

Local Optimizations in Eclipse QVTc and QVTr using the Micro-Mapping Model of Computation

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Abstract—The OMG QVT FAS¹ was the result of, perhaps premature, enthusiasm to standardize the fledgling model transformation community. The Eclipse implementation of the QVTo language prospers but the initial implementations of the declarative QVTr language had poor performance and have faded away. Perhaps it is time to consign QVTc and QVTr to the dustbin of misguided initiatives. In this paper we show how metamodel-driven analysis and a disciplined Model of Computation pave the way to fulfillment of the original aspirations.

I. INTRODUCTION

The OMG QVT specification [6] was planned as the standard solution to model transformation problems. The Request for Proposals in 2002 stimulated 8 responses that eventually coalesced as a merged submission in 2005 for three languages.

The QVTo language provides an imperative style of transformation. It stimulated two useful implementations, SmartQVT and Eclipse QVTo.

The QVTr language provides a rich declarative style of transformation. It stimulated two implementations. However ModelMorf never progressed beyond beta releases. Medini QVT had disappointing performance and is not maintained.

The QVTc language provides a much simpler declarative capability that was intended to provide a common core for the other languages. However there has never been a QVTc implementation since the Compuware prototype was not updated to track the evolution of the merged QVT submission.

The Eclipse QVTd project [12] extended and enhanced the Eclipse OCL [11] framework to provide QVTc and QVTr editors, but until now provided no execution capability. This paper introduces the Micro-Mapping and its Model of Computation that underpins the production of efficient schedules and describes local Micro-Mapping optimizations.

In Section II we briefly describe the Eclipse QVTd architecture in order to provide the application context for Micro-Mappings. In Section III we consider how a declarative transformation is executed to motivate the Micro-Mapping Model of Computation in Section V. A running example is presented in Section IV and resumed in Section VI. Results from the example appear in Section VII demonstrating some scalability and code generation speed-ups. Section VIII summarizes some related work and Section IX concludes.

¹Object Management Group Query/View/Transformation Final Adopted Specification.

II. PROGRESSIVE TRANSFORMATION ARCHITECTURE

The Eclipse QVTd architecture for QVTr and QVTc ‘solves’ the problem of implementing a triple language specification by introducing Yet Another Three QVT Languages[8] (QVTu, QVTm and QVTi). Figure 1 shows that a further two (QVTp and QVTs) have proved useful.

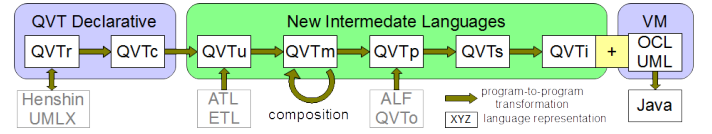


Fig. 1. Progressive transformation approach for Declarative QVT.

- 1) *QVTr2QVTc*: the incomplete RelToCore transformation from the QVT specification. This is still a work in progress.
- 2) *QVTc2QVTu*: creates a Unidirectional transformation without the bloat for the unwanted directions.
- 3) *QVTu2QVTm*: creates a Minimal transformation free from the complexities of mapping refinement and composition.
- 4) *QVTm2QVTp*: Partitions mappings into Micro-Mappings to avoid livelock / deadlock hazards.
- 5) *QVTp2QVTs*: uses a graphical representation for dependency analysis facilitating an efficient Schedule.
- 6) *QVTs2QVTi*: serializes to an Imperative form for direct execution by the QVTi interpreter that extends the OCL Virtual Machine. Alternatively an extension of the OCL code generator produces Java code with one outer class per transformation and a function or inner class per compound Micro-Mapping. The generated Java code bypasses many of the overheads of interpreted execution or dynamic EMF.

In this paper we concentrate on the creation of Micro-Mappings by the QVTm2QVTp transformation and the local schedule analyses and optimization performed at the start of the QVTp2QVTs transformation.

