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REPLI: Constraint-based reasoning and combinatorial optimization. Application to planning and uncertainty managemment TIC2002-04470-C03

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Abstract

We present a summary of the goals pursued in the REPLI project and their level of achievement after two years of project execution. We describe the project results in terms of PhD thesis in progress, publications, public code and collaborations with other groups. In this last part, we detail the activities performed at national and international levels.

1 Project Goals

This project considers two generic goals:

1. Soft constraints. Solving methods for soft constraints, extending some solving strategies from hard constraints.
2. Applications. Application of constraints to temporal planning and uncertainty management. Application of constraints to real-world problems of combinatorial optimization.

These two generic goals are decomposed in six (three + three) specific goals:

1. Soft local consistency. Local consistency has played a central role in solving classical (hard) CSP. The extension of local consistency to the soft case is not trivial when the aggregation operator is not idempotent [4]. We aim at developing soft local consistencies on which computational solving methods could be based. We plan to maintain such local consistency through the search process. In particular, we expect to develop filtering algorithms, able to reduce the search space in the resolution process, including good lower bounds to be used inside branch-and-bound algorithms.

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2. Solving methods for soft constraints. In classical (hard) CSP there are two main families of solving methods: search and inference. First, we aim at constructing specialized versions of these families for soft constraints. Second, we want to develop hybrid methods, combining search and inference, for soft constraints. Third, we plan to identify tractable classes.

3. Efficient formulation of soft constraint problems. A constraint problem can be formulated in different ways. The formulation determines in many cases the efficiency of the solving process. We want to investigate efficient formulations for soft constraint problems. We anticipate research on redundant constraints, constraint arity, and symmetry exploitation.

4. Application of constraint techniques to planning. Following the ideas of planning as heuristic search, we aim at developing a temporal planner of high performance using constraint techniques [2]. This is a non trivial task, since the number of constraints could be very high. We expect to produce both theoretical and practical results.

5. Application of constraint techniques to uncertainty management. There is a clear parallelism between soft constraint problems and some problems of uncertainty management [1]. We want to explore the application of solving methods, existing and new, for soft constraints to uncertainty management.

6. Application of constraint techniques to real-world problems. We want to apply the new solving methods to real-world problems, to assess their practical importance, and also to assess aspects that are not considered in the academical setting.

To achieve these goals, six tasks were proposed one per goal. All tasks are running in parallel, ending at the month 36 (the end of the project). A task is divided in several subtasks. The following schema gives an overall picture of the task structure (subtask ending is indicated between parenthesis):

1. Soft local consistency
   (a) Soft arc consistency (12 m)
   (b) Higher soft consistency (24 m)
   (c) Filtering algorithms and lower bounds (36 m)
2. Resolution of soft constraints
   (a) Search methods (12 m)
   (b) Inference methods (24 m)
   (c) Hybrid methods (36 m)
3. Formulation of soft constraints
   (a) Redundant constraints (12 m)
   (b) Constraint arity (24 m)

   (c) Symmetry exploitation (36 m)

4. Application to temporal planning

   (a) Formulation (12 m)

   (b) Implementation (24 m)

   (c) Validation (36 m)

5. Application to uncertainty management

   (a) Bayesian networks (18 m)

   (b) Possibilistic model (36 m)

6. Application to real-world problems

   (a) Design of logical circuits (24 m)

   (b) Other problems (36 m)

2 Research Accomplishments

In the following, we present the level of success reached in the project goals.

1. Soft local consistency. We have made a very significant contribution in reaching this goal. In (Larrosa and Schiex, IJCAI 2003) we proposed two new ways of soft local consistency: DAC* y FDAC*, and we presented efficient algorithms to maintain them which were evaluated both theoretical and empirically. In (Larrosa and Schiex, AIJ 2004) we studied how to efficiently integrate these algorithms inside a complete algorithm of branch-and-bound. With this aim, we exploited the incremental nature of data structures for these algorithms. Experimentally, we detected that local consistencies based on a static variable ordering (DAC* y FDAC*) generated algorithms very sensitive to this ordering. We solved this issue in (Heras and Larrosa, 2004), allowing that the branch and bound algorithm could use different orderings in different visited nodes.

