Rewriting Logic Revisited

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Introduction

Rewriting logic is almost a teenager! Thanks to the efforts of many researchers, a lot has happened since the first papers were written in 1990.

This talk will give a personal view of some of the recent developments in theory, applications, and tools.

So much has happened that it is impossible to do justice to all the work that thas been done (over 350 papers). The intent will instead be to give an impressionistic picture of some conceptual developments and some promising research directions, among others.

(Planned) Contents of the Talk

- I. Theoretical Developments
- II. Rewriting Logic and Formal Methods
- III. Semantic Framework Applications
- IV. Logical Framework Applications (no time)
- V. Rewriting Logic Languages (no time)
- VI. Conclusions (no time)

I. Theoretical Developments

- Rewrite Theories in General
- Rewriting Logic in General
- Extensions of RWL and Related Formalisms
- Reflection
- Coherence

Rewrite Theories in General

From the beginning, it was clear that rewriting logic has the underlying equational logic as a parameter. More general equational logics give rise to correspondingly more general notions of (conditional) rewrite rule. For example, for membership equational logic, rules have the general form,

$$l : t \longrightarrow t' \;\Leftarrow\; (\bigwedge_i u_i = u'_i) \wedge (\bigwedge_j v_j : s_j) \wedge (\bigwedge_k w_k \longrightarrow w'_k).$$

It has also become increasingly clear that frozen operators, that restrict the rewrites allowed below them, are also very useful in practice.

Rewrite Theories in General (II)

We can illustrate frozen operators with the following nondeterministic choice example (in Maude syntax):

```
mod CHOICE is
  protecting INT .
  sorts Elt MSet .
  subsorts Elt < MSet .
  ops a b c d e f g : -> Elt .
  op __ : MSet MSet -> MSet [assoc comm] .
  op card : MSet -> Int [frozen] .
  eq card(X:Elt) = 1 .
  eq card(X:Elt M:MSet) = 1 + card(M:MSet) .
  rl [choice] : X:MSet Y:MSet => Y:MSet .
endm
```

Rewrite Theories in General (III)

It does not make much sense to rewrite below the cardinality function `card`, because then the multiset whose cadinality we wish to determine becomes a moving target.

If `card` had not been declared `frozen`, then the rewrites, `a b c` $\longrightarrow$ `b c` $\longrightarrow$ `c` would induce rewrites, $3 \longrightarrow 2 \longrightarrow 1$, which seems bizarre.

The point is that we think of the kind `[MSet]` as the state kind in this example, whereas `[Int]` is the data kind. By declaring `card` frozen, we restrict rewrites to the state kind, where they belong.

Rewrite Theories in General (IV)

This leads to the following general definition of a rewrite theory on membership equational logic:

A rewrite theory is a 4-tuple, $\mathcal{R} = (\Sigma, E, \phi, R)$, where:

- (Σ, E) is a membership equational theory, with, say, kinds K, sorts S, and operations Σ
- $\phi : \Sigma \longrightarrow \mathcal{P}_{fin}(\mathbb{N})$ is a $K^* \times K$-indexed family of functions assigning to each $f : k_1 \ldots k_n \longrightarrow k$ in Σ the finite set $\phi(f) \subseteq \{1, \ldots, n\}$ of its frozen argument positions
- R is a set of (universally quantified) labeled conditional rewrite rules of the form (with t, t' and the w_k, w'_k pairs of terms of same kind)

$$l : t \longrightarrow t' \;\Leftarrow\; (\bigwedge_i u_i = u'_i) \wedge (\bigwedge_j v_j : s_j) \wedge (\bigwedge_k w_k \longrightarrow w'_k).$$

Rewrite Theories in General (V)

Given a rewrite theory $\mathcal{R} = (\Sigma, E, \phi, R)$, and given a Σ-term $t \in T_\Sigma(X)$, we call a variable $x \in vars(t)$ frozen in t iff there is a nonvariable position $\alpha \in \mathbb{N}^*$ such that $t/\alpha = f(u_1, \ldots, u_i, \ldots, u_n)$, with $i \in \phi(f)$, and $x \in vars(u_i)$. Otherwise, we call $x \in X$ unfrozen.