III. DECLARATIVE TRANSFORMATION EXECUTION

An imperative transformation author provides the control strategy that the transformation tooling must use in order to execute the transformation. The performance of the imperative transformation is therefore governed by the quality of the programmed control strategy and the ability of the transformation tool to implement what it has been instructed to do.

In contrast, a declarative transformation just expresses a truth that relates the output models to the input models. The truth can be demonstrated after the transformation completes, but how the constraints that express the truth are executed may not be obvious. A declarative transformation therefore requires less programming effort², but declarative transformation tooling must discover an appropriate control strategy to establish the required truth. This provides an opportunity to provide better solutions than those programmed manually for imperative transformation languages, but also requires substantial compilation effort to avoid poor quality solutions.

A. Commit-Actions, Micro-Mappings and Naive Scheduling

The result of a transformation is one or more intermediate or output models each of which may be rendered as a UML Instance Diagram with Class-typed nodes for the model elements and Property-typed edges for their relationships. A diagram may be drawn one node or edge at a time, nodes before edges. A declarative transformation may therefore execute one commit action at a time, where a commit action either creates a node or assigns an edge in a diagram. The type of object created, or the value assigned by the commit-action is computed from zero or more objects or values that must be ready for use. We therefore wrap the commit-action up inside a primitive Micro-Mapping to include the input parameters, predicates and computations that influence the commit-action. A primitive Micro-Mapping is therefore similar to the mapping or rule or relation of declarative transformation languages, but is constrained to a single commit-action. The correct sequence of primitive Micro-Mapping invocations can be found by a naive polling scheduler that executes each primitive Micro-Mapping once after checking that all the objects and values that the Micro-Mapping depends upon are ready and compatible.

- Retry loop - loop until finished
- Invocation loop - loop over all possible Micro-Mappings
- Object loops - loop over all object/parameter pairings
- Compatibility guard - if objects/parameters compatible
- Repetition guard - if this is not a repeated invocation
- Validity guard - if all input objects are ready
- Execute Micro-Mapping for object/parameter pairings
- Create a memento of the successful invocation

This is hideously inefficient. The speculative executions, wrapped in at least three loops, guards and mementos contrast poorly to the simple linear ‘loop’ nests of imperative programs. Fortunately there are many static analyses that we can perform on a declarative transformation in conjunction with its metamodels to tame the naive polling scheduler.

B. Global Micro-Mapping Optimizations

1) *Retries*: Most retries can be avoided by executing Micro-Mappings in a sensible order exploiting producer/consumer relationships between mappings. Where retries are necessary,

²Declarative transformation authors must learn to express the truth of what must happen rather than the mechanism by which it is done.

they can be a consequence of useful progress rather than naive polling.

2) *Invocations*: Dead Micro-Mappings can be eliminated, but most Micro-Mappings will normally be required. The invocation loop cannot be eliminated, rather it should be effectively sequenced.

3) *Objects*: Considering all permutations of all objects with respect to all parameters is unnecessary; the metamodel provides a strong type system that should allow only type compatible permutations to be considered. In particular a Micro-Mapping that produces some type can be followed by a Micro-Mapping that consumes that type.

Once Micro-Mappings are scheduled in a deterministic order, many of the guards can be optimized away and many of the invocation mementos eliminated since only a single invocation is possible.

The above optimizations are global. In this paper we concentrate on the utility of Micro-Mappings and local optimizations that facilitate the overall global optimizations. Global optimization will be described in another paper.

C. Local Micro-Mapping Optimizations

Permuting candidate objects and parameters can lead to very poor performance, typically quadratic for two parameters and steadily worse for further parameters. In this paper we will see how analysis of Micro-Mappings in conjunction with the metamodel relationships enables most Micro-Mappings to be reduced to a single parameter avoiding the very poor performance.