2. Solving methods for soft constraints. In addition to two state-of-the-art papers on solving methods (Larrosa and Meseguer 2003), we have made clear advances in the specialization of solving methods for soft constraints. First, the exploitation of special arrangements of the search tree was made in [3] (this paper was presented before the project actually started, it is not included in the project publications). Second, the use of inference methods for soft constraints has been pursued in (Larrosa CP 2003; Sanchez, Meseguer and Larrosa ECAI 2004; Sanchez, Meseguer and Larrosa CP 2004). The development of hybrid methods is a goal currently pursued, on which we expect to have results before the project ends. Regarding tractability, the work of (Chen and Dalmau TAST 2004; Chen and Dalmau CP 2004; Dalmau AMAI 2004) bring new contributions to the hard case.

3. Efficient formulation of soft constraint problems. The first idea explored, the use of redundant constraints, did not produced significant results because we are mostly interested in the weighted CSP model, and it requires a non-idempotent aggregation operator. In this case, adding redundant constraints (in the classical sense) may change the problem. Second, we have started to specialize inference methods when processing specific global constraints, getting advantage of the constraint semantics. In particular, we have obtained very promising results on capacity constraints, a constraint of high arity that appears in many scheduling problems. In (Larrosa and Rollon, ECAI 2004) presented this specialization for classical CSP and in (Larrosa and Rollon, CP 2004) this specialization was extended to soft constraints. The theoretical characterization of resolution width (Atserias and Dalmau 2003) can bring some insight on efficient formulations. Symmetry exploitation remains as a goal.

4. Application of constraint techniques to planning. A key feature of modern optimal planners such as Graphplan and Blackbox is their ability to prune large parts of the search space. Previous Partial Order Causal Link (POCL) planners provide an alternative branching scheme but lacking comparable pruning mechanisms do not perform as well. In this work, a domain-independent formulation of temporal planning based on Constraint Programming has been introduced that successfully combines a POCL branching scheme with powerful and sound pruning rules. The novelty in the formulation is the ability to reason about supports, precedences, and causal links involving actions that are not in the plan. Experiments over a wide range of benchmarks show that the resulting optimal temporal planner is much faster than current ones and is competitive with the best parallel planners in the special case in which actions have all the same duration. This work is the basis for the CPT temporal planner entered in the 2004 ICAPS Planning competition, and which got the 2nd place after the Optimal Parallel (Non-Temporal) Planning system SATPLAN04.

5. Application of constraint techniques to uncertainty management. We explored new solving methods based on maintaining new soft local consistencies in a search algorithm to solve Bayesian network tasks. It happens that these algorithms have not been shown competitive with standard methods for Bayesian networks. The reason for this relies in the structure of standard Bayesian benchmarks. They have a relatively small induced width, and this causes standard methods for Bayesian networks to have a better performance than search strategies. We expect that search methods could be more performant on networks with higher induced width. Finding such Bayesian networks and experimenting on them remains as further research.

6. Application of constraint techniques to real-world problems. We have explored the use of new soft local consistencies in a search algorithm to solve the Max-SAT problem, a problem with many practical applications (Givry, Larrosa, Meseguer, Schiex, CP 2003). It happened that our algorithm, using a generic implementation, was competitive with several Max-SAT solvers specially tailored for this problem. Using benchmarks from the SAT competition, we obtained very good results for our algorithm. A specific Max-SAT implementation is under way.

3 Results Yardsticks

3.1 PhD Students

Three FPI scholarships were associated to the project, one per subproject. The following PhD students got these scholarships, on the indicated topics:

- Federico Heras. Soft local consistency. Advisor: Javier Larrosa.
- Leticia Mara Peres. Constraint reasoning for planning with incomplete information. Advisor: Hector Geffner and Pedro Meseguer.
- Hector Palacios. Conformant planning and knowledge compilation. Advisor: Hector Geffner.