Similarly, given Σ-terms $t, t' \in T_\Sigma(X)$, we call a variable $x \in X$ unfrozen in t and t' iff it is unfrozen in both t and t'.

Rewriting Logic in General

Given a rewrite theory $\mathcal{R} = (\Sigma, E, \phi, R)$, the sentences that it proves are universally quantified rewrites of the form, $(\forall X)\ t \longrightarrow t'$, with $t, t' \in T_{\Sigma,E}(X)_k$, for some kind k, which are obtained by finite application of the following rules of deduction:

- **Reflexivity**. For each $t \in T_{\Sigma}(X)$, $\dfrac{}{(\forall X)\ t \longrightarrow t}$

- **Equality**.
$$\frac{(\forall X)\ u \longrightarrow v \quad E \vdash (\forall X) u = u' \quad E \vdash (\forall X) v = v'}{(\forall X)\ u' \longrightarrow v'}$$

- **Congruence**. For each $f : k_1 \ldots k_n \longrightarrow k$ in Σ, with $\{1, \ldots, n\} - \phi(f) = \{j_1, \ldots, j_m\}$, with $t_i, t'_i \in T_\Sigma(X)_{k_i}$, $1 \leq i \leq n$, and with $t'_{j_l} \in T_\Sigma(X)_{k_{j_l}}$, $1 \leq l \leq m$,
$$\frac{(\forall X)\ t_{j_1} \longrightarrow t'_{j_1} \quad \ldots \quad (\forall X)\ t_{j_m} \longrightarrow t'_{j_m}}{(\forall X)\ f(t_1, \ldots, t_{j_1}, \ldots, t_{j_m}, \ldots, t_n) \longrightarrow f(t_1, \ldots, t'_{j_1}, \ldots, t'_{j_m}, \ldots, t_n)}$$

- **Replacement**. For each finite substitution $\theta : X \longrightarrow T_{\Sigma}(Y)$, with, say, $X = \{x_1, \ldots, x_n\}$, and $\theta(x_l) = p_l$, $1 \leq l \leq n$, and for each rule in R of the form,

$$l : (\forall X)\; t \longrightarrow t' \;\Leftarrow\; (\bigwedge_i u_i = u'_i) \wedge (\bigwedge_j v_j : s_j) \wedge (\bigwedge_k w_k \longrightarrow w'_k)$$

with $Z = \{x_{j_1}, \ldots, x_{j_m}\}$, the set of unfrozen variables in t and t', then,

$$\frac{\begin{array}{c}(\bigwedge_r (\forall Y)\; p_{j_r} \longrightarrow p'_{j_r}) \\ (\bigwedge_i (\forall Y)\; \theta(u_i) = \theta(u'_i)) \wedge (\bigwedge_j (\forall Y)\; \theta(v_j) : s_j) \wedge (\bigwedge_k (\forall Y)\; \theta(w_k) \longrightarrow \theta(w'_k))\end{array}}{(\forall Y)\; \theta(t) \longrightarrow \theta'(t')}$$

where for $x \in X - Z$, $\theta'(x) = \theta(x)$, and for $x_{j_r} \in Z$, $\theta'(x_{j_r}) = p'_{j_r}$, $1 \leq r \leq m$.

- **Transitivity**

$$\frac{(\forall X)\ t_1 \longrightarrow t_2 \qquad (\forall X)\ t_2 \longrightarrow t_3}{(\forall X)\ t_1 \longrightarrow t_3}$$

Rewriting Logic in General (II)

Note that the above notion of rewrite theory and the proof rules exactly generalize the simpler unsorted and unfrozen case, since this is a special case of the general notion of theory and of the general proof rules.

Of course, the categorical model theory must also be generalized. This is current joint work with Roberto Bruni.

One advantage over the 1992 TCS paper is that we now have membership equational logic (MEL) available (including its partial version); therefore the model constructions can be carried out in the MEL framework.