D. Compound Micro-Mappings

Declarative transformation languages do not require each commit-action to be separately programmed, rather compound Micro-Mappings (mappings or rules or relations) aggregate one or more commit-actions as an output object pattern related to an input object pattern. These patterns impose dependencies on the availability of source objects and guard conditions upon their suitability. In the following example we will see how the failure to distinguish between primitive and compound Micro-Mappings causes trouble for some transformation languages and conversely how recognizing the distinction enables Eclipse QVTd to give good performance.

IV. MICRO-MAPPING EXAMPLE

We will consider a very simple example that has some interesting difficulties. We will transform a model comprising a DoublyLinkedList that owns a ring of Elements into another DoublyLinkedList that owns a copied ring of Elements with the order of elements in the ring reversed. The metamodel is shown in Figure 2. Since we use models rather than Java Objects, the complexities of maintaining bidirectional linkages are subsumed by the metamodel bidirectional relationships.

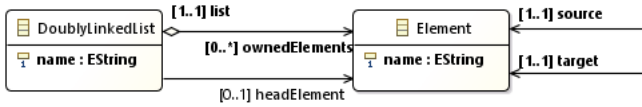


Fig. 2. Example Metamodel - Doubly Linked List.

A. ATL Implementation

The transformation is sufficiently simple to show the full unidirectional implementation in ATL in Figure 3. The transformation requires two rules. `list2list` declares the mapping from the `forwardList` input to the `reverseList` output, populating its `name` and `headElement`. `element2element` populates a `reverseElement` from a `forwardElement`.

```

module Forward2Reverse;
create OUT : ReverseList from IN : ForwardList;

rule list2list {
  from
    forwardList : ForwardList!DoublyLinkedList
  to
    reverseList : ReverseList!DoublyLinkedList (
      name <- forwardList.name,
      headElement <- forwardList.headElement -- resolveTemp
    )
}

rule element2element {
  from
    forwardElement : ForwardList!Element
  to
    reverseElement : ReverseList!Element (
      name <- forwardElement.name,
      list <- forwardElement.list,          -- resolveTemp
      source <- forwardElement.target       -- resolveTemp
    )
}

```

Fig. 3. Example transformation in ATL.

The exposition is particularly easy in ATL where the implicit resolution of the new-`headElement` from the old-`headElement` is done automatically. The commented lines show where an implicit resolution is performed.

Careful study of the transformation reveals that full execution of `list2list` requires that `element2element` has previously created the new `headElement` and that full execution of `element2element` requires that `list2list` has previously created the new `reverseList`. Further study reveals that full execution of `element2element` requires that another execution of `element2element` has created its new `source` which recurses to require that yet another execution of `element2element` has created the new `source's source`. The recursion terminates with full execution of `element2element` requiring that `element2element` has already created its `reverseElement`. These dependencies are not obvious, cyclic and seemingly insoluble.

B. QVTr Implementation

Figure 4 provides the bidirectional QVTr equivalent of ATL's unidirectional `list2list` rule. The asymmetric to/from patterns are replaced by symmetric forward/reverse patterns.

Explicit co-ordination of `forwardList.headElement` and `reverseList.headElement` uses a `when` clause rather than syntax sugar.

```

top relation list2list {
  enforce domain forward
  forwardList : DoublyLinkedList {
    name = listName : String{},
    headElement = forwardHead : Element{}
  };
  enforce domain reverse
  reverseList : DoublyLinkedList {
    name = listName,
    headElement = reverseHead : Element{}
  };
  when {
    element2element(forwardHead, reverseHead);
  }
}

```

Fig. 4. Example `list2list` Mapping in QVTr.

C. Colored Mapping Instance Diagrams

Once a forward execution direction has been selected, the Eclipse QVTr/QVTrC provides a graphical rendering of the two mappings as shown in Figures 5 and 6. The graphical rendering is very similar to a UML Object Diagram; boxes represent Classes with an instance name above a Class name. Edges represent directed named Property relationships with cardinalities. The left hand edge therefore depicts the navigation relationship `forwardHead = forwardList.headElement`.