Besides, the following PhD students are pursuing their thesis on topics related to the project:

- Nelson Becerra. SAT algorithms based on minimal models. Advisor: Gonzalo Escalada-Imaz.
- Ismel Brito. Distributed constraint satisfaction. Advisor: Pedro Meseguer.
- Marti Sanchez. Hybrid methods for constraint solving. Advisor: Pedro Meseguer.

3.2 Publications

The project has generated a long list of publications, most on project topics and some on related areas. In the following we provide the list of publications grouped by the project goals. Besides, an extra group of papers on related topics is added. It is worth noticing that publications include the highest quality conferences (like IJCAI) and journals (like Artificial Intelligence), as well as the most specific conferences on the considered topics.

1. Papers on soft local consistency.

   J. Larrosa, T. Schiex (2003) In the quest of the best form of local consistency for Weighted CSP. *Proc. Int. Joint Conference on Artificial Intelligence IJCAI-03.* Mexico, 2003.

   F. Heras, J. Larrosa (2004) Towards Robust DAC-based Solvers for WCSP. *CP-04 Workshop on Preferences and Soft Constraints.* Toronto, Canada, October 2004.

   J. Larrosa, T. Schiex (2004) Solving weighted CSP by maintaining arc consistency. *Artificial Intelligence*, vol. 159, 1-2, 1-26.

2. Papers on solving methods for soft constraints.

   J. Larrosa, P. Meseguer (2003) Algoritmos para satisfaccion de restricciones. *Inteligencia artificial, Revista iberoamericana de inteligencia artificial*, 20, 31-42.

   J. Larrosa, P. Meseguer (2003) Restricciones blandas: Modelos y algoritmos *Inteligencia artificial, Revista iberoamericana de inteligencia artificial*, 20, 69-82.

   J. Larrosa, E. Morancho (2003) Solving 'Still life' with soft constraints and bucket elimination. *Principles and Practice of Constraint Programming, CP-03.* LNCS 2833, Kinsale, Ireland, September 2003.

M. Sanchez, P. Meseguer, J. Larrosa (2004) Using Constraints with Memory to Implement Variable Elimination. *Proceedings of the 16th European Conference on Artificial Intelligence, ECAI-04*, Valencia, Spain, August 2004.

M. Sanchez, P. Meseguer, J. Larrosa (2004) Improving the Applicability of Adaptive Consistency: Preliminary Results. *Principles and Practice of Constraint Programming, CP-04*. LNCS 3258, Toronto, Canada, October 2004.

H.Chen, V.Dalmau (2004) Looking Algebraically at Tractable Quantified Boolean Formulas. *7th Int. Conf. on Theory and Applications of Satisfiability Testing*, 2004.

H.Chen, V.Dalmau (2004) (Smart) Look-Ahead Arc Consistency and the Pursuit of CSP Tractability *Principles and Practice of Constraint Programming, CP-04*, LNCS 3258, Toronto, Canada, October 2004.

V. Dalmau (2004?) A New Tractable Class of Constraint Satisfaction Problems *Annals of Mathematics and Artificial Intelligence*. In press.

3. Papers on efficient formulation of soft constraint problems.

A. Atserias, V.Dalmau (2003) A Combinatorial Characterization of Resolution Width. *18th IEEE Conference on Computational Complexity, CCC'03*, 239-247. Selected for an especial issue of the journal *Information and Computation*. In review.

J. Larrosa, E. Rollon (2004) Adaptive Consistency with Capacity Constraints. *ECAI-04 Workshop on Modelling and Solving Problems with Constraints*, Valencia, Spain, 2004.

J. Larrosa, E. Rollon (2004) Bucket Elimination with Capacity Constraints. *CP-04 Workshop on Preferences and Soft Constraints*. Toronto, Canada, October 2004.

4. Papers on application of constraint techniques to planning.

B. Bonet, H. Geffner (2003) Faster Heuristic Search Algorithms for Planning with Uncertainty and Full Feedback. *Int. Joint Conference on Artificial Intelligence, IJCAI-03*, Acapulco, Mexico, August 2003.

