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Case-based reasoning: a categorized bibliography

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1 Introduction

Case-Based Reasoning (CBR) is a fresh reasoning paradigm for the design of expert systems in domains that may not be appropriate for other reasoning paradigms such as model-based reasoning. As a result of this, and because of its resemblance to human reasoning, CBR has attracted increasing interest both from those experienced in developing expert systems and from novices. Although CBR is a relatively new discipline, there are an increasing number of papers and books being published on the subject. In this context, this bibliographic categorization is an accompanying paper to a review of CBR by the same authors. The objective of this paper is to help researchers quickly identify relevant references. The paper is structured to further this objective by:

- helping a CBR researcher or application developer to situate their problem amongst previous research and benefit from that previous work to resolve their specific problems, and
- indicating to theoretical researchers where CBR research is weak, and thereby focus attention on these issues to the benefit of CBR theory and practise.

This paper is divided as follows. The first section is devoted to papers that refer to the origins of CBR, the domains where CBR has succeeded, the tasks it can perform and, finally, to papers that give a background or survey of CBR. The second section is devoted to the different types of CBR, and to CBR techniques such as case representation, indexing, case memory, case retrieval and adaptation. The third section focuses on the practical application of CBR by listing the different software tools on the market along with their vendors, and by listing papers that refer to different applications (both academic demonstrators and commercial systems are dealt with). The final section concerns papers on the co-operation between CBR and different reasoning models and other papers of general relevance to CBR.

Where there are several publications by the same or similar authors on a particular subject (for example, an internal technical report, a PhD thesis, a conference paper and a journal paper), only the most recent and/or the most easily obtainable reference is given. It is assumed that in these circumstances the authors will have referred to their earlier work. Because a single paper may refer to several subjects, we decided to include the full reference to the work in all relevant categories rather than referring readers to a single bibliography at the end of the paper. We feel that this results in less work for the reader at only a small increase in the size of the paper.

We hope that this bibliographic categorization, along with the previous review paper, will help to introduce CBR to a new audience, and will be of service to those with experience of the subject, thus making an effective contribution to CBR research.

2 The origins of CBR

2.1 History of CBR

This section contains references that describe the evolution of CBR and the conditions that led to its occurrence. It starts with the philosophical investigation of Wittgenstein in 1953, and leads on to

the work of Roger Schank on dynamic memory in 1982 and other associated memory models. It also presents work and criticisms from both the cognitive and computer science communities that assisted the development of CBR theory. This includes psychological investigation, the relationship between human activity and reminding and methodology for building CBR systems.

Bareiss, ER, 1988, *PROTOS: A unified approach to concept representation, classification, and learning.* PhD thesis, Department of Computer Science, University of Texas (Technical Report CS 88-10, Dept. of Computer Science, Vanderbilt University, Nashville, TN).

Bareiss, R, 1989, *Exemplar-based knowledge acquisition: A unified approach to concept representation classification and learning.* Academic Press.

Cullingford, R, 1978, *Script application: Computer understanding of newspaper stories.* Yale University, Department of Computer Science Technical Report no. 116.

Dyer, M, 1983, *In-depth understanding.* MIT Press.

Gentner, D, 1983, "Structure-mapping: a theoretical framework for analogy". *Cognitive Science* **7**(2).

Harmon, P, 1992, "Case-based reasoning." *Intelligent Software Strategies* **7**(ii).

Keane, M, 1988, "Where's the Beef? The absence of pragmatic factors in pragmatic theories of analogy." In: *Proc. ECAI-88*, pp 327–332.

Klein, GA and Calderwood, R, 1988, "How do people use analogues to make decisions?" In: *DARPA'88 Proceedings* (Kolodner, JL, Ed.).

Klein, GA, Whitaker, LA and King, JA, 1988, "Using analogues to predict and plan." In: *DARPA'88 Proceeding* (Kolodner, JL, Ed.).

Kolodner, J, 1983a, "Maintaining organization in a dynamic long-term memory." *Cognitive Science* **7** 243–280.

Kolodner, J, 1983b, "Reconstructive memory, a computer model." *Cognitive Science* **7** 281–328.

Koton, P, 1989, *Using experience in learning and problem solving.* Massachusetts Institute of Technology, Laboratory of Computer Science (PhD diss. October 1988). MIT/LCS/TR-441.

McDougal, T, Hammond, JK and Seifert, C 1991, "A functional perspective on reminding." In: *Proceedings* (see Bareiss, R, Ed.).

Porter, BW and Bareiss, ER, 1986, "PROTOS: An experiment in knowledge acquisition for heuristic classification tasks." In: *Proceedings First International Meeting on Advances in Learning (IMAL),* Les Arcs, France, pp 159–174.

Riesbeck CK and Schank, RS, 1989, *Inside case-based reasoning.* Erlbaum.

Schank, R. (ed.), 1982, *Dynamic Memory: A Theory of Learning in Computers and People.* Cambridge University Press.

Schank, R and Abelson, R, (eds.), 1977, *Scripts, Plans, Goals and Understanding,* Erlbaum.

Seifert, CM, 1988, "Goals in reminding." In: *DARPA'88 Proceedings* (see Kolodner, JL, Ed.).

