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Gravity at Sixty: The Workhorse Model of Trade

Abstract

On the eve of its 60th anniversary, the gravity model of trade is a ‘celebrity’, due to its intuitive appeal, solid theoretical foundations, and remarkable empirical success. Yet, many economists still view gravity simply as an intuitive but naive reduced-form estimating equation and apply it without guidance from theory, while others are skeptical about its usefulness for counterfactual projections. The objective of this paper is to offer a historical overview of its evolution from an a-theoretical application to an estimating computable general equilibrium (E-CGE) model, which can be nested in more complex frameworks. Along the way, I address some misconceptions about the gravity model, summarize the current best practices for gravity estimations, and highlight some properties that have made gravity so successful.

JEL-Codes: F130, F140, F160.

Keywords: structural gravity, evolution, theory, estimation general equilibrium.

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1 Introduction

On the eve of its 60^{th} anniversary,[1] the gravity model of trade is probably the most popular and most successful framework in (international) economics. However, even nowadays, despite its solid theoretical foundations (e.g., Eaton and Kortum (2002), Anderson and van Wincoop (2003), and Arkolakis et al. (2012)) and remarkable predictive power, the gravity model is viewed by many economists, especially outside the field of trade, simply as an intuitive but naive reduced-form estimating equation.

Quite often, unfortunately, we see gravity applications that are not consistent with theory and do not take into account some major developments in the empirical structural gravity literature. As a result, the estimates in such papers could be severely biased and their policy recommendations could be misleading, or simply wrong. Moreover, while it is well understood that trade theory and trade-policy analysis should be set in general equilibrium (GE), there is still a division and skepticism among academic trade economists and trade-policy practitioners about the potential and usefulness of the gravity model as a Computable GE (CGE) framework for counterfactual projections. A prominent example is the debate among UK economists over gravity-based projections of the effects of Brexit.

Against this backdrop, the broad objective of this paper is to celebrate the gravity model of trade at its 60^{th} anniversary by tracing its evolution from a naive a-theoretical application (e.g., Tinbergen (1962)) to an estimating computable general equilibrium (E-CGE) model (e.g., Fally (2015), and Anderson et al. (2018b)), which can be nested in more complex models from other fields (e.g., Caliendo and Parro (2015), Eaton et al. (2016), and Anderson et al. (2020)). To this end, I will (i) review the most influential contributions to the gravity literature and direct the reader to

[1] Tinbergen (1962) is credited as the first application of gravity to trade. Section 2 clarifies.

a number of surveys; (ii) address some misconceptions about the gravity model; (iii) guided by theory, summarize the best current practices for gravity estimations; and (iv) demonstrate that gravity can be nested within more complex models (from other fields). While pursuing these objectives, I will (v) introduce eight properties of the gravity model, as summarized in Box 1.1, which highlight gravity's power and beauty and, therefore, have contributed to its popularity and success.

Box 1.1 Why Is Gravity So Popular and Successful?

Reason 1: It is very intuitive.

Reason 2: It has tremendous predictive power.

Reason 3: It is a very flexible environment.

Reason 4: It has many solid theoretical foundations.

Reason 5: It is a plausible general equilibrium framework.

Reason 6: It is an Estimating CGE (E-CGE) model.

Reason 7: It can be nested within more complex GE models.

Reason 8: It offers opportunities for new contributions.

After reviewing the most influential contributions to the gravity literature in the next section, the paper traces the main phases in the evolution of the gravity model. Section 3 discusses the three key reasons why most people like the 'naive' gravity equation. Section 4 describes the golden age for the structural gravity equation by demonstrating that it has many solid theoretical foundations with important implications for gravity estimations, which are presented in Section 5. Section 6 argues that not only gravity is a CGE model, but also it is an *Estimating* CGE framework. Section 7 shows that the gravity model can be nested within more complex production frameworks. Section 8 concludes by summarizing some of the latest developments in the gravity literature and by pointing out that, despite great progress and success, there are still many opportunities for new contributions.

2 The Evolution of Gravity: A Literature Review

This section reviews the main contributions to the development of the gravity model of trade in chronological order.

A-theoretical Applications: Social Physics. Tinbergen (1962) is often credited as the first application of gravity to economics. This is not correct. Others have used gravity in economics long before him. For example, Ravenstein (1885) applies the gravity equation to migration flows.[2] Nevertheless, the 1969 Nobel Laureate was (arguably) the first to apply gravity to international trade flows. Hence, the current anniversary. Ironically, while Tinbergen relied on gravity to study the impact of early European integration, one of the main applications of the gravity model at its 60^{th} anniversary is European dis-integration, i.e., for forecasting the effects of Brexit. Other early applications of gravity to trade include Poyhonen (1963), Pulliainen (1963), and Linnemann (1966).[3]

[2] In an excellent survey of the historical roots of the gravity equation, Bergstrand and Egger (2011) acknowledge Tinbergen (1962) as the *"first to specify econometrically what has become a benchmark 'traditional' gravity equation for studying international trade flows"* (p. 451), but they also note that there were other attempts to link physics and gravity to economics prior to him, e.g., Princeton's 'social physics school' (Stewart (1948)), 'deterministic approaches' to explain commodity trade flows (Niedercorn and Moorehead (1974)), and 'probabilistic approaches' to model spatial interactions (Savage and Deutsch (1960)).

[3] Poyhonen, Pulliainen, and Linnemann were all students of Tinbergen (Bergstrand (2019)).

Structural Gravity: A Star Was Born. There have been some debates and discussions about who was the first to apply gravity to economics. However, trade economists seem to be in unanimous agreement that the first theoretical foundation of the gravity equation of trade, as we know it today, belongs to Anderson (1979). In fact, I find it truly remarkable that, subject to some 'cosmetic' theoretical improvements (e.g., the definition of the Outward Multilateral Resistance) and due to major empirical developments (e.g., the use of PPML with high-dimensional fixed effects for gravity estimations), Anderson's 1979 model is perfectly consistent with all modern structural gravity regressions and benchmark counterfactual projections that are made with the gravity model nowadays.

Into Disrepute: An Intellectual Orphan. Despite its intuitive appeal, good empirical performance, and having a solid theoretical foundation already, the gravity model struggled to win the hearts of trade economists during the 70s, 80s, and even 90s – *"The gravity model fell into disrepute in the 1970s and 1980s."* Baldwin and Taglioni (2006). A sequence of influential surveys from the *Handbook of International Economics* – the compass for trade research – were not kind to gravity. Specifically, Deardorff (1984) questioned its theoretical heritage by dubbing it *'dubious'*, while Leamer and Levinsohn (1995) explained that *"[g]ravity theory was too complex and had virtually no effect on the subject of international trade."*[4] In retrospect, Anderson (2011) characterized the experience of the gravity model during this period as *'an*

[4]This quote suggests that, like many other remarkable inventions (e.g., the vending machine of the Hero of Alexandria, first-century, the contact lenses of Descartes, 1632, and the electric car of William Morrison, 1887), the gravity model was ahead of its time. According to Anderson himself, at the time when he built his gravity model *"he did not know of a practical solution to estimating multilateral resistance (the name itself came in 2003). The context is that (i) economists knew about system estimation (25 years later implemented in AvW 2003) but in the late 70s this was infeasible except with the resources of the US space program, and (ii) we knew about dummy variables in the 70s, granted their legitimacy but were suspicious about their meaning, hence the idea of hundreds of 'fixed effects' was too outlandish to imagine."* (From personal correspondence with Jim.)

intellectual orphan'. Despite several other excellent contributions to gravity theory during this period, e.g., Krugman (1980), Bergstrand (1985, 1989, 1990),[5] and even Deardorff (1998) warming up to it, the gravity model was still viewed as an example of *'social physics'* (Krugman (1997)) and continued being ignored and having *"a poor reputation among reputable economists"* (Baldwin (1994)) until the early 2000s.

