Rscript: a Relational Approach to Program and System Understanding

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Structure of Presentation

- Background and context
- About program understanding
- Roadmap: Rscript

Background

Application areas

Domain-specific languages

Software renovation

System understanding

System transformation

Technology

This talk

ASF+SDF Meta-Environment
Generalized LR parsing
(Compiled) term rewriting

ToolBus coordination architecture
Code Generators

Foundations

Formal languages
Term rewriting

Relational calculus

Process Algebra
Module algebra

Compilation is a mature area

- Some new developments
  - just-in-time compilation
  - energy-aware code generation
- Many research results are not yet used widely
  - interprocedural pointer analysis
  - slicing
- Why don't we just apply all these techniques to understanding and restructuring?

Compilation is a mature area

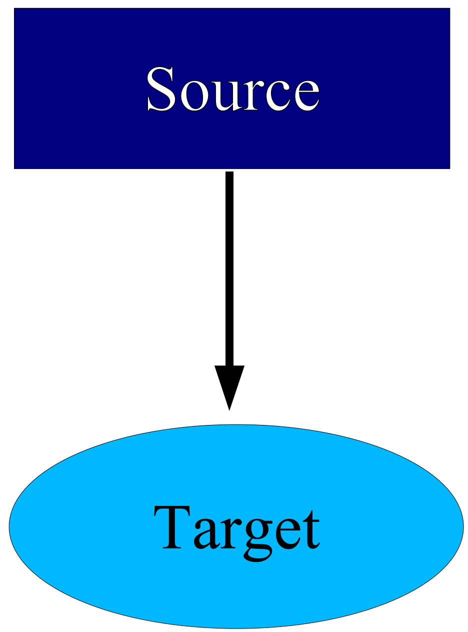
- ... of course, we do just that, but ...
- there is a mismatch between
  - standard compilation techniques and
  - the needs for understanding and restructuring

Compilation is ...

- A well-defined process with well-defined input, output and constraints
- Input: source program in a fixed language with well-defined syntax and semantics
- Output: a fixed target language with well-defined syntax and semantics
- Constraints are known (correctness, performance)
- A batch-like process

Compilation is ...

Single,
well defined,
source



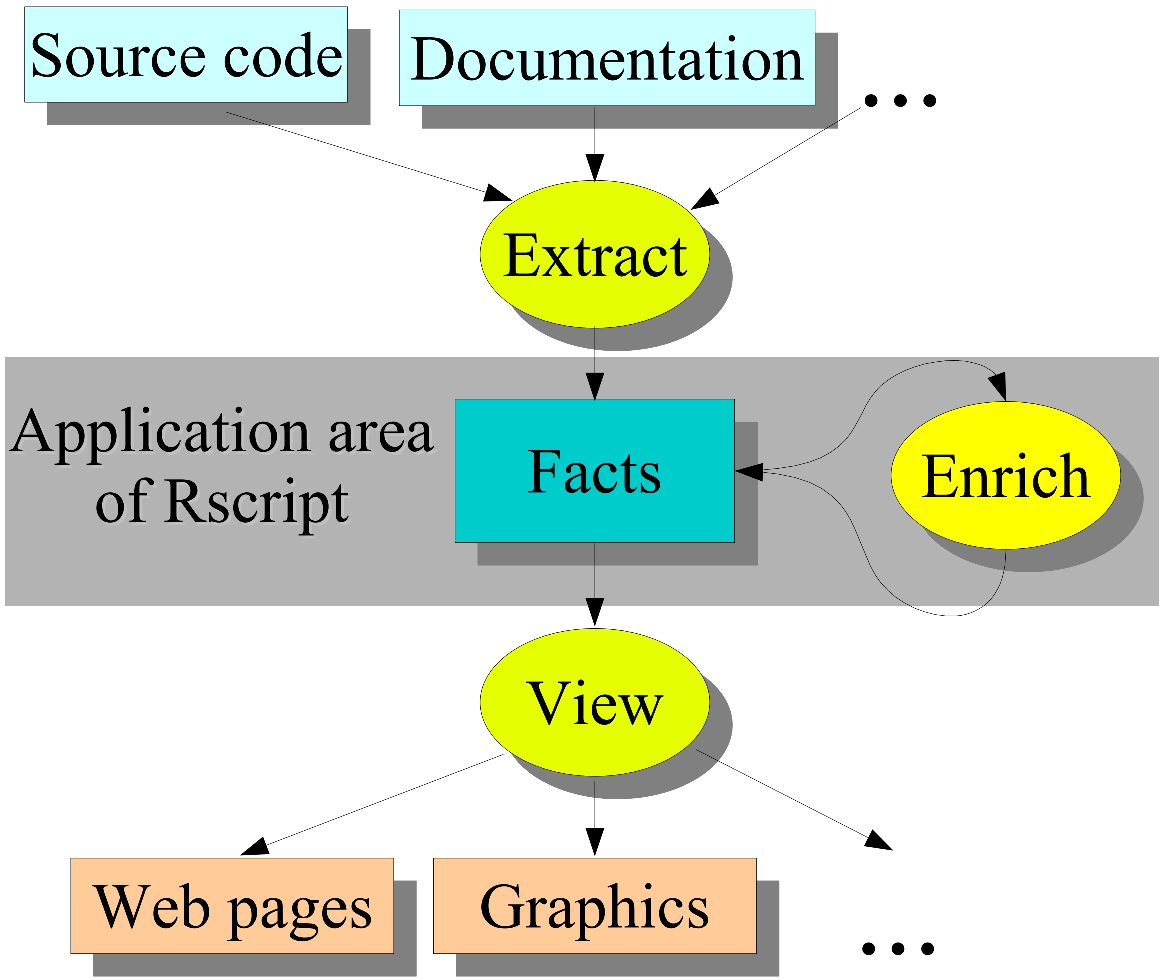
A batch-like process with
clear constraints

Single,
well
defined,
target

Understanding is ...

- An exploration process with as input
  - system artifacts (source, documentation, tests, ...)
  - implicit knowledge of its designers or maintainers
- There is no clear target language
- An interactive process:
  - Extract elementary facts
  - Abstract to get derived facts needed for analysis
  - View derived facts through visualization or browsing

Extract-Enrich-View Paradigm



Examples of understanding problems

- Which programs call each others?
- Which programs use which databases?
- If we change this database record, which programs are affected?
- Which programs are more complex than others?
- How much code clones exist in the code?

Examples of the results of understanding

- Textual reports indicating properties of system parts (complexity, use of certain utilities, ...)
- Same, but in hyperlinked format
- Graphs (call graphs, use def graphs for databases)
- More sophisticated visualizations

Other aspects of Understanding

- Systems consist of several source languages
- Analysis techniques over multiple language => a language-independent analysis framework is needed
- A very close link to the source text is needed

Related approaches

- Generic dataflow frameworks exist but are not used widely
- Relations have been used for querying of software (Rigi, GROK, RPA, ...)
  - All based on untyped, binary, relation algebra
  - Mostly used for architectural, coarse grain, queries

Relation-based analysis

- What happens if we use relations for fine grain software analysis (ex: find uninitialized variables)
- What happens if we use a relational calculus (as opposed to the relational algebra approaches)?
- What happens if we use term rewriting as basic computational mechanism?
  - relations can represent graphs in the rewriting world
- Could yield a unifying framework for analysis and transformation

Roadmap

- Rscript in a nutshell
- Example 1: call graph analysis
- Example 2: component structure
- Example 3: Java analysis
- Example 4: a toy language
- A vizualization experiment

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Rscript in a Nutshell

- Basic types: `bool`, `int`, `str`, `loc` (text location in specific file with comparison operators)
- Sets, relations and associated operations (domain, range, inverse, projection, ...)
- Comprehensions
- User-defined types
- Fully typed
- Functions and sets of equations over the above

Rscript: examples

- Set: `{3, 5, 3}`
  - type: `set[int]`
- Set: `{"y", "x","z"}`
  - type: `set[str]`
- Relation: `{<"y",3>, <"x",3>, <"z", 5>}`
  - type: `rel[str,int]`

Rscript: examples

- rel[str,int] U = {<"y",3>, <"x",3>, <"z", 5>}
- int Usize = #U
  - 3
- rel[int,str] Uinv = inv(U)
  - {<3, "y">, <3, "x">, <5, "z">}
- set[str] Udom = domain(U)
  - {"y", "x", "z"}

domain:
all elements in lhs of pairs
range:
all elements in rhs of pairs
carrier:
all elements in lhs or rhs of pairs

Comprehensions

- Comprehensions: {Exp | Gen1, Gen2, ... }
  - A generator is an enumerator or a test
  - Enumerators: V : SetExp or <V1,V2> : RelExp
  - Tests: any predicate
  - consider all combinations of values in Gen1, Gen2,...
  - if some Gen_i is false, reject that combination
  - compute Exp for all legal combinations

Comprehensions

- {X | int X : {1,2,3,4,5}}
  - yields {1,2,3,4,5}
- {X | int X : {1,2,3,4,5}, X > 3}
  - yields {4,5}
- {<Y, X> | <int X, int Y> : {<1,10>,<2,20>}}
  - yields {<10,1>,<20,2>}

Functions

- `rel[int, int] inv(rel[int,int] R) =`
  `{ <Y, X> | <int X, int Y> : R }`
  - `inv({1,10>, <2,20>}` yields `{<10,1>,<20,2>}`
- `rel[&B, &A] inv(rel[&A, &B] R) =`
  `{ <Y, X> | <&A X, &B Y> : R}`
  - `inv({<1,"a">, <2,"b">})` yields `{<"a",1>,<"b",2>}`

&A, &B indicate *any* type and are used to define polymorphic functions

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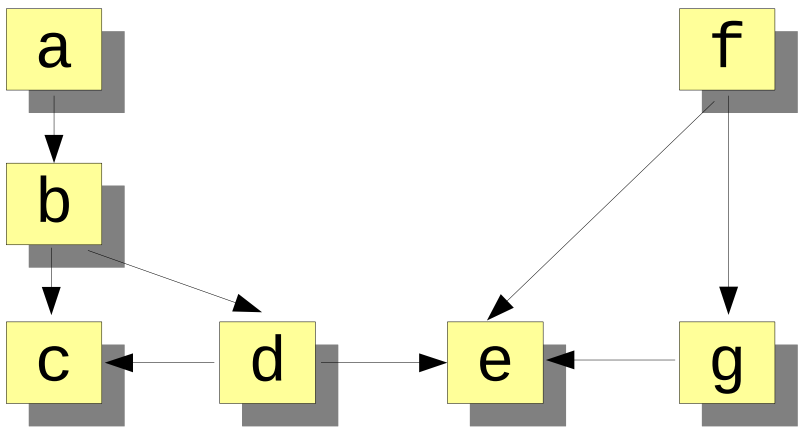
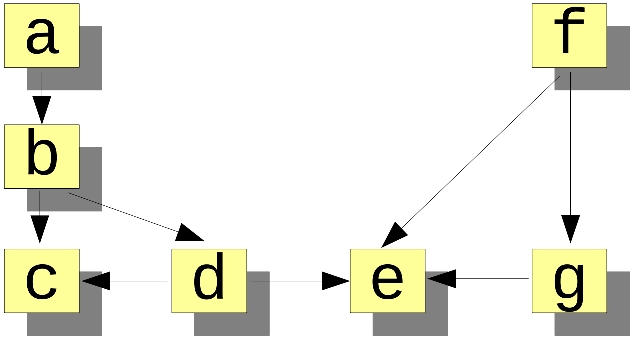
Analyzing the call structure of an application




```
rel[str, str] calls = {<"a", "b">, <"b", "c">, <"b", "d">, <"d", "c">,
                       <"d","e">, <"f", "e">, <"f", "g">, <"g", "e">}
```

Some questions

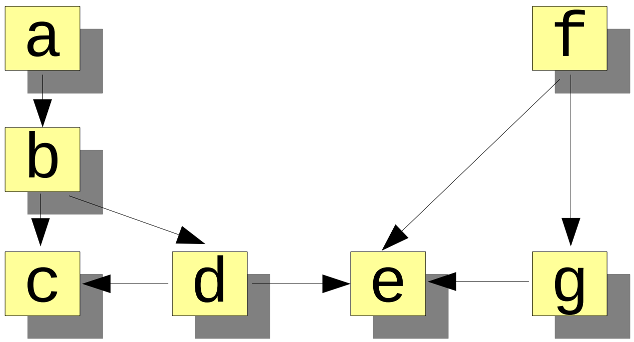


- How many calls are there?
  - int ncalls = # calls
  - 8
- How many procedures are there?
  - int nprocs = # carrier(calls)
  - 7

Number of elements

All elements in domain or range of a relations

Some questions



- What are the entry points?
  - set[str] entryPoints = top(calls)
  - {"a", "f"}

The *roots* of a relation (viewed as a graph)