Smith, EE and Adams, N, 1978, "Fact retrieval and the paradox of interference." *Cognitive Psychology* **10** 438–464.

Smith, EE and Medin, DL, 1981, *Categories and Concepts.* Harvard University Press.

Strube, G, 1991, "The role of cognitive science in knowledge engineering." In: F Schmalhofer (ed.), *Contemporary knowledge engineering and cognition: First joint workshop, proceedings,* pp 161–174, Springer-Verlag.

Tulving, E, 1977, "Episodic and semantic memory." In: E Tulving and W Donaldson (eds.), *Organization of memory*, pp 381–403, Academic Press.

Wilensky, R, 1978, *Understanding goal-based stories.* Yale University, Department of Computer Science Technical Report no. 140.

Wittgenstein, L, 1953, *Philosophical Investigations.* Blackwell.

2.2 Feasibility and uses of case-based reasoning

This section contains references on works that consolidate the philosophical and psychological claims of the feasibility and the use of case-based reasoning to model realistic world problems as humans do. In this context, it presents the advantages of CBR in relation to other reasoning paradigms such as rule-based and model-based reasoning through its success in performing complex tasks in various domains (e.g. legal, process control, history, planning, learning, tutoring, problem solving, explanation and prediction in strategic domains such as health, agriculture and education).

Aamodt, A, 1989, "Towards expert systems that learn from experience." In: *DARPA'89 Proceedings* (see Hammond).

Althof, KD and Webb, S, 1992, "Case-based reasoning and expert system development." In: *Contemporary Knowledge Engineering and Cognition, First Joint Workshop,* Kaiserslautern, Germany (Lecture Notes in Computer Science 622, pp 146–160).

Barnden, J and Srinivas, K 1992, "Overcoming rule-based rigidity and connectionist limitation through massively parallel case-based reasoning." *International Journal of Man–Machine Studies* **36**(2) 221–246.

Berger, J, 1994, "Roentgen: radiation therapy and case-based reasoning." In: *Proceedings Conference on Artificial Intelligence Applications,* pp 171–177.

Bladwin, JF, 1993, "Evidential support logic, FRIL and Case based reasoning." *International Journal of Intelligent Systems* **8**(9).

Bradburn, C and Zeleznikow, J, 1993, "The application of case based reasoning to the tasks of health care planning." In: *EWCBR'93* (see Richter, MM et al., eds.).

Branting, LK, 1988, "The role of explanation in reasoning from legal precedent." In: *DARPA'88 Proceedings* (see Kolodner, JL, ed.).

Chiriatti, KC and Plant, RE, 1993, "Case-based reasoning: application to the agricultural domain, a prototype." In: *EWCBR'93* (see Richter, MM et al., eds.).

Cunningham, P, 1993, "Using CBR techniques to detect plagiarism in computing assignments." In: *EWCBR'93* (see Richter, MM et al., eds., 1993a).

Dupuy, T, 1988, "Military history and case-based reasoning." In: *DARPA'88 Proceeding* (see Kolodner, JL).

Evans, C, 1993, "Case-based learning of dysmorphic syndromes." In: *EWCBR'93* (see Richter, MM et al., eds., 1993a).

Farrell, R, 1988, "Facilitating self-education by questioning assumptive reasoning using paradigm cases." In: *DARPA-88 Proceedings* (see Kolodner, JL, ed.).

Goodman, M, 1989, "CBR in battle planning." In: *DARPA'89 Proceedings* (see Hammond, KJ, ed., 1989).

Hammond, K, 1988, "Case-based planning: viewing planning as a memory tasks." In: *DARPA'88 Proceedings* (see Kolodner, JL, ed.).

Hoffmann, SG and Thakar, S, 1993, Facilitating sales consultation through case-based reasoning." In: *EWCBR'93* (see Richter, MM et al., eds., 1993a).

Hurley, N, 1993, "A priori selection of mesh densities for adaptive finite element analysis, using a case-based reasoning approach." In: *EWCBR'93* (see Richter, MM et al., eds., 1993a).

Kamp, G, 1993, "Integrating semantic structure and technical documentations in case-based service support systems." In: *EWCBR'93* (see Richter, MM et al., eds., 1993a).

Klein, GA, Whitaker, LA and King, JA, 1988, "Using analogues to predict and plan." In: *DARPA'88 Proceedings* (see Kolodner, JL, ed.).

Klein, GA and Calderwood, R, 1988, "How do people use analogues to make decisions?" In: *DARPA'88 Proceedings* (see Kolodner, JL, ed.).

Kolodner, JL, 1992, *The role of experience in natural problem solving.* College of Computing, Georgia Institute of Technology, Atlanta.

Kopeikina, L, Bandau, R and Lemmon, A 1988, "Case-based reasoning for continuous control." In: *Proceedings* (see Kolodner, JL, ed.).

Koton, P, 1988, "Reasoning about evidence in causal explanations." In: Kolodner, JL (ed.).

Marks, M, Hammond, KA and Converse, T, 1988, "Planning in an open world: a pluralistic approach." In: *DARPA-88 Proceedings* (see Kolodner, JL, ed.).