Extensions of RWL and Related Formalisms

To deal with other aspects besides concurrency, rewriting logic has been extended in several directions:

- Real-Time rewrite theories [ÖM01]
- Probabilistic rewrite theories (ongoing work by Kumar, Shen, Agha, and Meseguer at UIUC)
- Behavioral Extensions by Diaconescu [Dia96] and the recent work on behavioral MEL and BMaude by Meseguer and Roşu [MR02]

Extensions of RWL and Related Formalisms (II)

Furthermore, two related rewriting formalisms have been proposed, to deal, respectively, with synchronization, and with a λ-calculus-like universal rewriting model:

- Tile Logic by Gaducci, Montanari, and Bruni [GM00, Bru99]
- The ρ-calculus by Cirstea and Kirchner [CK99]

Reflection

Important progress has also happened in the area of reflection, showing that there are universal theories simulating all other (finitary) theories for:

- unsorted unconditional rewriting logic [Cla00]
- many-sorted conditional rewriting logic [CM01]
- membership conditional rewriting logic [CMP02]
- many-sorted equational and Horn logic with equality, and membership equational logic [CMP02]

Reflection (II)

Yet another area in which reflection has been substantially advanced is in the work by Basin Clavel and Meseguer on reflecting induction principles [BCM00].

This work makes possible reflective inductive proofs happening not in a sigle theory, but in a parameterized family of theories, and has many meta-reasoning applications.

Coherence

Thanks to the work of Viry, the important topic of coherence —a confluence-like property between rules and equations crucial for practical executability of rewrite theories— has been further advanced, particularly in the latest paper [Vir01] where,

- coherence modulo different combinations of A, C, and AC is treated, including completion algorithms

- the case of conditional rules is treated, and

- several important applications are discussed.

II. Rewriting Logic and Formal Methods

- A Wide Spectrum of Formal Methods
- System Specification vs. Property Specification
- Modal and Temporal Logics for Rewriting Logic
- Formal Tools

