“Structural vs. Reduced Form”
Language and Models in Empirical Economics

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Types of Empirical Work: A Functional Taxonomy?

1. Measurement
   - how much do prices change with the number of competitors?
   - how has productivity (e.g., TFP) in the U.S. auto industry changed over the last 30 years?
   - what is the effect of college attendance on expected wage?
   - what is the elasticity of aggreg demand for health insurance?
2. Model Testing
   - Is there evidence of moral hazard in auto insurance?
   - Does BNE do well in predicting bidding at oil auctions?
   - Do actual contracts resemble optimal contracts?
3. Model Estimation for Counterfactuals
   - How much would prices rise two firms merged? if the sales tax increased by 1%?
   - How would student outcomes differ under a different school choice mechanism?

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- *elasticity of demand*: can't just compare quantities purchased for goods with high prices vs. those with low prices.

Causality and Counterfactuals

Much of empirical economics is about “causal effects” (or, more simply, “effects”)

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This is true even for an RCT. There, after defining the counterfactual question of interest, one directly creates the counterfactual world. Sometimes the counterfactual question of interest is simple; but only after defining the question can one ask how to design the RCT to answer it.

Types of Empirical Work: A Better Taxonomy

1. **Descriptive**: estimate relationships between observables
   - establish facts about observable quantities, e.g.,
     - college grads earn 98% more per hour than others
     - income inequality higher now than 30 years ago
     - health care costs growing more slowly after ACA
     - airline prices higher now than before merger wave
   - facts sometimes suggest causal relationships
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2. **Structural:** estimate features of a data generating process (i.e., a model) that are (assumed to be) invariant to the policy changes or other *counterfactuals* of interest
   - estimate demand for schools⟶predict outcomes under a voucher system
   - estimate model of schooling, marriage, and labor supply choices⟶measure true male-female wage gap
   - estimate demand and firm costs⟶predict the welfare effects of a merger.

What about Program Evaluation?

Consider a RCT with interest only in the effect of the treatment in the population studied.

Here, program evaluation is *descriptive:* it involves only a characterization of relationships between observables.

It is also *structural*: it quantifies features of the underlying ("causal"/"structural") model characterized by the joint distribution

$$F(Y, D, X)$$

where $D \in \{0, 1\}$ indicates treatment, Y measures outcome, X are "controls."

What about Program Evaluation?

Program evaluation (indeed, any type of so-called "causal inference") is always a form of structural estimation. It requires a set of maintained hypotheses about the world (i.e., a model) allowing one to *define* and *identify* a counterfactual quantity of interest.

TT, ATE, LATE, QTE, etc. are all precisely defined only under a well specified model of how the data are being generated. Any suggestion that these objects are "model free" is nonsense.

Program Evaluation is Structural Estimation

Sometimes (e.g., in RCT) data description directly reveals a causal/structural/countefactual quantity like TT. But that is a *result*—one that follows from an explicit set of assumptions on the underlying structure that allows us to distinguish the idea of TT from other notions of causal effects and to logically conclude that the data directly reveal this quantity.

Typically program evaluation requires more than descriptive analysis: one must *counterfactually* hold *all else equal* in order learn the effect of D on Y, given X. This means treating $F(Y, D, X)$ (or a functional of F like LATE) as the counterfactual quantity of interest and using appropriate econometric techniques (IV, diff-in-diff, RD,...) to estimate it.

Causal Efffects, Causal Inference

Old Wine, New Labels

Causality is always *defined* by a counterfactual.

"Causal inference" is typically used to signal restriction to a restricted class of models (e.g., Rubin causal model) and estimation methods. One can certainly have preferences over models and methods. But causal estimation/inference is always a special case of structural estimation/inference as defined in econometrics 60+ years ago.

Likewise, the "causal effect" of X on Y is what for decades was called the "effect" of X on Y.

An Observation about Counterfactuals

A counterfactual may involve a feasible policy change (e.g., raise the minimum wage). But it could instead be a purely artificial notion (e.g., change women to men to see the resulting wage change).

Obviously one must think carefully about what the artificial ones mean: e.g., woman switched to man at age 25? at birth? But those suggesting that one cannot define the (causal) effect of being female rather than male (or, more generally, that only feasible policies constitute useful/meaningful counterfactuals) are confused.

What about "Reduced Form"?

Definition. A **reduced form** is a functional or stochastic mapping for which the inputs are (i) *exogenous* variables and (ii) unobservables ("structural errors"), and for which the outputs are *endogenous* variables. e.g., $Y = f(X, Z, U)$.

This is the only formal definition I am aware of. In econometrics this goes back at least to 1950. In math, much farther. Economic theorists also use this term.