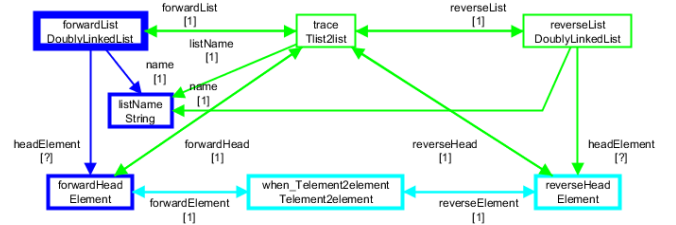


Fig. 5. `list2list` compound Micro-Mapping.

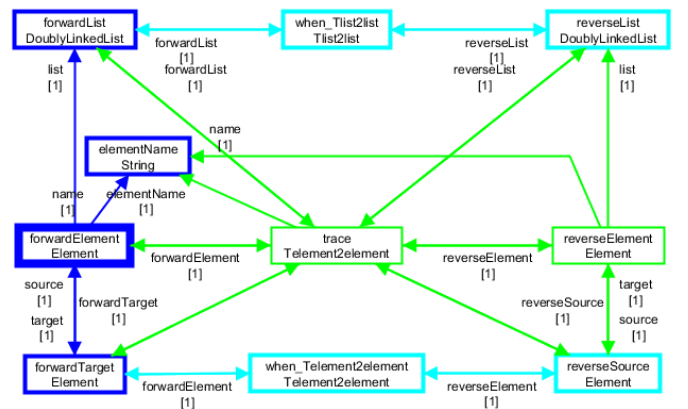


Fig. 6. `element2element` compound Micro-Mapping.

The pattern is colored so that the validity of each part of the mapping is clear.

- BLACK - model elements that are constant
- BLUE - model elements that form part of the input model
- CYAN - model elements required before execution
- GREEN - model elements created by execution

The diagrams are created automatically; only the layout has been enhanced manually. On the left hand side BLUE elements show the input sub-pattern. On the right hand side there is a corresponding output sub-pattern. QVTc and QVTr differ from other transformation languages through the use of explicit model elements to trace the execution of each mapping. There is therefore a column of trace elements directly connected to each other and to the side patterns. Since, in OCL which QVT extends, all unidirectional navigations are bidirectionally navigable, the trace elements are navigable from the sides and so left, trace and right are unified in an overall pattern. In other transformation languages the trace is an implementation detail requiring irregular language constructs to exploit it.

V. THE MICRO-MAPPING MODEL OF COMPUTATION

Diagrams or rather graphs of nodes and edges provide a useful way to understand systems and also computations. But as demonstrated by the Ptolemy group, diagrams only become really useful once there is a Model of Computation [5] to define the semantics of information flow along the edges.

A Micro-Mapping provides a pattern of constraints that are all satisfied once the Micro-Mapping has been executed. It therefore defines the overall truth. Colors are used to support intermediate partial truths. The BLACK color identifies compile-time truth. The BLUE is true after input models are loaded. The GREEN is true as a consequence of the truth of BLACK, BLUE and CYAN elements. Partial truths evolve as successively more BLACK then BLUE then CYAN then GREEN elements are resolved. Partial truths involving non-GREEN elements may be falsified when further satisfactory elements are not found. A partial truth involving any GREEN element involves a commit-action; this may not be falsified.

A. Typed Nodes

Each node is typed by a metamodel Class and has an instance name distinguishing its role in the overall pattern.

B. Typed Directed Edges

Each edge is typed by a metamodel Property that defines its name, direction and cardinality, which must be something-to-one. Consequently whenever a source object exists, a target object must form part of the final truth. Wherever the metamodel defines a something-to-one opposite relationship, the opposite edge is added to the Micro-Mapping. Thus in Figure 6 both `forwardElement.target` and `forwardTarget.source` are drawn.

C. Inputs and Outputs

The available outputs from the Micro-Mapping are all the GREEN elements (both nodes and edges). A Micro-Mapping

has no local knowledge of which GREEN nodes or edges appear in CYAN in another Micro-Mapping.

