A Spatial Knowledge Economy*

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May 29, 2018

Abstract

Leading empiricists and theorists of cities have recently argued that the generation and exchange of ideas must play a more central role in the analysis of cities. This paper develops the first system of cities model with costly idea exchange as the agglomeration force. The model replicates a broad set of established facts about the cross section of cities. It provides the first spatial equilibrium theory of why skill premia are higher in larger cities and how variation in these premia emerges from symmetric fundamentals. (JEL: J24, J61, R01)

*We thank the editor, four anonymous referees, Pol Antras, Kerem Coşar, Arnaud Costinot, Gilles Duranton, Jessie Handbury, Walker Hanlon, Sam Kortum, Corinne Low, Ben Marx, Joan Monras, Suresh Naidu, Kentaro Nakajima, Stephen Redding, Holger Sieg, Daniel Sturm, Eric Verhoogen, Reed Walker, David Weinstein, and seminar participants at the CESifo conference on heterogeneous firms in international trade, Columbia applied micro and international trade colloquia, Conference on Urban and Regional Economics, Empirical Investigations in International Trade, NBER ITI meeting, NYU, Urban Economics Association annual meeting, Princeton IES Summer Workshop, Spatial Economic Research Centre annual conference, and University of Toronto for helpful comments on various drafts. We thank Yuxiao Huang, Paul Piveteau, and especially Meru Bhanot for research assistance. We are grateful to Enrico Moretti and Stuart Rosenthal for sharing their housing-price measures with us. Dingel gratefully acknowledges resources provided by the University of Chicago Research Computing Center and financial support from the Institute for Humane Studies, the Program for Economic Research at Columbia University, and the Kathryn and Grant Swick Faculty Research Fund at the University of Chicago Booth School of Business.

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1 Introduction

In modern economies driven by innovation and ideas, local economic outcomes increasingly depend on local idea generation. Empirically, the spatial distribution of human capital has consequences for productivity, prices, and inequality (Rauch, 1993; Moretti, 2004; Diamond, 2016). Theoretically, however, the exchange of ideas in cities has often been treated as a special case of "black box" local external economies.[1]

This paper introduces a model in which costly exchange of ideas is the agglomeration force driving a variety of spatial phenomena. Heterogeneous individuals, drawn from a continuous distribution of ability, may produce tradables or non-tradables, and higher-ability individuals have comparative advantage in tradables. Tradables producers divide their time between producing and exchanging ideas with each other in order to raise their productivity. Cities with more numerous and higher-ability partners are better idea-exchange environments. Higher-ability individuals benefit more from these conversations, so they locate in larger cities, paying higher local prices to realize more valuable idea exchanges. In equilibrium, larger cities exhibit better idea-exchange opportunities because their tradables producers are more talented, greater in number, and devote more time to exchanging ideas. Less skilled individuals are employed in every city producing non-tradables, and larger cities have higher non-tradables prices to compensate them for their higher costs of living.

Our model replicates a broad set of empirical facts about the cross section of cities. First, while our model has symmetric fundamentals, idea-driven agglomeration generates cities of heterogeneous sizes.[2] Second, larger cities exhibit higher nominal wages, housing prices, and productivity in equilibrium (Glaeser, 2008). Third, larger cities' higher wages are partly attributable to higher-ability individual sorting into those locations, but this sorting is incomplete and individuals of many skill types are present in every city (Combes, Duranton and Gobillon, 2008; de la Roca and Puga, 2017; Gibbons, Overman and Pelkonen, 2014; Carlsen, Rattsø and Stokke, 2016).

This account of the spatial distribution of heterogeneous labor yields a novel prediction about spatial variation in skill premia. Since higher-ability tradables producers locate in

[1] Abdel-Rahman and Anas (2004, p.2300): "One way to interpret this black-box model [of Marshallian externalities] is that the productivity of each worker is enhanced by the innovative ideas freely contributed by the labor force working in close proximity." Fujita, Krugman and Venables (1999, p.4) and Fujita and Thisse (2002, p.129) criticize the black-box version for being evanescent in empirical terms and close to assuming the conclusion in theoretical terms. Duranton and Puga (2004, p.2065) describe "looking inside the black box... as one of the fundamental quests in urban economics."

[2] In classic models, heterogeneity across industries supports heterogeneous city sizes (Henderson, 1974). In our model, heterogeneity across individuals supports this outcome.

larger cities and raise their productivity by exchanging ideas while non-tradables productivity does not vary across locations, the relative productivity of tradables producers is increasing in city size. This causes relative wages to increase with city size when the productivity gap is only partially offset by higher non-tradables prices. Empirically, Table 1 shows that the college wage premium rises significantly with metropolitan population. This measure of the skill premium ranges from about 47% in metros with 100,000 residents to about 71% in metros with 10 million residents. This relationship is robust to controlling for two other city characteristics that prior work has linked to cities' skill premia: the fraction of the population possessing a college degree and housing prices.[3] The positive correlation between cities' population sizes and skill premia is a robust, persistent, first-order feature of the data.[4]

Table 1: Skill premia and metropolitan characteristics, 2000

Population (log)	0.031**	0.029**	0.034**	0.026**
	(0.0037)	(0.0053)	(0.0042)	(0.0049)
Rent (log)		0.019		0.097**
		(0.033)		(0.035)
College ratio (log)			-0.036*	-0.069**
			(0.018)	(0.018)
R^2	0.151	0.153	0.171	0.199

NOTES: Robust standard errors in parentheses. ** p<0.01, * p<0.05. Each column reports an OLS regression with 325 observations. The dependent variable is a metropolitan area's difference in average log hourly wages between college and high school graduates. See appendix C for details.

Theoretically linking together cities, ideas, and skill premia is non-trivial. Unlike temporal differences in wage premia, spatial differences in wage premia are disciplined by a no-arbitrage condition. As Glaeser (2008, 85) notes, when people are mobile, differences in productivity "tend to show up exclusively in changes in quantities of skilled people, not in different returns to skilled people across space." The canonical spatial-equilibrium model, in which there are two homogeneous skill groups and preferences are homothetic, predicts that skill premia are spatially invariant (Black, Kolesnikova and Taylor, 2009). Our departure from these standard assumptions yields a novel prediction that matches the data.

[3]See Glaeser (2008), Glaeser, Resseger and Tobio (2009), and Beaudry, Doms and Lewis (2010) on college shares and Black, Kolesnikova and Taylor (2009) on housing prices.

[4]Appendix C.2 reports regressions for 1990 and 2007 that also show a positive premia-size relationship. More broadly, Wheeler (2001), Glaeser, Resseger and Tobio (2009), Behrens and Robert-Nicoud (2014), and Baum-Snow and Pavan (2013) relate other measures of wage inequality to city size.

Our modeling of heterogeneous abilities, cities, and skill premia in a setting with spatially symmetric fundamentals distinguishes our theory from recent work that engages these topics by assuming either asymmetric fundamentals or talent-homogeneous cities. A number of recent contributions have sought to explain differences in outcomes for skilled and unskilled workers across cities by appealing to exogenous differences in fundamental characteristics of those cities.[5] A recent paper by Behrens, Duranton and Robert-Nicoud (2014) assumes symmetric fundamentals and a continuum of abilities, as we do, but they focus on equilibria with heterogeneous cities in which each city is populated by individuals of only one ability. A theory of talent-homogeneous cities cannot explain spatial variation in skill premia.[6]

The role of cities in facilitating idea exchange has been noted by economists since at least Marshall (1890). Empirical studies suggest that larger cities reward cognitive and people skills rather than motor skills or physical strength (Bacolod, Blum and Strange, 2009; Michaels, Rauch and Redding, 2018). Physical proximity is associated with increased communication and intellectual interaction (Jaffe, Trajtenberg and Henderson, 1993; Gaspar and Glaeser, 1998; Audretsch and Feldman, 2004; Charlot and Duranton, 2004; Arzaghi and Henderson, 2008). Since much knowledge is tacit and requires face-to-face transmission, we treat cities as the loci of idea exchange.

Our model unites two strands of theoretical literature on the exchange of ideas. One focuses on individuals' spatial choices when knowledge spillovers are exogenous externalities (Henderson, 1974; Black, 1999; Lucas, 2001). Another focuses on choices of learning activities within a single location of exogenous population (Jovanovic and Rob, 1989; Helsley and Strange, 2004; Berliant, Reed III and Wang, 2006; Berliant and Fujita, 2008). In our model, locational choices shape idea exchanges because learning opportunities are heterogeneous and depend upon the time-allocation decisions of local participants.[7] Our characterization of idea exchanges is simple compared to the second strand of literature, but this allows us to tractably model endogenous exchanges of ideas in a system of cities.

We focus on the exchange of ideas between rather than within firms. Idea exchange within firms is surely important, but it does not motivate firms to locate in cities, since

[5]For example, Glaeser (2008) and Beaudry, Doms and Lewis (2010) use skill-segmented housing markets and skill-biased housing supplies to explain spatial variation in skill premia. These neoclassical models do not relate skill premia to city sizes. Gyourko, Mayer and Sinai (2013) model exogenous differences in housing supply elasticities.

[6]In their model, all within-city inequality is due to exogeneous shocks that individuals experience after selecting their location. Educational attainment is neither randomly assigned nor location-specific.

[7]Glaeser (1999) is an important precursor to our approach. His model specifies two locations, a city and a rural hinterland. In contrast to our approach, the fundamental difference between the two locations is exogenous, since learning is possible only in the city.

intra-firm idea exchange may occur in geographic isolation. Our model describes inter-firm interactions because these are the idea exchanges that may underpin urban agglomeration.[8]

2 A spatial knowledge economy

The economy consists of a continuum of individuals of mass L, whose heterogeneous abilities are indexed by z and distributed with density $\mu(z)$ on connected support on $\mathbb{R}_+$. There are a number of homogeneous sites that may be cities with endogenous population and ability composition.

2.1 Preferences and production

Individuals consume three goods: tradables, non-tradable services, and (non-tradable) housing. Services and housing are strict necessities; after consuming $\bar{n}$ units of non-tradable services and one unit of housing, consumers spend all of their remaining income on tradables, which we use as the numeraire.[9] Therefore, the indirect utility function for a consumer with income y facing prices $p_{n,c}$ and $p_{h,c}$ in city c is

$$V(p_{n,c}, p_{h,c}, y) = y - p_{n,c}\bar{n} - p_{h,c}. \tag{1}$$

Individuals are perfectly mobile across cities and jobs, so their locational and occupational choices maximize $V(p_{n,c}, p_{h,c}, y)$.

An individual can produce tradables (t) or non-tradables (n). Non-tradables can be produced at a uniform level of productivity by all individuals, which we normalize to one by choice of units. Tradables, by contrast, make use of the underlying heterogeneity in ability. An individual's tradables output is $\tilde{z}(z, Z_c)$, which depends on both individual ability z and learning opportunities available through local interactions, Z_c. An individual working in

[8] Recent research suggests that physical proximity facilitates such activities. Allen, Raz and Gloor (2010) examine inter-firm communication amongst individual scientists at biotech firms in the Boston area and find that geographic proximity and firm size are both positively associated with inter-firm communication on the extensive and intensive margins. Inoue, Nakajima and Saito (2015) examine inter-firm collaboration on Japanese patent applications and find that it is more geographically concentrated than intra-firm collaboration and this localization is stable over the last two decades.

[9] The merit of this stark specification is tractability. Section 3.3 shows that our assumption of perfectly inelastic demand for housing and services generates a compensation effect that in fact works against finding a positive premia-population relationship. Section 3.4 shows that this inelastic specification is nonetheless consistent with realistic housing expenditure shares. Assuming unit demand for housing is common in urban theory (e.g. Moretti 2011; Behrens, Duranton and Robert-Nicoud 2014).

sector σ earns income equal to the value of her output, which is

$$y = \begin{cases} p_{n,c} & \text{if } \sigma = n \\ \tilde{z}(z, Z_c) & \text{if } \sigma = t \end{cases}. \tag{2}$$

Tradables productivity depends both on an individual's ability and participation in idea exchanges. Tradables producers can raise their productivity by exchanging ideas with other tradables producers in their city.[10] Each person has one unit of time that they divide between interacting and producing. Exchanging ideas is an economic decision, because time spent interacting trades off with time spent producing output directly. The production function for tradables B depends on time spent exchanging ideas $(1-\beta)$, time spent producing (β), own ability (z), and local learning opportunities (Z_c). When time is allocated optimally, the output of a tradables producer of ability z is

$$\tilde{z}(z, Z_c) = \max_{\beta\in[0,1]} B(1-\beta, z, Z_c). \tag{3}$$

The value of local idea exchanges, Z_c, is determined by the time-allocation decisions of all the tradables producers living in city c. In particular, it is a function of both the time they devote to exchanges and their abilities.[11] We denote the time devoted to idea exchange by individuals of ability z in city c by $1-\beta_{z,c}$ and the population of individuals of ability z in city c by $L \cdot \mu(z, c)$, where $\frac{\mu(z,c)}{\mu(z)}$ is the share of z-ability individuals who live in c. The value of the local idea-exchange environment Z_c is a functional of the time-allocation decisions and the population composition,

$$Z_c = Z(\{1-\beta_{z,c}\}, \{L \cdot \mu(z, c)\}). \tag{4}$$

Key to the tractability of our model is that that these local learning opportunities are summarized by a scalar. To further summarize behavior, denote the total time devoted to learning by tradables producers in city c by M_c, which is defined as

$$M_c = L \int_{z:\sigma(z)=t} (1-\beta_{z,c})\mu(z, c)dz.$$

[10] Our static model focuses on the location of idea exchange and abstracts from dynamic accumulation of knowledge. Lucas and Moll (2014) and Perla and Tonetti (2014) study knowledge accumulation while abstracting from the spatial dimension. We hope that future work might unify these topics.

[11] These elements distinguish our agglomeration mechanism from a "black box" function that depends on a location's population size. Heterogeneous individuals' choices of locations and time allocations are economic decisions that both have opportunity costs and determine local opportunities for idea exchange.