Magic Happened: The Golden Age of Gravity. *'Magical'* is indeed a proper epithet to describe the brilliant contributions of Eaton and Kortum (2002) and Anderson and van Wincoop (2003), which left no doubt about the fact that the gravity model had very solid theoretical foundations and led to the golden age of 'Structural Gravity' (2002-2012). During this relatively short (at least from an academic perspective) period, gravity established itself as the workhorse model in trade and appeared in hundreds of publications, including applications, theoretical developments, contributions to estimation, and new datasets. It was even featured in the advanced trade textbook of Feenstra (2004). Baldwin and Taglioni (2006), De Benedictis and Taglioni (2011), Bergstrand and Egger (2011) and Anderson (2011) offer excellent reviews of the gravity literature before and during this period.

Most gravity papers during this period were empirical applications aiming to estimate the impact of various determinants of bilateral trade flows, e.g., insecurity and institutions (Anderson and Marcouiller (2002)), border and home bias effects (Hillberry and Hummels (2003) and Balistreri and Hillberry (2007)) economic sanctions (Hufbauer and Oegg (2003)), membership to the World Trade Organization (WTO) (Rose (2004), Subramanian and Wei (2007), Eicher and Henn (2011)), non-

[5] Often cited next to Anderson (1979), Bergstrand (1985) is an important contribution to gravity theory. It is compatible with Anderson (1979) and, by explicitly focusing on the role of prices in the gravity equation, Bergstrand's gravity equation is also consistent with the seminal contribution of Anderson and van Wincoop (2003). See Bergstrand (2019) for an insightful discussion on the relationship between the three models.

tariff measures (Fontagne et al. (2005)), free trade agreements (FTAs) (De Benedictis et al. (2005), Baier and Bergstrand (2007) and Egger et al. (2011)), distance (Disdier and Head (2008)), trade missions (Head and Ries (2010)), and colonial relationships (Head et al. (2010)). While many still applied gravity only intuitively, closer adherence to theory led to better understanding of the drivers of the growth in trade flows (Baier and Bergstrand (2001)), more plausible gravity estimates, e.g., of the effects of currency unions (Glick and Rose (2002) and Micco et al. (2003)), and solutions to some empirical puzzles, e.g., 'Canada's border puzzle' (Anderson and van Wincoop (2003)) and 'the distance puzzle' (Yotov (2012)).

This period also witnessed significant developments on the theory side. For example, extending on Anderson and van Wincoop (2003), Anderson and van Wincoop (2004) derive a sectoral gravity model on the demand-side, while, following Eaton and Kortum (2002), Chor (2010) and Costinot et al. (2012) derive sectoral gravity on the supply-side. Redding and Venables (2004) extend the gravity framework to study the links between trade and the labor market, while Bergstrand and Egger (2007) set foundations for a gravity framework of trade and FDI. Building on the seminal work of Melitz (2003), Helpman et al. (2008) and Chaney (2008) derive gravity with heterogeneous firms, while Redding (2011) offers an excellent review of the recent firm heterogeneity literature with implications for gravity theory and estimations. Arkolakis (2010) nests endogenous marketing costs within the gravity model. Waugh (2010) demonstrates that, in order to match income differences, the gravity model should allow for trade cost differences between poor and large countries. Anderson and Yotov (2010) extend gravity to decompose the incidence of trade costs on consumers and producers and on international vs. domestic trade. Fieler (2011) builds a gravity model with non-homothetic preferences. Finally, inspired by Eichengreen and Irwin (1998), Olivero and Yotov (2012) derive a dynamic gravity model.

The increased interest in gravity theory and applications was accompanied by new contributions on the estimation and data fronts. Hummels (2001) promotes the use of exporter and importer fixed effects to control for the multilateral resistances in gravity regressions, and Egger and Pfaffermayr (2003) discuss the use of fixed effects in the gravity model more broadly. Baier and Bergstrand (2009) propose a reduced-form estimation approach to estimate structural gravity. Henderson and Millimet (2008) ask 'if gravity was linear' and recommend estimation of the gravity model in levels. While OLS was still the standard gravity estimator, this period witnessed one of the most influential contributions to gravity estimations – the introduction of the Poisson Pseudo Maximum Likelihood (PPML) estimator by Santos Silva and Tenreyro (2006). Due to its ability to successfully account for heteroskedasticity and zero trade flows, PPML quickly established itself as the leading gravity estimator. Finally, the boom in gravity applications lead to the development of new gravity databases, e.g., Mayer and Zignago (2011).

Universal Gravity: A New Quantitative Trade Model. In a seminal paper, Arkolakis et al. (2012) cemented the hegemony of the structural gravity model in trade by demonstrating that different micro-theoretical foundations converge to exactly the same gravity equation. Along with many new applications and theoretical developments, which I discuss next, the gravity model got its revenge with prominent coverage in two excellent chapters (Head and Mayer (2014) and Costinot and Rodriguez-Clare (2014)) in the *Handbook of International Economics*, the same publication where it was dismissed in the 80s and 90s. The gravity model was also featured in a chapter at the *Handbook of Transportation Economics* (Baier et al. (2018a)) and in dedicated books for trade policy analysis (Yotov et al. (2016)) and the impact of globalization (Bergstrand (2019)).

The empirical gravity equation remained the go-to model for new applications, while others revisited existing results with new, better methods, e.g., on the impact of currency unions (de Sousa (2012), Campbell (2013), Glick and Rose (2016) and Larch et al. (2019a)), the effects of piracy (Bensassi and Martinez-Zarzoso (2012)), trade cost measurement (Novy (2013a)), common language (Melitz and Toubal (2014)), trade creation (Baier et al. (2014)) and trade diversion (Dai et al. (2014)) effects of FTAs, exchange rates Anderson et al. (2016), WTO membership (Larch et al. (2019b) and Esteve-Pérez et al. (2020)), and commercial trade law (Gil-Pareja et al. (2020)). Anderson et al. (2015) and Anderson et al. (2018a) showed that structural gravity works well with new services trade data, while better panel trade data allowed for estimating heterogeneous policy effects, e.g., of FTAs (Baier et al. (2018b) and Baier et al. (2019) and currency unions (Chen and Novy (2018)). Stricter reliance on gravity theory also led to solutions of more empirical puzzles, e.g., 'the missing globalization puzzle' (Bergstrand et al. (2015)) and the puzzle from the macro and trade literatures that 'larger countries should be richer than smaller countries' (Ramondo et al. (2016)).