Where does it come from?

Formally, one obtains a reduced form by *solving a (structural) model* for each endogenous variable as a function of the exogenous observables and structural errors.

The classic example is perfectly competitive supply and demand:

$$\begin{aligned} Q &= D\left(P, X, U_d\right) \qquad \text{(demand)} \\ P &= MC\left(Q, Z, U_s\right) \qquad \text{(supply)} \end{aligned}$$

Solving for equilibrium yields the reduced form relations

$$\begin{aligned} P &= p\left(Z, X, U_s, U_d\right) \\ Q &= q\left(Z, X, U_s, U_d\right) \end{aligned}$$

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(Solving isn't actually essential, however. We just need to know what goes on which side and what restrictions, if any, should be imposed. Logically one can hypothesize a reduced form rather than hypothesizing structure.)

Reduced Form: One Source of Nuance and Confusion

Definition. A **reduced form** is a functional or stochastic mapping for which the inputs are (i) *exogenous* variables and (ii) unobservables ("structural errors"), and for which the outputs are *endogenous* variables. e.g., $Y = f(X, Z, U)$.

But what does *exogenous* mean?

- for a theorist, an exogenous variable is one taken as given in (not determined within) the model
- for an econometrician: an exogenous variable is one satisfying some kind of independence condition with respect to unobservables.

These can be different: the fact that something is treated as "given" does not mean it satisfies any independence conditions!

An Example: Monopoly Price and Quantity

- firm has marginal cost $c(q, t, \epsilon)$ where q is quantity, t is quality, and ϵ is a cost shock (unobserved shifter of costs)
- demand $D(p, t, \eta)$, where p is price, η is a demand shock
- taking (t, ϵ, η) as given, solve for eqm price and quantity:

$$p^*(t, \epsilon, \eta)$$

$$q^*(t, \epsilon, \eta) = D(p^*(t, \epsilon, \eta), t, \eta)$$

The theorist's reduced forms are $p^*(t, \epsilon, \eta)$ and $q^*(t, \epsilon, \eta)$.

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From the econometrician's perspective, these may not be reduced forms because t may be correlated with (ϵ, η). For example, correlation is generally *implied* if t is chosen by the firm with knowledge of (ϵ, η). In that case, t cannot appear on the RHS of a reduced form econometric model.

Example continued

So there is a nuance. But the real issue in the example is that the theorist's model left out something: how t was determined.

That may be fine for the purpose of the theory, but may mean that the econometrician has to *develop a richer model* in which more of the variables are endogenous. This is *always*, at least implicitly, what one is doing when discussing problems of "confounding factors"/selection/endogeneity/IV, etc.

Reduced Form: Some Observations

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3. RF can be used for some types of counterfactuals! (those that do not change the mapping from exogenous variables and structural errors to endogenous outcomes)
4. Sometimes there is no difference between the structural equation and reduced form: e.g., exogenous treatment with $Y = f(X, U)$ and scalar $U \perp X$.

“Reduced Form”

Confusion and Abuse of Terminology 101

“Reduced form” is sometimes used to mean “equation I won’t derive, justify, or take questions on, but which I will nonetheless treat as structural (i.e., ‘causal’) when I talk about conclusions”

This is just bad science.

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Confusion and Abuse of Terminology 102

“Reduced Form” label often combined with use of IV, RD, etc. “identification strategies,” due to endogeneity/selection: e.g., “reduced-form demand model” or “reduced-form estimation of the LATE”

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For this to make sense, one must mean that the equation is "structural" in the econometrics sense but "reduced form" in the (third!) sense of collapsing a more complex model into a simpler representation, e.g., by-passing some underlying mechanisms. This would be a "reduced form structural model."

But EVERY model involves collapsing a more complex world into to simpler representation! There is no coherent way to label only some models as reduced form in this third sense.

“Reduced Form”

Confusion and Abuse of Terminology 103

Sometimes reduced-form terminology used with the correct intent but without enough care to avoid error. Suppose someone has in mind the supply and demand model

$$\begin{aligned} Q &= D(P, X, U_d) \qquad \text{(demand)} \\ P &= MC(Q, Z, U_s) \qquad \text{(supply)} \end{aligned}$$

but then posits a reduced-form pricing equation of the form:

$$P = g(Z, X, \epsilon) \qquad \epsilon \in \mathbb{R}$$

This pricing equation is consistent with the supply and demand model *only* if the two original structural errors U_d and U_s enter the equilibrium solution through a scalar index $\epsilon(U_d, U_s)$: this is a strong functional form requirement, even when g is unrestricted.