This depends on the city's total population of tradables producers, their ability composition, and their time-allocation choices.

We make three assumptions about the production of tradables and exchange of ideas. First, tradables output is increasing in both ability z and the idea-exchange environment Z_c. In the absence of idea-exchange opportunities ($Z_c = 0$) or time devoted to them ($\beta = 1$), tradables output is the product of time spent producing and ability, βz.

Assumption 1. *The production function for tradables $B(1-\beta, z, Z_c)$ is continuous, strictly concave in $1-\beta$, strictly increasing in z, and increasing in Z_c. $B(1-\beta, z, 0) = \beta z$ and $B(0, z, Z_c) = z \ \forall z$.*

Second, individual ability and local learning opportunities are complements.[12] When exchanging ideas, the output gain from greater ability is increasing in Z_c.

Assumption 2. *Tradables output $\tilde{z}(z, Z_c)$ is supermodular and is strictly supermodular on $\otimes \equiv \{(z, Z) : \tilde{z}(z, Z) > z\}$.*

Third, the idea-exchange environment Z_c is better when those devoting time to idea exchange are of higher ability and when all tradables producers devote more time to idea exchange.

Assumption 3. *The idea-exchange functional $Z(\{1-\beta_{z,c}\}, \{L\cdot\mu(z,c)\})$ is continuous, equal to zero if $M_c = 0$, and bounded above by $\sup\{z : 1-\beta_{z,c} > 0, \mu(z,c) > 0\}$. If $M_c > M_{c'}$ and $\{(1-\beta_{z,c})\mu(z,c)\}$ stochastically dominates $\{(1-\beta_{z,c'})\mu(z,c')\}$, then $Z(\{1-\beta_{z,c}\}, \{L\cdot\mu(z,c)\}) > Z(\{1-\beta_{z,c'}\}, \{L\cdot\mu(z,c')\})$.*

Assumption 3 implies that knowledge has both horizontal and vertical dimensions. There is horizontal differentiation in the sense that individuals can learn something from anyone and are therefore better off when all tradables producers devote more time to exchange. Vertical differentiation means that they learn more from more able counterparts.

For some of our analysis, we focus on particular functional forms for $B(\cdot)$ and $Z(\cdot)$:

$$B(1-\beta, z, Z_c) = \beta z(1 + (1-\beta)AZ_c z) \tag{5}$$

$$Z(\{(1-\beta_{z,c}), L\cdot\mu(z,c)\}) = (1-\exp(-\nu M_c))\,\bar{z}_c \tag{6}$$

$$\bar{z}_c = \begin{cases} \int_{z:\sigma(z)=t} \frac{(1-\beta_{z,c})z}{\int_{z:\sigma(z)=t}(1-\beta_{z,c})\mu(z,c)dz}\mu(z,c)dz & \text{if } M_c > 0 \\ 0 & \text{otherwise} \end{cases}$$

[12] Assumption 2 is stated in terms of $\tilde{z}(z, Z_c)$, which incorporates the optimal choice of $1-\beta$. In Appendix A.5, we identify sufficient conditions for $B(1-\beta, z, Z_c)$ that imply Assumption 2. This Assumption 2′ is sufficient but not necessary. For example, equation (5) satisfies Assumption 2 but not Assumption 2′.

Appendix A.6 shows that these functions satisfy Assumptions 1 through 3.

In this special case, productivity gains are the product of random matches between individuals devoting time to idea exchange. A indexes the scope for gains from such interactions. With random matching, the expected value of devoting a moment of time to idea exchange in a city is the probability of encountering another individual during that moment times the expected ability of the individual encountered.[13] Since idea exchanges are instantaneous and individuals devote an interval of time to idea exchange, every individual devoting time to exchanging ideas realizes the expected gains from these exchanges, Z_c.

The probability of encountering someone during each moment of time spent seeking idea exchanges is $1 - \exp(-\nu M_c)$. As in Diamond (1982), exchange is easier when there are more potential exchange partners. Thus, one potential benefit of larger cities is that idea exchanges may occur with greater frequency there (Glaeser, 1999).[14] The population of individuals available for such encounters is determined endogenously by tradables producers' time-allocation choices.

The average ability of the individuals encountered in these matches is $\bar{z}_c$. This is a weighted average of the abilities of local tradables producers, in which the weights are the time each type of individual devotes to interactions. Conditional on meeting another learner and one's own ability, conversations with more able individuals are more valuable.

The agglomeration mechanism described by Assumptions 1 through 3 trades off with a simple congestion force. Each individual in a city of population L_c pays a net urban cost (in units of the numeraire) of

$$p_{h,c} = \theta L_c^{\gamma}, \tag{7}$$

[13]Random matching is not particularly realistic, but it is tractable. Related work in growth theory, Lucas and Moll (2014) and Perla and Tonetti (2014), also assumes random meetings. In those models, lower-ability agents spend time in order to observe a random competitor and improve their productivity through imitation of higher-ability agents. In our model, both participants in a meeting opt to spend time exchanging ideas. The benefit of the meeting can be interpreted as combining both what one can learn from the other and one's ability to learn from any encounter. Thus, even when participants in a meeting have different skill levels, both benefit. By contrast, those growth-theory papers feature meetings that benefit only the lower-ability participant, who imitates the higher-ability participant. Such perfectly asymmetric accounts of idea exchange are poorly suited as a foundation for spatial models. The highest-ability agent would never pay to be in a city where meetings occurs because idea exchanges with lower-ability agents yield zero benefit. By iteration, every agent would want to move to locations where higher-ability agents reside, while the latter would leave locations populated by lower-ability agents. Our approach in which idea exchange is mutually beneficial provides a framework consistent with spatial equilibrium.

[14]This city-level scale effect embodies the horizontal dimension of knowledge in Assumption 3 and implies an upper bound on the number of heterogeneous cities. See appendix sections A.2 and A.6.1. Most empirical evidence on matching processes describes job search, which is distinct from idea exchange in numerous dimensions. Early job-search studies, while noisy, were often interpreted to suggest constant returns (Pissarides and Petrongolo, 2001). More recent studies have found results more favorable to increasing returns to scale (Petrongolo and Pissarides, 2006; Di Addario, 2011; Bleakley and Lin, 2012).

with $\theta, \gamma > 0$. We will refer to $p_{h,c}$ as the price of housing in city c, though this object incorporates both land rents and commuting costs when given standard microfoundations.[15]

2.2 Equilibrium

Individuals choose their locations, occupations, and time allocations optimally. Since individuals are perfectly mobile, two individuals with the same ability z will obtain the same utility in equilibrium wherever they are located.

An equilibrium for a population L with ability distribution $\mu(z)$ in a set of locations $\{c\}$ is a set of prices $\{p_{h,c}, p_{n,c}\}$ and populations $\mu(z, c)$ such that workers maximize (1) by their choices of c, σ, and β and markets clear.[16] Markets clear when $\beta_{z,c} = \beta(z, Z_c)$, and equations (4), (7), and the following conditions hold:

$$\mu(z) = \sum_c \mu(z, c) \quad \forall z \tag{8}$$

$$L_c = L \int \mu(z, c) dz \quad \forall c \tag{9}$$

$$\bar{n} L_c = L \int_{z:\sigma(z)=n} \mu(z, c) dz \quad \forall c \tag{10}$$

The equilibrium value of local idea exchanges $Z_c = Z(\{1 - \beta_{z,c}\}, \{L \cdot \mu(z, c)\})$ in equation (4) is a fixed point, since individuals' choices of location and $\beta_{z,c}$ depend on local learning opportunities Z_c. Equation (7) defines the market-clearing housing price in each city. Equations (8) and (9) are adding-up constraints for worker types and city populations. Equation (10) equalizes demand and supply of non-tradable services within each location. The tradables market clears by Walras' Law.

3 The cross section of cities in equilibrium

We now characterize equilibrium outcomes. By comparative advantage, higher-ability individuals produce tradables and lower-ability individuals produce non-tradables. Since individual ability and idea-exchange opportunities are complements, there is spatial sorting

[15] Behrens, Duranton and Robert-Nicoud (2014) provide microeconomic foundations for this functional form, which they derive from a standard model of the internal structure of a monocentric city in which commuting costs increase with population size as governed by the technological parameters θ and γ. See appendix section A.1 for details.

[16] In this exposition, we define equilibrium where each member of the set $\{c\}$ is populated, $L_c > 0$. In appendix section A.2, we discuss the endogenous number of cities that make up this set, since not all potential city locations must be populated.

of tradables producers by ability. When cities are heterogeneous, tradables producers are sequentially segmented so that the lowest-ability tradables producers locate in the smallest city and the highest-ability tradables producers locate in the largest city.[17] For the marginal tradables producer, a larger city's idea-exchange benefits are exactly offset by its higher cost of living. Together, sorting and idea exchange cause larger cities to exhibit higher skill premia.

3.1 Equilibrium occupations and prices

Occupational choices are governed by comparative advantage. High-ability individuals produce tradables since labor heterogeneity matters in that sector.

Lemma 1 (Comparative advantage)**.** *Suppose that Assumption 1 holds. There is an ability level z_m such that individuals of greater ability produce tradables and individuals of lesser ability produce non-tradables.*

$$\sigma(z) = \begin{cases} t & \text{if } z > z_m \\ n & \text{if } z < z_m \end{cases}$$

The proofs of lemma 1 and subsequent results appear in appendix section A.6. By lemma 1 and equations (8) through (10), the ability level of the individual indifferent between producing tradables and non-tradables, z_m, is given by

$$\int_0^{z_m} \mu(z)dz = \bar{n} \ . \tag{11}$$

Since individual ability and local learning opportunities are complements, there is spatial sorting of tradables producers engaged in idea exchange. Higher-ability tradables producers locate in cities with better idea-exchange environments.

Lemma 2 (Spatial sorting of tradables producers engaged in idea exchange)**.** *Suppose that Assumptions 1 and 2 hold. For $z > z' > z_m$, if $\mu(z, c) > 0$, $\mu(z', c') > 0$, $\beta(z, Z_c) < 1$, and $\beta(z', Z_{c'}) < 1$, then $Z_c \geq Z_{c'}$.*

As a result, individuals of ability z_m producing tradables will be located in the city with the lowest value of Z_c. Label cities in order of the value of their idea exchanges, $Z_c \geq Z_{c-1}$, so

[17] Spatial models with a continuum of heterogeneous individuals sorting across a finite number of locations date to at least Westhoff (1977), who studied conditions for the existence of an equilibrium in a model of local public finance.

that $Z_1 = \min_c\{Z_c\}$. Indifference between producing tradables and non-tradables implies that $p_{n,1}$ satisfies

$$p_{n,1} = \tilde{z}(z_m, Z_1). \tag{12}$$

There is a population of non-tradables producers located in each city. In spatial equilibrium, each of these individuals obtains the same utility, so equation (1) implies that spatial differences in non-tradables prices exactly compensate for spatial differences in housing prices.

$$(1-\bar{n})p_{n,c} - p_{h,c} = (1-\bar{n})p_{n,c'} - p_{h,c'} \quad \forall c, c' \tag{13}$$

All equilibria exhibit this pattern of occupations and prices. We now distinguish between equilibria based on whether cities vary in size.

3.2 Equilibrium systems of cities

There are two classes of equilibria for this economy: equilibria in which all cities have the same population size and equilibria with heterogeneous cities. The latter are the empirically relevant class. We analyze the properties of equilibria with heterogeneous cities after describing why systems of equal-sized cities are only stable equilibria if the marginal gains from idea exchange are too small relative to marginal congestion costs to break the symmetric arrangement. When idea exchange is sufficiently rewarding, a system of heterogeneous cities is an equilibrium configuration.[18]

3.2.1 Systems of equal-sized cities

Given symmetric fundamentals, systems of equal-sized cities are possible equilibria. By equations (7) and (13), equal-sized cities have equal local prices. To be in equilibrium, they must also have equal idea-exchange benefits for the marginal tradables producer.

When idea exchange occurs nowhere, $Z_c = 0\ \forall c$, these benefits are equal because every tradables producer devotes zero time to idea exchange. This is individually rational when others do the same. While not the focus of our paper, the no-idea-exchange equilibrium illustrates an important aspect of the economic mechanism: ideas are not manna from heaven but the outcome of a costly allocation of time by those acquiring knowledge. Though not the empirically relevant case, this possibility highlights the relevant economic trade-off.

[18] We provide sufficient conditions for the existence of a stable equilibrium with two heterogeneous cities in appendix section A.3. While we do not provide conditions for the existence of equilibria with more than two cities, we have numerically computed equilibria with many more cities. Section 3.4 reports an example with 275 cities and Appendix B summarizes many more numerical results.

A system of equal-sized cities in which idea exchange occurs can only be a stable equilibrium when the marginal benefits of a better idea-exchange environment are small relative to marginal congestion costs. Denote the city with the best idea-exchange environment by C. Given identical prices, living in C is optimal for all individuals of ability such that $\beta(z, Z_C) < 1$. If C is the only city with idea exchanges, this is an equilibrium only if both Z_C and the ability distribution are so low that all those possibly gaining from idea exchange fit in this single city and the marginal tradables producer's idea-exchange benefit is zero. If another city also has idea exchanges, the value of its idea-exchange environment must be the same. An equilibrium with two cities with equal idea-exchange environments is locally stable only if the marginal gains from idea exchange are small relative to marginal congestion costs. Otherwise, the movement of some high-ability tradables producers from one city to the other would improve the latter's idea-exchange environment, thereby drawing in more tradables producers and breaking the symmetric arrangement.[19] In particular, if any improvement in the idea-exchange environment is sufficiently valuable to the highest-ability tradables producers, then an equilibrium of equal-sized cities cannot be stable.[20]

Thus, a system of equal-sized cities is a stable equilibrium in the trivial case that no one exchanges ideas or if marginal congestion costs are large relative to the benefits of a better idea-exchange environment. We henceforth focus on the empirically relevant equilibrium configuration, a system of heterogeneous cities.