On the theory front, Novy (2013b) departs from the standard CES demand assumption to build a 'translog gravity' model, Chaney (2014) derives gravity based on a network of input-output linkages between firms, Allen and Arkolakis (2014) nests gravity within a general equilibrium framework that governs the spatial distribution of economic activity, Fajgelbaum and Khandelwal (2016) build a non-homothetic gravity model to allow for heterogeneous trade effects on consumers within a country, Anderson and Yotov (2020b) propose a gravity model with bilateral dynamics, Carrére et al. (2020) build a subconvex gravity ("without apology") model to allow for heterogeneous trade elasticities, and Allen et al. (2020) establish the existence, uniqueness, and robustness for the counterfactual predictions of the *'Universal Gravity'* model.

During this period, gravity gained popularity as a central pillar within CGE frameworks that became known as the *'new quantitative trade models'*. It was used to study the links between trade and various economic outcomes, e.g., technology diffusion (Shikher (2014)), unemployment (Heid and Larch (2016)), efficiency of FTAs (Anderson and Yotov (2016)), and carbon emissions (Larch and Wanner (2017)). In addition, gravity was nested in more complex models with input-output linkages (Caliendo and Parro (2015)), domestic investment (Eaton et al. (2016), Ravikumar et al. (2019) and Anderson et al. (2020)), endogenous trade imbalances (Reyes-Heroles (2017)), foreign direct investment (FDI) (Anderson et al. (2019)), and labor market dynamics (Caliendo et al. (2019)).

Major contributions were made on the estimation and data fronts too. Arvis and Shepherd (2013) and Fally (2015) discover an additive property of the PPML estimator, which meant that the PPML gravity regression was perfectly consistent with the underlying theoretical model. Capitalizing on this property, Anderson et al. (2018b) show how to obtain GE effects with the gravity model directly in standard software packages (e.g., Stata) and without the need for custom programming. Anderson and Yotov (2016) and Pfaffermayr (2020) explore methods to construct GE confidence intervals, while Larch et al. (2019a) and Correia et al. (2020) propose new commands for fast PPML estimations with high-dimensional fixed effects. Martin and Pham (2020) revisit the importance of zeroes for gravity estimations. A new generation of gravity databases, including explanatory gravity variables (Gurevich and Herman (2018)) and international and domestic trade flows (Borchert et al. (2020)), were built to support the theoretical advances and the new application needs. Despite the proven success and so many existing developments and contributions, the interest in the gravity model remains strong even today. I summarize the latest and ongoing developments in the related literature in Section 8.

3 Naive Gravity: The People's Choice

The great success of the gravity equation among trade economists, policy practitioners, and colleagues from other fields is due to three main reasons. First, as recognized since its very early applications to trade (e.g., Tinbergen (1962), Poyhonen (1963), and Pulliainen (1963)), by analogy with physics, the gravity model is very intuitive.

> ***1. The gravity model of trade is very intuitive.***

The remarkable resemblance between the trade gravity equation and Newton's law of universal gravitation is captured in Box 3.1, which reveals that trade (the gravita-

Box 3.1 Naive Gravity: Gravity in Physics vs. Trade

Gravity in Physics	**Gravity in Trade**
$F_{ij} = G\frac{M_i M_j}{D_{ij}^2}$	$X_{ij} = \tilde{G}\frac{Y_i E_j}{T_{ij}^{\theta}}$
where:	where:
F_{ij} is the gravitational force between objects i and j;	X_{ij} is the value of trade flows between countries i and j;
G is the gravitational constant in physics;	$\tilde{G}$, is the gravitational constant in trade;
M_i denotes the mass of object i;	Y_i is the value of output in country i;
M_j denotes the mass of object j;	E_j is the value of expenditure in country j;
D_{ij} is the bilateral distance between objects i and j.	T_{ij} denotes the total bilateral trade frictions between i and j;
	θ is the trade elasticity.

Source: Adapted from Yotov et al. (2016).

tional force) between two countries (two objects) is directly proportional to the product of their sizes (masses) and inversely proportional to the trade frictions (the square of distance) between them. Put simply, the larger and the closer two countries are, the more they will trade with each other. What makes this analogy, and the already striking similarity between the gravity equations in trade vs. physics, even more impressive is that the gravity equation of trade from Box 3.1 can be derived based on solid microeconomic theories. I demonstrate this in Section 4.

The second main reason why the gravity equation is a popular favorite is that it works. The empirical gravity model predicts bilateral trade flows remarkably well.

2. The gravity equation has tremendous predictive power.

Since Tinbergen (1962), whose simple and 'naive' specification obtained $R^2 = 0.7$, the gravity equation consistently delivers very strong fit and plausible (in terms of magnitudes and signs) estimates on a number of covariates known as the *'standard set of gravity variables'*, including the log of bilateral distance, and indicator variables for contiguous borders, common official language, colonial relationships, and free trade agreements (FTAs). Head and Mayer (2014) offer summary statistics for the coefficient estimates on the standard gravity variables from a meta-analysis based on 159 papers and 2508 gravity regressions. More recently, Borchert et al. (2021) provide benchmark disaggregated gravity estimates for 170 industries within the broad sectors of agriculture, mining, manufacturing goods, and services.

Based on its exceptional predictive power, some have compared the gravity equation of trade to the *Mincer Earnings Regression* (Mincer (1974)).[6] It has also been

[6] The Mincer regression explains individual wages as a function of schooling and experience. While there are debates about how successful it really is, the general consensus is that the Mincer regression is the most prominent empirical model in labor economics (Heckman et al. (2003) and

pointed out that the good performance of the gravity model is probably due to the use of exporter and importer fixed effects, which have become standard in gravity regressions; this is not true. The gravity model would still perform quite well without any fixed effects (and even with only three explanatory variables, just like the Mincer regression). More importantly, owing to a very special additive property of the PPML estimator (Arvis and Shepherd (2013) and Fally (2015)), one can replace the full set of exporter and importer fixed effects in the gravity regression with just two structural variables, and the fit of the gravity model will remain unchanged. (Section 6 offers further details.) In sum, relative to the Mincer regression, the gravity equation not only delivers a great fit, but it reflects a structural model. Its predictive power is indeed unprecedented.

The third main reason for the celebrity status of the gravity equation is that it is very flexible. As such, it has been used to explain trade flows and to quantify the impact of their determinants in hundreds of academic papers, and it is routinely employed for policy analysis too.[7] Most authors have relied on gravity to study the

3. The gravity equation is a very flexible environment.

effects of *'traditional'* determinants of trade flows, e.g., distance (Disdier and Head (2008)), free trade agreements (Baier and Bergstrand (2007)), tariffs (Fontagné et al. (2020)), non-tariff measures (Fontagne et al. (2005)), WTO membership (Rose

Lemieux (2006)).

[7]In addition to the type of flexibility discussed here, there are two other flexibility dimensions of the gravity model. First, despite less developed theoretical foundations as compared to trade, gravity has been applied to study foreign direct investment (FDI), e.g., Eaton and Akiko (1994), Benassy-Quere et al. (2005), Bergstrand and Egger (2007) and Paniagua (2015), and migration, e.g., Poot et al. (2016). In addition, as demonstrated in Section 7, the gravity model can be flexibly nested within a broad class of GE models, including investment in physical capital (Eaton et al. (2016) and Anderson et al. (2020)), FDI (Anderson et al. (2019)), and labor markets Caliendo et al. (2019), etc.

