Introduction to High-Performance Computing with R

*UseR! 2009 Tutorial*

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Motivation: What describes our current situation?

Moore's Law: Computers keep getting *faster and faster*

But at the same time our datasets get *bigger and bigger.*

So we're still *waiting and waiting.*

Hence: A need for higher performance computing with R.
We will start by measuring how we are doing before looking at ways to improve our computing performance.

We will look at vectorisation, as well as various ways to compile code.

We will look briefly at debugging tools and tricks as well.

We will have a detailed discussion of several ways to get more things done at the same time by using simple parallel computing approaches.

We also look at ways to automate and script running R code.
We need to know where our code spends the time it takes to compute our tasks. Measuring—using *profiling tools*—is critical.

R already provides the basic tools for performance analysis.

- the `system.time` function for simple measurements.
- the `Rprof` function for profiling R code.
- the `Rprofmem` function for profiling R memory usage.

In addition, the `profr` and `proftools` package on CRAN can be used to visualize `Rprof` data.

We will also look at a script from the R Wiki for additional visualization.

The chapter *Tidying and profiling R code* in the *R Extensions* manual is a good first source for documentation on profiling and debugging.

Simon Urbanek has a page on benchmarks (for Macs) at [http://r.research.att.com/benchmarks/](http://r.research.att.com/benchmarks/)

One can also profile compiled code, either directly (using the `-pg` option to `gcc`) or by using *e.g.* the Google `perftools` library.
Consider the problem of repeatedly estimating a linear model, e.g. in the context of Monte Carlo simulation.

The `lm()` workhorse function is a natural first choice.

However, its generic nature as well the rich set of return arguments come at a cost. For experienced users, `lm.fit()` provides a more efficient alternative.

But how much more efficient?

We will use both functions on the `longley` data set to measure this.

---

This code runs both approaches 2000 times:

```r
data(longley)
Rprof("longley.lm.out")
invisible(replicate(2000,
    lm(Employed ~ ., data=longley)))
Rprof(NULL)

longleydm <- data.matrix(data.frame(intcp=1, longley))
Rprof("longley.lm.fit.out")
invisible(replicate(2000,
    lm.fit(longleydm[,8],
    longleydm[,8])))
Rprof(NULL)
```
We can analyse the output two different ways. First, directly from R into an R object:

```r
data <- summaryRprof("longley.lm.out")
print(str(data))
```

Second, from the command-line (on systems having **Perl**):

```
R CMD Prof longley.lm.out | less
```

The CRAN package / function `profr` by H. Wickham can profile, evaluate, and optionally plot, an expression directly. Or we can use `parse_profr()` to read the previously recorded output:

```r
plot(parse_rprof("longley.lm.out"),
     main="Profile of lm()")
plot(parse_rprof("longley.lm.fit.out"),
     main="Profile of lm.fit()")
```

We notice the different x and y axis scales

For the same number of runs, `lm.fit()` is about fourteen times faster as it makes fewer calls to other functions.
In addition, the `proftools` package by L. Tierney can read profiling data and summarize directly in R.

The `flatProfile` function aggregates the data, optionally with totals.

```r
lmfitprod <- readProfileData("longley.lm.fit.out")
plotProfileCallGraph(lmfitprof)
```

And `plotProfileCallGraph()` can be used to visualize profiling information using the `Rgraphviz` package (which is no longer on CRAN).

Color is used to indicate which nodes use the most of amount of time.

Use of color and other aspects can be configured.
Both packages can be very useful for their quick visualisation of the RProf output. Consider this contrived example:

```r
sillysum <- function(N) {s <- 0;
  for (i in 1:N) s <- s + i; s
ival <- 1/5000
plot(profr(a <- sillysum(1e6), ival))
```

and for a more efficient solution where we use a larger $N$:

```r
efficientsum <- function(N) {
  sum(as.numeric(seq(1,N))) }
ival <- 1/5000
plot(profr(a <- efficientsum(1e7), ival))
```

**profr and proftools** complement each other.

Numerical values in **profr** provide information too.

Choice of colour is useful in **proftools**.
Romain Francois has contributed a Perl script\(^1\) which can be used to visualize profiling output via the dot program (part of graphviz):

\[
./prof2dot.pl longley.lm.out | dot -Tpdf \\
> longley_lm.pdf
\]

\[
./prof2dot.pl longley.lm.fit.out | dot -Tpdf \\
> longley_lmfit.pdf
\]

Its key advantages are the ability to include, exclude or restrict functions.

\(^1\)http://wiki.r-project.org/rwiki/doku.php?id=tips:misc:profiling:current

For \texttt{lm()}\texttt{, this yields:}\n
\[
\text{lm ()}
\]

\[
\text{lm .fit ()}
\]
When R has been built with the `enable-memory-profiling` option, we can also look at use of memory and allocation.

To continue with the *R Extensions* manual example, we issue calls to `Rprofmem` to start and stop logging to a file as we did for `Rprof`. This can be a helpful check for code that is suspected to have an error in its memory allocations.

We also mention in passing that the `tracemem` function can log when copies of a (presumably large) object are being made. Details are in section 3.3.3 of the *R Extensions* manual.

Profiling compiled code typically entails rebuilding the binary and libraries with the `-pg` compiler option. In the case of R, a complete rebuild is required as R itself needs to be compiled with profiling options.

Add-on tools like `valgrind` and `kcachegrind` can be very helpful and may not require rebuilds.

Two other options for Linux are mentioned in the *R Extensions* manual. First, `sprof`, part of the C library, can profile shared libraries. Second, the add-on package `oprofile` provides a daemon that has to be started (stopped) when profiling data collection is to start (end).

A third possibility is the use of the Google Perftools which we will illustrate.
Profiling with Google Perftools

The Google Perftools provide four modes of performance analysis / improvement:

- a thread-caching malloc (memory allocator),
- a heap-checking facility,
- a heap-profiling facility and
- cpu profiling.

Here, we will focus on the last feature.

There are two possible modes of running code with the cpu profiler.

The preferred approach is to link with `-lprofiler`. Alternatively, one can dynamically pre-load the profiler library.

# turn on profiling and provide a profile log file
LD_PRELOAD="/usr/lib/libprofiler.so.0" \
CPUPROFILE=/tmp/rprof.log \
r profilingSmall.R

We can then analyse the profiling output in the file. The profiler (renamed from `pprof` to `google-pprof` on Debian) has a large number of options. Here just use two different formats:

# show text output
google-pprof --cum --text \ 
    /usr/bin/r /tmp/rprof.log | less

# or analyse call graph using gv
google-pprof --gv /usr/bin/r /tmp/rprof.log

The shell script `googlePerftools.sh` runs the complete example.
Another output format is used by the *callgrind* analyser that is part of *valgrind*—a frontend to a variety of analysis tools such as *cachegrind* (cache simulator), *callgrind* (call graph tracer), *helpgrind* (race condition analyser), *massif* (heap profiler), and *memcheck* (fine-grained memory checker).

