GRoundTram Version 0.9.3a
User Manual

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Part I

Overview

Chapter 1

A Tutorial for the GRoundTram System

This tutorial will be taking you through a tour of the use of the GRoundTram [1] (Graph Roundtrip Transformation for Models) system to build a bidirectional transformation between two models (graphs).

1.1 Introduction

Bidirectional model transformation plays an important role in maintaining consistency between two models, and has many potential applications in software development, including model synchronization, round-trip engineering, software evolution, multiple-view software development, and reverse engineering.

The GRoundTram system was developed by the BiG team of the National Institute of Informatics for supporting systematic development of bidirectional model transformation. Figure 1.1 depicts an architecture (the basic idea) of the GRoundTram system. A model transformation is described in UnQL+, which is functional (rather than rule-based as in many existing tools) and compositional with high modularity for reuse and maintenance. The model transformation is then desugared to a core graph algebra which consists of a set of constructors for building graphs and a powerful structural recursion for manipulating graphs. This graph algebra can have clear bidirectional semantics and be efficiently evaluated in a bidirectional manner.

The note is intended to demonstrate, through a concrete example, how to use the GRoundTram system to build a bidirectional transformation between two models (graphs). The readers who are interested in the technical details are referred to the technical papers (Hidaka et al. 2008, 2009a,b).

Note that all the sources discussed in this tutorial are available in the `examples` directory in the distribution.

[1] Pronounced [gráund træ̀m].

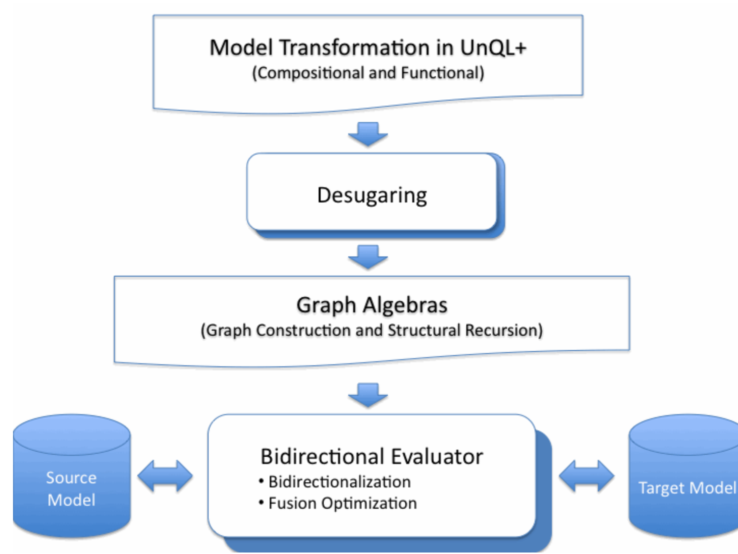


Figure 1.1: A Compositional Framework for Bidirectional Model Transformation

1.2 The Customer2Order Problem

As a concrete example, we consider the problem of developing a bidirectional transformation between the customer model (customer graph) and the order model (order graph), which is adapted from a similar example in the textbook on model-driven software development (Pastor and Molina 2007).

Figure 1.2 gives a simple graph representing customers' information. The graph has a root pointing to two customers, each having a name, some email addresses, several addresses of different types (e.g. shipping or contractual customer address). A customer can have many customer orders. On the other hand, Figure 1.3 shows orders' information, which actually corresponds to those orders in the customers' graph that are of type "shipping". Each order contains order information of the date, the order number, the customer name, and the address to which the goods should be delivered.

We shall show how to construct a bidirectional transformation between these two graphs such that changes on one graph can be propagated to the other one. For example, if we change the "BiG Office of Tokyo" to "BIG Office at NII of Tokyo" in either graph, we should propagate it to the other.

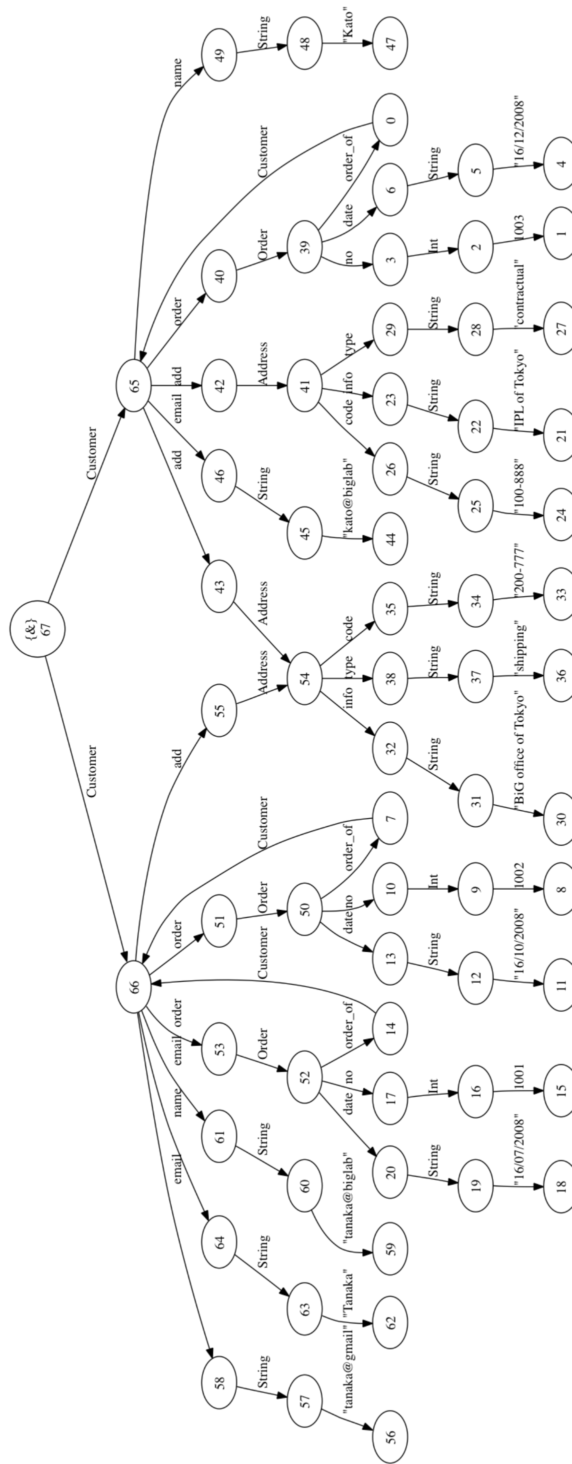


Figure 1.2: Cyclic Graph g_{cus} Representing Customer-Centric Database

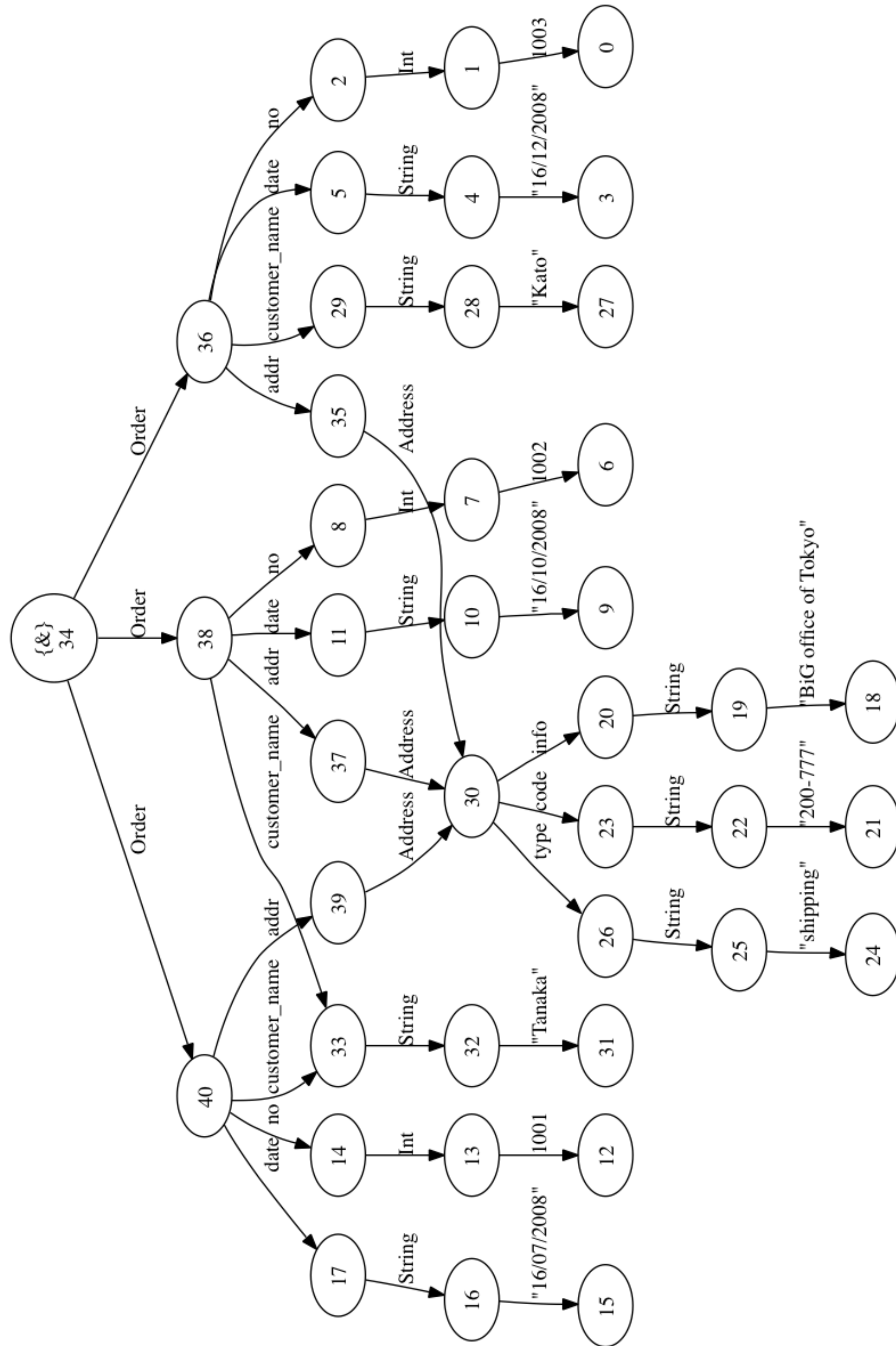


Figure 1.3: Graph g_{ord} Representing Order-Centric Database

1.3 Bidirectional Transformation Development

The development consists of the following three big steps. An important feature of the GRoundTram system is that if a transformation from one model to the other is given, then updating of either model can be correctly propagated to the other. So in the development of our bidirectional transformation between the customer model and the order model, we will put effort into development of a transformation mapping the customer graph (model) to the order graph (model).

1.3.1 Representing Customers' and Orders' Graphs

To develop bidirectional transformation between two graphs (models), first of all, we should be clear about the structures of the two graphs, i.e., the graph schemas of the two graphs. For our running example, the structure of the customer graph can be defined in the schema language KM3 (ATLAS group 2006). To be concrete, we build a file called `Customer.km3` as follows.

```
package Customer {

  datatype String;
  datatype Int;

  class Customer {
    reference name: String;
    reference email [1-*]: String;
    reference add [1-*]: Address;
    reference order [0-*]: Order;
  }

  class Address {
    reference type: String;
    reference code: String;
    reference info: String;
  }

  class Order {
    reference date: String;
    reference no: Int;
    reference order_of: Customer;
  }
}
```

Figure 1.2 gives an instance graph that satisfies this structure. This instance graph is clearly specified in UnCAL as follows. For later explanation, we save it in the file `customers_c.uncal`.

```
&src @ cycle(
(
  &src :=
     { Customer: &customer1,
       Customer: &customer2
```

```
    },

  &customer1 :=
    { name: {String: {"Tanaka"}},
      email: {String: {"tanaka@biglab"}},
      email: {String: {"tanaka@gmail"}},
      add: {Address: &add1},
      order: {Order: &order1},
      order: {Order: &order2}
    },

  &customer2 :=
    { name: {String: {"Kato"}},
      email: {String: {"kato@biglab"}},
      add: {Address: &add1},
      add: {Address: &add2},
      order: {Order: &order3}
    },

  &add1 :=
    { type: {String: {"shipping"}},
      code: {String: {"200-777"}},
      info: {String: {"BiG office of Tokyo"}}
    },

  &add2 :=
    { type: {String: {"contractual"}},
      code: {String: {"100-888"}},
      info: {String: {"IPL of Tokyo"}}
    },

  &order1 :=
    { date: {String: {"16/07/2008"}},
      no: {Int: {1001}},
      order_of: {Customer: &customer1}
    },

  &order2 :=
    { date: {String: {"16/10/2008"}},
      no: {Int: {1002}},
      order_of: {Customer: &customer1}
    },

  &order3 :=
    { date: {String: {"16/12/2008"}},
      no: {Int: {1003}},
      order_of: {Customer: &customer2}
    }
)
)
```

This is a rooted graph starting from the node `&src`, which points to two customers. This UnCAL representation of a graph can be mapped to a graph in the DOT format by the following command.

```
> uncalcmd -q customers_c.uncal -dot customers_c.dot
```

This will produce a dot file named `customers_c.dot`, which can be viewed using the standard `graphviz` system. For example, we can produce a graph in the PNG format by the following command.

```
> dot customers_c.dot -T png -o customers_c.png
```

This will produce exactly the same graph as in Figure 1.2.