(2004)), colonial ties (Head et al. (2010)), and common language (Melitz and Toubal (2014)). Others have used gravity to quantify the effects of more *'exotic'* determinants of trade flows, including culture and trust (Guiso et al. (2009)), reputation for people and products (Dimitrova et al. (2017)), conflict and wars (Garfinkel et al. (2020)), and piracy (Bensassi and Martinez-Zarzoso (2012)), among many others.[8] A third group of authors have relied on gravity to link trade to other economic outcomes, e.g., income and growth (Frankel and Romer (1999)), labor market outcomes (Redding and Venables (2004)), and FDI (Bergstrand and Egger (2007)). In sum, it is safe to conclude that, to study the impact of any determinant of trade flows or other economic outcomes via trade flows, one would inevitably resort to some version of the gravity model.

4 Structural Gravity: All Roads Lead to ... Gravity

Despite its celebrity status, the gravity model is still viewed by many economists, especially outside international trade, simply as an intuitive but naive reduced-form estimating equation. However, as seminally demonstrated by Arkolakis et al. (2012), many different microeconomic theories converge to exactly the same gravity equation.

4. Gravity has solid (and many) theoretical foundations.

Box 4.1 presents a list of gravity equations derived from alternative micro-foundations. Red color is used to denote the differences between these structural gravity models. The first equation, *'Demand-side Gravity'*, is based on Anderson (1979) and Anderson and van Wincoop (2003), where σ denotes the elasticity of substitution between

[8] See Section 2 for a more detailed (but still far from exhaustive) list of gravity applications.

domestic and foreign varieties. The *'Supply-side Gravity'* model is based on Eaton and Kortum (2002), where θ is a parameter from a Fréchet distribution, which, in the current gravity/trade context, is interpreted as capturing the dispersion of comparative advantage. Intuitively, θ reflects differences across varieties on the supply-side, just like σ measures how substitutable varieties are on the demand side.[9]

Box 4.1 Structural Gravity: Many Theories ... Same Gravity Equation

Demand-side Gravity: $$X_{ij} = \frac{E_j Y_i}{Y}\left(\frac{t_{ij}}{P_j \Pi_i}\right)^{1-\sigma}$$

Supply-side Gravity: $$X_{ij} = \frac{E_j Y_i}{Y}\left(\frac{t_{ij}}{P_j \Pi_i}\right)^{-\theta}$$

Demand-side Sectoral Gravity: $$X_{ij}^k = \frac{E_j^k Y_i^k}{Y^k}\left(\frac{t_{ij}^k}{P_j^k \Pi_i^k}\right)^{1-\sigma^k}$$

Supply-side Sectoral Gravity: $$X_{ij}^k = \frac{E_j^k Y_i^k}{Y^k}\left(\frac{t_{ij}^k}{P_j^k \Pi_i^k}\right)^{-\theta^k}$$

Gravity with Firms: $$X_{ij}^k = \frac{E_j^k Y_i^k}{Y^k}\left(\frac{t_{ij}^k}{P_j^k \Pi_i^k}\right)^{-\gamma^k}$$

Country-specific Dynamics: $$X_{ij,t} = \frac{E_{j,t} Y_{i,t}}{Y_t}\left(\frac{t_{ij,t}}{P_{j,t} \Pi_{i,t}}\right)^{1-\sigma}$$

Gravity with Bilateral Dynamics: $$X_{ij,t} = \frac{E_{j,t} Y_{i,t}}{Y_t}\left(\frac{t_{ij,t}}{P_{j,t} \Pi_{i,t}}\right)^{\rho(1-\sigma)}$$

[9] Best known as the trade elasticity, $\theta = \sigma - 1$ has been of interest to both the international trade (e.g., Eaton and Kortum (2002), Anderson and van Wincoop (2003), Broda and Weinstein (2006), and Broda et al. (2006)) and international macro (e.g., Backus et al. (1994), Zimmermann (1997), and Heathcote and Perri (2002)) literatures for a long time. See Ruhl (2008) for a review and comparison. Due to Arkolakis et al. (2012), θ regained attention as the most important parameter in international trade and motivated a literature with new methods to compute the trade elasticity and corresponding estimates at various levels of aggregation, e.g., Feenstra et al. (2012), Egger et al. (2012), Hillberry and Hummels (2013), Simonovska and Waugh (2014), Soderbery (2015), Caliendo and Parro (2015), Anderson and Yotov (2020b), Fontagné et al. (2020), Boehm et al. (2020), and Giri et al. (2021). Feenstra et al. (2018) offers an excellent review of the related literature.

Anderson and van Wincoop (2004) derive *'Demand-side Sectoral Gravity',* while Chor (2010) and Costinot et al. (2012) obtain *'Supply-side Sectoral Gravity'*, where k denotes sectors. An important implication (known as 'the separability property of gravity') of these sectoral gravity models is that gravity theory provides guidance for estimations at any desired level of aggregation, e.g., from 'Electronic, integrated, circuits', through 'Nuclear reactors' and 'Health services,' to aggregate trade. Building on Melitz (2003), Chaney (2008) derives *'Gravity with Firms',* where γ^k is the dispersion parameter from a Pareto distribution and the bilateral trade cost vector includes not only variable but also the fixed costs of exporting.[10]

Inspired by Eichengreen and Irwin (1998), Olivero and Yotov (2012) derive a dynamic gravity equation with *'Country-specific Dynamics',* where t is a time subscript, and the main implication is that gravity theory also provides guidance for estimations with panel data. Finally, Anderson and Yotov (2020b) derive *'Gravity with Bilateral Dynamics',* with two new components: a structural parameter ρ, which drives a wedge between the short-run and the long-run trade elasticity; and a time-varying bilateral capacity component in the vector of trade costs, which motivates the use of anticipation and phasing-in trade policy variables in gravity regressions. In sum, consistent with Arkolakis et al. (2012), Box 4.1 demonstrates that, subject to parameter interpretation, the gravity equations from a series of alternative theories are indeed identical.

To confirm the intuitive relationship between the gravity equation in physics from Box 3.1 and the structural gravity equation of trade from Box 4.1, define $\tilde{G} = \frac{1}{Y}$ as the gravitational constant, and $T_{ij} = \frac{t_{ij}}{P_j \Pi_i}$ as the total (effective) bilateral trade cost, which consists of the direct bilateral trade cost frictions, t_{ij} (e.g., transport costs,

[10]For derivations of the aggregate and sectoral supply-side gravity models with the notation used in this paper and in Anderson and van Wincoop (2003), I refer the reader to Yotov et al. (2016). Egger et al. (2021) derive gravity with heterogeneous firms using the same notation.

tariffs, FTAs, etc.), and multilateral resistance terms, P_j and Π_i, of Anderson and van Wincoop (2003). Section 6 offers a more formal discussion of the multilateral resistances (MRs), however, even at this stage, it is important to emphasize some of their key properties and implications. From a theoretical perspective, the MRs are the crucial link between the estimating gravity equation and the CGE gravity system, thus, enabling counterfactual analysis. From a policy point of view, not properly accounting for effects of trade policies that are channeled through the MRs may lead to severely biased (e.g., up to 40% in the case of NAFTA, Yotov et al. (2016)) projections. Finally, with respect to estimations, not accounting for the MRs in gravity regressions is considered a capital offense or, put starkly, a *'gold medal mistake'* (Baldwin and Taglioni (2006)).

