

Introduction and Solving Equations

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Model Meets Data: A “Typical” JMP Today

- Motivational facts: may include reduced-form results
- Model:
 - Setup and equilibrium
 - Theoretical results: key mechanisms
- Bring model to data
 - Estimate key parameters
 - Calibrate other parameters
- Counterfactuals
 - Quantify existing or proposed policies/shocks
 - Optimal policies

Why Guide Empirics by Theories?

- Lucas critique:
 - *It is naive to try to predict the effects of a change in economic policy entirely on the basis of relationships observed in historical data*
 - Policy evaluation should base on deep/structural parameters
 - How deep? Depend on your questions and theoretical interpretations
 - Tariffs \Rightarrow Employment: Firm productivities can be regarded as “deep”
 - Innovation subsidies \Rightarrow Employment: Firm productivities are not “deep” (an outcome of innovation investments)
- Example: Gravity equation

Gravity Equation

- The “naive” gravity equation proposed by Tinbergen (1962)

$$\log X_{in} = -\epsilon \log (1 + t_{in}) + D'_{in}\gamma + \alpha X_i + \beta X_n + u_{in}, \quad (1)$$

where X_{in} is the total export from country i to n , t_{in} is the tariff rates of country n on imports from country i , D_{in} is a vector of distance measures such as physical distance, common border, common language, and so on. X_i is the total expenditure of country i

- The fixed-effect gravity equation:

$$\log X_{in} = -\epsilon \log (1 + t_{in}) + D'_{in}\gamma + fe_i + fe_n + u_{in}, \quad (2)$$

where the fixed effects fe_i and fe_n do not only absorb the total expenditure but also all factors that are exporter- or importer-specific

- Tariff \Rightarrow Trade flows
 - What does ϵ measure?
 - Tariff \Rightarrow Wage \Rightarrow Expenditure \Rightarrow Trade flows?

Structural gravity equation: Armington Model

- N countries. Each country i produces a distinctive variety of goods. Consumers in country n has a CES preference over all varieties:

$$U_n = \left[\sum_{i=1}^N C_{in}^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}}, \quad \sigma > 1, \quad (3)$$

where C_{in} is the quantity of goods from country i consumed in country n

- Country i is endowed with L_i workers. The variety i is produced using labor under perfect competition. The unit cost of producing good i is

$$c_i = \frac{w_i}{A_i}, \quad (4)$$

where w_i is the wage and A_i is the productivity in country i

- Exporting from country i to n incurs
 - an iceberg trade cost, $\tau_{in} \geq 1$, with $\tau_{ii} = 1$
 - an import tariff, $t_{in} \geq 0$, with $t_{ii} = 0$

Armington Model: Equilibrium

- Let X_n be the total expenditure in country n and X_{in} be the value of exports from i to n . Then bilateral trade share can be expressed as

$$\lambda_{in} \equiv \frac{X_{in}}{X_n} = \left[\frac{w_i \kappa_{in}}{A_i} \right]^{1-\sigma} P_n^{\sigma-1}, \quad \kappa_{in} \equiv \tau_{in} (1 + t_{in}), \quad (5)$$

where $P_n = \left[\sum_{i=1}^N \left[\frac{w_i \kappa_{in}}{A_i} \right]^{1-\sigma} \right]^{\frac{1}{1-\sigma}}$

- Labor market clearing:

$$w_i L_i = \sum_{n=1}^N \frac{1}{1 + t_{in}} \lambda_{in} X_n. \quad (6)$$

- Total expenditure equates total income:

$$X_n = w_n L_n + \sum_{i=1}^N \frac{t_{in}}{1 + t_{in}} \lambda_{in} X_n. \quad (7)$$

- Welfare measure: real income

$$U_i = \frac{X_i}{P_i}. \quad (8)$$

Armington Model: Gravity

- Equation (5) can be re-written into

$$\log(X_{in}) = -(\sigma - 1) \log(1 + t_{in}) - (\sigma - 1) \log \tau_{in} + (\sigma - 1) \log \left(\frac{w_i}{A_i} \right) + \log(P_n^{\sigma-1} X_n) \quad (9)$$

