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2. CAUSALITY: MODELS, REASONING AND INFERENCE. Judea Pearl, Cambridge University Press, New York, 2000. No. of pages: 384. Price: $39.95. ISBN 0-521-77362-8

The question of causal inference is obviously highly relevant for any empirical research. For a long time, scientists have struggled to find appropriate definitions and formalizations to cope with this problem, sometimes with the conclusion that causal inference is not possible at all. Many more optimistic contributions are due to Judea Pearl and his co-workers. His new book, *Causality: Models, Reasoning, and Inference*, now provides an overdue comprehensive account of the problem. Pearl demonstrates how and under what conditions causal inference from empirical data can be given a clear mathematical formulation and solution, yet emphasizing that substantive background information is a necessary ingredient. Besides presenting a concise formal approach, the book offers numerous fictitious and real-data examples from such different fields as epidemiology, sociology and legal reasoning, thus facilitating the access for a wide readership.

It is divided into ten chapters taking different perspectives and relating the topic to concepts such as confounding, structural models, exogeneity or instrumental variables. This is completed by an epilogue and an exhaustive bibliography. The epilogue provides an easy-to-read overview for readers who are less interested in the mathematical details.

To understand Pearl's approach it is crucial to be familiar with some basic concepts of conditional probability and graphical models which are briefly introduced at the beginning. In contrast to models describing pure statistical associations, causal models, as conceived by Pearl, aim at reflecting the behaviour of a system under interventions, that is, subject to some external manipulation. This is complicated by the fact that typically only non-interventional associations can be observed. The following questions are therefore successively addressed in the book: (i) How and under which conditions can a causal graph be inferred from raw data? (ii) Given a causal model, how and under which conditions is the effect of an intervention identifiable? (iii) Given a causal model and empirical evidence, how and under which conditions can we trace back the cause of a specific effect?

As to the first question, algorithms are proposed relying on several conditions. One basic principle is that any association (beyond sampling inaccuracy) has a causal explanation, either through direct causation or through common, possibly hidden, causes. In addition, Pearl argues that specific patterns of statistical associations only make sense when interpreted in terms of causality. The search for causal structures of course also depends on the critical assumption of no unobserved common causes. Similar conditions and principles can be found throughout the book.

The question of identifying causal effects is addressed at different levels of complexity. The results for 'atomic' interventions, fixing a variable to a specific value, are generalized to conditional interventions and sequential plans. Based on a formal calculus of intervention, conditions can be derived to find a set of covariates such that their observation is sufficient for the identification. Moreover, quite general formulae are given to adjust for these covariates implying, for example, (a) that standard adjustment can be misleading and (b) that the assumption of no unmeasured common causes might be substantially relaxed. The results are compared with other approaches, for example, the G-computation developed by J. Robins.

The importance of the intervention calculus is further illustrated by its application to the problem of confounding. This is first (re)defined in terms of causality before showing that a statistical test for confounding is impossible, yet demonstrating that one can get pretty close to such a test. The particular issues raised in this context should prove very valuable for epidemiological research. The reasoning, however, often refers to and discusses approaches proposed by other authors making it hard to understand when not familiar with the literature.

While the first half of the book almost avoids the topic of counterfactuals, the last four chapters are heavily based on this controversial concept. A typical counterfactual statement is: 'Mr A would not have died had he not been exposed (counter to the fact) to nuclear radiation.' Clearly, most of the intuitive reasoning about causality is based on such statements, but the possibility of a precise mathematical formulation and, in particular, the testability of counterfactual assumptions could and has been disputed. However, Pearl gives a very lucid introduction to counterfactuals, their mathematical representation and handling, and their empirical content. The clarity is mainly due to simple examples and a distinct endeavour to relate the formalization to intuitive human reasoning. The practical use becomes clear in situations where the identification of a causal effect is not possible, for example, the partial compliance situation. Instead, bounds for the average causal effect are derived based on counterfactual reasons, although without mentioning that other derivations are possible [1]. Somewhat hidden in the same chapter is also a brief discussion of causal inference from finite samples using Gibbs sampling. Unfortunately, this important topic, although illustrated by some small real data examples, is not given enough attention.

Finally, the counterfactual approach is applied to assessing the contribution of a potential cause to a specific effect as might be relevant in epidemiology or legal inquiries. Among others, the use of the excess risk rate is explored. Pearl gives clear conditions under which this yields valid results, and describes when and how it has to be corrected. Despite these promising results, there is no doubt that the 'quest for the actual cause' cannot be satisfactorily solved at the present stage and that more research on this topic is needed.

In conclusion, the new book by Judea Pearl raises many issues crucial for the thorough interpretation of empirical findings deserving to be considered by any empirical researcher. It demonstrates that empirical data can reveal much more about causal relations than admitted by 'mainstream' statistical analysis, albeit tied to assumptions that have to be scrutinized in every specific case.

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