Given a (graph) schema and a graph, we can validate whether the graph satisfies the schema using the command `unqlplus`. For instance, we may validate whether the graph `customers_c.uncal` satisfies the schema `Customers.km3` by the following command.

```
> unqlplus -db customers_c.uncal \
           -iv Customer.km3 -ip Customer \
           -q c2o_c.unql
```

The last line specifies the transformation over the customers' graph, which will be developed later and is not important at this stage. One may create the following simple identity transformation in the file `c2o_c.unql` .

```
select $db
```

Similarly, we can specify the schema of the orders' graphs (in the file `Order.km3`) as follows.

```
package Order {

  datatype String;
  datatype Int;

  class Order {
    reference no: Int;
    reference date: String;
    reference customer_name: String;
    reference addr: Address;
  }

 class Address {
    reference type: String;
    reference code: String;
    reference info: String;
  }
}
```

1.3.2 Constructing Forward Transformation from Customer Model to Order Model

After formalizing the two graph schemas, we step to develop transformation from the customer graph to the order graph. Suppose that this transformation is to generate from the customers' graph a graph that represents those information of those orders that have type of "shipping", such that its root points to all the orders and each order contains order information of the date, the order number, the customer name, and the address to which the goods should be delivered. We can code this in UnQL+, our graph query/transformation language, as follows (say in the file `c2o_c.unql`).

```
select
  {Order:
    {date: $date,
     no: $no,
     customer_name: $name,
     addr: {Address: $a}
    }
  }
where
  {Customer.order.Order:$o} in $db,
  {order_of.Customer:$c, date:$date, no:$no} in $o,
  {add.Address:$a, name:$name} in $c,
  {code:$code, info:$info, type.String:{$t:{}}} in $a,
  $t = "shipping"
```

Now we can use the GRoundTram system to apply the transformation on the customer graph `customers_c.uncal` (that meets the schema `Customer.km3`) to generate an order graph (say orders_c.uncal) (that should meet the schema `Order.km3`) by the command `unqlplus`.

```
> unqlplus \
    -db customers_c.uncal \
    -q c2o_c.unql \
    -cal orders_c.uncal \
    -iv Customer.km3 \
    -ip Customer \
    -ov Order.km3 \
    -op Order
    -t -pa -pu
```

This will produce an order graph in the file `orders_c.uncal`, giving a bunch of messages showing the intermediate results in the transformation: validating the input graph, parsing the transformation (query), de-sugaring the transformation to the internal core graph algebra in UnCAL, performing transformation, and validating the output.

```
********* begin Input validation message *************
Input validation took 0.000345 CPU seconds
Validation succeeded.
VMap{Bid(0) => ‘klasse{kname = "Customer"}; Bid(3) => ‘datatype "Int";
  Bid(6) => ‘datatype "String"; Bid(7) => ‘klasse{kname = "Customer"};
```

```
  Bid(10) => ‘datatype "Int"; Bid(13) => ‘datatype "String";
  Bid(14) => ‘klasse{kname = "Customer"}; Bid(17) => ‘datatype "Int";
  Bid(20) => ‘datatype "String"; Bid(23) => ‘datatype "String";
  Bid(26) => ‘datatype "String"; Bid(29) => ‘datatype "String";
  Bid(32) => ‘datatype "String"; Bid(35) => ‘datatype "String";
  Bid(38) => ‘datatype "String"; Bid(40) => ‘klasse{kname = "Order"};
  Bid(42) => ‘klasse{kname = "Address"};
  Bid(43) => ‘klasse{kname = "Address"}; Bid(46) => ‘datatype "String";
  Bid(49) => ‘datatype "String"; Bid(51) => ‘klasse{kname = "Order"};
  Bid(53) => ‘klasse{kname = "Order"}; Bid(55) => ‘klasse{kname = "Address"};
  Bid(58) => ‘datatype "String"; Bid(61) => ‘datatype "String";
  Bid(64) => ‘datatype "String"}
********** end Input validation message **************
(************** begin Submitted Query ****************)
select {Order:{date:$date, no:$no, customer_name:$name, addr:{Address:$a}}}
where
  {Customer.order.Order:$o} in $db,
  {order_of.Customer:$c, date:$date, no:$no} in $o,
  {add.Address:$a, name:$name} in $c,
  {code:$code, info:$info, type.String:{$t:{}}} in $a,
  $t = "shipping"
(**************  end  Submitted Query ****************)
Desugaring took 0.000080 CPU seconds
(************** begin Executed UnCAL expr. ****************)
rec(\ ($L,$fv6).
  if $L = Customer
  then rec(\ ($L,$fv7).
         if $L = order
         then rec(\ ($L,$o).
                if $L = Order
                then rec(\ ($L,$fv5).
                       if $L = order_of
                       then rec(\ ($L,$c).
                              if $L = Customer
                              then rec(\ ($L,$date).
                                     if $L = date
                                     then rec(\ ($L,$no).
                                            if $L = no
                                            then rec(\ ($L,$fv4).
                                                   if $L = add
                                                   then rec(\ ($L,$a).
                                                          if $L = Address
                                                          then rec(\ ($L,$name).
                                                                 if $L = name
                                                                 then
                                                                 rec(\ ($L,$code).
                                                                   if
                                                                   $L = code
                                                                   then
                                                                   rec(\ ($L,$info).
                                                                    if
                                                                    $L = info
                                                                    then
                                                                    rec(\ ($L,$fv1).
                                                                    if
                                                                    $L = type
                                                                    then
```

```
                                                                   rec(\ ($L,$fv2).
                                                                   if
                                                                   $L
                                                                   = String
                                                                   then
                                                                   rec(\ ($t,$fv3).
                                                                   if
                                                                   $t
                                                                   = "shipping"
                                                                   then
                                                                   {
                                                                   Order:
                                                                   {
                                                                   date:
                                                                   $date,
                                                                   no: $no,
                                                                   customer_name:
                                                                   $name,
                                                                   addr:
                                                                   {
                                                                   Address:
                                                                   $a}}}
                                                                   else
                                                                   {})(
                                                                   $fv2)
                                                                   else
                                                                   {})(
                                                                   $fv1)
                                                                   else
                                                                   {})(
                                                                   $a)
                                                                   else
                                                                   {})
                                                                  ($a)
                                                                  else
                                                                  {})
                                                                 ($a)
                                                                 else
                                                                 {})
                                                                ($c)
                                                             else {})
                                                            ($fv4)
                                                        else {})
                                                       ($c)
                                                    else {})
                                                   ($o)
                                                else {})
                                               ($o)
                                            else {})
                                           ($fv5)
                                        else {})
                                       ($o)
                                    else {})
                                   ($fv7)
                                else {})
                               ($fv6)
                            else {})
```

```
($db)
(**************  end  Executed UnCAL expr. ****************)
Evaluation took 1.629894 CPU seconds
********* begin Output validation message *************
Output validation took 0.000101 CPU seconds
Validation succeeded.
VMap{Bid(2) => `datatype "Int"; Bid(5) => `datatype "String";
  Bid(8) => `datatype "Int"; Bid(11) => `datatype "String";
  Bid(14) => `datatype "Int"; Bid(17) => `datatype "String";
  Bid(20) => `datatype "String"; Bid(23) => `datatype "String";
  Bid(26) => `datatype "String"; Bid(29) => `datatype "String";
  Bid(33) => `datatype "String"; Bid(35) => `klasse{kname = "Address"};
  Bid(37) => `klasse{kname = "Address"};
  Bid(39) => `klasse{kname = "Address"}}
********** end Output validation message **************
```

This finishes development of the (forward) transformation. Two remarks are worth making. First, the command `unqlplus` is very powerful, with many useful options; one can get information about the options of the command `unqlplus` by typing

```
> unqlplus --help
```

Second, we can alternatively execute the following command to perform the forward transformation which will produce more additional files (the ei file that contains more editing information and the xg file that represents the result graph being attached to the abstract syntax tree) that are necessary in the backward transformation. Note that we omit graph validation here.

```
> fwd_uncal \
    -db customers_c.uncal \
    -uq c2o_c.unql \
    -dot orders_c.dot \
    -png orders_c.png \
    -xg orders_c.xg \
    -ei orders_c.ei \
    -ge  -pa
```

One can check the result graph by either seeing the graph in the PNG format (i.e, `orders_c.png`) or that in the DOT format (i.e., `orders_c.dot`). Note that this forward transformation command without validation is quite convenient and useful, because it allows us to test transformation without giving the definition of graph schemas.

1.3.3 Type Checking Forward Transformation

By specifying KM3 schemas via `-iv` and `-ov` options of the `unqlplus` command, we can dynamically check at each run whether the given input graph and the generated output graph meet the KM3 schemas.

In fact, the check can also be done statically. By passing input/output KM3 schema files and a transformation described either in UnQL$^+$ or UnCAL to the `chkuncal` command, we can verify that *any* graph satisfying the input schema will *always* be transformed to an output graph satisfying the output schema. In other words, once we have verified the correctness by `chkuncal`, we can be

sure that for all correct input graphs, the output graphs must meet the schema. After the static checking, we can safely omit the per-run checking by `-ov`.

To use the typechecking facility of `chkuncal`, we need the MONA tool (Project) to be installed on our system. Before trying the following examples, please download and set up MONA from `http://www.brics.dk/mona/`.

Static Type Checking Example

Consider we would like to check the correctness of the following transformation `c2date.uncal`, which extracts all the shipping dates from the customer database (the examples are placed in the `example/typecheck` directory):

```
rec( \($L,$G).
       if $L = Customer then &
  else if $L = order then &
  else if $L = Order then &
  else if $L = date then {Date: {date: $G}}
  else {}
)($db)
```

Expected input graphs are those meeting the schema `Customer.km3` used in the previous section. But since for a technical reason the current version of `chkuncal` does not accept the schema, we check the correctness against a slight variant of the schema, `Customer_tc.km3`:

```
package Customer_tc {
  datatype String;
  datatype Int;
  class Customer {
    reference name [0-*]: String;
    reference email [0-*]: String;
    reference add [0-*]: Address;
    reference order [0-*]: Order;
  }
  class Address {
    reference type[0-*]: String;
    reference code[0-*]: String;
    reference info[0-*]: String;
  }
  class Order {
    reference date[0-*]: String;
    reference no[0-*]: Int;
    reference order_of[0-*]: Customer;
  }
}
```

The difference is that we have added the number constraints `[0-*]` to all fields; currently `chkuncal` can deal only with this type of schemas. The restriction will be eliminated in a future version. For the detailed description of the subset of languages supported by `chkuncal`, please consult Chapter 15.

Expected output graphs from `c2date.uncal` should be a collection of `date` fields, capture by the following KM3 schema `Date.km3`:

```
package Date {
  datatype String;
  class Date {
    reference date[0-*]: String;
  }
}
```

To verify that the transformation is really correct with respect to the schemas, what we need to type is the following one line of command:

```
> chkuncal Customer_tc.km3 c2date.uncal Date.km3
```

Then we will get the following diagnostics:

```
> chkuncal Customer_tc.km3 c2date.uncal Date.km3
...Loading Schema and UnCAL files...
...Converting UnCAL to MSO...
...Generating auxiliary formulas...
...Converting Schemas to MSO...
...Validation process is running (may take time)...
Success!
```

The message `Success!` means that the transformation is verified that it never produces ill-typed outputs.

To see what happens if we try to verify a type-incorrect transformation, let us consider another example, `c2date-bad.uncal`:

```
rec( \($L,$G).
       if $L = Customer then &
  else if $L = order then &
  else if $L = Order then &
  else if $L = date then {Date: {data: $G}}
  else {}
)($db)
```

Can you see the difference? This version has a typo `data` (instead of `date`), which makes the output not conforming to the schema. The `chkuncal` can detect the badness as follows:

```
> chkuncal Customer_tc.km3 c2date-bad.uncal Date.km3
...Loading Schema and UnCAL files...
...Converting UnCAL to MSO...
...Generating auxiliary formulas...
...Converting Schemas to MSO...
...Validation process is running (may take time)...
Failure!
For a valid input
  {Customer: {order: {Order: {date}}, order}, Customer},
the UnCAL program will produce an invalid output
  {Date: {data}}.
```

When an error was found as above, `chkuncal` always exhibits a counter-example (i.e., a graph that satisfies the input schema but yields an output graph not satisfying the output schema) to help fixing the bug.

By using the `-g` option, the counter-example is exported in the `.dot` format of the `graphviz` system.

