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## QUESTIONS

1. Please verify our additions to headings or reword as necessary.
2. Please verify that it is correct to have quotation marks around “selection bias on a common effect.”

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## COMMENTS ON NEUBERG'S REVIEW OF *CAUSALITY*

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I am grateful to Professor Neuberger for taking the time to study my book *Causality* and for summarizing its main ideas in a language familiar to readers of *Econometric Theory*. I will comment on several issues that I believe warrant further discussion. First, I will summarize in my own style what economists can learn from *Causality*, and, second, I will correct several inaccuracies in the summary of Professor Neuberger.

### 1. WHAT ECONOMISTS CAN LEARN FROM *CAUSALITY*

Economists have had a long and treacherous encounter with the notion of causation. Although the standard econometric literature prefers to skirt the issue and relegates causal relationships to the province of human intuition, the more foundation-inspired economics literature admits the importance of capturing such relationships mathematically and usually concludes by lamenting the “controversial” and “illusive” nature of causation.

The first benefit readers of *Causality* should gain is the recognition that causation is not controversial or illusive; rather, it is a well-defined concept that is amenable to mathematical analysis. There is hardly any causal concept that does not lend itself to a formal analysis through the framework developed in *Causality*.

Neuberger mentions several economics issues whose analysis seems to escape the structural framework introduced in *Causality*, among them, problems connected with equilibrium constraints (e.g., that supply and demand quantities are equal at equilibrium) and behavior emanating from rational expectations. However, as mentioned on page 137 of *Causality*, the analysis of these issues can well be managed within the proposed framework, albeit one that invokes deeper, more refined, levels of structural equations. For example, the equilibrium condition  $q_D = q_S$  need not be taken as a constraint but can be formulated as a consequence of cause-effect processes involving inventory costs. The concepts and tools developed in *Causality* are basic to causal analysis at all levels of analysis. If intervention occurs only at the utility production level, as suggested by Neuberger, then the variables under direct manipulation can be made explicit in a deeper level of analysis, and the results would illuminate the coarser analysis. Additionally, Section 4.2 (p. 113) of *Causality* shows how problems

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involving function-modification interventions can be reduced to those involving variable-fixing interventions.

To let readers judge whether *Causality* would merit one's investment of time and thought, I will now list a set of problems that a typical economist will find hard or impossible to solve and for which *Causality* offers simple mathematical solutions.

We start by assuming that one is given an economic model  $M$  in the form of a set of linear equations with undetermined parameters and stochastic disturbances with unknown correlation matrix  $C$ . The only information available to us is the set of zero correlation entries in  $C$  (i.e., the set of disturbance pairs that are uncorrelated).

1. Identifying independence in linear models: Given model  $M$  and an arbitrary pair of variables  $X$  and  $Y$ , determine if  $X$  and  $Y$  are correlated (for some possible values of the parameters and for some matrix  $C$  with same zero entries).
2. Identifying conditional independence in linear models: Given model  $M$  as in problem 1, and a set of three variables,  $X$ ,  $Y$ , and  $Z$ , determine if  $X$  and  $Y$  are correlated given observations on  $Z$  (again, for some possible values of the parameters and for some matrix  $C$  with same zero entries).
3. Identifying conditional independence in nonlinear models: Assume that the model  $M$  is composed of a set of recursive (i.e., feedback free) nonlinear equations, with unknown parameters, and a set of disturbances having arbitrary statistics. Given model  $M$  and three subsets of variables,  $X$ ,  $Y$ , and  $Z$ , determine if  $X$  and  $Y$  are independent given observations on  $Z$  (again, for all possible values of the parameters).
4. Conditional independence in nonparametric models: Same as problem 3, except that model  $M$  is now composed of a set of arbitrary functions, the form of which is unknown, and the disturbance statistics are, likewise, unknown. The only information available is a set of subsets of disturbances that are mutually independent.
5. Causal effects in linear systems: Given a fully specified economic model  $M$  as in problem 1 (i.e., all parameters, including matrix  $C$ , are known), let  $X$  and  $Y$  be two arbitrary variables. Determine the causal effect of variable  $X$  on variable  $Y$ , namely, the increase in  $E(Y)$  due to unit increase in  $X$ .
6. Counterfactuals in linear systems: Given a fully specified economic model  $M$  as in problem 5 (i.e., all parameters, including matrix  $C$ , are known), let  $X$  and  $Y$  be two arbitrary variables. Determine what  $E(Y)$  would be if  $X$  were equal to  $x$ , given that, in reality,  $X = x'$  and  $Y = y'$ .
7. Causal effects in nonlinear systems: Same as problem 5, but model  $M$  is composed of a nonlinear set of functions (with unique equilibrium) with known parameters and known distribution of disturbances.
8. Counterfactuals in nonlinear systems: Same as problem 6, but model  $M$  is composed of a nonlinear set of functions (with unique equilibrium) with known parameters and known distribution of disturbances.
9. Identification of causal effects: Given a nonparametric economic model  $M$  as in problem 4, let  $X$  and  $Y$  be two arbitrary variables. Let the causal effect of  $X$  on  $Y$  be defined as the probability  $P(Y = y)$  that would ensue if we were to intervene

