I/O-Efficient Statistical Computing with RIOT

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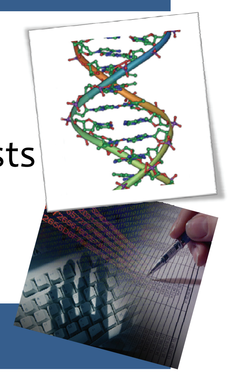
New Challenges In Massive Data Analysis

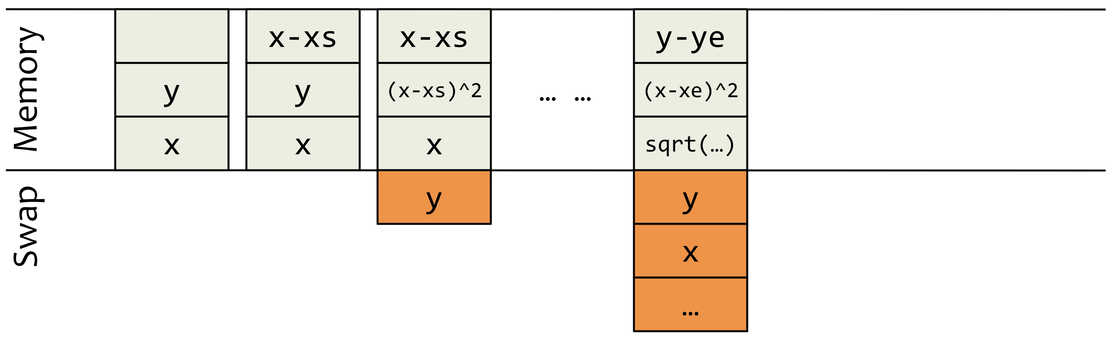
- Exploding data in sciences, business, society, …
- Increasingly sophisticated analysis
- Lack of easy-to-use, efficient tools for statisticians/analysts
  - Traditional platforms often assume datasets fit in memory
  - Large datasets cause excessive and inefficient I/O



Example in R

- R: a popular open-source language for statistical computing

```
# n points with coordinates stored in x[1:n], y[1:n]
d <- sqrt((x-xs)^2+(y-ys)^2)+sqrt((x-xe)^2+(y-ye)^2)
s <- sample(n, 100) # draw 100 samples from 1:n
z <- d[s] # extract elements of d whose indices are in s
```



Opportunities for Improvement

Avoid intermediate results	– Multiple large intermediate results take up memory + Can we avoid them, but without hand-coding loops?
Deferred & selective evaluation	– Each expression gets evaluated in full immediately + Can we defer evaluation until necessary?
Optimize data layouts & algorithms	– Main-memory model offers few layout/algorithm options + Can we have better layouts/algorithms for out-of-core data?
Algebraic rewrite	– Operations are carried out in order of appearance + Can we use linear algebra laws for more efficient execution?

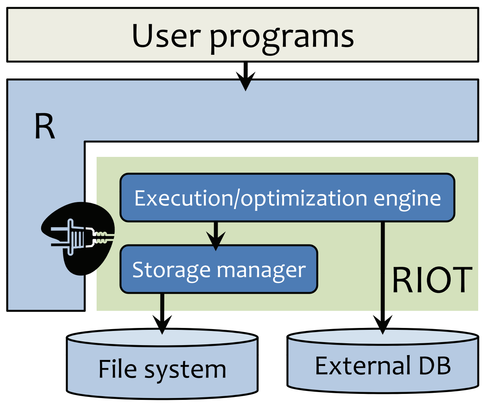
Déjà Vu for Database Researchers?

- Why don't they use/extend a database?
- Current database systems are awful at storing arrays, executing numerical code, and optimizing linear algebra expressions
- And good luck with impedance mismatch!
- Try writing this piece of R code in SQL:

```
w <- solve(t(A) %*% A) %*% t(A) %*% b
# Least square fit for y = w'x + e, with n covariates
# b is a column vector of m observations, with corresponding inputs in A (m-by-n)
```

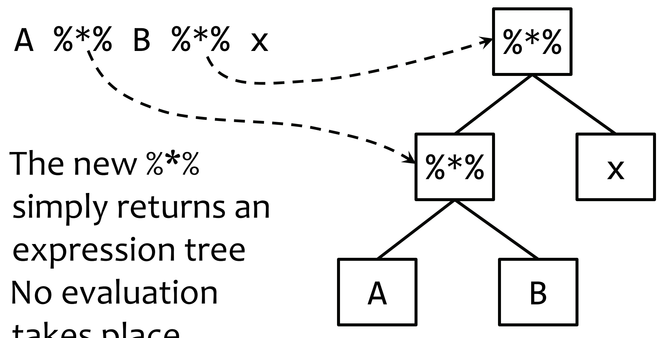
RIOT: R with I/O Transparency

- Allow user to stay with R—no new languages/APIs, no SQL
- Get I/O-efficiency without user intervention
- Support integration with database
- Blur boundary between R and backend processing

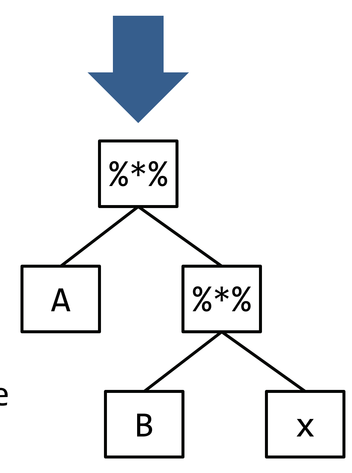


Achieving Transparency

- Leverage R's extension mechanism
- Define types and operators to "mask" standard ones
- New types do not require data to be memory-resident
- New operators defer computation when possible



- The new %*% simply returns an expression tree
- No evaluation takes place
- Build up larger and larger expressions, one operation at a time



Execution

- Trigger computation when result is needed (e.g., for printing)
- Avoid intermediate results with pipelined execution
- Support I/O-efficient algorithms specialized for linear algebra

Optimization

- Work at the level of linear algebra operations
- Make cost-based choices of data layouts and algorithms

- Optimize chains of %*%'s by dynamic programming
- For each %*%, prefer 3 square blocks (2 in + 1 out) dividing up available memory equally

Database Integration

- Allow users to analyze data in databases without "glue" code
- Let users focus what to do instead of how to do it

```
A <- matrix.db("SELECT i, j, value FROM ... WHERE ...", ...)
B <- matrix.db("SELECT...", ...)
A %*% B + C
```

  - If A is "–"-shaped and B is "|"-shaped, compute A %*%B inside database
  - If A is "|"-shaped and B is "–"-shaped, load A and B and compute %*% in RIOT

Native Storage

- Flexible disk layout with different linearization options
- Optimized B-tree with special compression and reorganization tricks for arrays
  - Good for varying array sparsity across both space and time