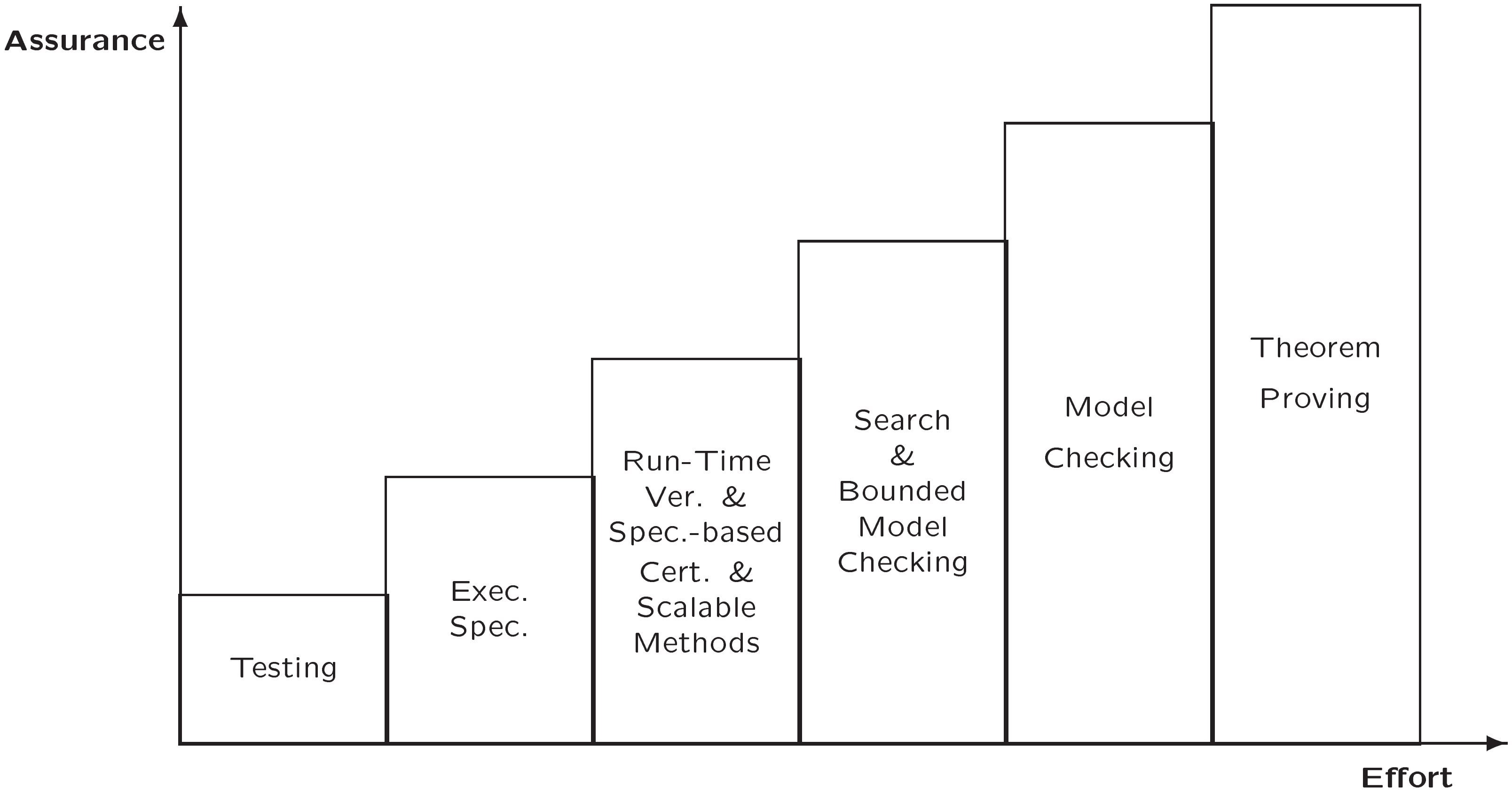
A Wide Spectrum of Formal Methods

Rewriting logic and its formal tools support a wide spectrum of formal methods. This allows great flexibilty in negotiating cost vs. assurance tradeoffs, which vary from application to application.

From less costly methods such as executable specification, through scalable methods such as runtime verification and specification-based certification, to increasingly stronger methods such as model checking and theorem proving, all methods can be supported.

All this can be done for rewriting logic specifications and programs, and for conventional code to which a rewriting logic semantics has been given.

Formal Methods: their Cost and Assurance



System Specification vs. Property Specification

Rewriting logic has good properties as a logical and semantic framework to specify systems. They may be formal systems, such as a logic or a theorem prover's inference system, or computational systems such as a programming language, a middleware system or a ceryptographic protocol: both can be specified very naturaly.

To ensure existence of initial models and executability, both rewriting logic and its underlying equational logic are lean logics, with no extra fat. While they have high expressive power to specify systems, they have more limited expressiveness to specify system properties.

System Specification vs. Property Specification (II)

The obvious idea is that we should use the most suitable tool for each purpose, rather than trying to use the same tool for everything. The system vs. property specification distinction helps us do that.

For property specification we do not need to be executable in any reasonably efficient sense (although the logic can be mechanizable), nor do we need theories with initial models. We can therefore choose more expressive logic extensions, such as full fist-order logic extensions of equational and rewriting logic. Or we can use semantically related logics, using appropriate mappings.

System Specification vs. Property Specification (III)

Some very natural choices, which have already been used as property specification logics for rewriting logic include:

- Full First-Order Logic, enriched with induction principles for the equational and rewriting specifications
- Modal and Temporal Logics
- Higher-Order Logics (e.g., OCC)

I discuss modal and temporal logics in more detail.

Modal and Temporal Logics for Rewriting Logic

The following modal and temporal logics have been proposed to reason about rewriting logic specifications:

- different modal logics by Fiadeiro et al. [FMMO^{+}00], and by Pattinson [Pat00]
- an object-oriented modal μ-calculus proposed by Lechner [Lec97]
- Denker's object-oriented distributed temporal logic [Den98]
- Ölveczky's timed linear time temporal logic used in Real-Time Maude [Ölv00]
- the logic $LTL(\mathcal{R})$ used in Maude's Model Checker [EMS02]