For example, the KDE frontend *kcachegrind* can be used to visualize the profiler output as follows:

```bash
google-pprof --callgrind /usr/bin/r /tmp/gpProfile.log > googlePerftools.callgrind
kcachegrind googlePerftools.callgrind
```
Kcachegrind running on the the profiling output looks as follows:

One problem with the 'global' approach to profiling is that a large number of internal functions are being reported as well—this may obscure our functions of interest. An alternative is to re-compile the portion of code that we want to profile, and to bracket the code with

```c
ProfilerStart()

// ... code to be profiled here ...

ProfilerEnd()
```

which are defined in `google/profiler.h` which needs to be included. One uses the environment variable `CPUPROFILE` to designate an output file for the profiling information, or designates a file as argument to `ProfilerStart()`.
Revisiting our trivial trivial example from the preceding section:

```r
> sillysum <- function(N) { s <- 0;
    for (i in 1:N) s <- s + i; return(s) }
> system.time(print(sillysum(1e7))

[1] 5e+13
    user  system elapsed
   13.617   0.020   13.701
>
> system.time(print(sum(as.numeric(seq(1,1e7))))

[1] 5e+13
    user  system elapsed
    0.224   0.092   0.315
>
Replacing the loop yielded a gain of a factor of more than 40. It really pays to know the corpus of available functions.

A more interesting example is provided in a case study on the Ra (c.f. next section) site and taken from the S Programming book:

Consider the problem of finding the distribution of the determinant of a 2 x 2 matrix where the entries are independent and uniformly distributed digits 0, 1, ..., 9. This amounts to finding all possible values of \(ac - bd\) where \(a, b, c\) and \(d\) are digits.
The brute-force solution is using explicit loops over all combinations:

```r
dd.for.c <- function() {
  val <- NULL
  for (a in 0:9)
    for (b in 0:9)
      for (d in 0:9)
        for (e in 0:9)
          val <- c(val, a * b - d * e)
  table(val)
}
```

The naive time is

```r
> mean(replicate(10, system.time(dd.for.c())["elapsed"]))

[1] 0.2678
```

The case study discusses two important points that bear repeating:

- **pre-allocating space helps with performance:**
  ```r
  val <- double(10000)
  and using val[i <- i + 1] as the left-hand side reduces the time to 0.1204
  ```

- **switching to faster functions can help too as tabulate outperforms table and reduced the time further to 0.1180.**
Why Measure Vector Ra BLAS/GPUs Compile Parallel Automation

Vectorisation cont.

However, by far the largest improvement comes from eliminating the four loops with two calls each to `outer`:

```r
dd.fast.tabulate <- function() {
  val <- outer(0:9, 0:9, "*")
  val <- outer(val, val, "-")
  tabulate(val)
}
```

The time for the most efficient solution is:

```r
> mean(replicate(10,
          system.time(dd.fast.tabulate())["elapsed"]))
[1] 0.0014
```

which is orders of magnitude faster.

All examples can be run via the script `dd.naive.r`.

Accelerated R with just-in-time compilation

Stephen Milborrow maintains “Ra”, a set of patches to R that allow ’just-in-time compilation’ of loops and arithmetic expressions. Together with his `jit` package on CRAN, this can be used to obtain speedups of standard R operations.

Our trivial example run in Ra:

```r
library(jit)
sillysum <- function(N) { jit(1); s <- 0; \
                 for (i in 1:N) s <- s + i; return(s) }

> system.time(print(sillysum(1e7)))
[1] 5e+13
   user  system elapsed
  1.548   0.028  1.577
```

which gets a speed increase of a factor of five—not bad at all.
The last looping example can be improved with jit:

```r
dd.for.pre.tabulate.jit <- function() {
  jit(1)
  val <- double(10000)
  i <- 0
  for (a in 0:9) for (b in 0:9)
    for (d in 0:9) for (e in 0:9) {
      val[i <- i + 1] <- a*b - d*e
    }
  tabulate(val)
}
```

```r
> mean(replicate(10, system.time(dd.for.pre.tabulate.jit())["elapsed"]))
[1] 0.0053
```

or only about three to four times slower than the non-looped solution using 'outer'—a rather decent improvement.

Ra achieves very good decreases in total computing time in these examples but cannot improve the efficient solution any further.

Ra and jit are still fairly new and not widely deployed yet, but readily available in Debian and Ubuntu.
Blas ('basic linear algebra subprogram', see Wikipedia) are standard building blocks for linear algebra. Highly-optimised libraries exist that can provide considerable performance gains.

R can be built using so-called optimised Blas such as Atlas ('free'), Goto (not 'free'), or those from Intel or AMD; see the 'R Admin' manual, section A.3 'Linear Algebra'.

The speed gains can be noticeable. For Debian/Ubuntu, one can simply install one of the atlas-base-* packages.

An example from the old README.Atlas, running with a R 2.8.1 on a four-core machine:

```r
# with Atlas
> mm <- matrix(rnorm(4*10^6), ncol = 2*10^3)
> mean(replicate(10,
    system.time(crossprod(mm))['elapsed'],trim=0.1)
[1] 2.6465

# with basic. non-optmised Blas,
> mm <- matrix(rnorm(4*10^6), ncol = 2*10^3)
> mean(replicate(10,
    system.time(crossprod(mm))['elapsed'],trim=0.1)
[1] 16.42813
```

For linear algebra problems, we may get an improvement by an integer factor that may be as large (or even larger) than the number of cores as we benefit from both better code and multithreaded execution. Even higher increases are possibly by 'tuning' the library, see the Atlas documentation.
Why Measure Vector Ra BLAS/GPUs Compile Parallel Automation

The next frontier for hardware acceleration is computing on GPUs (`graphics programming units`, see Wikipedia).

GPUs are essentially hardware that is optimised for both I/O and floating point operations, leading to much faster code execution than standard CPUs on floating-point operations.

Development kits are available (e.g. Nvidia CUDA) and the recently announced OpenCL programming specification should make GPU-computing vendor-independent.

Some initial work on integration with R has been undertaken but there appear to be very few easy-to-install and easy-to-use kits for R – the gputools packages is a first, providing a few accelerated data-mining functions.

So this provides a perfect intro for the next subsection on compilation.

Overview Inline Rcpp RInside Debug

Compiled Code

Beyond smarter code (using e.g. vectorised expression and/or just-in-time compilation) or optimised libraries, the most direct speed gain comes from switching to compiled code.

This section covers two possible approaches:

- `inline` for automated wrapping of simple expression
- `Rcpp` for easing the interface between R and C++

A different approach is to keep the core logic 'outside' but to embed R into the application. There is some documentation in the 'R Extensions' manual—and the RInside package on R-Forge offers C++ classes to automate this. This may still require some familiarity with R internals.
Compiled Code: The Basics

R offers several functions to access compiled code: `.C` and `.Fortran` as well as `.Call` and `.External` (*R Extensions*, sections 5.2 and 5.9; *Software for Data Analysis*). `.C` and `.Fortran` are older and simpler, but more restrictive in the long run.

The canonical example in the documentation is the convolution function:

```c
void convolve(double *a, int *na, double *b, int *nb, double *ab)
{
    int i, j, nab = *na + *nb - 1;
    for(i = 0; i < nab; i++)
        ab[i] = 0.0;
    for(i = 0; i < *na; i++)
        for(j = 0; j < *nb; j++)
            ab[i + j] += a[i] * b[j];
}
```

As stated in the manual, one must take care to coerce all the arguments to the correct R storage mode before calling `.C` as mistakes in matching the types can lead to wrong results or hard-to-catch errors.

The script *convolve.C.sh* compiles and links the source code, and then calls R to run the example.
Using `.Call`, the example becomes

```c
#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);
}
```

Now the call becomes easier by just using the function name and the vector arguments—all other handling is done at the C/C++ level:

```r
conv <- function(a, b) .Call("convolve2", a, b)
```

The script `convolve.Call.sh` compiles and links the source code, and then calls R to run the example.

In summary, we see that

- there are different entry points
- using different calling conventions
- leading to code that may need to do more work at the lower level.
inline is a package by Oleg Sklyar et al that provides the function cfunction that can wrap Fortran, C or C++ code.

```r
## A simple Fortran example
code <- "
integer i
  do 1 i=1, n(1)
    1 x(i) = x(i)**3
"
cubefn <- cfunction(signature(n="integer", x="numeric"),
             code, convention=".Fortran")
x <- as.numeric(1:10)
n <- as.integer(10)
cubefn(n, x)
```

cfunction takes care of compiling, linking, loading, ... by placing the resulting dynamically-loadable object code in the per-session temporary directory used by R.

Run this via `cat inline.Fortran.R | R -no-save`.

inline defaults to using the .Call() interface:

```r
## Use of .Call convention with C code
## Multiplying each image in a stack with a 2D Gaussian at a given position
code <- "
 SEXP res:
 int nprotect = 0, nx, ny, nz, x, y;
 PROTECT(res = Rf_duplicate(a)); nprotect++;
 nx = INTEGER(GET_DIM(a))[0];
 ny = INTEGER(GET_DIM(a))[1];
 nz = INTEGER(GET_DIM(a))[2];
 double sigma2 = REAL(s)[0]*REAL(s)[0], d2 ;
 double cx = REAL(centre)[0], cy = REAL(centre)[1], +data, +rdata;
 for (int im = 0; im < nz; im++) {
   data = &REAL(a)[im*nx*ny]);
   rdata = &REAL(res)[im*nx*ny]);
   for (x = 0; x < nx; x++)
     for (y = 0; y < ny; y++) {
       d2 = (x-cx)*(x-cx) + (y-cy)*(y-cy);
       rdata[x + y*nx] = data[x + y*nx] + exp(-d2/sigma2);
     }
 }
UNPROTECT(nprotect);
return res;
"
funx <- cfunction(signature(a="array", s="numeric", centre="numeric"), code)
x <- array(runif(50*50), c(50,50,1))
res <- funx(a=x, s=10, centre=c(25,15)) ## actual call of compiled function
if (interactive()) image(res[,1])
```
We can revisit the earlier distribution of determinants example. If we keep it very simple and pre-allocate the temporary vector in R, the example becomes

```r
code <- "
if (isNumeric(vec)) {
  int *pv = INTEGER(vec);
  int n = length(vec);
  if (n == 10000) {
    int i = 0;
    for (int a = 0; a < 9; a++)
      for (int b = 0; b < 9; b++)
        for (int c = 0; c < 9; c++)
          for (int d = 0; d < 9; d++)
            pv[i++] = a*b - c*d;
  }
}
return(vec);
"

funx <- cfunction(signature(vec="numeric"), code)
```

We can use the inlined function in a new function to be timed:

```r
dd.inline <- function() {
  x <- integer(10000)
  res <- funx(vec=x)
  tabulate(res)
}

> mean(replicate(100, system.time(dd.inline())["elapsed")))
[1] 0.00051
```

Even though it uses the simplest algorithm, pre-allocates memory in R and analyses the result in R, it is still more than twice as fast as the previous best solution.

The script `dd.inline.r` runs this example.
**Rcpp** makes it easier to interface C++ and R code.

Using the `.Call` interface, we can use features of the C++ language to automate the tedious bits of the macro-based C-level interface to R.

One major advantage of using `.Call` is that vectors (or matrices) can be passed directly between R and C++ without the need for explicit passing of dimension arguments. And by using the C++ class layers, we do not need to directly manipulate the SEXP objects.

So let us rewrite the 'distribution of determinant' example one more time.

```c++
#include <Rcpp.h>

RcppExport SEXP dd_rcpp(SEXP v) {
  SEXP rl = R_NilValue;  // Use this when nothing is returned

  RcppVector<int> vec(v);  // vec parameter viewed as vector of doubles
  int n = vec.size(), i = 0;

  for (int a = 0; a < 9; a++)
    for (int b = 0; b < 9; b++)
      for (int c = 0; c < 9; c++)
        for (int d = 0; d < 9; d++)
          vec(i++) = a*b - c*d;

  RcppResultSet rs;  // Build result set returned as list to R
  rs.add("vec", vec);  // vec as named element with name 'vec'
  rl = rs.getReturnList();  // Get the list to be returned to R.

  return rl;
}
```

but it is actually preferable to use the exception-handling feature of C++ as in the slightly longer next version.
```cpp
#include <Rcpp.h>

RcppExport SEXP dd_rcpp(SEXP v)
{
  SEXP rl = R_NilValue;  // Use this when there is nothing to be returned.
  char* exceptionMesg = NULL;  // msg var in case of error

  try {
    RcppVector<int> vec(v);  // vec parameter viewed as vector of doubles.
    int n = vec.size(), i = 0;
    for (int a = 0; a < 9; a++)
      for (int b = 0; b < 9; b++)
        for (int c = 0; c < 9; c++)
          for (int d = 0; d < 9; d++)
            vec[i++] = a * b - c * d;

    RcppResultSet rs;  // Build result set to be returned as a list to R.
    rs.add("vec", vec);  // vec as named element with name 'vec'
    rl = rs.getReturnList();  // Get the list to be returned to R.
  } catch (std::exception& ex) {
    exceptionMesg = copyMessageToR(ex.what());
  } catch (...) {
    exceptionMesg = copyMessageToR("unknown reason");
  }

  if (exceptionMesg != NULL)
    error(exceptionMesg);

  return rl;
}
```

We can create a shared library from the source file as follows:

```bash
PKG_CPPFLAGS='r -e'Rcpp:::CxxFlags()'' \
R CMD SHLIB dd.rcpp.cpp \
'r -e'Rcpp:::LdFlags()''

g++ -I/usr/share/R/include \ 
  -I/usr/lib/R/site-library/Rcpp/lib \ 
  -fpic -g -O2 \ 
  -c dd.rcpp.cpp -o dd.rcpp.o

g++ -shared -o dd.rcpp.so dd.rcpp.o \ 
  -L/usr/lib/R/site-library/Rcpp/lib \ 
  -L/usr/lib/R/site-library/Rcpp/lib \ 
  -L/usr/lib/R/lib -lR