An Aside on Structural Errors

This supply and demand example illustrates a general substantive point: it is important to ask what the unobservable(s) are in the relevant economic model, rather than treating them as unnamed "residuals" or "error terms."

It is hard to speak coherently about the properties unnamed unobservables!

Reduced Form vs. Descriptive

Baby and Bathwater

"Reduced-form" sometimes used to mean descriptive, sometimes to mean that the structural model is viewed as simple, sometimes to mean "sloppy," and sometimes in a way consistent with its formal definition.

Many interesting papers involve descriptive analysis that evaluates model predictions or suggests interesting/important patterns/phenomena that one might investigate further using other methods. And for many questions, simple structural models make sense and allow one to answer questions of interest. Mis-labeling these things as "reduced-form" causes confusion and guilt by association with sloppy work.

“Structural”

Confusion and Abuse of Terminology 201

Sometimes “structural” mis-used. . .

- to describe *how* one estimates rather than *what* one estimates “We *structurally estimate* a model of...”
  - this is nonsense
- that one is estimating the “deepest” primitives one thinks of
  - this defines terminology based on the speaker’s knowledge/imagination. It is also just incorrect.

“Structural”

Confusion and Abuse of Terminology 202

Sometimes “structural” mis-used...

- to mean use of a complex model, or a model with many parametric/functional form assumptions
  - this is completely orthogonal to the question of structural vs. descriptive vs reduced form;
- to mean that all functional forms and distributions have been specified up to a finite parameter vector
  - this is nonsense; there is a big literature on nonparametric identification of structural models

The misuses of “structural,” like those of “reduced form,” come from both sides. This results in more more baby going out with bathwater.

“Structural”

Some Observations (Clear already in the 40s and 50s)

Structural estimation can involve estimation of “deep primitives” like distributions of consumer preferences over product characteristics, “less deep primitives” like aggregate demand elasticities, or a particular function of the primitives like the change in welfare under a particular counterfactual.

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For example, we don't need to know entire demand curve to measure change in consumer surplus due to a small price change: local properties of the demand curve are enough.

(See "sufficient statistics" approach: this is just a standard type of structural econometrics already used for decades, just without the abuse of formal terminology.)

"Structural"

Some Observations (Clear already in the 40s and 50s)

Although we think of "structure" as a set of policy-invariant features of a model, exactly what "policy invariant" means may vary with the kinds of policy or questions we consider. An example is short-run vs. long-run demand elasticities, which reflect two different counterfactuals.

Structural estimation can involve estimation/inference on points or sets (e.g., bounds on LATE or on a demand curve).

Identification, Formally

Hurwicz (1950), Koopmans and Reiersol (1950), Berry and Haile (2018):

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Definition. A structural feature $\theta(S_0)$ is *identified* (or *point identified*, or *identifiable*) under the hypothesis $\mathcal{H}$ if $\theta(S_0)$ is uniquely determined within the set $\{\theta(S) : S \in \mathcal{H}\}$ by the joint distribution of observables.

Remarks on Identification

- *Identification is not even defined without the notion of a true structure within a class defined by maintained hypotheses (what we usually call a "model").* The model may be simple or complicated, may involve economics or only hypothesized statistical relationships (e.g., Rubin causal model). But identification presumes that there are structural features—abstract notions not defined by data alone—that one wishes to uncover.

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- *Identification has nothing to do with a given sample or an estimator.* In fact, strictly speaking it is not even about what one could learn from an infinitely large sample
- *Identification of a structural feature $\theta(S_0)$ may hold even when the true structure S_0 is itself not identified.*

Does all this language really matter?

Or is this only Phil's pet peeve?

"Oxford English Dictionary View": A word's everyday use determines its meaning, not the other way around. It is nonsense to assert that a word's common use is incorrect.

My View: The Words We Use Matter

(1) Misuse/inconsistent use of terminology destroys information. This may be mildly annoying or amusing in everyday conversation

> *"I literally died laughing when I heard what Josh Angrist said about empirical IO!"*

but is sloppiness that should be avoided in serious scholarship.

(2) The language we use shapes the way we think and how we are understood. Precise language encourages precise thinking and transparent exchange of ideas.

(3) We should debate modeling approaches and tradeoffs between the assumptions relied upon and the questions answered. This is all that the "structural vs. reduced form" divide is about—i.e., different types of structural models. Misuses of language creates barrier that shut down those conversations and slow scientific progress.

The Role of Economic Models in Empirical Work

A Case for Structure Based on Economic Models

We are economists, not statisticians.

- Statisticians are good at describing the data.
- Economists are good at interpreting it using formal logic:

  given a set of maintained hypotheses, the data imply . . . .

- Where do the maintained hypotheses come from? How can they be evaluated? How do we know which maintained hypotheses are useful?