The potential inputs to the Micro-Mapping are all the BLUE and CYAN elements. A naive implementation may therefore need to invoke the Micro-Mapping for all possible permutations of objects and input nodes. Most invocations will fail through type mismatch of a node or edge.

D. Heads

The heads are the smallest set of input (BLUE or CYAN) nodes from which all input nodes can be reached by following directed edges. The heads therefore correspond to the necessary inputs of the Micro-Mapping; all other input elements can be computed from them. In Figure 6 `forwardElement` is the single head. It is drawn with a thick border to emphasize its importance. We observe that 90% of Micro-Mappings require only a single head and so are amenable to invocation within a loop over compatible input objects. This contrasts with a more naive pattern match that might have attempted a three dimensional search to locate all the compatible `forwardList`, `forwardElement` and `forwardTarget` objects. Use of the metamodel connectivity and cardinality constraints has automatically identified the efficient common sense solution.

E. Computations

This example involves no guards or complicated OCL expressions. For more general purposes, the Micro-Mapping diagram notation is extended with dashed nodes to denote iteration and operation calls and dashed edges to denote OCL expression results. This ensures that the Micro-Mapping captures all of the declarative mapping. ‘common subexpression elimination’ occurs for free. OCL operations such as `oclIsKindOf`, `oclAsType` and `includes` are converted directly to edges.

F. Null, Optional and Collection Nodes

The foregoing description stresses the utility of to-one cardinalities. We can generalize this to support to-zero cardinalities by specifying that a node is optional. A null Node may be used to denote the absence of an object. We can also generalize to support to-many cardinalities and a Collection of objects as a single collected object provided the collection is not dismantled by an OCL computation.

VI. LOCAL OPTIMIZATION

The graphical Micro-Mapping provides a representation that is much easier to analyze than diverse textual syntaxes. The Model of Computation provides the power to reason about the functionality. GREEN elements identify commit-actions that are performed once the CYAN parts are available to support execution of the commit-actions. CYAN elements therefore inhibit execution until corresponding GREEN elements of other mapping invocations creates them.

It is immediately clear from Figure 5 that `list2list` has a dependency on an `element2element` execution since

there is a CYAN Telement2element. Similarly in Figure 6 element2element has a dependency on another element2element and a list2list execution. The two invocations of element2element can be seen as two instances of Telement2element; one in GREEN named trace that represents the successful execution of this invocation, and another in CYAN named when_Telement2element that represents the predicate on the successful execution of an element2element referenced in a when clause.

A. Partitioning

Any attempt to execute these mappings is doomed to fail. list2list cannot execute until element2element has executed for the headElement. element2element cannot execute until list2list has executed. A naive polling scheduler will livelock as it polls in vain for something to execute. A slightly smarter scheduler will deadlock once nothing executes. Yet ATL executes this transformation successfully. How? See Section VI-D.

Our earlier discussion argued that execution of primitive Micro-Mappings with a single commit action is sound and our example demonstrates that compound Micro-Mappings with multiple commit actions (GREEN elements) may be unsound. We can partition each compound Micro-Mapping into primitive Micro-Mappings to achieve soundness. This is rather easy graphically. Figure 5 involves two GREEN nodes and seven GREEN edges and so nine primitive Micro-Mappings can replace the compound Micro-Mapping, each primitive Micro-Mapping containing only one GREEN element and the other elements necessary to preserve the partial truth. Where the support requires other GREEN elements they are recolored CYAN to ensure that they are computed first.

Nine primitive Micro-Mappings for a rather simple mapping is a rather frightening prospect that can be solved once we understand the conditions that allow some Micro-Mappings to be merged to form a compound Micro-Mapping.

