University of Kent | Computing

Provenance Tracking in CXXR

Chris A. Silles
Andrew R. Runnalls

Computing Laboratory, University of Kent, UK

Outline

Motivating Example

A simple exploration

R Session

```
> library(MASS)
      # For 'mammals' dataset
```

Motivating Example

A simple exploration

R Session

```
> library(MASS)
      # For 'mammals' dataset
```

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...
```

Motivating Example

A simple exploration

R Session

```
> library(MASS)
     # For 'mammals' dataset
> brain <- mammals[,2]
```

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...
```

Motivating Example

A simple exploration

R Session

```
> library(MASS)
     # For 'mammals' dataset
> brain <- mammals[,2]
> body <- mammals[,1]
```

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...
```

Motivating Example

A simple exploration

R Session

```
> library(MASS)
     # For 'mammals' dataset
> brain <- mammals[,2]
> body <- mammals[,1]
> plot(body,brain)
```

First few rows of 'mammals':

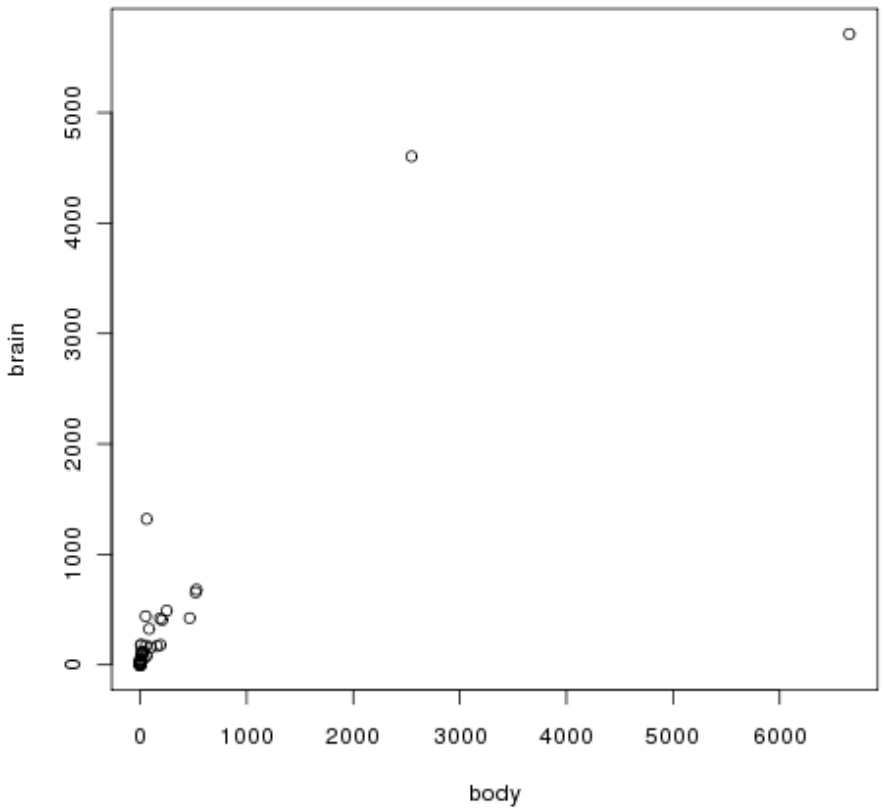
```
> mammals
                    body      brain
Arctic fox         3.385      44.50
Owl monkey         0.480      15.50
Mountain beaver    1.350       8.10
Cow              465.000     423.00
Grey wolf         36.330     119.50
...57 rows omitted...
```

Motivating Example

A simple exploration

R Session

```
> library(MASS)
      # For 'mammals' dataset
> brain <- mammals[,2]
> body <- mammals[,1]
> plot(body,brain)
```

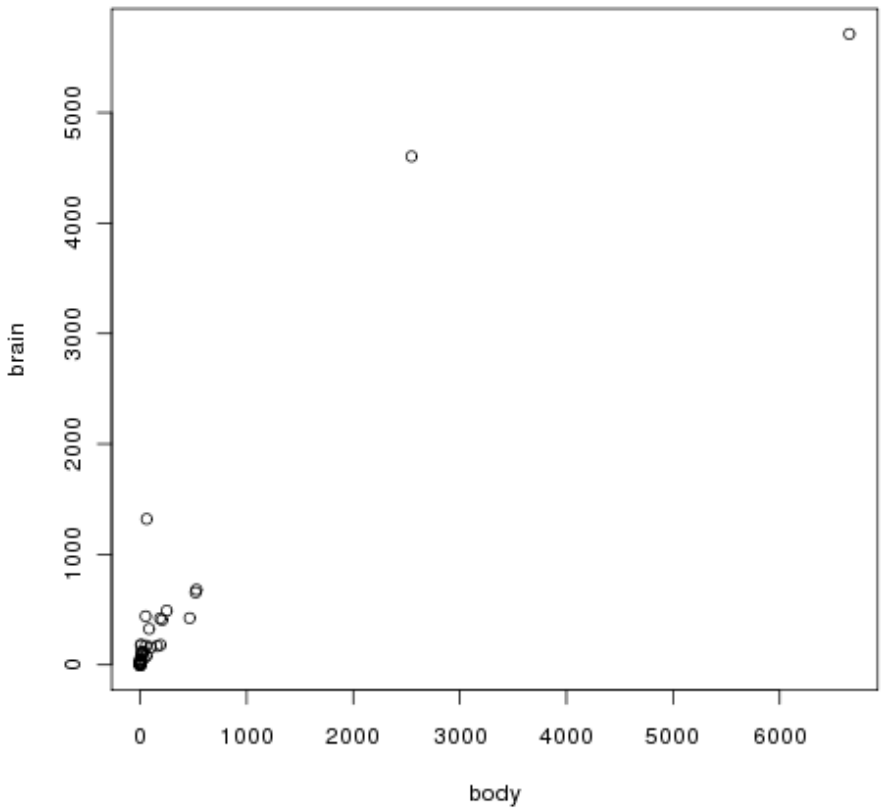


Motivating Example

A simple exploration

R Session