5 Estimating Gravity ... with Gravitas

Despite the large number of widely accepted theoretical foundations, many authors still apply gravity intuitively and without adherence to theory. This may lead to biased/inconsistent gravity estimates and wrong policy predictions. For example, as mentioned earlier, Baldwin and Taglioni (2006) describe the omission to properly control for the structural multilateral resistance terms as *"the gold medal of classic gravity model mistakes."*

There is plenty of evidence that adhering to theory may have significant benefits and important implications for gravity estimations. For example, proper control for the structural multilateral resistances (i) leads to more plausible gravity estimates (e.g. for currency unions, Rose (2000), Rose and van Wincoop (2001), Glick and Rose (2002), and Micco et al. (2003)), (ii) resolves empirical puzzles (e.g., 'Canada's border puzzle', McCallum (1995) and Anderson and van Wincoop (2003)), and (iii) improves the overall performance of the gravity model (e.g., to predict bilateral trade imbalances, Davis and Weinstein (2002) and Felbermayr and Yotov (2021)). Similarly, Yotov (2021) argues that the theory-consistent use of domestic trade flows for gravity estimations leads to solutions of some empirical puzzles, e.g., 'the distance puzzle' (Disdier and Head (2008)) and 'the missing globalization puzzle' (Bhavnani et al. (2002)), and addresses certain estimation challenges, e.g., allows for estimating the impact of non-discriminatory policies and country-specific effects within the structural gravity model in the presence of exporter-time and importer-time fixed effects.

Capitalizing on the developments in the theoretical and empirical gravity literatures, as reviewed in Section 2, Larch and Yotov (2021) synthesize eleven best practice recommendations for gravity estimations, which I have listed in Box 5.1.[11] Based on these recommendations, Larch and Yotov (2021) specify the benchmark econometric gravity model in Box 5.2, which has the following key features. The dependent variable, $X_{ij,t}$, denotes *nominal* (Baldwin and Taglioni (2006)) exports from source i to destination j, *in levels* (Santos Silva and Tenreyro (2006)), *for consecutive years* (Egger et al. (2022)), and *including domestic trade flows* (Yotov (2021)). The model is estimated multiplicatively *with PPML* (Santos Silva and Tenreyro (2006, 2021)), and *multi-way (two-way or three-way) clustered standard errors* (Egger and Tarlea (2015)).

The econometric model includes four sets of fixed effects. $\pi_{\mathbf{i,t}}$ and $\chi_{\mathbf{j,t}}$ are exporter-time and importer-time fixed effects (Hummels (2001) and Olivero and Yotov (2012)), which control for the multilateral resistances (Anderson and van Wincoop (2003)) and any other observable or unobservable uniform effects of country-specific characteristics

[11] I refer the reader to Larch and Yotov (2021) for a detailed discussion on the motivation, implementation, caveats, and possible alternatives to each of the recommendations from Box 5.1. For earlier surveys of the empirical gravity literature, I recommend Baldwin and Taglioni (2006), De Benedictis and Taglioni (2011), Head and Mayer (2014), and Yotov et al. (2016).

Box 5.1 Best Practices for Gravity Estimations

Recommendation 1: Use Panel Data. *When available, panel data should be used for gravity estimations.*

Recommendation 2: Use Directional Time-varying Fixed Effects. *Use exporter-time and importer-time fixed effects.*

Recommendation 3: Employ Pair Fixed Effects. *When possible, gravity should be estimated with pair fixed effects.*

Recommendation 4: Include Domestic Trade Flows. *Consistent with theory, gravity should be estimated with domestic trade flows.*

Recommendation 5: Use Consecutive-year Data. *Estimations with consecutive-year data should be favored over averaged or interval data.*

Recommendation 6: Estimate Gravity with PPML. *The PPML estimator is the leading estimator for (structural) gravity regressions.*

Recommendation 7: Allow for Adjustment in Trade Costs. *Gravity estimations should allow for changes in the trade cost estimates over time.*

Recommendation 8: Allow for Heterogeneous Policy Effects. *Gravity estimations should allow for heterogeneous trade policy effects.*

Recommendation 9: Use Estimation Commands from the 'HDFE' family. *Consider estimating gravity with* ppmlhdfe *(and* reghdfe*).*

Recommendation 10: Implement Incidental Parameter Bias Correction. *Consider implementing corrections for incidental parameter biases.*

Recommendation 11: Use Clustered Standard Errors. *The standard errors in gravity regressions should be clustered by pair or three-way.*

Source:Adapted from Larch and Yotov (2021).

on exports and imports. The country pair fixed effects, $\gamma_{\mathbf{ij}}$, absorb all possible time-invariant bilateral trade costs (Egger and Nigai (2015), Agnosteva et al. (2019)) and mitigate endogeneity concerns related to the bilateral time-varying trade policy variables (Baier and Bergstrand (2007)). Finally, the vector of time-varying border dummies, $\mathbf{BRDR_{ij,t}}$, controls for common globalization trends and further mitigates endogeneity concerns with the bilateral policy covariates (Bergstrand et al. (2015)).

Box 5.2 Estimating Gravity with Gravitas

$$X_{ij,t} = \exp\left(\pi_{i,t} + \chi_{j,t} + \gamma_{ij} + BLTRL_{ij,t}\beta_1 + BRDR_{ij,t}\beta_{i,t} + EXS_{i,t}\times BRDR_{ij}\beta_2\right) \times$$
$$\exp\left(IMP_{j,t}\times BRDR_{ij}\beta_3 + CNTRY_{j,t}\times BRDR_{ij}\beta_4 + \beta_5 EXR_{ij,t}\times BRDR_{ij}\right), \ \forall \mathbf{i}, \mathbf{j}$$

- $\pi_{\mathbf{i,t}}$, $\chi_{j,t}$ and $\gamma_{\mathbf{ij}}$ are exporter-time, importer-time, and pair fixed effects.
- $\mathbf{BRDR_{ij,t}}$ are border indicators, controlling for common globalization effects.
- $\mathbf{BLTRL_{ij,t}}$ is a vector of time-varying bilateral covariates.
- $\mathbf{EXS_{i,t}}$ is a vector of non-discriminatory export support policies.
- $\mathbf{IMP_{j,t}}$ is a vector of non-discriminatory import protection policies.
- $\mathbf{CNTRY_{j,t}}$ denotes a vector of country-specific characteristics.
- $\mathbf{EXR_{ij,t}}$ is the exchange rate between countries i and j at t.

Source: Adapted from Larch and Yotov (2021).