Mukhopadhyay, T, Vicinanaza, SS and Prieutula, MJ, 1992, "Examining the feasibility of a case-based reasoning model for software effort estimation." *MIS Quarterly: Management information systems* **16**(2) 155–172.

Nakakoji, K, 1993, "Case-deliverer: making cases relevant to the task at hand." In: *EWCBR'93* (see Richter, MM et al., eds., 1993b).

Nakatani, Y, Tsukiyama, M and Fukuda, T, 1992, "Engineering design support framework by case-based reasoning." *ISA Transactions* **31**(2).

Owens, C, 1988, "Domain-independent prototype cases for planning." In: *DARPA'88 Proceedings* (see Kolodner, JL, ed.).

Paquet, E, Chaib-draa, B and Lizotte, 1993, "Towards a case-based identification process." In: *EWCBR'93* (see Richter, MM et al., eds., 1993a).

Richter, AM and Weiss, S, 1991, "Similarity, uncertainty and case-based reasoning in PATDEX." In: RS Boyer (ed.), *Automated reasoning, essays in honour of Woody Beledsoe.* pp. 249–265, Kluwer.

Rougegrez, S, 1993, "Case-based reasoning system that avoids the problem of the case identification." In: *Proceedings IEEE International Conference on Systems, Man and Cybernetics, Vol. 3,* pp 182–186.

Schmitt, G, Baily, SF and Smith, IFC, 1994, "Advances and challenges in case-based design." In: *Proceedings First Congress held in Conjunction with AI/EIC Systems '94, Vol. 1* (K Khozeimeh, ed., Washington, DC, June 20–22 1994).

Slade, S, 1991, "Qualitative decision theory." In: *Proceedings,* (see Bareiss, R, ed.).

Stadler, M, 1993, "Case-based reasoning for network management." In: EWCBR'93 (see Richter, MM et al., eds., 1993a).

Vargas, JE and Bourne, JR, 1993, "Scale-guided object matching for case-based reasoning." *Journal of Intelligent & Robotic Systems* **7**(1).

Vietze, T, 1993, "Case-based configuration in technical domains: combining case selection and modification." In: *EWCBR'93* (see Richter, MM et al., 1993b).

Vo, DP and Macchion, D, 1993, "Use of case-based reasoning technique in building expert systems." *Future Generation Computer Systems* **9**(4) 311–319.

Wall, RS, Donahue, D and Hill, S, 1988, "The use of domain semantics for retrieval and explanation in case-based reasoning." (see Kolodner, JL).

Wendel, O, 1993, "Case-based reasoning in simulation environment for biological neural networks." In: *EWCBR'93* (see Richter, MM et al., eds., 1993a).

Woltering, A and Schult, TJ, 1993, "Management strategy consultation using a case-based reasoning shell." In: *EWCBR'93* (see Richter, MM et al., eds., 1993a).

Yavner, J, Alterman, R and Sherman, F, 1989, "Diachronic analysis of political-event cases." In: *DARPA'89 Proceedings* (see Hammond, KJ, ed.).

Ziarko, W, 1989, "Analysis and case-based expert system development tool "Rough"." In: *DARPA'89 Proceedings* (see Hammond, KJ, ed.).

2.3 Background and review of CBR literature

This section presents references on papers that give a survey of or background to CBR.

Aamodt, A and Plaza, E, 1994, "Case-based reasoning: foundational issues, methodological variations, and system approaches." *AI Communications* **7**(1) 39–59.

Ashley, K and Rissland, E, 1987, "Compare and contrast, a test of expertise." In: *Proceedings of AAAI-87.*

Bareiss, ER (ed.), 1991, *Proceedings: Workshop on case-based reasoning (DARPA),* Washington, D.C. Morgan Kaufmann.

Barlet, S, 1991, "An introduction to case-based reasoning." *AI Expert* **6**(8).

Borner, K, 1993, "Structural similarity as guidance in case-based design." In: *EWCBR'93* (see Richter, MM et al., eds., 1993a).

Domeshek, E and Kolodner, JL, 1991, "Toward a case-based aid for conceptual design." *International Journal of Expert Systems* **4**(2) 201–220.

Domeshek, E and Kolodner, J, 1992, "A case-based design aid for architecture." In: *Artificial Intelligence in Design 1992* (J Gero, ed.). Kluwer.

IEEE Expert, 1992, **7**(5). Special issue on case-based reasoning.

Klein, GA and Calderwood, R, 1988, "How do people use analogues to make decisions?" In: Kolodner, JL (ed.).

Kolodner, JL (ed.), 1988, *Proceedings of a workshop on case-based reasoning. May 10–13 1988.* Clearwater Beach, FL.

Kolodner, JL, 1991, "Improving human decision making through case-based decision aiding." *AI Magazine* **12** 52–68.

Kolodner, JL, 1992, "An introduction to case-based reasoning." *Artificial Intelligence Review* **6**(1) 3–34.

Kolodner, JL, 1993, *Case-based reasoning.* Morgan Kaufmann.

Hammond, KJ, 1988, "Case-based planning: viewing planning as a memory task." In: *DARPA'88 Proceedings* (see Kolodner, JL, ed.).

Hammond, KJ (ed.), 1989, *Proceedings: Workshop on case-based reasoning (DARPA), May–June 1989,* Pensacola Beach, FL. Morgan Kaufmann.