```
> library(MASS)
     # For 'mammals' dataset
> brain <- mammals[,2]
> body <- mammals[,1]
> plot(body,brain)
> lbrain <- log(brain)
```

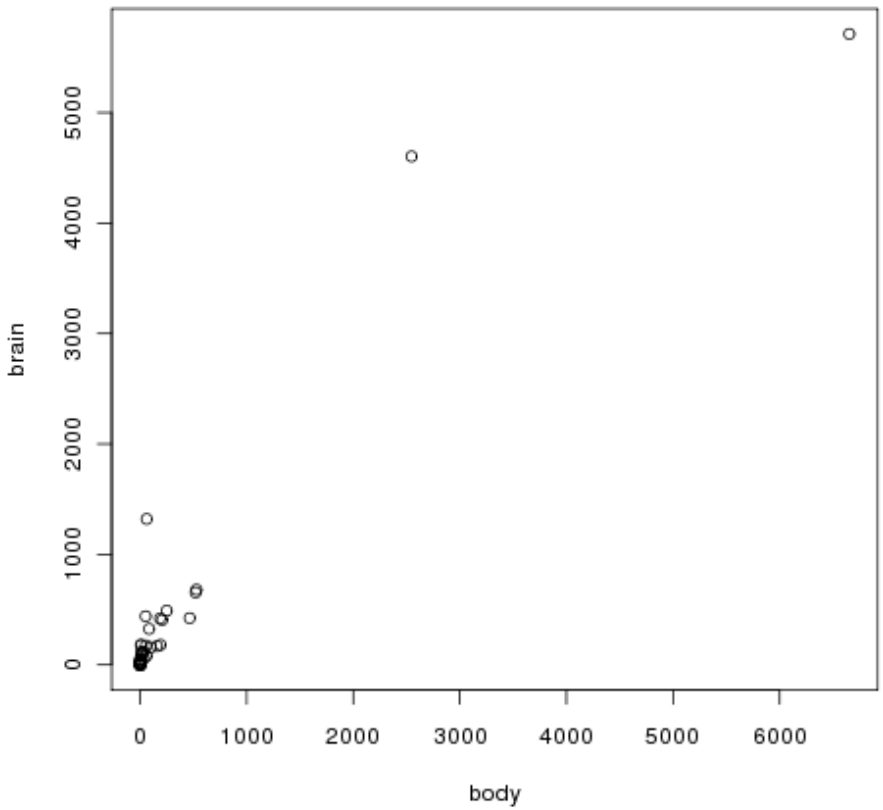


Motivating Example

A simple exploration

R Session

```
> library(MASS)
     # For 'mammals' dataset
> brain <- mammals[,2]
> body <- mammals[,1]
> plot(body,brain)
> lbrain <- log(brain)
> lbody <- log(body)
```

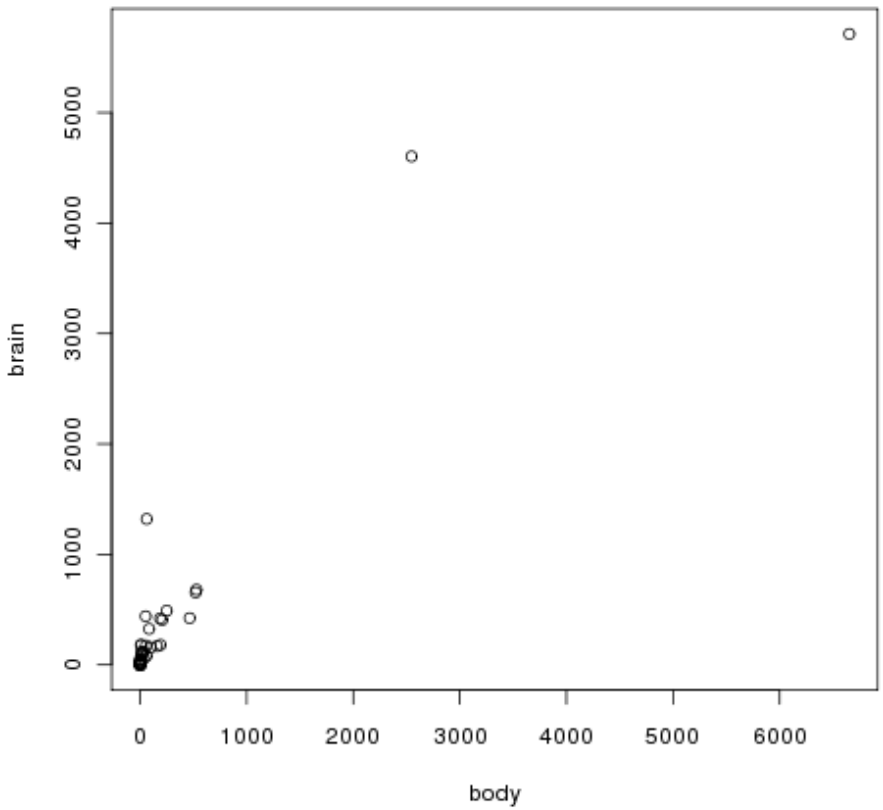


Motivating Example

A simple exploration

R Session

```
> library(MASS)
     # For 'mammals' dataset
> brain <- mammals[,2]
> body <- mammals[,1]
> plot(body,brain)
> lbrain <- log(brain)
> lbody <- log(body)
> plot(lbody,lbrain)
```

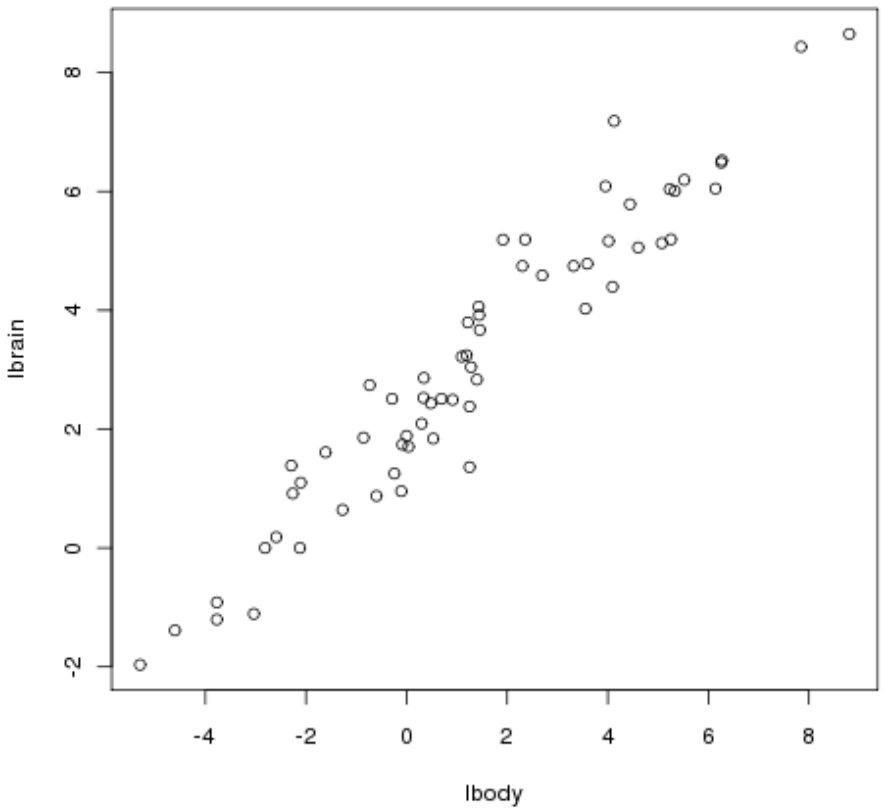


Motivating Example

A simple exploration

R Session