- Suppose that $\tau_{in} = D'_{in} \tilde{\gamma} + \tilde{u}_{in}$. Then we have the fixed-effect gravity equation:

$$\log X_{in} = -(\sigma - 1) \log(1 + t_{in}) + D'_{in} \gamma + fe_i + fe_n + u_{in}. \quad (10)$$

- The coefficient of $\log(1 + t_{in})$ has a structural interpretation: $-(\sigma - 1)$

Armington Model: Counterfactuals

- How do changes in (t_{in}) affect trade share λ_{in} , considering direct and indirect effects?
- Parameters: $(A_i, L_i, \tau_{in}, t_{in}; \sigma)$
- Equilibrium outcomes (w_i, X_i) such that

1.

$$w_i L_i = \sum_{n=1}^N \frac{1}{1 + t_{in}} \lambda_{in} X_n, \quad \lambda_{in} = \frac{\left(\frac{w_i \kappa_{in}}{A_i} \right)^{1-\sigma}}{\sum_{k=1}^N \left(\frac{w_k \kappa_{kn}}{A_k} \right)^{1-\sigma}}, \quad \kappa_{in} = \tau_{in} (1 + t_{in}). \quad (11)$$

2.

$$X_n = w_n L_n + \sum_{i=1}^N \frac{t_{in}}{1 + t_{in}} \lambda_{in} X_n. \quad (12)$$

- Counterfactual:
 - Solve (w_i, X_i) and (λ_{in}) under baseline (t_{in}) .
 - Do it again under alternative (t_{in}) .

Reduced-Form vs. Structural Trade Elasticities

- Reduced-form trade elasticity:
 - Fixed-effect gravity equation:

$$\log \lambda_{in} = -(\sigma - 1) \log(1 + t_{in}) + D'_{in} \gamma + fe_i + fe_n + u_{in} \quad (13)$$

- Ceteris paribus: capture, by design, the **direct** effect
- Structural trade elasticity:
 - *Structural interpretation* of reduced-form trade elasticity: Elasticity of substitution \Rightarrow Deep parameters
 - GE counterfactual elasticity for *policy evaluation*: $\Delta(1 + t_{in}) \Rightarrow$ Overall effects ΔX_{in} ?

Reduced-Form vs. Structural Trade Elasticities

- Log-linearizing the equilibrium system: for any $Z > 0$, denote $\tilde{Z} = d \log Z$

$$\begin{aligned}
 w_i L_i &= \sum_{n=1}^N \frac{1}{1 + t_{in}} \lambda_{in} X_n, \quad \lambda_{in} = \frac{\left(\frac{w_i \kappa_{in}}{A_i} \right)^{1-\sigma}}{\sum_{k=1}^N \left(\frac{w_k \kappa_{kn}}{A_k} \right)^{1-\sigma}}, \quad \kappa_{in} = \tau_{in} (1 + t_{in}) \\
 X_n &= w_n L_n + \sum_{i=1}^N \frac{t_{in}}{1 + t_{in}} \lambda_{in} X_n
 \end{aligned} \tag{14}$$

- Linearized system: Deriving $\frac{\partial \log \lambda_{in}}{\partial \log(1+t_{in})}$ from a GE model

$$\begin{aligned}
 \tilde{w}_i + \tilde{L}_i &= \sum_{n=1}^N \chi_{in} \left(\tilde{\lambda}_{in} + \tilde{X}_n - \widetilde{1 + t_{in}} \right), \quad \chi_{in} \equiv \frac{\frac{1}{1+t_{in}} \lambda_{in} X_n}{w_i L_i} \\
 \tilde{\lambda}_{in} &= (1 - \sigma) \left(\tilde{w}_i + \tilde{\kappa}_{in} - \tilde{A}_i \right) - \sum_{k=1}^N \lambda_{kn} \left(\tilde{w}_k + \tilde{\kappa}_{kn} - \tilde{A}_k \right), \quad \tilde{\kappa}_{in} \equiv \tilde{\tau}_{in} + \widetilde{1 + t_{in}} \\
 \tilde{X}_n &= \frac{w_n L_n}{X_n} \left(\tilde{w}_n + \tilde{L}_n \right) + \sum_{i=1}^N \left[\frac{t_{in} \lambda_{in}}{1 + t_{in}} \left(\tilde{\lambda}_{in} + \tilde{X}_n \right) + \frac{\lambda_{in}}{1 + t_{in}} \widetilde{1 + t_{in}} \right]
 \end{aligned} \tag{15}$$