B. Local Merging

A pair of Micro-Mappings may be safely merged when their head and predicate (BLUE and CYAN) elements involve the same partial truth. The ‘same partial truth’ is a little more complicated and generous than requiring exactly the same BLUE and CYAN elements. As a consequence of mandatory to-one metamodel relationships we require an intersection between two Micro-Mappings that includes all the heads. The non-intersections must involve mandatory to-one relationships so that addition of the non-intersection from one Micro-Mapping to the other makes no difference to its overall truth.

C. Speculative commits

Figure 7 shows the result of merging four primitive Micro-Mappings, one for the trace creation and three for the trace assignments to BLUE inputs.

We have not solved the problem. We still cannot create the Tlist2list trace until we have created the Telement2element trace and vice-versa. We must be able to create at least one of the GREEN trace elements before its CYAN trace dependency.

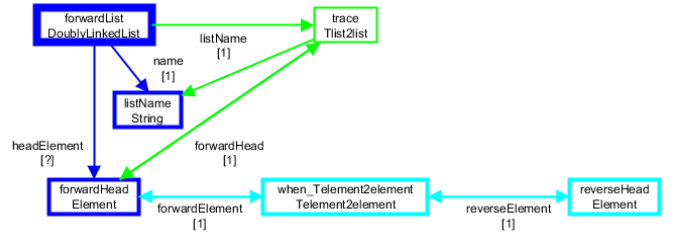


Fig. 7. list2list trace Micro-Mapping.

We need to introduce a speculative phase to the trace objects in order to break the deadlock. Figures 8, 9 and 10 show a sequence of compound Micro-Mappings that speculatively execute list2list.

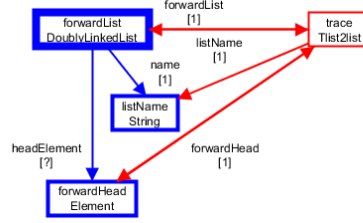


Fig. 8. list2list speculative trace Micro-Mapping.

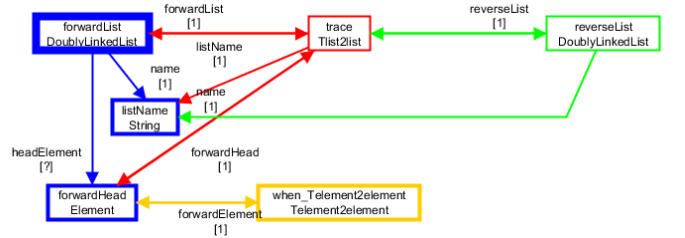


Fig. 9. list2list DoublyLinkedList.reverseList Micro-Mapping.

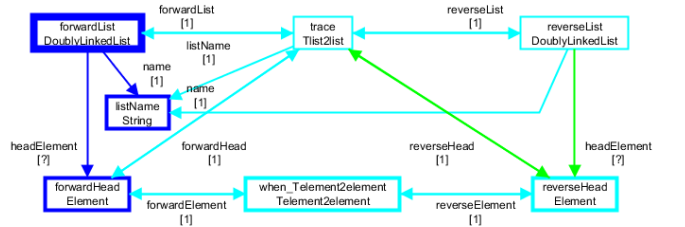


Fig. 10. list2list DoublyLinkedList.reverseHead Micro-Mapping.

Figure 8 performs a speculative RED creation of the trace element and its simple assignments. Once the corresponding speculative execution of element2element occurs, the AMBER speculative dependency of Figure 9 is satisfied allowing the reverseList to be created and the speculation to terminate

successfully. Then once the corresponding element2element has completed its speculation the reverseHead dependency is satisfied and Figure 9 can perform the remaining two assignments.

The speculation may fail, in which case Figures 9 and 10 do not execute and no output model elements are created; the failed speculation is only visible as a still-speculating trace element in the trace model.