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and hold  $X$  constant, at  $x$ . Determine whether the causal effect of  $X$  on  $Y$  can be estimated consistently from nonexperimental data. If the answer is positive, determine whether there exists a set  $Z$  of variables that can be adjusted for, to yield the desired causal effect.

10. Identification of counterfactual claims: Given a nonparametric economic model  $M$  as in problem 4, let  $X$  and  $Y$  be two arbitrary variables.
  - a. Determine whether the following quantity,  $Q$ , can be estimated consistently from nonexperimental data:  $Q$  is the probability of  $Y = y$  that would prevail had  $X$  been equal to  $x$ , given that, in reality,  $X$  is equal to  $x'$ .
  - b. Determine whether  $Q$  can be estimated consistently from experimental data.

**2. CORRECTIONS TO NEUBERG'S REVIEW****2.1. First Correction**

Q1

Throughout his review, Neuberg refers to my framework as “the theory of inferred causation.” This is not accurate. I have used the phrase “theory of inferred causation” when dealing with one task only, that of inferring the structure of a model from nonexperimental data (Chapter 2). The reader would do well to replace this phrase with “the structural model approach.”

**2.2. Second Correction**

Neuberg asserts that “Pearl . . . takes third variable common causes as the only source of confounding bias.” This is not the case. Any association between two disturbances can lead to confounding bias, whether or not the association is created by a common cause. For example, an association can be caused by the two disturbances having a common effect  $E$ , when the data are selected such that all samples satisfy  $E = 0$ . This leads to the Berkson paradox (see *Causality*, p. 17).

Graphically, associated disturbances are represented by curved arcs connecting the corresponding variables. Thus, the approach in *Causality* does not “rule out a priori” the problem of multicollinearity, or “two associated causes of an effect.” It in fact offers effective solution to such problems, elaborated in chapters 3, 4, and 5 (e.g., Figure 3.8, p. 92). If the association emanates from “selection bias on a common effect,” as in the Berkson paradox, the approach offers a formal graphical method of managing such associations also. Q2

**2.3. Third Correction**

Referring to Figure 1(iii), the caption reads: “Don’t adjust for  $Z$  when finding the causal effect of  $x$  on  $Y$ .” A more accurate caption would read: “There is no need to adjust for  $Z$  when finding the causal effect of  $X$  on  $Y$ .” The reason is as follows. The absence of a curved arc between  $X$  and  $Z$  conveys the assumption that  $X$  and  $Z$  are not associated and, under such an assumption, adjusting for  $Z$

is superfluous (i.e., it may improve power but not gain consistency). Adding a curved arc between  $X$  and  $Z$  would qualify  $Z$  for adjustment by the back-door criterion. Thus, to answer Neuberger's question, if  $Z$  and  $X$  are collinear, adjustment for  $Z$  is warranted by the back-door criterion, which coincides with econometric intuitions.

#### 2.4. Fourth Correction

In the Conclusion section, Neuberger asks, "If there are situations where the graph theory approach says to adjust for intermediate effects but statisticians say not to do so, how can we decide who is right?" The answer is simple. Conclusions based on the graphical approach are mathematically proven, whereas those based on statistical tradition are folklore. The choice is clear. Fortunately, however, the clash that Neuberger alludes to does not occur in the model of Figure 2. Statistical intuition warns us against adjusting for  $T$ , and so does the graph-theoretic approach; simple adjustment for  $T$  would introduce bias. What graph-theoretical analysis provides—that statistical intuition does not—is the realization that the causal effect of  $X$  on  $Y$  can be estimated by a two-stage adjustment for  $T$ , as given by the front-door formula (*Causality*, p. 83).