$\mathbf{BLTRL_{ij,t}}$ is a vector of time-varying bilateral variables, e.g., FTAs, trade sanctions, tariffs (Anderson and van Wincoop (2004)).[12] Following Heid et al. (2021),

[12]While featured prominently in most theoretical trade models as revenue generating trade frictions, tariffs are often ignored in gravity estimations due to their diminishing role in shaping trade policy and due to lack of good data. Tariffs, however, have an important place in the structural gravity model because, as direct price-shifters, their estimates in the gravity equation can be used to recover the important trade elasticity parameter. Capitalizing on this property and using reli-

$\mathbf{EXS_{i,t}}$ and $\mathbf{IMP_{j,t}}$ are vectors of non-discriminatory export support policies (e.g., export subsidies) and import protection policies (e.g., uniform customs bureaucracy/time to clear customs), respectively. These variables are interacted with a dummy variable for international borders, $BRDR_{ij}$, to make it explicit that these policies do not apply to domestic trade.[13] $\mathbf{CNTRY_{j,t}}$ denotes a vector of country-specific characteristics (e.g., institutional quality, technical barriers to trade (TBTs), etc.) whose differential effects on international trade can also be identified in a structural gravity setting with domestic trade flows (Beverelli et al. (2018)).[14]

Finally, $EXR_{ij,t}$ is a variable for exchange rates, which has been used in gravity models for a long time, e.g., Bergstrand (1985). I added this variable to the benchmark gravity model in Box 5.2 for two reasons. First, to emphasize that, despite seemingly being a bilateral variable, its impact cannot be identified when gravity is estimated with data on international trade flows only because of perfect collinearity with the country fixed effects, which control for the multilateral resistances.[15] Anderson et al. (2016) demonstrate this empirically and use domestic trade flows to identify the effects of exchange rates on trade.

Second, more broadly, I want to caution the reader that it is dangerous to include in the gravity regression bilateral variables that are constructed as a combination of country-specific variables, e.g., add or multiply the country specific indexes for institutional quality or minimum residue limits for two countries to construct a new

able tariff data, Fontagné et al. (2020) obtain and deliver trade elasticities at a very disaggregated (product) level. Teti (2020) also describes a recent and carefully constructed tariff database.

[13]In fact, the inclusion of domestic trade flows is exactly the reason Heid et al. (2021) are able to identify the effects of non-discriminatory trade policies in the presence of exporter-time and importer-time fixed effects.

[14]More recently, Freeman et al. (2021) demonstrate how to obtain the full (differential plus uniform) effects of country-specific policies on international trade within the structural gravity model.

[15]The intuition is that when one currency appreciates against another currency, it also changes proportionately against all other currencies. Thus, in effect, the exchange rate is a country-specific variable for gravity estimation purposes.

bilateral variable (Head and Mayer (2014), Beverelli et al. (2018)). In many cases, the new bilateral variable would still be perfectly collinear with the country fixed effects in the gravity model, by construction. Identification may be possible in some cases, e.g., due to a non-linear combination of the country-specific variables, however, the resulting estimates should be interpreted with caution.

6 CGE Gravity: An Estimating-CGE Model

It is well understood that trade theory and trade policy analysis should be set in general equilibrium. However, there is still a division and skepticism among academic trade economists and trade policy practitioners about the potential and usefulness of the gravity model as a "CGE framework" for counterfactual analysis. The debate among UK economists over gravity-based projections of the effects of Brexit is a prominent example.

Indeed, the gravity equation alone delivers estimates of the partial equilibrium effects of policies and other determinants of trade, but partial equilibrium policy analysis alone is inadequate to appropriately quantify big or wide policy changes such as trade agreements because it necessarily misses third party effects that can be quite important. However, gravity is well-suited to conduct tractable and transparent GE analysis because the estimating gravity equation is part of a GE system.

5. Gravity is a computable general equilibrium model.

Box 6.1 illustrates with a representative *'Structural Gravity System'*.[16] The first equa-

[16]Similar to the gravity equations in Box 4.1, the gravity system Box 6.1, can be derived from different theoretical foundations, e.g., Eaton and Kortum (2002), Anderson and van Wincoop (2003), and Arkolakis et al. (2012)). See Yotov et al. (2016) for alternative derivations of the structural gravity system from Box 6.1 with the same notation.

tion is the gravity equation from Box 4.1. The next two equations are the solutions

Box 6.1 CGE Gravity

Structural Gravity Equation: $$X_{ij} = \frac{E_j Y_i}{Y}\left(\frac{t_{ij}}{\Pi_i P_j}\right)^{1-\sigma},$$

Inward Multilateral Resistance: $$P_j^{1-\sigma} = \sum_i \left(\frac{t_{ij}}{\Pi_i}\right)^{1-\sigma}\frac{Y_i}{Y},$$

Outward Multilateral Resistance: $$\Pi_i^{1-\sigma} = \sum_j \left(\frac{t_{ij}}{P_j}\right)^{1-\sigma}\frac{E_j}{Y},$$

Market Clearing Condition: $$p_j = \frac{(Y_j/Y)^{\frac{1}{1-\sigma}}}{\beta_j \Pi_j},$$

Expenditure & Output: $$E_j = \psi_j Y_j = \psi_j A_i L_i^{1-\alpha} K_i^{\alpha} p_j.$$

Source: Adapted from Anderson and van Wincoop (2003).

for the structural multilateral resistances (MRs). From a theory perspective, the MRs can be interpreted as general equilibrium trade costs that consistently aggregate the bilateral trade costs and decompose their incidence on the producers and the consumers in each country, as if they buy from and sell to a single world market. The MRs are the crucial link between the estimating gravity equation and the CGE gravity system. The second to last equation in Box 6.1 is just a restatement of the market clearing condition, $Y_j = \sum X_{ij}$, which explicitly links the OMR to the factory gate price. The last equations define the value of output subject to Cobb-Douglas production technology and allow for exogenous trade imbalances (via ψ_j).

To illustrate how the structural gravity system from Box 6.1 can translate trade cost changes into GE effects, consider the effects on trade of a hypothetical FTA between two countries.[17] The initial FTA effects are captured by the 'Structural Gravity Equation' and can be labeled as *'Direct' or 'Partial Equilibrium'* effects. Most gravity papers aim at quantifying exactly these direct/partial effects, and the estimating gravity model is very well-suited for this purpose. Specifically, subject to data availability, the empirical gravity equation from Section 5 can deliver unbiased estimates of the impact on trade of any bilateral or country-specific policy at the aggregate or sectoral level. Importantly, however, the direct estimates of the trade policy effects may lead to biased/wrong predictions of the true policy effects because they do not account for some important GE effects, which I discuss next.

When two countries start trading more with each other due to an FTA, they may trade less with other countries or sell less domestically, i.e., the FTA may trigger GE *'Trade Diversion Effects'*, even without any changes in country size. These effects are formally captured by the 'Multilateral Resistance' equations. Intuitively, all else equal, when two countries become 'closer' to each other, they also become 'more remote' from everyone else. In terms of direction, the trade diversion effects will lead to less overall trade for the outside countries,[18] and they will mitigate the positive partial effects for the FTA members. By definition, the trade diversion effects cannot be strong enough to completely outweigh the direct trade creation effects for the FTA countries. Still, they can eliminate a very large fraction of them (e.g., up to 40% in the case of NAFTA, Yotov et al. (2016)). Thus, if the trade diversion effects are not properly accounted for, policy impact projections could be severely biased.