3.2.2 Systems of heterogeneous cities

Equilibria with heterogeneous cities exhibit cross-city patterns that can be established independent of the number of cities that arise.[21] Proposition 1 characterizes the characteristics of heterogeneous cities in equilibrium.

Proposition 1 (Heterogeneous cities' characteristics)**.** *Suppose that Assumptions 1 and 2 hold. In any equilibrium, a larger city has higher housing prices, higher non-tradables prices, a better idea-exchange environment, and higher-ability tradables producers. If* $L_c > L_{c'}$ *in equilibrium, then* $p_{h,c} > p_{h,c'}$, $p_{n,c} > p_{n,c'}$, $Z_c > Z_{c'}$, *and* $z > z' > z_m \Rightarrow \mu(z,c)\mu(z',c') \geq \mu(z,c')\mu(z',c) = 0$.

The mechanics of Proposition 1 are straightforward. Larger cities have higher housing prices due to congestion, so non-tradables producers require higher wages in these locations.

[19]See appendix section A.4 for our definition of local stability and the relevant argument.

[20]See Proposition 3 for the formal result.

[21]Since these patterns characterize all equilibria with heterogeneous cities, we do not address issues of uniqueness or determine the equilibrium number of cities. See appendix section A.2 for further discussion.

Larger cities attract tradables producers because the benefits of more valuable idea exchanges offset their higher housing and non-tradables prices. More able tradables producers benefit more from participating in better idea exchanges, so there is spatial sorting of tradables producers.[22] This spatial sorting supports equilibrium differences in idea-exchange environments because these high-ability individuals are better idea-exchange partners, conditional on population size and time allocations.

Equilibria with heterogeneous cities match the fundamental facts that cities differ in size and these size differences are accompanied by differences in wages, housing prices, and productivity (Glaeser, 2008). Empirically, larger cities exhibit higher nominal wages in industries that produce tradable goods, which means that productivity is higher in these locations (Moretti, 2011). Our model of why larger cities generate more productivity-increasing idea exchanges is a microfounded explanation of these phenomena. Having matched these well-established facts, we now describe the novel implication that skill premia will be higher in larger cities.

3.3 Skill premia with heterogeneous cities

We define a city's skill premium as the average income of its tradable producers relative to the wage of its non-tradable producers. Our model typically predicts that skill premia are higher in more populous cities. After discussing the mechanisms contributing to spatial variation in skill premia, we formally state this prediction for two cities in Proposition 2. Numerical analysis, detailed in Appendix B, suggests that this prediction generalizes from two cities to a large number of heterogeneous cities.

The nominal wages of both non-tradables and tradables producers are higher in larger cities. For non-tradables producers, higher nominal wages in larger cities are compensation for higher housing prices that keeps their utility constant across cities, per equation (13).

Differences in tradables producers' wages across cities can be expressed as the sum of three components: composition, learning, and compensation effects. First, due to spatial sorting, tradables producers in larger cities have higher innate abilities that generate higher incomes in any location. Second, since one's own ability complements others' abilities in idea exchanges, these tradables producers realize larger income gains in larger cities' better idea-exchange environments. Third, producers who are indifferent between two cities realize

[22]Our prediction of sorting among the more able and indifference among the less able is consistent with the limited evidence available. Using Norweign administrative data, Carlsen, Rattsø and Stokke (2016) estimate unobserved ability with individual fixed effects in wage regressions and find sorting among college-educated workers but none among those with primary and secondary education.

learning gains in the larger city that exactly compensate for its higher non-tradables and housing prices. For convenience, let z_b denote the ability of this boundary tradables producer who is indifferent, define inframarginal learning $\Delta(z,c,c')$ as the idea-exchange gains accruing to a producer of ability z from locating in environment $Z_c > Z_{c'}$ compared to those gains for ability z_b, and define the density of tradables producers' abilities in city c by $\tilde{\mu}(z,c)$.[23] When a tradables producer of ability z_b is indifferent between cities c and c', the difference in the cities' average tradables wages can be expressed as

$$\begin{aligned}\bar{w}_c - \bar{w}_{c'} &\equiv \frac{\int_{z:\sigma(z)=t} \tilde{z}(z,Z_c)\mu(z,c)dz}{\int_{z:\sigma(z)=t}\mu(z,c)dz} - \frac{\int_{z:\sigma(z)=t} \tilde{z}(z,Z_{c'})\mu(z,c')dz}{\int_{z:\sigma(z)=t}\mu(z,c')dz} \\ &= \underbrace{\int_{z_m}^{\infty}[\tilde{\mu}(z,c)-\tilde{\mu}(z,c')]\tilde{z}(z,Z_{c'})dz}_{\text{composition}} + \underbrace{\int_{z_m}^{\infty}\tilde{\mu}(z,c)\Delta(z,c,c')dz}_{\text{inframarginal learning}} + \underbrace{p_{n,c}-p_{n,c'}}_{\text{compensation}}.\end{aligned}$$

Cross-city variation in skill premia can also be expressed in terms of these three components. We define a city's observed skill premium as its average tradables wage divided by its (common) non-tradables wage, $\frac{\bar{w}_c}{p_{n,c}}$. When a tradables producer of ability z_b is indifferent between cities c and c', this skill premium is higher in c if and only if

$$\underbrace{\int_{z_m}^{\infty}[\tilde{\mu}(z,c)-\tilde{\mu}(z,c')]\tilde{z}(z,Z_{c'})dz}_{\text{composition}} + \underbrace{\int_{z_m}^{\infty}\tilde{\mu}(z,c)\Delta(z,c,c')dz}_{\text{inframarginal learning}} \geq \underbrace{(p_{n,c}-p_{n,c'})\left(\frac{\bar{w}_{c'}}{p_{n,c'}}-1\right)}_{\text{relative compensation}} \quad (14)$$

The composition and inframarginal learning effects yield higher nominal incomes for tradables producers in larger cities. These raise tradables producers' wages relative to non-tradables producers' wages in larger cities and therefore generate a positive premium-population relationship. The compensation effect that reflects differences in local prices makes the nominal wages of both tradables and non-tradables producers in larger cities higher by the same amount. Since higher-ability individuals earn higher incomes, this compensation is a larger proportion of the non-tradables producers' incomes and therefore pushes towards a negative premium-population relationship. When the composition and learning effects dominate this implication of the compensation effect, the skill premium is higher in the larger city.

The sizes of these three effects depend on the distribution of abilities, $\mu(z)$, the strength of the complementarity between z and Z_c in $\tilde{z}(z,Z_c)$, and equilibrium differences in cities' sizes. The composition and inframarginal learning effects necessarily depend on heterogeneity in

[23] That is, $\Delta(z,c,c') \equiv [\tilde{z}(z,Z_c)-\tilde{z}(z,Z_{c'})] - [\tilde{z}(z_b,Z_c)-\tilde{z}(z_b,Z_{c'})]$ and $\tilde{\mu}(z,c) \equiv \frac{\mu(z,c)}{\int_{z':\sigma(z')=t}\mu(z',c)dz'}$.

tradables producers' abilities.[24] Inframarginal learning also depends on the degree to which higher-ability individuals experience larger gains from locating in a better idea-exchange environment. The relative compensation effect is the product of size-related differences in costs of living ($p_{n,c} - p_{n,c'}$) and the level of the skill premium ($\bar{w}_{c'}/p_{n,c'}$).[25]

Proposition 2 states three different sets of sufficient conditions under which, when the smallest city has population L_1 and the second-smallest city has population $L_2 > L_1$, the skill premium is higher in the more populous city. These sufficient conditions depend jointly on assumptions about $\mu(z)$, $\tilde{z}(z, Z_c)$, and equilibrium city sizes. For the production function, the relevant property concerns the ability elasticity of tradable output, $\frac{\partial \ln \tilde{z}(z,Z_c)}{\partial \ln z}$.

Condition 1. *The ability elasticity of tradable output is non-decreasing in z and Z_c.*

Condition 1 is satisfied by the production function in equation (5), as well as other production functions, as described in Appendix A.5.

Proposition 2 (Skill premia)**.** *Suppose that Assumptions 1 and 2 hold. In an equilibrium in which the smallest city has population L_1 and the second-smallest city has population $L_2 > L_1$,*

1. *if the ability distribution is decreasing, $\mu'(z) \leq 0$, $\tilde{z}(z, Z_c)$ is log-convex in z, and $\tilde{z}(z, Z_c)$ is log-supermodular, then $\frac{\bar{w}_2}{p_{n,2}} > \frac{\bar{w}_1}{p_{n,1}}$;*
2. *if the ability distribution is Pareto, $\mu(z) \propto z^{-k-1}$ for $z \geq z_{\min}$ and $k > 0$, and the production function satisfies Condition 1, then $\frac{\bar{w}_2}{p_{n,2}} > \frac{\bar{w}_1}{p_{n,1}}$;*
3. *if the ability distribution is uniform, $z \sim U(z_{\min}, z_{\max})$, the production function satisfies Condition 1, and $\frac{L_2-L_1}{L_1^2} > \frac{1}{L}\frac{(1-\bar{n})(z_{\max}-z_{\min})}{z_{\min}+\bar{n}(z_{\max}-z_{\min})}$, then $\frac{\bar{w}_2}{p_{n,2}} > \frac{\bar{w}_1}{p_{n,1}}$.*

These three cases trade off stronger assumptions about the production function with weaker assumptions about the ability distribution. In case 1, the log-supermodularity of $\tilde{z}$ implies large inframarginal learning, and the log convexity of $\tilde{z}$ implies a large composition effect when higher-ability individuals are not relatively abundant. Together, these are sufficient to dominate the relative compensation effect, such that the skill premium is

[24] In a model with only two skill types (i.e., homogeneous tradables producers and homogeneous non-tradables producers), the skill premium is lower in the larger city. Homogeneity makes the composition and inframarginal learning components zero, leaving only the compensation term. This two-type case is the basis for the prediction by Black, Kolesnikova and Taylor (2009) that skill premia will be lower in cities with higher housing prices. Empirically, larger cities have both higher housing prices and skill premia.

[25] Since $p_{n,1} = \tilde{z}(z_m, Z_1)$, the level of the skill premium in city 1 depends on the heterogeneity in tradables producers' abilities, $\mu(z, 1)$, and the complementarity between z and Z_1 in $\tilde{z}(z, Z_1)$.

higher in the larger city. In case 2, the Pareto ability distribution and the ability elasticity of tradable output jointly generate composition and inframarginal-learning effects sufficient to dominate the relative compensation effect. In case 3, the uniform ability distribution generates weaker compensation and inframarginal-learning effects for a given ability elasticity of tradable output. The sufficient condition in case 3 is written in terms of endogenous equilibrium outcomes. It establishes a value of L_1 small enough relative to the heterogeneity in tradables producers' abilities such that the relative compensation effect is less than these effects.[26] Note that this condition is far from necessary, as demonstrated in Appendix B.1. The relative compensation effect approaches zero as $L_1 \to L_2$ because $p_{n,2} - p_{n,1} \to 0$.

Since the sufficient condition in case 3 depends on endogenous city sizes, we study the two-city, uniform-ability case further by numerically characterizing equilibria for the special case of equations (5) and (6) for a wide range of parameter values in appendix B. We do find examples of parameter combinations that yield equilibria in which a larger city has a lower skill premium, but they are rare (less than 0.3% of the parameter combinations for which equilibria exist). These examples generate very large relative compensation effects (the right-hand side of inequality (14)) by generating values of $\frac{\bar{w}_1}{p_{n,1}}$ an order of magnitude larger than those in the data. They also require values of γ, the congestion cost elasticity, that are implausibly large relative to empirical estimates, though non-increasing skill premia are atypical in equilibrium even for extreme parameter values.[27]

To extend the prediction of Proposition 2 to more than two cities, in appendix B we numerically solve the special case of equations (5) and (6) for a wide number of heterogeneous cities and wide range of parameter values for the uniform- and Pareto-ability cases. In the uniform-ability case, we again find that skill premia are monotonically increasing in population size in almost all equilibria. The exceptions to this pattern occur when $\frac{\bar{w}_1}{p_{n,1}}$ and γ are implausibly large relative to empirical values, consistent with the two-city case. In the Pareto-ability case, we find that all equilibria examined exhibit monotonically increasing skill premia.[28] Thus, our two-city result appears to generalize to many cities.

To summarize, our model typically predicts that skill premia are higher in more populous cities, in line with the empirical pattern documented in Table 1. Proposition 2 analytically characterizes the pattern of premia for the two smallest cities in an equilibrium, and numeri-

[26] This sufficient condition can also be written as $\frac{L_2 - L_1}{L_1^2} > \frac{1}{L} \frac{z_{\max} - z_m}{z_m}$.

[27] For example, we find non-increasing skill premia in parameter combinations in which $\gamma = 5$, but less than 0.5% of parameter combinations with $\gamma = 5$ for which equilibria exist exhibit non-increasing skill premia.

[28] The numerical findings for hundreds of thousands of parameter values are strongly suggestive. Unfortunately, our analytical proof of the two-city result for a Pareto ability distribution does not extend naturally to an arbitrary number of cities.

cal computations reported in appendix B show that this pattern of premia generalizes across all cities in equilibrium for a wide range of parameter values. This novel prediction distinguishes our model from the canonical spatial-equilibrium model, which predicts spatially invariant skill premia.