Formal Tools

The first reasoning tools to be mentioned are the CafeOBJ, ELAN, and Maude rewriting logic languages (to be further discussed in Part V). Indeed, besides supporting executable specification, these tools can be directly used to perform quite sophisticated forms of formal reasoning, including:

- behavioral rewriting and OTS verification (CafeOBJ)
- search-based reasoning (ELAN and Maude)
- efficient LTL model checking (Maude)

Formal Tools (II)

Next come tools belonging to formal environments supporting different kinds of formal reasoning for rewriting logic languages. Formal tools in this category include:

- CafeOBJ's Pig Nose resolution prover
- Maude's ITP [Cla00, CDEM00], and Church-Rosser Checker, KB completion, and Termination tools [CDEM00, Dur00]
- Real-Time Maude [Ölv00]
- the Open Calculus of Constructions (OCC) [Ste02]

Formal Tools (III)

A third category of tools comprises rewriting-logic-based formal tools used to support inference, reason about, or interoperate, different formal and computational sytems.

Both ELAN and Maude have been used to develop a wide variety of formal tools and automated deduction algorithms in this third category.

Some of them will be discussed as part of RWL's semantic framework (Part III) and logical framework (Part IV) applications.

III. Semantic Framework Applications

- Models of Computation
- Programming Languages and Hardware
- Software Architectures, Components, and Middleware
- Communication Protocols and Networks
- Bioinformatics

Models of Computation

The following models of computation have been naturally expressed in rewriting logic:

- equational programming, lambda calculi, and combinatory reduction systems [Mes92, LM92, LM96, SM99, Ste00]
- labeled transition systems, grammars and string-rewriting systems [Mes92]
- Petri nets, including place/transition nets, contextual nets, algebraic nets, colored nets, and timed Petri nets [Mes92, Mes96b, Ste01b, SMÖ01, ÖM01, Ste01a]

- Gamma and the Chemical Abstract Machine [Mes92]
- CCS, LOTOS, and E-LOTOS [MFW92, MOM93, Vir94, CDG98, DGP00, VMO00b, VMO, LN00]
- the π calculus [Vir96, Ste00]
- concurrent objects and actors [Mes92, Mes93, Tal96, Tal97b, Tal01]
- the UNITY language [Mes92]
- concurrent graph rewriting [Mes96b]
- dataflow [Mes96b]
- neural networks [Mes96b]

- real-time systems, including timed automata, timed transition systems, hybrid automata, and timed Petri nets [ÖM01, Ölv00]; and

- the tile logic [GM96, GM00, FM00] model of synchronized concurrent computation [MM98, BMM98, Bru99, GM01].

Operational vs. Mathematical Semantics

Since the above specifications of models of computation as rewrite theories are typically executable, this suggests that rewriting logic is a very flexible operational semantic framework to specify the semantics of such models.

What is not immediately apparent from the above list is that rewriting logic is also a flexible mathematical semantic framework for concurrency models.

Quite well-known mathematical models of concurrency happen to be isomorphic to the initial model $\mathcal{T}_{\mathcal{R}}$ of the rewrite theory $\mathcal{R}$ axiomatizing the particular models:

- Laneve and Montanari [LM96] show that for rewrite theories of the form $\mathcal{R} = (\Sigma, \emptyset, L, R)$, with the rules R left-linear, $\mathcal{T}_{\mathcal{R}}$ is isomorphic to a model based on residuals and permutation equivalence proposed by Boudol

- in the same paper they also show that for $\mathcal{R} = (\Sigma, E, L, R)$ a rewrite theory axiomatizing an orthogonal combinatory reduction system, including the λ-calculus, a quotient of $\mathcal{T}_{\mathcal{R}}$ by a few additional equations is isomorphic to a well-known model of parallel reductions based on residuals and permutation equivalence

- Stehr, Meseguer, and Ölveczky [SMÖ01] show in detail that for $\mathcal{R} = (\Sigma, E, L, R)$ a rewrite theory axiomatizing a place/transition net, $\mathcal{T}_{\mathcal{R}}$ is naturally isomorphic to the Best-Devillers net process model and then generalize this natural isomorphism to one between $\mathcal{T}_{\mathcal{R}}$ and a Best-Devillers-like model for $\mathcal{R}$ the axiomatization of an algebraic net