The FTA will lead to higher nominal income in the liberalizing countries and

[17]The focus on the effects of bilateral trade liberalization on trade is for clarity and expositional simplicity. However, the analysis can be extended to cover effects on welfare, due to multilateral or unilateral trade liberalization, as well as trade protection. I refer the reader to Head and Mayer (2014) and Yotov et al. (2016) for similar decompositions with a slightly different terminology.

[18]Based on my experience, the predicted negative effects of trade liberalization on third countries are relatively small, even for large trade deals (e.g., NAFTA, TTIP, CETA), and especially for bilateral agreements.

lower nominal income in non-member countries. These *'First-order (nominal) GE size effects'* are captured by the last two equations in Box 6.1.[19] The 'Market Clearing' equation implies that the lower shipping costs (i.e., lower OMRs) for the producers in the FTA will lead to higher factory-gate prices. In turn, via the last equation, higher factory-gate prices mean larger value of output and expenditure. Then, via the 'Structural Gravity Equation', larger size leads to more trade between the FTA members and also between them and all other countries. By definition, the nominal size effects are weaker than the trade diversion effects on average. However, it is possible that the size effects for the FTA members could be strong enough to outweigh the trade diversion effects for some particular outside countries.

Thus far, it was established that the gravity model of trade is suitable for CGE counterfactual projections. As such, an important advantage of the 'Structural Gravity System' is that allows researchers and policy makers to easily move from partial equilibrium trade policy effect estimates to first-order GE indexes (i.e., policy effects obtained while holding the supply vector constant) within the same theoretical framework and with the same data. However, what makes the gravity model unique and truly remarkable is that the CGE gravity system is fully estimating.

6. Gravity is an Estimating CGE (E-CGE) model.

This is demonstrated in Box 6.2, where the gravity system from Box 6.1 is translated into an econometric model. The first equation is the estimating gravity model from Box 5.2; However, for brevity, I have combined all bilateral and country-specific

[19] I label these effects 'first-order' or 'nominal', because they reflect the direct response of producer prices to changes in trade costs. The changes in producer prices can also trigger accumulation of factors of production. Such second-order (real) size effects are outside the gravity system, but can be modeled by nesting gravity within more complex production structures. Section 7 demonstrates.

gravity covariates (except for the exporter-time and importer-time fixed effects) into a single vector $\mathbf{GRAV_{ij,t}}$.

Box 6.2 E-CGE Gravity

$$
\begin{aligned}
\text{Trade:} \quad X_{ij,t} &= \exp[\mathbf{GRAV_{ij,t}}\gamma + \chi_{j,t} + \pi_{i,t}] \times \epsilon_{ij,t}, \\
\text{IMR:} \quad \hat{P}_{j,t}^{1-\sigma} &= \tfrac{E_{j,t}}{\exp(\hat{\chi}_{j,t})}, \\
\text{OMR:} \quad \hat{\Pi}_{i,t}^{1-\sigma} &= \tfrac{Y_{i,t}}{\exp(\hat{\pi}_{i,t})}, \\
\text{Output:} \quad \ln Y_{i,t} &= \tfrac{(\sigma-1)(1-\alpha)}{\sigma} \ln L_{i,t} + \tfrac{(\sigma-1)\alpha}{\sigma} \ln K_{i,t} + \tfrac{1}{-\sigma} \ln \hat{\Pi}_{i,t}^{\sigma-1} + \nu_t + \omega_i + \varepsilon_{i,t}.
\end{aligned}
$$

Source: Adapted from Anderson et al. (2020).

The next two equations reveal that the structural MR terms can be recovered directly from the estimates of the exporter-time and importer-time fixed effects from the gravity regression. This remarkable relationship is due to an additive property of the PPML estimator (Arvis and Shepherd (2013) and Fally (2015)), and it has two important implications. First, it means that the label *'structural gravity estimation'* is indeed appropriate when the gravity model is estimated with PPML because the exporter(-time) and importer(-time) fixed effects capture *exactly and only* the corresponding terms from the theoretical model. In other words, if the full set of fixed effects is replaced with the corresponding structural variables, the fit of the gravity model, as well as the estimates of all other covariates, will remain unchanged. This was the reason for my earlier argument regarding the unprecedented predictive power of gravity. The second implication is that, when gravity is estimated with PPML, there is no need for custom programming to solve for the MRs, i.e., the PPML estimator is a structural gravity solver that ensures perfect consistency between the estimating gravity equation and the CGE gravity system.

Finally, following Anderson et al. (2020), the estimating equation for 'Output' is obtained by combining the last two equations from Box 6.1. To this end, the market-clearing condition is substituted in the production function and the resulting expression is simplified and log-linearized. The 'Output' equation in Box 6.2 is the structural version of the famous income-and-trade regression of Frankel and Romer (1999), where the OMR term, which I have marked in red color, replaces the covariate for total exports from the Frankel and Romer (1999). Intuitively, as a GE trade cost on the producer side, the OMR can be interpreted as a structural trade openness index. Importantly, the estimate on the OMR coefficient has structural interpretation and, as such, it allows for recovery of the important trade elasticity parameter.

Anderson et al. (2018b) implement the model from Box 6.2 in Stata to demonstrate how gravity can deliver partial and GE projections with built-in commands, i.e., without custom coding, directly in standard statistical software packages. In sum, this section showed that structural gravity is an estimating-CGE model, which can be used to establish causal links that are simply assumed in standard CGE models and estimate a number of key structural parameters within the same model and with the same data that are used for the CGE counterfactuals. As such, structural gravity is a complement and a benchmark that may provide useful information for calibration and selection of parameter values in more complex CGE structures, which rely on external parameters and assume without testing some important relationships.

7 Nested Gravity: The Sky Is the Limit

As demonstrated in the previous section, the structural gravity system is a self-sufficient estimating-CGE model, which can be used for counterfactual projections. However, the simplicity and tractability of GE analysis with the model from Box 6.1 come with limitations. For example, it assumes exogenous factors of production, i.e., an endowment setting. Moreover, while the gravity system from Box 6.1 can be estimated for individual sectors, it does not account for very important intersectoral linkages. Thus, as presented in Box 6.1, the gravity system can be characterized as a *'small scale'* CGE model. However, as I will argue in this section, the structural gravity system can be nested within (production) models from different fields, while preserving tractability, transparency, and, in some cases, even the ability to estimate the additional GE equations.