3.4 An illustrative example with 275 cities

To illustrate our model's capacity to match empirical patterns linking cities' sizes, wages, and prices, we report an example of an equilibrium for the special case of equations (5) and (6) that is consistent with three empirical moments of interest. First, Zipf's law says that a city's size rank is inversely proportional to its size (Gabaix, 1999). Second, there is the positive correlation between skill premia and population size documented in Table 1. Third, Davis and Ortalo-Magne (2011) document that housing expenditure shares vary little across cities.[29]

Our illustrative example is a uniform-ability equilibrium with 275 heterogeneous cities, akin to the number of US metropolitan areas.[30] The exogenous parameter values are $A = 3, \bar{n} = .4, \theta = 1, \gamma = .1, L = 2062.5, \nu = 50, z_{\min} = 1, z_{\max} = 2$. The large values of ν and L make the equilibrium matching rate $m(M_c)$ exceed 0.99 in every city, so cross-city variation in idea-exchange environments is much more due to variation in average ability $\bar{z}_c$ than scale effects. The average time devoted to idea exchange ranges from 0.41 to 0.46 and is monotonically increasing in city size. Regressing log population rank on log size yields a coefficient of -1.025, near the typical empirical estimate of this power-law exponent. Regressing log skill premium on log size yields a coefficient of 0.092, which is greater than those reported in Table 1 but plausible. Housing expenditure shares vary from .32 to .36 and have a population elasticity reasonably close to zero, -0.023. Thus, this illustrative example exhibits properties consistent with empirical patterns.[31]

While our model does not yield closed-form comparative statics, this illustrative example exhibits local comparative statics consistent with economic shifts in recent decades. Work

[29]In light of their finding, Davis and Ortalo-Magne (2011) use Cobb-Douglas preferences. Our results show that such preferences are not necessary to obtain housing expenditure shares that are approximately spatially invariant, as previously established by Behrens, Duranton and Robert-Nicoud (2014).

[30]The geographic delineations used in Census 2000 publications define 280 (consolidated) metropolitan statistical areas, including four in Puerto Rico.

[31]While this example matches empirical regularities well, our model does not generically generate these patterns. Other parameterizations can yield equilibria in which the power-law exponent is quite far from -1. In our numerical explorations, small changes to the parameter values cause small changes in the equilibrium distribution of outcomes and all eight parameters are quantitatively important to the joint determination of outcomes such as the power-law exponent.

in labor economics has emphasized skill-biased technical change, which we interpret as an increase in A, as one reason for growth in the (economy-wide) skill premium (Acemoglu and Autor, 2011). Around the illustrative equilibrium, a 10% increase in A leaves the power-law exponent virtually unchanged and increases both the economy-wide average skill premium and the population elasticity of skill premia by about 7%-8%. Table C.2 shows that the population elasticity of skill premia did increase from 1990 to 2007. Thus, our model's mechanics are qualitatively consistent with and introduce a spatial dimension to the leading explanation for changes in the skill premium in recent decades.

4 Conclusion

The presence of skyscrapers is a defining characteristic of cities' central business districts. These attest to an intense desire to concentrate large numbers of people in a tiny geography. This extreme concentration is neither to exchange goods nor to facilitate hiring. One benefit of this concentration is that it facilitates idea exchange. While idea exchange within firms is surely of great importance, an individual firm need not pay the costs to be in a central business district for this benefit. Idea exchange outside the boundaries of the firm provides a foundation for agglomeration.

It is precisely this costly, voluntary interaction that we seek to capture in our model of idea exchange. In our theory, individuals allocate their time according to the expected gains from exchanging ideas in their city. The gains from idea exchange are greater in places where conversation partners are more numerous, devote more time to idea exchange, and are of higher ability. The highest-ability tradables producers reap the most from such learning opportunities. This simple setup, designed to overcome the "black box" critique that has inhibited research in this crucial area, nonetheless yields a rich set of spatial patterns. Larger cities are places with more idea exchanges between higher-ability participants, and they in turn exhibit higher wages, productivity, housing prices, and skill premia – all prominent features in the data.

This account suggests important implications for various aspects of urban policy that affect the city as a locus of idea exchange. Transportation policy determines the frequency with which meetings may feasibly occur. Zoning shapes not only the population density of potential participants but the venues in which idea exchanges may arise. And our model provides an account in which larger cities' higher nominal wage inequality does not imply that their lower-income residents have lower welfare than their counterparts in other locations.

Our static model characterizes the cross section of cities resulting from the complementarity between individual ability and idea-exchange opportunities. We thus provide a microfounded account of the spatial distribution of economic activity in a world in which cities are defined by the skills and ideas of those who choose to live in them. Future theoretical work might also capture the dynamics of knowledge accumulation and innovation, in light of the empirical evidence in Wang (2016), de la Roca and Puga (2017), and Carlsen, Rattsø and Stokke (2016) that larger cities' benefits to high-ability individuals accrue over time.

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A Theory

A.1 Internal urban structure

To introduce congestion costs, we follow Behrens, Duranton and Robert-Nicoud (2014) and adopt a standard, highly stylized model of cities' internal structure.[32] City residences of unit size are located on a line and center around a single point where economic activities occur, called the central business district (CBD). Individuals commute to the CBD at a cost that is denoted in units of the numeraire. The cost of commuting from a distance x is τx^γ and independent of the resident's income and occupation.

Individuals choose a residential location x to minimize the sum of land rent and commuting cost, $r(x) + \tau x^\gamma$. In equilibrium, individuals are indifferent across residential locations. In a city with population mass L, the rents fulfilling this indifference condition are $r(x) = r\left(\frac{L}{2}\right) + \tau\left(\frac{L}{2}\right)^\gamma - \tau x^\gamma$ for $0 \leq x \leq \frac{L}{2}$. Normalizing rents at the edge to zero yields $r(x) = \tau\left(\frac{L}{2}\right)^\gamma - \tau x^\gamma$.

The city's total land rent is

$$TLR = \int_{\frac{-L}{2}}^{\frac{L}{2}} r(x)dx = 2\int_0^{\frac{L}{2}} r(x)dx = 2\tau\left(\left(\frac{L}{2}\right)^{\gamma+1} - \frac{1}{\gamma+1}\left(\frac{L}{2}\right)^{\gamma+1}\right) = \frac{2\tau\gamma}{\gamma+1}\left(\frac{L}{2}\right)^{\gamma+1}$$

The city's total commuting cost is

$$TCC = 2\int_0^{\frac{L}{2}} \tau x^\gamma dx = \frac{2\tau}{\gamma+1}\left(\frac{L}{2}\right)^{\gamma+1} \equiv \theta L^{\gamma+1}$$

The city's total land rents are lump-sum redistributed equally to all city residents. Since they each receive $\frac{TLR}{L}$, every resident pays the average commuting cost, $\frac{TCC}{L} = \theta L^\gamma$, as her net urban cost. Since this urban cost is proportional to the average land rent, we say the "consumer price of housing" in city c is $p_{h,c} = \theta L_c^\gamma$.

[32] There is nothing original in this urban structure. We use notation identical to, and taken from, Behrens, Duranton and Robert-Nicoud (2014).

A.2 The number of cities

In section 2.2, we define equilibrium for a finite set of locations $\{c\}$ in which each member of the set is populated, $L_c > 0$. This section discusses properties of this set. In our model, the equilibrium number of cities is not uniquely determined by exogenous parameters. This is a standard result in models with symmetric fundamentals, and our predictions about the cross section of cities do not depend upon the number of populated locations.

While the equilibrium number of cities is not uniquely determined, the equilibrium number of cities where idea exchange occurs is bounded by the exogenous parameters governing agglomeration and congestion. In the case of equations (5) and (6), there is an upper bound on the equilibrium number of cities with positive idea exchange for a given population L because the matching process in equation (6) features scale economies and the production function in equation (5) requires a minimum value of AZ_cz for positive participation. There is a lower bound on the equilibrium number of cities because congestion costs are unboundedly increasing in L_c while Z_c has a finite upper bound. Between these bounds, there may exist multiple equilibria that have distinct numbers of heterogeneous cities.

The equilibrium number of heterogeneous cities will tend to increase with population. The upper bound increases with population because a larger population makes it feasible to achieve the minimum scale for idea exchange in a larger number of cities. Holding other parameters fixed, a higher value of L can be accommodated by the same number of larger cities or an increase in the number of cities. The intensive margin cannot entirely absorb population increases of arbitrary size, since congestion costs must eventually exceed agglomeration benefits. Increases along the extensive margin – the number of cities – could result in a greater number of distinct city sizes or a greater number of instances of a given population size. The latter possibility is constrained by the fact that locally stable equilibria can have equal-sized cities only if the agglomeration force is weak relative to the congestion force at the margin, as we prove in Proposition 3 below.

Recent related research with heterogeneous agents and symmetric fundamentals has taken distinct approaches to thinking about the inter-related problems of city formation, the number (mass) of cities, and uniqueness of equilibrium. With heterogeneous firms, Gaubert (2015) assumes that there is a uniquely optimal city size distinct to each productivity level and that cities are created by developers who make zero profits. With a continuum of cities, this yields a one-to-one mapping between firm productivities and city sizes, and so the distribution of firm productivity determines the distribution of city sizes. With heterogeneous individuals, Behrens, Duranton and Robert-Nicoud (2014) assume a continuum of cities and characterize equilibria in which each city is talent-homogeneous, which yields a differential equation that maps between individual talents and city sizes.[33] Combined with the assumption of a boundary condition, this yields the distribution of city sizes as a function of the distribution of talent.[34]

We take a different path by assuming that the number of cities is an integer. This matches the empirical fact that cities are discrete. The top ten metropolitan areas account for one-quarter of the United States population. With a continuum, any countable set would be measure zero. Similarly, our model implies that the population size of the largest city is less than the economy's total population. In Behrens, Duranton and Robert-Nicoud (2014) and Gaubert (2015), the population size of the largest city is a function only of the talent/productivity distribution, so the fact that New York is larger than Zurich is attributable to differences in the US and Swiss talent/productivity distributions, not the fact that New York City has more residents than the entirety of Switzerland.

This greater realism comes at a cost. The equilibrium number and sizes of cities are not necessarily unique. In our numerical work, we take as given the number of cities and identify equilibria consistent with this number. For example, while we present a 275-city equilibrium in section 3.4, the same parameter values are also consistent with a 270-city equilibrium. This multiplicity may simply be a feature of the world rather than something that needs to be refined away. Treating cities as discrete allows us to explain spatial variation in skill premia, whereas this form of within-city heterogeneity is absent in models with a one-to-one mapping between agents' heterogeneous characteristic and city size. We focus on results that are cross-sectional properties that do not rely on the number of cities or the uniqueness of equilibrium.

A.3 Existence of equilibrium with two heterogeneous cities

Here we characterize three sufficient conditions for $\{L, \mu(z), \bar{n}, B(\cdot), Z(\cdot), \theta, \gamma\}$ such that there exists a two-city equilibrium in which $L_1 < L_2$. The first is that idea exchange creates potential gains from agglomeration. The second is that congestion costs prevent the entire population from living in a single city. The third is that it is feasible for the entire population to live in two cities.

[33] While these authors focus on the properties of equilibria with talent-homogeneous cities, these are not the only equilibria in their model. It also yields equilibria with discrete number of cities, but in that case analytical results cannot be obtained in general.

[34] To obtain their city-size distribution that approximates Zipf's law, Behrens, Duranton and Robert-Nicoud (2014) impose the boundary condition that individuals of zero talent live in cities of zero population where they produce zero output.

To help define the three conditions, let $Z_c(x,y)$ denote the maximum value of Z_c satisfying equation (4) with $\beta_{z,c} = \beta(z, Z_c)$ when the population of tradables producers in city c is all individuals with abilities in the $[x, y]$ interval. Formally, the maximum value of Z_c satisfying that equation when $\mu(z,c) = \mu(z)\ \forall z \in [x,y]$ and $\mu(z,c) = 0\ \forall z \in [z_m, x) \cup (y, \infty)$ where z_m is given by $\bar{n} = \int_0^{z_m} \mu(z)dz$.

The *agglomeration condition* is that $\tilde{z}\left(\underline{z}, Z_c(\underline{z}, \infty)\right) > \tilde{z}\left(\underline{z}, Z_c(z_m, \underline{z})\right)$ where $\underline{z}$ is the median tradables producer, identified by $\frac{1-\bar{n}}{2} = \int_{z_m}^{\underline{z}} \mu(z)dz$. This condition says that technology $(Z(\cdot,\cdot), \bar{n})$ and population $(L, \mu(z))$ are such that the median tradables producer and every individual of greater ability would find idea exchange with one another profitable if they all colocated. In other words, there are potential gains from agglomeration via idea exchange. The *congestion condition* is that the congestion costs of locating the economy's entire population in a single city exceed the gains from idea exchange for the lowest-ability tradables producer, $\frac{\theta}{1-\bar{n}} L^{\gamma} > \tilde{z}(z_m, Z_c(z_m, \infty)) - \tilde{z}(z_m, 0)$. The *feasibility condition* is that the least-able tradables producer generates enough output to cover the congestion costs associated with two cities, $\tilde{z}(z_m, 0) \geq \frac{\theta}{1-\bar{n}} \left(\frac{L}{2}\right)^{\gamma}$.

We now characterize the economy in terms of L_1 and define a function $\Omega(L_1)$ that equals zero when the economy is in equilibrium. Choose a value $L_1 \leq \frac{1}{2}L$, which implies $L_2 = L - L_1$. Define values z_b and $z_{b,n}$ that respectively denote the highest-ability tradables and non-tradables producers in city 1 by

$$(1-\bar{n})L_1 = L \int_{z_m}^{z_b} \mu(z)dz \qquad \bar{n}L_1 = L \int_0^{z_{b,n}} \mu(z)dz.$$

Because the support of $\mu(z)$ is connected, z_b is continuous in L_1. The locational assignments

$$\mu(z,1) = \begin{cases} \mu(z) & 0 \leq z < z_{b,n} \\ 0 & z_{b,n} \leq z < z_m \\ \mu(z) & z_m \leq z < z_b \\ 0 & z_b \leq z \end{cases} \qquad \mu(z,2) = \begin{cases} 0 & 0 \leq z < z_{b,n} \\ \mu(z) & z_{b,n} \leq z < z_m \\ 0 & z_m \leq z < z_b \\ \mu(z) & z_b \leq z \end{cases}$$

satisfy equations (8), (9), and (10). These assignments imply values for $p_{h,1}, p_{h,2}, p_{n,1}, p_{n,2}, Z_1, Z_2$, and $\beta_{z,c}$ via equations (4), (7), (12), and (13), where we select the maximal values of Z_1 and Z_2 satisfying those equations. The feasibility condition ensures these assignments are possible for all L_1.