Note how we let the Rcpp package tell us where header and library files are stored.
```
We can then load the file using `dyn.load` and proceed as in the `inline` example.

dyn.load("dd.rcpp.so")

dd.rcpp <- function() {
  x <- integer(10000)
  res <- .Call("dd_rcpp", x)
  tabulate(res$vec)
}

mean(replicate(100,system.time(dd.rcpp())["elapsed"])))

[1] 0.00047

This beats the `inline` example by a negligible amount which is probably due to some overhead the in the easy-to-use inlining.

The file `dd.rcpp.sh` runs the full Rcpp example.

**Basic Rcpp usage**

Rcpp eases data transfer from R to C++, and back. We always convert to and from SEXP, and return a SEXP to R.

The key is that we can consider this to be a 'variant' type permitting us to extract using appropriate C++ classes. We pass data from R via named lists that may contain different types:

```r
list(intnb=42, fltnb=6.78, date=Sys.Date(),
     txt="some thing", bool=FALSE)
```

by initialising a RcppParams object and extracting as in

```r
RcppParams param(inputsexp);
int nmb = param.getIntValue("intnb");
double dbl = param.getIntValue("fltnb");
string txt = param.getStringValue("txt");
bool flg = param.getBoolValue("bool");
RcppDate dt = param.getDateValue("date");
```
Similarly, we can construct vectors and matrices of \texttt{double}, \texttt{int}, as well as vectors of types \texttt{string} and date and datetime. The key is that we \textit{never} have to deal with dimensions and / or memory allocations — all this is shielded by C++ classes.

Similarly, for the return, we declare an object of type \texttt{RcppResultSet} and use the \texttt{add} methods to insert named elements before converting this into a list that is assigned to the returned \texttt{SEXP}.

Back in \texttt{R}, we access them as elements of a standard \texttt{R} list by position or name.

Another Rcpp example

Let us revisit the \texttt{lm()} versus \texttt{lm.fit()} example. How fast could compiled code be? Let's wrap a GNU GSL function.

```c
#include <stdio.h>
extern "C" {
#include <gsl/gsl_matrix.h>
#include <Rcpp.h>

RcppExport SEXP gsl_matrix_multifit(SEXP Xexp, SEXP Yexp) {
  SEXP ri=R_NilValue;
  char *exceptionMesg=NULL;

  try {
    RcppMatrixView<double> Xr(Xexp);
    RcppVectorView<double> Yr(Yexp);
    int i,j,n = Xr.dim1(), k = Xr.dim2();
    double chisq;
    gsl_matrix *X = gsl_matrix_alloc (n, k);
    gsl_vector *y = gsl_vector_alloc (n);
    gsl_vector *c = gsl_vector_alloc (k);
    gsl_matrix *cov = gsl_matrix_alloc (k, k);
    for (i = 0; i < n; i++) {
      for (j = 0; j < k; j++)
        gsl_matrix_set (X, i, j, Xr(i,j));
    }
    gsl_matrix_set (y, i, Yr(i));
  }
```
Another Rcpp example (cont.)

```r
27 gsl_multifit_linear_workspace *work = gsl_multifit_linear_alloc (n, k);
28 gsl_multifit_linear (X, y, c, cov, &chisq, work);
29 gsl_multifit_linear_free (work);
30
31 RcppMatrix<double> CovMat(k, k);
32 RcppVector<double> Coef(k);
33 for (i = 0; i < k; i++) {
34   for (j = 0; j < k; j++)
35     CovMat(i,j) = gsl_matrix_get(cov,i,j);
36   Coef(i) = gsl_vector_get(c,i);
37 }
38 gsl_matrix_free (X);
39 gsl_vector_free (y);
40 gsl_vector_free (c);
41 gsl_matrix_free (cov);
42
43 RcppResultSet rs;
44 rs.add("coef", Coef);
45 rs.add("covmat", CovMat);
46 rI = rs.getReturnList();
47 }
48 catch(std::exception & ex) {
49   exceptionMesg = copyMessageToR(ex.what());
50 } catch(...) {
51   exceptionMesg = copyMessageToR("unknown reason");
52 }
53 if(exceptionMesg != NULL)
54   Rf_error(exceptionMesg);
55 return rI;
56 }
```

Comparison of R and linear model fit routines

The small `longley` example exhibits less variability between methods, but the larger data set shows the gains more clearly.

The `lm.fit()` approach appears unchanged between `longley` and the larger simulated data set.

Source: Our calculations
Another Rcpp example (cont.)

Comparison of R and linear model fit routines

By inverting the times to see how many ‘regressions per second’ we can fit, the merits of the compiled code become clearer.

One caveat, measurements depends critically on the size of the data as well as the cpu and libraries that are used.

Source: Our calculations

Revisiting profiling

We can also use the preceding example to illustrate how to profile subroutines. We can add the following to the top of the function:

```r
ProfilerStart("/tmp/ols.profile");
for (unsigned int i=1; i<10000; i++) {
    and similarly
}
ProfilerStop();
at end before returning. If we then call this function just once from R as in

```r
print(system.time(invisible(val <- .Call("gsl_multifit", X, y))))
```

we can then call the profiling tools on the output:

```r
google-pprof --gv /usr/bin/r /tmp/ols.profile
```
Revisiting profiling

Two tips for easing builds with Rcpp:

For command-line use, a shortcut is to copy Rcpp.h to /usr/local/include, and libRcpp.so to /usr/local/lib.

The earlier example reduces to

```
R CMD SHLIB dd.rcpp.cpp
```

as header and library will be found in the default locations.

For package building, we can have a file src/Makevars with

```r
# compile flag providing header directory
PKG_CXXFLAGS=`Rscript -e 'Rcpp:::CxxFlags()'`

# link flag providing library and path
PKG_LIBS=`Rscript -e 'Rcpp:::LdFlags()'`
```

See help(Rcpp-package) for more details.
RInside and bringing R to C++

Sometimes we may want to go the other way and add R to an existing C++ project.