- What are the leaves?
  - set[str] bottomCalls = bottom(calls)
  - {"c", "e"}

The *leaves* of a relation (viewed as a graph)

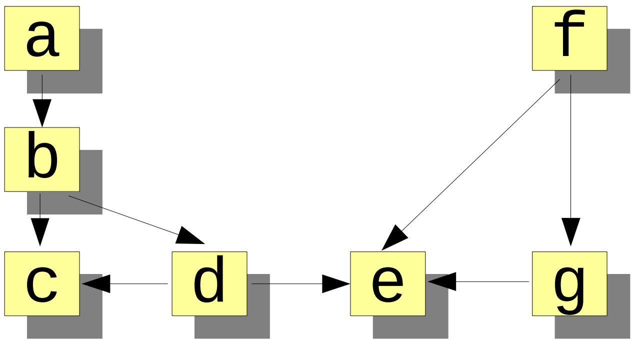
Intermezzo: Top

- The roots of a relation viewed as a graph
- `top({<1,2>,<1,3>,<2,4>,<3,4>})` yields `{1}`
- Consists of all elements that occur on the lhs but not on the rhs of a tuple
- ```
  set[&T] top(rel[&T, &T] R) =
          domain(R) \ range(R)
  ```
  ```

Intermezzo: Bottom

- The leaves of a relation viewed as a graph
- bottom({<1,2>,<1,3>,<2,4>,<3,4>}) yields {4}
- Consists of all elements that occur on the rhs but not on the lhs of a tuple
- set[&T] bottom(rel[&T, &T] R) =
      range(R) \ domain(R)

Some questions



- What are the indirect calls between procedures?
  - rel[str,str] closureCalls = calls+
  - {<"a", "b">, <"b", "c">, <"b", "d">, <"d", "c">, <"d","e">, <"f", "e">, <"f", "g">, <"g", "e">, <"a", "c">, <"a", "d">, <"b", "e">, <"a", "e">}
- What are the calls from entry point a?
  - set[str] calledFromA = closureCalls["a"]
  - {"b", "c", "d", "e"}

The image of domain value "a"

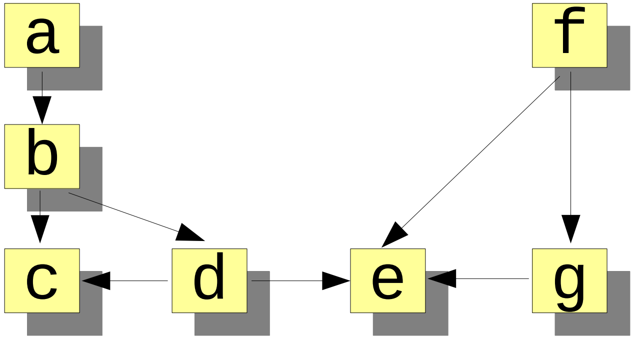