This is a spatial equilibrium if z_b is indifferent between the two cities. Utility in the smaller city minus utility in the larger city for the marginal tradables producer, z_b, is

$$\tilde{z}(z_b, Z_1(z_m, z_b)) - \bar{n}p_{n,1} - p_{h,1} - (\tilde{z}(z_b, Z_2(z_b, \infty)) - \bar{n}p_{n,2} - p_{h,2})$$

Using equations (7) and (13) and rearranging terms, we call this difference $\Omega(L_1)$.

$$\Omega(L_1) \equiv \frac{\theta}{1-\bar{n}}\left(L_2^\gamma - L_1^\gamma\right) - \tilde{z}(z_b, Z_2(z_b, \infty)) + \tilde{z}(z_b, Z_1(z_m, z_b))$$

Ω can be written solely as a function of L_1 because all the other variables are given by L_1 via $z_{b,n}$ and z_b through the locational assignments and other equilibrium conditions.

$\Omega(L_1) = 0$ is an equilibrium. $\lim_{L_1 \to 0} \Omega(L_1) > 0$ due to the congestion condition. $\Omega\left(\frac{L}{2}\right) < 0$ since equal-sized cities have equal prices and the agglomeration condition ensures that $Z_2 > Z_1$ at $L_1 = \frac{1}{2}L$. If $\Omega(L_1)$ is appropriately continuous, then there is an intermediate value $L_1 \in (0, \frac{L}{2})$ satisfying $\Omega(L_1) = 0$. We now show that any discontinuity in $\Omega(L_1)$ is a discontinuous increase, so that such an intermediate value must exist.

The first term, $\frac{\theta}{1-\bar{n}}\left(L_2^\gamma - L_1^\gamma\right)$, is obviously continuous in L_1.

The second term is continuous in L_1 if the agglomeration condition holds. Since $\beta_{z,c}$ is a function of Z_c, the equilibrium value of Z_c satisfying equation (4) is a fixed point. The agglomeration condition means that such an intersection $Z_2 = Z(\{1-\beta(z, Z_2)\}, \{L \cdot \mu(z, 2)\},)$ exists for all values $L_1 \in (0, \frac{1}{2}L)$. Since $Z(\cdot, \cdot)$ is continuous by Assumption 3, $\beta(z, Z)$ is continuous by Assumption 1 and the maximum theorem, and our chosen $\mu(z, 2)$ is continuous in L_1, $Z_2(z_b, \infty)$ is a continuous function of L_1. Since $\tilde{z}(z, Z_c)$ is continuous by Assumption 1, $\tilde{z}(z_b, Z_2(z_b, \infty))$ is continuous in L_1.

The third term is increasing in L_1. By Assumption 3 and our chosen $\mu(z, 1)$, $Z(\{1 - \beta(z, Z_1)\}, \{L \cdot \mu(z, 1)\})$ is increasing in L_1 for any value of Z_1. By Assumption 3, for any L_1 the value of $Z(\{1 - \beta_{z,1}\}, \{L \cdot \mu(z, 1)\})$ is bounded above by z_b. Thus, if $Z_1(z_m, z_b) > 0$, for $\epsilon > 0$ $Z_1(z_m, z_b + \epsilon) > Z_1(z_m, z_b)$. Therefore, $Z_1(z_m, z_b)$ is increasing in L_1. By Assumption 1, $\tilde{z}(z_b, Z_1(z_m, z_b))$ is increasing in L_1. Therefore the third term in $\Omega(L_1)$ is increasing, and any discontinuity in $\Omega(L_1)$ is a discontinuous increase.

Since $\lim_{L_1 \to 0} \Omega(L_1) > 0$, $\Omega\left(\frac{L}{2}\right) < 0$, and Ω increases at any point at which Ω is not continuous in L_1, there exists a value of L_1 such that $\Omega(L_1) = 0$. This is an equilibrium with heterogeneous cities. Since $\Omega(L_1)$ crosses zero from above, it is a stable equilibrium, as will be defined in appendix section A.4.

A.4 Stability of equilibria

This section concerns the stability of equilibria. First, we adapt the notion of stability standard in the spatial-equilibrium literature to our setting. Second, we use this definition of local stability to show that stable equilibria can have equal-sized cities only if the agglomeration force is weak relative to the congestion force at the margin. This is the standard result.

The standard definition of stability in spatial-equilibrium models considers perturbations that reallocate a small mass of individuals away from their equilibrium locations (Henderson, 1974; Krugman, 1991; Behrens, Duranton and Robert-Nicoud, 2014; Allen and Arkolakis, 2014). If individuals would obtain greater utility in their initial equilibrium locations than in their arbitrarily assigned locations, then the equilibrium is stable.

Comparing equilibrium utilities to utilities under the perturbation requires calculating each individual's utility in a location given an arbitrary population allocation. This calculation is straightforward in models in which goods and labor markets clear city-by-city, so that an individual's utility in a location can be written solely as a function of the population in that location, as in Henderson (1974) and Behrens, Duranton and Robert-Nicoud (2014). It is also feasible in models in which the goods and labor markets clear for any arbitrary population allocation through inter-city trade, as in Krugman (1991) and Allen and Arkolakis (2014). In all these models, the spatial-equilibrium outcomes are identical to the economic outcomes that arise if individuals do not choose locations and are exogenously assigned to locations with assignments that coincide with the spatial-equilibrium population allocations.

In our model, spatial-equilibrium outcomes depend on the potential movement of individuals, so we cannot compute utility under an arbitrary population allocation without introducing additional assumptions. Our theory differs from the prior literature because non-tradables prices are linked across cities in equilibrium by a no-arbitrage condition, equation (13). If we were to solve for an equilibrium with arbitrary population assignments rather than locational choice, clearing the goods and labor markets would require $p_{n,c} = \tilde{z}(z_{m,c}, Z_c)$ in each city, where $z_{m,c}$ is defined by $\int_0^{z_{m,c}} \mu(z,c)dz = \bar{n} \int_0^{\infty} \mu(z,c)dz$ for the arbitrary $\mu(z,c)$. Therefore, the prices and utilities obtained when clearing markets conditional on an arbitrary population allocation would not equal the equilibrium prices and utilities even when evaluated at the equilibrium population allocation. The inseparability of labor-market outcomes and labor mobility through this no-arbitrage condition distinguishes our model from prior work and require us to adapt the standard definition of stability to our setting.

We define a class of perturbations that maintains spatial equilibrium amongst non-tradables producers so that stability can be assessed in terms of tradables producers' incentives. Starting from an equilibrium allocation $\mu^*(z,c)$, we consider perturbations in which a small mass of tradables producers and a mass of non-tradables producers whose net supply equals the tradables producers' demand for non-tradables move from one city to another. The equilibrium allocation is stable if the tradables producers who moved would obtain higher utility in their equilibrium city than in their new location.

Definition 1 (Perturbation)**.** *A perturbation of size ϵ is a measure $d\mu(z,c)$ satisfying*

- *$\{c : d\mu(z,c) > 0\}$ is a singleton and $\{c : d\mu(z,c) < 0\}$ is a singleton, location changes are in one direction from a single city to another;*
- *$L\sum_c \int |d\mu(z,c)|dz = 2\epsilon$, individuals changing location have mass ϵ;*
- *$(1-\bar{n})\int_0^{z_m} |d\mu(z,c)|dz = \bar{n}\int_{z_m}^{\infty} |d\mu(z,c)|dz$, the movement of non-tradables producers satisfies demand from the movement of tradables producers; and*
- *$\sum_c d\mu(z,c) = 0\ \forall z$, the aggregate population of any z is unchanged.*

Definition 2 (Local stability)**.** *An equilibrium with prices $\{p^*_{h,c}, p^*_{n,c}\}$ and populations $\mu^*(z,c)$ is locally stable if there exists an $\bar{\epsilon} > 0$ such that*

$$\tilde{z}(z, Z'_{c_1}) - \frac{\theta}{1-\bar{n}} L'^{\gamma}_{c_1} \geq \tilde{z}(z, Z'_{c_2}) - \frac{\theta}{1-\bar{n}} L'^{\gamma}_{c_2}\ \forall z, c_1, c_2 : z > z_m\ \&\ d\mu(z,c_1) < 0\ \&\ d\mu(z,c_2) > 0$$

for all population allocations $\mu'(z,c) = \mu^*(z,c) + d\mu(z,c)$ in which $d\mu$ is a perturbation of size $\epsilon \leq \bar{\epsilon}$, where Z'_c, and L'_c denote the values of these variables when the population allocation is μ', individuals maximize (1) by their choices of σ and β, markets clear, and prices satisfy equations (12) and (13).

Using this definition of local stability, we obtain the standard result that locally stable equilibria can have equal-sized cities only if the marginal gains from idea exchange are small relative to marginal congestion costs.

Proposition 3 (Instability of symmetric cities)**.** *Suppose Assumptions 1 and 2 hold.*

(a) If the population elasticity of congestion costs γ is sufficiently small, two cities of equal population size with positive idea exchange cannot coexist in a locally stable equilibrium.

(b) If the production function is equation (5) and A is sufficiently large, two cities of equal population size with positive idea exchange cannot coexist in a locally stable equilibrium.

(c) *If the production function is equation (5) and* $\sup\{z : \mu(z,c) > 0 \text{ or } \mu(z,c') > 0\}$ *is sufficiently large, then cities* c *and* c' *cannot coexist with* $L_c = L_{c'}$ *and* $Z_c = Z_{c'} > 0$ *in a locally stable equilibrium.*

In a canonical model with symmetric fundamentals and homogeneous agents (i.e., Henderson 1974), net agglomeration benefits are strictly concave in city size. Stability is therefore closely connected to whether the city is smaller or larger than the utility-maximizing population size. In our model, net agglomeration benefits are not necessarily concave, but stability is still defined in terms of the relative strength of agglomeration and congestion forces at the margin. As an example, with a uniform ability distribution and the functional forms in equations (5) and (6), agglomeration benefits are bounded from above for a given value of A, while the congestion costs in equation (7) are a convex function of population size. Thus, two identical cities of sufficient population size could be a stable equilibrium because their size generates a sufficiently large marginal congestion cost. As parts (a) and (b) of Proposition 3 report, the comparison of marginal congestion costs and marginal agglomeration benefits is governed by γ and A.

In distinction from the canonical model, our model's heterogeneity of abilities can make symmetric equilibria unstable. While all tradables producers face the same congestion costs, their benefits from idea exchange are heterogeneous, as higher-ability individuals benefit more from better opportunities. When these differences in benefits are unbounded from above, as in part (c) of Proposition 3, a symmetric equilibrium cannot be stable. Individuals of arbitrarily high ability have arbitrarily high willingness to pay for a better idea-exchange environment, so any perturbation generating a difference in idea-exchange benefits breaks the symmetric arrangement.

Finally, our sufficient conditions for existence of a two-city equilibrium with heterogeneous cities are also sufficient for it to be locally stable.

Proposition 4 (Stability of two heterogeneous cities)**.** *Suppose Assumptions 1, 2, and 3 hold. If the agglomeration, congestion, and feasibility conditions defined in appendix section A.3 hold, there exists a locally stable equilibrium with two heterogeneous cities.*

A.5 Properties of production functions

A.5.1 Assumptions on $B(1-\beta, z, Z_c)$ that imply Assumption 2

Assumption 2 is written in terms of the function $\tilde{z}(z, Z_c)$, which depends on an optimizing individual's choice of $1-\beta$. Assumption $2'$ states conditions on the production function for tradables $B(1-\beta, z, Z_c)$ sufficient for Assumption 2 to be true.

Assumption 2′. *$B(1-\beta, z, Z)$ is supermodular in $(1-\beta, z, Z)$ and if $\beta < 1$, $B(1-\beta, z, Z_c)$ is strictly supermodular in (z, Z_c).*

Assumption 2′ implies Assumption 2 by Theorems 2.7.6 and 2.7.7 of Topkis (1998).

While sufficient, Assumption 2′ is not necessary. The production function in equation (5) satisfies Assumption 2 but not Assumption 2′.

A.5.2 Examples of production functions satisfying Condition 1

What are examples of production functions satisfying Condition 1? The main text focuses on the case of equation (5). Here, we define a class of $B(1-\beta, z, Z_c)$ functions that satisfy Condition 1 because their ability elasticity of tradable output is constant and therefore trivially non-decreasing in z and Z_c.

Suppose that $B(1-\beta, z, Z_c)$ can be written as $B(1-\beta, z, Z_c) = z\mathbb{B}(1-\beta, Z_c)$. Note that the output-maximizing choice of β is independent of ability z for this class of production functions. Denoting this optimal choice $\beta(Z_c)$, tradables output is $\tilde{z}(z, Z_c) = z\mathbb{B}(1-\beta(Z_c), Z_c)$. Thus, the ability elasticity of tradable output is $\frac{\partial \ln \tilde{z}(z,Z_c)}{\partial \ln z} = 1$ and the production function satisfies Condition 1.

We now identify conditions such that $B(1-\beta, z, Z_c) = z\mathbb{B}(1-\beta, Z_c)$ satisfies Assumptions 1 and 2. If $\mathbb{B}(1-\beta, Z_c)$ is continuous, strictly positive, strictly concave in $1-\beta$, and increasing in Z_c, if $\mathbb{B}(0, Z_c) = 1\ \forall Z_c$, and if $\mathbb{B}(1-\beta, 0) = \beta$, then the production function satisfies Assumption 1. If $\mathbb{B}(1-\beta, Z_c)$ is continuously differentiable, increasing in Z_c, and strictly increasing in Z_c when $\beta < 1$, then the production function satisfies Assumption 2. If $\mathbb{B}(1-\beta, Z_c)$ is supermodular, then the production function satisfies Assumption 2′.

A.6 Proofs

This appendix contains proofs of our main results.

