Provenance Tracking in CXXR

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Motivating Example
A simple exploration

R Session

> library(MASS)
    # For 'mammals' dataset
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First few rows of ‘mammals’:

> mammals

  body   brain
Arctic fox 3.385 44.50
Owl monkey 0.480 15.50
Mountain beaver 1.350 8.10
Cow 465.000 423.00
Grey wolf 36.330 119.50
...57 rows omitted...
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    # For ‘mammals’ dataset
> brain <- mammals[,2]
> body <- mammals[,1]
> plot(body,brain)
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First few rows of ‘mammals’:

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<table>
<thead>
<tr>
<th></th>
<th>body</th>
<th>brain</th>
</tr>
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<tbody>
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> r <- lm(lbrain ~ lbody)
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> abline(r)
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What is Provenance?

From the Oxford English Dictionary:

**provenance**, *n*

1. The proceeds from a business. *Obs. rare.*
2. The fact of coming from some particular source or quarter; origin, derivation.
3. The history of the ownership of a work of art or an antique, used as a guide to authenticity or quality; a documented record of this.
4. *Forestry*. The geographic source of tree seed; the place of origin of a tree. Also: seed from a specific location.

Provenance of data objects:
- What primary data items were drawn upon during creation
- What sequence of operations was performed
- How a data object has later been used
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The beginning of Provenance-Aware Computing

When, in 1988 *New-S* succeeded *S*, it became one of – if not – the first provenance-aware software application(s) with its novel *S AUDIT* facility.

It is described by Becker and Chambers in their paper *Auditing of Data Analyses*\(^1\).

An **audit file** was maintained by *New-S* which recorded each top-level command issued in this and previous sessions within the workspace, and identified those objects read from and written to. The audit file was then processed by *S AUDIT*.

---

Example S AUDIT File

```r
#~New session: Time: 542034997; Version: "S Tue Mar 3 10:14:20 EST 1987"
m<-matrix(read("brain.body"),byrow=T,ncol=2)
#~put "/usr/rab/.Data/m" 542035057 "structure"
brain<-m[,1]
#~get "/usr/rab/.Data/m" 542035057 "any"
#~put "/usr/rab/.Data/brain" 542035066 "real"
body<-m[,2]
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#~put "/usr/rab/.Data/body" 542035072 "real"
plot(body,brain)
#~get "/usr/rab/.Data/body" 542035072 "any"
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What is recorded in the S AUDIT file:

- Top-level commands
- Data objects read
- Data objects written
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- **2006** IPAW’06 International Provenance and Annotation Workshop
- **2006** First Provenance Challenge
- **2006** Second Provenance Challenge
- **2007** Open Provenance Model (OPM) Draft
- **2008** IPAW’08 and OPM Workshop
- **2009** Third Provenance Challenge

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Open Provenance Model

The OPM has been designed to meet the following requirements:

- To allow provenance information to be exchanged between systems;
- To allow developers to build and share tools that operate on such a model;
- To be technology-agnostic;
- Support a digital representation of provenance for any "thing", produced by computer systems or not;
- Define rules that identify valid inferences on provenance graphs.
Open Provenance Model

Example: Victoria Sponge Cake Provenance

Entities
- **Artifacts**: Cake, 100g butter, 2 eggs, 100g sugar, 100g flour
- **Processes**: Bake
- **Agents**: John

Causal Relationships
- wasGeneratedBy(cake)
- used(butter)
- used(egg)
- used(sugar)
- used(flour)
- wasControlledBy(cook)
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Founded in 2007, CXXR\(^2\) aims to progressively reengineer the R interpreter from C into C++, with the intention that:

- Full functionality of the standard R distribution is preserved;
- The behaviour of R code is unaffected (unless it probes into the interpreter internals);
- The primary interfaces between the interpreter and C and Fortran code are as far as possible unaffected.

CXXR is intended to make it easier to produce experimental versions of the R interpreter.

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Environments and Bindings

During the evaluation of:
\[ x \leftarrow 5 \]
- \( x \) is a symbol
- \( 5 \) is a vector value
- A binding associates a value with a symbol
- This binding is stored in the global environment
- CXXR provides hooks on bindings, allowing callbacks on
  - Read, i.e. when an object is looked-up in the global environment
  - Write, i.e. when a symbol-to-value binding is created
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- Auditing, and accountability
- Informative to the user
- Enabling reproducibility
- Understand how objects are used
  - For instance, identifying all objects which used a given function
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We want to identify, of a given object:
- Pedigree: The series of commands issued
- Parents: Objects which have been read during its creation
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What we need to go about this:

- A mechanism for trapping reads and writes in the user workspace (i.e. the global environment)
  - Recall that CXXR provides monitor hooks on access and mutation of bindings
- Containers for storing provenance information
- New R commands for inspecting provenance
  - provenance(x): Returns a list comprising: expression, symbol, timestamp, parents, children
  - pedigree(x): Displays the sequence of commands issued, which results in x's current state
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Associating Provenance with Bindings

- When an object is read from:
  - It is recorded in a Parentage
- When an object is written to:
  - A Provenance object is created, comprising:
    - The top level expression being evaluated
    - The current timestamp
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    - This object's parentage
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  - Functions assigned in the global environment are also handled in this way
  - Therefore objects resulting from function calls have the function as a parent
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    - This objects’ **parentage**
  - This **Provenance** object is then associated with the relevant binding
  - **Functions** assigned in the global environment are also handled in this way
  - Therefore objects resulting from function calls have the function as a parent
Associating Provenance with Bindings

- When an object is read from:
  - It is recorded in a Parentage

- When an object is written to:
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    - The current timestamp
    - The symbol being written to
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Where were we?
Recall our session...

> ls()
Where were we?
Recall our session...