Harmon, P, 1992, "Case-based reasoning II." *Intelligence Software Strategies* **7**(12).

Lewis, L et al, 1992, "A case-based reasoning solution to the problem of redundant engineering in large scale manufacturing." *International Journal of Expert Systems* **4** 189–200.

Richter, MM, Wess, S, Althoff, KD and Maurer, F (eds.), 1993a, *First European Workshop on Case-Based Reasoning, (EWCBR'93) Presentation and Posters,* University of Kaiserslauten (Germany) Vol. 2, 1–5 November.

Richter, MM, Wess, S, Althoff, KD and Maurer, F (eds.), 1993b, *First European Workshop on Case-Based Reasoning, (EWCBR'93) Presentation and Posters,* University of Kaiserslauten (Germany) Vol. 2, 1–5 November.

Riesbeck, CK and Schank, RS, 1989, *Inside case-based reasoning.* Erlbaum.
Simoudis, E, 1991, "Special issue on case-based reasoning." *International Journal of Expert Systems* **4**(2).
Slade, S, 1991, "Case-based reasoning: A research paradigm." *AI Magazine* 42–55.
Vargas, JE and Raj, S, 1993, "Developing maintainable expert systems using case-based reasoning." *Expert Systems* **10**(4) 219–225.
Watson, I and Marir, F, 1994, "Case-based reasoning: a review." *The Knowledge Engineering Review* **9**(4) 355–381.

3 CBR types

Case-based reasoning encapsulates different reasoning sub-tasks, and when one of these sub-tasks is dominant in the reasoning, the generic CBR will be instantiated to the term of that dominant sub-task. For instance, if the reasoner uses examples to reason with it is called "exemplar-based reasoning". If it makes intensive use of memory to recall specific episodes from the prior problem solving, it is called "memory-based reasoning". In this context, there is "schema-based reasoning", concerned with the retrieval of old schemes to resolve or interpret a problem and "analogy-based reasoning" that uses analogous domains to interpret a new problem in a different context. More elaboration on reasoning types can be found in the following references.

Aamodt, A, 1993, "Explanation-driven retrieval, reuse, and learning of cases." In: *EWCBR-93, First European Workshop on Case-Based Reasoning,* University of Kaiserslautern SEKI Report SR-93-12 (SFB 314) (Kaiserslautern, Germany) 279–284.
Becker, L and Jazayeri, K, 1989, "A connectionist approach to case-based reasoning." In: *DARPA'89 Proceedings* (see Hammond, KJ, ed.).
Hall, RP, 1989, "Computational approaches to analogical reasoning: A comparative analysis." *Artificial Intelligence* **39**(1) 39–120.
Kedar-Cabelli, S, 1988, "Analogy—from a unified perspective." In: DH Helman (ed.), *Analogical reasoning.* pp 65–103, Kluwer Academic.
Kibler, D and Aha, D, 1987, "Learning representative exemplars of concepts: An initial study." In: *Proceedings Fourth International Workshop on Machine Learning*, UC-Irvine, pp 24–29.
Kitano, H, 1993, "Challenges for massive parallelism." In: *IJCAI-93 Proceedings of the Thirteenth International Conference on Artificial Intelligence* Chambery, France. Morgan Kauffmann, pp 813–834.
Manago, M, Althoff, KD and Traphoner, R, 1993, "Induction and reasoning from cases." In: *ECML European Conference on Machine Learning Workshop on Intelligent Learning Architectures*, Vienna, Austria.
Smith, E and Medin, D, 1981, *Categories and concepts.* Harvard University Press.
Stanfill, C and Waltz, DL, 1988, "The memory-based reasoning paradigm." In: Kolodner, JL (ed.).
Steels, L, 1990, "Components of expertise." *AI Magazine* **11**(2) 29–49.
Steels, L, 1993, "The componential framework and its role in reusability." In: JM David, JP Krivine and R Simmons (eds.), *Second Generation Expert Systems*, pp 273–298, Springer-Verlag.
Turner, R, 1989, "Case-based and schema-based reasoning for problem solving." In: *DARPA'89 Proceedings* (see Hammond, KJ, ed.).
Van de Velde, W, 1993, "Issues in knowledge level modelling." In: JM David, JP Krivine and R Simmons (eds.), *Second Generation Expert Systems,* pp 211–231, Springer-Verlag.
Veloso, MM and Carbonell, J 1993, "Derivational analogy in PRODIGY." *Machine Learning* **10**(3) 249–278.
Zhang, X and Waltz, D, 1989, "Protein structure prediction using memory-based reasoning: a case study of data exploration." In: *DARPA'89 Proceedings* (see Hammond, KJ, ed.).

3.1 Case-based reasoning methods

CBR can be used for problem solving tasks such as planning or design and interpretation tasks such as legal reasoning or strategic planning. In a problem solving approach, a concrete solution is presented to a given problem by modifying and adapting a solution of a similar previous case. However, in the *interpretation approach,* options on accepting or rejecting an old solution are presented based on similarities or differences. There is also a *learning feature* in CBR that can be used to create cases that facilitate later problem solving or interpretation. This section presents papers on problem solving, interpreting problems and learning.