Intermezzo: right image

- Right-image of a relation: all elements that have a given value as left element (resembles array access)
- Notation: relation followed by [Value]
- Ex. Rel = {<1,10>,<2,20>,<1,11>,<3,30>,<2,21>}
- Rel[1] yields {10,11}
- Rel[{1,2}] yields {10, 11, 20, 21}

Intermezzo: left image

- Left-image of a relation: all elements that have a given value as right element
- Notation: relation followed by [-,Value]
- Ex. Rel = {<1,10>,<2,20>,<1,11>,<3,30>,<2,21>}
- Rel[-,10] yields {1}
- Rel[-,{10,20}] yields {1,2}

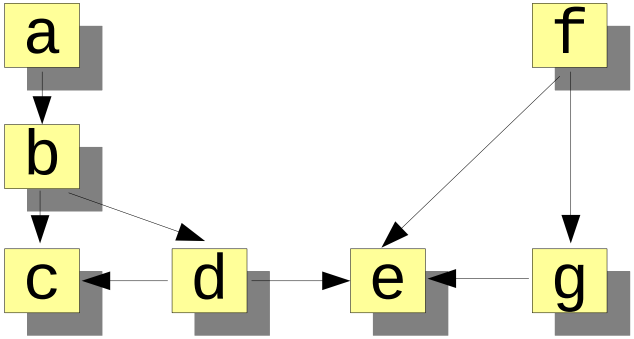
Some questions



- What are the calls to procedure `e`?
  - `set[str] callsToE = closureCalls[-,"e"]`
  - {"a", "b", "d", "f", "g"}

The domain of image value "e"

Some questions



- What are the calls from entry point `f`?
  - `set[str] calledFromF = closureCalls["f"]`
  - `{"e", "g"}`
- What are the common procedures?
  - `set[str] commonProcs = calledFromA inter calledFromF`
  - `{"e"}`

Intersection

Running Rscript using rscript-meta

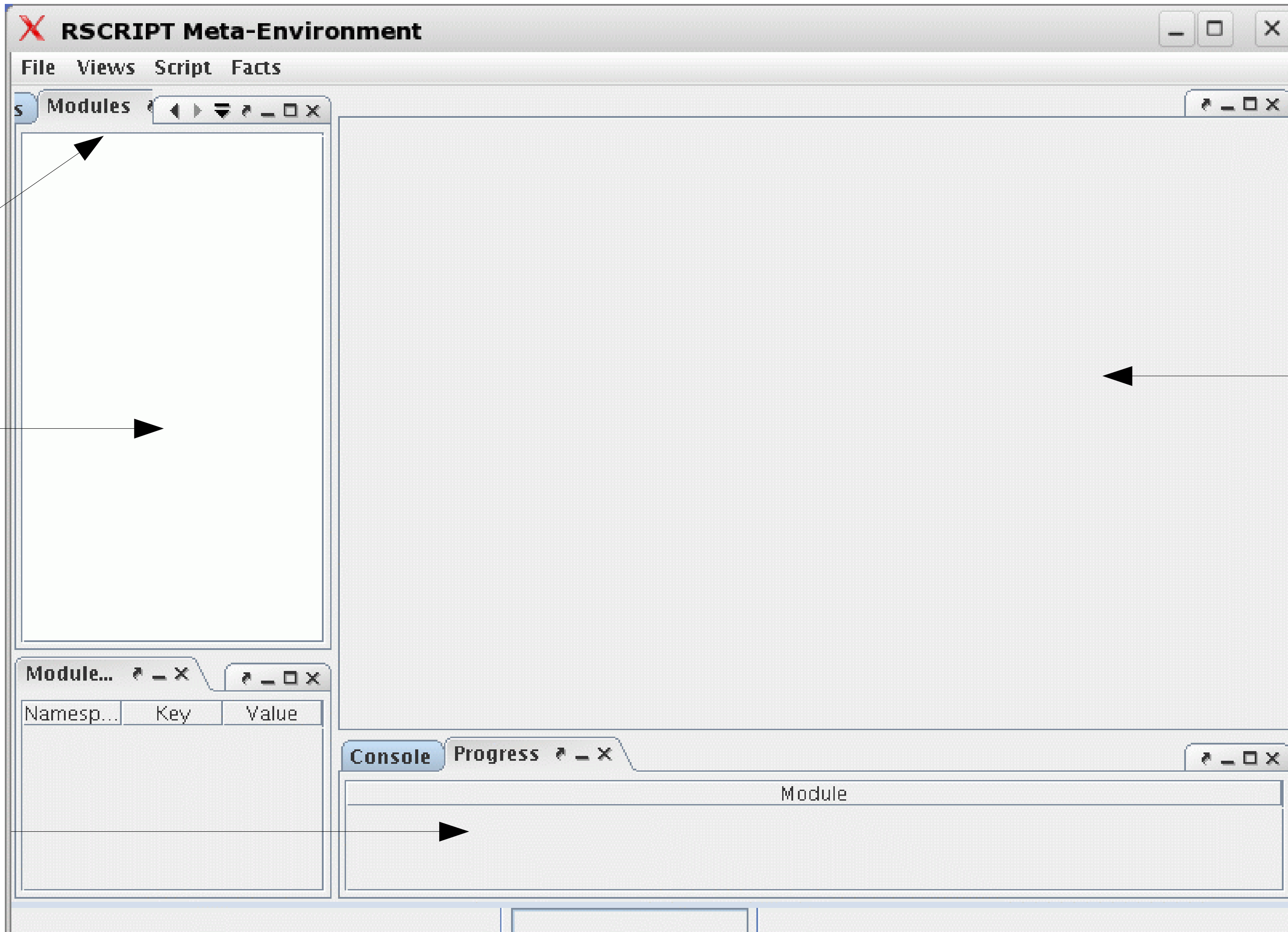
Facts tab

Modules tab