B. Bonet, H. Geffner (2003) Labeled RTDP: Improving Convergence of Real Time Dynamic Programming. *13th Int. Conference on Planning and Scheduling, ICAPS-03*. Trento, Italy, June 2003.

J. Hoffmann, H. Geffner (2003) Branching Matters: Alternative Branching in Graphplan. *13th Int. Conference on Planning and Scheduling, ICAPS-2003*, Trento, Italy, June 2003.

H. Geffner (2003) PDDL 2.1: Representation vs. Computation. *Journal of Artificial Intelligence Research, JAIR*, Volume 20, 139-144, December 2003.

V.Vidal, H. Geffner (2004) Branching and Pruning: An Optimal Temporal POCL Planner based on Constraint Programming. *Proc. 19th National Conference on Artificial Intelligence, AAAI-04*, AAAI/MIT Press, 571-577, July 2004.

H. Geffner (2004) Planning Graphs and Knowledge Compilation. *Proc. 9th Int. Conf. on Principles of Knowledge Representation and Reasoning, KR-04*, 662-672. 2004.

M. Martin, H. Geffner (2004) Learning Generalized Policies from Planning Examples Using Concept Languages. *Applied Intelligence* 20(1): 9-19 (2004).

5. Papers on application of constraint techniques to uncertainty management.

6. Papers on application of constraint techniques to real-world problems.

   S. de Givry, J. Larrosa, P. Meseguer, T. Schiex (2003) Solving Max-SAT as Weighted CSP. *Principles and Practice of Constraint Programming, CP-03.* LNCS 2833, 363-376, Kinsale, Ireland, September 2003.

7. Papers on related topics.

   I. Brito, P. Meseguer (2003) Distributed Forward Checking. *Principles and Practice of Constraint Programming, CP-03.* LNCS 2833, 801-806, Kinsale, Ireland, 2003.

   I. Brito, P. Meseguer (2004) Synchronous, asynchronous and hybrid algorithms for DisCSP. *CP-04 Workshop on Distributed Constraint Reasoning*, Toronto, Canada, October 2004.

   I. Brito, F. Herrero, P. Meseguer (2004) On the evaluation of DisCSP algorithms. *CP-04 Workshop on Distributed Constraint Reasoning*, Toronto, Canada, October 2004.

   V.Dalmau, D.Ford (2003) Generalized Satisfiability with k Occurrences per Variable: A Study through Delta-Matroid Parity. *28th International Symposium of Mathematical Foundations of Computer Science, MFCS'03.*

   A.Bulatov, V.Dalmau (2003) Towards a Dichotomy Theorem for Counting Constraint Satisfaction Problem. *44th Annual IEEE Symposium on Foundations of Computer Science, FOCS'03*, 562–573.

   V.Dalmau, P. Jeavons (2003) Learnability of Quantified Formulas. *Theoretical Computer Science*, 306(1-3) (2003), 485-511.

   V.Dalmau, A.Krokhin, B.Larose (2004) First-order definable retraction problems for posets and reflexive graphs. *19th Annual IEEE Symposium on Logic in Computer Science, LICS'04.*

   A.Bulatov, H.Chen, V.Dalmau (2004) Learnability of Relatively Quantified Formulas *15th International Conference on Algorithmic Learning Theory, ALT'04.*

   C. Bessiere, I. Brito, A. Maestre, P. Meseguer (2004?) Asynchronous Backtracking without Adding Links: A New Member in the ABT Family. *Artificial Intelligence.* In press.

   M. Silaghi, J. Landwehr, J. Larrosa (2004?) Asynchronous Branch and Bound and A* for DisWCSPs, with heuristic function based on Consistency-Maintenance. *Frontiers in Artificial Intelligence and Applications.* IOS press. In press.

   V. Dalmau, P. Jonsson (2004?) The Complexity of Counting Homomorphisms Seen from the Other Side. *Theoretical Computer Science.* In press.