7. Gravity can be nested within more complex GE models.

To support this argument formally, Box 7.1 presents the solution of the dynamic model of trade and growth from Anderson et al. (2020), which nests structural gravity within a production model with endogenous physical capital accumulation. The new element in Box 7.1, as compared to Box 6.1, is the solution for the evolution of physical capital, which is marked in red color. Intuitively, through the variables in the numerator, this equation captures the direct relationship between investment and the value of marginal product of capital.[20] More important for the current purposes, it also establishes a structural relationship between capital accumulation and trade (via

[20]In the capital accumulation equation, δ can be interpreted as a capital depreciation and friction in investment parameter, while Γ_j is a composite parameter. All other variables have been previously defined.

the MRs). Specifically, the inverse relationship between capital accumulation and the IMRs is a reflection of the fact that higher prices (due to higher trade costs) of investment and consumer goods will lead to less investment, and vice versa. Similarly,

Box 7.1 Nested Gravity: Trade and Growth

Structural Gravity Equation: $$X_{ij,t} = \frac{E_{j,t}Y_{i,t}}{Y_t}\left(\frac{t_{ij,t}}{\Pi_{i,t}P_{j,t}}\right)^{1-\sigma},$$

Inward Multilateral Resistance: $$P_{j,t}^{1-\sigma} = \sum_i \left(\frac{t_{ij,t}}{\Pi_{i,t}}\right)^{1-\sigma} \frac{Y_{i,t}}{Y_t},$$

Outward Multilateral Resistance: $$\Pi_{i,t}^{1-\sigma} = \sum_j \left(\frac{t_{ij,t}}{P_{j,t}}\right)^{1-\sigma} \frac{E_{j,t}}{Y_t},$$

Market Clearing Condition: $$p_{j,t} = \frac{(Y_{j,t}/Y_t)^{\frac{1}{1-\sigma}}}{\beta_j \Pi_{j,t}},$$

Expenditure & Output: $$E_{j,t} = \psi_j Y_{j,t} = \psi_j A_{j,t} L_{j,t}^{1-\alpha} {K_{j,t}}^{\alpha} p_{j,t},$$

Capital Accumulation: $$K_{j,t+1} = \Gamma_j \left[\frac{A_{j,t}L_{j,t}^{1-\alpha}}{P_{j,t}\Pi_{j,t}}\right]^{\delta} \left(\frac{Y_{j,t}}{Y_t}\right)^{\frac{\delta}{1-\sigma}} K_{j,t}^{\alpha\delta+1-\delta}.$$

Source: Adapted from Anderson et al. (2020).

the inverse relationship between capital accumulation and the OMRs means that higher shipping costs for the producers in country j would make investment in physical capital in this country less attractive.

Four main implications stand out from Box 7.1. First, the top five equations in Box 7.1 are identical to those from Box 6.1. Thus, the gravity system is indeed *structurally nested* within the production superstructure with endogenous investment in physical capital. Second, on a related note and consistent with the 'universal engine' metaphor, the link between structural gravity and the new production model is through the multilateral resistances, which appear directly in the capital accumulation equation. Third, the resulting system is still tractable and transparent. The decomposition of the effects of trade policy from the previous section into *direct* vs. *trade diversion* vs. *nominal size* effects remains valid; However, there is now an additional, *dynamic GE channel* through which trade impacts *real size* via capital accumulation.[21]

Finally, the new general equilibrium trade and production model in Box 7.1 can still be fully estimated. Specifically, in addition to the four estimating equations from Box 6.2, the new capital accumulation equation from Box 7.1 can easily be transformed into an estimating model after log-linearizing it and adding an error term. Thus, the system in Box 6.2 is also an estimating-CGE model, which can be used (i) to test for and establish causal links that are simply assumed in standard CGE analysis (e.g., between trade and income and between trade and capital accumulation), and (ii) to deliver a number of key structural parameters (e.g., the trade elasticity and the production function shares) within the same model and with the same data that are used for the CGE counterfactuals.

Under certain restrictions, it is possible to nest gravity into even more complex structures that can be fully estimated.[22] However, deriving a fully estimating CGE model with rich GE linkages is an exception rather than the standard in the literature. For example, this is not possible for models with input-output links. Nevertheless, even when the resulting CGE model is not fully estimating, the main argument from this section, i.e., that gravity system can be structurally nested within more complex GE frameworks, remains valid. This is demonstrated in several recent and influential

[21] Anderson et al. (2020) estimate that the new dynamic channel magnifies the static gains from trade liberalization by a dynamic path multiplier of 1.8.

[22] For example, Anderson et al. (2019) extend the model from Box 7.1 to allow for FDI. In addition to the gravity system and the equation for physical capital accumulation, the resulting solution includes a structural estimating equation for FDI.

contributions, which combine gravity with models with input-output links (Caliendo and Parro (2015)), sectoral investment dynamics (Eaton et al. (2016)), and labor market dynamics (Caliendo et al. (2019)). Importantly, in combination with its additive and separability properties, the ability to structurally nest gravity in other models implies that one could still capitalize on all the attractive properties of gravity, e.g., to establish causal relationships and estimate key structural parameters with the same data and within the same framework that is used for the CGE counterfactual analysis.

A broader implication of the analysis in this section is that, as long as the objective is to quantify the effects of trade policy or changes in trade costs, the gravity model is the heart/engine in all complex CGE frameworks. Therefore, I believe that it is impossible to perform and deliver sound trade-policy analysis without taking into account and understanding the fundamental, albeit 'small scale', GE relationships that are captured by the structural gravity system. To me, doing complicated CGE trade-policy analysis without (understanding) gravity is like building an impressive skyscraper without a solid foundation.

8 Gravity Is Endless Fun

To celebrate gravity's 60^{th} anniversary, I reviewed the development of the workhorse model of trade from an intuitive a-theoretical application to an estimating-CGE model that can be nested within many complex frameworks. Gravity continues to be very popular today. Furthermore, despite proven success, there are still many opportunities for improvements and new contributions. The following brief review of recent papers, which either have just been published in 2021 or are still at a working paper stage, offers clear evidence of that.

As usual, most papers still apply the gravity model to address new questions or to improve on existing analysis by relying on better methods or using better data. Some recent gravity applications include analysis of the impact of COVID (Baldwin and Dingel (2021), Cunat and Zymek (2020), and Sforza and Steininger (2020)), preferential trade agreements (Egger and Tarlea (2021)), border effects (Coughlin and Novy (2021)), tariffs (Fontagné et al. (2020)), language (Gurevich et al. (2021)), trade imbalances (Felbermayr and Yotov (2021)), heterogeneous trade cost elasticities (Chen and Novy (2021)), time as a trade barrier (Oberhofer et al. (2021)), experience (Dutt et al. (2020)), and value added taxes (Benzarti and Tazhitdinova (2021) and Schneider et al. (2021)). Stricter reliance on theory opens new opportunities to estimate the effects of country-specific determinants of trade (Beverelli et al. (2018) and Freeman et al. (2021)) and non-discriminatory trade policies (Heid et al. (2021)).

On the estimation front, Weidner and Zylkin (2021) add to the list of attractive PPML properties by demonstrating that, even when estimated with three-way fixed effects, PPML does not suffer from the incidental parameter problem under fairly general conditions, while Santos Silva and Tenreyro (2021) reflect on the reasons for the success of the PPML estimator 15 years after its introduction to trade.

Finally, from a theory perspective, Breinich et al. (2020) and Heid and Stahler (2020) derive gravity models with imperfect competition, Dix-Carneiro et al. (2021) nest gravity within a dynamic model with endogenous trade imbalances and labor market frictions, Anderson and Yotov (2020a) build a dynamic gravity model on the extensive margin of trade, and Adao et al. (2020) and Anderson (2021) generalize the gravity model to a non-parametric framework and test implications without parametric restrictions. To conclude, I will use a quote from one of our last exchanges with brilliant late Peter Neary, who commented: *"Gravity is endless fun!"*. He was right!

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