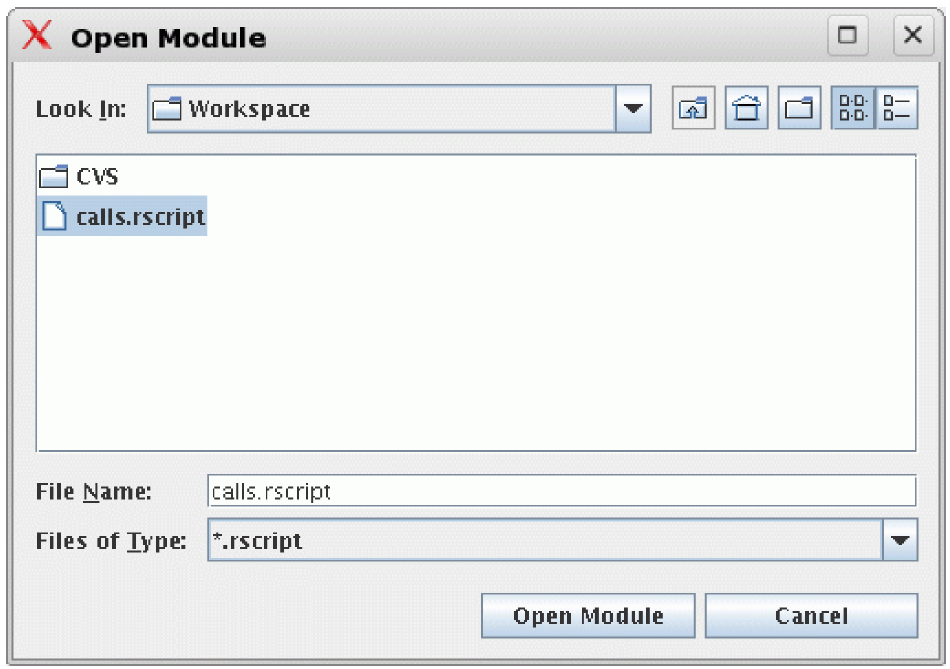
Navigator pane

Message pane

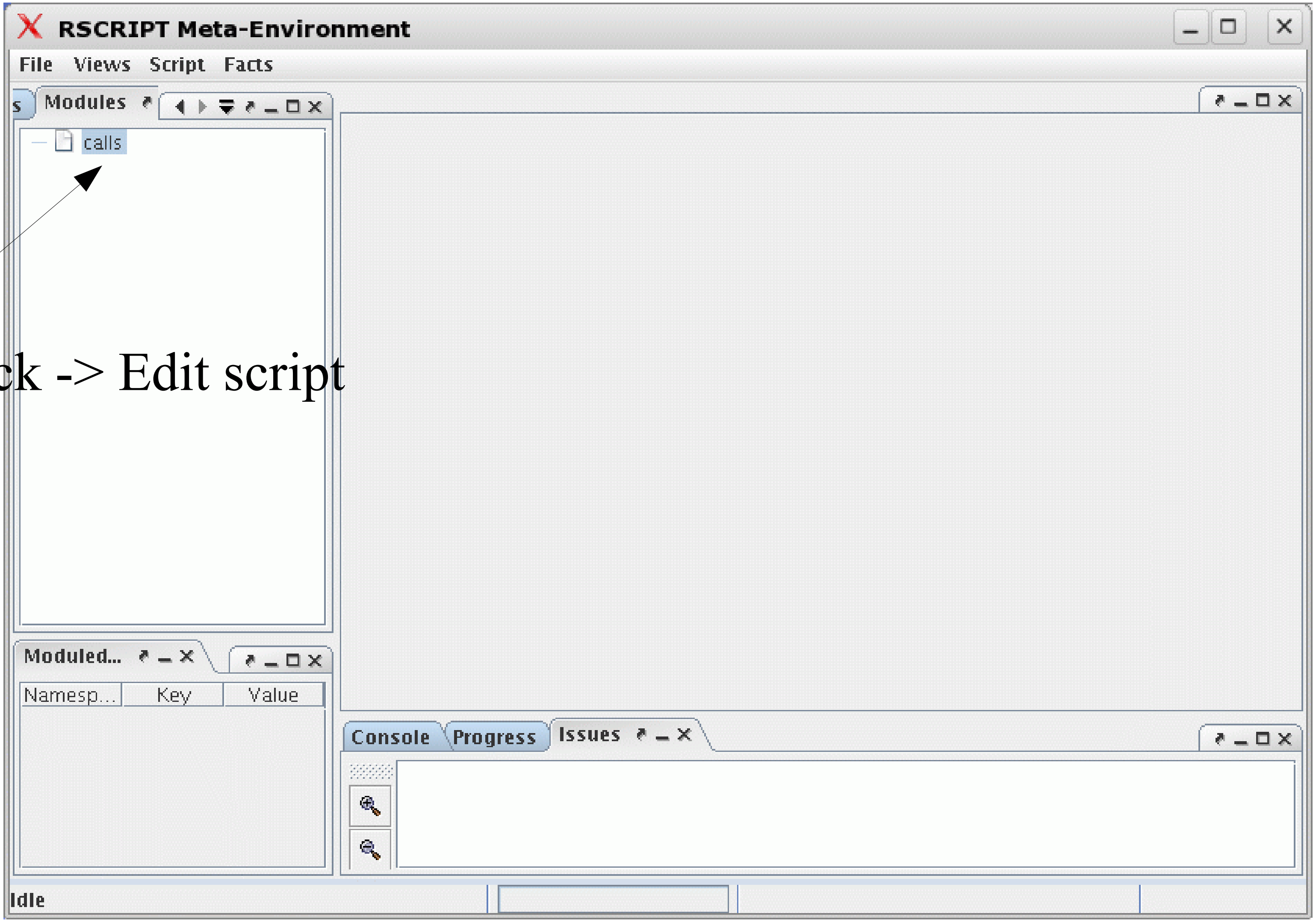
Edit pane



Script -> Open...

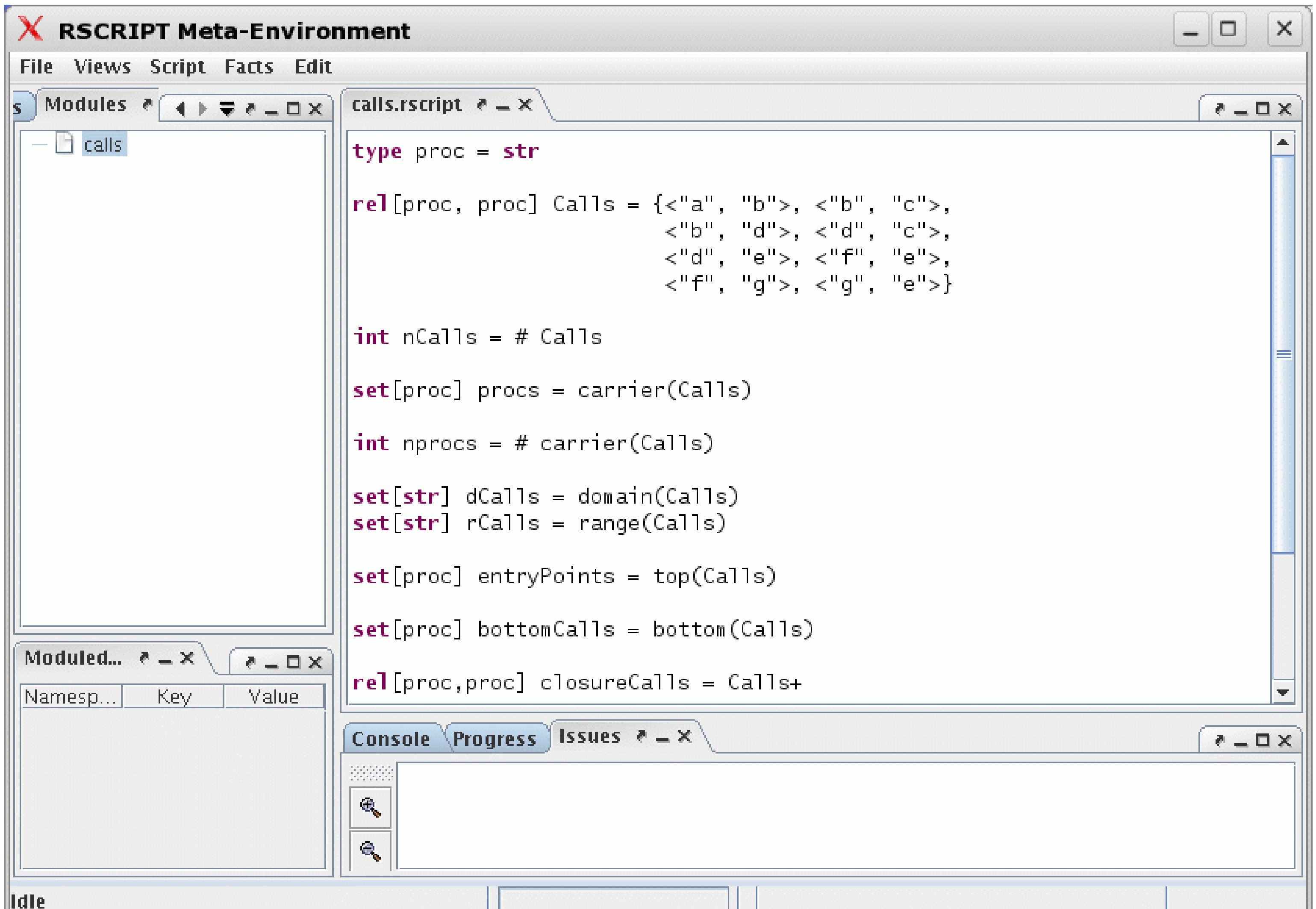

Open Module
Look In:
Workspace
CVS
calls.rscript
File Name:
calls.rscript
Files of Type:
*.rscript
Open Module
Cancel

File calls has been opened

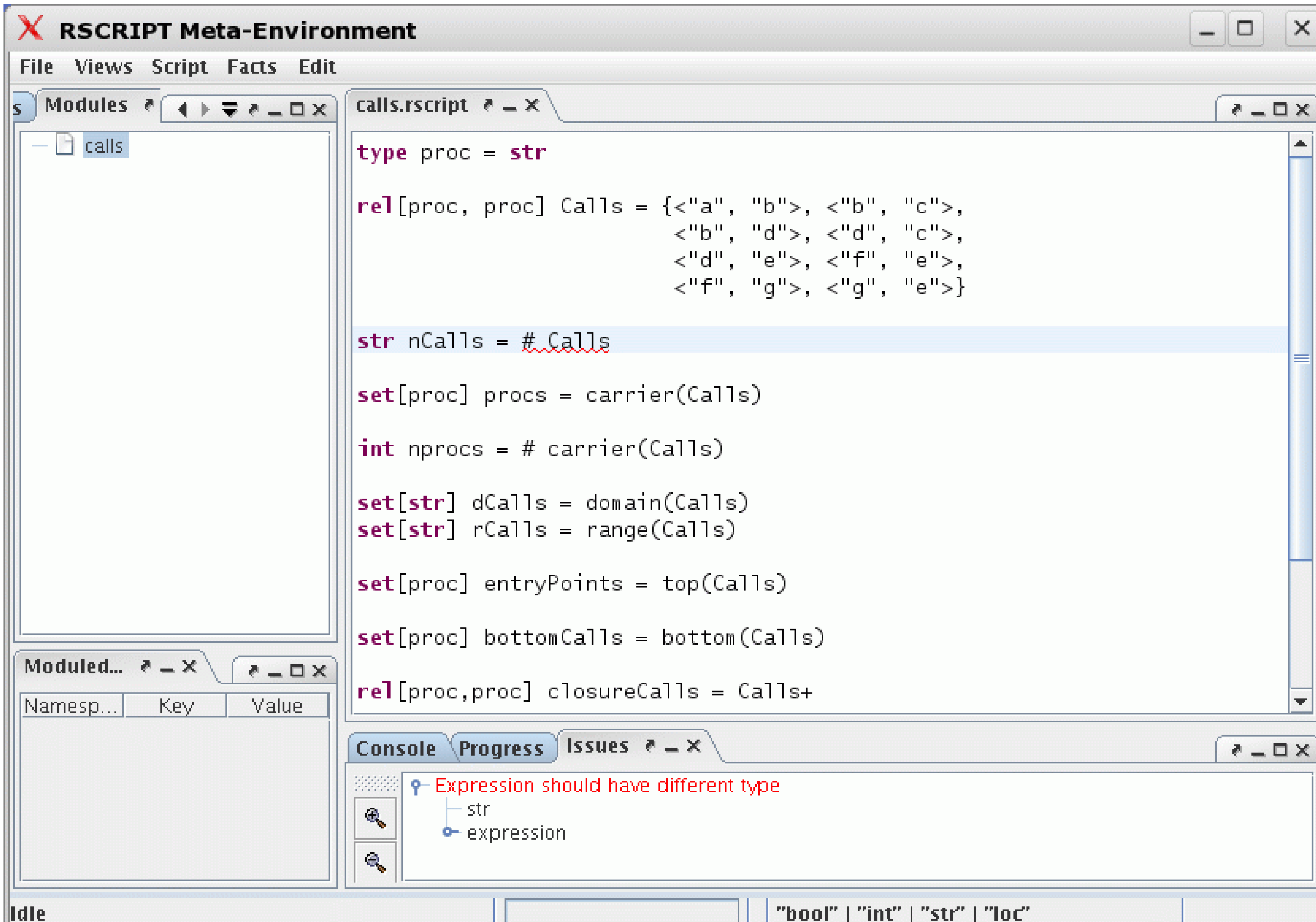


Right click -> Edit script

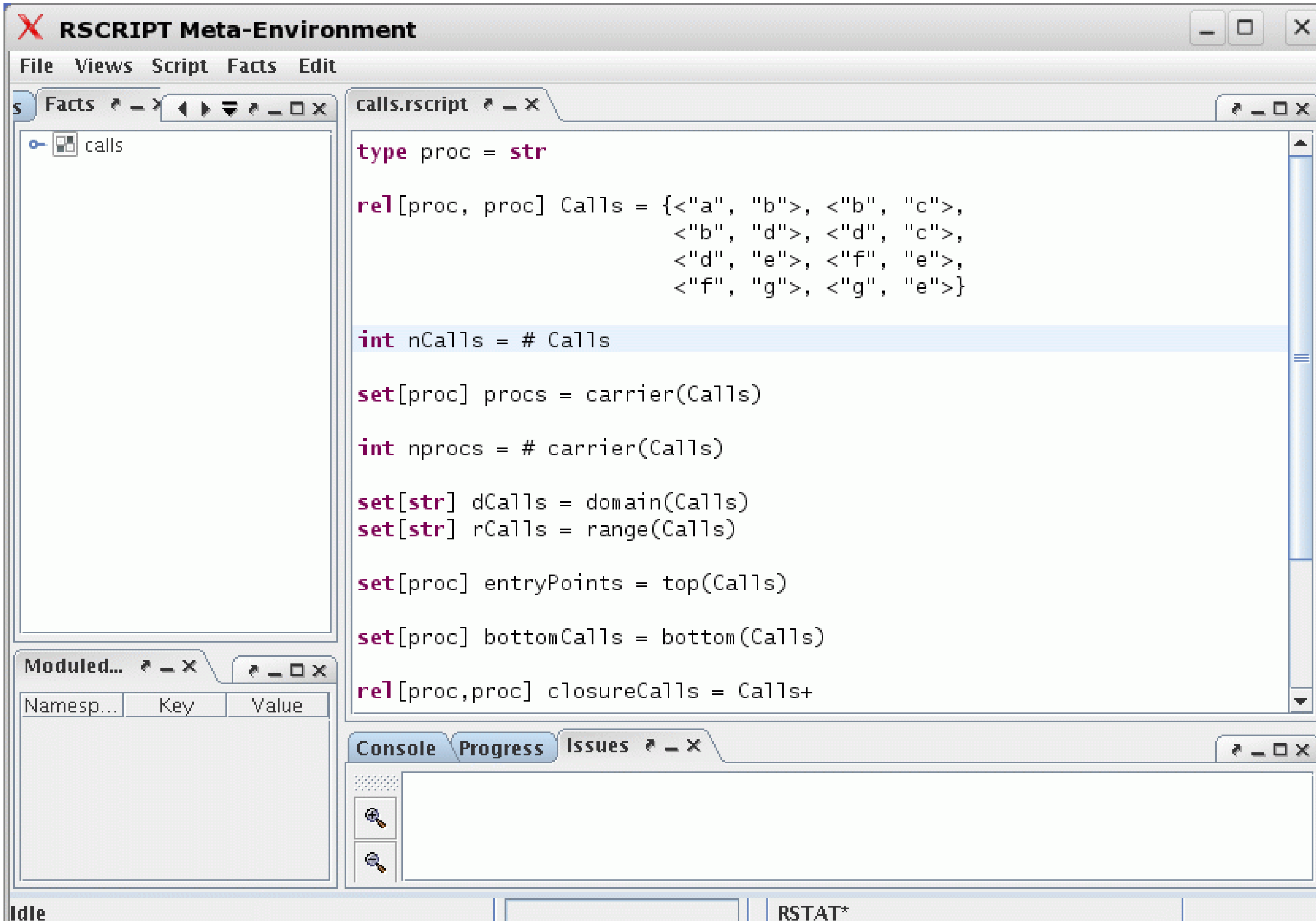
Editing calls.rscript



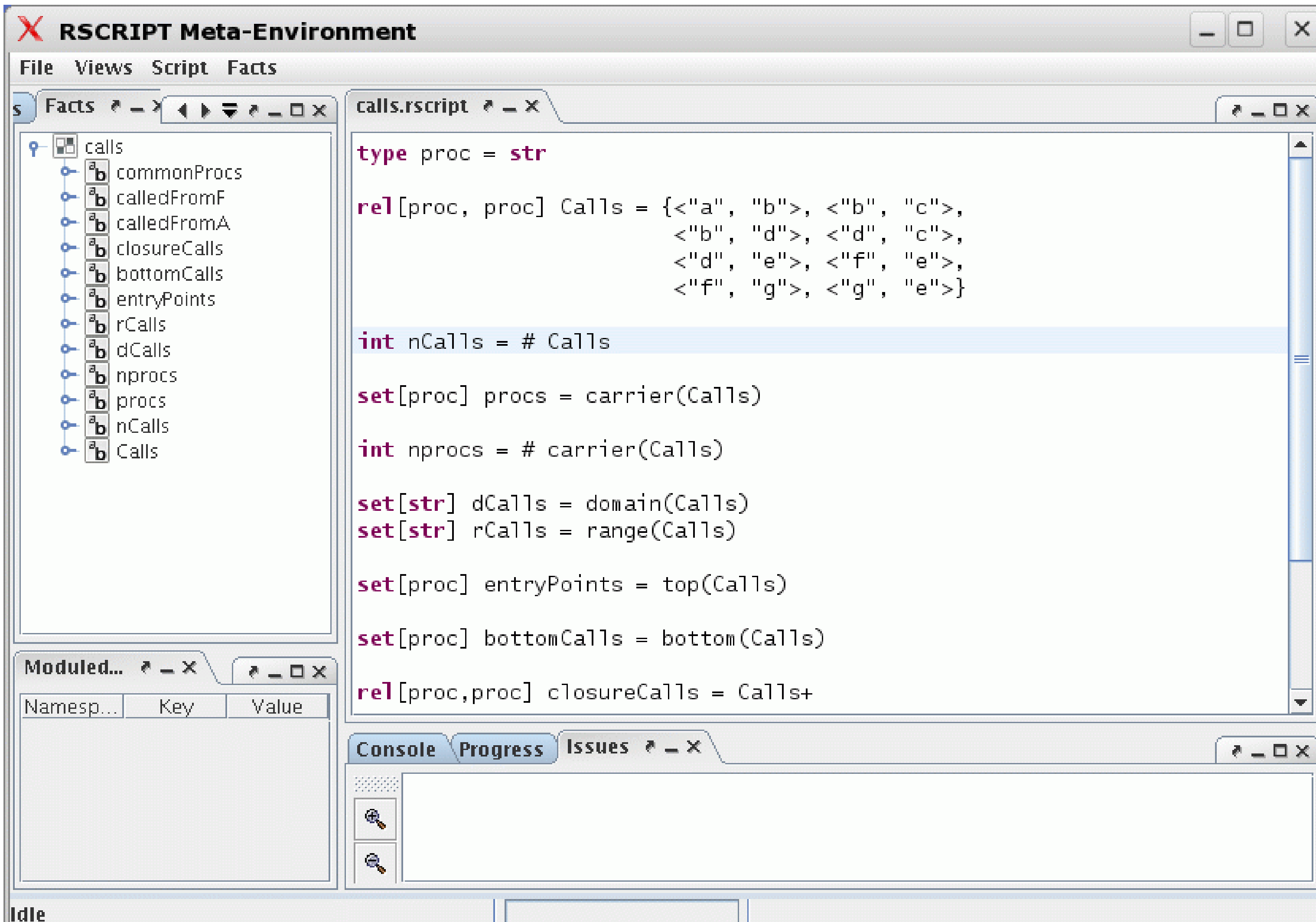
Making errors ...



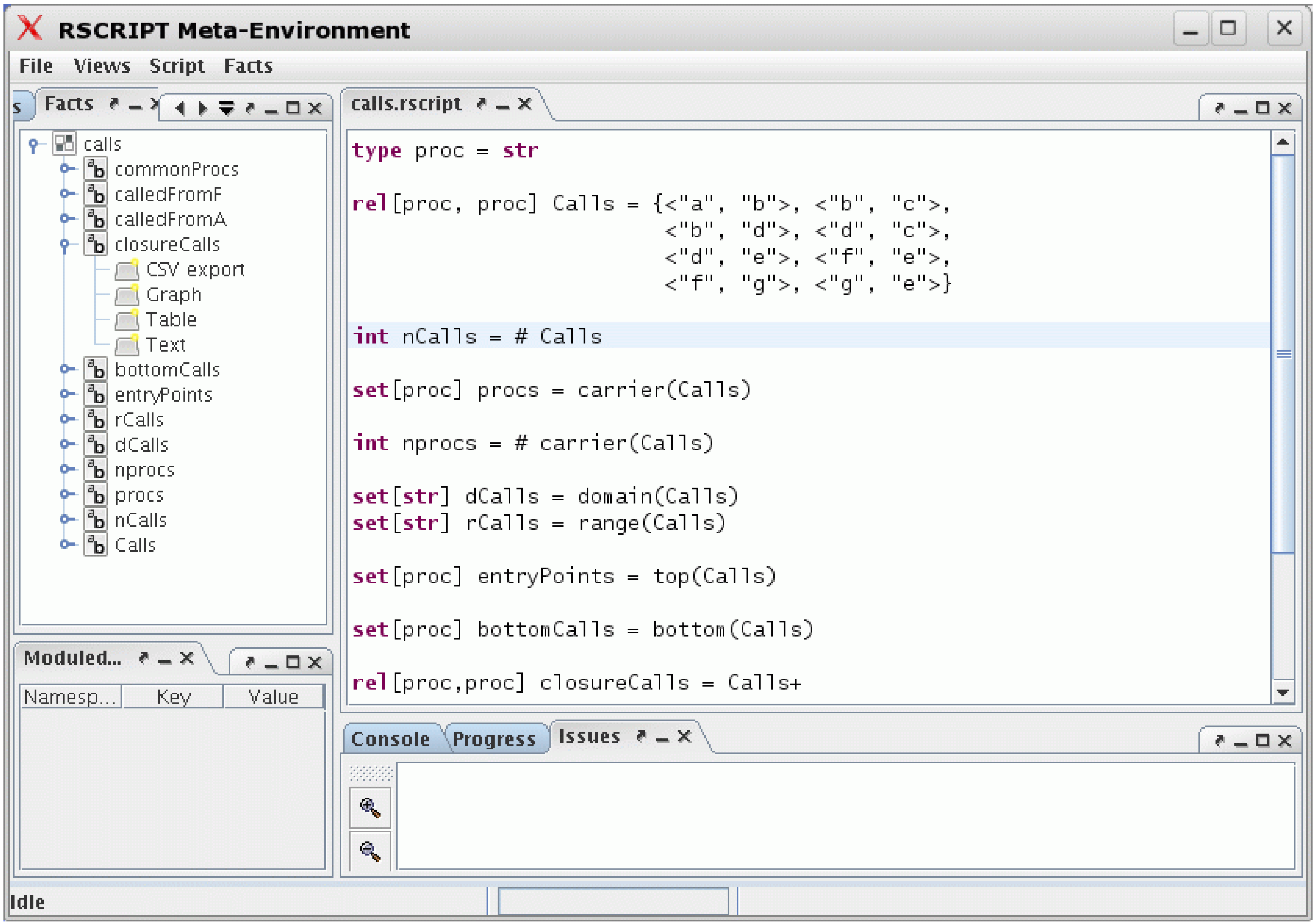
Script -> Run


RSCRIPT Meta-Environment
File Views Script Facts Edit
Facts
calls
calls.rscript
type proc = str
rel[proc, proc] Calls = {<"a", "b">, <"b", "c">,
<"b", "d">, <"d", "c">,
<"d", "e">, <"f", "e">,
<"f", "g">, <"g", "e">}
int nCalls = # Calls
set[proc] procs = carrier(Calls)
int nprocs = # carrier(Calls)
set[str] dCalls = domain(Calls)
set[str] rCalls = range(Calls)
set[proc] entryPoints = top(Calls)
set[proc] bottomCalls = bottom(Calls)
rel[proc,proc] closureCalls = Calls+
Moduled...
Namesp... Key Value
Console Progress Issues
Idle
RSTAT*