3.3 Technology Transfer

So far, no technology transfer has been performed. This is a difficult point for a basic research project like this one, where the results are obtained on generic problems. Nevertheless, the code generated in the project has been made public in different settings, to allow other researchers to get advantage of it. See the 3.6.3 Section.

3.4 Patents

So far, project results have not generated patents. This is an unclear point for project researchers, since the expected results are software, and in Europe software cannot be patented.

3.5 Participation in International Projects

No participation in international research projects has been performed.

3.6 Collaboration with Other Groups

3.6.1 Specific Collaborations

Leadered by Javier Larrosa, a specific collaboration has been made with the group of INRA-Toulouse on solving methods for soft constraints. This collaboration has been financed by a Spanish-French Integrated Action. It has been very fruitful because it has produced several publications of high quality (Larrosa and Schiex 2003, Givry, Larrosa, Meseguer and Schiex 2003; Larrosa and Schiex 2004). In addition, a public code including these results has been produced (see 3.6.3 Section).

In Spring 2004, Pedro Meseguer gave a graduate course in the University of Padova on Constraint Solving Algorithms, invited by the professor Francesca Rossi. This two-weeks visit was an opportunity to establish some collaboration with her on soft constraints, which is expected to be maintained in the future.

Hector Geffner has kept his collaboration with Blai Bonet (Venezuela), Vincent Vidal (France), Patrick Haslum (Sweden) and Joerg Hoffman (Germany). From these collaborations, several papers have been produced (Bonet and Geffner 2003; Bonet and Geffner 2003b; Geffner and Vidal 2004) as well as the two planners GPT and CPT that were distinguished at the ICAPS-04 planning competition (see 3.6.3 Section).

In Summer 2004, Javier Larrosa spend three months visiting the Chinese University of Hong-Kong, hosted by the professor Jimmy Lee. The main research topic was weighed CSP.

Further international collaboration is intended, since some Integrated Action proposals were submitted in the last year.

3.6.2 AI Problem Solving Seminar

An international Seminar was organized on topics related to the project. It was called the "AI Problem Solving Seminar", and it was held in Barcelona, at the Universitat Pompeu Fabra in May 28-30, 2003. It focused on SAT problems, constraint-based reasoning and planning. Four prestigious researchers gave invited talks: Richard Korf (UCLA, USA), Peter van Beek (U. Waterloo, Canada), Enrico Giunchiglia (U. Genova, Italy) and Francois Laburthe (Bouygues, France). In addition, twelve Spanish researchers presented their research on the proposed topics. The Seminar also included a session for PhD students, where twelve students presented their thesis topics. The Seminar was financed with contributions from the "Red Nacional de Planificacion Scheduling y Razonamiento Temporal", the PhD program of UPF on "Computer Science and Digital Communication" and the REPLI project. Further details can be obtained from the web site http://www.iiia.csic.es/p̃edro/SEMINAR2003.html, where the program is detailed. It also contains the slides of most presentations.

3.6.3 Public Code

In collaboration with researchers of INRA-Toulouse, a constraint solver for weighted CSP has been implemented. This solver called toolbar (from Toulouse-Barcelona) can be found in http://carlit.toulouse.inra.fr/cgi-bin/awki.cgi/AlgorithmS and it contains the most advanced algorithms for these kind of problems, including those developed in the project. This implementation is made public (under the conditions of Artistic License) with the purpose that it will become in the reference algorithm for empirical studies of new solving techniques for weighted CSP.

Two planners were distinguished in the ICAPS-2004 Planning Competition:

- B. Bonet, H. Geffner (2004) GPT planner – 2nd place, overall; 2004 ICAPS Probabilistic Planning Competition.
- H. Geffner, V. Vidal (2004) CPT Planning – 2nd place, Optimal Planning; 2004 ICAPS Planning Competition.

Both planners are available from http://www.tecn.upf.es/h̃geffner.