```
> library(MASS)
     # For 'mammals' dataset
> brain <- mammals[,2]
> body <- mammals[,1]
> plot(body,brain)
> lbrain <- log(brain)
> lbody <- log(body)
> plot(lbody,lbrain)
```

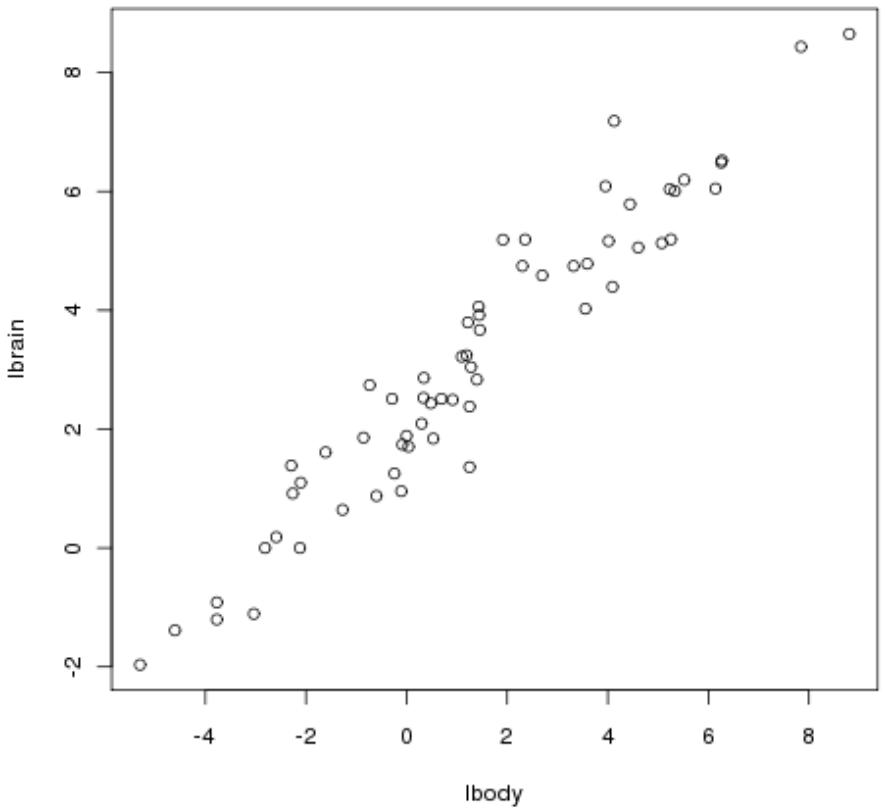


Motivating Example

A simple exploration

R Session

```
> library(MASS)
      # For 'mammals' dataset
> brain <- mammals[,2]
> body <- mammals[,1]
> plot(body,brain)
> lbrain <- log(brain)
> lbody <- log(body)
> plot(lbody,lbrain)
> r <- lm(lbrain ~ lbody)
```

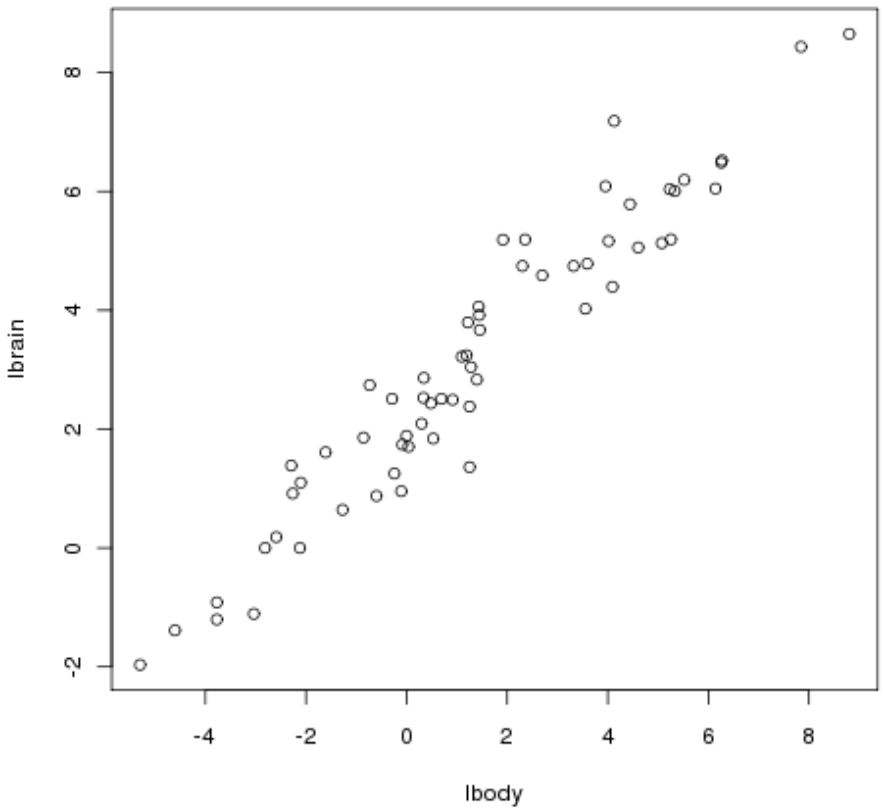


Motivating Example

A simple exploration

R Session

```
> library(MASS)
     # For 'mammals' dataset
> brain <- mammals[,2]
> body <- mammals[,1]
> plot(body,brain)
> lbrain <- log(brain)
> lbody <- log(body)
> plot(lbody,lbrain)
> r <- lm(lbrain ~ lbody)
> abline(r)
```

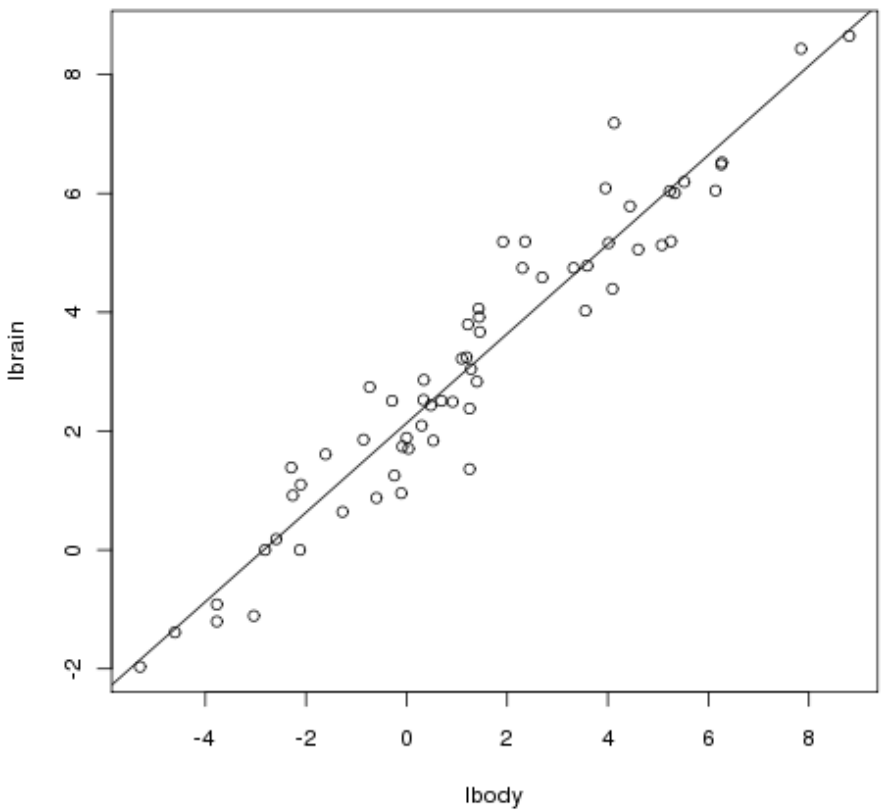


Motivating Example

A simple exploration

R Session