Economic Models in Empirical Work

Many important questions can be answered only by exploiting economic models (vs. statistical or DAG models) to provide a logical framework for interpreting the data:

- to tell us what to look at: what are the structural features of interest for our questions? One should not define the object of interest based only on what some statistical procedure produces!
- to define what it means to have a "valid" estimation method
- to provide functional/probabilistic relationships that can be used to estimate of the structural features of interest; e.g.,
  - optimality conditions that relate observables to primitives
  - IV conditions (absent an experiment, what are valid instruments? this requires economic reasoning, which means at least an informal model).

The Role of Economic Models, An Example: Part 1

- A researcher observes price P and quantity Q of a good in many markets
- He says: "I do not want to impose arbitrary restrictions from a model. I just want to let the data speak."
- He regresses Q on P, finds a positive correlation, and concludes "Initial evidence suggests that P has a positive effect on Q."
- He then adds some covariates Z to the regression and obtains similar results. The researcher concludes, "The positive effect of P on Q is robust to the inclusion of a rich set of controls."

(So far, nonsense.)

An Example: Part 2

- The researcher now considers the use of instrumental variables methods, characterizing this either as a robustness check on the original "reduced form" analysis, or as a way for controlling for possible "confounds"
- The researcher suggests that a measure of the availability of a substitute goods, be used as an instrument for P. TSLS now reveals a stronger positive "causal effect" of P on Q. The researcher concludes that the original results are qualitatively robust, but that controlling for endogeneity of P eliminates a downward bias in the OLS estimates.

(still nonsense)

An Example: Part 3

- Another researcher reads the paper and has a different idea for an instrument: the manufacturing wage in the local market, something also left out of Z that plausibly affects prices.
- TSLS now yields a precisely estimated *negative* "causal effect" of price on quantity
- The researcher concludes, "the causal effect of P on Q is heterogeneous. The effect one measures depends on which prices are changing in response to variation in the instrument one uses."

(more nonsense).

Why Do We Know This Is Nonsense?

Our researcher started with a common approach: he (correctly!) conjectures that a variable X may affect another, Y, and explores the relationship with regression, with or without IV, interpreting at least the latter as “the causal effect of X on Y.” Where did he go wrong? How do *we know* that something has gone wrong?

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Here we know something is wrong because we already have a deeply ingrained idea of how prices and quantities are determined in a market. *We have a structural model in mind* –one that that suggest to us what the underlying objects of interest are, what the challenges are for estimating them, and what are valid/invalid solutions.

Avoiding Nonsense

Once the researcher suspects that there may be omitted factors, selection, endogeneity, etc., *some type of model is necessary* to determine what "fixes" will work (indeed, what "work" even means). In the example a model is needed

- even to recognize demand and supply as distinct objects—that *there is no such thing as "the causal effect of P on Q"*
- to even define what objects should be measured
- to define what it would mean to have a valid IV, which variables might be valid as IV.

The Role of Models

Stepping Back

"all models are wrong, but some are useful." – George Box

Useful at a minimum because without a model of some kind there is typically only hand waving. Attempts to go beyond data description without a model are "not even wrong" — i.e., one cannot even define what "right" means.

The Role of Models

Stepping Back

"Art is not truth. Art is a lie that makes us realize truth..." – Pablo Picasso

The art of empirical work includes selecting a model that captures essential features *for the purpose at hand* and allows one to justify an interpretation of a measurement. This will involve assumptions that one could question.

But only by specifying a model can one speak coherently about whether the maintained assumptions are problematic, whether certain data allow measurement, what alternative assumptions might imply, and how science might progress.

Summary

1. Be carefuly about the language of empirical economics. Don't be fooled by common (ubiquitous!) abuses. Try not to become part of the problem yourself. Better yet, look for opportunities to overcome the false barriers by bringing insights from artificially disconnected literatures together.
2. Don't underestimate the extent to which an economic model can be useful—even essential—to good empirical work.

   My part of the course will illustrate some roles models can play.

Fun Reading

Koopmans, T. (1947). "Measurement Without Theory," Cowles Foundation Discussion paper 25a. http://www.jstor.org/stable/1928627

Koopmans, T. (ed) (1950). *Cowles Monograph 10. Statistical Inference in Dynamic Economic Models*, London: Wiley. (esp. chapters by Hurwicz, Koopmans) http://cowles.yale.edu/sites/default/files/files/pub/mon/m10-all.pdf

Marschak, J. and W.C. Andrews Jr. (1944), "Random Simultaneous Equations and the Theory of Production," *Econometrica*, 12, 143-205., http://www.jstor.org/stable/1905432