This can be simplified using RInside:

```cpp
#include "RInside.h" // for the embedded R via RInside
#include "Rcpp.h" // for the R / Cpp interface

int main(int argc, char *argv[]) {
    RInside R(argc, argv); // create an embedded R instance
    std::string txt = "Hello, world!\n"; // assign a standard C++ string to 'txt'
    R.assign(txt, "txt"); // assign string var to R variable 'txt'
    std::string evalstr = "cat('txt')";
    R.parseEvalQ(evalstr); // eval the init string, ignoring any returns
    exit(0);
}
```

```cpp
#include "RInside.h" // for the embedded R via RInside
#include "Rcpp.h" // for the R / Cpp interface used for transfer

std::vector< std::vector<double> > createMatrix(const int n) {
    std::vector< std::vector<double> > mat;
    for (int i=0; i<n; i++) {
        std::vector<double> row;
        for (int j=0; j<n; j++) row.push_back((i*10+j));
        mat.push_back(row);
    }
    return(mat);
}

int main(int argc, char *argv[]) {
    const int mdim = 4;
    std::string evalstr = "cat('Running ls()\n'); print(ls()); \n cat('Showing M\n'); print(M); cat('Showing colSums()\n'); \n Z <- colSums(M); print(Z); Z"; // returns Z
    RInside R(argc, argv);
    SEXP ans;
    std::vector< std::vector<double> > myMatrix = createMatrix(mdim);
    R.assign( myMatrix, "M"); // assign STL matrix to R's 'M' var
    R.parseEval(evalstr, ans); // eval the init string — Z is now in ans
    RcppVector<double> vec(ans); // now vec contains Z via ans
    vector<double> v = vec.stlVector(); // convert RcppVector to STL vector
    for (unsigned i=0; i<v.size(); i++)
        std::cout << "In C++ element " << i << " is " << v[i] << std::endl;
    exit(0);
}
```
Analysis of compiled code is mainly undertaken with a debugger like gdb, or a graphical frontend like ddd.

Another useful tool is valgrind which can find memory leaks. We can illustrate its use with a recent real-life example.

RMySQL had recently been found to be leaking memory when database connections are being established and closed. Given how RPostgreSQL shares a common heritage, it seemed like a good idea to check.

We create a small test script which opens and closes a connection to the database in a loop and sends a small 'select' query. We can run this in a way that is close to the suggested use from the 'R Extensions' manual:

```
R -d "valgrind -tool=memcheck -leak-check=full" -vanilla < valgrindTest.R
```

which creates copious output, including what is on the next slide.

Given the source file and line number, it is fairly straightforward to locate the source of error: a vector of pointers was freed without freeing the individual entries first.
The state before the fix:

 [...] 

```text
#==21642== 2,991 bytes in 299 blocks are definitely lost in loss record 34 of 47
#==21642== at 0x4023D6E: malloc (vg_replace_malloc.c:207)
#==21642== by 0x4E781CAF: RS_DBI_copyString (RS-DBI.c:592)
#==21642== by 0x4E784B91: RS_PostgreSQL_createDataMappings (RS-PostgreSQL.c:400)
#==21642== by 0x4E785191: RS_PostgreSQL_exec (RS-PostgreSQL.c:366)
#==21642== by 0x4C05B88: (within /usr/lib/R/lib/libR.so)
#==21642== by 0x40EED49F: Rf_eval (in /usr/lib/R/lib/libR.so)
#==21642== by 0x40F0000C: (within /usr/lib/R/lib/libR.so)
#==21642== by 0x40EED474: Rf_eval (in /usr/lib/R/lib/libR.so)
#==21642== by 0x40F0186: (within /usr/lib/R/lib/libR.so)
#==21642== by 0x40EDE743: Rf_eval (in /usr/lib/R/lib/libR.so)
#==21642== by 0x40F166E6: RSApplyClosure (in /usr/lib/R/lib/libR.so)
#==21642== by 0x40EDE99A: Rf_eval (in /usr/lib/R/lib/libR.so)
#==21642== LEAK SUMMARY:
#==21642== definitely lost: 3,063 bytes in 301 blocks.
#==21642== indirectly lost: 240 bytes in 20 blocks.
#==21642== possibly lost: 9 bytes in 1 blocks.
#==21642== still reachable: 13,800,378 bytes in 8,420 blocks.
#==21642== suppressed: 0 bytes in 0 blocks.
#==21642== Reachable blocks (those to which a pointer was found) are not shown.
#==21642== To see them, rerun with: --leak-check=full --show-reachable=yes
```

The state after the fix:

 [...] 

```text
#==3820== 312 (72 direct, 240 indirect) bytes in 2 blocks are definitely lost in loss record 14 of 45
#==3820== at 0x4023D6E: malloc (vg_replace_malloc.c:207)
#==3820== by 0x4F1FC63: nss_parse_service_list (nsswitch.c:530)
#==3820== by 0x4F1FC7a3: __nss_database_lookup (nsswitch.c:134)
#==3820== by 0x44F48: ???
#==3820== by 0x44FFCEC: ???
#==3820== by 0x439BBF1: getpwuid_r@@GLIBC_2.1.2 (getXXbyYY_r.c:226)
#==3820== by 0x439BA76: getpwuid (getXXbyYY.c:116)
#==3820== by 0x4149412: (within /usr/lib/R/lib/libR.so)
#==3820== by 0x4127790: (within /usr/lib/R/lib/libR.so)
#==3820== by 0x40EDE743: Rf_eval (in /usr/lib/R/lib/libR.so)
#==3820== by 0x40F166E6: RSApplyClosure (in /usr/lib/R/lib/libR.so)
#==3820== LEAK SUMMARY:
#==3820== definitely lost: 72 bytes in 2 blocks.
#==3820== indirectly lost: 240 bytes in 20 blocks.
#==3820== possibly lost: 0 bytes in 0 blocks.
#==3820== still reachable: 13,800,378 bytes in 8,420 blocks.
#==3820== suppressed: 0 bytes in 0 blocks.
#==3820== Reachable blocks (those to which a pointer was found) are not shown.
#==3820== To see them, rerun with: --leak-check=full --show-reachable=yes
```

showing that we recovered 3000 bytes.
Several R packages on CRAN provide the ability to execute code in parallel:

- NWS
- Rmpi
- snow (using MPI, PVM, NWS or sockets)
- papply
- taskPR
- multicore

A recent paper by Schmidberger, Morgan, Eddelbuettel, Yu, Tierney and Mansmann (JSS, 2009) provides a survey of this field.

**NWS Intro**

NWS, or NetWorkSpaces, is an alternative to MPI (which we discuss below). Based on Python, it may be easier to install (in case administrator rights are unavailable) and use than MPI. It is accessible from R, Python and Matlab. It is also cross-platform.

NWS is available via Sourceforge as well as CRAN. An introductory article (focussing on Python) appeared last summer in Dr. Dobb's.

On Debian and Ubuntu, installing the *python-nwsserver* package on at least the server node, and installing *r-cran-nws* on each client is all that is needed. Other system may need to install the *twisted* framework for Python first.
A simple example, adapted from one of the package demos:

```
ws <- netWorkSpace('r place') # create a 'value store'
nwsStore(ws, 'x', 1) # place a value (as fifo)

cat(nwsListVars(ws), "\n") # we can list
nwsFind(ws, 'x') # and lookup
nwsStore(ws, 'x', 2) # and overwrite
cat(nwsListVars(ws), "\n") # now see two entries


cat(nwsFetch(ws, 'x'), '\n') # we can fetch
cat(nwsFetch(ws, 'x'), '\n') # we can fetch
cat(nwsListVars(ws), '\n') # and none left

cat(nwsFetchTry(ws,'x','no go'),'\n') # can't fetch
```

The script `nwsVariableStore.r` contains this and a few more commands.