3.1.1 Problem solving CBR

This section contains papers that use CBR to solve problems in, for example, planning, design and diagnosis. There are also references that integrate other problem solving methods such as derivational analogy with CBR problem solving methods.

Aamodt, A, 1989, "Towards robust expert systems that learn from experience—an architectural framework." In: J Boose, B Gaines and J-G Ganascia (eds.), *EKAW-89 Third European Knowledge Acquisition for Knowledge-Based Systems Workshop,* Paris, pp 311–326.

Aamodt, A, 1991, *A knowledge-intensive approach to problem solving and sustained learning,* PhD dissertation, University of Trondheim, Norwegian Institute of Technology, May 1991.

Alterman, R, 1988, "An adaptive planner." In: *Proceedings AAAI-86* (In: *DARPA'88 Proceedings* see Kolodner, JL, ed.).

Barletta, R and Mark, W, 1988, "Explanation-based indexing of cases." In: *DARPA'88 Proceeding* (see Kolodner, JL, ed.).

Berger, J, 1989, "ROENTGEN: A case-based approach to radiation therapy planning." In: *DARPA'89 Proceedings* (see Hammond, KJ, ed.).

Beauboucher, N, 1993, "ANAIS: A case-based reasoning system in a problem solving environment." In: EWCBR-93 (see Richter, MM, et al., eds., 1993a).

Birnbaum, L, Collins, G, Brand, M, Freed, M, Krulwich, B and Pryor, L, 1991, "A model-based approach to the construction of adaptive case-based planning systems." In: *Proceedings* (see Bareiss, R, ed.).

Carbonell, JG, 1986, "Derivational analogy: A theory of reconstructive problem solving and expertise acquisition." *Machine Learning* **2**.

Carbonell, J and Velose, M, 1988, "Integrating derivational analogy into a general problem solving architecture." In: *DARPA'88 Proceedings* (see Kolodner, JL, ed.).

Gentner, D, 1983, "Structure-mapping: A theoretical framework for analogy." *Cognitive Science* **7**(2).

Goel, AK, Kolodner, JL, Pearce, M, Billington, R and Zimring, C, 1991, "Towards a case-based tool for aiding conceptual design problem solving". In: *Proceedings* (see Bareiss R, ed.).

Hammond, KJ, 1988, "Opportunistic memory: Storing and recalling suspended goals." In: *DARPA'88 Proceeding* (see Kolodner, JL, ed.).

Hammond, KJ and Hurwitz, N, 1988, "Extracting diagnostic features from explanations." In: *DARPA'88 Proceeding* (see Kolodner, JL, ed.).

Hammond, KJ, 1988, "Opportunistic memory: Storing and recalling suspended goals." In: *DARPA'88 Proceeding* (see Kolodner, JL, ed.).

Hendler, JA, 1988, "Refitting plans for case-based reasoning." In: *DARPA'88 Proceeding* (see Kolodner, JL, ed.).

Hennessy, D and Hinkle, D, 1991, "Initial results from clavier: A case-based autoclave loading assistant." In: *Proceedings* (see Bareiss, R, ed.).

Hinrichs, TR, 1988, "Towards an architecture for open world problem solving." In: *DARPA'88 Proceeding* (see Kolodner, JL, ed.).

Hinrichs, TR, 1988, "Towards an architecture for open world problem solving." In: *DARPA'88 Proceeding* (see Kolodner, JL, ed.).

Hinrichs, JR and Kolodner, JL, 1991, "The roles of adaptation in case-based design." In: *Proceedings* (see Bareiss, R, ed.).

Kolodner, J, 1987, "Extending problem solving capabilities through case-based inference." In: *Proceedings 4th Annual International Machine Learning Workshop.*

Koton, P, 1988, "Reasoning about evidence in causal explanation." In: *DARPA'88 Proceedings* (see Kolodner, JL, ed.).

Marks, M, Hammond, KA and Converse, T, 1988, "Planning in an open world: A pluralistic approach." In: *DARPA'88 Proceeding* (see Kolodner, JL, ed.).

Navinchandra, D, 1988, "Case-based reasoning in CYCLOPS, a design problem solver." In: *DRAPA'88 Proceedings* (see Kolodner, JL, ed.).

Plaza, E and Arcos, JL, 1993, "Reflection and analogy in memory-based learning." In: *Proc. Multistrategy Learning Workshop,* pp 42–49.

Owens, C, 1988, "Domain-independent prototype cases for planning." In: *DARPA'88 Proceeding* (see Kolodner, JL, ed.).

Shinn, HS, 1988, "Abstractional analogy: A model of analogical reasoning." In: *DARPA'88 Proceeding* (see Kolodner JL, ed.).

Sycara, K, 1988, "Using case-based reasoning for plan adaptation and repair." In: *Proceedings DARPA'88* (see Kolodner JL, ed.).

Sycara, KP and Navinchandra, D, 1991, "Influences: A thematic abstraction for creative use of multiple cases." In: *Proceedings* (see Bareiss R, ed.).
Turner, RM, 1988, "Organizing and using schematic knowledge for medical diagnosis." In: *DARPA'88 Proceedings* (see Kolodner JL, ed.).
Veloso, MM and Carbonell, JG, 1991, "Variable-precision case retrieval in analogical problem solving." In: *Proceedings* (see Bareiss, R, ed.).