D. ATL Execution

We can now understand how ATL successfully executes the example. ATL executes its rules in two stages, first all the new objects are created, then all the inter-object references are populated. ATL has therefore effectively partitioned the two list2list and element2element rules into four list2list-create, list2list-assign, element2element-create and element2element-assign mini-rules and by executing the create mini-rules before the assign mini-rules, the execution is tractable. This is very similar to the speculative partitioning above. However ATL speculates the outputs rather than the traces and so if a failing guard is introduced to the example, ATL does not roll-back the erroneous speculation and so produces an inconsistent partial result rather than a correct no result.

E. More Model of Computation Facilities

Space permits only a very brief summary of the other benefits of the analyses facilitated by the Micro-Mapping Model of Computation.

1) *Multiple Heads*: Micro-Mappings with multiple heads require multiple inputs and consequently incur invocation difficulties and non-linear execution performance. Analysis of the too-many metamodel relationships allows most multiple head Micro-Mappings to be realized by a single head Micro-Mapping with local rather than global loops for the other heads. This typically gives linear performance with respect to the output model size. Only genuinely Cartesian problems need incur Cartesian costs.

2) *Global optimizations*: The simple relationship between GREEN creation and CYAN use facilitates powerful global analysis. Some of these were briefly mentioned in Section III-B

3) *Static Scheduling*: We find that most Micro-Mappings can be statically scheduled and so only a small number incur dynamic scheduling overheads at run-time.

4) *Global Merging*: The local merging in Section VI-B is heavily constrained by the requirement for a mutually shared partial truth. Once a static schedule has been established merging can be much more aggressive. Invoked Micro-Mappings may be merged into invokers. Predicates guaranteed by the invoker can be pruned from the invoked.

5) *Incremental Execution*: Execution of Micro-Mappings can be persisted as an evaluation graph comprising

- input nodes for each BLUE input element
- invocation nodes for each Micro-Mapping invocation
- BLUE-BLUE dependency edges between invocation nodes and input nodes

- CYAN-GREEN dependency edges between consuming invocation nodes and producing invocation nodes

Each invocation node holds its prevailing GREEN state and is aware of the nodes that consume it. The graph can be selectively re-evaluated to propagate BLUE input changes efficiently.

VII. RESULTS

In Figure 11 we plot³ the performance of the DoublyLinkedListReversal transformation using a variety of transformation engines and a couple of manual implementations⁴. The plot demonstrates the scalability and the underlying tooling efficiency.

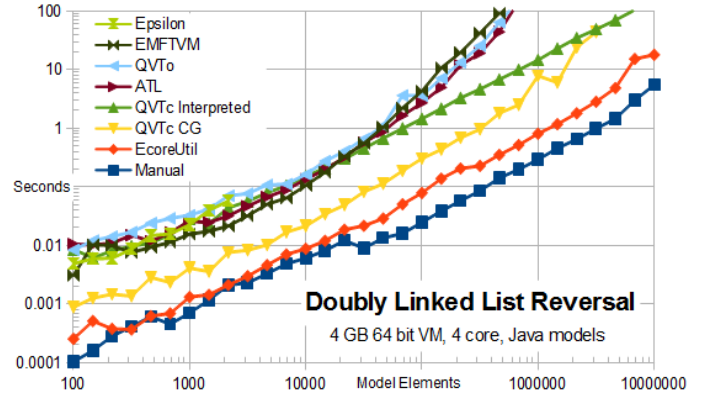


Fig. 11. Performance of the Doubly Linked List Reversal transformation.

The top three and a half lines are very similar showing that each of ATL, EMFTVM (the improved ATL executor) and Eclipse QVTo exhibit quadratic performance, probably as a consequence of requiring a linear search of the trace to resolve output/input correspondences. The half line for Epsilon terminates very prematurely because Epsilon resolves data dependences recursively and so runs out of stack for lists longer than about 1000 elements.

The interpreted mode of Eclipse QVTo is again very similar up to about 30000 model elements, at which point the distinction between linear and quadratic execution becomes apparent. At 1000000 elements interpreted QVTo is 50 times faster.

The next line shows a 5 to 10 fold speed up for the code generated mode of Eclipse QVTo. This speed up fades above 500,000 elements suggesting some opportunities for a bug fix.