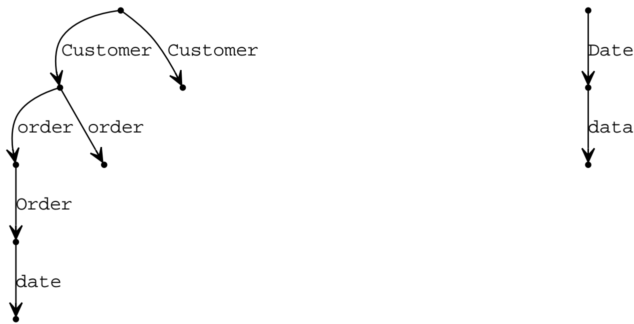


Figure 1.4: A Counter-Example from `chkuncal`

```
> chkuncal Customer_tc.km3 c2date-bad.uncal Date.km3 \
     -g counter-example.dot
> dot counter-example.dot -Tpng -o counter-example.png
```

This will produce the visualized counter-example in Figure 1.4.

1.3.4 Testing Backward Transformation

One important feature of the GRoundTram system is that it can not only keep trace information between the source (input) and the target (result) models, but can also propagate the changes on the target model to the source.

Checking Trace Information

We can check the trace information by turning on the option `-sb` (set skolem-bulk) when executing the `fwd_uncal` command so that the nodes of the result graph can be attached with information showing where the nodes come in the source graph.

```
> fwd_uncal \
    -db customers_c.uncal \
    -uq c2o_c.unql \
    -dot orders_c_trace.dot \
    -png orders_c_trace.png \
    -xg orders_c_trace.xg \
    -ei orders_c_trace.ei \
    -sb -ge  -pa
```

The generated graph is saved in the file `orders_c_trace.dot`. It has the following contents.

```
digraph "g" {
    node [ shape = "ellipse" ]

    "FrE(FrE(FrE(FrE(FrE(FrE(FrE(FrE(FrE(FrE(FrE(FrE(FrE(FrE(FrE(
      ImT (1047,&),
      (37,\"shipping\",36),1051),
      (38,String,37),1053),
      (54,type,38),1055),
      (54,info,32),1057),
      (54,code,35),1059),
      (66,name,64),1061),
      (55,Address,54),1063),
      (66,add,55),1065),
      (52,no,17),1067),
      (52,date,20),1069),
      (14,Customer,66),1071),
      (52,order_of,14),1073),
      (53,Order,52),1075),
      (66,order,53),1077),
      (67,Customer,66),1079)"   [ label = "\N" ]

     "FrE(FrE(FrE(FrE(FrE(FrE(FrE(FrE(FrE(FrE(FrE(FrE(FrE(FrE(FrE(
       ImT (1047,&),(37,\"shipping\",36),1051),
       (38,String,37),1053),(54,type,38),1055),
       ...

    ...
}
```

Here the name of each node is very long, containing information of all the edges in the source graph that contribute to the construction of this node. For example, the first node in the above example shows that it is related to the edges such as `(37,"shipping",36)`, `(38,String,37)` in the source graph in Figure 1.2.

Editing the Order Graph

Before showing how to do backward computation to propagate changes on the order graph to the original customer graph, let us see how to change the order graph by editing. Since the order graph with trace information is long and difficult to read, we shall work on the order graph in the file `orders_c.dot`, where all the nodes have simpler names.

```
digraph "g" {
    node [ shape = "ellipse" ]
    "n65658" [ label = "{&}\n\N" ]
    "n65115" [ label = "\N" ]
    "n65109" [ label = "\N" ]
```

```
    "n44897" [ label = "\N" ]
    "n44891" [ label = "\N" ]
    "n44201" [ label = "\N" ]
    "n44195" [ label = "\N" ]
    "n64" [ label = "\N" ]
    "n63" [ label = "\N" ]
    "n62" [ label = "\N" ]
    ...

    "n65658" -> "n65115" [ label = "Order" ]
    "n65658" -> "n44897" [ label = "Order" ]
    "n65658" -> "n44201" [ label = "Order" ]
    "n65115" -> "n17" [ label = "no" ]
    "n65115" -> "n20" [ label = "date" ]
    "n65115" -> "n64" [ label = "customer_name" ]
    "n65115" -> "n65109" [ label = "addr" ]
    "n64" -> "n63" [ label = "String" ]
    "n63" -> "n62" [ label = "\"Tanaka\"" ]
    "n54" -> "n38" [ label = "type" ]
    "n54" -> "n32" [ label = "info" ]
    "n54" -> "n35" [ label = "code" ]
    "n49" -> "n48" [ label = "String" ]
    "n48" -> "n47" [ label = "\"Kato\"" ]
    "n38" -> "n37" [ label = "String" ]
    "n37" -> "n36" [ label = "\"shipping\"" ]
    "n35" -> "n34" [ label = "String" ]
    "n34" -> "n33" [ label = "\"200-777\"" ]
    "n32" -> "n31" [ label = "String" ]
    "n31" -> "n30" [ label = "\"BiG office of Tokyo\"" ]
    "n20" -> "n19" [ label = "String" ]
    "n19" -> "n18" [ label = "\"16/07/2008\"" ]
    "n17" -> "n16" [ label = "Int" ]
    "n16" -> "n15" [ label = "1001" ]
    "n13" -> "n12" [ label = "String" ]
    "n12" -> "n11" [ label = "\"16/10/2008\"" ]
    "n10" -> "n9" [ label = "Int" ]
    "n9" -> "n8" [ label = "1002" ]
    "n6" -> "n5" [ label = "String" ]
    "n5" -> "n4" [ label = "\"16/12/2008\"" ]
    "n3" -> "n2" [ label = "Int" ]
    "n2" -> "n1" [ label = "1003" ]
}
```

Changes on the order graph can be done by directly editing its dot file. For instance, we may edit the above file by changing the line

```
"n31" -> "n30" [ label = "\"BiG office of Tokyo\"" ]
```

to

```
"n31" -> "n30" [ label = "\"BiG office at NII of Tokyo\"" ]
```

and save it to `orders_c_mod.dot`.

Alternatively, we may use our tool, Bdotty, a small extension of DOTTY editor, for this editing. The tool should be installed easily if you already have DOTTY installed. Please refer to Bdotty User's Guide for installation instructions. Here we assume you have Bdotty command installed. With this tool, you can, for example, edit the label of an edge by selecting "set edge label" on the context menu that appears when it is called while pointing on the circle on the edge. On the text box in the dialog window, type in "XXX" to set the label to value "XXX".

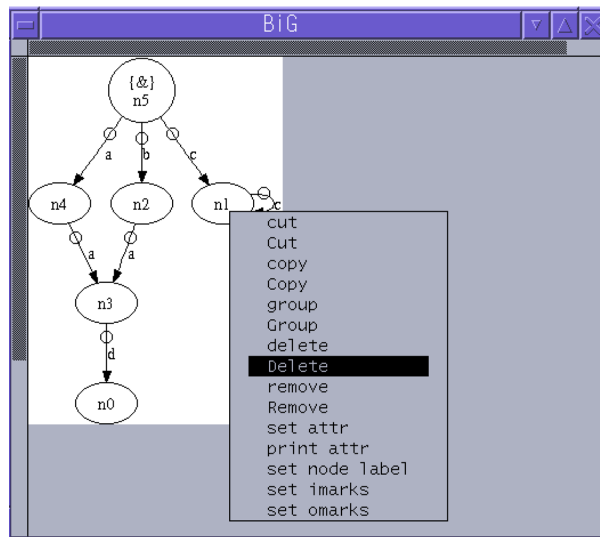


Figure 1.5: DOTTY screen shot while editing the result of a forward evaluation

Performing Backward Updating

Now we can propagate the changes on the target graph (the order model) to the source graph (the customer model) with the following command.

```
> bwd_uncal \
    -db customers_c.uncal \
    -xg orders_c.xg \
    -ei orders_c.ei \
    -dot orders_c_mod.dot \
    -png customers_c_mod.png \
    -ucal customers_c_mod.uncal \
    -udot customers_c_mod.dot -pa -cm
```

This will update the customer model and save the updated result in different formats (`customers_c_mod.png`, `customers_c_mod.uncal`, `customers_c_mod.dot`). Note that the current version of the system is

a bit slow in this backward transformation; it may take a few minutes for this example.

Figure 1.11 shows the result of the backward transformation in which propagated modifications on edges or nodes are indicated by the following colors: deleted parts are displayed in lightpink, added parts are displayed in purple, and modified labels are displayed in red. Unreachable parts (if any) are displayed in gray.

It is worth noting that the current backward transformation can fully support propagation of all valid in-place modification, but only partially support propagation of insertion and deletion (that are independent of computation of structural recursions). We treat complex insertion and deletion on graphs that are produced by structural recursion in a special way, as discussed below.

Reflecting General Insertion

To be concrete, assume that we are given three files:

- `a2d_xc.uncal`: a transformation to replace all labels `a` by `d` and short edges labeled `c`.

```
rec(\ ($l,$g).
  if $l = a then {d: &}
  else if $l = c then &
  else                {$l: &})($db)
```

- `db.dot`: a dot file representing the input graph (in Figure 1.6). Note that this dot file can be obtained from the following uncal code (`db.uncal`)

```
cycle((
         &  := {a:{a:&z1},b:{a:&z1},c:&z2},
         &z1:= {d:{}},
         &z2:= {c:&z2}
    ))
```

  by the following command.

```
> uncalcmd -q db.uncal -dot db.dot
```

- `to_be_inserted.dot`: a dot file representing the graph (in Figure 1.8) to be inserted to the view later. Note this dot file can be obtained from an uncal file, as seen above.

Note that by forward evaluation of `a2d_xc` on `db.dot`, we can easily obtain a view (`view.dot`) (as in Figure 1.7) by running

```
> uncalcmd -idot db.dot -q a2d_xc.uncal -odot view.dot
```

Now to demonstrate reflection of insertion on the view to the input, we may execute the following command

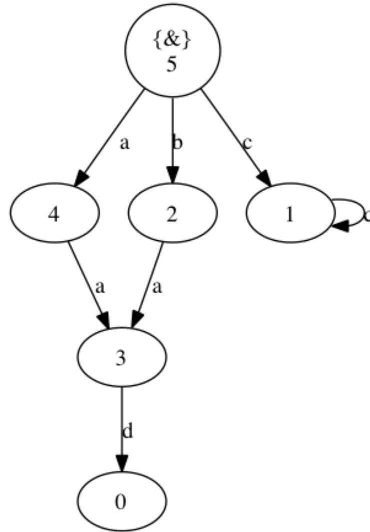


Figure 1.6: An Input Graph for `a2d_xc`

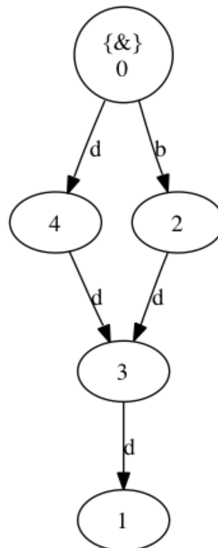


Figure 1.7: A View Graph Produced by `a2d_xc`

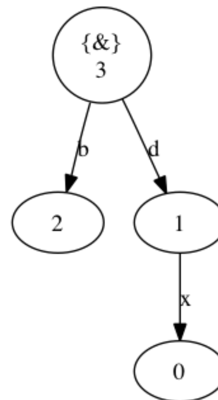


Figure 1.8: A Graph to be Inserted to the View Produced by a2d_xc

```
> bwdIg_uncal \
   -idot db.dot \
   -q a2d_xc.uncal \
   -odot oview.dot \
   -ipt 3 \
   -tidot to_be_inserted.dot \
   -uidot udb.dot \
   -uodot uview.dot
```

to insert the to_be_inserted graph to the view at the node, say numbered 3, resulting in the graph in Figure 1.9, and reflect this insertion to the input graph, resulting in the graph in Figure 1.10.

1.4 More Examples

More examples for bidirectional model transformation can be found at the following demo page of the GRoundTram system.

http : //www.biglab.org/demo.html

This demo page enables one to test all the functionality of the GRoundTram system without the need to install the system on one's local computer.

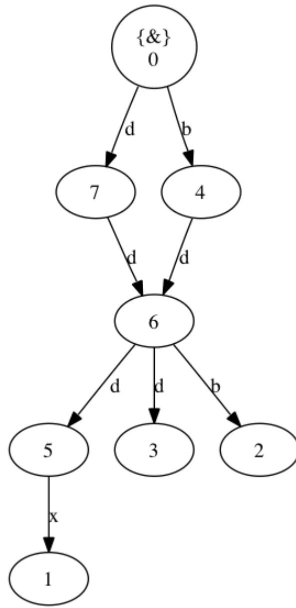


Figure 1.9: An Updated View

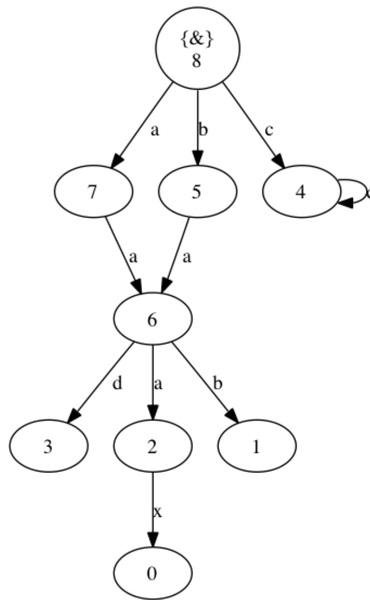


Figure 1.10: An Updated Input Graph

Figure 1.11: Updated Customers' Graph

Part II

Language References

Chapter 2

UnQL$^+$

UnQL$^+$ is a high-level, SQL-like programming language for describing graph transformations. UnQL$^+$ extends the UnQL graph querying language (Buneman et al. 2000) with three simple graph editing constructs: `replace`, `delete`, and `extend`.