Structural Modeling

- Theoretical model: $F(Y, X, \theta) = 0$: Y : equilibrium outcomes; X : policies; θ : deep parameters
- Model characterization: properties of the equilibrium; elasticities $\nabla_X Y$, given θ
- Empirical model: $G(Y, X, \theta, \varepsilon) = 0$: ε : structural errors to fit the data
- Solve the model: Given θ and ε , solve (X, Y) from $G(Y, X, \theta, \varepsilon) = 0$
- Bring the model to the data: $G(Y, X, \theta, \varepsilon) = 0 + \text{Data on } (X, Y) + \text{Assumptions} \Rightarrow \theta$
- Counterfactuals: Given θ , changes in $X \Rightarrow$ changes in Y

Whited (2023): Five types of integration of structural and reduced-form methods

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 - e.g. Fixed-effect gravity equation \Rightarrow elasticity of substitution in the Armington model

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 - e.g. Reduced-form effects of corporate taxes on multinationals' location choice \Rightarrow A GE model of multinational production and corporate taxes

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 - e.g. [Berry, Levinsohn, and Pakes \(1995\)](#)
- **#5 Economic models can be used to address sample selection problems in regressions**
 - e.g. [Irrarrazabal, Moxnes, and Opromolla \(2013\)](#)

Trade-offs

- Structural modeling:
 - Answering more questions in interest
 - Useful in policy evaluation (both actual and hypothetical policies)
 - With stronger assumptions (some may not be easily justifiable)
- Structural modeling excels in the topics with:
 - Well-established and uncontroversial theories
 - Rich data that can characterize agents' entire behaviors
 - Relevant to important policy questions

Solving Non-Linear Equations

- General problem:

$$f(\mathbf{x}) = 0, \quad \mathbf{x} \in \mathcal{X} \subseteq \mathbb{R}^N, \quad f(\mathbf{x}) \in \mathbb{R}^N, \forall \mathbf{x} \in \mathcal{X} \quad (16)$$

- Example from Burden and Faires

$$\begin{aligned} 3x_1 - \cos(x_2 x_3) - \frac{1}{2} &= 0 \\ x_1^2 - 81(x_2 + 0.1)^2 + \sin x_3 + 1.06 &= 0 \\ \exp[-x_1 x_2] + 20x_3 + \frac{10\pi - 3}{3} &= 0 \end{aligned} \quad (17)$$

Solving Non-Linear Equations

- Jacobian matrix:

$$J(\mathbf{x}) = \begin{bmatrix} \frac{\partial f_1(\mathbf{x})}{\partial x_1} & \frac{\partial f_1(\mathbf{x})}{\partial x_2} & \cdots & \frac{\partial f_1(\mathbf{x})}{\partial x_N} \\ \frac{\partial f_2(\mathbf{x})}{\partial x_1} & \frac{\partial f_2(\mathbf{x})}{\partial x_2} & \cdots & \frac{\partial f_2(\mathbf{x})}{\partial x_N} \\ \vdots & \vdots & \cdots & \vdots \\ \frac{\partial f_N(\mathbf{x})}{\partial x_1} & \frac{\partial f_N(\mathbf{x})}{\partial x_2} & \cdots & \frac{\partial f_N(\mathbf{x})}{\partial x_N} \end{bmatrix} \quad (18)$$

