Code Analysis and Parallelizing Vector Operations in R

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Introduction

- R is a language for interactive data analysis and graphics.
- Some features intended to make interactive use easier:
  - Named arguments.
  - Partial matching of argument names.
  - Lazy evaluation of arguments and use of argument expressions.
- R is also
  - a powerful high level language
  - well suited to expressing complex statistical computations
- Two concerns:
  - correctness of code
  - performance

Improving Correctness of R Code

- The R package system provides an infrastructure for testing:
  - examples are run
  - code in a `tests` directory is run

  by R CMD check.
- Unit testing frameworks have been developed, e.g. `RUnit`.
- Testing is essential, but there are issues:
  - Most tests need to be created manually.
  - Complete coverage is hard to achieve.
- Static code analysis is a useful supplement.

Static Code Analysis

- Static code analysis examines source code without executing it.
- Analysis can look at
  - individual expressions
  - larger patterns of expressions
  - relationships among functions and modules
- For C, for example,
  - compilers carry out basic code analysis and report errors
  - more sophisticated tools have been developed recently
  - these have been used successfully on the Linux kernel
- Most code analysis involves approximations
  - not all issues can be detected (undecidable)
  - there are false positives
  - being able to tune specificity/sensitivity is helpful
  - methods of ranking possible issues are useful
  - statistical error ranking methods have been studied (Engler et al.)

Code Analysis for R

The R language presents some unusual challenges:

- Whether a variable is global or local may depend on data.
- Functions can create new variables in their callers.
  - used in glm.fit with family$initialize
- Functions can remove variables from their callers.
- Some functions use nonstandard evaluation of some arguments.
  - library, curve, link functions
- Evaluation context may not be statically available
  - with function

The codetools Package

Outline

- codetools analyzes expressions in the context of visible definitions.
- Some of the things it can detect:
  - Calls not consistent with visible function definitions.
  - Bad assignment expressions.
  - Improper use of ..., next, or break.
  - Undefined functions or variables used.
  - Calls with no visible function definition.
  - Local variables assigned but not used.
  - Parameters changed by assignment.
  - Multiple incompatible definitions of a local function.

The codetools Package

Usage

- The two main functions are
  - checkUsage for checking individual R functions.
  - checkUsagePackage for checking a (loaded) package.
- A range of arguments are provided select classes of warnings:
  - all: enable all warnings.
  - suppressLocal: suppress all local variable warnings.
  - suppressParamUnused: suppress warnings about unused parameters.
  - suppressLocalUnused: suppress warnings about unused local variables
  - suppressUndefined: suppress warnings about undefined variables.
  - ...
- A better approach to managing which warnings to show is needed.

The codetools Package

Some Examples

A function definition with some possible errors:

```
g<-function(x, exp = TRUE) {
    nexp <- ! exp
    if (exp)
        exp(x+3) + ext(z-3)
    else
        log(x, bace=2)
}
```

The code analysis:

```
> checkUsage(g, name = "g")

g: no visible global function definition for ‘ext’
g: no visible binding for global variable ‘z’
g: possible error in log(x, bace = 2): unused argument(s) (bace = 2)
g: local variable ‘nexp’ assigned but may not be used
```

The codetools Package

Some Examples

Running checkUsagePackage on base in R 2.4.1 produces

```
> checkUsagePackage("base")

...
substring: local variable ‘x’ assigned but may not be used
...
```

The definition of substring is

```
substring <- function (text, first, last = 1e+06)
{
    if (!is.character(text))
        x <- as.character(text)
    n <- max(lt <- length(text), length(first), length(last))
    if (lt && lt < n)
        text <- rep(text, length.out = n)
    substr(text, first, last)
}
```

An obscure bug, but a bug nonetheless.

The codetools Package
Current Applications and Availability

- codetools was first used extensively for screening CRAN submissions.
- As of R 2.6.0 codetools is a recommended package bundled with R.
- By default, codetools is used as part of R CMD check.
- codetools is also used by the weaver package.

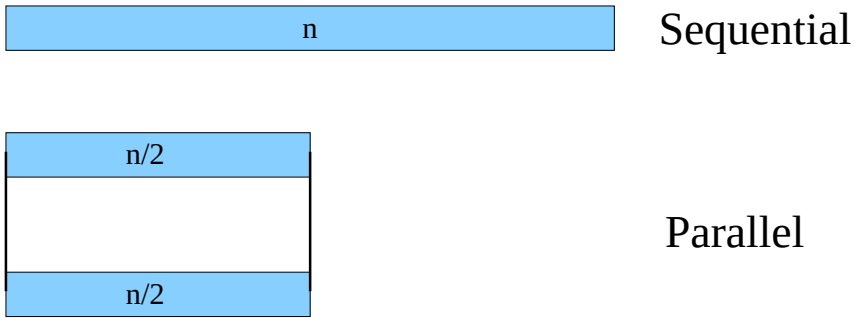
- Develop a framework for adding rules, checks.
- Look at larger units than expressions.
- Explore allowing declarations to clarify ambiguities, intent.
- Identify common idioms that
  - are often errors
  - represent common inefficiencies
- Interactive features, such as
  - call graph display
  - editor integration support
- ...