The NWS component sleigh is an R class that makes it very easy to write simple parallel programs. Sleigh uses the master/worker paradigm: The master submits tasks to the workers, who may or may not be on the same machine as the master.

```r
# create a sleigh object on two nodes using ssh
s <- sleigh(nodeList=c("joe", "ron"), launch=sshcmd)

# execute a statement on each worker node
eachWorker(s, function() x <<- 1)

# get system info from each worker
eachWorker(s, Sys.info)

# run a lapply-style funct. over each list elem.
eachElem(s, function(x) {x+1}, list(1:10))

stopSleigh(s)
```
Also of note is the extended caretNWS version of caret by Max Kuhn, and described in a recent Journal of Statistical Software article.

`caret` (short for 'Classification and Regression Training') provides a consistent interface for dozens of modern regression and classification techniques.

`caretNWS` uses `nws` and `sleigh` to execute embarrassingly parallel task: bagging, boosting, cross-validation, bootstrapping, ... This is all done 'behind the scenes' and thus easy to deploy.

Schmidberger et al find NWS to be competitive with the other parallel methods for non-degenerate cases where the ratio between communication and computation is balanced.

`Rmpi` is a CRAN package that provides an interface between `R` and the Message Passing Interface (MPI), a standard for parallel computing. (c.f. Wikipedia for more and links to the Open MPI and MPICH2 projects for implementations).

The preferred implementation for MPI is now Open MPI. However, the older LAM implementation can be used on those platforms where Open MPI is unavailable. There is also an alternate implementation called MPICH2. Lastly, we should also mention the similar Parallel Virtual Machine (PVM) tool; see its Wikipedia page for more.

`Rmpi` allows us to use MPI directly from `R` and comes with several examples. However, we will focus on the higher-level usage via snow.
Let us look at the MPI variant of the 'Hello, World!' program:

```c
#include <stdio.h>
#include "mpi.h"

int main(int argc, char** argv)
{
    int rank, size, nameLen;
    char processorName[ MPI_MAX_PROCESSOR_NAME ];

    MPI_Init(&argc, &argv);
    MPI_Comm_rank(MPI_COMM_WORLD, &rank);
    MPI_Comm_size(MPI_COMM_WORLD, &size);

    MPI_Get_processor_name(processorName, &nameLen);

    printf("Hello, rank %d, size %d on processor %s\n", rank, size, processorName);

    MPI_Finalize();
    return 0;
}
```

We can compile the previous example via

```
$ mpicc -o mpiHelloWorld mpiHelloWorld.c
```

If it it has been copied across several Open MPI-equipped hosts, we can execute it $N$ times on the $M$ listed hosts via:

```
$ orterun -H ron,joe,tony,mccoy -n 8 /tmp/mpiHelloWorld
```

Hello, rank 0, size 8 on processor ron
Hello, rank 4, size 8 on processor ron
Hello, rank 7, size 8 on processor mccoy
Hello, rank 3, size 8 on processor mccoy
Hello, rank 2, size 8 on processor tony
Hello, rank 5, size 8 on processor joe
Hello, rank 6, size 8 on processor tony
Hello, rank 1, size 8 on processor joe

Notice how the order of execution is indeterminate.
Besides `orterun` (which replaces the `mpirun` command used by other MPI implementations), Open MPI also supplies `ompi_info` to query parameter settings.

Open MPI has very fine-grained configuration options that permit e.g. attaching particular jobs to particular cpus or cores.

Detailed documentation is provided at the web site `http://www.openmpi.org`.

We will concentrate on using MPI via the `Rmpi` package.

Rmpi, a CRAN package by Hao Yu, wraps many of the MPI API calls for use by R.

The preceding example can be rewritten in R as

```r
#!/usr/bin/env r
library(Rmpi) # calls MPI_Init
rk <- mpi.comm.rank(0)
sz <- mpi.comm.size(0)
name <- mpi.get.processor.name()
cat("Hello, rank", rk, "size", sz, "on", name, "\n")
```
Rmpi: cont.

```r
$ orterun -H ron,joe,tony,mccoy -n 8 \\
/tmp/mpiHelloWorld.r
Hello, rank 4 size 8 on ron
Hello, rank 0 size 8 on ron
Hello, rank 3 size 8 on mccoy
Hello, rank 7 size 8 on mccoy
Hello, rank 21 size 8 on joe
size 8 on tony
Hello, rank 6 size 8 on tony
Hello, rank 5 size 8 on joe
```

We can also execute this as a one-liner using `r` (which we discuss later):

```r
$ orterun -n 8 -H ron,joe,tony,mccoy \\
r -lRmpi -e'cat("Hello", \\
mpi.comm.rank(0), "of", \\
mpi.comm.size(0), "on", \\
mpi.get.processor.name(), "\n"); mpi.quit()
'
Hello 4 of 8 on ron
Hello 3 of 8 on mccoy
Hello 7 of 8 on mccoy
Hello 0 of 8 on ron
HelloHello 2 of 8 on tony
Hello 1 of 8 on joe
Hello 5 of 8 on joe
6 of 8 on tony
Rmpi offers a large number functions, mirroring the rich API provided by MPI.

Rmpi also offers extensions specific to working with R and its objects, including a set of apply-style functions to spread load across the worker nodes.

However, we will use Rmpi mostly indirectly via snow.

The snow package by Tierney et al provides a convenient abstraction directly from R.

It can be used to initialize and use a compute cluster using one of the available methods direct socket connections, MPI, PVM, or (since the most recent release), NWS. We will focus on MPI.

A simple example:

```r
cl <- makeCluster(4, "MPI")
print(clusterCall(cl, function() \ 
    Sys.info()[c("nodename","machine")]))
stopCluster(cl)
```

which we can as a one-liner as shown on the next slide.
$ orterun -n 1 -H ron,joe,tony,mccoy r -lsnow,Rmpi \ 
   -e'cl <- makeCluster(4, "MPI"); \ 
       res <- clusterCall(cl, \ 
               function() Sys.info()["nodename"]); \ 
       print(do.call(rbind,res)); \ 
       stopCluster(cl); mpi.quit()' 

4 slaves are spawned successfully. 0 failed.

nodename
[1,] "joe"
[2,] "tony"
[3,] "mccoy"
[4,] "ron"

Note that we told `orterun` to start on only one node – as `snow` then starts four instances (which are split evenly over the four given hosts).

The power of `snow` lies in the ability to use the `apply`-style paradigm over a cluster of machines:

```r
cl <- makeCluster(4, "MPI")
res <- parSapply(cl, params, \ 
                 FUN=function(x) myBigFunction(x))
```

will 'unroll' the parameters `params` one-each over the function argument given, utilising the cluster `cl`. In other words, we will be running four copies of `myBigFunction()` at once.

So the `snow` package provides a unifying framework for parallely executed `apply` functions.

We will come back to more examples with `snow` below.
We saw that `Rmpi` and `NWS` have apply-style functions, and that `snow` provides a unified layer. `papply` is another CRAN package that wraps around `Rmpi` to distribute processing of apply-style functions across a cluster.

However, using the Open MPI-based `Rmpi` package, I was not able to get `papply` to actually successfully distribute – and retrieve – results across a cluster. So `snow` remains the preferred wrapper.

`biopara` is another package to distribute load across a cluster using direct socket-based communication. We consider `snow` to be a more general-purpose package for the same task.

`taskPR` uses the MPI protocol directly rather than via `Rmpi`. It is however hard-wired to use LAM and failed to launch under the Open MPI-implementation.

---

Once the number of compute nodes increases, it becomes important to be able to allocate and manage resources, and to queue and batch jobs. A suitable tool is `slurm`, an open-source resource manager for Linux clusters.

Paraphrasing from the slurm website:

- it allocates exclusive and/or non-exclusive access to resources (computer nodes) to users;
- it provides a framework for starting, executing, and monitoring (typically parallel) work on a set of allocated nodes.
- it arbitrates contention for resources by managing a queue of pending work.

Slurm is being developed by a consortium including LLNL, HP, Bull, and Linux Networks.
Slurm is rather rich in features; we will only scratch the surface here. Slurm can use many underlying message passing / communications protocols, and MPI is well supported. In particular, Open MPI works well with slurm. That is an advantage inasmuch as it permits use of Rmpi.

A simple example:

```bash
$ srun -N 2 r -lRmpi -e'cat("Hello", 
    mpi.comm.rank(0), "of", 
    mpi.comm.size(0), "on", 
    mpi.get.processor.name(), "\n")'

Hello 0 of 1 on ron
Hello 0 of 1 on joe

$ srun -n 4 -N 2 -O r -lRmpi -e'cat("Hello", 
    mpi.comm.rank(0), "of", 
    mpi.comm.size(0), "on", 
    mpi.get.processor.name(), "\n")'

Hello 0 of 1 on ron
Hello 0 of 1 on ron
Hello 0 of 1 on joe
Hello 0 of 1 on joe
```

This shows how to overcommit jobs per node, and provides an example where we set the number of worker instances on the command-line.
Additional command-line tools of interest are `salloc`, `sbatch`, `scontrol`, `squeue`, `scancel` and `sinfo`. For example, to see the status of a compute cluster:

```
$ sinfo

PARTITION   AVAIL TIMELIMIT NODES  STATE  NODELIST
debug*       up    infinite     2  idle  mccoy,ron
```

This shows two idle nodes in a partition with the default name 'debug'.

The `sview` graphical user interface combines the functionality of a few of the command-line tools.

A more complete example will be provided below.

---

**Using all those cores**

Multi-core hardware is now a default, and the number of cores per cpus will only increase. It is therefore becoming more important for software to take advantage of these features.

Two recent (and still 'experimental') packages by Luke Tierney are addressing this question:

- `pnmath` uses OpenMP compiler directives for parallel code;
- `pnmath0` uses pthreads and implements the same interface.

They can be found at [http://www.stat.uiowa.edu/~luke/R/experimental/](http://www.stat.uiowa.edu/~luke/R/experimental/)

More recently, Simon Urbanek released the 'multicore' package which provides parallel execution of R code on machines with multiple cores or cpu. All jobs share the full state of R when spawned, no data or code needs to be initialized. This make the actual spawning very fast since no new R instance needs to be started.
Both pnmath and pnmath0 provide parallelized vector math functions and support routines.

Upon loading either package, a number of vector math functions are replaced with versions that are parallelized using OpenMP. The functions will be run using multiple threads if their results will be long enough for the parallel overhead to be outweighed by the parallel gains. On load a calibration calculation is carried out to assess the parallel overhead and adjust these thresholds.

Profiling is probably the best way to assess the possible usefulness. As a quick illustration, we compute the `qtukey` function on an eight-core machine:

```
$ r -e'N=1e3;print(system.time(qtukey(seq(1,N)/N,2,2)))'
    user  system elapsed
   66.590   0.000   66.649
$ r -lpnmath -e'N=1e3; \nprint(system.time(qtukey(seq(1,N)/N,2,2)))'
    user  system elapsed
   67.580   0.080   9.938
$ r -lpnmath0 -e'N=1e3; \nprint(system.time(qtukey(seq(1,N)/N,2,2)))'
    user  system elapsed
   68.230   0.010   9.983
```

The 6.7-fold reduction in 'elapsed' time shows that the multithreaded version takes advantage of the 8 available cores at a sub-linear fashion as some communications overhead is involved.

These improvements will likely be folded into future R versions.
The multicore package provides two main interfaces:

- `mclapply`, a parallel / multicore version of `lapply`
- The functions `parallel` and `collect` to launch parallel execution and gather results at end

For setups in which a sufficient number of cores is available without requiring network traffic, multicore is likely to be a very compelling package.

Given that future cpu generation will offer 16, 32 or more cores, this package may become increasingly popular.

One thing to note is that 'anything but Windows' is required to take advantage of multicore.

---

Scripting example for R and slurm

Being able to launch numerous R jobs in a parallel environments is helped by the ability to 'script' R.

Several simple methods existed to start R:

- `R CMD BATCH file.R`
- `echo "commands" | R -no-save`
- `R -no-save < file.R > file.Rout`

These are suitable for one-off scripts, but may be too fragile for distributed computing.
The \texttt{r} command of the \texttt{littler} package (as well as \texttt{R}'s \texttt{Rscript}) provide more robust alternatives.

\texttt{r} can also be used four different ways:

- \texttt{r file.R}
- \texttt{echo "commands"} \texttt{| r}
- \texttt{r -lRmpi -e 'cat("Hello", mpi.get.processor.name())'}
- and \texttt{shebang}-style in script files: \texttt{#!/usr/bin/r}

It is the last point that is of particular interest in this HPC context. Also of note is the availability of the \texttt{getopt} package on CRAN.

Having introduced \texttt{snow}, \texttt{slurm} and \texttt{r}, we would like to combine them.

However, there is are problems:

- \texttt{snow} has a master/worker paradigm yet \texttt{slurm} launches its nodes symmetrically,
- \texttt{slurm}'s \texttt{srun} has limits in spawning jobs
- with \texttt{srun}, we cannot communicate the number of nodes 'dynamically’ into the script: \texttt{snow}'s cluster creation needs a hardwired number of nodes
snow solves the master / worker problem by auto-discovery upon startup. The package contains two internal files RMPISNOW and RMPISNOWprofile that use a combination of shell and R code to determine the node identity allowing it to switch to master or worker functionality.

We can reduce the same problem to this for our R script:

```r
mpirank <- mpi::mpi.comm.rank(0)
if (mpirank == 0) { # are we the master ?
  makeMPIcluster()
} else { # or are we a slave ?
  sink(file="/dev/null")
  slaveLoop(makeMPImaster())
  q()
}
```

For example