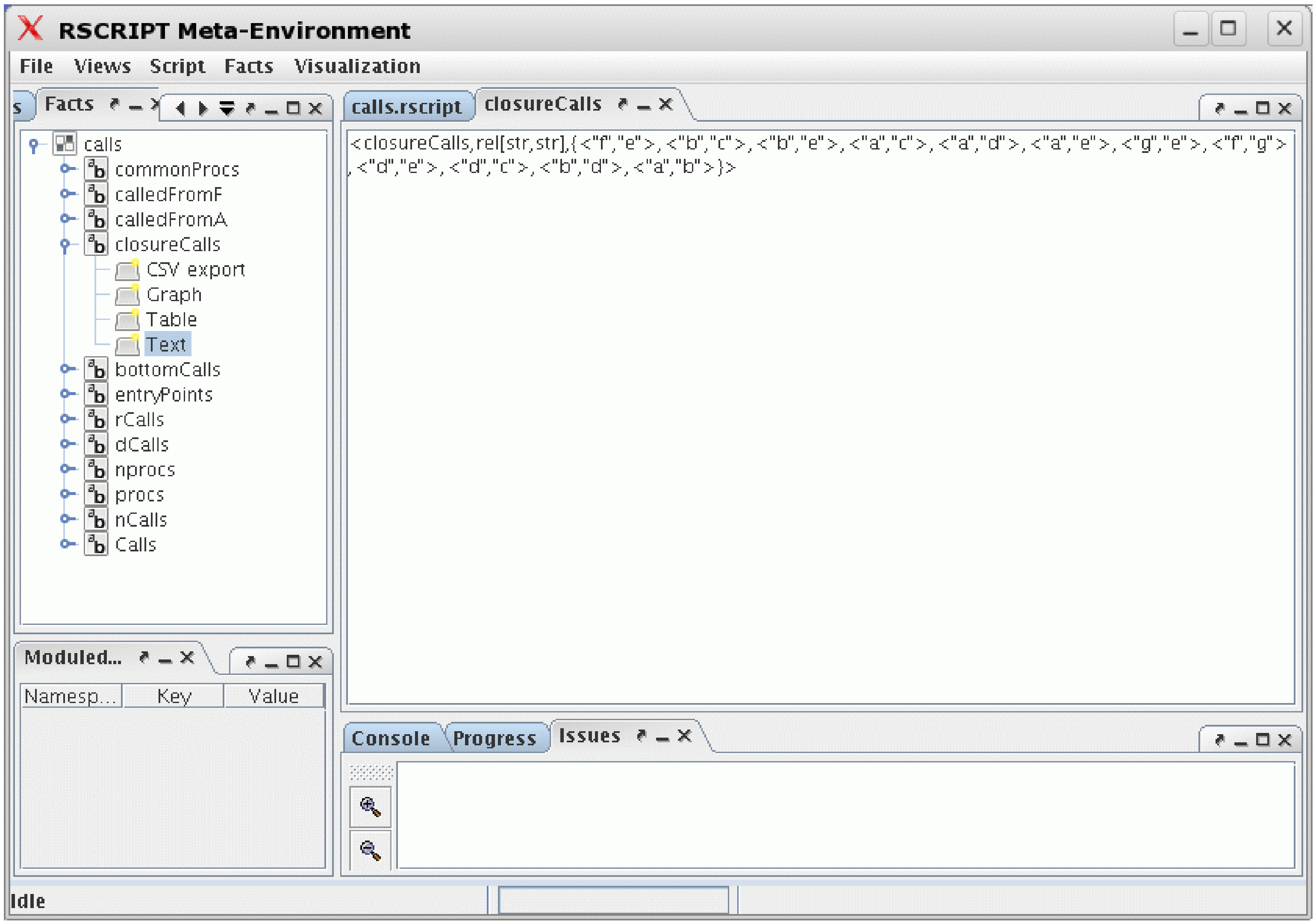
Unfolding the rstore ...



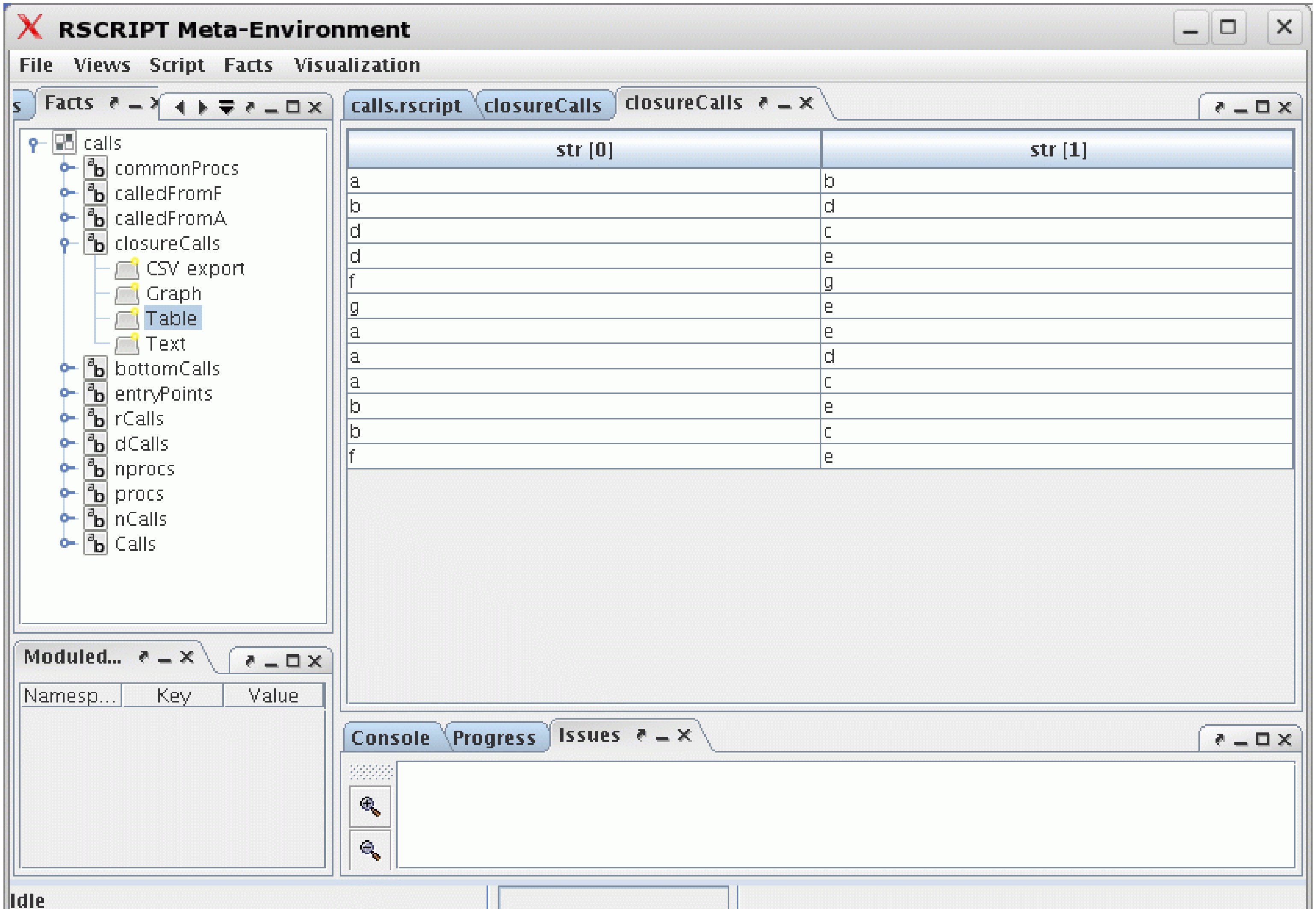
Unfolding closureCalls



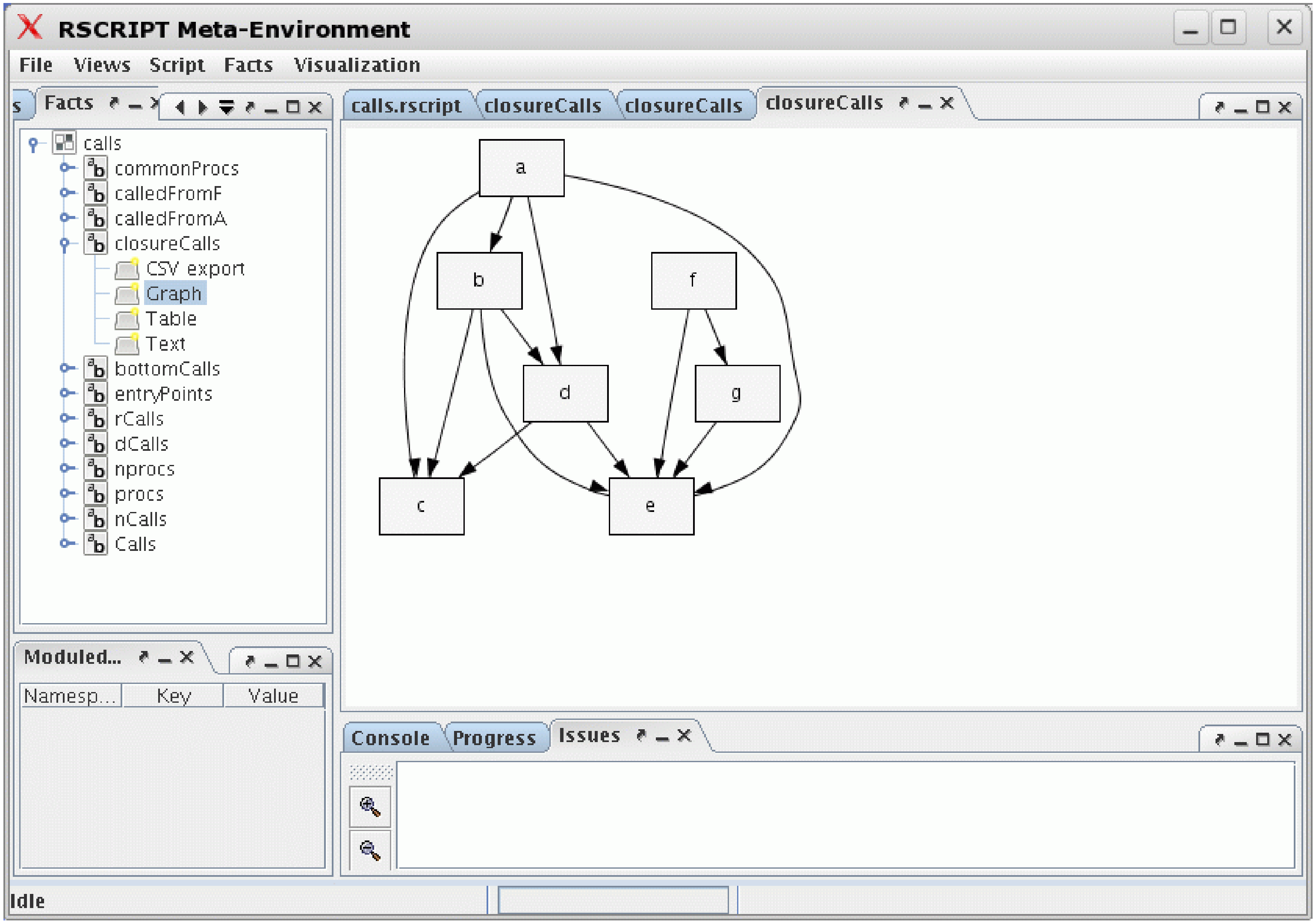
closureCalls as Text



closureCalls as Table



closureCalls as Graph



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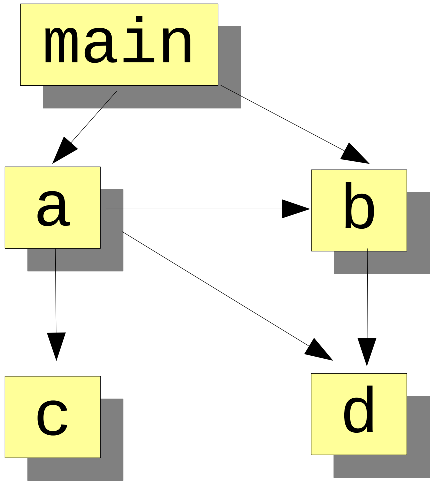
Component Structure of Application

- Suppose, we know:
  - the call relation between procedures (Calls)
  - the component of each procedure (PartOf)
- Question:
  - Can we lift the relation between procedures to a relation between components (ComponentCalls)?
- This is usefull for checking that real code conforms to architectural constraints

Calls

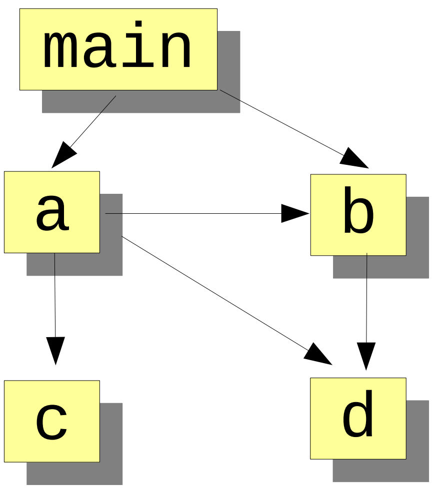


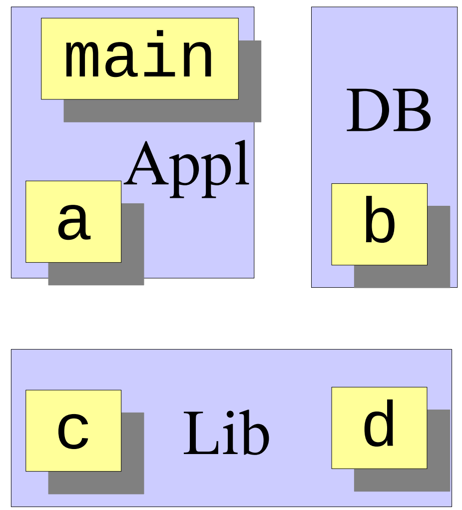
type proc = str

type comp = str

rel[proc,proc] Calls = {<"main", "a">, <"main", "b">, <"a", "b">,
<"a", "c">, <"a", "d">, <"b", "d">}

PartOf

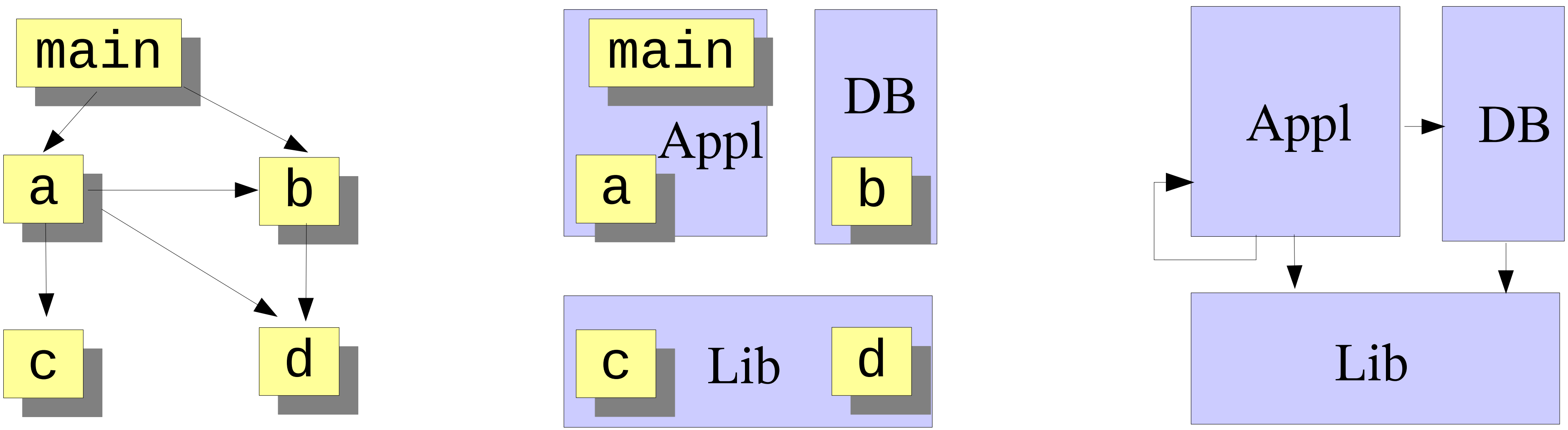




set[comp] Components = {"Appl", "DB", "Lib"}

rel[proc, comp] PartOf =
{<"main", "Appl">, <"a", "Appl">, <"b", "DB">,
<"c", "Lib">, <"d", "Lib">}

lift




