cd "C:\Program Files\Microsoft\MRO\R-3.3.0\bin\x64"  
$ pexports R.dll > R.exp
```

- ▶ Note if C:\MinGW\bin is not in your path, you will need to use the full path to pexports

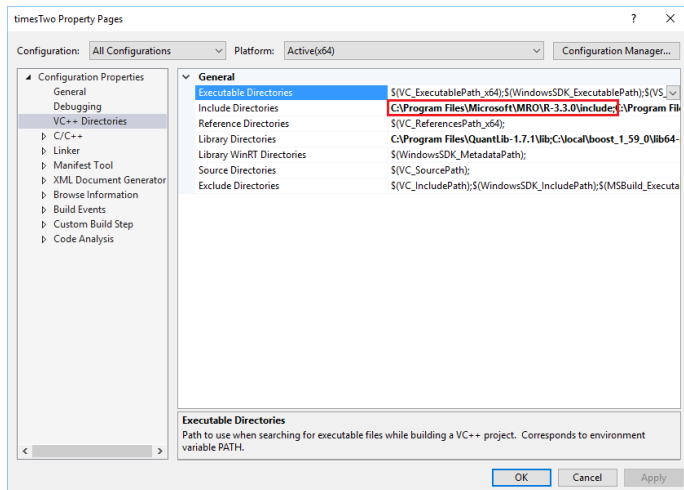
2. Then create the library file using VC++ developer command prompt

```
$ lib /def:R.exp /out:Rdll.lib /MACHINE:X64
```

- ▶ Now we can use this library in Visual Studio.

Add the path to the R-Version\include

- ▶ In Visual Studio, right-click the project to open up the property pages
- ▶ Add the path to the R header files

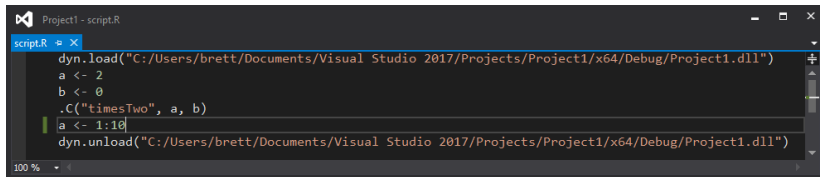


R's random number generator in C++

```
extern "C" void randNorm(double *out)
{
    GetRNGstate();
    out[0] = norm_rand();
    PutRNGstate();
}
```

Using VS to Debug a dll for R (1)

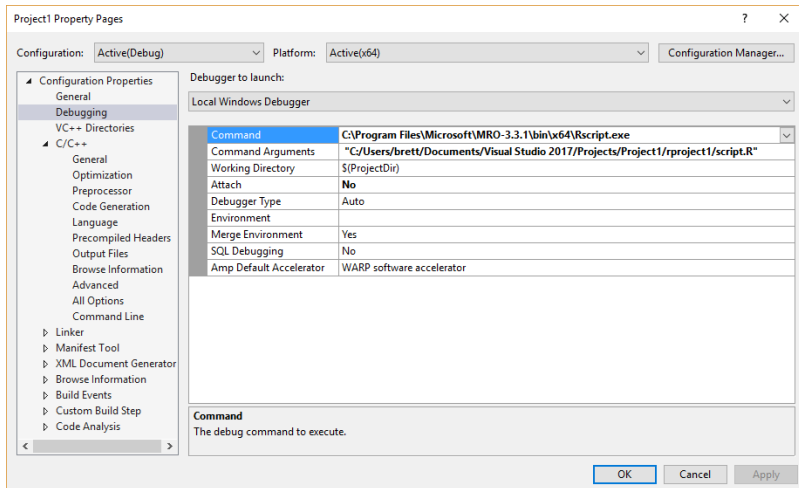
- First, create a script in R to test your code:



```
Project1 - script.R
script.R
dyn.load("C:/Users/brett/Documents/Visual Studio 2017/Projects/Project1/x64/Debug/Project1.dll")
a <- 2
b <- 0
.C("timesTwo", a, b)
a <- 1:10
dyn.unload("C:/Users/brett/Documents/Visual Studio 2017/Projects/Project1/x64/Debug/Project1.dll")
```

Using VS to Debug a dll for R (2)

- ▶ Next, enter the path to Rscript.exe and your script in the project's property pages. Click OK.
- ▶ Finally, press F5 to start the debugger.



Rcpp

Rcpp

- ▶ Written by [Dirk Eddelbuettel](#).
- ▶ I wanted to show you how build a DLL in Visual Studio, because it can be useful for more complicated projects
- ▶ Often it is easiest to use the Rcpp package instead.
- ▶ Rcpp makes it easy to pass vectors, matrices, lists, ect, back to R.
 - ▶ However, there is overhead in doing this.
 - ▶ If you are concerned about speed, consider using the simplest structure.
- ▶ Resources:
 - ▶ [Rcpp book](#) by Dirk Eddelbuettel. Can download it from [SpringerLink](#) on UCLA network.
 - ▶ [Advanced R](#) by Hadley Wickham: [Rcpp](#) and [R's C interface](#) chapetrs.
 - ▶ [Rcpp Gallery](#): Articles and code examples for the Rcpp package.
 - ▶ [Writing R Extensions](#) from CRAN.

Loops are very slow in R

- ▶ One big difference between R and C++ is that the cost of loops is much lower in C++.
- ▶ Let's compare

```
sumR <- function(x) {  
  total <- 0  
  for (i in seq_along(x)) {  
    total <- total + x[i]  
  }  
  total  
}
```

In C++ loops have very little overhead

```
library(Rcpp)
cppFunction('double sumC(NumericVector x) {
    int n = x.size();
    double total = 0;
    for(int i = 0; i < n; ++i) {
        total += x[i];
    }
    return total;
}')
```

C++ vs. R

- ▶ The C++ version is similar, but:
 - ▶ To find the length of the vector, we use the `.size()` method, which returns an integer. C++ methods are called with `.` (i.e., a full stop).
 - ▶ The `for` statement has a different syntax: `for(init; check; increment)`. This loop is initialised by creating a new variable called `i` with value 0. Before each iteration we check that `i < n`, and terminate the loop if it's not. After each iteration, we increment the value of `i` by one, using the special prefix operator `++` which increases the value of `i` by 1.
 - ▶ **IN C++, VECTOR INDICES START AT 0!** This is a very common source of bugs when converting R functions to C++.
 - ▶ Use `=` for assignment, not `<-`.
 - ▶ C++ provides operators that modify in-place: `total += x[i]` is equivalent to `total = total + x[i]`. Similar in-place operators are `-=`, `*=`, and `/=`.

Bechmarking

- ▶ In this example C++ is much more efficient than R:
 - ▶ `sumC()` is competitive with the highly optimized built-in `sum()`,
 - ▶ `sumR()` is several orders of magnitude slower.

```
library(microbenchmark)
x <- runif(2000)
microbenchmark(sum(x), sumC(x), sumR(x))
```

Unit: microseconds

##	expr	min	lq	mean	median	uq	max
##	sum(x)	1.551	1.862	1.94591	1.862	1.8620	8.068
##	sumC(x)	2.482	2.793	11.22086	2.793	3.1030	789.412
##	sumR(x)	96.194	96.505	127.70557	96.815	97.5905	3154.853

Using sourceCpp

- ▶ So far, we've used inline C++ with `cppFunction()`.
- ▶ For real problems, it's usually easier to use stand-alone C++ files and then source them into R using `sourceCpp()`.
- ▶ Your stand-alone C++ file should have extension `.cpp`, and needs to start with:

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

- ▶ And for each function that you want available within R, you need to prefix it with:

```
// [[Rcpp::export]]
```

- ▶ In RStudio File/New File/C++ File does these steps for you.

Compile the C++ code

- ▶ To compile the C++ code, use `sourceCpp("path/to/file.cpp")`.
- ▶ This will create the matching R functions and add them to your current session.
- ▶ Note that these functions can not be saved in a `.Rdata` file and reloaded in a later session; they must be recreated each time you restart R.
- ▶ You can embed R code in special C++ comment blocks.

```
/** R  
# This is R code  
*/
```


Example: meanC vs. the built-in mean():

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

// [[Rcpp::export]]
double meanC(NumericVector x) {
  int n = x.size();
  double total = 0;
  for(int i = 0; i < n; ++i) {
    total += x[i];
  }
  return total / n;
}

/** R
library(microbenchmark)
x <- runif(1e5)
microbenchmark(mean(x), meanC(x))
*/
```

Another Rcpp Example

1. In RStudio, File / New File / C++ File.
2. Enter code in timesTwoRcpp.cpp

```
#include <Rcpp.h>
// [[Rcpp::export]]
Rcpp::NumericVector timesTwo(Rcpp::NumericVector x) {
  return x * 2;
}
```

3. In R,

```
library(Rcpp)
Rcpp::sourceCpp("./examples/timesTwoRcpp.cpp")
timesTwo(c(32,64))
```

```
## [1] 64 128
```

Lab 4

Let's work on Lab 4.