3.1.2 Interpretation and CBR

The references in this section refer to the interpretative or precedent-based approach to CBR. It includes argumentation to decide whether a new situation should or should not be treated like a past experience based on similarities or difference. These types of CBR are mostly used in precedent-based fields like the law, or where the explanation or justification of a solution or the interpretation or assessment of a situation is required. The section also includes papers that treat the subject of checking the appropriateness of results from the interpretation, especially when based on unexplained experience or derived in unpredicted worlds.

Ashley, K and Rissland, E, 1988, "Compare and contrast, a test of expertise." In: *Proceedings of AAAI-87.* (In *DARPA'88 Proceeding* (see Kolodner, JL, ed.).
Ashley, K, 1991, *Modelling legal arguments. Reasoning with cases and hypothetical.* MIT Press, Bradford Books, Cambridge.
Barletta, R and Mark, W, 1988, "Explanation-based indexing of cases." In *DARPA'88 Proceeding* (see Kolodner, JL, ed.).
Birnbaum, L and Collins, G 1988, "The transfer of experience across planning domains through the acquisition of abstract strategies." In: *DARPA'88 Proceedings* (see Kolodner, JL, ed.).
Branting, LK, 1988, "The role of explanation in reasoning from legal precedent." In: *DARPA'88 Proceedings* (see Kolodner, JL, ed.).
Branting, K, 1991, "Exploiting the complementarity of rules and precedents with reciprocity and fairness." In: *Proceedings* (see Bareiss, R, ed.).
Carbonell, J and Velose, M, 1988, "Integrating derivational analogy into a general problem solving architecture." In: *DARPA'88 Proceedings* (see Kolodner, JL, ed.).
Hammond, KJ, 1987, "Explaining and repairing plans that fail." In: *Proceedings International Joint Conferences on Artificial Intelligence, IJCAI-87,* August, Milan, Italy.
Hammond, KJ and Hurwitz, N, 1988, "Extracting diagnostic features from explanations." In: *DARPA'88 Proceedings* (see Kolodner, JL, ed.).
Kass, AM and Leake, DB, 1988, "Case-based reasoning applied to constructing explanations." In: *DARPA'88 Proceeding* (see Kolodner, JL, ed.).
Koton, P, 1988, "Reasoning about evidence in causal explanations." In: *DARPA'88 Proceeding* (see Kolodner, JL, ed.).
Rissland, E, 1983, "Examples in legal reasoning: Legal hypothetical." In: *Proceedings of the Eighth International Joint Conference on Artificial Intelligence, IJCAI,* Karlsruhe.
Rissland, EL and Ashley, KD, 1988, "Credit assignment and the problem of competing factors in case-based reasoning." In: *DARPA'88 Proceeding* (see Kolodner, JL, ed.).
Skalak, CB and Rissland, E, 1992, "Arguments and cases: An inevitable twining." *Artificial Intelligence and Law, An International Journal* **1** 3–48.
Sycara, K, 1988, "Using case-based reasoning for plan adaptation and repair." In: *DARPA'88 Proceeding* (see Kolodner, JL, ed.).
Wall, RS, Donahue, D and Hill, S, 1988, "The use of domain semantics for retrieval and explanation in case-based reasoning." In: *DARPA'88 Proceeding* (see Kolodner, JL, ed.).

3.1.3 Learning from cases

This section contains references on case-based learning algorithms and CBR systems that focus on the learning of a topic. They can be used for knowledge acquisition and to improve future problem solving or interpretation. The result of this learning process is the creation and storage of new cases that can be used to help solve or interpret new problems.

Aamodt, A, 1989, "Towards expert systems that learn from experience." In: *DARPA'89 Proceedings* (see Hammond, JK, ed.).

Aamodt, A, 1993, "Explanation-driven retrieval, reuse, and learning of cases." In: *EWCBR-93. First European Workshop on Case-Based Reasoning.* University of Kaiserslautern SEKI Report SR-93-12 (SFB 314) (Kaiserslautern, Germany, 1993), pp 279–284.

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4 Case-based reasoning techniques

This section presents theoretical contributions into CBR techniques and application papers that present ways of representing, indexing, retrieving and adapting cases.

4.1 Case representation

The case representation process is one of the most important phases in designing a CBR system. The case representation should contain all information that describes a situation that has a direct impact on the outcome or the solution of that situation. Depending on the complexity of the situation cases can be represented in a flat form or a complex or hierarchical form. This section is

composed of papers that presents a variety of ways of representing the information in the computer using a wide range of representational formalisms including frames, semantic nets, rules and relational database techniques or a combination of different knowledge representations.

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4.3 Memory organization

The memory organization or case memory is the most important aspect in designing efficient case-based reasoning. It should reflect and translate into the computer, the conceptual view of what is represented in the case, taking into account the indexes that characterize the case from any perspective. It should also organize cases into a manageable structure to allow efficient search and retrieval methods of relevant cases. Extensive references to this important phase of CBR design are presented below.