A.6.1 Special case

The special case described in equations (5) and (6) satisfies Assumptions 1-3. The $B(1-\beta, z, Z_c)$ specified in equation (5) satisfies Assumption 1. To confirm that it satisfies Assumption 2, we explicitly derive $\tilde{z}(z, Z_c)$ and $\frac{\partial^2}{\partial z \partial Z_c}\tilde{z}(z, Z_c)$ by solving for $1-\beta(z, Z_c)$:

$$1-\beta(z, Z_c) = \begin{cases} 1-\frac{1}{2}\frac{AZ_c z+1}{AZ_c z} & \text{if } AZ_c z \geq 1 \\ 0 & \text{otherwise} \end{cases}$$

The resulting $\tilde{z}(z, Z_c)$ and $\frac{\partial^2 \tilde{z}(z,Z_c)}{\partial z \partial Z_c}$ are

$$\tilde{z}(z, Z_c) = \begin{cases} \frac{1}{4AZ_c}\left(AZ_c z+1\right)^2 & \text{if } AZ_c z \geq 1 \\ z & \text{otherwise} \end{cases} \qquad \frac{\partial^2}{\partial z \partial Z_c}\tilde{z}(z, Z_c) = \begin{cases} \frac{Az}{2} & \text{if } AZ_c z \geq 1 \\ 0 & \text{otherwise} \end{cases}$$

The twice-differentiable function $\tilde{z}(z, Z_c)$ is supermodular if and only if $\frac{\partial^2}{\partial z \partial Z_c}\tilde{z}(z, Z_c) \geq 0$ (Topkis, 1998). It is thus evident that this $\tilde{z}(z, Z_c)$ satisfies Assumption 2.

The function $Z(\{(1-\beta_{z,c})\}, \{L \cdot \mu(z, c)\})$ specified in equation (6) satisfies Assumption 3. $Z(\cdot, \cdot) = 0$ if $M_c = 0$. It is continuous. It is bounded above because $\bar{z}_c \leq \sup\{z : 1-\beta_{z,c} > 0, \mu(z, c) > 0\}$. If $\{(1-\beta_{z,c})\mu(z, c)\}$ stochastically dominates $\{(1-\beta_{z,c'})\mu(z, c')\}$, then $\bar{z}_c \geq \bar{z}_{c'}$. If $\bar{z}_c \geq \bar{z}_{c'}$ and $M_c > M_{c'}$, then $Z(\{1-\beta_{z,c}\}, \{L \cdot \mu(z, c)\}) > Z(\{1-\beta_{z,c'}\}, \{L \cdot \mu(z, c')\})$, satisfying Assumption 3.

The $B(1-\beta, z, Z_c)$ specified in equation (5) satisfies Condition 1. Using the expression for $\tilde{z}(z, Z_c)$ above, we obtain the following ability elasticity of tradable output:

$$\frac{\partial \ln \tilde{z}\,(z, Z_c)}{\partial \ln z} = \begin{cases} \frac{2AZ_c z}{AZ_c z+1} & \text{if } AZ_c z \geq 1 \\ 0 & \text{otherwise} \end{cases}.$$

This is non-decreasing in Z_c and z.

A.6.2 Lemma 1: Comparative advantage

Lemma 1: Suppose that Assumption 1 holds. There is an ability level z_m such that individuals of greater ability produce tradables and individuals of lesser ability produce non-tradables.

$$\sigma(z) = \begin{cases} t & \text{if } z > z_m \\ n & \text{if } z < z_m \end{cases}$$

Proof. First, we can identify an ability level dividing tradables and non-tradables producers in each city. Denote it $z_{m,c}$. Consider city c with price $p_{n,c} \geq 0$ and idea-exchange opportunities Z_c. If $p_{n,c} > \tilde{z}(\sup(z), Z_c)$, then $z_{m,c} = \sup(z)$ and all individuals in c produce non-tradables. If $p_{n,c} < \tilde{z}(\inf(z), Z_c)$, then $z_{m,c} = \inf(z)$ and all individuals in c produce tradables. Otherwise, since tradables output $\tilde{z}(z, Z_c)$ is strictly increasing and continuous in z by Assumption 1, there is a unique value $z_{m,c}$ such that $p_{n,c} = \tilde{z}(z_{m,c}, Z_c)$. Individuals of ability $z < z_{m,c}$ produce non-tradables and individuals of ability $z > z_{m,c}$ produce tradables in city c.

Second, there is an ability level dividing tradables and non-tradables producers across all locations, which we denote z_m. Individuals of ability $z \leq z_m$ produce non-tradables and individuals of ability $z \geq z_m$ produce tradables. Suppose not. If there is not an ability level dividing tradables and non-tradables production across all locations, there are abilities z', z'' such that, without loss of generality, $z' < z''$ and z' produces tradables in city c' and z'' produces non-tradables in city c''. The former's choice means $\tilde{z}(z', Z_{c'}) - p_{n,c'}\bar{n} - p_{h,c'} \geq (1-\bar{n})p_{n,c''} - p_{h,c''}$. The latter's choice means $(1-\bar{n})p_{n,c''} - p_{h,c''} \geq \tilde{z}(z'', Z_{c'}) - p_{n,c'}\bar{n} - p_{h,c'}$. Together, these imply $\tilde{z}(z', Z_{c'}) \geq \tilde{z}(z'', Z_{c'})$, contrary to the fact that $\tilde{z}(z, Z_c)$ is strictly increasing in z by Assumption 1. □

A.6.3 Lemma 2: Spatial sorting

Lemma 2: Suppose that Assumptions 1 and 2 hold. For $z > z' > z_m$, if $\mu(z, c) > 0$, $\mu(z', c') > 0$, $\beta(z, Z_c) < 1$, and $\beta(z', Z_{c'}) < 1$, then $Z_c \geq Z_{c'}$.

Proof. By Assumption 1, $\beta(z, Z_c) < 1$ implies $(z, Z_c) \in \otimes$ and $\beta(z', Z_{c'}) < 1$ implies $(z', Z_{c'}) \in \otimes$.
$\mu(z, c) > 0 \Rightarrow \tilde{z}(z, Z_c) - \bar{n}p_{n,c} - p_{h,c} \geq \tilde{z}(z, Z_{c'}) - \bar{n}p_{n,c'} - p_{h,c'}$
$\mu(z', c') > 0 \Rightarrow \tilde{z}(z', Z_{c'}) - \bar{n}p_{n,c'} - p_{h,c'} \geq \tilde{z}(z', Z_c) - \bar{n}p_{n,c} - p_{h,c}$
Therefore $\tilde{z}(z, Z_c) + \tilde{z}(z', Z_{c'}) \geq \tilde{z}(z, Z_{c'}) + \tilde{z}(z', Z_c)$. By Assumption 2, $\tilde{z}$ is strictly supermodular on $\otimes$, so this inequality requires $Z_c \geq Z_{c'}$. □

A.6.4 Proposition 1: Heterogeneous cities' characteristics

Proposition 1: Suppose that Assumptions 1 and 2 hold. In any equilibrium, a larger city has higher housing prices, higher non-tradables prices, a better idea-exchange environment, and higher-ability tradables producers. If $L_c > L_{c'}$ in equilibrium, then $p_{h,c} > p_{h,c'}$, $p_{n,c} > p_{n,c'}$, $Z_c > Z_{c'}$, and $z > z' > z_m \Rightarrow \mu(z, c)\mu(z', c') \geq \mu(z, c')\mu(z', c) = 0$.

Proof.

- Equation (7) says that $L_c > L_{c'} \iff p_{h,c} > p_{h,c'}$.
- Equation (13) says that $p_{h,c} > p_{h,c'} \iff p_{n,c} > p_{n,c'}$

- If $p_{h,c} > p_{h,c'}$ and $p_{n,c} > p_{n,c'}$, then $Z_c > Z_{c'}$. Suppose not. Then, since $\tilde{z}(z, Z_c)$ is increasing in Z_c by Assumption 1, $\tilde{z}(z, Z_c) - \bar{n}p_{n,c} - p_{h,c} < \tilde{z}(z, Z_{c'}) - \bar{n}p_{n,c'} - p_{h,c'}$ $\forall z > z_m$ and $\mu(z, c) = 0$ $\forall z > z_m$. Then $L_c = 0$ by equations (9) and (10), contrary to the premise that $L_c > L_{c'}$.
- If $z > z' > z_m$ and $L_c > L_{c'}$, then $\mu(z, c')\mu(z', c) = 0$. Suppose not, such that $\mu(z, c')\mu(z', c) > 0$. By equations (1) and (2) and Assumption 2, if z' strictly prefers c to c' then z strictly prefers c to c'. Since $Z_c > Z_{c'}$, $\mu(z, c')\mu(z', c) > 0$ is possible only if z and z' are both indifferent between c and c'. Since $p_{n,c} > p_{n,c'}$ and $p_{h,c} > p_{h,c'}$, such indifference implies that $(z, Z_c) \in \otimes$, $(z', Z_c) \in \otimes$ and $\tilde{z}(z, Z_c) - \tilde{z}(z', Z_c) = \tilde{z}(z, Z_{c'}) - \tilde{z}(z', Z_{c'})$. By continuity of $\tilde{z}(z, Z_c)$, there exists a $Z'' \in (Z_{c'}, Z_c)$ such that $(z, Z'') \in \otimes$ and $(z', Z'') \in \otimes$. By Assumption 2, the strict supermodularity of $\tilde{z}$ on $\otimes$, $\tilde{z}(z, Z_c) - \tilde{z}(z', Z_c) > \tilde{z}(z, Z'') - \tilde{z}(z', Z'')$. By Assumption 2, the supermodularity of $\tilde{z}$, $\tilde{z}(z, Z'') - \tilde{z}(z', Z'') \geq \tilde{z}(z, Z_{c'}) - \tilde{z}(z', Z_{c'})$. Thus $\tilde{z}(z, Z_c) - \tilde{z}(z', Z_c) > \tilde{z}(z, Z_{c'}) - \tilde{z}(z', Z_{c'})$, so z and z' cannot both be indifferent between c and c'. $\mu(z, c')\mu(z', c) = 0$.

□

A.6.5 Proposition 2: Skill premia

Proposition 2: Suppose that Assumptions 1 and 2 hold. In an equilibrium in which the smallest city has population L_1 and the second-smallest city has population $L_2 > L_1$,

1. if the ability distribution is decreasing, $\mu'(z) \leq 0$, $\tilde{z}(z, Z_c)$ is log-convex in z, and $\tilde{z}(z, Z_c)$ is log-supermodular, then $\frac{\bar{w}_2}{p_{n,2}} > \frac{\bar{w}_1}{p_{n,1}}$;
2. if the ability distribution is Pareto, $\mu(z) \propto z^{-k-1}$ for $z \geq z_{\min}$ and $k > 0$, and the production function satisfies Condition 1, then $\frac{\bar{w}_2}{p_{n,2}} > \frac{\bar{w}_1}{p_{n,1}}$;
3. if the ability distribution is uniform, $z \sim U(z_{\min}, z_{\max})$, the production function satisfies Condition 1, and $\frac{L_2 - L_1}{L_1^2} > \frac{1}{L} \frac{(1-\bar{n})(z_{\max} - z_{\min})}{z_{\min} + \bar{n}(z_{\max} - z_{\min})}$, then $\frac{\bar{w}_2}{p_{n,2}} > \frac{\bar{w}_1}{p_{n,1}}$.

Proof. By $L_2 > L_1$ and Proposition 1, the abilities of tradables producers in the two cities are intervals, which we can denote by (z_m, z_b) and $(z_b, \hat{z})$. The skill premium is higher in city 2 when $\frac{\bar{w}_2}{p_{n,2}} > \frac{\bar{w}_1}{p_{n,1}}$, which can rewritten as

$$\frac{1}{L_2 p_{n,2}} \int_{z_b}^{\hat{z}} \tilde{z}(z, Z_2)\mu(z) dz > \frac{1}{L_1 p_{n,1}} \int_{z_m}^{z_b} \tilde{z}(z, Z_1)\mu(z) dz.$$

We now obtain this condition in four steps.

1. Implicitly define the function $f(z)$ by a differential equation, $f'(z) = \frac{L_2}{L_1}\frac{\mu(z)}{\mu(f(z))}$, with the endpoint $f(z_m) = z_b$.

2. $\tilde{z}(f(z_m), Z_2) > \frac{p_{n,2}}{p_{n,1}}\tilde{z}(z_m, Z_1)$ because $\tilde{z}(z_m, Z_1) = p_{n,1}$ and $\tilde{z}(z_b, Z_2) > p_{n,2}$.

3. If $\frac{\partial \ln(\tilde{z}(x,Z_2))}{\partial x}|_{x=f(z)} f'(z) \geq \frac{\partial \ln(\tilde{z}(z,Z_1))}{\partial z}$ $\forall z \in (z_m, z_b)$, then $\tilde{z}(f(z), Z_2) > \frac{p_{n,2}}{p_{n,1}}\tilde{z}(z, Z_1)$ $\forall z \in (z_m, z_b)$.