Parallelizing Vector Operations

- Multi-core processors are becoming increasingly common:
  - Many laptops have dual core processors.
  - Quad core workstations are available and affordable.
- In principle this allows speedups by a factor of 2 or 4.
- This is attractive if "free," but
  - maybe not enough to justify extra user programming
  - useful if it can be activated automatically
- Already possible in linear algebra by using a threaded BLAS.
- Possible candidates for automatic parallelization:
  - Vectorized arithmetic operations.
  - Some uses of apply family and sweep.

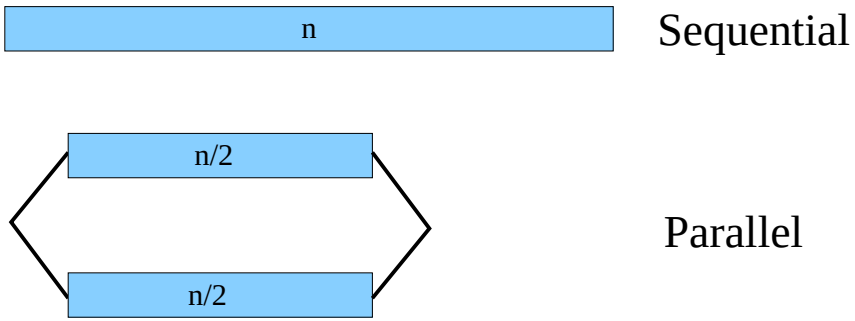
Parallelizing Vector Operations
An Idealized View

- Basic idea for computing f(x[1:n]) on a two-processor system:
  - Run two worker threads.
  - Place half the computation on each thread.
- Ideally this would produce a two-fold speed up.



Parallelizing Vector Operations
A More Realistic View

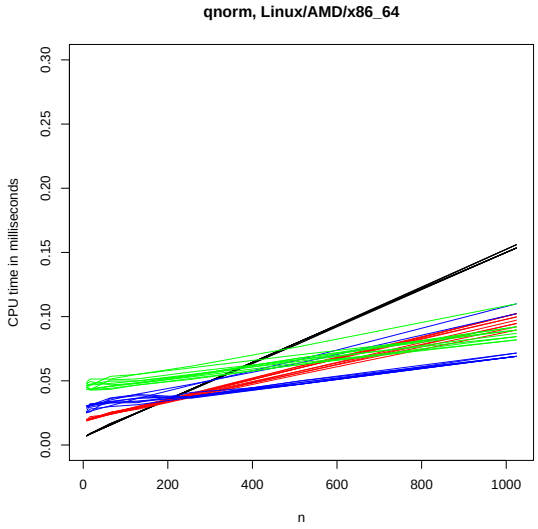
- Reality is a bit different:

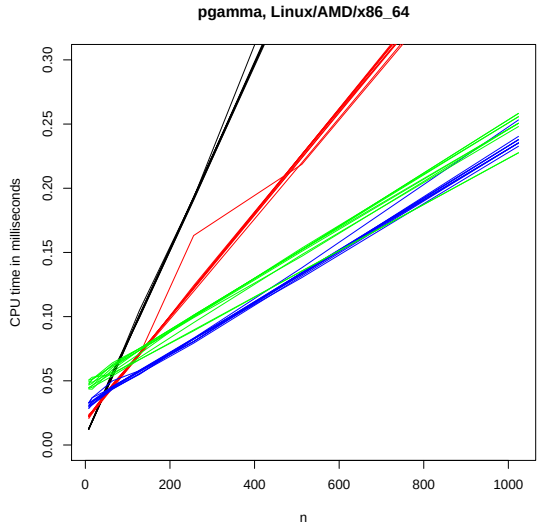


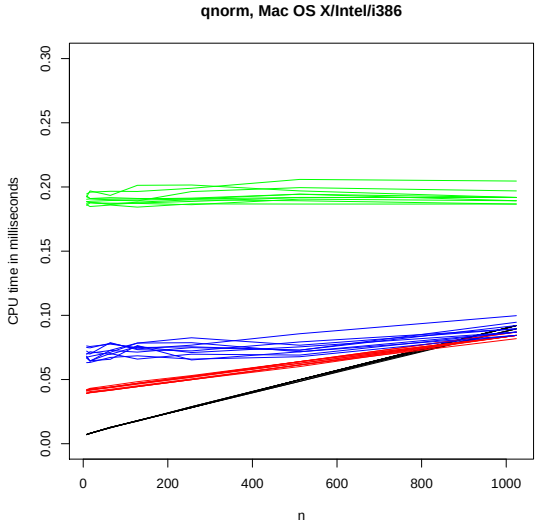
- There is synchronization overhead.
- Use of shared resources is sequential (memory, bus, . . .)
- Parallelizing will only pay off if n is large enough.
  - For some functions, e.g. qbeta, $n \approx 10$ may be large enough.
  - For some, e.g. qnorm, $n \approx 1000$ is needed.
  - For basic arithmetic operations $n \approx 30000$ may be needed.
- Careful tuning to insure improvement will be needed.
- Some aspects will depend on architecture and OS.

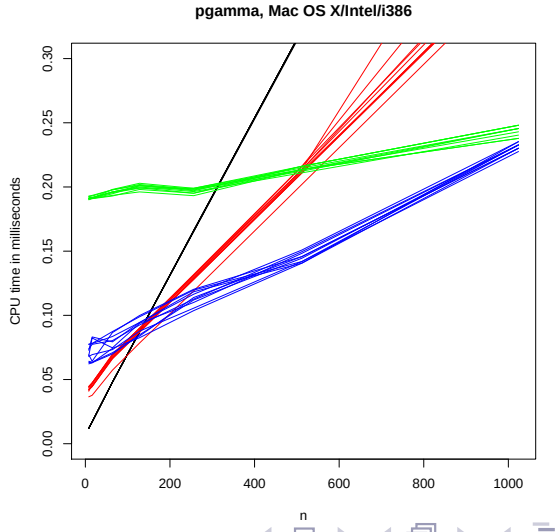
Parallelizing Vector Operations

Some Experimental Results









Parallelizing Vector Operations
Some Experimental Results

Some observations:

- Times are roughly linear in vector length.
- Intercepts on a given platform are roughly the same for all functions.
- If the slope for P processors is s_P, then at least for $P = 2$ and $P = 4$,

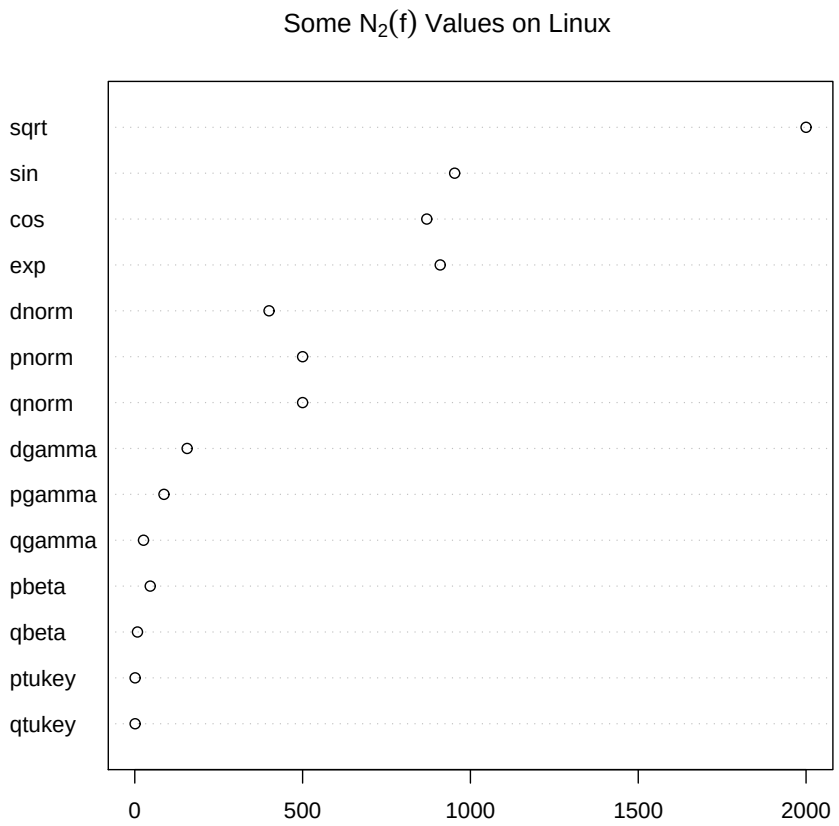
$$s_P \approx s_1/P$$

- Relative slopes of functions seem roughly independent of OS/architecture.