```
rel[comp,comp] lift(rel[proc,proc] aCalls,  rel[proc,comp] aPartOf) =
  { <C1, C2> | <proc P1, proc P2> : aCalls,
               <comp C1, comp C2> : aPartOf[P1] x aPartOf[P2] }
```

```
rel[comp,comp] ComponentCalls = lift(Calls2, PartOf)
```

Resultaat: {<"DB", "Lib">, <"Appl", "Lib">, <"Appl", "DB">, <"Appl", "Appl">}

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Cyclic Dependencies

A class uses (directly or indirectly) itself

Use = methods calls, inheritance, containment

```
class ContainedClass { }
class SuperClass {}
class SubClass extends SuperClass {
   ContainedClass C;
}
```

Example of
a contained class

Motivation: cyclic class dependencies are difficult to understand/maintain

Cyclic Dependencies: Examples

```
class A {  B B1; ... }
class B extends A { ... }
```

```
class A {  C C1; ... }
class B extends A{ ... }
class C { B B1;  ...}
```

Java analysis: classes in cycles

- Assume the following extracted information:
  - `rel[str,str] CALL`
    - method call from first class to the second
  - `rel[str,str] INHERITANCE`
    - extends and implements
  - `rel[str,str] CONTAINMENT`
    - attribute of first class is of the type of the second class
- Question: which classes occur in a cyclic dependency?

Java analysis: cycles in classes

- Define the USE relation between two classes:
  - rel[str,str] USE = CALL union CONTAINMENT union INHERITANCE
  - set[str] ClassesInCycle = {C1 | <str C1, str C2> : USE+, C1 == C2}
- In this way we get a set of classes that occur in a cyclic dependency, but ...
- ... which classes are in the cycle?

Java analysis: cyclic classes

- `rel[str,str] USE = CALL union CONTAINMENT`
  `union INHERITANCE`
- `set[str] CLASSES = carrier(USE)`
- `rel[str,str] USETRANS = USE+`
- `rel[str,set[str]] =`
  `{<C, USETRANS[C]> | str C : CLASSES,`
  `<C, C> in USETRANS}`
- Each cyclic class is associated with a set of classes that form a cycle

Applications of this approach

- Search for “similar” classes
- Search for design patterns (as characterized by specific relations between the classes in the pattern)
- ...

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Toy program

```
begin declare x : natural, y : natural,
              z : natural;
    x :=  3;
    if      3 then
            z := y + x
    else
            x := 4
    fi
    y := z
end
```

y is undefined

z may be undefined

Toy program

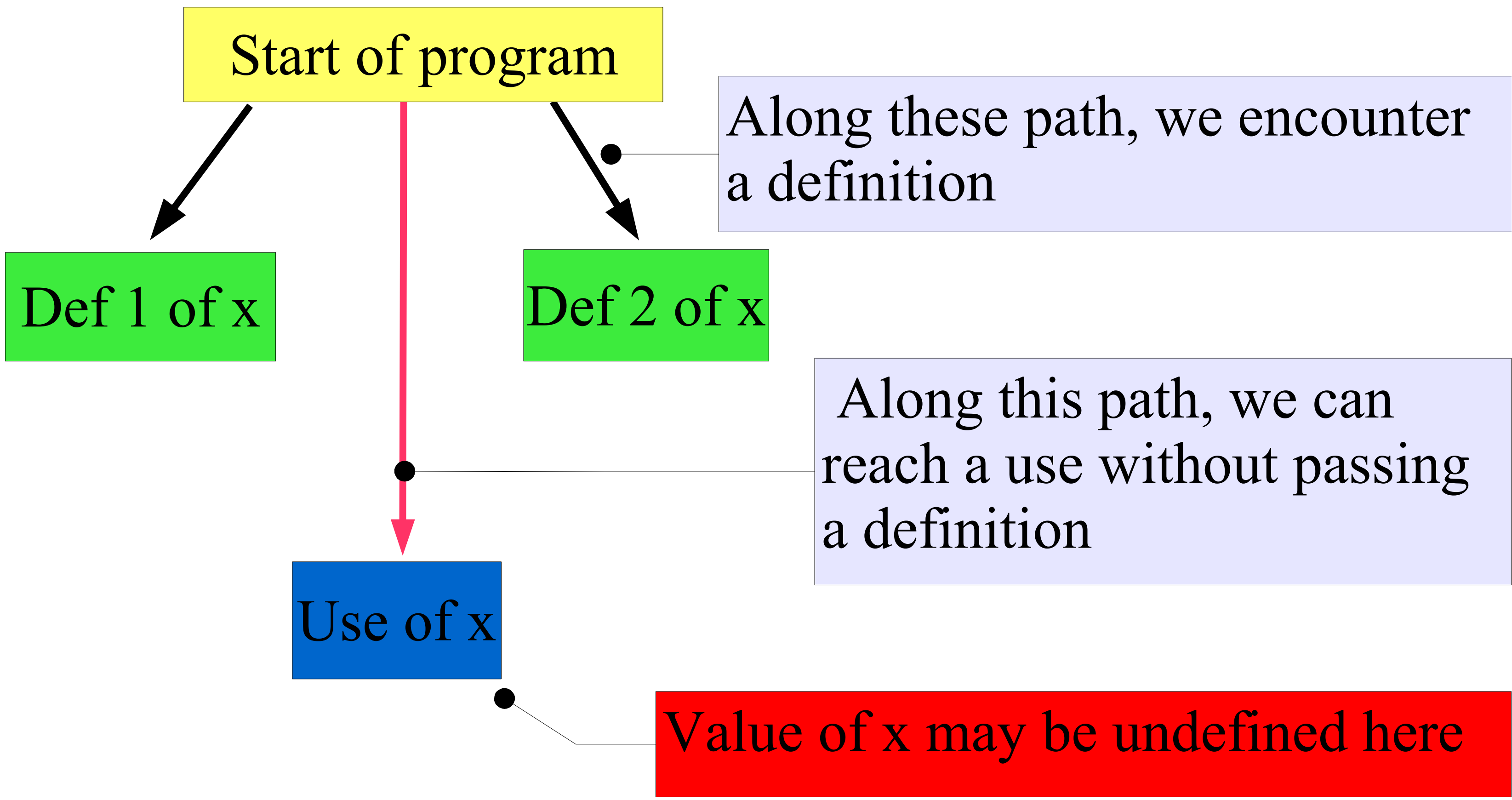
```
rel[int,str] DEFS = {<1,"x">, <3,"z">, <4,"x">, <5,"y">}
```

```
begin declare x : natural, y : natural,
              z : natural;
[1]  x :=  3;
     if [2]  3 then
       [3]  z := y + x
     else
       [4]  x := 4
     fi
[5]  y := z
end
```

```
rel[int,str] USES = {<3,"y">, <3,"x">, <5,"z">}
```

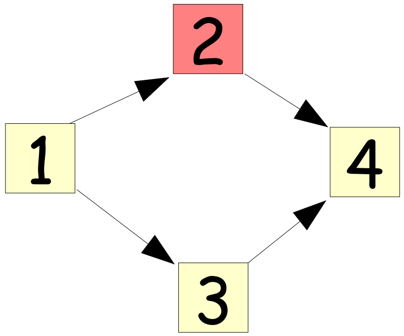
```
rel[int,int] PRED = {<0,1>, <1,2>, <2,3>,<2,4>,
                     <3,5>,<4,5>}
```

Finding uninitialized variables



Intermezzo: reachX

- Reachability with exclusion of certain elements
- set[&T] reachX(
  - set[&T] Start,
  - set[&T] Excl,
  - rel[&T,&T] Rel)
- reachX({1}, {2}, {<1,2>,<1,3>,<2,4>,<3,4>})
  yields {<3,4>}



The undefined query

```
rel[int,str] DEFS = ...
rel[int,str] USES = ...
rel[int,int] PRED = ...

rel[int,str] UNINIT =
{ <N,V> | <int N, str V>:USES, N in reachX({0}, DEFS[-,V],PRED)}
```

Start from the root

Exclude all definitions of V

There is a path from the root to N: V is not initialized

Use the PRED relation

Reach exclude

Applying the undefined query

```
 begin declare x : natural, y : natural,
               z : natural;
[1]  x :=  3;
     if[2]  3 then
       [3]  z := y + x
     else
       [4]  x := 4
     fi
[5]  y := z
 end
```

y is undefined

z may be undefined

Result:

{<5,"z">, <3,"y">}

Some Questions

- There are several additional questions:
  - In the example so far we have worked with statement numbers but how do we make a connection with the source text? (Discussed now)
  - How do we extract relations like `PRED` and `USE` from the source text? (Discussed later)

Use locations to connect with the source text

```
rel[int,str] DEFS = ...
rel[int,str] USES = ...
rel[int,int] PRED = ...
```

Use *location* instead of number

```
rel[loc,str] DEFS
rel[loc,str] USES
rel[loc,loc] PRED
rel[str, loc] OCCURS
```

Variable occurrence in a statement

Example Rstore

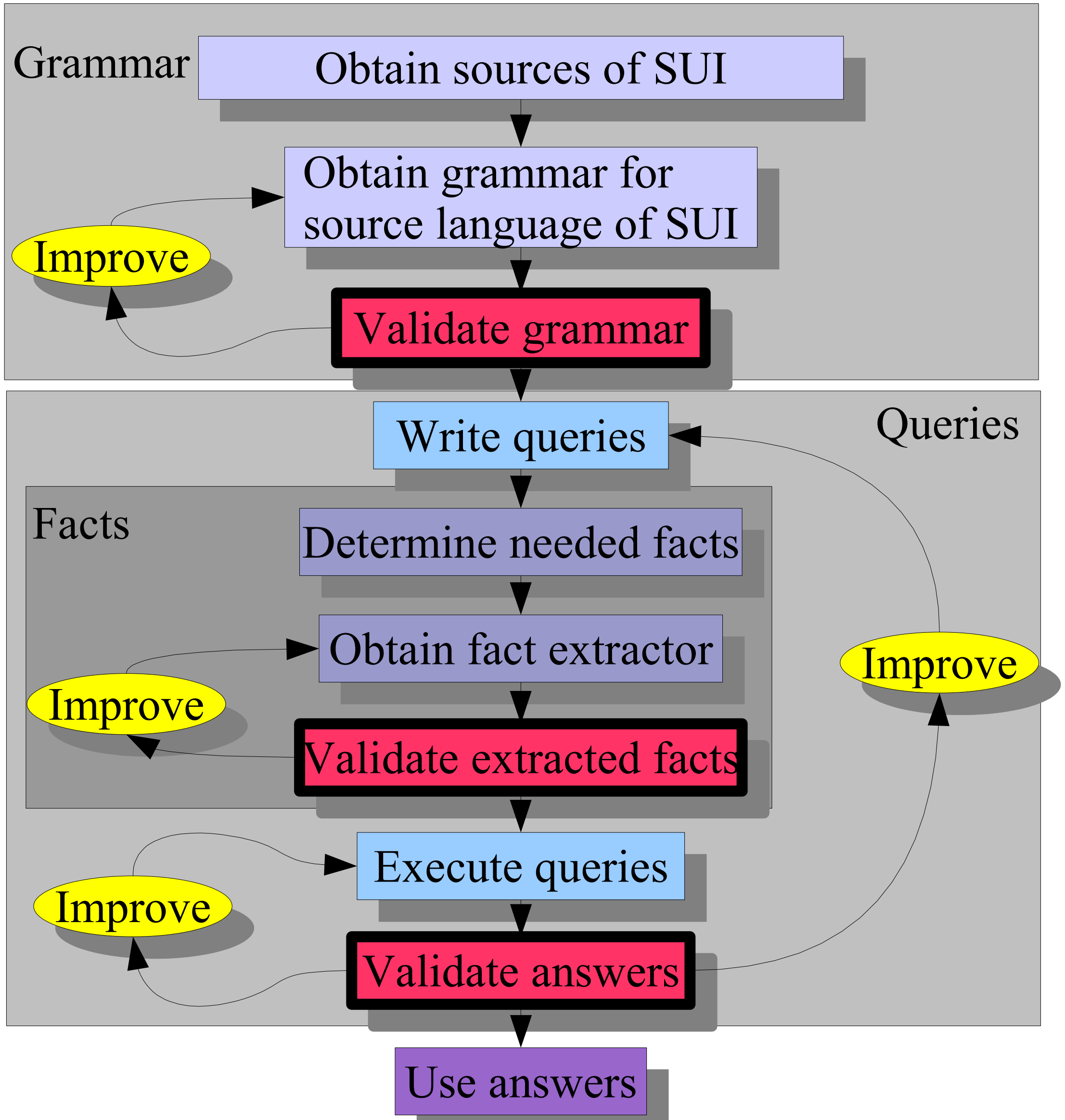
```
rstore(
  <PRED, rel[loc,loc],
        {<area-in-file("/home/paulk/.../example.pico", area(4, 2,4, 8,84, 6)),
          area-in-file("/home/paulk/.../example.pico", area(5, 2,5, 8,94, 6))>,
         <area-in-file("/home/paulk/.../example.pico", area(5, 2,5, 8, 94, 6)),
          area-in-file("/home/paulk/.../example.pico", area(6, 2,10, 4, 104, 56))>,
         ... }>,