```
> library(MASS)
     # For 'mammals' dataset
> brain <- mammals[,2]
> body <- mammals[,1]
> plot(body,brain)
> lbrain <- log(brain)
> lbody <- log(body)
> plot(lbody,lbrain)
> r <- lm(lbrain ~ lbody)
> abline(r)
```



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

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

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

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*.

[1] SIAM J. Sci. Stat. Comput. 9 [1988] pp. 747–60

S AUDIT

Example S AUDIT File

```
#~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]
#~get "/usr/rab/.Data/m" 542035057 "any"
#~put "/usr/rab/.Data/body" 542035072 "real"
plot(body,brain)
#~get "/usr/rab/.Data/body" 542035072 "any"
#~get "/usr/rab/.Data/brain" 542035066 "any"
```

What is recorded in the S AUDIT file:

- Top-level commands
- Data objects read
- Data objects written

S AUDIT

Example S AUDIT File

```
#~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]
#~get "/usr/rab/.Data/m" 542035057 "any"
#~put "/usr/rab/.Data/body" 542035072 "real"
plot(body,brain)
#~get "/usr/rab/.Data/body" 542035072 "any"
#~get "/usr/rab/.Data/brain" 542035066 "any"
```

What is recorded in the S AUDIT file:

- Top-level commands
- Data objects read
- Data objects written

S AUDIT

Example S AUDIT File

```
#~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]
#~get "/usr/rab/.Data/m" 542035057 "any"
#~put "/usr/rab/.Data/body" 542035072 "real"
plot(body,brain)
#~get "/usr/rab/.Data/body" 542035072 "any"
#~get "/usr/rab/.Data/brain" 542035066 "any"
```

What is recorded in the S AUDIT file:

- Top-level commands
- Data objects read
- Data objects written

S AUDIT

Example S AUDIT File