Parallelizing Vector Operations
A Calibration Strategy

- A simple strategy:
  - Compute relative slopes once, or average across several setups.
  - Base line is a single element dnorm computation.
  - For each OS/architecture combination compute the intercepts.
  - Estimate the values $N_2(f)$ such that using $P = 2$ is faster if $n > N_2(f)$.
  - Use $N_4(f) = 2N_2(f)$ and $N_8(f) = 4N_2(f)$.
- Some intercepts, in units of a single element dnorm computation:
  - about 200 for Linux/AMD/x86_64
  - about 500 for Mac OS X 10.4/Intel/i386
  - between 300 and 400 for Win32/Intel(?)

Parallelizing Vector Operations



Parallelizing Vector Operations
Implementation

- Need to use threads
- One possibility: using raw `pthreads`
- Better choice: use Open MP
- Open MP consists of
  - compiler directives (#pragma statements in C)
  - a runtime support library
- Most commercial compilers support Open MP.
- gcc 4.2 supports Open MP.
- Redhat has back-ported Open MP into gcc 2.4.1 on RH, Fedora.
- MinGW also supports Open MP; an additional `pthreads` download is needed.

Parallelizing Vector Operations
Implementation

- Basic loop for a one-argument function:

```
#pragma omp parallel for if (P > 0) num_threads(P) \
        default(shared) private(i) reduction(&&:naflag)
    for (i = 0; i < n; i++) {
        double ai = a[i];
        MATH1_LOOP_BODY(y[i], f(ai), ai, naflag);
    }
```

- Steps in converting to Open MP:
  - check f is thread-safe; modify if not
  - rewrite loop to work with the Open MP directive
  - test without Open MP, then enable Open MP

Parallelizing Vector Operations
Implementation

- Some things that are not thread-safe:
  - use of global variables
  - R memory allocation
  - signaling warnings and errors
  - user interrupt checking
  - creating internationalized messages (calls to gettext)
- Random number generation is also problematic.
- Functions in `nmath` that have not been parallelized yet:
  - Bessel functions
  - Wilcoxon, signed rank functions
  - random number generators

Parallelizing Vector Operations
Availability

- Package `pnmath` is available at

  `http://www.stat.uiowa.edu/~luke/R/experimental/`

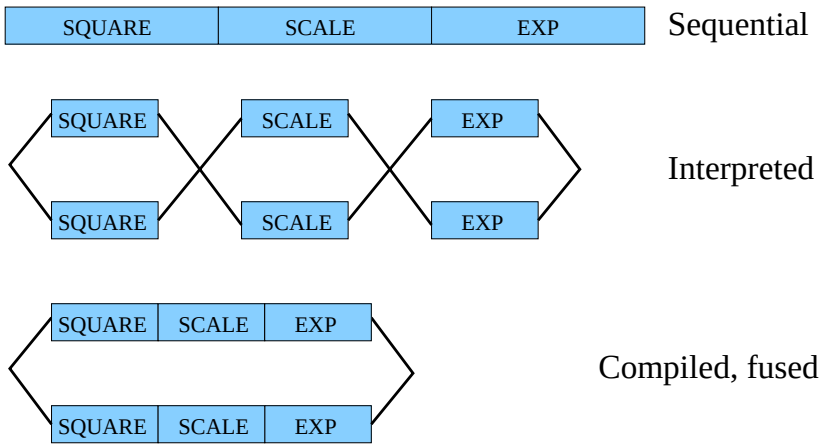
- This requires a version of `gcc` that
  - supports Open MP
  - allows dlopen to be used on libgomp.so
- A version using just `pthreads` is available in `pnmath0`.
- Loading these packages replaces builtin operations by parallelized ones.
- For Linux, Mac OS X predetermined intercept calibrations are used.
- For other platforms a calibration test is run at package load time.
- The calibration can be run manually by calling calibratePnmath
- Hopefully we will be able to include this in R 2.7 or 2.8.

The Connection: Compilation

- Developing a byte code compiler for R is an ongoing project.
- The current `codetools` implementation is a by-product.
- Compilation will also be useful for parallelizing vector operations:
  - Many vector operations occur in compound expressions, like

    ```
    exp(-0.5*x^2)
    ```

  - A compiler may be able to fuse these operations:



- Compilation may also allow many simple uses of apply functions and sweep to be parallelized.

Challenges

- Tuning issues:
  - Hardware/OS plays a role.
  - Competing system usage may be important.
  - Performance may vary with inputs.
  - Load balancing may be useful.
- Error handling and user interrupts.
- Parallelization interface for package use.
- Extensible byte code for package use.
- Generic functions and non-default methods.
- Declarations may be useful.

Summary

- Two concerns:
  - correctness
  - performance
- There is a strong synergy:
  - Code analysis tools help with automated performance improvement.
  - They may also be able to suggest opportunities for rewriting.
- Work on code analysis has progressed, but much more can be done.
- Parallelization work is just starting but seems promising.
- Hopefully there will be significant progress in the near future.