4. Multiplying each side of $\tilde{z}(f(z), Z_2) > \frac{p_{n,2}}{p_{n,1}}\tilde{z}(z, Z_1)$ by $\mu(z)$ and integrating from z_m to z_b yields the desired result after a change of variables:

$$\int_{z_m}^{z_b} \tilde{z}(f(z), Z_2)\,\mu(z)dz > \frac{p_{n,2}}{p_{n,1}}\int_{z_m}^{z_b} \tilde{z}(z, Z_1)\,\mu(z)dz$$
$$\iff \int_{z_m}^{z_b} \tilde{z}(f(z), Z_2)\, f'(z)\mu(f(z))\frac{L_1}{L_2}dz > \frac{p_{n,2}}{p_{n,1}}\int_{z_m}^{z_b} \tilde{z}(z, Z_1)\,\mu(z)dz$$
$$\iff \frac{1}{L_2 p_{n,2}}\int_{z_b}^{\hat{z}} \tilde{z}(z, Z_2)\mu(z)dz > \frac{1}{L_1 p_{n,1}}\int_{z_m}^{z_b} \tilde{z}(z, Z_1)\,\mu(z)dz$$

The sufficient condition in step three, $\frac{\partial \ln(\tilde{z}(x,Z_2))}{\partial x}|_{x=f(z)} f'(z) \geq \frac{\partial \ln(\tilde{z}(z,Z_1))}{\partial z}$ $\forall z \in (z_m, z_b)$, depends jointly on the production function $B(1-\beta, z, Z_c)$, the ability distribution $\mu(z)$, and endogenous equilibrium outcomes. Knowing only $Z_2 > Z_1$, $L_2 > L_1$, the following joint assumptions on $\tilde{z}(z, Z)$ and $\mu(z)$ are sufficient to yield the result:

1. Suppose the ability distribution is decreasing, $\mu'(z) \leq 0$, $\tilde{z}(z, Z_c)$ is log-supermodular, and $\tilde{z}(z, Z_c)$ is log-convex in z. If $\mu'(z) \leq 0$, then $f'(z) \geq 1$. If $\tilde{z}(z, Z_c)$ is log-supermodular in (z, Z_c) and log-convex in z, then $\frac{\partial \ln(\tilde{z}(x,Z_2))}{\partial x} \geq \frac{\partial \ln(\tilde{z}(z,Z_1))}{\partial z}$ for any $x \geq z$, including $x = f(z)$. Thus, $\frac{\partial \ln(\tilde{z}(x,Z_2))}{\partial x}|_{x=f(z)} f'(z) \geq \frac{\partial \ln(\tilde{z}(z,Z_1))}{\partial z}$ $\forall z \in (z_m, z_b)$.

2. The condition in step three, $\frac{\partial \ln(\tilde{z}(x,Z_2))}{\partial x}|_{x=f(z)} f'(z) \geq \frac{\partial \ln(\tilde{z}(z,Z_1))}{\partial z}$, can be written as

$$\frac{\partial \ln(\tilde{z}(x, Z_2))}{\partial \ln x}\bigg|_{x=f(z)} \frac{L_2}{L_1}\frac{\mu(z)}{\mu(f(z))}\frac{z}{f(z)} \geq \frac{\partial \ln(\tilde{z}(z, Z_1))}{\partial \ln z}.$$

   If the ability distribution is Pareto, $\mu(z) \propto z^{-k-1}$ for $z \geq z_{\min}$ and $k > 0$, then $\frac{\mu(z)}{\mu(f(z))}\frac{z}{f(z)} = \left(\frac{f(z)}{z}\right)^k$. The inequality is true because $Z_2 > Z_1$, $L_2 > L_1$, $f(z) > z$, and by Condition 1 the ability elasticity of tradable output is non-decreasing in z and Z_c.

3. Suppose the ability distribution is uniform, $z \sim U(z_{\min}, z_{\max})$, the production function satisfies Condition 1, and $\frac{L_2 - L_1}{L_1^2} > \frac{1}{L}\frac{(1-\bar{n})(z_{\max} - z_{\min})}{z_{\min} + \bar{n}(z_{\max} - z_{\min})}$. In this case, the condition in step

three can be written as

$$\frac{\partial \ln(\tilde{z}(x, Z_2))}{\partial \ln x}\Big|_{x=f(z)} \frac{L_2}{L_1}\frac{z}{f(z)} \geq \frac{\partial \ln(\tilde{z}(z, Z_1))}{\partial \ln z}.$$

Since $f(z) = z_b + \frac{L_2}{L_1}(z - z_m)$, $\frac{L_2}{L_1}\frac{z}{f(z)} \geq 1 \iff \frac{L_2}{L_1} z_m \geq z_b$. $\frac{L_2 - L_1}{L_1^2} > \frac{1}{L}\frac{(1-\bar{n})(z_{\max} - z_{\min})}{z_{\min} + \bar{n}(z_{\max} - z_{\min})} = \frac{1}{L}\frac{z_{\max} - z_m}{z_m}$ implies that

$$\frac{L_2}{L_1} z_m - z_b = \frac{L_2 - L_1}{L_1} z_m - \frac{L_1}{L}(z_{\max} - z_m) > 0.$$

This inequality and the fact that the ability elasticity of tradable output is non-decreasing in z and Z_c are sufficient for the inequality in step three to be true.

□

A.6.6 Proposition 3: Instability of symmetric equilibria

Proof. Suppose $L_1 = L_2$ and $Z_1 = Z_2 > 0$. Without loss of generality, consider perturbations of size $\epsilon \leq \bar{\epsilon}$ moving individuals from city 1 to city 2. By Assumption 2, the highest-ability producers have the most to gain from a move and it is sufficient to consider perturbations of size ϵ in which all tradables producers in the range $[z^*(\epsilon), \infty]$ move from city 1 to city 2; these are perturbations $d\mu$ that satisfy $L \int_{z^*(\epsilon)}^{\infty} \mu(z, 1) dz = (1 - \bar{n})\epsilon$ and $d\mu(z, 2) = -d\mu(z, 1) = \mu(z, 1)\ \forall z \geq z^*(\epsilon)$. Since an interval of the highest-ability tradables producers, accompanied by the appropriate mass of non-tradables producers, moves from city 1 to city 2, $Z'_2 > Z'_1$ and $L'_2 > L'_1$ with $L'_2 = L_1 + \epsilon$ and $L'_1 = L_1 - \epsilon$. Denote $\hat{z} = \sup\{z : \mu(z, 1) > 0\}$. The equilibrium is stable with respect to this perturbation only if

$$\tilde{z}(\hat{z}, Z'_2) - \tilde{z}(\hat{z}, Z'_1) \leq \frac{\theta}{1 - \bar{n}}\left((L_1 + \epsilon)^\gamma - (L_1 - \epsilon)^\gamma\right)$$

By Assumptions 1 and 2, $Z'_2 > Z'_1$, and $Z'_2 > 0$, the left side is strictly greater than zero. The right side is arbitrarily small if γ is arbitrarily small. This proves part (a). If the production function is that of equation (5), the left side is increasing without bound in A and z. This proves parts (b) and (c). This inequality is violated if A or $\hat{z}$ is sufficiently high relative to γ. □

A.6.7 Proposition 4: Stability of two heterogeneous cities

Proof. Appendix section A.3 shows that these three conditions are sufficient for the existence of an equilibrium with two cities in which $L_1 < L_2$ and $\Omega(L_1)$ crosses zero from above. Amongst tradables producers in city 1, those with the most to gain by moving to city 2 are those of the highest ability. Amongst tradables producers in city 2, those with the most to gain by moving to city 1 are those of the lowest ability. It is therefore sufficient to consider perturbations that are changes in z_b and consummate changes in $z_{b,n}$ as defined in appendix section A.3. Since $\Omega(L_1)$ crosses zero from above, this equilibrium is stable. □

B Numerical results

This appendix reports numerical results that complement the analytical results in Proposition 2. In all our numerical work, we use the functional forms for $B(\cdot)$ and $Z(\cdot)$ given by equations (5) and (6). Section B.1 shows that the sufficient condition on the equilibrium size of the smallest city in the uniform-ability case of Proposition 2 is typically true in two-city equilibria and that larger cities exhibit lower skill premia only when the skill premia are unrealistically large. Sections B.2 and B.3 extend our results for uniform and Pareto ability distributions, respectively, to greater numbers of cities. The overwhelming pattern is that larger cities have higher skill premia.

B.1 Uniform ability distribution and two cities

In the case of the uniform ability distribution, the sufficient condition in Proposition 2 is written in terms of exogenous parameters and the two cities' equilibrium population sizes, L_1 and L_2. For the larger city's skill premium to be lower, it must be the case that $\frac{L_2-L_1}{L_1^2} < \frac{1}{L}\frac{z_{\max}-z_m}{z_m}$. This will occur when L_1 is sufficiently large. However, we also know that the relative compensation effect on the right-hand side of inequality (14) approaches zero as $L_1 \to L_2$, so it is clear that this sufficient condition is not necessary for the larger city to have a higher skill premium. An equilibrium in which the larger city has a lower skill premium must exhibit some intermediate value of L_1.

To examine whether such an equilibrium exists and to more generally characterize the properties of two-city equilibria when the ability distribution is uniform, we compute equilibria for a range of parameter values. Our choice of the parameter values is admittedly arbitrary, but the results are sufficiently stark that they are suggestive of broader patterns.

We examine vectors of the form $[A, \bar{n}, \theta, \gamma, L, \nu, z_{\min}, z_{\max}]$ obtained by combining the following possible parameter values: $A \in [1, 2, 3, 4, 5, 10], \bar{n} \in [.1, .2, .3, .4, .5], \theta \in [.1, .5, 1, 2, 5], \gamma \in [.01, .1, .5, 1, 5], L \in [2, 6, 10, 15, 20, 40], \nu \in [1, 5, 10, 25, 50], z_{\min} \in [0, 1, 2.5, 5, 10, 25, 50], z_{\max} - z_{\min} \in [1, 5, 10, 25, 50]$. The Cartesian product of these sets has 787,500 elements. For each parameter vector, we seek values of L_1 and L_2, with $L_1 < L_2 = L - L_1$, constituting an equilibrium as defined in section 2.2.

A large number of these 787,500 parameter combinations are inconsistent with the existence of any two-city equilibrium. We nonetheless explore these parts of the parameter space in order to identify exceptions to the pattern predicted by Proposition 2. For example, we find that a two-city equilibrium often does not exist when $z_{\max} - z_{\min}$ is large, but these parameter combinations also are more likely to violate the sufficient condition in Proposition 2 and yield an equilibrium in which the larger city has a smaller skill premium. The cost of exploring the extremes of the parameter space is that sometimes no equilibrium is feasible and sometimes the entire population lives in a single city.

In some cases, existence of an equilibrium can be ruled out prior to computing potential solutions. Consider two conditions that are necessary for a two-city equilibrium to exist. A modest feasibility condition is $\tilde{z}(\underline{z}, z_{\max}) \geq \theta\,(L/2)^{\gamma}$, which requires that the greatest conceivable tradables output for the median tradables producer be greater than the lowest conceivable housing cost in the larger city. If this failed, every conceivable two-city population allocation would be infeasible. A modest agglomeration condition is $A \cdot z_{\max} \cdot \underline{z} > 1$, which requires that the median tradables producer would find idea exchange with the most able producer profitable. If this failed, there would be no benefits to agglomeration. Of the 787,500 parameter combinations, 94,903 fail the former, 985 fail the latter, and 3,015 fail both modest necessary conditions.

An equilibrium with two heterogeneous cities exists for 58,005 of the parameter combinations. For the parameter vectors that do not yield a two-city equilibrium, this is overwhelmingly due to the entire population agglomerating in a single city (598,197 combinations). Since the necessary conditions described in the previous paragraph are very modest, there are also a number of parameter combinations for which agglomeration is not realized in equilibrium (644) or is insufficient to cover housing costs (31,226).

Of the 58,005 parameter combinations yielding two-city equilibria, only 159 (0.3%) yield equilibria in which the larger city has a lower skill premium. 46,055 of the equilibria satisfy the sufficient condition of Proposition 2 case 3, and 11,791 of the equilibria not satisfying that sufficient condition nonetheless have a higher skill premium in the more populous city. Table B.1 reports the fraction of equilibria in which the larger city has a lower skill premium for each parameter value.

The equilibria in which the larger city has a lower skill premium exhibit implausibly large skill premia. Large skill premia make the relative compensation effect large. Across the 159 equilibria in which the larger city has a lower skill premium, the mean skill premium in the smaller city is 563%. By contrast, the 95$^{\text{th}}$ percentile of $\frac{\bar{w}_1}{p_{n,1}}$ for equilibria with increasing skill premia is only 195%. Recall that, in the data, the college wage premium varies across metropolitan areas in the range of 47% to 71%.

Table B.1: Share of equilibria with decreasing skill premia, by parameter

A		$\bar{n}$		θ		γ		L		ν		$z_{\min}$		$z_{\max} - z_{\min}$	
1	.0017	0.1	0.0134	0.1	0.0038	0.01	0	2	0.0013	1	0.0036	0	0.0096	1	0
2	.0016	0.2	0	0.5	0.0028	0.1	0	6	0.005	5	0.003	1	0.0057	5	0.0003
3	.0035	0.3	0	1	0.0026	0.5	0	10	0.0043	10	0.0027	2.5	0.0019	10	0.001
4	.0034	0.4	0	2	0.0021	1	0	15	0.002	25	0.0025	5	0	25	0.0064
5	.0037	0.5	0	5	0.0024	5	0.0046	20	0	50	0.0023	10	0	50	0.0106
10	.0028							40	0			25	0		
												50	0		

NOTES: This table summarizes the parameter values yielding two-city equilibria in which the larger city has a lower skill premium. For each pair of columns, the first column lists the value of the parameter and the second column lists the share of the 58,005 equilibria in which the premium-size relationship is negative. Since the latter occurs in only 159 cases, these shares are typically less than 1% and often zero.

The parameter values yielding equilibria in which the larger city has a lower skill premium can be understand in terms of facilitating large equilibrium values of $\frac{\bar{w}_1}{p_{n,1}}$. When $z_{\max} - z_{\min}$ is larger and $z_{\min}$ and $\bar{n}$ are smaller, there is greater heterogeneity of ability within tradables producers, raising the value of $\frac{\bar{w}_1}{p_{n,1}}$. Since greater heterogeneity in these abilities generates larger differences in idea-exchange environments, two-city equilibria only exist when these greater agglomeration benefits are offset by higher congestion costs, governed by γ. We obtain a lower skill premium in the larger city only when γ is 5. This is a very large population elasticity of congestion costs. Empirical work typically estimates a value of γ below 0.1; Combes, Duranton and Gobillon (2012) report an estimate of 0.041. Empirically plausible values of the congestion-cost elasticity yield zero cases of non-increasing skill premia.

Thus, our examination of a large set of parameter vectors suggests that the larger city typically has a higher skill premium in two-city equilibria with a uniform ability distribution. The sufficient condition in Proposition 2 holds for most two-city equilibria, and the larger city almost always has a higher skill premium. Deviations from the predicted pattern are produced only by assuming empirically implausible values of γ that generate skill premia much higher than those observed in the data.