2.1 Syntax

UnQL$^+$ is a small extension of UnQL to support convenient specification of graph transformations (model transformations). We extend UnQL with three editing constructs for transforming graphs. An UnQL$^+$ expression takes a graph as input and results in a graph.

The following BNF defines the syntax of UnQL$^+$ *expr*ession.

```
expr ::= select template ( where bc1 , ..., bcn )?                     (* selection *)
       | replace rpp ->gvar by template1 in template2
           where bc1 , ..., bcn                                     (* replacement *)
       | delete rpp ->gvar in template
           where bc1 , ..., bcn                                        (* deletion *)
       | extend rpp ->gvar with template1 in template2
           where bc1 , ..., bcn                                       (* extension *)
```

The following BNF defines a graph.

```
template ::= {label_1 : template_1 , . . . , label_n : template_n} (* union of graphs *)
           | template_1 U template_2                                (* union of graphs *)
           | (expr)                                                 (* value of an expression *)
           | fname(template)                                        (* function application *)
           | if bool_cond then template_1 else template_2           (* conditional *)
           | let gvar = template_1 in template_2                    (* variable binding *)
           | let sfun fname({lp_1 : gp_1}) = template_1
                    | fname({lp_2 : gp_2}) = template_2
                      . . .
                    | fname({lp_n : gp_n}) = template_n
             in template                                            (* structural recursion *)
           | letrec sfun fname_1 ({lp_11 : gp_11}) = template_11
                       | fname_1 ({lp_12 : gp_12}) = template_12
                         . . .
                       | fname_1 ({lp_1m_1 : gp_1m_1}) = template_1m_1
             and
                       . . .
             and
                    sfun fname_n ({lp_nm_1 : gp_nm_1}) = template_nm_1
                       | fname_n ({lp_n2 : gp_n2}) = template_n2
                         . . .
                       | fname_n ({lp_nm_n : gp_nm_n}) = template_nm_n
             in template                                            (* mutual structural recursion *)
           | gvar                                                   (* graph variable *)
```

The following BNF defines Boolean conditions and/or binding conditions.

```
bc ::= bool_cond (* boolean condition *)
     | bind_cond (* binding condition *)
```

```
bool_cond ::= (bool_cond)                              (* parenthesized expression *)
            | isempty(template)                        (* is the graph empty? *)
            | true | false                             (* boolean literal *)
            | not bool_cond | bool_cond_1 and bool_cond_2
            | bool_cond_1 or bool_cond_2               (* logical op *)
            | label_1 = label_2
            | label_1 < label_2 | label_1 > label_2    (* label comparison *)
```

```
bind_cond ::= gp in template (* binding condition *)
```

The following BNF defines label patterns.

```
lp ::= lvar          (* label variable *)
     | rpp (* regular path pattern *)
```

The following BNF defines graph patterns.

```
gp ::= gvar                                  (* graph variable *)
     | {lp_1 : gp_1 , . . . , lp_n : gp_n}   (* union of graphs *)
     | const                                 (* constant *)
```

The following BNF defines regular path patterns.

rpp	::=	*label_const*	(* label *)
	|	_	(* any label *)
	|	*rpp* . *rpp*	(* concatenation *)
	|	(*rpp* | *rpp*)	(* union *)
	|	*rpp*?	(* option *)
	|	*rpp*+	(* one or more *)
	|	*rpp**	(* zero or more *)

The following BNF defines label expressions.

label	::=	*lvar*	(* label variable *)
	|	*label_const*	(* constant *)
	|	*label* ^ *label*	(* concatenation *)

*Var*iables start with the `$` sign. The label variables *lvar* and graph variables *gvar* are not lexically distinguished.

letter	::=	`a-z` | `A-Z` | `0-9` | _ | '
lvar	::=	`$`*letter**
gvar	::=	`$`*letter**
fname	::=	*letter** (* function name *)

Operator precedence and associativity is:

	Operator	Associativity
(high)	`not`, `isempty`	-
	`*`	left
	`.`	left
	|	left
	`^`	right
	`=`,`<`,`>`	-
	`and`	left
	`or`	left
	`U`	left
(low)	`,`	left

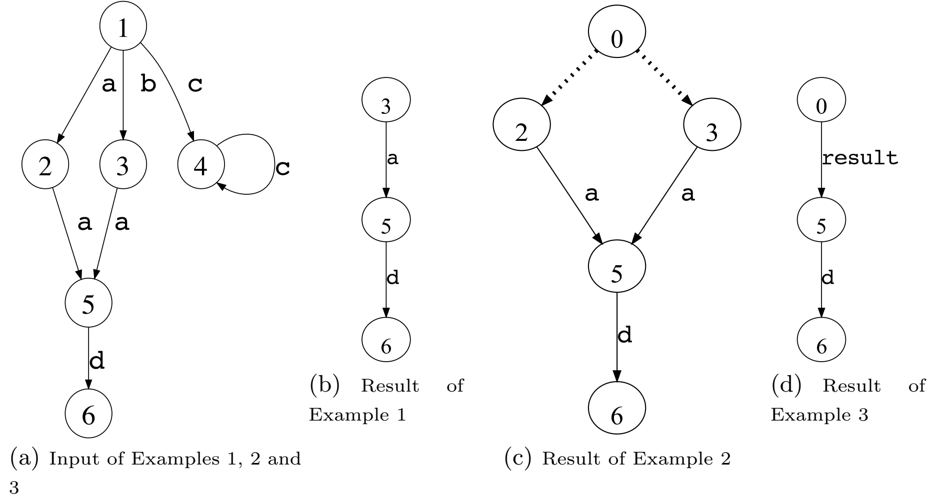
2.2 Graph Querying

2.2.1 The `select-where` Construct

A query of the form `select` *template* `where` $bc_1, \ldots, bc_n$ extracts information from graphs based on the binding and/or Boolean conditions bc_1 , ... , bc_n and constructs a graph according to the *template*.

Example 1. The following query returns subgraphs that are pointed by `b` from the root of $\$db$.

`select` $\$G$ `where` {`b` : $\$G$} `in` $\$db$



(a) Input of Examples 1, 2 and 3

(b) Result of Example 1

(c) Result of Example 2

(d) Result of Example 3

Figure 2.1: Result Graphs of Query Examples on Figure 2.1(a)

This query first matches the graph pattern $\{\texttt{b} : \$G\}$ against the graph $\$db$ and gets bindings for $\$G$, and then produces the result according to the `select` part. Figure 2.1(b) shows the result of this query. □

Example 2. The following query has multiple conditions in the `where` part and construction of graphs in the `select` part.

$$\texttt{select}\ \$G_1 \cup \$G_2\ \texttt{where}\ \{\texttt{b} : \$G_1\}\ \texttt{in}\ \$db, \\ \{\texttt{a} : \$G_2\}\ \texttt{in}\ \$db$$

It returns all subgraphs that are pointed by either `b` or `a` from the root. Figure 2.1(c) shows the result of this query. □

Regular Path Patterns

Regular path patterns, similar to XPath, are provided for concisely expressing "deep" queries against a graph.

Example 3. Consider the following query.

$$\texttt{select}\ \{\texttt{result} : \$G_1\}\ \texttt{where}\ \{_*.(\texttt{a}|\texttt{b}) : \$G_1\}\ \texttt{in}\ \$db, \\ \{\$l : \$G_2\}\ \texttt{in}\ \$G_1, \\ \$l \neq \texttt{a}$$

It extracts all subgraphs $\$G_1$ according to the regular path $_*.(\texttt{a}|\texttt{b})$ (i.e., any path ending with an edge labelled `a` or `b`), keeps those subgraphs that do not contain an edge of `a` from their root, and glues the results with new edges labelled `result`. It returns all subgraphs that are pointed by either `b` or `a` from the root. Figure 2.1(d) shows the result of this query. □

2.3 Graph Editing

UnQL$^+$ is a small extension of UnQL to support convenient specification of graph transformations (model transformations). We extend UnQL with three editing constructs for transforming graphs: `replace`, `delete` and `extend`. For graph editing, UnQL$^+$ employs snapshot semantics, which is widely used in many query languages such as SQL, XQuery!, XQueryU, Flux and so on. Snapshot semantics consists of two logical phases of processing: first, it specifies nodes to be updated then updates are applied to the nodes. The semantics of the graph editing is that for a given graph, starting from the root node of the graph, it traverses every path and specifies nodes to be updated, then performs editing on the nodes.

2.3.1 The `replace-where` Construct

The replacement construct, `replace ... where ...`, is used to replace a subgraph by a new graph. For example, consider the Class graph in Figure 2.2, how to prefix every name of the class by "class_" can be specified as follows. Note that "^" is a built-in function, which performs string concatenation.

```
replace _*.Class.name.String -> $u
by {("class_" ^ $name):{}} in $db
where {$name: $v} in $u
```

2.3.2 The `delete-where` Construct

The deletion construct, `delete ... where ...`, is used to describe deletion of part of the graph. Consider the Class graph in Figure 2.2, how to delete all persistent classes can be described by

```
delete Association.(src|dest).Class -> $class in $db
where {is_persistent.Boolean:true} in $class
```

where the subgraph matched with $class will be deleted from its original graph. In contrast, the following transformation keeps the persistent classes as result.

```
select {result: $class}
where
 {Association.(src|dest).Class: $class} in $db,
 {is_persistent.Boolean:true} in $class
```

So, we may consider the `delete` as the dual of the `select`.

2.3.3 The `extend-where` Construct

The extension construct, `extend ... where ...`, is used to extend a graph with another one. For example, we may write the following transformation to add a `date` to each `class`.

```
extend _*.Class -> $u with {date:"2011/3/4"} in $db
```

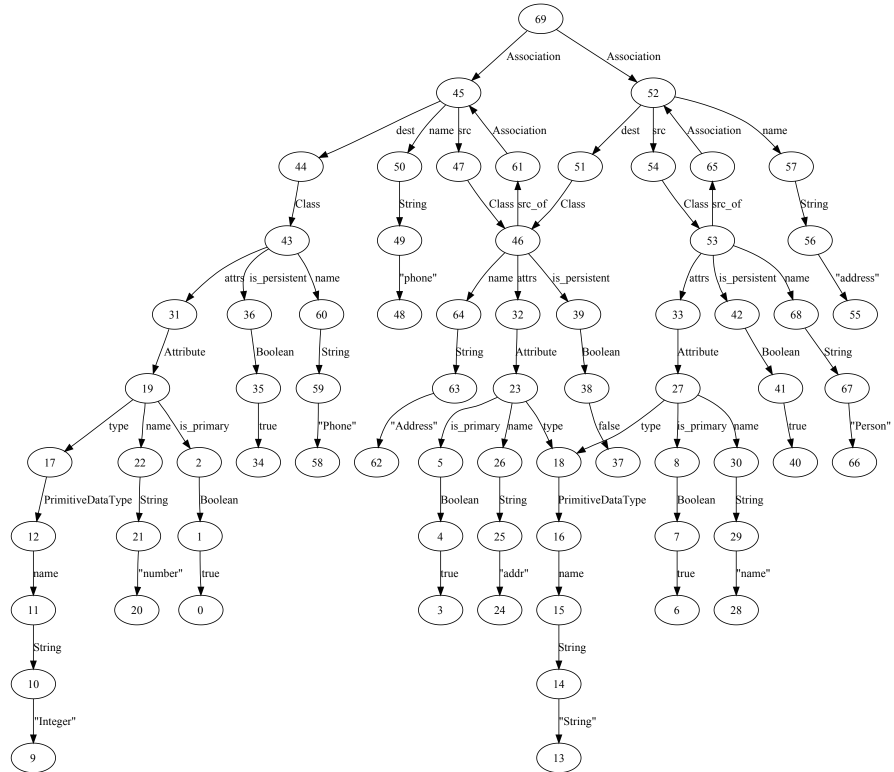


Figure 2.2: A Class Model Represented by an Edge-Labelled Graph

Chapter 3

UnCAL

UnCAL is the core graph algebra of the graph query language UnQL (Buneman et al. 2000) and our extension UnQL$^+$ (see Chapter 2). Input and output graphs for an UnQL$^+$ program are written in the UnCAL format.

Moreover, UnCAL can also describe graph *transformations*, not just graphs themselves. So, we have two graph transformation languages (UnQL$^+$ and UnCAL) in the GRoundTram system. Compared to UnQL$^+$, which is a more high-level and user-friendly language, UnCAL is rather low-level and machine-friendly; indeed, in the GRoundTram system, all UnQL$^+$ programs are first compiled into UnCAL and then run. Although in most cases UnQL$^+$ should be sufficient for writing graph transformations, you can also write UnCAL programs directly. Besides, since the bidirectional transformation semantics of the GRoundTram system is defined in terms of UnCAL, it might be helpful to know the overview of UnCAL for understanding the bidirectional behavior.