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4.4 Retrieval

Given a description of a problem, the retrieval algorithm, using the indices, should retrieve the most similar cases to the current problem or situation. The retrieval or search algorithm relies heavily on the indices and the structure and organization of the memory to direct search to appropriate cases. Heuristic search and matching techniques may be used to retrieve an ordered set of useful cases from the case base. Several retrieval algorithms are presented in the following papers including: concept refinement and parallel search techniques. The issue of choosing and ranking a best-matching case has been addressed using several approaches such as analogy, similarity metrics, combinations of analytical and similarity-based CBR, and qualitative or multi-attribute similarity.

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4.5 Adaptation and repair

Once cases are retrieved efficiently, a CBR should adapt the solution stored in a retrieved case to the needs of the current case. This occurs when the retrieved case is different to the current case. The adaptation process looks for prominent differences between the retrieved case and the input case and then applies rules that take those differences in the account. Several types of adaptation are presented in the following references. These include: *structural adaptation*, where the adaptation rules are applied directly to the solution stored in cases and *derivational adaptation*, where the rules that generated the original solution are re-run to the problem. Evaluation and interpretation processes are also included.

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5 CBR application

5.1 CBR software tools

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At the time of going to press (Summer 1994), the following software tools with a CBR component are commercially available and supported. These have been ordered by company:

AknoSoft, **KATE**
58a, Rue du Dessous des Berger
75013 Paris, France
Tel: (33 1) 44 24 88 00
Fax: (33 1) 44 24 88 66
and
2460 Waverley Street
Palo Alto CA 94301, USA
Tel: (1 415) 326 24 60
Fax: (1 415) 323 47 38

ReMind
220–230 Commercial Street, Boston, MA 02 109, USA
Tel: (617) 742 7227
Fax: (617) 742 1139

ESTEEM
302E. Main Street Cambridge City
IN 47327, USA
Tel: (317) 478 3955
Fax: (317) 478 35550

CasePower (formerly called Induce-It)
380 Rector Place, Suit 4A
New York, NY 10280, USA
Tel: (212) 945 0630
Fax: (212) 945 0367

ART* Enterprise, CBR-Express and **CasePoint**
550 North Continental Blvd
El Segundo, CA 90245, USA
and
Inference Europe Ltd
31–37 Windsor Road
Slough SL1 2ED, UK
Tel: 0753 811855
Fax: 0753 811860

ReCall
ISoft
Chemin de Moulon
F-91190 Gif sur Yvette
France
Tel: (33-1)69.41.27.77
Fax: (33-1)69.41.25.32

Eclipse—The Easy Reasoner
413 Orchard Street
Sewickley, PA 15143, USA
Tel: (412) 741 6420
Fax: (412) 741 6457

5.2 Academic demonstrators

This section contains reference to academic demonstrator CBR systems. These systems are used in tasks such as knowledge acquisition and refinement, legal reasoning, explanation of anomalies, diagnosis, arbitration, design, adaptation and repair, tutoring, planning, help desks, etc.

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5.2.12 Adaptation and repair

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6 CBR and other reasoning methods

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6.1 CBR and rule-based, deep causal and model-based reasoning methods

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Koton, P, 1989, *Using experience in learning and problem solving.* Massachusetts Institute of Technology, Laboratory of Computer Science (Ph.D. diss. October 1988). MIT/LCS/TR-441.

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Schmalhofer, F and Thoben, J, 1992, "The model-based construction of a case-oriented expert system." *AI Communication* **5**(1) 3–18.

Skalak, DB, 1989, "Options for controlling mixed paradigm systems." In: *Proceedings* (see Hammond, KJ, ed.).

6.2 CBR and analogy

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Cunningham, P and Slattery, S, 1993, "Modelling of engineering thermal problems—An implementation using CBR with derivational analogy." In: *EWCBR'93* (see Richter, MM, et al., 1993a).

Lenz, M, 1993, "CABAT—A hybrid CBR system." In: *EWCBR'93* (see Richter, MM, et al., 1993a).

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Rissland, EL, Basu, C, Daniels, JJ, McCarthy, J, Rubenstein, B and Skalak, DB, 1991, "A blackboard-based architecture for CBR: An initial report." In: *Proceedings* (see Bareiss, R, ed.).

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7 CBR related works

This section refers to works that are related to CBR. Obviously this could be extremely extensive, so a fairly narrow definition has been taken where the referral to CBR is explicitly stated or very strongly implicitly implied.

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Ramamoorthy, CV, Chandra, C, Ishihara, S and Ng, Y, 1993, "Knowledge based tools for risk assessment in software development and reuse." In: *Proceedings of the International Conference on Tools with Artificial Intelligence 1993* pp 364–371.

Ravikumar, CP, 1993, "Parallel search-and-learn technique for solving large scale TSP." In: *Proceedings of the International Conference on Tools with Artificial Intelligence.* pp 381–388.

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Yoo, JS, et al., 1993, "Performance evaluation of signature-based access mechanisms for efficient information retrieval." In: *Transactions on Information and Systems 93 VE76-D No. 2* pp. 179–188.

8 Internet CBR sources

The following section presents sources that provide information via the Internet on CBR. These include ftp sites where CBR software and papers can be downloaded, and email newsletters and forums that discuss CBR.