B.2 Uniform ability distribution and more than two cities

We now extend the uniform-ability-distribution results to more than two heterogeneous cities. We examine the same values of $[A, \bar{n}, \theta, \gamma, \nu, z_{\min}, z_{\max}]$ examined in the previous section. The population L is proportional to the number of cities under consideration (so as to facilitate existence of these equilibria). That is, $L \in C \times [1, 3, 5, 7.5, 10, 20]$, where C is the number of cities and the previous section considered $C = 2$. There are therefore, again, 787,500 parameter combinations for each C. We solve for equilibria in which $L_1 < L_2 < \cdots < L_C$.

The results for equibrilia with three to seven cities, summarized in Table B.2, are consistent with those found for two cities. First, in the vast majority (more than 99.5%) of equilibria, larger cities have higher skill premia. Second, the correlation between population size and skill premia is frequently positive even when the relationship isn't monotone. As in the two-city case, the exceptions to these patterns occur when equilibria exhibit very large values of $\frac{\bar{w}_1}{p_{n,1}}$. The 95$^{\text{th}}$ percentile of $\frac{\bar{w}_1}{p_{n,1}}$ in equilibria with monotonically increasing premia lies below the 25$^{\text{th}}$ percentile for equilibria with non-monotone premia. These non-monotone equilibria with very high skill premia can arise only when $z_{\max} - z_{\min}$ and γ are large and $z_{\min}$ and $\bar{n}$ are small. For this set of parameter combinations, the value of $\frac{\bar{w}_1}{p_{n,1}}$ is lower in equilibria with larger numbers of cities. Thus, all equilibria with six or seven cities exhibit monotonically increasing skill premia, and all equilibria with four or more cities exhibit positive premia-population correlations.

Table B.2: Uniform-ability equilibria, 2 to 7 cities

Number of cities	Number of equilibria	Share of non-monotone premia	Share of $corr(L_c, \frac{\bar{w}_c}{p_{n,c}}) < 0$	Percentiles of $\bar{w}_1/p_{n,1}$: monotone premia, 95$^{\text{th}}$	Percentiles of $\bar{w}_1/p_{n,1}$: non-monotone premia, 25$^{\text{th}}$	Maximal $\bar{n}$	Maximal $z_{\min}$	Minimal $z_{\max} - z_{\min}$	Minimal γ
2	58005	.0027	.0027	1.95	5.02	0.1	2.5	5	5
3	43367	.0157	.0006	1.46	1.53	0.2	2.5	1	5
4	38300	.0056	0	1.32	1.79	0.1	2.5	5	5
5	33305	.0005	0	1.21	1.41	0.1	0	5	5
6	30903	0	0	1.15					
7	26213	0	0	1.09					

NOTES: This table summarizes the existence and properties of equilibria with the number of cities listed in the first column. The second column lists the number of equilibria that exist for uniformly distributed abilities and the 787,500 parameter combinations described in the text. The third column lists the share of those equilibria that exhibit skill premia that are not monotone in city population size. The fourth column lists the share of equilibria that exhibit negative premia-size correlations. The fifth and sixth columns list the 95$^{\text{th}}$ and 25$^{\text{th}}$ percentiles of $\bar{w}_1/p_{n,1}$ for equilibria with monotonically increasing and non-monotone skill premia, respectively. The seventh through tenth columns list the maximal values of $\bar{n}$ and $z_{\min}$ and minimal values of $z_{\max} - z_{\min}$ and γ that yield equilibria with non-monotone skill premia.

Since the computational burden increases with the number of cities, we have also examined tens of thousands of parameter combinations for the cases of 10-, 20-, and 30-city equilibria, rather than hundreds of thousands. All these equilibria exhibit monotonically increasing skill premia.

In short, for uniformly distributed abilities and over a wide range of parameter values, equilibria typically exhibit monotonically increasing skill premia. In fact, equilibria with larger numbers of heterogeneous cities yield more consistently monotone premia-size relationships than those obtained for the two-city case. The exceptions involve very large relative compensation effects due to very large skill premia.

B.3 Pareto ability distribution and more than two cities

This section extends the analytical result of Proposition 2 for Pareto-distributed abilities to greater numbers of cities. We compute equilibria for a wide range of parameter values to examine their properties. We find that the skill premium is monotonically increasing with city size in every case.

We compute equilibria for vectors of the form $[A, \bar{n}, \theta, \gamma, L, \nu, z_{\min}, k]$, where k is the shape parameter of the Pareto distribution. We examine parameter vectors obtained by combining the following possible values: $A \in [1, 3, 5, 10]$, $\bar{n} \in [.1, .2, .3, .4, .5]$, $\theta \in [.1, .5, 1, 2, 5]$, $\gamma \in [.01, .1, .5, 1, 5]$, $L \in C \times [1, 3, 5, 10]$, $\nu \in [1, 5, 10, 25, 50]$, $k\left(z_{\min}\right)^k \in [1, 5, 10, 50]$, $k \in [2.1, 3, 5, 10, 50]$. The Cartesian product yields 200,000 parameter combinations. We solve for equilibria in which $L_1 < L_2 < \cdots < L_C$.

Once again, a large number of these 200,000 parameter combinations are inconsistent with the existence of equilibrium. For example, in the two-city case, 16,925 do not satisfy the modest feasibility condition that $\tilde{z}(\underline{z}, z_{\max}) \geq \theta\left(L/2\right)^{\gamma}$. For more than half the parameter values (primarily those with high θ and L), there is no pair of L_1 and L_2 that is feasible in the sense that tradables output is less than congestion costs. Nonetheless, we examine a wide range of parameter values in an effort to find a counterexample. As Table B.3 reports, we find none. Among hundreds of thousands of parameter combinations, zero yield a case in which a larger city has a lower skill premium. This suggests that the result proved in Proposition 2 for two cities extends to all cities in equilibrium when ability is Pareto distributed.[35]

[35] While we have found that skill premia are increasing in city size for every parameter vector examined in the case of the Pareto ability distribution, the technique employed to analytically prove the two-city result in Proposition 2 cannot be extended to apply to an arbitrary number of cities. Step 2 of our proof employs the fact that $\tilde{z}\left(f\left(z_m\right), Z_2\right) > \frac{p_{n,2}}{p_{n,1}}\tilde{z}\left(z_m, Z_1\right)$, where z_m is the least talented tradables producer in city 1. The analogous condition that, for example, $\tilde{z}\left(f\left(z_{b,1}\right), Z_3\right) > \frac{p_{n,3}}{p_{n,2}}\tilde{z}\left(z_{b,1}, Z_2\right)$, where $z_{b,1}$ is the lowest-ability tradables producer in city 2, is not necessarily true in equilibrium; in fact, some of the equilibria reported in Table B.3 fail to exhibit this property.

Table B.3: Pareto-ability equilibria, 2 to 7 cities

Number of cities	Number of equilibria	Number of non-monotone premia
2	31806	0
3	18871	0
4	17461	0
5	15214	0
6	14388	0
7	12643	0

NOTES: This table summarizes the existence and properties of equilibria with the number of cities listed in the first column. The second column lists the number of equilibria that exist for Pareto-distributed abilities and 200,000 parameter combinations described in the text. The third column lists the number of those equilibria that exhibit skill premia that are not monotone in city population size.

C Data and estimates

C.1 Data description

Data sources: Our population data are from the US Census website (1990, 2000, 2007). Our data on individuals' wages, education, demographics, and housing costs come from public-use samples of the decennial US Census and the annual American Community Survey made available by IPUMS-USA (Ruggles et al., 2010). We use the 1990 5% and 2000 5% Census samples and the 2005-2007 American Community Survey 3-year sample. We use the 2005-2007 ACS data because ACS data from 2008 onwards only report weeks worked in intervals.

Wages: We exclude observations missing the age, education, or wage income variables. We study individuals who report their highest educational attainment as a high-school diploma or GED or a bachelor's degree and are between ages 25 and 55. We study full-time, full-year employees, defined as individuals who work at least 40 weeks during the year and usually work at least 35 hours per week. We obtain weekly and hourly wages by dividing salary and wage income by weeks worked during the year and weeks worked times usual hours per week. Following Acemoglu and Autor (2011), we exclude observations reporting an hourly wage below $1.675 per hour in 1982 dollars, using the GDP PCE deflator. We define potential work experience as age minus 18 for high-school graduates and age minus 22 for individuals with a bachelor's degree. We weight observations by the "person weight" variable provided by IPUMS.

Housing: To calculate the average housing price in a metropolitan statistical area, we use all observations in which the household pays rent for their dwelling that has two or three bedrooms. We do not restrict the sample by any labor-market outcomes. We drop observations that lack a kitchen or phone. We calculate the average gross monthly rent for each metropolitan area using the "household weight" variable provided by IPUMS.

Note that both income and rent observations are top-coded in IPUMS data.

College ratio: Following Beaudry, Doms and Lewis (2010), we define the "college ratio" as the number of employed individuals in the MSA possessing a bachelor's degree or higher educational attainment plus one half the number of individuals with some college relative to the number of employed individuals in the MSA with educational attainment less than college plus one half the number of individuals with some college. We weight observations by the "person weight" variable provided by IPUMS.

Geography: We map the public-use microdata areas (PUMAs) to metropolitan statistical areas (MSAs) using the "'MABLE Geocorr90, Geocorr2K, and Geocorr2010" geographic correspondence engines from the Missouri Census Data Center. For 1990 and 2000, we consider both primary metropolitan statistical areas (PMSAs) and consolidated metropolitan statistical areas (CMSAs). The 2005-2007 geographies are MSAs. In some sparsely populated areas, only a fraction of a PUMA's population belongs to a MSA. We include PUMAs that have more than 50% of their population in a metropolitan area. Table 1 describes PMSAs in 2000.

C.2 Empirical estimates

Our empirical approach is to estimate cities' college wage premia and then study spatial variation in those premia. Our first-stage estimates of cities' skill premia are obtained by comparing the average log hourly wages of full-time, full-year employees whose highest educational attainment is a bachelor's degree to those whose highest educational attainment is a high school degree.

Our first specification uses the difference in average log hourly wages y in city c without any individual controls as the first-stage estimator. The dummy variable college_i indicates that individual i is a college graduate. Expectations are estimated by their sample analogues.

$$\text{premium}_c = \mathbb{E}(y_{ic}|\text{college}_i = 1) - \mathbb{E}(y_{ic}|\text{college}_i = 0)$$

Our second approach uses a first-stage Mincer regression to estimate cities' college wage premia after controlling for experience, sex, and race. The first-stage equation describing variation in the log hourly wage y of individual i in city c is

$$y_i = \gamma X_i + \alpha_c + \rho_c \text{college}_i + \epsilon_i$$

X_i is a vector containing years of potential work experience, potential experience squared, a dummy variable for males, dummies for white, Hispanic, and black demographics, and the college dummy interacted with the male and demographic dummies. The estimated skill premium in each city, $\hat{\rho}_c$, is the dependent variable used in the second-stage regression. We refer to these estimates as "composition-adjusted skill premia."

One may be inclined to think that the estimators that control for individual characteristics are more informative. But if differences in demographics or experience are correlated with differences in ability, controlling for spatial variation in skill premia attributable to spatial variation in these factors removes a dimension of the data potentially explained by our model. To the degree that individuals' observable characteristics reflect differences in their abilities, the unadjusted estimates of cities' skill premia are more informative for comparing our model's predictions to empirical outcomes.

Table 1 describes variation in skill premia using the first skill-premium measure that lacks individual controls. Table C.1 reports analogous regressions for composition-adjusted skill premia that yield very similar results. In the lower panel, we use a quality-adjusted annual rent from Chen and Rosenthal (2008) that includes both owner-occupied housing and rental properties. This reduces the number of observations because Chen and Rosenthal do not report quality-adjusted rent values for every PMSA in 2000, but the results are very similar.

Table C.2 shows the correlation between estimated skill premia and population sizes for various years and geographies using log weekly wages. These specifications are akin to those appearing in the first column of Table 1 and the first column of the upper panel of C.1.

Table C.1: Skill premia and metropolitan characteristics, 2000

Composition-adjusted skill premia				
log population	0.026**	0.029**	0.029**	0.028**
	(0.0031)	(0.0047)	(0.0036)	(0.0045)
log rent		-0.027		0.0051
		(0.032)		(0.034)
log college ratio			-0.027	-0.029
			(0.016)	(0.016)
Observations	325	325	325	325
R^2	0.146	0.151	0.162	0.162
Composition-adjusted skill premia and quality-adjusted rent				
log population	0.027**	0.030**	0.029**	0.030**
	(0.0034)	(0.0047)	(0.0040)	(0.0048)
log quality-adjusted rent		-0.019		-0.015
		(0.026)		(0.025)
log college ratio			-0.014	-0.0069
			(0.018)	(0.015)
Observations	297	297	297	297
R^2	0.145	0.150	0.149	0.151

NOTES: Robust standard errors in parentheses. ** p<0.01, * p<0.05. In both panels, the dependent variable is a metropolitan area's skill premium, measured as the difference in average log hourly wages between college and high school graduates after controlling for for experience, sex, and race. The upper panel uses average gross monthly rent; the lower panel uses quality-adjusted annual rent from Chen and Rosenthal (2008). Details in text of appendix C.

Table C.2: Skill premia and metropolitan populations

Dependent variable	1990 PMSA	1990 CMSA	2000 PMSA	2000 CMSA	2005-7 MSA
Skill premia	0.015**	0.014**	0.033**	0.029**	0.040**
	(0.0038)	(0.0039)	(0.0038)	(0.0036)	(0.0038)
Composition-adjusted skill premia	0.013**	0.013**	0.029**	0.025**	0.028**
	(0.0030)	(0.0031)	(0.0032)	(0.0030)	(0.0033)
Observations	322	271	325	270	353

NOTES: Robust standard errors in parentheses. ** p<0.01, * p<0.05. Each cell reports the coefficient and standard error for log population from an OLS regression of the estimated college premia for weekly wages on log population (and a constant). The sample is full-time, full-year employees whose highest educational attainment is a bachelor's degree or a high-school degree.

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