We first show the full grammar of UnCAL in Section 3.1, and then, we give a brief overview of each feature. For those who are interested only in how to write input/output graph data by UnCAL, Section 3.2 is the important part. You may skip other sections concerning graph transformations in Section 3.3. Note that this manual is not intended to give a rigorous description of the UnCAL language; the readers who are interested in the formal definition of the semantics might want to consult the technical papers (Buneman et al. 2000; Hidaka et al. 2008, 2009a,b).

3.1 Syntax

The hole UnCAL program consists of one graph construction *expr*ession, defined as in the following BNF. Compared to the original definition in (Buneman et al. 2000), the one implemented in the GRoundTram system adds two constructs `let` and `llet` for ease of programming.

```
expr ::= {}                                              (* one-node graph *)
       | { label1 : expr1 , ... , labeln : exprn }       (* new node *)
       | expr1 U expr2                                   (* union *)
       | marker := expr        (* label the root node with input marker *)
       | marker                          (* graph with output marker *)
       | ()                                                (* empty graph *)
       | expr1 ++ expr2                                  (* disjoint union *)
       | expr1 @ expr2                                         (* append *)
       | cycle( expr)                                (* graph with cycles *)
       | (expr1 , ... , exprn)         (* same as expr1++···++exprn *)
       | literal                           (* same as {literal : {}} *)
       | gvar                                   (* variable reference *)
       | doc("char*")                          (* loading another file *)
       | if cond then expr1 else expr2                    (* conditional *)
       | rec(\(lvar , gvar) . expr1)( expr2 ) (* structural recursion *)
       | let gvar = expr1 in expr2                  (* variable binding *)
       | llet lvar = expr1 in expr2           (* label variable binding *)
```

Operator precedence and associativity is:

	Operator	Associativity
(high)	`@`	left
	`if then else`	-
	`U`	right
	`:=`	left
	`++`	right
(low)	`,`	left

*Var*iables start with the `$` sign and *mark*ers start with the `&` sign. The label variables *lvar* and graph variables *gvar* are not lexically distinguished.

```
letter ::= a-z | A-Z | 0-9 | _ | '

lvar   ::= $letter*
gvar   ::= $letter*
marker ::= (&letter*)+
```

Boolean *cond*itions are used as the branching condition for `if` expressions:

```
cond ::= ( cond )                           (* parenthesized expression *)
       | isempty( expr)                         (* is the graph empty? *)
       | isBool( label) | isString( label)
       | isInt( label) | isFloat( label)
       | isLabel( label)                                (* type testing *)
       | true | false                                (* boolean literal *)
       | not cond | cond1 and cond2 | cond1 or cond2      (* logical op *)
       | label1 = label2
       | label1 < label2 | label1 > label2          (* label comparison *)
```

A *label* is either a (plain) label, an integer, a floating point number, or a string. Arithmetic operations and string concatenation can be used:

```
label   ::= lvar                                  (* label variable reference *)
          | literal                               (* label literal *)
          | label ^ label                         (* concatenation *)
          | label + label   | label - label
          | label * label   | label / label       (* arithmetic operation *)

char    ::= \"   | \\   | [^"\]
literal ::= letter+                               (* edge label *)
          | [0-9]+                                (* decimal integer *)
          | [0-9]+.[0-9]+                         (* float number *)
          | "char*"                               (* string *)
```

Here is the operator precedence table:

	Operator	Associativity
(high)	`* /`	left
	`+ - ^`	left
	`< >`	-
	`=`	left
	`not`	-
	`and`	left
(low)	`or`	left

UnCAL has two kinds of comments: line comments start from `//` and terminate at the end of the line, and block comments start from `(*` and terminate at `*)`. Block comments are allowed to be nested.

3.2 Graph Construction

Graphs in UnQL$^+$ and UnCAL are rooted and directed cyclic graphs with no order between outgoing edges. They are edge-labeled in the sense that all information is stored as labels on edges and the labels on nodes serve as a unique identifier and have no particular meaning. Figure 3.1 gives a small example of a directed cyclic graph with six nodes and seven edges.

Nine data constructors are provided to build arbitrary graphs (Buneman et al. 2000).

- `{}`: constructs a graph with a single node without edges.
- `{` $label_1$ `:` $expr_1$ `, ... ,` $label_n$ `:` $expr_n$ `}`: constructs a graph with the new root node having n outgoing edges. Each edge is labeled $label_i$ and points to the root node of the graph $expr_i$. A label can either be one of the following type of values:
  - Normal edge label, e.g., `abc`.
  - String value, e.g., `"world"`.

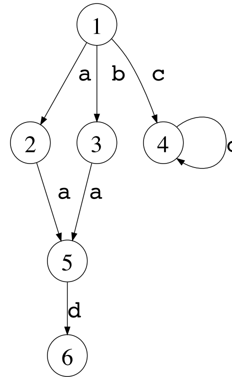


Figure 3.1: A Simple Graph

  - Integer value, e.g., `42`.
  - Floating point value, e.g., `3.14`.

Data-valued edges, i.e., edges labeled with string, integer, or floating point values, must point to a node with no further outgoing edges. For these edges, destination *expr* can be omitted; `{"world", 42}` is equivalent to `{"world":{}, 42:{}}`.

- *expr₁* `U` *expr₂*: unifies two graphs by creating a new root and connect it to the roots of *expr₁* and *expr₂* using ε-edges. An ε-edge is used to represent a shortcut of two nodes, and works like ε-transition in automaton. For instance, `{a:100} U {b:200}` is defined to be the graph `{`ε`:{a:100},` ε`:{b:200}}`, which is equivalent to `{a:100, b:200}`.
- `&x :=` *expr*: adds an input marker `&x` to the root of *expr*. A node marked with an input marker is sometimes called an *input node*. Intuitively, input nodes can be regarded as root nodes of the graph fragment. For singly rooted graphs, we implicitly use the default marker `&` to indicate its single root.
- `&y`: constructs a graph with a single node, which is marked with an output marker `&y`. Such a node is called an *output node*. An output node can be regarded as a "context-hole" of graphs where an input node with the same marker is plugged later.
- `()`: constructs an empty graph which has neither a node nor an edge.
- *expr₁* `++` *expr₂*: constructs the disjoint union of two graphs. Two graphs are simply juxtaposed and no connecting edges (like ε-edges of the `U` operator) are added. A syntactic sugar `(`*expr₁*`,` $\cdots$`,` $expr_n$`)` stands for *expr₁* `++` $\cdots$ `++` $expr_n$.
- *expr₁* `@` *expr₂*: appends two graphs. The resulting graph is obtained by plugging the input nodes of *expr₂* into their corresponding output nodes in *expr₁*.

- `cycle(` *expr* `)`: connects the input nodes with the output nodes of *expr* to form cycles.

As an instance, the graph in Figure 3.1 can be expressed in the following UnCAL expression:

```
&root @ cycle(
   (
      &root := {a: {a: &5}, b: {a:&5}, c: &4},
      &5 := {d: {}},
      &4 := {c: &4}
   )
)
```

3.3 Graph Transformation

3.3.1 Structural Recursion

In addition to the graph constructors, *structural recursion* is essential for writing graph transformations.

expr	::=	⋯
	|	`rec(\(`*lvar* `,` *gvar* `) .` $expr_1$ `)(` $expr_2$ `)` (* structural recursion *)
	|	⋯

Structural recursion has two equivalent semantics under the graph bisimulation: *bulk* semantics and *recursive* semantics. The former is the prominent feature of structural recursion, whereas the latter is the usual recursive semantics with memoization. Informally, the bulk semantics for the expression `rec(\($L, $G) .` $expr_1$ `)(` $expr_2$ `)` is that the function `\($L, $G) .` $expr_1$ (backslash should be read as λ of the lambda-calculus) is applied independently on all edges of graph $expr_2$, then the results are joined together with ε-edges (as in the `@` operation). At each edge, the label of the edge is bound to the label variable `$L` and the graph rooted from the destination node of the edge is bound to the variable `$G`. For instance,

```
&z @ rec(\($L,$G).
  if $L = a then
     &z := {b: &z}
  else if $L = c then
     &z := {c: $G}
  else
     &z := {$L: &z}
)($db)
```

this recursion replaces each edge labeled `a` by a graph `&z:={b:&z}`, edge labeled `c` by `{c:$G}` where `$G` is the destination node of the original edge, and other edges labeled `$L` are replaced by `&z:={$L:&z}`. Those graph fragments are glued together by the `&z` marker. In effect, we obtain a graph whose `a`-edges (except the ones under `c`-edges) are replaced by `b`-edges.

3.3.2 Input and Output Graphs of Transformations

The input graph of a transformation is given to an UnCAL program as the global variable `$db`, which is specified by the `-db` or the `-dbd` option of the `uncalcmd` command (see Chapter 8). Additionally, by using the `doc(`*filename*`)` expression, a graph is read from the UnCAL file *filename*. The name of the file must be supplied by a string literal: e.g., `"my-database.uncal"`. Dynamically computed string values cannot be used there.

The output graph of the transformation is the result obtained by evaluating the whole expression.

Chapter 4

KM3

The GRoundTram system validates input and output graphs against given schemata of them. We employ the Kernel MetaMetaModel (KM3) (ATLAS group 2006) to describe schemata. KM3 is an architecture-neutral language to write metamodels, which was developed at INRIA and is supported under the Eclipse platform. KM3 is structurally close to EMOF 2.0 and Ecore, but much simpler. We refer to a metamodel written in KM3 notation as *KM3 schema*.

4.1 Syntax

A KM3 schema has a structure similar to an XML schema based on regular tree grammars such as W3C XML schema (W3C XML Schema WG) in the sense that a schema prescribes which kind of set of nodes must be referred to by a node by regular expression. Figure 4.1 gives the definition of the core of KM3. The difference from the original definition (ATLAS group 2006) is that the enumeration class is not supported in our system. Note that validation with regard to ordered references and multiplicities of features does not make sense in the context of UnQL/UnCAL graph models where bisimilar graphs are treated as the same. There are two bisimilar graphs, one has only one child at the root node and another has two. For a similar reason, we cannot deal with `oppositeOf` relationships (ATLAS group 2006) between two classes in UnCAL graphs.

We will not explain the details of KM3. Instead we explain KM3 informally with an example.

A KM3 schema is a set of packages which consists of classes, data types and enumerations. Figure 4.2 shows an example of a KM3 schema for a simplified UML Class specification. The schema consists of four classes, `Association`, `Class`, `Attribute` and `PrimitiveDataType`. A class has some *features*, either *references* or *attributes*. Every feature has a type, either class or data type. Since all of them inherit from their super class `NamedElt`, they have an attribute `name` which is of type `String`. The `Association` class has two references `src` and `dest` which are of type `Class`. The `Class` class has an attribute `is_persistent` which is `Boolean` and an arbitrary number of references `attrs` which are of type `Attribute`. The `Attribute` class has an attribute `is_primary` which is `Boolean`

```
package        ::=  package name { ( classifier )* }                              (* package *)
classifier     ::=  (abstract)? class name
                      (extends name(, name)*)? { ( feature )* }                   (* class *)
               |    datatype name ;                                    (* primitive datatype *)
feature        ::=  attribute name ( multiplicity )? : name ;                   (* attribute *)
               |    reference name ( multiplicity )? : name ;                   (* reference *)
multiplicity   ::=  [ number - number ]                       (* with lower and upper bound *)
               |    [ (number -)? * ]                                   (* with lower bound *)
```

Figure 4.1: KM3 Syntax

and a reference `type` which is a `PrimitiveDataType`. The `PrimitiveDataType` class has neither an attribute nor a reference besides the inherited attribute `name`.

4.2 Validation

We validate a graph by matching each contained edge with a name of a class or a feature in a given schema. A validation of a graph proceeds as follows.

1. All class inheritances are eliminated from a given schema by expanding features of classes with their super classes. The elimination is recursively done since a super class may inherit another super class.

2. We associate a vertex following from the root of the graph with a class whose name is the same as the label of the edge between the vertex and the root.

3. We match a set of labels on edges from the vertex with a set of names of features of the class. Every destination vertex of the edge should have edges which are labelled by the name of a class or a data type of the feature and the number of which is specified by a multiplicity in the KM3 schema such as `[*]` in Figure 4.2. If the label of the edge is the name of the class, the destination vertex of the edge is associated with the class and is checked the feature again. If the label of the edge is the name of the data type, the destination vertex of the edge should have an edge whose label has the same type and whose destination vertex has no edge. This step is repeatedly performed until all vertices in the graph are visited.

This procedure always terminates because the number of vertices are finite.

```
package Class {
  datatype String;
  datatype Boolean;
  abstract class NamedElt {
    attribute name : String;
  }
  class Association extends NamedElt {
    reference src : Class;
    reference dest : Class;
  }
  class Class extends NamedElt {
    attribute is_persistent : Boolean;
    reference attrs [*] : Attribute;
  }
  class Attribute extends NamedElt {
    attribute is_primary : Boolean;
    reference type : PrimitiveDataType;
  }
  class PrimitiveDataType extends NamedElt {
  }
}
```

Figure 4.2: KM3 Schema for UML Classes

Part III

Command References

Chapter 5

GRoundTram Main Command (gtram)

This chapter describes the main command that invokes subcommands. They are described in the following chapters.