```
#~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]
#~get "/usr/rab/.Data/m" 542035057 "any"
#~put "/usr/rab/.Data/body" 542035072 "real"
plot(body,brain)
#~get "/usr/rab/.Data/body" 542035072 "any"
#~get "/usr/rab/.Data/brain" 542035066 "any"
```

What is recorded in the S AUDIT file:

- Top-level commands
- Data objects read
- Data objects written

Provenance-Aware Computing Today

Recent Timeline

- **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

The primary goal of the Third Provenance Challenge was to evaluate the Open Provenance Model.

Provenance-Aware Computing Today

Recent Timeline

- **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

The primary goal of the Third Provenance Challenge was to evaluate the Open Provenance Model.

Provenance-Aware Computing Today

Recent Timeline

- **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

The primary goal of the Third Provenance Challenge was to evaluate the Open Provenance Model.

Provenance-Aware Computing Today

Recent Timeline

- **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

The primary goal of the Third Provenance Challenge was to evaluate the Open Provenance Model.

Provenance-Aware Computing Today

Recent Timeline

- **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

The primary goal of the Third Provenance Challenge was to evaluate the Open Provenance Model.

Provenance-Aware Computing Today

Recent Timeline

- **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

The primary goal of the Third Provenance Challenge was to evaluate the Open Provenance Model.

Provenance-Aware Computing Today

Recent Timeline

- **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

The primary goal of the Third Provenance Challenge was to evaluate the Open Provenance Model.

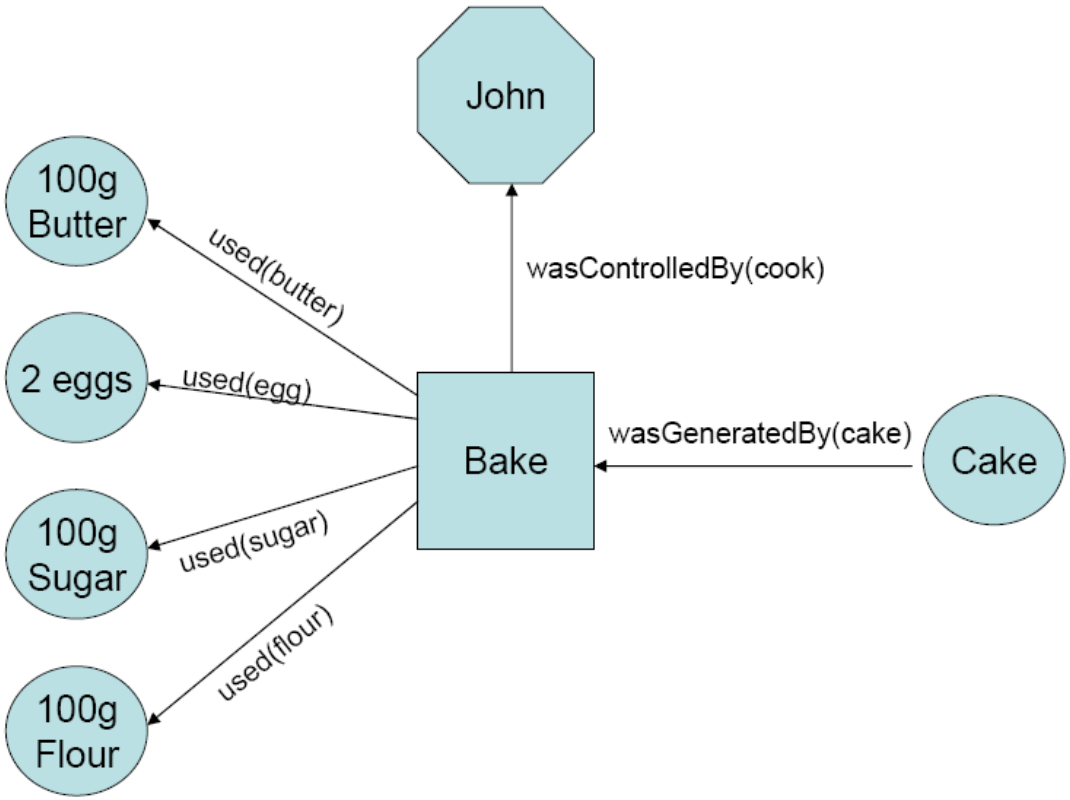
Open Provenance Model

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

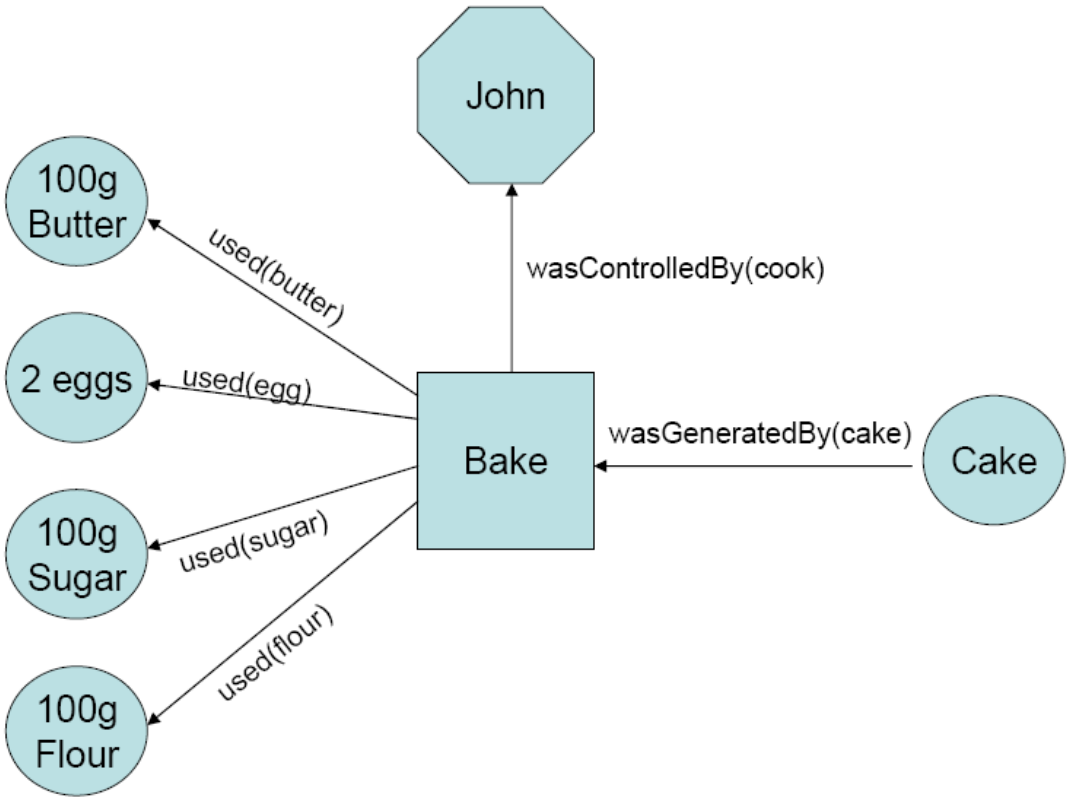
- Artifacts: Cake, 100g butter, 2 eggs, 100g sugar, 100g flour
- Processes: Bake
- Agents: John

Causal Relationships

- wasGeneratedBy
- wasControlledBy