 <DEFS, {
   <OCCURS, rel[str,loc],
         {<"y", area-in-file("/home/paulk/.../example.pico",area(11, 2,11, 3,164, 1))>,
          <"z", area-in-file("/home/paulk/.../example.pico", area(11, 7,11, 8,169, 1))>,
          ... }
 }
)
```

Extracting Facts

- Goal: extract facts from source code and use as input for queries
- How should fact extraction be organized?
- How to write a fact extractor?

Workflow Fact Extraction



SUI
=
System
Under
Investigation

Roadmap

- Rscript in a nutshell
- Example 1: call graph analysis
- Example 2: component structure
- Example 3: Java analysis
- Example 4: a toy language
- A vizualization experiment

Roadmap

- Rscript in a nutshell
- Example 1: call graph analysis
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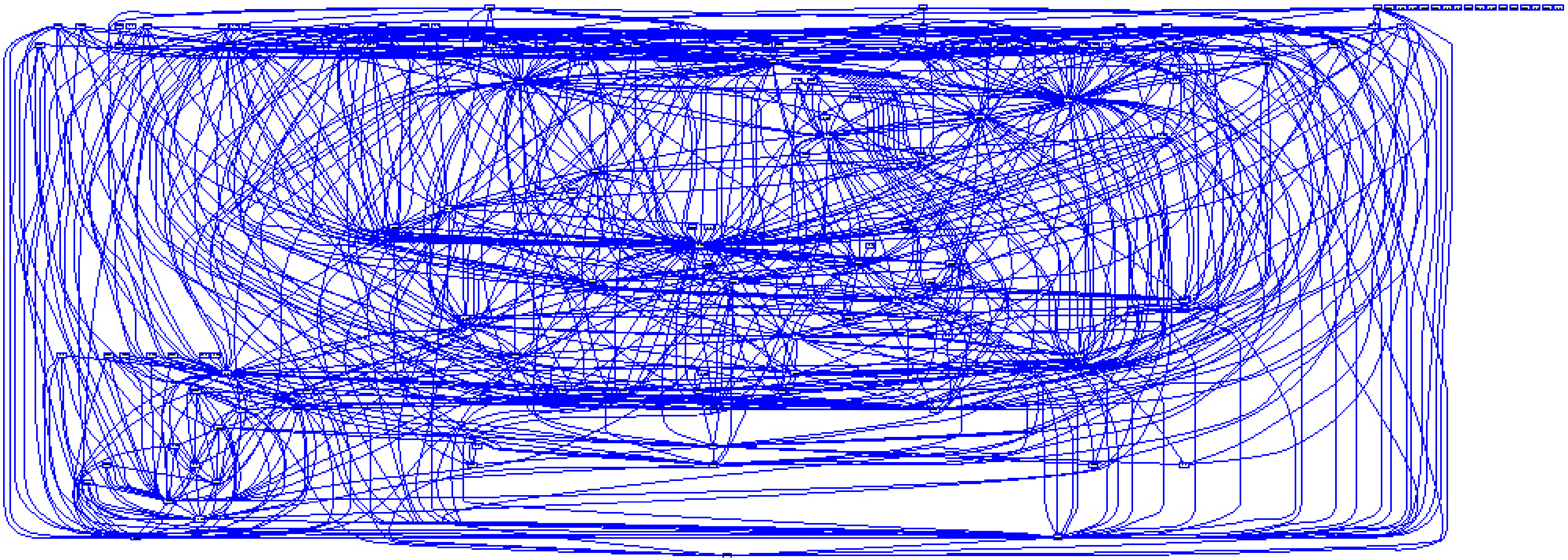
Issues in Program Visualization

- Small graphs are nice, large graph are a disaster



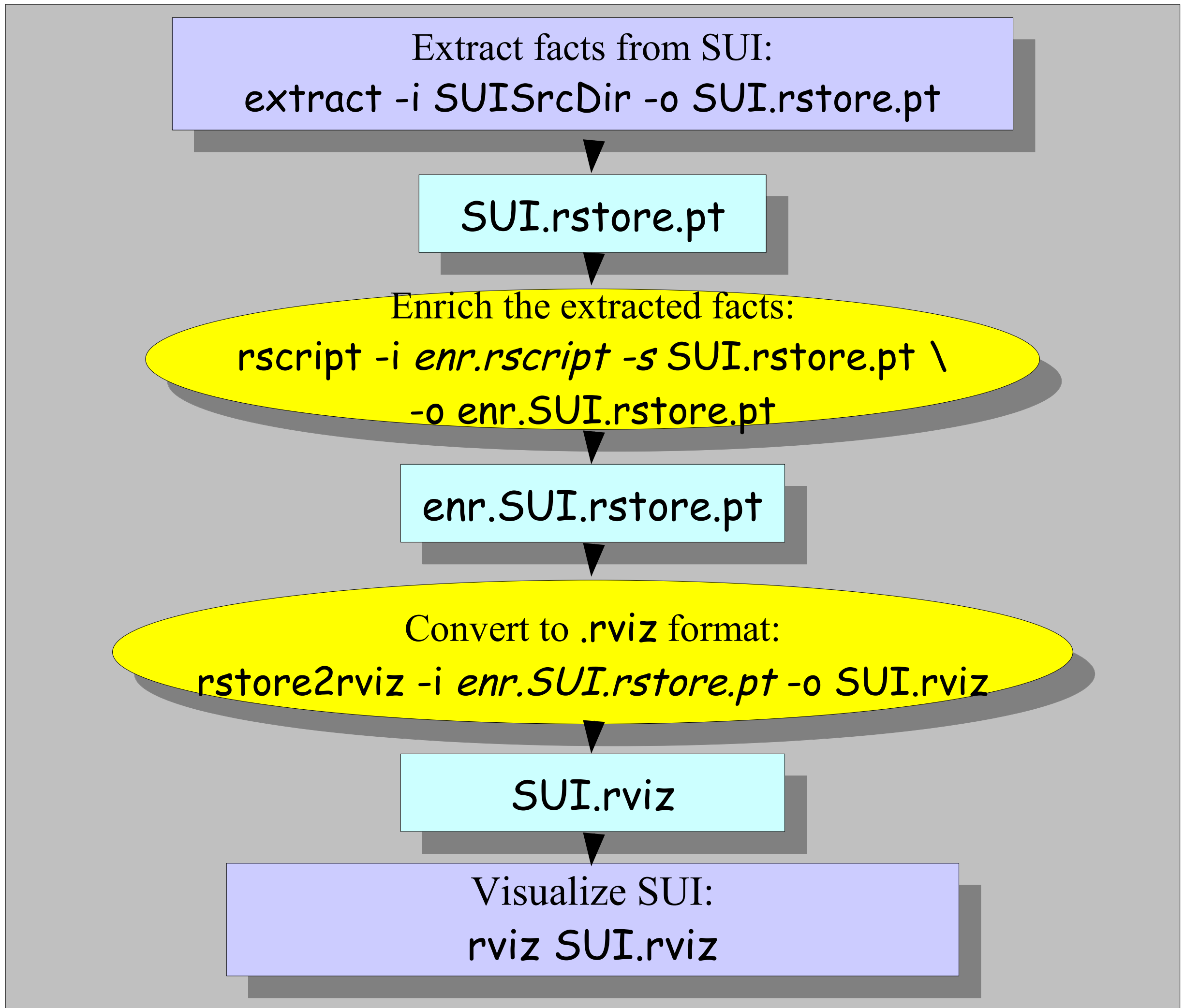
(Courtesy: Arie van Deursen)

Issues in Program Visualization

- Howto display information related to source text?
- Approach (Steven Eick): use a pixel-based image of the source text
- Over 100.000 LOC on one screen!
- Experiment: visualize an Rstore for JHotDRaw (15.000 LOC)

Extraction by Hayco de Jong and Taeke Kooiker (using ASF+SDF)

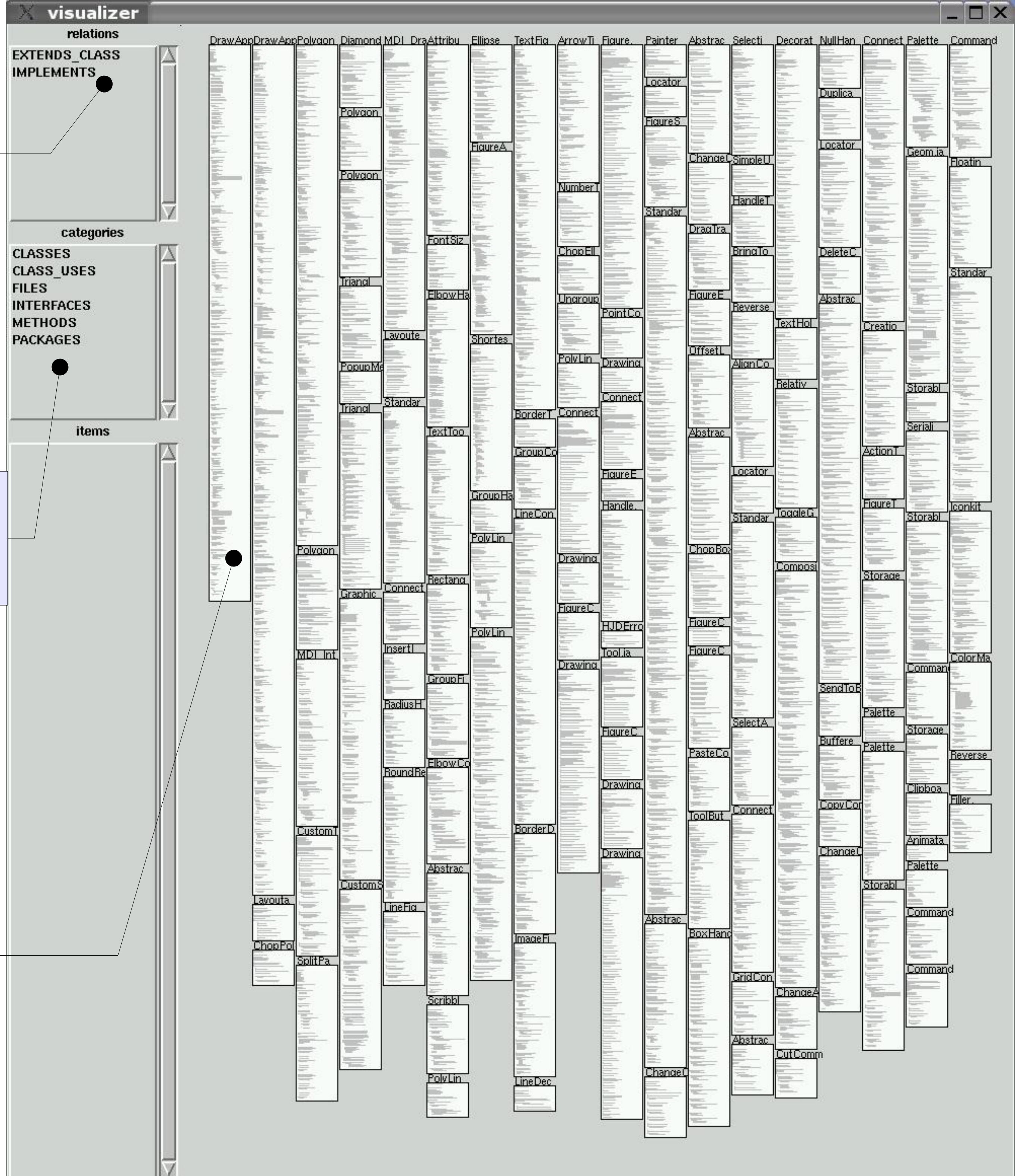
Visualization Workflow

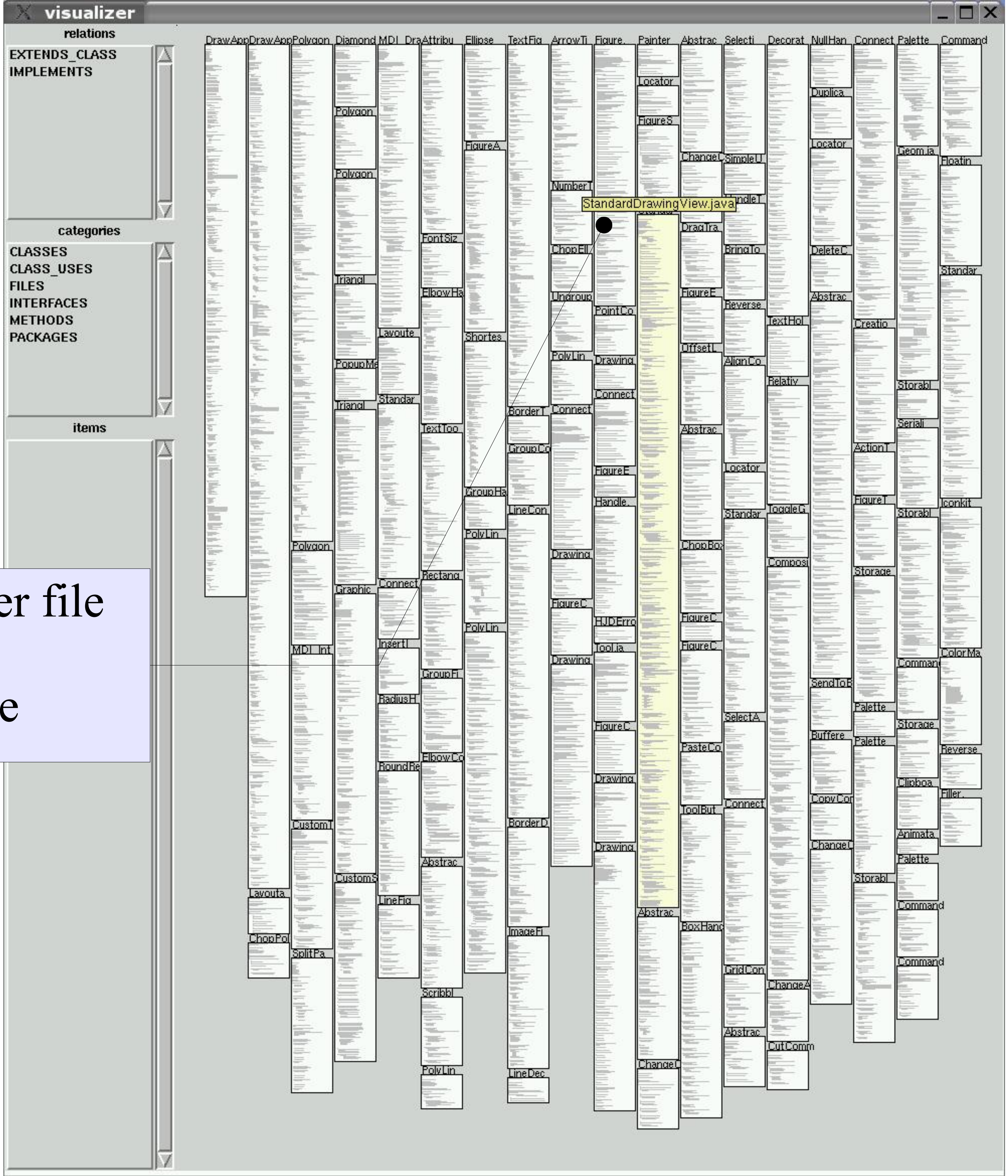


Relations

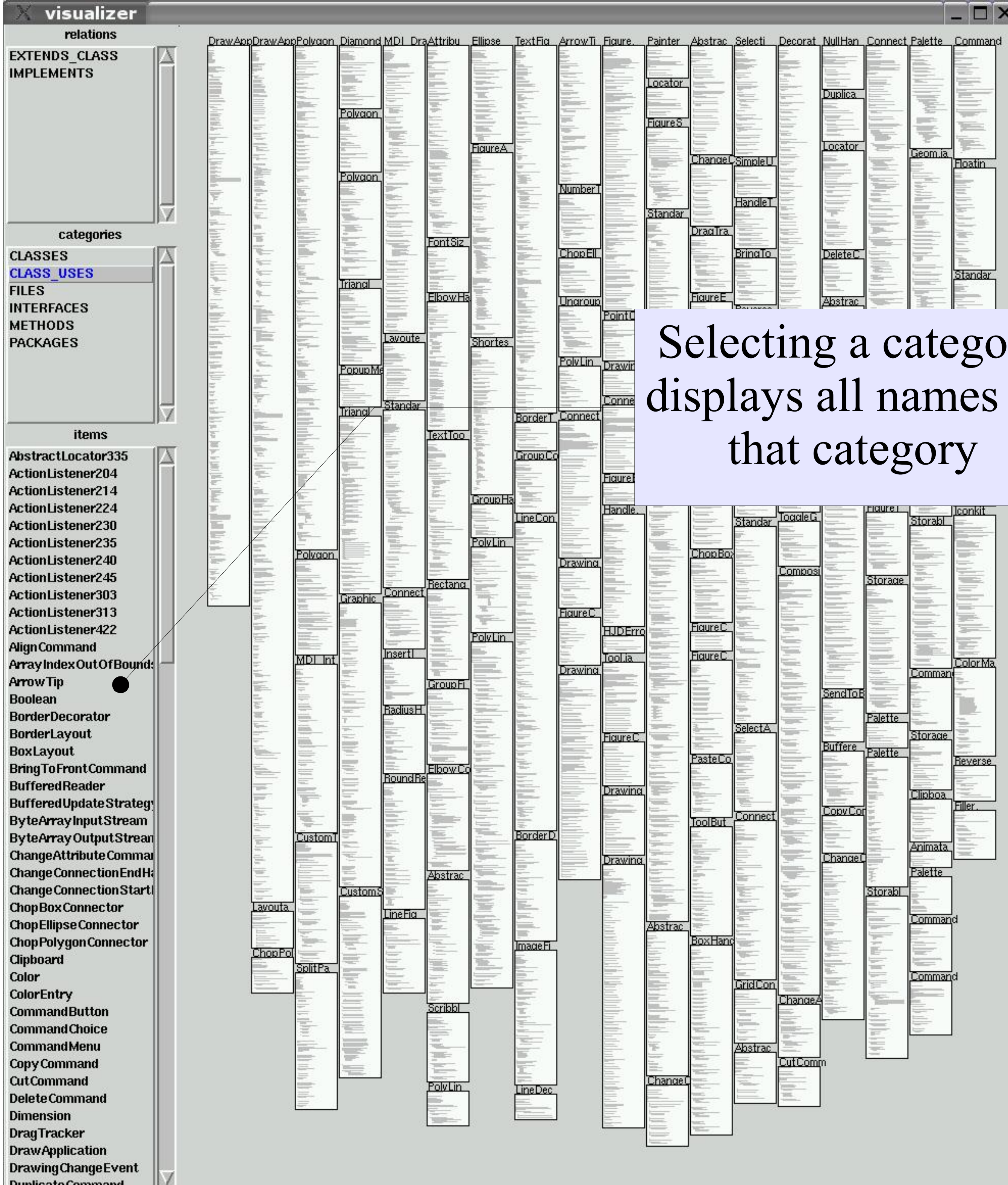
Categories of names

Rectangle per file

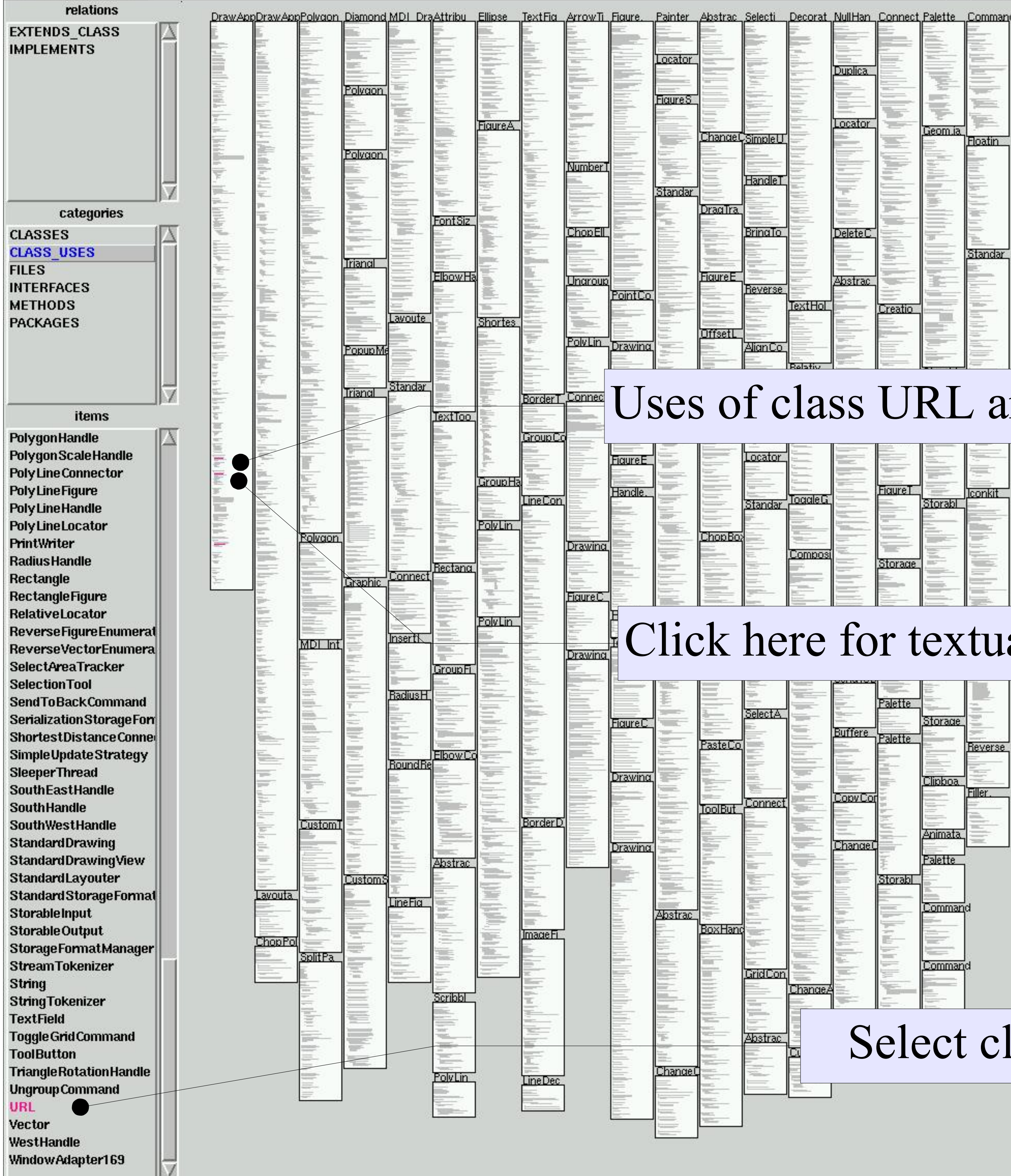




Hovering over file shows full name



Selecting a category displays all names in that category



Uses of class URL are here

Click here for textual view ...

Select class URL

/home/paulk/software/source/sources/CH/ifa/