5.1 Overview of the Main Command

This command invokes each subcommand with their respective arguments. The following command line

```
> gtram fwdI_uncal -- -db db.dot -q trans.uncal -png result.png \
  -dot result.dot
```

invokes command `fwd_uncal` described in chapter 9. Note that the arguments for the subcommand should follow a double hyphen ("–'). The commands that can be invoked are summarized in Table 5.1. Each command should be executable by having its inhabiting directory included in the user's command search paths.

5.2 Options

The following additional command-line options are recognized by `gtram`.

-d Prints debugging information.

-help
  Displays list of options.

command	**chap.**	**description**
`unqlplus`	6	execute UnQL+ transformation/validate graph against KM3 schema.
`desugar`	7	converts UnQL+ file to equivalent UnCAL files.
`uncalcmd`	8	execute UnCAL unidirectionally.
`fwd_uncal`	9	foward execution of UnQL+/UnCAL for in-place updates.
`bwd_uncal`	10	backward execution of UnQL+/UnCAL for in-place updates.
`bwdIg_uncal`	11	bidir. execution of UnCAL for insertions.
`bwdI_enum_uncal`	12	bidir. execution of UnCAL for insertions based on candidate enumeration.
`fwdI_uncal`	13	forward execution of UnCAL for insertions based on insertion units.
`bwdI_uncal`	14	backward execution of UnCAL for insertions based on insertion units.
`chkuncal`	15	static typechecking of UnQL+/UnCAL.

Chapter 6

UnQL$^+$ Interpreter (unqlplus)

This chapter describes the UnQL$^+$ interpreter `unqlplus`, which interprets UnQL$^+$ source files for input graphs and produces output graphs in various formats.

6.1 Overview of the Interpreter

This command evaluates UnQL$^+$ queries on a specified input graph by translating the UnQL$^+$ to UnCAL graph algebra and then interpret the algebra to produce an output graph. Output formats can be DOT for Graphviz package, UnCAL, and other image formats supported by the Graphviz package. It can optionally validate input and output graphs when a KM3 schema is specified.

The command line

```
> unqlplus -db src.uncal -q trans.unql -png result.png
```

loads an input graph specified by file `src.uncal` and binds to variable $\$db$, interprets UnQL$^+$ source `trans.unql`, and saves the result graph to `result.png`. Option `-db` is mandatory.

Multiple input may be specified using `-var` options as described in the next section.

If you just want to verify a graph, `-q` option is not necessary – just specify `-iv` and `-ip` options like

```
> unqlplus -db src.uncal -iv Class.km3 -ip Class
```

6.2 Options

The following additional command-line options are recognized by `unqlplus`.

-v Prints version information.

-oi *file*
Saves the image of result graph to *file*. Format of the image is specified by the extension of the filename. Supported formats are the same as those supported by `-T` option of `dot` command in Graphviz.

-png *file*
Saves PNG image of result graph to *file*.

-dot *file*
Saves result graph in DOT format to *file*.

-cal *file*
Saves result graph in UnCAL format to *file*.

-var *v=file*
Binds a graph in UnCAL format specified by *file* to variable $v. Multiple variables can be bound by repeatedly using this option.

-iv *file* -ip *package*
Validates the input graph specified by `-db` option using KM3 schema package *package* defined in *file*. If validation succeeds, a map of known classifiers which maps a node number to the name of feature associated with the node is printed. BNF for the output syntax is as follows.

Result	::=	`VMap{` *entry* (`;` *entry*)* `}`
entry	::=	*node* `=>` *classifier*
classifier	::=	`‘datatype` *string*
	|	`‘klasse { kname =` *string* `}`
node	::=	*Node ID in the UnCAL graph data model*

For example, the output

```
Bid(2) => ‘datatype "Boolean";
Bid(32) => ‘klasse{kname = "Attribute"}
```

denotes that the node No. 2 is detected to have a primitive data type “Boolean”, and node No. 32 belongs to a class named “Attribute”.

-ov *file* -op *package*
Validates the output graph using KM3 schema package *package* defined in *file*. Output format is identical to that of `-ov` and `-op` option.

-bulk
Bulk semantics is used for the interpretation of UnCAL structural recursion **rec**. Recursive semantics is used without this option.

-t Prints elapsed user (CPU) time broken down to

- input validation (if `-iv` and `-ip` options are specified)
- desugaring
- execution of UnCAL expression
- output validation (if `-ov` and `-op` options are specified)

-oa Optimizes evaluation of @ and equivalent operation in evaluation of **rec** when recursive semantics (default) is used. @ usually evaluates both operands and connects matching I/O nodes. However, if an I/O node does not match, the second operand is left unconnected and made unreachable. This option suppresses the evaluation of the second operand to save evaluation time. In case of recursive semantics that is based on primary definition of structural recursion

$$f\{l : t\} = e(l, t) \mathbin{@} f(t),$$

it suppress recursion to $f(t)$ if $e(l, t)$ produces no output marker, i.e., f is essentially non-recursive.

-ea Applies Skolem term to each node of the graph generated by the first operand of @. Users usually do not have to specify this option. See Description of bidirectional UnQL+/UnCAL demonstration for more information.

-pa Prints UnCAL expression after desugaring.

-pu Prints UnQL expression before desugaring.

-m Produces unique name for each marker in the body of **rec**. Desugaring module usually reuses marker symbols for different **rec** bodies. However, when results of two different **rec** are unified using operators such as `U`, undesired node sharing may result. This form of UnCAL may be produced from an UnQL expression of the form `select ... U select`. This option suppresses this sharing by using different set of markers for different **rec**. This sharing can be avoided using -pi option as well. Non-recursive **rec** also uses explicit markers when this option is specified. For example,

$$\mathbf{rec}(\lambda(l, t).\{l : t\})(\$db)$$

becomes

$$\&z_1 \mathbin{@} \mathbf{rec}(\lambda(l, t).\&z_1 := \{l : t\})(\$db)$$

-sr Uses Skolem term (S1 in (Buneman et al. 2000)) in the evaluation of **rec** using recursive semantics. Straightforward interpretation of recursive semantics would not use Skolem term that is usually used for bulk semantics, but undesired sharing might result when transformation is in a specific form described in -m option section without this option.

-pi Uses node id based on lexical position of node construction expression. Without this option, new node id is generated for each evaluation even if node construction expression is lexically identical. This option makes expressions referentially transparent albeit with more complicated node IDs that may make visualized graph nodes larger.

-pn Prefixes output base node number with “n”. This is an alignment to the node id format produced by DOTTY (and our variant of it BDOTTY). This option is necessary if you edit output DOT file with these editors.

-cg Contracts the output graphs to their normal form based on bisimulation equivalence[1]. After contraction, no two nodes are bisimilar to each other. In particular, leaf nodes (nodes that has no outgoing edges) are bisimilar to each other, so they all shrink to one node.

Since UnQL (and UnCAL) is based on bisimulation, transformation may introduce redundant nodes that are bisimilar to each other. This option is useful when such redundancy has to be eliminated.

Note that the normal forms obtained may have different node ID assignments — although they are isomorphic to each other — even if they are generated from bisimilar graphs. Since Graphviz which we use as our graph layout tool depends on the ID, the difference may result in a different layout.

-ht Turns on holistic transitive closure (TC) computation optimization in **rec** for both bulk and recursive semantics.

rec$(\lambda(l,t).e)(\$db)$ requires computation of TC for every node in the graph bound to $\$db$. By default, this TC is computed on per-node basis. `-ht` option let the interpreter compute the TC at once, enabling the reuse of TC for a node to compute TC of the nodes in the vicinity of the former node.

However, since default TC computation is already efficient for a small number of nodes because it performs one depth-first search only using index from node to outgoing edges, this option may cause a performance slowdown. It performs better only when the input graph has large strongly-connected components[2](i.e., many of the nodes in the graph are connected to each other either directly or indirectly) and query visits most of the nodes.

-help
Displays list of options.

[1]The partition refinement alogithm by Paige and Tarjan (Paige and Tarjan 1987) is used.
[2]Captured by Tarjan's algorithm(Tarjan 1972)

Chapter 7

UnQL$^+$ to UnCAL Compiler (desugar)

This chapter describes UnQL$^+$ compiler `desugar`, which converts UnQL$^+$ source files to equivalent UnCAL file.

7.1 Overview of the Compiler

The command line

```
> desugar trans.unql
```

translates an UnQL$^+$ source file `trans.unql` to UnCAL and prints it to standard output.

7.2 Options

The following additional command-line options are recognized by `desugar`.

-v and -m
The meanings are identical to those of `unqlplus`. See section 6.2.

Chapter 8

UnCAL Interpreter (`uncalcmd`)

This chapter describes UnCAL interpreter `uncalcmd`, which interprets UnCAL source files for input graphs and produces output graphs in various formats.

8.1 Overview of the Interpreter

This command evaluates an UnCAL query on specified input graph and produces an output graph.

The command line

```
> uncalcmd -db db.uncal -q trans.uncal -png result.png
```

loads input graph specified by file `src.uncal` and binds to variable $\$db$, interprets UnCAL source `trans.uncal`, and saves the result graph to `result.png`. The option `-q` is mandatory.

It can also be used to perform conversion between DOT and UnCAL formats as follows.

UnCAL to DOT

```
> uncalcmd -q a.uncal -dot a.dot
```

converts UnCAL file a.uncal to DOT file a.dot.

DOT to UnCAL

```
> uncalcmd -dbd a.dot -q identity.uncal -cal a.uncal
```

converts DOT file a.dot to UnCAL file a.uncal, where identity.uncal is a text file that only contains `$db` that represents identity transformation.

If you want to generate a PNG from UnCAL file or DOT file, do the following.

UnCAL to PNG

```
> uncalcmd -q a.uncal -png a.png
```

DOT to PNG

```
> uncalcmd -dbd a.dot -q identity.uncal -png a.uncal
```

where identity.uncal is a text file described above, or you can directly use dot command by

```
> dot -Tpng -o a.png a.dot
```

8.2 Options

The following additional command-line options are recognized by `uncalcmd`.

-dbd *file*
Loads a graph DOT format specified by *file* and binds it to variable $\$db$.

-v, -oi, -png, -dot, -cal, -t, -oa, -ea, -pa, -sr, -pi, -pn, -cg, -ht, -help
The meanings are identical to those of `unqlplus`. See section 6.2.

-rw Applies rewriting rules. This includes fusion rules of two successive applications of **rec** in (Buneman et al. 2000):

$$\begin{aligned}
&\mathbf{rec}(e_2) \circ \mathbf{rec}(e_1) = \mathbf{rec}(\mathbf{rec}(e_2)) \circ e_1 \\
&\mathbf{rec}(e_2) \circ \mathbf{rec}(e_1) = \\
&\quad \mathbf{rec}(\lambda(l,t).\, \mathbf{rec}(e_2)(e_1(l,t) \mathbin{@} \mathbf{rec}(e_1)(t)))
\end{aligned}$$

The first rule is applied when $e_2(l,t)$ does not depend on t. The second rule is applied otherwise.

-rec
Interprets **rec** using recursive semantics. Bulk semantics is used without this option.

-lu Leaves unreachable parts in the result graph. Since bulk semantics typically produces many unreachable parts, these parts are removed by default. Other operators that produces unreachable parts are **cycle** and @. This option is useful to examine the formal behavior of these operators.

-le Leaves ε-edges in the result graph. Since **rec** typically produces many ε-edges especially in bulk semantics, they are removed by default. Other operators that produces ε-edges are **cycle**, @ and $\cup$. This option is useful to examine the formal behavior of these operators.

-ls Leaves Skolem terms in the result graph. Since **rec** produces Skolem terms which nests according to nesting of **rec**, and may make the result graph too large to perceive the entire structure, they are renamed to flat numbers by default. This option is useful to examine the formal behavior of **rec**. Other operators are extended by us to produce similar structured IDs if `-pi` option is specified. These are $\cup$, $\{\}$, $\{_ : _\}$, $\&_$ (output marker), @ (with `-ea` option), and **cycle**.

-pr Prints UnCAL expression that is actually evaluated. This is useful to examine the expression after rewriting. This is identical to the expression printed by `-pa` option if `-rw` option is not specified.

-rc Renders record shape nodes using node attribute `record` in DOT format of Graphviz. Default is `ellipse`. This option is useful when you edit the DOT format file produced by `-dot` option using DOTTY instead of BDOTTY. Please refer to Description of bidirectional UnQL+/UnCAL demonstration for the usage of record mode.

Chapter 9

UnQL$^+$/UnCAL Forward Interpreter (`fwd_uncal`)

This chapter describes the forward transformation part of bidirectional UnQL$^+$/UnCAL interpreter `fwd_uncal`, which interprets UnQL$^+$/UnCAL source files for input graphs and produces an output graph with trace information for backward evaluation. This command is intended to be used with `bwd_uncal` described in chapter 10.

9.1 Overview of the Forward Interpreter

This command evaluates UnQL$^+$/UnCAL queries on a specified input graph and produces an output graph with trace information.