- used

Open Provenance Model

Example: Victoria Sponge Cake Provenance



Entities

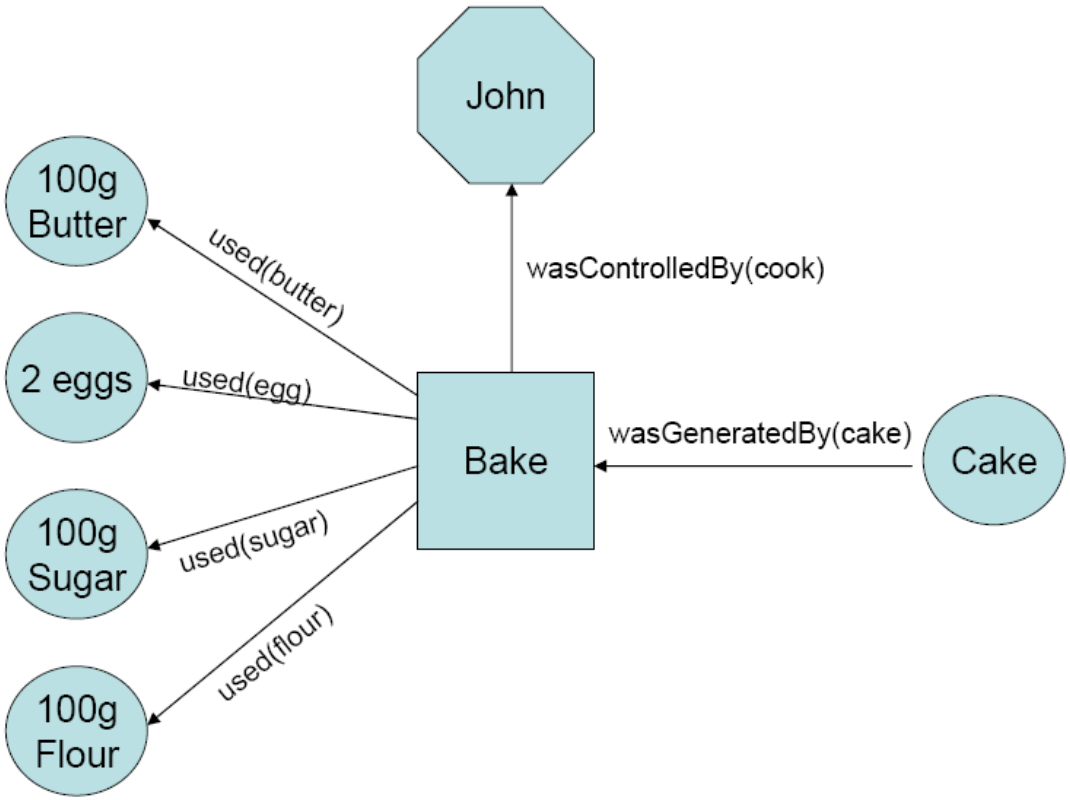
- Artifacts: Cake, 100g butter, 2 eggs, 100g sugar, 100g flour
- Processes: Bake
- Agents: John

Causal Relationships

- wasGeneratedBy
- wasControlledBy
- used

Open Provenance Model

Example: Victoria Sponge Cake Provenance



Entities

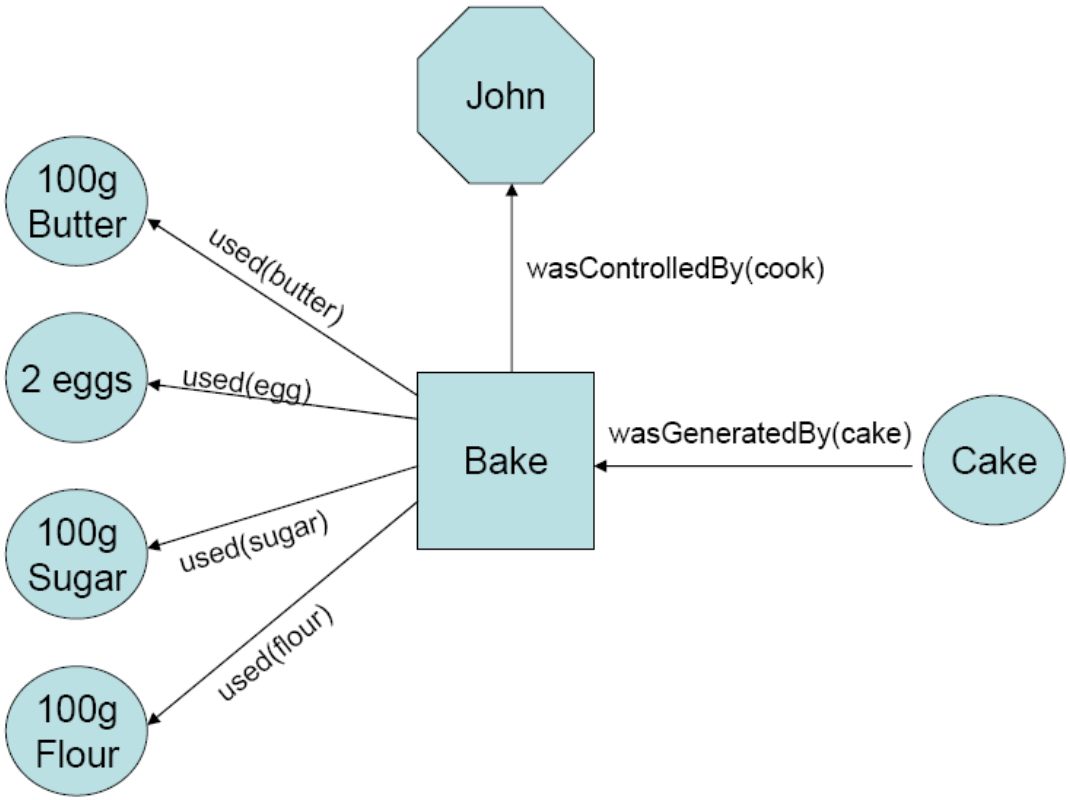
- Artifacts: Cake, 100g butter, 2 eggs, 100g sugar, 100g flour
- Processes: Bake
- Agents: John

Causal Relationships

- wasGeneratedBy
- wasControlledBy
- used

Open Provenance Model

Example: Victoria Sponge Cake Provenance



Entities

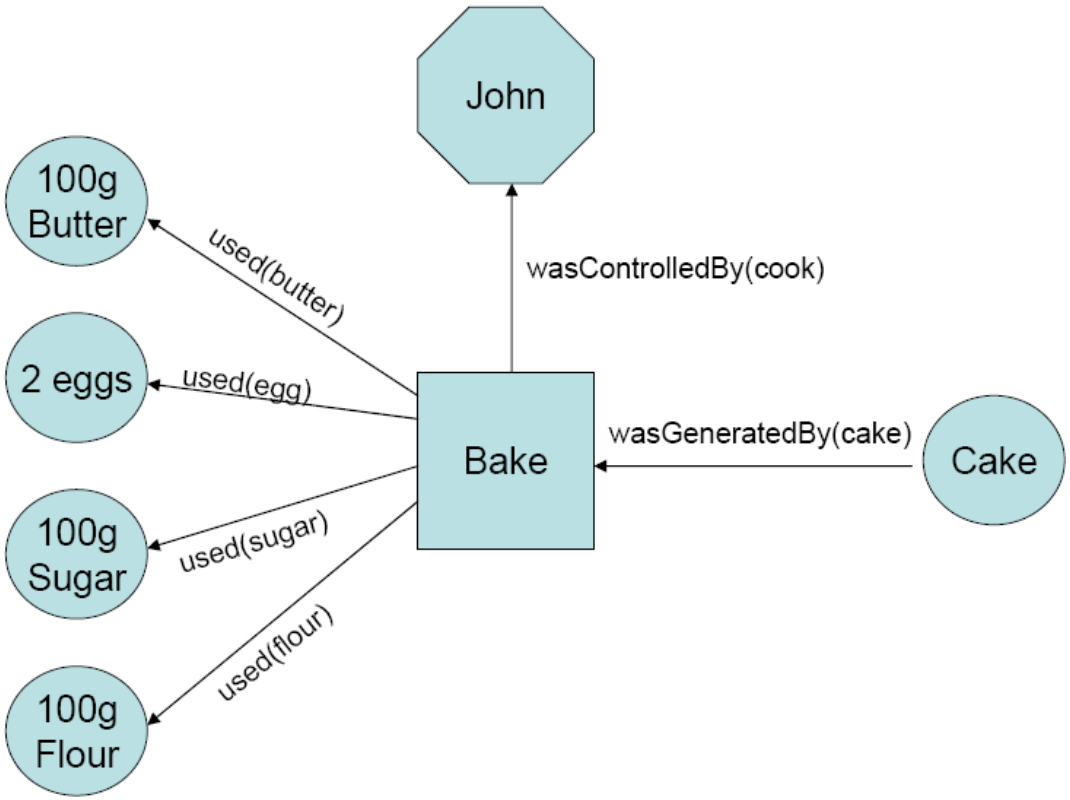
- Artifacts: Cake, 100g butter, 2 eggs, 100g sugar, 100g flour
- Processes: Bake
- Agents: John

Causal Relationships

- wasGeneratedBy
- wasControlledBy
- used

Open Provenance Model

Example: Victoria Sponge Cake Provenance



Entities

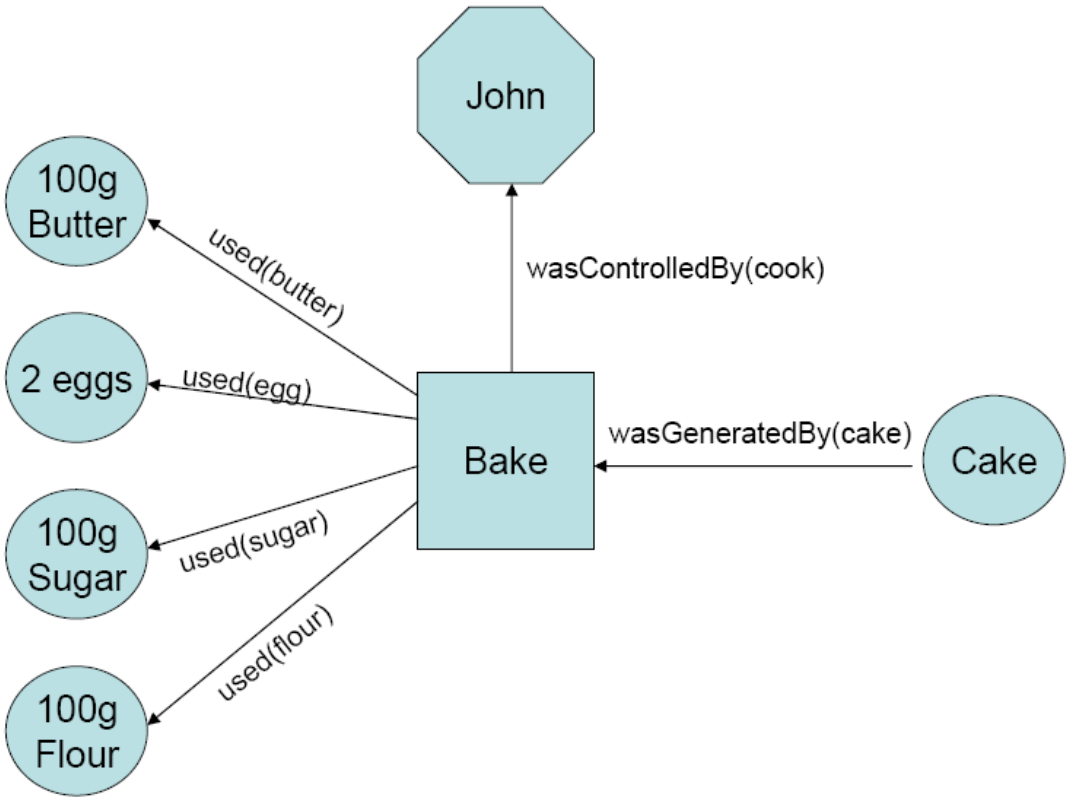
- Artifacts: Cake, 100g butter, 2 eggs, 100g sugar, 100g flour
- Processes: Bake
- Agents: John

Causal Relationships

- wasGeneratedBy
- wasControlledBy
- used

Open Provenance Model

Example: Victoria Sponge Cake Provenance



Entities

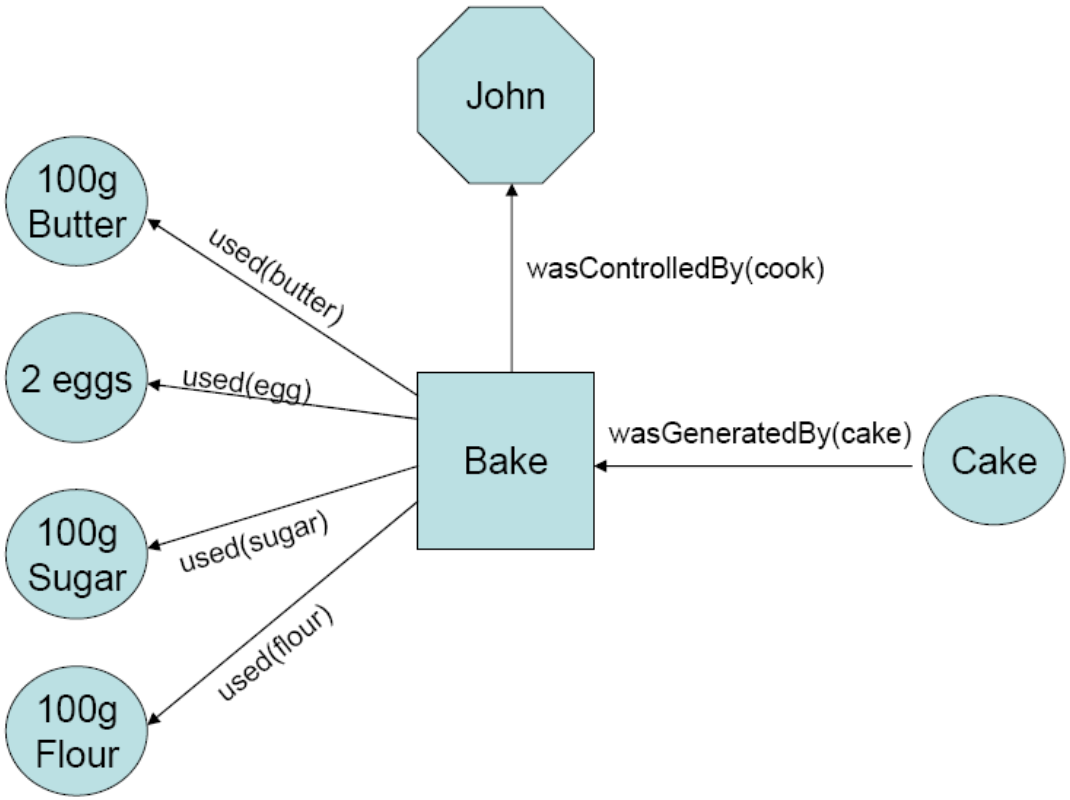
- Artifacts: Cake, 100g butter, 2 eggs, 100g sugar, 100g flour
- Processes: Bake
- Agents: John

Causal Relationships

- wasGeneratedBy
- wasControlledBy
- used

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
- wasControlledBy
- used

The CXXR Project

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.

[2] www.cs.kent.ac.uk/projects/cxxr

The CXXR Project

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.

[2] www.cs.kent.ac.uk/projects/cxxr

The CXXR Project

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.

[2] www.cs.kent.ac.uk/projects/cxxr

The CXXR Project

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.

[2] www.cs.kent.ac.uk/projects/cxxr

The CXXR Project

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.

[2] www.cs.kent.ac.uk/projects/cxxr

Environments and Bindings

During the evaluation of:

```
x <- 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

Environments and Bindings

During the evaluation of:

```
x <- 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

Environments and Bindings

During the evaluation of:

```
x <- 5
```

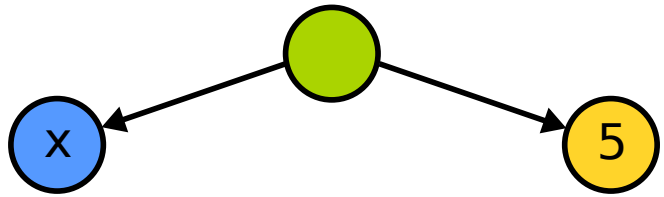
- *x* is a symbol
- *5* is a vector value
- A binding associates a value with a symbol
- This binding is stored in the global environment
- CXXR provides hooks on bindings, allowing callbacks on
  - Read, i.e. when an object is looked-up in the global environment
  - Write, i.e. when a symbol-to-value binding is created

Environments and Bindings

During the evaluation of:

```
x <- 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

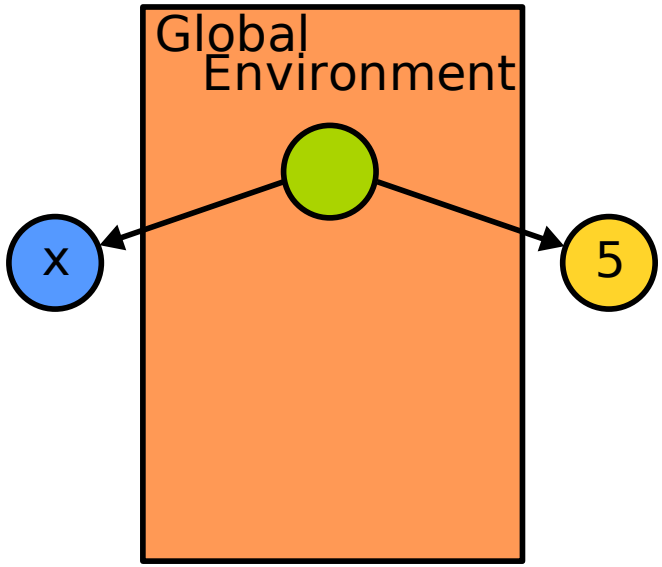


Environments and Bindings

During the evaluation of:

```
x <- 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

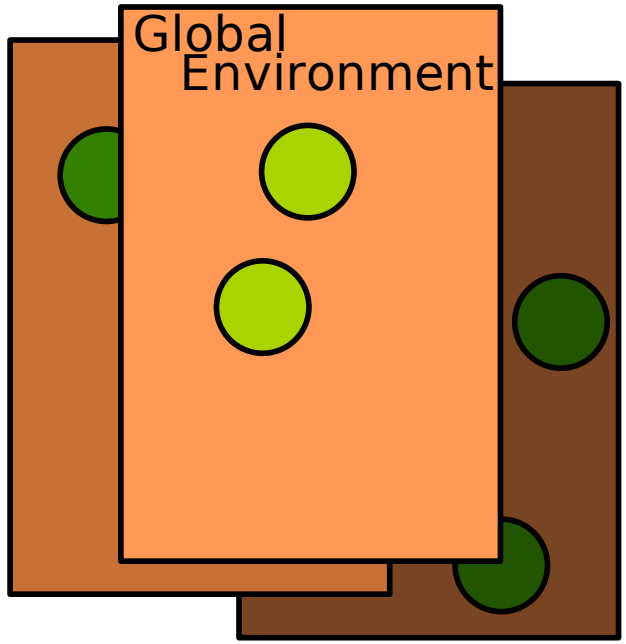


Environments and Bindings

During the evaluation of:

```
x <- 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

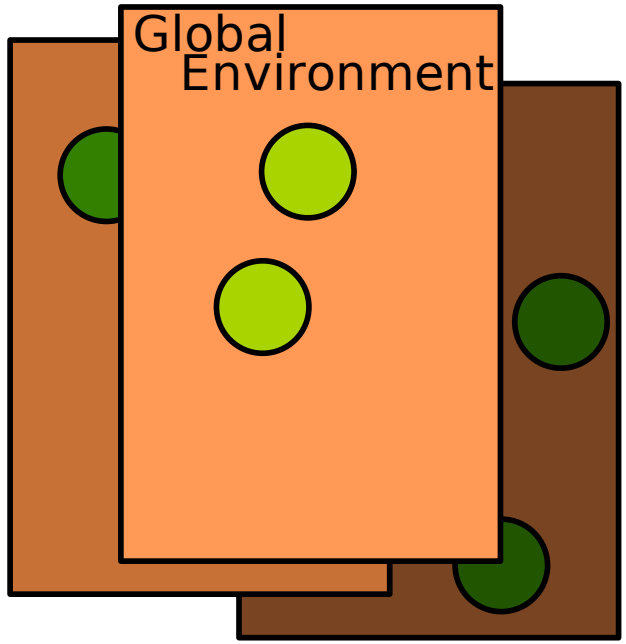


Environments and Bindings

During the evaluation of:

```
x <- 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



Objectives

Why record provenance?

- Auditing, and accountability
- Informative to the user
- Enabling reproducibility
- Understand how objects are used
  - For instance, identifying all objects which used a given function

Objectives

Why record provenance?

- Auditing, and accountability
- Informative to the user
- Enabling reproducibility
- Understand how objects are used
  - For instance, identifying all objects which used a given function

Objectives

Why record provenance?

- Auditing, and accountability
- Informative to the user
- Enabling reproducibility
- Understand how objects are used
  - For instance, identifying all objects which used a given function

Objectives

Why record provenance?

- Auditing, and accountability
- Informative to the user
- Enabling reproducibility
- Understand how objects are used
  - For instance, identifying all objects which used a given function

Objectives

Why record provenance?

- Auditing, and accountability
- Informative to the user
- Enabling reproducibility
- Understand how objects are used
  - For instance, identifying all objects which used a given function

Objectives

Why record provenance?

- Auditing, and accountability
- Informative to the user
- Enabling reproducibility
- Understand how objects are used
  - For instance, identifying all objects which used a given function

Objectives

Why record provenance?

- Auditing, and accountability
- Informative to the user
- Enabling reproducibility
- Understand how objects are used
  - For instance, identifying all objects which used a given function

What provenance to record?
We want to identify, of a given object:

- Pedigree: The series of commands issued
- Parents: Objects which have been read during its creation
- Children: Objects which have read it during their creation

Objectives

Why record provenance?

- Auditing, and accountability
- Informative to the user
- Enabling reproducibility
- Understand how objects are used
  - For instance, identifying all objects which used a given function

What provenance to record?
We want to identify, of a given object:

- Pedigree: The series of commands issued
- Parents: Objects which have been read during its creation
- Children: Objects which have read it during their creation

Objectives

Why record provenance?

- Auditing, and accountability
- Informative to the user
- Enabling reproducibility
- Understand how objects are used
  - For instance, identifying all objects which used a given function

What provenance to record?
We want to identify, of a given object:

- Pedigree: The series of commands issued
- Parents: Objects which have been read during its creation
- Children: Objects which have read it during their creation

Objectives

Why record provenance?

- Auditing, and accountability
- Informative to the user
- Enabling reproducibility
- Understand how objects are used
  - For instance, identifying all objects which used a given function

What provenance to record?
We want to identify, of a given object:

- Pedigree: The series of commands issued
- Parents: Objects which have been read during its creation
- Children: Objects which have read it during their creation

Objectives

Why record provenance?

- Auditing, and accountability
- Informative to the user
- Enabling reproducibility
- Understand how objects are used
  - For instance, identifying all objects which used a given function

What provenance to record?
We want to identify, of a given object:

- Pedigree: The series of commands issued
- Parents: Objects which have been read during its creation
- Children: Objects which have read it during their creation

Strategy

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

Strategy

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

Strategy

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

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:
    - 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:
  - A Provenance object is created, comprising:
    - The [illegible] being evaluated
    - The current [illegible]
    - The [illegible] being written to
    - This object's [illegible]
  - 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:
  - A Provenance object is created, comprising:
    - The top level expression being evaluated
    - The current timestamp
    - The symbol being written to
    - 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:
  - A Provenance object is created, comprising:
    - The top level expression being evaluated
    - The current timestamp
    - The symbol being written to
    - 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:
  - A Provenance object is created, comprising:
    - The top level expression being evaluated
    - The current timestamp
    - The symbol being written to
    - 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:
  - A Provenance object is created, comprising:
    - The top level expression being evaluated
    - The current timestamp
    - The symbol being written to
    - 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:
  - A Provenance object is created, comprising:
    - The top level expression being evaluated
    - The current timestamp
    - The symbol being written to
    - 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:
  - A Provenance object is created, comprising:
    - The top level expression being evaluated
    - The current timestamp
    - The symbol being written to
    - 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:
  - A Provenance object is created, comprising:
    - The top level expression being evaluated
    - The current timestamp
    - The symbol being written to
    - 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:
  - A Provenance object is created, comprising:
    - The top level expression being evaluated
    - The current timestamp
    - The symbol being written to
    - 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:
  - A Provenance object is created, comprising:
    - The top level expression being evaluated
    - The current timestamp
    - The symbol being written to
    - 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

Where were we?

Recall our session...

```
> ls()
```

Where were we?

Recall our session...

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

Where were we?

Recall our session...

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

Where were we?

Recall our session...

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

$symbol
body

$timestamp
[1] "07/03/2009 11:33:49 AM.763807"

$parents
NULL

$children
[1] "lbody"
```

Where were we?

Recall our session...

```
> 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...

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

Where were we?

Recall our session...

```
> 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

```
> sq <- function(x) { x*x }
```

A Further Example

Function Provenance

```
> sq <- function(x) { x*x }
> three <- 3
```

A Further Example

Function Provenance

```
> sq <- function(x) { x*x }
> three <- 3
> nine <- sq(three)
```

A Further Example

Function Provenance

```
> sq <- function(x) { x*x }
> three <- 3
> nine <- sq(three)
> provenance(nine)$parents
```

A Further Example

Function Provenance

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

A Further Example

Function Provenance

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

A Further Example

Function Provenance

```
> 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

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

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

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

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