

# DYNAMIC NETWORKS TECHNIQUES FOR AUTONOMOUS PLANNING AND CONTROL

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## 1 Summary of research progress

Starting with functional description of physical mechanisms we were able to derive the standard probabilistic properties of Bayesian networks and to show:

1. how the effects of unanticipated actions can be predicted from the network topology,
2. qualitative causal judgments can be integrated with statistical data,
3. how actions interact with observations,
4. how counterfactuals sentences can be interpreted and evaluated,
5. how explanations and single-event causation can be defined in a given causal model.

Additionally, we have established an axiomatic characterization of causal dependencies, analogously to the characterization of informational dependencies, and we have demonstrated that network-based identification techniques, in the presence of hidden variables, have a broad scope of new applications, ranging from skill acquisition by autonomous agents, to the analysis of treatment effectiveness in clinical trials.

The following specific results were obtained during the period of performance:

1. Computer programs were developed to assist clinicians with assessing the efficacy of treatments in experimental studies for which subject compliance is imperfect
2. Methods were developed for selecting sufficient set of measurements that permit unbiased estimation of causal effects in observational studies
3. Polynomial algorithms were developed for finding minimal separators in a directed acyclic graphs.

4. A formal model has been developed, based on modifiable structural equations, which generalizes and unifies the structural and counterfactual approaches to causal inference, explicates their conceptual and mathematical bases and resolves their technical difficulties
5. We proved that the structural and counterfactual formalisms are equivalent in recursive causal models (i.e., systems without feedback) but not when feedback is considered possible.
6. Simple rules were devised for translating a problem back and forth, between the structural and counterfactual representations. A new semantics for “actual causation” was developed based on a construct named “causal beam,” that is, a minimally modified causal model, in reference to which the standard counterfactual criterion is adequate for identifying causes of singular events.
7. Formal semantics was developed, based on structural models of counterfactuals, for the probabilities that event  $x$  is a necessary or sufficient cause (or both) of another event  $y$
8. Conditions were discovered under which probabilities of necessary and sufficient causation can be learned from a combination of actions and observations. It was found that data from both experimental and nonexperimental studies can be combined to yield information that neither study alone can provide
9. New definition of causal explanation was formulated in which explanation is treated as a fragment of knowledge needed to support causation.

## 2 List of publications resulting from the AFOSR grant (December 15, 2000 – December 14, 2001)

- Pearl, J., *Causality: Models, Reasoning and Inference* Cambridge University Press, 2000.
- Tian, J. and Pearl, J., “Probabilistic of causation: Bounds and identification,” in Craig Boutilier and Moises Goldszmidt (Eds.), *Proceedings of the Sixteenth Conference on Uncertainty in Artificial Intelligence*, San Francisco, CA: Morgan Kaufmann, 589–598, 2000.
- Tian, J. “A branch-and-bound algorithm for MDL Learning Bayesian Networks,” in Craig Boutilier and Moises Goldszmidt (Eds.), *Proceedings of the Sixteenth Conference on Uncertainty in Artificial Intelligence*, San Francisco, CA: Morgan Kaufmann, 580–588, 2000.
- Pearl, J., “The logic of counterfactuals in causal inference,” *Journal of American Statistical Association*, Vol. 95, No. 450, 428–435, 2000.
- Halpern, J.Y. and Pearl, J., “Causes and Explanations,” UCLA Computer Science Department, Technical Report (R-266), July 2000.
- Tian, J. “A branch-and-bound algorithm for MDL Learning Bayesian Networks,” In Craig Boutilier and Moises Goldszmidt (Eds.), *Proceedings of the Sixteenth Conference on Uncertainty in Artificial Intelligence*, San Francisco, CA: Morgan Kaufmann, 580–588, 2000. UCLA Computer Science Department, Technical Report (R-277), August 2000.

- Pearl, J., "On two pseudo-paradoxes in Bayesian analysis," *Annals of Mathematics in artificial Intelligence*, Special Issue on Representations of Uncertainty, Vol. 32, 171–177, 2001.
- Tian, J. and Pearl, J., "Causal Discovery from Changes," In *Proceedings of the Seventeenth Conference on Uncertainty in Artificial Intelligence*, San Francisco, CA: Morgan Kaufmann, 512–521, 2001.
- Pearl, J. "Bayesian Networks, Causal Inference and Knowledge Discovery" UCLA Cognitive Systems Laboratory, Technical Report (R-281), March 2001. In *Second Moment*, (<http://www.secondmoment.org>), March 1, 2001.
- Pearl, "Causal Inference in the Health Sciences: A Conceptual Introduction" UCLA Cognitive Systems Laboratory, Technical Report (R-282), February 2001. Forthcoming, *Health Services and Outcomes Research Methodology*, special issue on causal inference, Kluwer Academic Publishers, 2001.
- Pearl, J. "Comments on Seeing and Doing" UCLA Cognitive Systems Laboratory, Technical Report (R-283-A), February 2001. To appear in *International Statistic Reviews*.
- Pearl, J. "Comments on Nozer Singpurwalla's 'On Causality and Causal Mechanisms'" UCLA Cognitive Systems Laboratory, Technical Report (R-283-B), February 2001.
- Pearl, J. "Bayesianism and Causality, or, Why I am Only a Half-Bayesian" In D. Corfield and J. Williamson (Eds.) *Foundations of Bayesianism*, Applied Logic Series Volume 24, Kluwer Academic Publishers, the Netherlands, 19–36, 2001.
- Tian, J. and Pearl, J., "Causal discovery from changes: A Bayesian approach," UCLA Computer Science Department, Technical Report (R-285), 2001. Submitted to UAI-2001
- Pearl, J., "Causal Inference in Statistics: A Gentle Introduction," UCLA Computer Science Department, Technical Report (R-289), August 2001. In *Computing Science and Statistics, Proceedings of Interface '01*, Volume 33, 2001.
- Tian, J. and Pearl, J., "On the identification of causal effects," UCLA Computer Science Department, Technical Report (R-290), July 2001.
- Brito, C. and Pearl, J., "A New Identification Condition for Recursive Models with Correlated Errors," UCLA Computer Science Department, Technical Report (R-291), October 2001. Forthcoming *Journal Structural Equation Modeling*.
- Paz, A., "An Alternative Version of Lauritzen et al.'s Algorithm for Checking Representation of Independencies," UCLA Computer Science Department, Technical Report (R-292), August 2001.
- Cognitive Systems Laboratory selected publications website ([http://bayes.cs.ucla.edu/csl\\_papers.html](http://bayes.cs.ucla.edu/csl_papers.html)).

### 3 Awards

J. Pearl's book, *Causality: Models, Reasoning and Inference*, has won the Lakatos Award for 2001. The Lakatos is awarded each year by the London School of Economics for the most outstanding contribution to the philosophy of science.

B. Bonet's paper "Instrumentality Tests Revisited" was selected as a Best-student paper award runner-up" at the Seventeenth Conference on Uncertainty in Artificial Intelligence, UAI-01, Seattle, August 2001.