- Jacobian matrix for the example from Burden and Faires

$$J(\mathbf{x}) = \begin{bmatrix} 3 & x_3 \sin(x_2 x_3) & x_2 \sin(x_2 x_3) \\ 2x_1 & -162(x_2 + 0.1) & \cos x_3 \\ -x_2 \exp[-x_1 x_2] & -x_1 \exp[-x_1 x_2] & 20 \end{bmatrix} \quad (19)$$

Simple Iteration

1. Initial guess $\mathbf{x}^{(0)}$
2. Compute $f(\mathbf{x}^{(0)})$
3. Update $\mathbf{x}^{(1)} = \mathbf{x}^{(0)} - f(\mathbf{x}^{(0)})$
4. Iterate until $\mathbf{x}^{(k)} = \mathbf{x}^{(k-1)}$ where $k = 1, 2, \dots$

Matlab Programming

- Matrix manipulation
- Function
- Iteration

Newton's Method

- First-order Taylor expansion at $\mathbf{x} = \mathbf{x}^{(0)}$:

$$f(\mathbf{x}) = f(\mathbf{x}_0) + J(\mathbf{x}^{(0)}) [\mathbf{x} - \mathbf{x}^{(0)}] \quad (20)$$

- Since $f(\mathbf{x}) = 0$, we approximate \mathbf{x} by

$$\mathbf{x}^{(1)} = \mathbf{x}^{(0)} - J(\mathbf{x}^{(0)})^{-1} f(\mathbf{x}^{(0)}) \quad (21)$$

- Newton's iterative method:

$$\mathbf{x}^{(k)} = \mathbf{x}^{(k-1)} - J(\mathbf{x}^{(k-1)})^{-1} f(\mathbf{x}^{(k-1)}), \quad k = 1, 2, \dots \quad (22)$$

Newton's Method

1. Initial guess $\mathbf{x}^{(0)}$
2. Compute $f(\mathbf{x}^{(0)})$ and $J(\mathbf{x}^{(0)})$
3. Update $\mathbf{x}^{(1)} = \mathbf{x}^{(0)} - J(\mathbf{x}^{(0)})^{-1} f(\mathbf{x}^{(0)})$
4. Iterate until $\mathbf{x}^{(k)} = \mathbf{x}^{(k-1)}$ where $k = 1, 2, \dots$

Broyden's Method (Quansi-Newton)

1. Approximate the inverse of the Jacobian matrix: Initial guess $\mathbf{x}^{(0)}$ and $B_0 = \mathbf{I}$
2. Update $\mathbf{x}^{(1)} = \mathbf{x}^{(0)} - B_0 f(\mathbf{x}^{(0)})$
3. Let $\mathbf{h} = \mathbf{x}^{(1)} - \mathbf{x}^{(0)}$ and $\mathbf{y} = f(\mathbf{x}^{(1)}) - f(\mathbf{x}^{(0)})$. By the definition of the Jacobian matrix, we want to obtain B_1 such that $B_1 \mathbf{y} = \mathbf{h}$
4. Update $B_1 = B_0 + \frac{1}{\mathbf{h}' B_0 \mathbf{y}} (\mathbf{h} - B_0 \mathbf{y}) \mathbf{h}' B_0$. It is straightforward to verify that $B_1 \mathbf{y} = \mathbf{h}$
5. Iterate until $\mathbf{x}^{(k)} = \mathbf{x}^{(k-1)}$ where $k = 1, 2, \dots$

Armington Model: Counterfactuals

- Equilibrium outcomes (w_i, X_i) such that

1.

$$w_i L_i = \sum_{n=1}^N \frac{1}{1 + t_{in}} \lambda_{in} X_n, \quad \lambda_{in} = \frac{\left(\frac{w_i \kappa_{in}}{A_i} \right)^{1-\sigma}}{\sum_{k=1}^N \left(\frac{w_k \kappa_{kn}}{A_k} \right)^{1-\sigma}}, \quad \kappa_{in} = \tau_{in} (1 + t_{in}). \quad (23)$$

2.

$$X_n = w_n L_n + \sum_{i=1}^N \frac{t_{in}}{1 + t_{in}} \lambda_{in} X_n. \quad (24)$$