The command line

```
> fwd_uncal -db src.uncal -uq trans.unql -png result.png \
  -dot result.dot -xg result.xg -ei bd.ei
```

loads an input graph specified by file `src.uncal`[1] and binds to variable $\$db$, interprets UnQL$^+$ source `trans.unql`, and saves the executed UnCAL expression augmented with result graph to `result.xg`. It also saves the result graph to DOT file `result.dot` for editing and further backward evaluation with `bwd_uncal`. Various evaluation information is also stored in `bd.ei`. These files, together with source graph `src.uncal` should be passed to `bwd_uncal` when backward evaluation is necessary. Options `-db`, `-dot`, `-xg` and `-ei` are mandatory. As for transformation, either `-uq` (UnQL$^+$ query) or `-q` (UnCAL query) should be specified. The image of the result graph stored in `result.png` is just for preview and not required for backward evaluation.

Unlike the unidirectional evaluator `uncalcmd`, bulk semantics is always used for traceability.

[1] DOT file can be accepted as well.

9.2 Options

The following additional command-line options are recognized by `fwd_uncal`.

-q *file*
Evaluates an UnCAL query specified by file instead of UnQL$^+$.

-v, -pa, -rw, -su, -ea
The meanings are identical to those of `uncalcmd`. See section 8.2.

-ge Glues source node and target node of each ε-edge and removes that edge if it is safe to do so. In general, if the source of an ε-edge is an input node or has other outgoing edges, and the target of the ε-edge has other incoming edges, gluing would introduce a spurious path that is inexistent before the gluing, so gluing does not take place. Another source of danger is the ambiguity of correspondences between graphs before and after gluing. If the two edges end up with sharing their source and target as a result of gluing, and users edit either of both of the edges, it is difficult to determine to which edge before gluing the editing effect should be propagated. In this situation, this option is ignored and gluing does not take place. Specifying this option produces a simple graph which is easy to edit, while unchecking helps understanding of the forward semantics of the constructors.

Since rendering a large graph is time-consuming (it may take several minutes), when you execute a query that is expected to produce a large graph if gluing would not be applied, this option is recommended.

-sb Uses Skolem terms which are constructors that enables rendezvous between connected subgraphs. For example, bulk semantics uses $\mathrm{Hub}(\mathit{nodeid}, \mathit{marker}, \mathit{exprid})$ 4 where *expid* identifies subexpression, and *nodeid* itself is a node ID. Bulk semantics generates nodes and edges independently from each input node and edge. Connecting these components are possible thanks to the Skolem terms. While edges (n1, l1, n2) and (n3, l2, n4) can be connected via node IDs n5 if n2, n3 and n5 coincide, the Skolem terms generated by rec and other constructors enable this coincident.

-to *time*
Sets timeout to *time* seconds. Evaluation is aborted after this time period. The bidirectional evaluator takes more time than unidirectional evaluators due to maintenance of trace information. This option is useful for batch processing in which a long-running execution is undesirable.

-cs Use simplified semantics for **cycle** in which only mismatched marker remains. Default semantics leaves every input node regardless of combination of I/O nodes in the operand.

-np Do not prefix output base node number with “n”. This flag is just the opposite effect of `-pn` in `unqlplus` and `uncalcmd`. Since our current editor is DOTTY (and our variant of it BDOTTY), the default behavior is prefixing to align with these tools.

-t Prints elapsed user (CPU) time broken down to

- rewriting (if `-rw` option is specified)
- forward execution of UnCAL expression

Chapter 10

UnCAL Backward Interpreter (bwd_uncal)

This chapter describes the backward transformation part of bidirectional UnQL$^+$/UnCAL interpreter `bwd_uncal`, which interprets UnQL$^+$/UnCAL source files for modified output graphs and produces input graph in which modification on the output graph is reflected. Note that this propagation does not always succeed. This command is intended to be used with `fwd_uncal` described in chapter 9.

10.1 Overview of the Backward Interpreter

This command evaluates an UnQL$^+$/UnCAL query on specified output graph along with trace information and produces an input graph with modification on the output graph being reflected.

The command line

```
> bwd_uncal -db src.uncal -xg result.xg -ei bd.ei \
  -dot result.dot -ucal srcprime.uncal -png srcprime.png
```

loads an input graph specified by file `src.uncal`[1] and binds to variable $\$db$, interprets UnQL$^+$/UnCAL source backwards using evaluation mode that had been saved in `result.xg` and `result.ei` by the `fwd_uncal` command, and saves updated source graph to `srcprime.uncal` in UnCAL format. It also saves the image of the updated source graph in `srcprime.png` for preview. Options `-db`, `-xg`, `-ei` and `-dot` are mandatory.

10.2 Options

The following additional command-line options are recognized by `bwd_uncal`.

-v Prints version information.

[1] DOT file can be accepted as well.

-udot *file*
Saves updated source graph to *file* in DOT format.

-pa Prints UnCAL input expression saved in file specified by `-xg` option.

-cm Colors modification to source DB specified by `-png`. Modifications propagated by the backward transformation are indicated by the color of edges or nodes: deleted parts are displayed in lightpink, added parts are displayed in purple, and modified labels are displayed in red. Unreachable parts (if any) are displayed in gray.

-np Do not prefix node number in the update source DB specified by -png or -udot DB with "n". See also the same option of `fwd_uncal` described in chapter 9.

-t Prints elapsed user (CPU) time for the backward execution of the UnCAL expression.

Chapter 11

UnCAL Backward Interpreter with Insertion of Graph (`bwdIg_uncal`)

11.1 Overview of the UnCAL Backward Interpreter for Insertion of Graph

This command performs the reflection of insertion of a graph on the target back to the source graph. It is implemented in a completely different manner than command `bwdI_uncal` in chapter 14, and provides a more intuitive interface.

This command is used in the following steps:

1. Forward execution.

   ```
   > bwdIg_uncal -idot db.dot -q q.uncal -odot output.dot \
     [-opng result.png]
   ```

   loads input graph specified by file `db.dot` and binds to variable $\$db$, interprets UnCAL source `q.uncal`, and save the output target graph in file `output.dot`. It optionally saves the PNG file of the output in `result.png` if it is specified. Options `-idot`, `-q` and `-odot` are mandatory.

2. User determines the insertion point in terms of the ID of the node on the target graph by examining `output.dot` or `result.png`. Let's assume here that the node number 1 is selected.

3. User determines the graph to be inserted and prepare it as a dot file. Let's assume here that it is saved in `tidot.dot`.

4. Reflection of insertion to the input graph.

   ```
   > bwdIg_uncal -idot db.dot -q q.uncal -odot output.dot  \
    -ipt 1 -tidot tidot.dot -uidot udb.dot -uodot uoutput.dot
   ```

executes the query `q.uncal` in "insertion mode", and reflects the insertion of the graph `tidot.dot` at the target graph `output.dot` rooted at node id `1`, and saves the new input graph to `udb.dot` as well as a new target graph to `uoutput.dot`. In this step, options `-ipt`, `-tidot`, `-uidot` and `-uodot` are mandatory. The other options (and content of the files) should be exactly identical to those specified in the first step.

Note that this step does not always succeed. For example, if the result graph of insertion on the target side (i.e., to be saved in `uoutput.dot` in the above command line) is not within the range of the transformation (specified by `q.uncal`), then the insertion is inherently impossible, because no matter what graph you give as an input, the new target graph can never be generated by the transformation.

In case of this failure, you either get the error message "no insertion exists on the source side", or the command does not return (i.e., does not terminate).

Also note that if you insert a large graph, then this step may take a long time.

11.2 Options

The following additional command-line options are recognized by `bwdIg_uncal`.

-pa

Prints the UnCAL expression given by `-q` option.

Chapter 12

UnCAL Backward Interpreter with Insertion of Graph (`bwdI_enum_uncal`)

12.1 Overview of the UnCAL Backward Interpreter for Insertion of Graph based on Enumeration

This command performs the reflection of insertion of a graph on the target back to the source graph. It provides more direct access to the implementation of the command `bwdIg_uncal` in chapter 11. `bwdI_enum_uncal` works on the view that reveals trace information in their node IDs, epsilon edges, and requires selection of a graph to be inserted from the candidates enumerated by the implementation.

This command is used in the following steps:

1. Forward execution.

   ```
   > bwdI_enum_uncal -idot db.dot -q q.uncal -odot output.dot \
     [-opng result.png]
   ```

   loads an input graph specified by file `db.dot` and and binds to variable $\$db$, interprets UnCAL source `q.uncal`, and saves the output target graph in file `output.dot`. It optionally saves the PNG file of the output in `result.png` if it is specified. Options `-idot`, `-q` and `-odot` are mandatory. Note that unlike `bwdIg_uncal`, the target graph saved in `output.dot` reveals the raw internal representation which includes trace ID of the nodes and epsilon edges.

2. The user determines the insertion point in terms of the ID of the node on the target graph by examining `output.dot` or `result.png`. Let's assume here that the node `Hub(2,&,9)` is selected. The node ID enriched with

trace information may be complex to type in, but if you open the dot file with bdotty and select "print node" in the bdotty context menu, it prints the id to the console so that you can copy and paste it.

3. Enumerate insertion template, and choose a template.

```
> bwdI_enum_uncal -idot db.dot -q q.uncal -odot output.dot \
  [-opng result.png] -ipt "Hub(2,&,9)" -uidot udb.dot \
   -k 0 -uodot uoutput.dot
```

   executes the query `q.uncal` in "insertion mode", and reflects the insertion of the 0th template at the target graph `output.dot` rooted at node id `Hub(2,&,9)`, and saves the new input graph to `udb.dot` as well as the new target graph to `uoutput.dot`. In this step, options `-ipt`, `-k`, `-uidot` and `-uodot` are mandatory. The other options (and content of the files) should be exactly identical to those specified in the first step. The target and input graph may include unspecified labels indicated by negative numbers. In that case, the restriction on them is printed in the form like

```
Restriction=(neqL:{c!=a; $l_1003!=c; $l_1005!=a}])
```

   which means that the edge numbered -1003 and -1005 should not be equal to the values c and a, respectively.

   If the user is dissatisfied with the template presented by the implementation, one can change the value specified by option `-k` to see other candidates. As the value increases, the size of the inserted graphs may grow.

   Note that this step does not always succeed. For example, if the node on the source that corresponds to the node on the target that is specified by `-ipt` option does not exist, this step fails. Please select another node in this case.

4. The user specifies the concrete values for each variable indicated by edges labeled with negative numbers. Assume here that there are edges numbered -1003 and -1005 and the user want to fill them respectively with labels 'a' and 'b'.

```
> bwdI_enum_uncal -idot db.dot -q q.uncal -odot output.dot \
  [-opng result.png]  -ipt "Hub(2,&,9)" -uidot udb.dot -k 0 \
  -uodot uoutput.dot -nlv 1003=a -nlv 1005=b
```

   executes similarly to the previous step, but with the unspecified labels filled with the concrete values specified by `-nlv` option(s).

12.2 Options

The following additional command-line options are recognized by `bwdIg_uncal`.

-pa
   Prints the UnCAL expression given by `-q` option.

Chapter 13

UnCAL Forward Interpreter with Insertion (fwdI_uncal)

This chapter describes the forward transformation part of bidirectional UnCAL interpreter with insertion handling `fwdI_uncal`, which interprets UnCAL source files for input graphs and produces output graphs with trace information for backward evaluation with insertion. It also produces an insertion unit – the unit of insertion on the view that corresponds to the source. The insertion unit can not be produced all at once, but incrementally, as described in the following section.

This command is intended to be used with backward interpreter `bwdI_uncal` described in chapter 14.

13.1 Overview of the Forward Interpreter

This command evaluates UnCAL queries on a specified input graph and produces an output graph with trace information. It can also produce *insertion unit*, a unit of insertion on the target that corresponds to an inserted edge on the source.

To produce the insertion unit, we have to specify insertion endpoints as two hub nodes on the target. The target can be produced by the following command line

```
> fwdI_uncal -db db.dot -q trans.uncal -png result.png \
  -dot result.dot
```

that loads the input graph specified by DOT file `src.dot` and binds to variable $\$db$, interprets UnCAL source `trans.uncal`, and saves the result graph to the DOT file `result.dot` as well as a PNG image file in `result.png`.

Secondly, decide insertion endpoints (ex: `"Hub(2,&,9)"` and `"Hub(3,&,9)"`) by viewing these result files.

Multiple insertion units may be generated depending on the UnCAL expression and the input, as well as the selected endpoints. So the user should tentatively select the first (0th) one by the following command line:

```
> fwdI_uncal -db db.dot -q trans.uncal -png result.png \
  -dot result.dot -src "Hub(2,&,9)" -dst "Hub(3,&,9)" \
  -iu result.iu -in 0 -id iu.dot
```

If the insertion units are generated successfully, the number of total units are printed. For example the message

```
Total number of insertion units: 3
```

indicates that three different units can be generated. Note that insertion units are not always generated. It depends on the input graph, query and insertion endpoints selected. The above command line saves the first (specified by "-in 0") insertion unit to file `result.iu`. For your information, a graph in which the generated insertion unit and the target graph are combined are saved to DOT file `iu.dot`. In that file, insertion endpoints are displayed in red while the subgraph in the insertion unit are displayed in purple.