The bottom two lines show manual implementations firstly using EcoreUtil.Copy and then manual code. The EcoreUtil line therefore demonstrates what is perhaps the performance limit when using EMF extensively while the manual plot represents the limit of what can be achieved in Java when using EMF sparingly. Midway between the two lines is perhaps a realistic goal for future optimization of the Eclipse QVTo tooling.

³The plots use no averaging. Single point wobbles may be due to concurrent activity. Discontinuities may be due to fortuitous cache alignment.

⁴Model overheads are reduced by Java generated by an EMF genmodel.

The results demonstrate that an efficient declarative schedule can be derived automatically for a difficult dependency problem.

The results also demonstrate, unintentionally, the benefit of QVTc's explicit trace model and the consequent linear performance when an appropriate cache is synthesized for the unnavigable opposite accesses. The quadratic performance of ATL, EMFTVM and QVTo highlights an implementation deficiency that can be remedied at the expense of some extra working memory. Ensuring that the extra memory cost is modest and the additional execution time is small probably requires similar static compile-time or load-time analyses to those performed by Eclipse QVTc.

The code and results for this example are available in the tests/org.eclipse.qvtd.doc.exe2016.tests plugin of the <https://git.eclipse.org/r/mmt/org.eclipse.qvtd> GIT repository. Two significant bugs in Eclipse QVTc were fixed to support this example. These fixes should be available in the Oxygen M1 milestone build on August 2016.

This example was also attempted with Eclipse QVTr, but unfortunately the partitioning algorithm neglected to partition to respect a Class dependency; the resulting code compiled and executed but produced no output. The corresponding QVTc exposed the dependency as a Property dependency and the partitioning succeeded. Hopefully the partitioning bug will be fixed in time for the camera ready copy. The QVTr performance is likely to be very similar to the QVTc performance.

These results were produced before the write up of Micro-Mapping partitioning revealed the need for speculative trace creation. The results for at least ATL and QVTc are therefore based on an unsound execution model that all objects can be created early.

VIII. RELATED WORK

Scheduling and particularly static scheduling has been a rich research topic with provision of optimized schedules recognized as a computationally hard problem. The many works of the Ptolemy group [1] that build upon [4] has been a strong background influence. However the appreciation that metamodels impose such strong constraints that sensible schedules can be produced rapidly for declarative transformations appears to be novel.

The Graph Transformation community has been very active in providing a rigorous foundation for graph mappings. Sadly the QVT specification ignored this important work, preferring instead to define the semantics of the QVTr transformation language using an incomplete exposition of a transformation of QVTr written in an untested QVTr to another language (QVTc) that has at best informal semantics. The utility and power of the QVTs graphical Micro-Mapping and its Model of Computation may begin to bridge the gap between these two communities. The coloring in QVTs is inspired by Henshin's [2] use of colors to denote create/delete/no-change in endogenous transformations. The reification of the QVTc traceability

element mirrors the evolution operators in UMLX [7] for heterogeneous transformations.

Active Operations [3] also reify mappings to persist the state necessary for incremental execution. Micro-Mappings similarly support incremental execution, but their primary rationale is to be a deadlock-free unit of computation.

IX. CONCLUSION

We have introduced the Micro-Mapping Model of Computation and shown how it supports efficient declarative schedules for Eclipse QVTc.

We used the Micro-Mapping Model of Computation to demonstrate the need for speculative creation of trace objects.

We have shown how a graph presentation of metamodel and dependency analyses tames the naive inefficiencies of a declarative schedule.

We have introduced the first implementation of the QVTc specification.

We have introduced the first direct code generator for model transformations.

We have reported first results and mentioned some future works. Many more optimizations to do, and of course, QVTr.

ACKNOWLEDGMENT

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- [12] Eclipse QVT Declarative Project. <https://projects.eclipse.org/projects/modeling.mmt.qvtd>