```java
}

private void readFromStorableInput(String filename) {
    try {
        URL url = new URL(getCodeBase(), filename);
        InputStream stream = url.openStream();
        StorableInput input = new StorableInput(stream);
        fDrawing.release();

        fDrawing = (Drawing)input.readStorable();
        fView.setDrawing(fDrawing);
    } catch (IOException e) {
        initDrawing();
        showStatus("Error:"+e);
    }
}

private void readFromObjectInput(String filename) {
    try {
        URL url = new URL(getCodeBase(), filename);
        InputStream stream = url.openStream();
        ObjectInput input = new ObjectInputStream(stream);
        fDrawing.release();
        fDrawing = (Drawing)input.readObject();
        fView.setDrawing(fDrawing);
    } catch (IOException e) {
        initDrawing();
        showStatus("Error: " + e);
    } catch (ClassNotFoundException e) {
        initDrawing();
        showStatus("Class not found: " + e);
    }
}

private String guessType(String file) {
    if (file.endsWith(".draw"))
        return "storable";
    if (file.endsWith(".ser"))
        return "serialized";
```

Wrap up: Rscript

- A simple, language-independent, relational calculus
- Fully typed
- Equation solver (=> dataflow equations)
- Areas allow close link with source text
- Implementation: ASF+SDF
- IDE: `rscript-meta`
  - an instance of The Meta-Environment

Wrap up : Rscript

- Calls analysis
- Lifting of procedure calls to component relations
- Unitialized/unused variables
- McCabe & friends
- Clones in C code
- Dataflow analysis
  - reaching definitions
  - live variables
- Program slicing
- Java &ToolBus analysis
- Feature Descriptions/ package dependencies

Wrap up: visualization

- A lot of work to do but promising start
- Alternative pixel representations?
- Treemaps for directory structure of files?
- Colormaps for displaying metrics?
- Implementation: Tcl/Tk but may change to Swing
- Some simple visualizations are included in `rscript-meta`

Further reading

- P. Klint, How understanding and restructuring differ from compiling: a rewriting approach, IWPC03
- P. Klint, A tutorial introduction to Rscript on www.meta-environment.org
- `www.cwi.nl/~paulk/publications/all.html`