These files should be passed to `bwdI_uncal` when a backward evaluation with insertion is necessary. Options `-db`, `-q`, `-png`, `-dot` are mandatory.

The image of the result graph stored in `result.png` is just for preview and not required for backward evaluation.

13.2 Options

The following additional command-line options are recognized by `fwdI_uncal`.

-vv Prints debugging information.

-pa Prints UnCAL input expression.

-help
Displays list of options.

Chapter 14

UnCAL Backward Interpreter with Insertion (bwdI_uncal)

This chapter describes the backward transformation part of the bidirectional UnCAL interpreter `bwdI_uncal`, which interprets UnCAL source files for possible insertions on the target and produces input graphs in which the insertions are reflected. Note that this reflection does not always succeed. This command is intended to be used with `fwdI_uncal` described in chapter 13.

14.1 Overview of the Backward Interpreter

This command evaluates UnCAL queries on a specified output graph along with trace information and an insertion unit described in chapter 13 and produces an input graph with insertion on the output graph being reflected.

The command line

```
> bwdI_uncal -db src.dot -q trans.uncal -png srcprime.png \
  -dot result.dot -iu result.iu
```

loads the input graph specified by file `src.dot` and binds to variable $\$db$, interprets UnCAL source `trans.uncal` backwards using output graph and the insertion unit respectively specified by `result.dot` and `result.iu`. It also saves the image of the updated source graph in `srcprime.png` for preview. Options `-db`, `-q`, `-png`, `-dot` and `-iu` are mandatory.

14.2 Options

The following additional command-line options are recognized by `bwdI_uncal`.

-v, -udot, -pa, -cm
: The meanings are identical to those of `bwd_uncal`. See section 10.2.

Chapter 15

UnQL$^+$/UnCAL Typechecker (chkuncal)

This chapter describes the static typechecker `chkuncal` of the UnQL$^+$/UnCAL transformations. To use this typechecker, you first need to install the MONA tool (Project), and set up the `PATH` environment variable so that the `mona` command can be found.

15.1 Overview of the Typechecker

This command requires three files as arguments. Namely, a KM3 file (e.g., `in.km3`) describing the type of input graphs, an UnQL$^+$/UnCAL transformation (e.g., `transform.unql` or `transform.uncal`) of which the type-correctness is tested, and a KM3 file (e.g., `out.km3`) describing the output type.

The command line

```
> chkuncal in.km3 transform.uncal out.km3
```

checks whether the transformation `transform.uncal` converts all graphs satisfying the input KM3 schema `in.km3` into graphs satisfying `out.km3`. If the check succeeds, the command prints `Success!` as follows

```
...Loading Schema and UnCAL files...
...Converting UnCAL to MSO...
...Generating auxiliary formulas...
...Converting Schemas to MSO...
...Validation process is running (may take time)...
Success!
```

and returns exit-code 0. If there found some error, the command prints 'Failure!'. Moreover, it prints a counter-example.

```
...Loading Schema and UnCAL files...
...Converting UnCAL to MSO...
...Generating auxiliary formulas...
```

```
...Converting Schemas to MSO...
...Validation process is running (may take time)...
Failure!
For a valid input
  {T: {b: {T}}, T},
the UnCAL program will produce an invalid output
  {S: {c: {T}}, S}.
```

In this case, the exit-code of the command is 1.

15.2 Supported Subset of the Languages

Currently, the typechecker does not support the full languages of KM3, UnQL$^+$, and UnCAL. Here is the list of current restrictions. For KM3:

- All cardinality constraints must be `[0-*]`.
- Inheritance by `extends` is ignored.
- `datatype`s must be either of type `Int` or `String`.
- Multiple packages are not supported. The schema must be closed in a single package.
- `oppositeOf` is ignored.

For UnCAL:

- Nested structural recursion cannot refer to outer variables, e.g., in `rec(\($L1,$G1).rec(\($L2,$G2).`*e*`)(...)  )($db)`, the body *e* of the inner `rec` can use `$L2` and `$G2`, but not `$L1`, `$G1`, nor `$db`. To verify nested recursion, a user needs to add *annotations* to the UnCAL source code. For the details, see Section 15.3.
- In the condition part of `if` expressions, predicates such as `isempty` or `isString` cannot be used. Comparisons (`$L = lab`) between label variables and literal labels and their boolean combination are allowed.
- `let` or `llet` expressions are not supported. Neither is `doc()`.

For UnQL$^+$, the above restrictions on UnCAL can be rephrased as follows:

- Joins (i.e., twice or more occurrence of the same variable in `where` clause) are not allowed. To verify joins, user needs to add *annotations* to the UnCAL source code. For the details, see Section 15.3.
- Variable bindings `where $x in {...}` (i.e., non-variable expression in right-hand side of `in`) in `where` clauses are not allowed. Querying `where {...} in $x` (right-hand side of `in` is a variable) is ok.
- Cannot use `isempty()`, `isString()`, `doc()`, etc.

In the future, these restrictions should be removed.

15.3 Annotation

For verifying an UnCAL transformation that contains *nested recursion* that refers to variables introduced by the outer structural recursion, the user must add type annotations. Consider the following simplest example:

```
rec( \($L1,$G1).
  if $L1 = In then
    {Out:
      rec( \($L2,$G2).
        if $L2 = keep then $G1 else {}
      )($G1)
    }
  else
    {}
)($db)
```

It selects a list of elements pointed by edges labeled `In` in the outer recursion, and only when it (`$G1`) has an edge labeled `keep`, it is kept for the output and the labeled `Out`. This transformation should conform to the following pair of input/output schemas.

```
package annot_in {
  class In { reference keep [0-*]: In; }
}

package annot_out {
  class Out { reference keep [0-*]: In; }
  class In  { reference keep [0-*]: In; }
}
```

To verify that the transformation indeed conforms to the schema, we need to annotate type information, because the variable `$G1` is used inside the nested recursion apart from its declaration. Otherwise we get an error message like:

```
...Loading Schema and UnCAL files...
...Converting UnCAL to MSO...
Error: [UNSUPPORTED in Typecheck] nested recursion
 requires variable annotation for $G1
```

Here is the annotated version of the transformation:

```
rec( \($L1,$G1).
  if $L1 = In then
    {Out:
      rec( \($L2,$G2).
        if $L2 = keep then ($G1 @@ "annot_in.km3 BIn") else {}
      )($G1) @@ "annot_in.km3 BIn"
    }
  else
    {}
)($db) @@ "annot_out.km3"
```

The annotation is expressed by specifying the name of the schema file followed by the `@@` symbol, and it asserts that the result of evaluating the expression conforms to the schema. The variable `$G1` itself needs to be annotated, and moreover, if we use annotations inside each `rec` expression, the `rec` expression itself must be annotated, too. In other words, to use annotated verification, we need to declare the types of input parameters and return values of each recursive function.

In the name of schema files, by separating by a whitespace, we can also specify a specific type to be used, as in `"annot_in.km3 BIn"`. If omitted, the root type of the schema is used, as is in `"annot_out.km3"`. For the names of the types, for each `Class` in the schema, two types `HClass` and `BClass` can be used. The former denotes the *h*ead node of the class, from which the edge labeled `Class` should go out. The latter, denoting the nodes *b*elow the edge `Class` is the type for nodes that have the set of edges labeled by the `reference` fields in the schema definition.

An annotation `$G @@ "schema"` works for typechecker in two ways. First, the graph obtained by the annotated expression must conform to the schema: the verifier is obliged to verify the conformance. Second, in the body of the rec expression, the use of the variable `$G` can be assumed to be bound to a node pointing to an arbitrary graph satisfying the schema: the verifier can use this assumption for checking the other parts of the transformation. Note that, currently, the counter-example in the case of a verification failure is generated only for the whole transformation, and not for each annotation.

15.4 Options

The following additional command-line options are recognized by `chkuncal`.

-c Compilation only. It just generates an MSO formula representing the type-correctness and does not carry out its validation.

-g *file*
Saves a counter-example graph to *file* in DOT format. Specifying "`-g -`" will output the graph to the standard output.

-help, –help Prints the help message.

-I Specifies a path to find KM3 and UnQL$^+$/UnCAL files.

-o *file*
Specifies the name of the intermediate `.mona` file to be passed to the MONA tool. The default file name is obtained by replacing the suffix `.uncal` (or `.unql`) of the specified UnQL$^+$/UnCAL file by `.mona`. Specifying "`-o -`" will output the MSO formula to the standard output.

-q Suppress printing some messages.

-v Prints version information.

Chapter 16

A Lightweight Quick Bidirectional Interpreter (bx_quick)

This chapter describes how to use the bx_quick command for both forward and backward transformation. There are two purposes for implementing this command. One is to provide a single command for both forward and backward interpreters. The second, also very important, it does backward transformation very quickly in a lightweight way. Different from the general backward transformation which reverses the forward transformation step by step, we do backward transformation by a direct reflection of the updates on the view to the source by just analysing the tracing information without looking into computation steps. This reflection cannot guarantee the PutGet property, and we check it by another forward transformation and report an error if the PutGet is not satisfied.

16.1 Forward Transformation

We can run a forward transformation by

```
> bx_quick -f -uq c2o_c.unql \
  -idot customers_c.dot \
  -odot orders_c.dot
```

which will apply the transformation c2s_c.unql to the database customers_c.dot and will produce the result in orders_c.dot.

If we want to check if the input database meets the schema Customers.km3 during forward transformation, we can do so by the following command line.

```
> bx_quick -f -uq c2o_c.unql \
  -idot customers_c.dot \
  -odot orders_c.dot \
  -ikm3 Customer.km3 \
```

```
-ip Customer
```

Here, the last option denotes the input validation package as used in the type checker.

16.2 Backward Transformation

For the backward transformation, we do not allow insertion to be done together with inplace updates or deletion; they can be done one after another.

First of all, let us see how to proceed with inplace udpates and deletion. Now suppose that we modify the `orders_c.dot` as follows:

- update the edge "(11,"16/10/2008",10)" to "(11,"31/01/2010",10)"
- Update the edge "(14,1001,13)" to "(14,1100,13)"
- Delete the edge "(50,info,26)"

and save it to `orders_c1.dot`. To reflect these changes to the source database, we apply the backward transformation as follows.

```
> bx_quick -b -uq c2o_c.unql \
  -idot customers_c.dot \
  -odot orders_c1.dot
```

The updated source and view will be saved in `udb.dot` and `uout.dot` respectively as a default. We can specify the names of these files for saving these updated results by

```
> bx_quick -b -uq c2o_c.unql \
   -idot customers_c.dot \
   -odot orders_c1.dot \
   -uidot xx.dot \
   -uodot yy.dot
```

It is a bit tricky to deal with insertions. We adopt a simple way. First, we specify where a new tree is to be inserted. For instance, we may want to insert a subtree

```
{info:...}
```

below the node pointed by the edge

```
(59,Address,50)
```

To do so, we can modify the above edge to

```
(59,_info,50)
```

and save the modified view to, say `orders_c2.dot`. Now we can reflect this change to the source by

```
> bx_quick -b -uq c2o_c.unql \
   -idot customers_c.dot \
   -odot orders_c2.dot \
   -tdot customer_c_template.dot
```

where `customer_c_template.dot` denotes an instance of a customer's data following the schema Customer, which should be prepared by the user.

16.3 Options

The following additional command-line options are recognized by `bx_quick`.

-v
: Print version info

-f
: Perform Forward transformation (default)

-b
: Perform backward transformation

-u1p
: Do one-pass optimization of UnQL (experimental) to fuse modifications.

-idot textitfile
: Specify the source db file (in DOT)

-uq *file*
: Evaluate the UnQL query specified by file.

-idot *file*
: Specify the target DOT file for editing and backward input

-idot *file*
: Specify a template input dot file, which is used only for reflection of insertion.

-uidot *file*
: Specify the updated DOT db file

-uodot *file*
: Specify the updated DOT view file

-ikm3 *file*
: Specify the source validation schema in KM3

-okm3 *file*
: Specify the view validation schema in KM3

-ip
: Specify the input validation package (the root node type of the source)

-op
: Specify the output validation package (the root node type of the view)

Chapter 17

Flat ID to Structured ID Conversion (fi2si)

This chapter describes the ID expansion command for traceability fi2sil, which expands the node ID in the contracted view after stage 2 in fwd_uncal. This command is intended to be used with bwdI_enum_uncal to compute candidates for the insertion point.

17.1 Overview of the Flat ID Expander

This command takes the flat ID of a node in the result of fwd_uncal command invoked with -sb, -cl, -zn and -fi options, and the evaluation information file that is also produced by fwd_uncal and prints corresponding structured IDs one per line.

The command line

```
> fi2si -ei bd.ei -ipt 5
```

loads mapping of stage 2 that stores node ID mapping before and after stage 2 from file bd.ei and returns the list of nodes that corresponds to node 5 in the structured form at the end of stage 1. The multiplicity of the result is due to the contraction of ε-edges in stage 1.

17.2 Options

The following additional command-line options are recognized by fi2si.

-v

The meanings are identical to those of uncalcmd. See section 8.2.

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