- work by Carabetta, Degano, Gadducci, and Priami [CDG98, DGP00] shows that for $\mathcal{R} = (\Sigma, E, L, R)$ a rewrite theory axiomatizing CCS, a truly concurrent semantics causal model based on proved transition systems is isomorphic to a quotient of $\mathcal{T}_{\mathcal{R}}$ by a few additional axioms

- Meseguer and Talcott [MT99] show that for $\mathcal{R} = (\Sigma, E, L, R)$ a rewrite theory axiomatizing a concurrent object-oriented system satisfying reasonable requirements, a subcategory of $\mathcal{T}_{\mathcal{R}}$ is isomorphic to a partial order of events model which, for asynchronous object systems corresponding to actors, coincides with the finitary part of the Hewitt-Baker partial order of events model.

Programming Languages and Hardware

Rewriting logic is a promising semantic framework for formally specifying programming languages as rewrite theories. Since those specifications usually can be executed in a rewriting logic language, they in fact become interpreters for the languages in question.

In addition, such language specifications can be subjected to a variety of formal analyses. These analyses can be carried out either through features and tools of rewriting logic languages, or through rewriting-logic-based program analysis tools.

Rewritig Logic vs. SOS

In particular, there is a close connection between SOS language specifications and their rewriting logic specification counterparts. One can:

- view SOS definitions directly as conditional rewrite theories [MOM93], or
- define a mapping $MSOS \longrightarrow RWL$ from Mosses' modular SOS [Mos98, Mos99], and prove its correctness, as done by Braga [Bra01], or
- use tile logic rewrite rules as an alternative formalism [GM96, GM00, GM01], which can then be mapped into rewriting logic for execution purposes [MM98, BMM98, Bru99].

Language and Hardware Specification Case Studies

A number of encouraging case studies, giving rewriting logic definitions of programming languages and harware, have been carried out by different authors:

- rewriting logic definitions of the lambda calculus and (mini-) ML, CCS, the π-calculus, and sketches of UNITY and Gamma (references given earlier)

- the usefulness of rewriting strategies to specify program evaluations has been clearly demonstrated in ELAN specifications of Prolog and of Babel [Vit94], and also in Maude specifications of CCS by Bruni and Clavel [Cla98, Bru99], and by Verdejo and Martí-Oliet [VMO00b, VMO00a]

- the fact that rewriting logic naturally supports concurrent objects has proved very useful in formally specifying a number of novel concurrent and mobile languages, including:
  - Ishikawa et al.'s formal specification of the GAEA language [IMW+97, IFW]
  - Mason and Talcott's rewriting logic semantic definitions of actor languages [MT97]
  - the use of Maude by Van Baalen, Caldwell, and Mishra, to give a formal semantics to the DaAgent mobile agent language [BCM]

- ◦ Stehr and Talcott's formal executable specification in Maude of UPenn's PLAN active network programming language [**?**].
- ◦ the semantic definition in Maude of its Mobile Maude extension [DELM00]

- finally, Harman has used Maude to specify and verify microprocessors [Har00a, Har00b].

RWL-Based Program Specification & Analysis Tools

The following tools use Maude for program specification and analysis:

- Braga et al.'s Maude Action Tool (for Action Semantics) [BHMM00]

- Braga's tool for MSOS specification and execution [Bra01]

- Fischer and Roșu's abstract interpretation specification, execution, and verification tool [FR01]

- Havelund and Roșu's LTL runtime verification module of Java Path Explorer [HR01]

- Roșu et al.'s domain-specific program certifiers for: (1) units of measurment, and (2) state estimation.

- Verdejo and Martí-Oliet's CCS specification and verification tool [VMO00b]

Software Architectures, Components, and Middleware

It is very important to detect errors and inconsistencies as early as possible in the software design cycle. Formal approaches can increase the analytic power of architectural notations such as architectural description languages (ADLs) and object-oriented design notations like UML.

A related concern is the formal specification and analysis of distributed component architectures, including middleware systems.