```sh
#!/usr/bin/env r
suppressMessages(library(Rmpi))
suppressMessages(library(snow))

mpirank <- mpi::mpi.comm.rank(0)
if (mpirank == 0) {
  cat("Launching master, mpi rank=", mpirank, ",\n"
  makeMPIcluster()
} else {
  cat("Launching slave with, mpi rank=", mpirank, ",\n"
  sink(file="/dev/null")
  slaveLoop(makeMPImaster())
  mpi.finalize()
  q()
}
stopCluster(cl)
```
The example creates

```r
$ orterun -H ron,joe,tony,mccoy -n 4 mpiSnowSimple.r
```

Launching slave 2
Launching master 0
Launching slave 1
Launching slave 3

and we see that \( N - 1 \) workers are running with one instance running as the coordinating manager node.

The other important aspect is to switch to `salloc` (which will call `orterun`) instead of `srun`.

We can either supply the hosts used using the `-w` switch, or rely on the `slurm.conf` file.

But importantly, we can govern from the call how many instances we want running (and have neither the `srun` limitation requiring overcommitting nor the hard-coded `snow` cluster-creation size):

```r
$ salloc -w ron,mccoy orterun -n 7 mpiSnowSimple.r
```

We ask for a `slurm` allocation on the given hosts, and instruct Open MPI to run seven instances.
salloc for snow

```r
#!/usr/bin/env r
suppressMessages(library(Rmpi))
suppressMessages(library(snow))

mpirank <- mpi.comm.rank(0)
if (mpirank == 0) {
cat("Launching master, mpi rank=" , mpirank , ";\n"
makeMPIcluster()
} else { # or are we a slave ?
cat("Launching slave with, mpi rank=" , mpirank , ";\n"
sink(file="/dev/null")
slaveLoop(makeMPImaster())
mpi.finalize()
q()
}

## a trivial main body, but note how getMPIcluster() learns from the
## launched cluster how many nodes are available
cl <- getMPIcluster()
clusterEvalQ(cl, options("digits.secs"=3)) # use millisecond granularity
res <- clusterCall(cl, function() paste(format(Sys.time()),Sys.info()("nodename")))
print(do.call(rbind, res))
stopCluster(cl)
mpi.quit()
```

```shell
$ salloc \-w ron,joe,tony orterun \-n 7 /tmp/mpiSnowSimple.r
salloc: Granted job allocation 39
Launching slave with, mpi rank= 5
Launching slave with, mpi rank= 2
Launching slave with, mpi rank= 6
Launching master, mpi rank= 0
Launching slave with, mpi rank= 3
Launching slave with, mpi rank= 1
Launching slave with, mpi rank= 4
[,1]
[1,] "2009-06-25 20:51:20.536 joe"
[2,] "2009-06-25 20:51:33.747 tony"
[4,] "2009-06-25 20:51:20.544 joe"
[5,] "2009-06-25 20:51:33.766 tony"
[6,] "2009-06-25 20:51:20.537 ron"
salloc: Relinquishing job allocation 39
```
A complete example

```r
cl <- NULL
mpirank <- mpi.comm.rank(0)
if (mpirank == 0) {
  cl <- makeMPIcluster()
} else { # or are we a slave?
  sink(file="/dev/null")
  slaveLoop(makeMPImaster())
  mpi.finalize(); q()
}
clusterEvalQ(cl, library(RDieHarder))
res <- parLapply(cl, c("mt19937","mt19937_1999",
                       "mt19937_1998", "R_mersenne_twister"),
                 function(x) {
                   dieharder(rng=x, test="operm5",
                             psamples=100, seed=12345)
               })
stopCluster(cl)
print( do.call(rbind, lapply(res, function(x) { x[[1]] } )))
mpi.quit()
```

This uses **RDieHarder** to test four Mersenne-Twister implementations at once.

A simple analysis shows the four charts and prints the four \( p \)-values:

```r
pdf("/tmp/snowRDH.pdf")
lapply(res, function(x) plot(x))
dev.off()

print( do.call(rbind,
               lapply(res, function(x) { x[[1]] } )))
```
A complete example cont.

```r
$ salloc -w ron,joe orterun -n 5 snowRDieharder.r
salloc: Granted job allocation 10
   [,1] 0.1443805247
   [2,] 0.0022301018
   [3,] 0.0001014794
   [4,] 0.0061524281
salloc: Relinquishing job allocation 10
```

Example summary

We have seen
- how `littler` can help us script R tasks
- how `Rmpi`, `snow` and `slurm` can interact nicely
- a complete example using `RDieHarder` to illustrate these concepts
Both `r` (from the `littler` package) and `Rscript` (included with R) allow us to write simple scripts for repeated tasks.

```r
#!/usr/bin/env r
# a simple example to install one or more packages
if (is.null(argv) | length(argv)<1) {
    cat("Usage: installr.r pkg1 [pkg2 pkg3 ...]\n")
    q()
}
## adjust as necessary, see help('download.packages')
repos <- "http://cran.us.r-project.org"
lib.loc <- "/usr/local/lib/R/site-library"
install.packages(argv, lib.loc, 
    repos, dependencies=TRUE)
```

If saved as `install.r`, we can call it via

```
$ install.r ff bigmemory
```

The `getopt` package makes it a lot easier for `r` to support command-line options.

---

`Rscript` can be used in a similar fashion.

Previously we had to use

```
$ R --slave < cmdfile.R
$ cat cmdfile.R | R --slave
$ R CMD BATCH cmdfile.R
```

or some shell-script variations around this theme.

By providing `r` and `Rscript`, we can now write 'R scripts' that are executable. This allows for automation in cron jobs, Makefile, job queues, ...
**RPy** packages provides access to R from Python:

```r
from rpy import *
set_default_mode(NO_CONVERSION)  # avoid automatic conversion
r.library("nnet")
model = r("Fxy~x+y")
df = r.data_frame(x = r.c(0,2,5,10,15),
                   y = r.c(0,2,5,8,10),
                   Fxy = r.c(0,2,5,8,10))
NNModel = r.nnet(model, data = df,
                 , size =10, decay =1e-3
                 , lineout=True, skip=True
                 , maxit=1000, Hess=True)
XG = r.expand_grid(x = r.seq(0,7,1), y = r.seq(0,7,1))
x = r.seq(0,7,1)
y = r.seq(0,7,1)
set_default_mode(BASIC_CONVERSION) # automatic conv. back on
fit = r.predict(NNModel,XG)
print(fit)
```

**Wrapping up**

In this tutorial session, we covered

- **profiling** and tools for **visualising profiling** output
- gaining speed using **vectorisation**
- gaining speed using **Ra** and **just-in-time** compilation
- how to link **R** to compiled code using tools like **inline** and **Rcpp**
- how to embed **R** in C++ programs
- running **R** code in **parallel** using MPI, nws, snow, ...
- scripting and automation using littler
Further questions?

Two good resources are:
- the mailing list r-sig-hpc on HPC with R,
- and the HighPerformanceComputing task view on CRAN.

Scripts are at http://dirk.eddelbuettel.com/code/hpcR/.
Lastly, don’t hesitate to email me at edd@debian.org