```r
> ls()
[1] "body"  "brain"  "lbody"  "lbrain"  "r"
```
Where were we?

Recall our session...

R> ls()
[1] "body"  "brain"  "lbody"  "lbrain"  "r"

R> provenance(body)
Where were we?
Recall our session...

```r
> ls()
[1] "body"  "brain"  "lbody"  "lbrain"  "r"
> provenance(body)
$command
body <- mammals[, 1]

$symbol
body

$timestamp

$parents
NULL

$children
[1] "lbody"
```
Where were we?
Recall our session...

```r
> ls()
[1] "body"  "brain"  "lbody"  "lbrain"  "r"
> provenance(lbrain)
```
Where were we?
Recall our session...

> ls()
[1] "body"  "brain"  "lbody"  "lbrain"  "r"

> provenance(lbrain)
$command
lbrain <- log(brain)

$symbol
lbrain

$timestamp
[1] "07/03/2009 11:33:54 AM.221827"

$parents
[1] "brain"

$children
[1] "r"
Where were we?
Recall our session...

> ls()
[1] "body"   "brain"   "lbody"   "lbrain"   "r"
> provenance(r)
Where were we?
Recall our session...

> ls()
[1] "body" "brain" "lbody" "lbrain" "r"

> provenance(r)
$command
r <- lm(lbrain ~ lbody)

$symbol
r

$timestamp
[1] "07/03/2009 11:34:04 AM.117156"

$parents
[1] "lbrain" "lbody"

$children
NULL
Where were we?
Recall our session...

```r
> ls()
[1] "body"  "brain"  "lbody"  "lbrain"  "r"
> pedigree(r)
```
Where were we?
Recall our session...

```r
> ls()
[1] "body"   "brain"   "lbody"   "lbrain"   "r"
> pedigree(r)
brain <- mammals[, 2]
body <- mammals[, 1]
lbrain <- log(brain)
lbody <- log(body)
r <- lm(lbrain ~ lbody)
```
A Further Example

Function Provenance

```r
> sq <- function(x) { x*x }
```
A Further Example

Function Provenance

```r
> sq <- function(x) { x*x }
> three <- 3
```
A Further Example

Function Provenance

\[
\begin{align*}
& \text{sq} <- \text{function}(x) \{ x^2 \} \\
& \text{three} <- 3 \\
& \text{nine} <- \text{sq}(\text{three})
\end{align*}
\]
A Further Example

Function Provenance

```r
sq <- function(x) { x*x }
three <- 3
nine <- sq(three)
provenance(nine)$parents
```
A Further Example

Function Provenance

```r
> sq <- function(x) { x*x }
> three <- 3
> nine <- sq(three)
> provenance(nine)$parents
[1] "sq"    "three"
```
A Further Example

Function Provenance

```r
> sq <- function(x) { x*x }
> three <- 3
> nine <- sq(three)
> provenance(nine)$parents
[1] "sq"   "three"
> provenance(sq)$children
```

Chris A. Silles  (University of Kent)
A Further Example

Function Provenance

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> sq <- function(x) { x*x }
> three <- 3
> nine <- sq(three)
> provenance(nine)$parents
[1] "sq"  "three"
> provenance(sq)$children
[1] "nine"
```
Conclusion and Future Work

We have demonstrated that it is possible to introduce provenance tracking facilities to a statistical environment, and as a result we can identify an object’s pedigree, parents and children. We now need to look into the following:

- Reproducing objects from provenance information
- Effectively handle pseudo-random number generation
  - To enable reproducibility of results
- Tracking provenance in other R environments
  - Packages
  - Attached data frames
  - Functions
- Serializing provenance information
  - To enable cross-session provenance-tracking
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