3.6.4 Tutorials

As a related activity, three tutorials on constraint reasoning have been given by project researchers. They are the following:

- J. Larrosa, P. Meseguer (2003) Tutorial. Razonamiento con Restricciones. *Conferencia Española de Inteligencia Artificial, CAEPIA 2003*, San Sebastian, Spain, November 2003.
- P. Meseguer, T. Schiex (2004) Tutorial. Constraint Processing. *16th European Conference on Artificial Intelligence, ECAI-04*, Valencia, Spain, August 2004.
- J. Larrosa (2004) Tutorial. Constraint Satisfaction Problems. *V Jornadas de Inteligencia Artificial*, October 2004, Universidad Distrital, Bogota, Colombia.

3.6.5 Invited Talks

Also, project researchers have given five invited talks on related topics. They are the following:

- P. Meseguer (2002) Constraint Satisfaction and Constraint Programming. *VIII Iberoamerican Conference on Artificial Intelligence, IBERAMIA-2002*, Sevilla, Spain, Nov. 2002.
- P. Meseguer (2002) Algoritmos para Satisfaccion de Restricciones. *Segundas Jornadas de Lenguajes de Programacion, PROLE-2002*, El Escorial, Spain, Nov. 2002.
- H. Geffner (2004) Inference and Problem Solving. *1st Cuban Symposium on Artificial Intelligence*, La Habana, Cuba, May 2004.
- J. Larrosa (2004) Solving Methods for Weighted Constraint Satisfaction Problems. *Joint Annual Workshop Ercim/Colognet*, EPFL, Lausanne, Switzerland, June 2004.
- H. Geffner (2004) Perspectives on AI Planning, *European Conference on Cased Based Reasoning*, Madrid, Spain, September 2004.

3.6.6 International Program Committees

A way of collaboration has been the participation in Program Committees of international conferences. Project researchers have been (and are) involved in the following program committees:

- 16th Int. FLAIRS Conf. Constraint Solving and Programming track, 2003, USA.
- 13th Int. Conf. on Automated Planning and Scheduling, ICAPS 2003, Trento, Italy.
- 2nd. Int. Conf. Autonomous Agents and Multiagent Systems, AAMAS 2003, Australia.
- 19th Conf. on Uncertainty in Artificial Intelligence, UAI 2003. Mexico.
- 9th Int. Conf. on Principles and Practice of Constraint Programming, CP 2003, Ireland.
- 17th Int. FLAIRS Conf. Constraint Solving and Programming track, 2004, USA.
- 3rd Int. Conf. Autonomous Agents and Multiagent Systems, AAMAS 2004, USA.
- 14th Int. Conf. on Automated Planning and Scheduling, ICAPS 2004, Whitsler, Canada.
- 9th Int. Conf. Principles of Knowledge Representation and Reasoning, KR 2004, Canada.
- 20th Conf. on Uncertainty in Artificial Intelligence, UAI 2004. Canada.
- 10th Int. Conf. on Principles and Practice of Constraint Programming, CP 2004, Canada.
- 18th Int. FLAIRS Conf. Constraint Solving and Programming track, 2005, USA.
- 21th Conf. on Uncertainty in Artificial Intelligence, UAI 2005. UK.
- 19th Int. Joint Conf. on Artificial Intelligence, IJCAI 2005, Edimburgh, UK.

3.6.7 Organization of International Conferences

Although it is not directly related to the project, it is relevant to indicate that the researchers Pedro Meseguer and Javier Larrosa have been selected as Conference Chairs for the next Constraint Programming Conference (CP 2005) and the next Logic Programming Conference (ICLP 2005). Both will be held in Sitges, Spain, during the first week of October 2005.

References

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[2] Geffner H. (2001) Planning as branch and bound and its relation to constraint-based approaches. Research report, http://www.tecn.upf.es/~hgeffner.

[3] Larrosa J., Meseguer P., Sanchez M. (2002) Pseudo-Tree Search with Soft Constraints. *Proc. 15th European Conference on Artificial Intelligence, ECAI-02*, France, 131-135.

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