8.1 AI-CBR

This is an Internet email forum for the discussion of all aspects of CBR research and practice. Membership is free and members include academics, industrialists and many of the CBR software vendors. In addition to an electronic conference, AI-CBR contains papers and articles on CBR that may be downloaded along with a bibliography of CBR research.

To join send the following message to "mailbase@mailbase.ac.uk":

join ai-cbr <first name><last name>

If your name were Joan Smith your message would be as follows:

To: mailbase@mailbase.ac.uk
Subject: join ai-cbr Joan Smith

Further information can be obtained from i.d. watson@surveying.salford.ac.uk or f.marir@surveying.salford.ac.uk.

8.2 CASUEL

CASUEL is a case representation language. Developed by the European INREKA project it is in the public domain and available by ftp from

>email address<

further information on CASUEL is available from:

casuel@informatic.uni-kl.de

8.3 CBR-MED

The CBR-MED mailing list provides a forum for the discussion of CBR methods in medicine. The list brings together medical practitioners, health informaticians, and CBR researchers in service of two goals:

- To support the delivery of medical care by fostering the development of CBR software that performs health care related tasks.
- To spur the development of CBR methods by focusing the efforts of researchers on the challenges (large databases, knowledge representation problems, etc.) provided by medical and health informatics problems.

To subscribe to CBR-MED, send a message that looks like this:

To: listproc@cs.uchicago.edu
Subject: subscribe CBR-MED <your first name> <your last name>

If your name were Joan Smith, your subscription request would look like this:

To: listproc@cs.uchicago.edu
Subject:subscribe CBR-MED Joan Smith

Further information about CBR-MED may be obtained from Jeff Berger [OWNER-CBR-MED@cs.uchicago.edu].

8.4 The European CBR newsletter

The case-based reasoning electronic newsletter is delivered to the members of the German AK-CBR and to the participants of the EWCBR-workshops. Thus, the *CBR Newsletter* addresses mainly a European readership. Its objective is to support an exchange of information, news, and opinions on CBR that relate to both scientific and application-oriented issues. Submissions to the CBR-Newsletter should be made to:

Dietmar Janetzko or Stefan Wess
dietmar@cognition.iig.uni-freiburg.de wess@informatik.uni-kl.de

People who want/do not want to receive the *CBR Newsletter* in the future should also send a short message to the above addresses.

8.5 Public domain CBR systems

The following algorithms/systems can be obtained via anonymous ftp on the Internet.

Programs referred to in Riesbeck and Schank (1989) *Inside Case-Based Reasoning,* can be obtained via anonymous ftp from cs.umd.edu directory: /pub/schank/icbr.

Programmes referred to in Riesbeck and Schank (1981), *Inside Computer Understanding,* can also be obtained via anonymous ftp from cs.umd.edu directory: /pub/schank/icu. This source contains Common Lisp implementation of the mini programs from *Inside Computer Understanding*. These programs have been written to run in any standard Common Lisp environment, and should work without modification. See the list section in the book on support if they do not work in your lisp environment. The programs are identical in functionality to those in the book, with the exception that some of the functions have been optimized to achieve more reasonable performance.

To use these programs effectively you will have to get a copy of the text, since a lot of critical documentation is not repeated in the source code, nor are the exercises for extending the programs.

CL-Protos referred to in Bareiss (1989), *Exemplar-Based Knowledge Acquisition,* can be obtained via anonymous ftp from cs.utexas.edu directory: pub/porter.

CL-Protos is a Common Lisp reconstruction of the research version of the Protos exemplar-based learning apprentice conceived by E Ray Bareiss and Bruce W Porter of the Artificial Intelligence Laboratory at The University of Texas at Austin. Protos was originally developed as an experiment in knowledge acquisition for heuristic classification tasks. The original research version of Protos was written in Prolog. This Common Lisp implementation is a reconstruction, not a Prolog-to-Lisp rewrite. Thus, CL-Protos differs from the original Protos in several places, but mostly by intention. Ray Bareiss had a consulting role in this reconstruction and suggested many of the changes.

CL-Protos is a research tool, not a product, so no warranties are given about the absence of bugs. CL-Protos is distributed as a courtesy among researchers; all commercial rights are reserved.

8.6 Useful e-mail addresses

A holiday planning case base containing approximately 1500 cases from a travel catalogue with all the information relevant for deciding which tour package comes closest to the customer's wishes. It is available from lenz@informatik.hu-berlin.de (Source: *Case-Based Reasoning Newsletter,* Vol. 2, No. 6 1994).

Georgia Institute of Technology (GTECH), College of Computing, Atlanta, GA. Ftp from ftp.cc.gatech.edu directory /pub/ai/ram.

This directory contains technical reports published by the AI Group, College of Computing, Georgia Tech, as well as electronic reprints of articles from major journals and conferences. Each publication is available as a text file in standard Postscript format, and should be printable using any standard method of printing Postscript files. The directory also contains an index of cognitive science technical reports.

The files are compressed; FTP them in binary mode and uncompress them using "uncompress file.ps.Z". If you have trouble uncompressing, send the author e-mail and they will send you the uncompressed version. The files are also accessible through WWW/Mosaic, WAIS and ALEX.

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