- A toy example:
 - $N = 3$ and $\sigma = 4$
 - $A = [2, 1, 1]$, $L = [1, 2, 4]$
 - $\tau_{in} = 2$ for all $i \neq n$
 - Initially $t_{in} = 0$ for all i, n

Bringing the Armington Model to Data

- Challenges:
 - High-dimensional (A_i, L_i, τ_{in})
 - How to get σ ?
- Data:
 - Bilateral trade flows: X_{in} for all i, n
 - Bilateral tariffs: t_{in} for all i, n
 - Bilateral distance measures: D_{in} for all $i \neq n$

Exact-Hat Algebra

- Starting from the observed economy, how would changes in tariffs affect trade flows, wages, and welfare?
 - Observed economy: a set of parameters, e.g. $(A_i, L_i, \tau_{in}) \Leftarrow \text{Data, e.g. } (X_{in}, t_{in})$
 - Shortcut: computing counterfactuals based on **Data**, without explicitly obtaining parameter values
- Notation: For any variable $Z > 0$
 - Let Z' be the value of Z after shocks in interest
 - Let $\hat{Z} = Z' / Z$
 - WTH: $(\hat{w}_i, \hat{X}_i, \hat{P}_i)$ under $(\widehat{1 + t_{in}})$

Exact-Hat Algebra

- Equilibrium in relative changes: (\hat{w}_i, \hat{X}_i) satisfy

1.

$$\hat{w}_i \hat{L}_i w_i L_i = \sum_{n=1}^N \frac{1}{1 + t'_{in}} \hat{\lambda}_{in} \hat{X}_n \lambda_{in} X_n, \quad \hat{\lambda}_{in} = \frac{\left(\frac{\hat{w}_i \hat{\kappa}_{in}}{\hat{A}_i} \right)^{1-\sigma}}{\sum_{k=1}^N \lambda_{kn} \left(\frac{\hat{w}_k \hat{\kappa}_{kn}}{\hat{A}_k} \right)^{1-\sigma}}, \quad \hat{\kappa}_{in} = \hat{\tau}_{in} \widehat{1 + t_{in}}. \quad (25)$$

2.

$$\hat{X}_n X_n = \hat{w}_n \hat{L}_n w_n L_n + \sum_{i=1}^N \frac{t'_{in}}{1 + t'_{in}} \hat{\lambda}_{in} \hat{X}_n \lambda_{in} X_n. \quad (26)$$

- Welfare: measured by real income $\hat{U}_i \equiv \frac{\hat{X}_i}{\hat{P}_i}$ where $\hat{P}_i = \left[\sum_{k=1}^N \lambda_{ki} \left(\frac{\hat{w}_k \hat{\kappa}_{ki}}{\hat{A}_k} \right)^{1-\sigma} \right]^{\frac{1}{1-\sigma}}$
- Exogenous shocks: $\left(\widehat{1 + t_{in}}; \hat{\tau}_{in}, \hat{A}_i, \hat{L}_i \right)$

Exact-Hat Algebra

- Data: (X_{in}, t_{in}, D_{in})
- Exact-hat algebra requires
 - $\lambda_{in} \equiv \frac{X_{in}}{X_n}$ where $X_n = \sum_{k=1}^N X_{kn}$
 - $w_i L_i = \sum_{n=1}^N \frac{1}{1+t_{in}} X_{in}$
 - σ : estimated by the gravity equation

Summary of Structural Gravity Model

- Question: Tariff changes \Rightarrow Equilibrium outcomes: trade, wages, welfare
- Armington model
- Model characterization: equilibrium existence and uniqueness; equilibrium in relative changes; stylized version of the model
- Estimation and calibration: data; estimation of σ
- Counterfactual experiments
- Sensitivity analysis: e.g. the value of σ

Summary

- Reduced-form vs. Structural modeling
- Example: Armington model
 - Build an equilibrium system
 - Numerically solve the equilibrium system
 - Bring the model to the data
- Structural modeling: sketch