Rewriting logic applications in these areas include:

- Nodelman and Talcott's work representing the Wright ADL and its CSP semantics in Maude
- Durán, Meseguer, and Talcott's work on semantic

interoperation of heterogeneous software architectures [MT, CDE+99]

- Wirsing and Knapp's work on transforming UML diagrams into Maude specifications [WK96, Kna00, Kna01, WK01];
- Fernández-Alemán and Toval's formalization in Maude of the UML metamodel and its evolution, for formal analysis and prototyping [TF00, FT01, FT00, TF01]
- Nakajima and Futatsugi's work on the transformation of GILO-2 O-O design diagrams for execution and formal analysis [NF97];
- Talcott's work on actor-based distributed components [Tal96, Tal97a, Tal97b, Tal00, Tal01]

- Denker, Meseguer, and Talcott's work on a composable distributed communication services [DMT00b];
- Najm and Stefani's work on the Reference Model for Open Distributed Processing (RM-ODP) [NS94, NS95, NS97] (see also [DV01])
- work by Nakajima on the architecture of WEB-NMS, a Java/ORB implementation of a network management system [Nak]
- work by Albarrán, Durán, and Vallecillo on interoperating Maude executable specifications with distributed component platforms such as CORBA and SOAP [ADV01a, ADV01b, ADV01c], and
- Meseguer and Talcott's work on semantic models of reflective distributed systems [MT02].

Communication Protocols and Networks

Because of its flexibility to model distributed objects with different modes of communication and interaction, rewriting logic is very well suited to specify and analyze communication protocols, including cryptographic protocols, and, more generally, network software such as active network programming languages, active network algorithms, and network management systems.

Applications of this kind include:

- work by researchers at Stanford, SRI, and at the Computer Communications Research Group at University of California Santa Cruz using Maude to analyze the early design of a new reliable broadcast protocol for active networks [DGLAM+99a, DGLAM+99b]

- work of Denker, Meseguer, and Talcott on the specification and analysis of cryptographic protocols using Maude [DMT98, DMT00a]

- work by Rodriguez on analysis of security prptocols [Rod00]

- work of Basin and Denker on an experimental comparison of the advantages and disadvantages of using Maude versus using Haskell to analyze security protocols [BD00]

- work of Millen and Denker at SRI using Maude to give a formal semantics to CAPSL, and to endow CAPSL with an execution and formal analysis environment [DM99a, DM99b, DM00a, DM00b];

- work of Wang, Gunter, and Meseguer using Maude to formally specify and analyze a PLAN active network algorithm [WMG00]

- work by Ölvecky et al. using Real-Time Maude to specify and analyze the AER/NCA suite of active network protocol components for reliable multicast [ÖKM+01]

- work of Verdejo, Pita, and Martí-Oliet on the Maude specification and verification of the FireWire leader election protocol [VPMO00];

- work of Mason and Talcott on modeling, simulation and analysis of network architectures and communication protocols [MT00]; and

- work of Pita and Martí-Oliet using the reflective features of Maude to specify some management processes of broadband telecommunication networks [PMO96, PMO99, PMO01].

Bioinformatics

Biology lacks at present adequate mathematical models that can provide something analogous to the analytic and predicitive power that mathematical models provide for, say, Physics.

Of course, the mathematical models of Chemistry describing, say, molecular structures are still applicable. The problem is that they do not scale up to something like a cell.

What are needed, and what rewriting logic contributes, are new computable mathematical models of cell biology that are at a high enough level of abstraction so that:

Bioinformatics (II)

- they fit biologist's intuitions and informal notations
- they make those intuitions mathematically precise
- they provide biologists with the predictive power of mathematical models, so that the consequences of their hypotheses and theories can be analyzed, and can then suggest laboratory experiments to prove them or disprove them.

Specifically, the approach of S. Eker, M. Knapp, K. Laderoute, P.Lincoln, J. Meseguer, K. Sonmez, and C. Talcott [pat02] develops computable models based on rewriting logic that fit very well the biologists' natural level of abstraction, and have good predictive and analytic capabilities.

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